



Nondestructive testing : a curriculum developed for industrial education
by Merle Clifford Thomas

A thesis submitted in partial fulfillment of the requirements for the degree of DOCTOR OF
EDUCATION

Montana State University

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Abstract:

This study dealt with the problem of selecting methods of nondestructive testing which met the criteria selected by the writer for this study. This criteria included an evaluation of eddy currents, liquid penetrants, magnetic particles, radiography, and ultrasonics in terms of their: (1) compatibility to existing industrial education programs, (2) ability to satisfy one or more of the present needs of industry, (3) relative simplicity and broad encompassing nature, (4) potential in satisfying what the writer believes to be a weakness of the present industrial education program; the exclusion of nondestructive testing methods from the industrial education program, and (5) the educational requirements and competency levels expected of inspectors. The radiographic and ultrasonic methods of testing did not meet the criteria of this study; therefore, procedures for applying these tests in an industrial education program were not included in the study.

Although numerous articles and books exist which deal with the various aspects of nondestructive testing, there are few which deal with this subject in a form easily understood by industrial education teachers. The writer found that there is a definite need for these testing methods in the industrial education program since they could provide a closer correlation between the goals and objectives of industrial education and the needs of industry. This study points out the requirements for initiating a program of nondestructive testing in the areas of eddy current testing, liquid penetrant testing, and magnetic particle testing.

The conclusions reached as a result of this study were: (1) industrial education should provide individuals with measurable competencies in the area of nondestructive testing; (2) there is a definite need for individuals with these competencies in industry; (3) this type of curriculum can easily and quickly be incorporated into existing educational programs; or (4) new programs could be developed in conjunction with chemistry, science, or industrial education programs.

The major recommendations reached as a result of this study were: (1) the guidelines developed in this study were applicable to teachers as well as individuals considering careers in industrial technology; (2) a curriculum committee should be established to develop goals and objectives which are essential to the success of the program; and (3) the curriculum committee should develop a continuous program of evaluation to determine the degree to which the goals and objectives of the nondestructive testing program are being realized and to recommend changes in the program as the need arises.

NONDESTRUCTIVE TESTING: A CURRICULUM DEVELOPED
FOR INDUSTRIAL EDUCATION

by

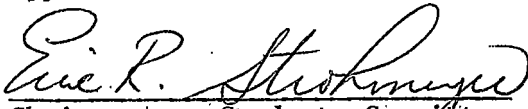
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ABSTRACT

This study dealt with the problem of selecting methods of nondestructive testing which met the criteria selected by the writer for this study. This criteria included an evaluation of eddy currents, liquid penetrants, magnetic particles, radiography, and ultrasonics in terms of their: (1) compatibility to existing industrial education programs, (2) ability to satisfy one or more of the present needs of industry, (3) relative simplicity and broad encompassing nature, (4) potential in satisfying what the writer believes to be a weakness of the present industrial education program; the exclusion of nondestructive testing methods from the industrial education program, and (5) the educational requirements and competency levels expected of inspectors. The radiographic and ultrasonic methods of testing did not meet the criteria of this study; therefore, procedures for applying these tests in an industrial education program were not included in the study.

Although numerous articles and books exist which deal with the various aspects of nondestructive testing, there are few which deal with this subject in a form easily understood by industrial education teachers. The writer found that there is a definite need for these testing methods in the industrial education program since they could provide a closer correlation between the goals and objectives of industrial education and the needs of industry. This study points out the requirements for initiating a program of nondestructive testing in the areas of eddy current testing, liquid penetrant testing, and magnetic particle testing.

The conclusions reached as a result of this study were: (1) industrial education should provide individuals with measurable competencies in the area of nondestructive testing; (2) there is a definite need for individuals with these competencies in industry; (3) this type of curriculum can easily and quickly be incorporated into existing educational programs; or (4) new programs could be developed in conjunction with chemistry, science, or industrial education programs.

The major recommendations reached as a result of this study were: (1) the guidelines developed in this study were applicable to teachers as well as individuals considering careers in industrial technology; (2) a curriculum committee should be established to develop goals and objectives which are essential to the success of the program; and (3) the curriculum committee should develop a continuous program of evaluation to determine the degree to which the goals and objectives of the nondestructive testing program are being realized and to recommend changes in the program as the need arises.

Chapter 1

INTRODUCTION

The term "nondestructive testing" as it is used in this study is a term given to all methods of testing which permit the inspection and evaluation of a metal without impairing its future usefulness.

There is a common tendency to think of nondestructive testing as being limited to the detection of harmful flaws, but such is not the case since these tests can be designed to measure properties which are not considered flaws in the usual sense (Betz, 1966:19). The eddy current method of inspection can, for example, determine material thickness coatings, sort items according to their composition or alloy and monitor metallurgical conditions such as hardness, grain size, and degree of heat treatment. From a quality control point of view, the results of these tests are most significant.

Nondestructive testing in industrial education is still considered to be in its infancy. If it is expected to satisfy the demanding needs of society, new methods and techniques must be developed, including more sophisticated equipment and materials. To accomplish this goal, basic research should be accelerated and programs developed which insure a steady supply of competent inspectors.

With all of our advanced technology, all of our high specialized processes and all of our devices developed for quality control, industry is still unable to produce materials which possess the high

degree of freedom from imperfection that complicated machines and demanding services require. Industry continues to have defective materials, and it should be prepared to evaluate every possible means of locating defects before they can be built into machines and eventually cause them to fail (Betz, 1958:8).

During the period 1930 to 1940, considerable progress was made in the field of nondestructive testing. Industries were coming to regard these methods of inspection with important, if not vital, significance. This was especially true in aircraft maintenance and manufacture. In airframe and engine inspections, nondestructive testing methods were eagerly accepted. The aircraft industry had become so safety conscious that for many years expense was a secondary consideration to any method of testing that would help to assure the integrity and safe life of engines and structures (Betz, 1963:1-2).

Today the acceptance of nondestructive testing methods in industry is practically universal and experience with these methods is now so extensive that complete confidence exists in nondestructive testing methods and in the ability of competent inspectors to interpret the test results (Betz, 1967:59).

Statement of the Problem

Five major methods (Betz, 1966:19) of nondestructive testing are in use today, and it is to these methods that this study is directed. The problem of this study was twofold:

1. To evaluate the five major methods, to determine those applicable to industrial education in a high school situations, and
2. To describe procedures for applying the methods selected in a form more easily understood by high school teachers.

Importance of the Study

McGonnagle (1961:vii) states that ". . . one of the primary requirements in expanding the technology demanded for the solution of tomorrow's problems is education in the field of nondestructive testing."

The writer believes that industrial education has values which apply to all levels of education and in a continuous program these values should become progressively more intensive and cumulative in their effect. It appears to the writer that the statement by Jacobsen (1968:4) can no longer be ignored: "Industrial education too often reflects the revolution of the past century rather than the technological evolution which has taken place since 1940. Much of the relevant content to which we must relate did not exist at that time."

The need to include these methods of testing in the industrial education program becomes increasingly apparent as one considers the statement by Mr. F. B. Stern, Director of Nondestructive Testing, Magnaflux Corporation (1970 personal letter to the writer): "Training in all areas of nondestructive testing is desperately needed by industry. The initial training of prospective operators must be initiated by the

schools."

Further justification for including these testing methods in the educational curriculum can be found in the statement by Mr. T. W. Judd, Assistant Division Head of Nondestructive Testing, Republic Steel Corporation (1974:personal letter to the writer):

. . . at Republic, nondestructive testing is extensively employed to control manufacturing costs and processes, to maintain a uniformly high level of quality and to assure product compliance with technical specifications. Toward this end we employ three to four hundred personnel in nondestructive testing research, product testing, and equipment maintenance and repair. The majority of these people have had no more than a high school education and probably none have had the type of training you are suggesting. However, such training would be most valuable to one working in this field.

The significance of including nondestructive testing methods in the industrial education curriculum has been stated by those who are most knowledgeable in this field. Mr. Carl E. Betz, Nondestructive Testing Consultant and past Vice President, Magnaflux Corporation (1974:personal letter to the writer), makes his opinion quite clear in the following statement:

. . . I believe the high school senior, in general, is quite capable of understanding the basic concepts of nondestructive testing if they are presented without the complex theoretical details. If they are interested in a program which is orientated toward any of the branches of engineering or mechanics, the subject of nondestructive testing would be most useful and interesting. But it must be a carefully planned program which should, if possible, include some laboratory work with either the actual equipment or some simple demonstrations.

For many years I have advocated the teaching of this subject at an early age in the education of young persons who are following a program leading to any branch of engineering or mechanics. Just how early it is considered profitable to begin such

instruction however, may depend upon the ability of the instructor to create interest in the subject and upon the capability of the students to assimilate these methods.

Further evidence of the importance of including these methods in the industrial education curriculum have been stated by Mr. Bruce D. Taylor, Director of Training, Magnaflux Corporation (1974: personal letter to the writer):

. . . who says this method of testing should be included in the high school curriculum? There is not really one single source or even a large group that can make that statement. But my question to them might be, who says that auto mechanics, wood-working, metalworking or welding should be taught in the high schools? Who is to say where anything should have its start?

I cannot give one good reason for not teaching nondestructive testing in the high school other than the mental laziness on the part of the instructor. It does require work preparation on the part of the instructor presenting the course.

Trained nondestructive testing personnel are in great demand, especially in the nuclear inspection field. It can be a great advantage to a youth coming out of high school to have this specialized training. This is especially true if he is going directly to work in industry.

These statements are reinforced by Mr. Roy L. Odell, Western Manager, Automation Industrial Incorporated, Sperry Division (1974: personal letter to the writer):

. . . as a salesman, I encountered many applications for nondestructive testing in industry and it is extremely evident that there is a manpower shortage for trained and qualified personnel.

At the present time there are a few community colleges in the northwest which have nondestructive testing programs in their curriculums. But, there is in my opinion a definite need for new people in this field.

It has been stated that the principles of nondestructive testing date back to the period prior to World War II (Betz, 1963:47).

However, in the opinion of the writer, very little effort has been made to include these methods of testing in the industrial education curriculum. This is particularly disheartening in light of the statement of Mr. J. E. Hinkel, Manager, Application Engineering, Lincoln Electric Company (1974: personal letter to the writer):

. . . all of the processes used in nondestructive testing operate on sound and relatively simple principles of physics, electricity and science. As such they are extremely interesting to students who are so-minded. A casual exposure to these principles could be very rewarding to at least a few of these students. If the curriculum could support it time-wise, I would be in favor of including it.

As an educator in the field of industrial education, David M. Goin (1968:33-34) indicated that nondestructive testing methods could be incorporated into existing metal working programs without disrupting them. It is his opinion that these methods of testing could do much to enhance the present industrial education program.

. . . in the metal industry today, nondestructive testing is of great importance in design and quality control. These methods can be integrated into the curriculum of the machine shop, welding shop and general metals shop or they could be taught as a separate testing and metallurgy unit involving different tests, heat treating, or the study of metals in general. I sincerely hope that other industrial arts teachers will see the need for this type of program and will work to initiate it in different parts of our country, to try and get away from the old "manual training" concept of teaching metal working in our high schools.

Since industrial education has been charged with the formidable task of reflecting the current image of one of the most important aspects of our present culture: the correlation between education, technology, and industry, the writer believes industrial education

teachers cannot be expected to satisfy the needs of their profession until they have developed a certain measure of competency in the area of nondestructive testing. This includes an awareness and knowledge of:

1. The basic theories and principles of these tests
2. The advantages and limitations of these tests
3. The potential safety hazards of the tests, and
4. The skills required to satisfactorily perform these methods

of testing

This belief is reinforced by the American Vocational Education Association in their report, A Guide to Improving Instruction in Industrial Education (1968:9-11). In this report, their stated goals and objectives for industrial education were:

- A. To develop an insight and understanding of industry and its place in our culture
- B. To discover and develop talents, aptitudes, interests and potentialities of individuals interested in technical pursuits
- C. To develop an understanding of industrial processes and the practical applications of scientific principles
- D. To develop basic skills in the proper care and use of common industrial tools, machines and processes, and
- E. To develop problem solving and creative abilities involving materials, processes and products of industry

Methods of Collecting Data

The general procedures which the writer used to gain background knowledge for this study were:

- A. An extensive and thorough review of existing published

literature as it pertained to past and present methods of conducting nondestructive tests. Professional journals of scientific and trade associations, United States Government publications, current industrial texts and selected publications from manufacturers of nondestructive test equipment and materials were analyzed for relevant data.

B. Personal letters were written to selected specialists in the field of nondestructive testing who were considered to have first-hand knowledge and technical experience in the field of nondestructive testing. A copy of this letter has been included in Appendix C, page 374. Authoritative data were obtained from:

1. Automation Industries Incorporated, Sperry Division,
Renton, Washington
2. General Dynamics, San Diego, California
3. Magnaflux Corporation, Chicago, Illinois
4. Office of the Assistant Secretary of Defense, Washington,
District of Columbia
5. Pacific Northwest Laboratories, Richland, Washington
6. Republic Steel Corporation, Cleveland, Ohio
7. The Lincoln Electric Company, Cleveland, Ohio

C. In addition to the authoritative knowledge from selected specialists in the field of nondestructive testing, certain knowledge was available to the writer as a direct result of:

1. Completion of a certified Class (C) school of nondestructive testing at the Naval Air Station, Pensacola, Florida

in 1962

2. His past position as supervisor of the nondestructive testing department at Ellyson Field, Pensacola, Florida from 1962-1964

3. Feedback from personal discussions with other members of the United States Navy who were actively engaged in testing aircraft parts with nondestructive testing processes and other civilian personnel who worked in the nondestructive testing division of the overhaul and repair department at the Naval Air Station, Pensacola, Florida

Methods of Organizing Data

Chapters 2 through 6 of this study deal with a critical analysis and evaluation by the writer of the five major nondestructive methods of testing metals. Each of these chapters include:

1. A brief history of one testing process
2. A description of one testing process, the materials, and equipment required to perform the test, the types of discontinuities which could be located with the test and the advantages and limitations of the test
3. The principles of the test
4. The purpose of the test
5. The types of test materials and test equipment commercially available

6. An evaluation of the testing process by the five criteria set forth in the analysis of data section of this chapter

When a testing process met the five criteria, procedures for applying the test in an industrial education program at the high school level were described in depth. These descriptions included:

1. The preparation of the parts prior to the actual test
2. The application of the test materials, if any, to the part being tested
3. The inspection procedures and the methods used to evaluate the parts
4. The methods used to establish acceptable inspection standards
5. The various factors which could adversely affect these tests

Chapter 7 provides a summary of the study and the conclusions and recommendations of the writer.

Analysis of the Data

Once the data had been collected and organized, each of the testing processes was analyzed and evaluated in terms of its:

1. Compatibility to existing industrial education programs
2. Ability to satisfy one or more of the present needs of industry
3. Relative simplicity and broad encompassing nature
4. Potential in satisfying what the writer believes to be a

weakness of the present industrial education program: the exclusion of nondestructive testing methods from the industrial education program

5. The educational requirements and competency levels expected of inspectors

When a test satisfactorily met the five criteria, procedures for applying the test in an industrial education program was described. The premise of the writer was, that once suitable nondestructive testing guidelines had been described, teachers would be encouraged by the availability of these guidelines to include these testing processes in their programs.

Questions to be Answered

It was stated earlier in this study that the acceptance of nondestructive testing by industry is practically universal, that there is no question as to the usefulness of nondestructive testing and that experience with these methods of inspection is now so extensive that confidence in its indications and in the ability of experienced inspectors to interpret these indications is now the rule in those industries where nondestructive methods of inspection are applicable. Since this study was written specifically for teachers in the area of industrial education, the following question was answered: did the eddy current liquid penetrant, magnetic particle, radiographic and ultrasonic method of inspection meet the evaluative criteria for inclusion in the industrial education program?

Limitations of the Study

1. No attempt was made in this study to provide the reader with information pertinent to the development of the various types of nondestructive test equipment. Emphasis was placed on the description of procedures which the writer considered "need to know."

2. Only those processes, procedures, methods of inspection, and evaluation which were applicable to the nondestructive testing of metals were included in this study.

3. Procedures for applying the nondestructive testing processes were described only when a test process met the five criteria set by the writer.

Delimitations of the Study

This study was further limited to the study of:

1. The five major methods of nondestructive testing. No attempt was made by the writer to examine or evaluate the more than sixty variations of these five major testing methods.

2. Each of the methods selected was examined in terms of whether or not it could specifically meet the five criteria set by the writer for inclusion in the industrial education program.

SUMMARY

The term "nondestructive testing" as it is used in this study is a general term given to all methods of testing which permit the

inspection and evaluation of a metal without impairing its future usefulness.

With all of our advanced technology and all of the devices industry has developed for quality control, our nation is still unable to produce materials which possess the high degree from imperfection that our highly complicated machines and demanding services require. The acceptance of nondestructive testing by industry is practically universal today, and experience with these methods is now so extensive that complete confidence exists in these testing processes and in the ability of competent inspectors to interpret the results.

Statements by Betz, Goin, Stern, and Tyler indicated a growing awareness on the part of industry and education that nondestructive testing methods should become an integral part of the educational program. In their opinion, it is the responsibility of the schools to initiate methods of instruction and provide the means for the practical application of these methods of testing.

Numerous volumes have been written on the subject of nondestructive testing, but the writer believes that large amounts of this data were not available in a form easily understood by industrial education teachers.

The problem of this study was twofold: (1) to evaluate the five major methods of nondestructive testing according to the criteria set by the writer for inclusion in industrial education programs; and

(2) to describe procedures for applying those testing processes found acceptable to the industrial education program in a form more easily understood by teachers. Once the data had been collected and organized, each of the testing processes was evaluated in terms of five criteria:

1. Compatibility to existing industrial education programs
2. Ability to satisfy one or more of the present needs of industry
3. Relative simplicity of the test and its broad encompassing nature
4. Potential in satisfying what the writer believes to be a weakness of the present industrial education program: the exclusion of nondestructive testing methods from the industrial education program
5. The educational requirements and the competency levels expected of entry-level inspectors

An in-depth description for applying these tests in industrial education programs was included only when a test satisfactorily met the five criteria set by the writer. The premise of the writer was, that once suitable nondestructive testing guidelines had been described, teachers would be encouraged by the availability of these guidelines to include these testing processes in their industrial education program.

No attempt was made by the writer to provide the reader with data pertinent to the development of test equipment or materials.

Emphasis was placed on the description of "need to know" data in a form more easily understood by industrial education teachers.

Chapter 2

LIQUID PENETRANT TEST

The liquid penetrant method of nondestructive testing is a method used to locate discontinuities which are open to the surface in solid and essentially nonporous metals. The method employs a penetrating liquid which is applied evenly over the surface and subsequently enters the discontinuity or crack. After the excess penetrant has been removed from the surface, the penetrant which exudes or is drawn out of the crack by the developer is observed thus indicating the presence and the location of the discontinuity (Betz, 1963:17).

History of the Liquid Penetrant Process

The forerunner of the present day liquid penetrant testing process was the oil and whiting method. This process was effectively used by the railroad industry in the Nineteenth Century for a maintenance of steam locomotives. The penetrant, a heavy and usually dirty lubricating oil was thinned with kerosene or a light oil to make it more functional. Locomotive parts, such as rods, axles, and crank pins were cleaned by immersing them in a caustic soda solution, allowing them to dry, and then immersing them in the diluted lubricating oil. The inspection was performed by wiping the part clean and then applying a mixture of chalk and denatured alcohol. This mixture dried rapidly leaving a dead-white uniform surface. The oil entrapped by the

discontinuity would then seep out leaving a dark stain as an indication of a possible defect.

In 1938, as a direct result of the defense effort, experimentation was conducted with colored dyes in an attempt to increase the contrast of the indications. Maximum sensitivity was achieved by using a penetrant mixed with a dye to produce a high degree of color contrast. A red dye was most generally used, because the deep red color presented an excellent contrast with the white background of the developer.

In 1941 a greatly improved liquid penetrant containing fluorescent rather than visible dye was introduced on the industrial market. This fluorescent dye gave superior contrast when it was used in conjunction with an ultra violet light. This so called "black light" caused the dye to fluoresce. Through continued experimentation with these fluorescent dyes, ranging in color from red to blue, it was discovered that maximum visibility or effect on the human eye was obtained when a yellow-green dye was used. That is, maximum stand out was obtained using a yellow-green luminescence which was viewed under an ultra violet light in an otherwise dark area (Lomerson, 1972:2.1-2.2).

With the expanding use of nonmagnetic materials such as aluminum, magnesium, and some grades of stainless steel, the lack of an acceptable method of nondestructive testing to effectively locate critical surface defects was felt by industry. Since the magnetic

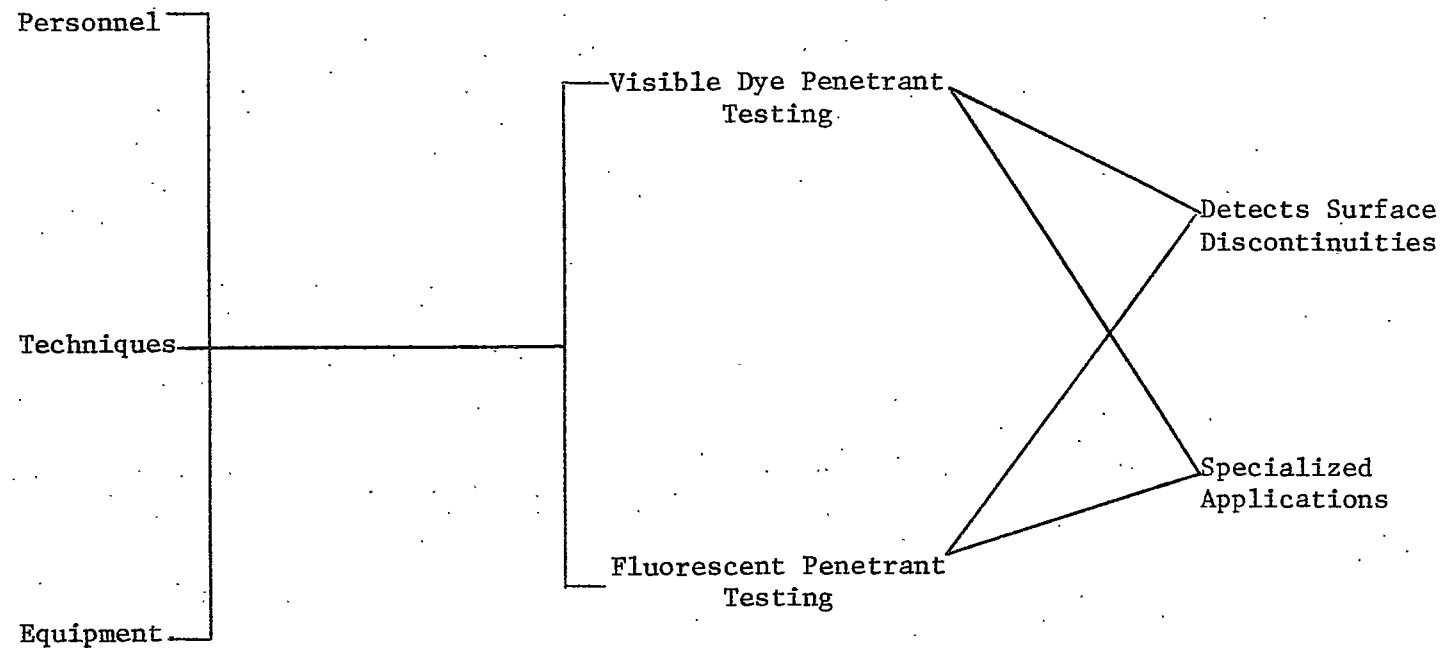
particle testing process is limited to ferro-magnetic materials, what was desperately needed by industry was a quick, easy, and inexpensive method of testing nonmagnetic materials.

Today, the automotive industry uses the liquid penetrant process to inspect aluminum castings and forgings, plastic components, bonded joints, automatic transmissions and housings, running gears, and welds. Overhaul and rebuild shops are heavy users of this method of inspection when they test components for trucks, busses, sport, and racing cars.

Description of the Liquid Penetrant Process

A basic description of the liquid penetrant methods of inspection is provided in Figure 1, page 19 (General Dynamics, 1967:7.5-7.6). The equipment required, types of discontinuities detected with the penetrant method, and the limitations of this method of testing are (Hinkel, n.d.:13):

1. Equipment required: Commerical kits containing fluorescent dyes, dye penetrants and developers, application equipment for the developer, and a source of ultra violet light when the fluorescent method is used.
2. Enables the detection of: Surface cracks not readily visible to the unaided eye, and the location of leaks in weldments.
3. Advantages: Applicable to magnetic and non-magnetic



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Figure 1
Liquid Penetrant Testing

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materials, easy to use, and relatively low in cost.

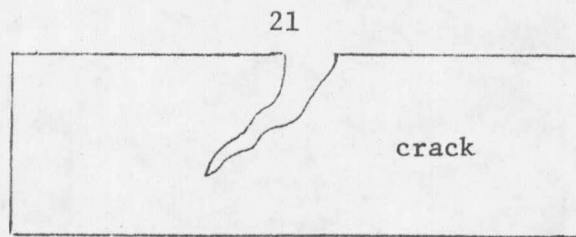
4. Limitations: Only surface defects are detectable and the process cannot be used on hot surfaces.

Principles of Liquid Penetrant Testing

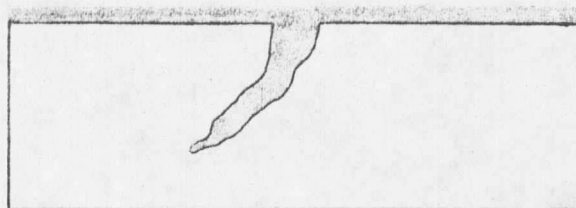
Liquid penetrants depend for their success upon the principle that a penetrating liquid entering a surface opening and remaining in that opening will be made clearly visible to the inspector when the proper developer is applied. This process can be used successfully to detect discontinuities caused by shrinkage, porosity, fatigue, seams, cold shuts, forging bursts, and heat treating processes. The liquid penetrant method also provides an excellent means of detecting a lack of bond between joined metals.

The principles involved in the liquid penetrant inspection process are simple. They involve three basic steps: (1) application of the penetrant; (2) removal of the excess penetrant; and (3) application of a suitable developer. These basic concepts are illustrated in Figure 2, page 21 (McMaster, 1959:8.1).

Regardless of the type of penetrant being used, the inspector should adhere closely to the procedures listed for the type of penetrant inspection being performed.



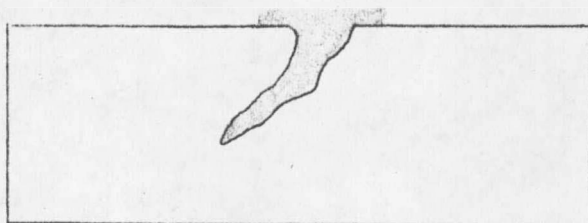
A. Cleaned Surface



B. Application of the Penetrant



C. Removal of Excess Penetrant



D. Application of the Developer

Figure 2

Mechanism of Penetrant Flaw Detection

Purpose of Liquid
Penetrant Tests

Up to this point, the penetrant method has been described in terms of what it is, how it works, and what it can do. Not much has been said about how these tests are actually used in industry. The liquid penetrant tests are used with three different philosophical points of view, each of which has a different principal purpose.

1. To use these tests to locate flaws before the finished product goes to the consumer.

2. To apply these tests at various stages of the production process thus permitting the removal of defective parts before further processing costs occur.

3. To tabulate and analyze data obtained for the specific purpose of improving the product design of future products.

All of these concepts are an integral part of the production process, and each is equally responsible for reducing the cost and increasing the service life of the product.

For many years a great argument has raged through the penetrant field as to just what qualities make a good penetrant and what types of tests should be used to separate acceptable parts from unacceptable ones. The most important quality of a good penetrant is its ability to locate discontinuities with accuracy and reliability. However, other criteria should be given careful consideration before the final selection is made. Past experience has indicated that many factors

must be considered by those selecting penetrants on the basis of performance. A good penetrant:

- A. Readily penetrates very fine openings
- B. Is able to remain in relatively coarse openings
- C. Does not dry or evaporate too easily
- D. Is easily removed from the surface
- E. Bleeds easily from discontinuities when the developer is applied
- F. Has the ability to spread out from the edge of a very small opening in a very fine film
- G. Has great brilliance of color or fluorescence
- H. Has permanence of color when it is exposed to heat, light, or ultra violet light
- I. Is inert with respect to the materials being tested and to the containers
- J. Is odorless, nonflammable, and nontoxic
- K. Is stable under conditions of use and storage
- L. Is relatively low in cost

Penetrants meeting the requirements listed should be quite sophisticated. On one hand, they are required to wash thoroughly away from areas which are of little or no significant interest, and at the same time they are expected to locate discontinuities which are extremely tight, fairly wide, shallow, or deep.

Types of Penetrants and Test
Equipment Commercially Available

Penetrants which are commercially available can be divided into two basic categories: dye penetrants and fluorescent penetrants.

In the case of the dye penetrants, a special dye is selected which provides a high degree of contrast between the penetrant and the developer. In the fluorescent penetrant process, the material which is added requires excitation by ultra violet radiation, and observation under subdued light. Since all petroleum products fluoresce to a certain degree, fluorescent penetrants usually have an oil base. Table 1, page 25 (McGonnagle, 1961:58), provides a brief summary of the characteristics of commercial penetrants available today.

Generally speaking, no special equipment is required for conducting the penetrant inspection. Color contrast and fluorescent penetrants can be applied by hand, the excess penetrant can be removed by hand cleaning and the developer can be applied by hand. In this respect, the only item of special equipment required is the ultra violet light for the fluorescent penetrant process. This type of inspection is considered acceptable when: (1) there are only a few parts to be inspected, (2) maximum sensitivity is not required, and (3) it is the most suitable method to use because the part is too large or the proper equipment to do the inspection is not available.

On the other hand, standard industrial inspection equipment is considered essential for the proper employment of the penetrant when:

Table 1

Commercially Available Liquid Penetrants

Trade Name	Dy-Chek	Metal-Chek	Spotcheck	Zyglo
Manufacturer	Turko Products	Met-L-Chek	Magnaflux	Magnaflux
Penetrant Type	Liquid Red Dye	Liquid Red Dye	Liquid Red Dye	Fluorescent Liquid
Applied By	Brush, spray, or dip	Brush, spray or dip	Spray can	Brush, dip, or spray
Removed by	Solvent	Water	No. 1 cleaner	Water
Developer	White powder suspension	White power suspension	Volatile Liquid Suspension of white powder	Power or liquid
Indication Visible by	White light	White light	Ordinary light	Ultra Violet light
Auxiliary Apparatus	None	Source of water	None	Source of water and light

(1) many parts are to be inspected on a production line, (2) large parts are to be inspected regularly, (3) a high degree of sensitivity is required, and (4) consistent repetitive results are required as they are in production testing (Betz, 1963:241-242).

The equipment considered essential to the success of the penetrant process in industrial departments includes: (1) precleaning and penetrating stations, (2) solvent remover and washing stations, and (3) drying and rinsing stations. Since automation is moving into the penetrant testing process, units have been designed using prepunched computer cards which program various aspects of the testing process.

Prepunched computer cards have been successfully programmed to account for variables such as penetration time, drying time, and developing time. When the testing specifications have been predetermined for a given part, a pallet of parts carrying process specifications can be automatically processed in accordance with a predetermined program. The sequence of operations for individual pallets can easily be varied.

Black light. The ultra violet light (black light) used in the penetrant process has been standardized at 3,650 angstrom units. This is the peak transmission wave length for commonly used black light filters. The recommended intensity level for the black light is 200 foot candles at a distance of twelve inches. A typical black light test unit is illustrated in Figure 3, page 27 (Magnaflux Corp., 1957:5).

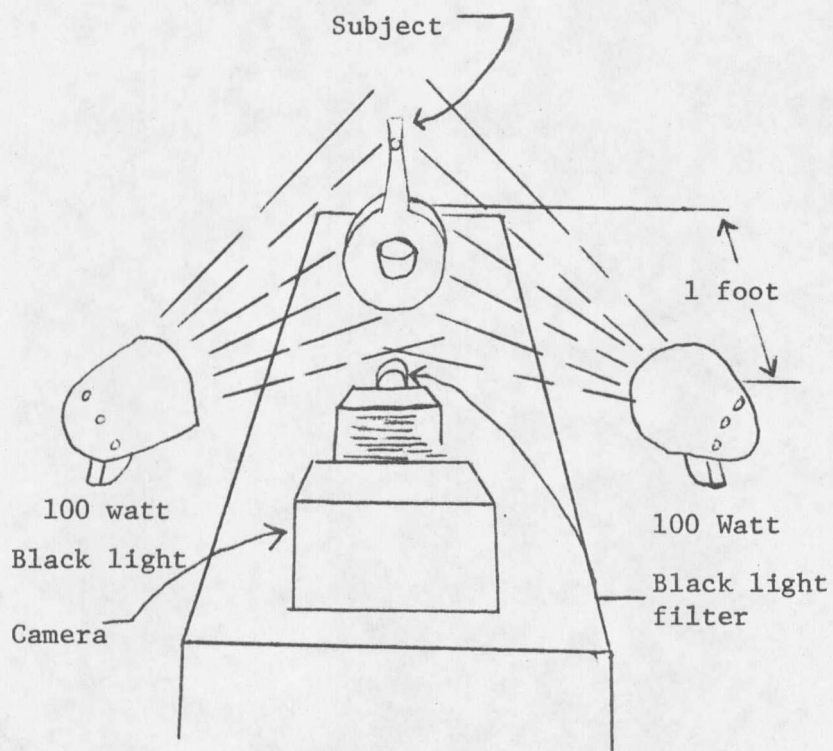


Figure 3
Typical Black Light Test Unit

The term "black light" is applied to near ultraviolet radiation having a wave length shorter than the shortest wave length in the visible spectrum. It has the property of causing many substances, such as certain minerals and dyes, to fluoresce. Though this radiation is not visible to the human eye and is therefore characterized as being "black," it is produced by the mercury arc as a byproduct of visible white light, along with other shorter wave length radiation.

The black light used to energize the dyes in the fluorescent penetrant process, thus making them appear to glow in the dark, is an integral part of the inspection process. The user of the black light should therefore understand the theory of black light and should know how to make proper use of the equipment which generates this light. He should also become familiar with the techniques required for successful inspections using the fluorescent penetrants.

The lamps used in the penetrant process are susceptible to fluctuations in line voltage. A small percentage of line voltage drop may cause the bulb to be extinguished. When this occurs, the bulb should be allowed to cool completely before any attempt is made to relight it. It is recommended that the line to which the black lights are connected have a voltage as constant as possible. If necessary, a constant voltage transformer should be used in the circuit.

The inspector should allow his eyes to become accustomed to the darkness of the inspection booth before he attempts to inspect

components. He should avoid going from darkness to light and back without allowing sufficient time for his eyes to adjust to the dark.

Black light entering the eyeball will cause a cloudy effect due to the fact that the liquid in the eyeball fluoresces. This may be caused by either direct or reflected black light. This effect, however, lasts only as long as the light enters the eye and it is not considered harmful. It is fatiguing and therefore reduces the sensitivity of the inspection. Care should be taken to arrange the black lights so that neither the direct light from the lamp nor the reflected light enters the inspector's eyes.

Temperature requirements. Maximum penetration into extremely small openings requires both the penetrant and the surface of the part being inspected to be maintained within the guidelines set by the manufacturer. In no case should the temperature be allowed to go below 50° F. Nor should the temperature of the penetrant and the test part be allowed to exceed 100° F at the time of application. Therefore, the use of an open flame for heating purposes is prohibited (Department of the Navy, 1965:29).

Maintaining penetrant serviceability. Penetrant inspections are normally considered to be a very sensitive and critical process. Since it is used to detect discontinuities in vital parts, which are not readily detectable by other means of inspection, the dependability of

the materials used in the inspection process are of considerable importance to those who purchase parts which have been inspected by this process.

Penetrant procedures are not a fail-safe process. The absence of an indication may indicate that the part in question is an acceptable part, but it might also mean that the inspection process has failed to detect a defective part. Therefore, it is very important that the inspector be sure that the penetrant inspection is actually doing the job expected of it. Proper supervision can keep the equipment and procedures within specifications, but how can one be sure that the materials being used in the process are actually capable of accomplishing the required job? One way is to purchase trustworthy inspection materials, keep them sealed and protected until they are needed, and once they have been used discard the remainder. This procedure is often considered the most practical for field tests or highly automated test operations. In most cases, however, the inspection materials are kept in open tanks with the parts being dipped or sprayed with the penetrant materials, and the remainder being returned to the tank for reuse. Here, ample opportunity exists for contamination. Even when no contamination occurs, the inspection materials are left unprotected from the ravages of evaporation and time.

Inspection materials can be ruined suddenly by the introduction of substantial amounts of foreign matter. Far more insidious, and for

that reason more dangerous, is the gradual day-by-day deterioration which usually goes unnoticed. Normally, this type of deterioration is readily detectable, if a comparison is made between the new penetrant materials and the old penetrant materials. Such comparisons, however, must be made on a side-by-side basis to eliminate not only the effect of individual testing techniques, but because the human memory for an absolute order of magnitude is very poor (Schmidt, 1969:259).

Selection of the Penetrant Testing Method

Although many inspection problems can be solved in a satisfactory manner using one or another of the penetrant testing methods, one testing process may be preferred for a specific material. When a choice of inspection method is possible, the selection may be just as important as the testing procedures used by the inspector. Tables 2, 3, 4, and 5, pages 32 through 35, respectively, provide guidelines for the selection of a process when the type of defect and inspection situation are known (McMaster, 1959:6.22-6.23). The advantages and disadvantages of each test are listed in these tables.

Generally speaking, penetrant inspection processes are evaluated on the basis of: (1) their ability to locate open and shallow discontinuities, (2) their sensitivity to very fine discontinuities, and (3) their relative brightness. Other criteria by which these processes are evaluated are mainly economic. In general, the most effective

Table 2

Liquid Penetrant Tests

Inspection Problem	Preferred Process *	Remarks
High production of many small parts	W	Small parts in baskets
High production of a few large parts	P-V	Large extrusions and forgings
High sensitivity to fine defects required	P	Brightest indication, most sensitive
Detection of shallow defects and scratches	P-V	Controlled depth of emulsification
Parts with medium rough surfaces	W-P	Choice depends upon production and sensitivity required
Threaded parts and parts with keyways	W-V	Process (P) Penetrant may lodge in the corners
Parts have rough surfaces	W	
Spot testing of local areas	V	
Portable equipment required	V	
Water and electricity not available	V	
Anodized parts cracked after anodizing to be inspected	V-P-W	Order of preference
Repeated applications of the process is required	V-P	Five or six repeats should be the limit
Leak detection	W-V	Penetrant only

* P = Post Emulsifier Fluorescent Penetrant

V = Water Washable Visible Dye Penetrant

W = Water Washable Fluorescent Penetrant

Table 3

Post Emulsification Fluorescent Penetrant Process
(Process P)

Advantages	Disadvantages
1. Has fluorescence for greater visibility	Application of emulsifier in separate operation
2. Higher sensitivity to very fine defects	Requires inspection in the dark with a black light
3. Can locate wide and shallow defects	Sometimes difficult to wash penetrant from: A. threads B. keyways C. blind holes
4. Easily washed with water after emulsification	Some materials flammable
5. Short penetration time	Difficult to use on rough surfaces, especially on castings
6. High production, especially with large parts	Requires a rinsing aid
7. Can be used on anodized surfaces	
8. Can be used on chromate surfaces	
9. Parts can be rerun satisfactorily	

Table 4

Water Emulsifiable Visible Dye Penetrant
(Process V)

Advantages	Disadvantages
1. Has greater portability, requires no black light	Some materials flammable
2. Can be used on suspected local areas of large parts, aids in rework and repair	Expensive in man hours
3. Can be used on parts where contact with water is not permissible or water is not available	Indications are less visible than fluorescent indications
4. Can be used on anodized surfaces	Difficult to use on rough surfaces, especially on castings
5. Can be used where parts are to be inspected in ordinary light	Materials should not be used in open tanks
6. Best technique for contaminated defects not sensitive to residual acidity or alkalinity	Requires a rinsing aid
7. High sensitivity to very fine defects	Not very good on wide or shallow defects

Table 5

Water Washable Fluorescent Penetrant
(Process W)

Advantages	Disadvantages
1. Has greater fluorescent visibility	May be difficult to rerun parts
2. Easily washes with water	Anodizing may effect sensitivity
3. Good for quantities of small parts	Chromate finish may affect sensitivity
4. Good on rough surfaces	Requires inspection in the dark with a black light
5. Good in keyways and on threaded parts	Not reliable for detecting scratches and similar shallow surface conditions
6. High speed, economical of time, and good on a wide range of defects	

penetrant would be the one which reliably exposed shallow and open discontinuities, had the highest degree of sensitivity for very fine discontinuities, took the least amount of time, and was the most economical to use.

EVALUATION OF THE LIQUID PENETRANT TEST

The liquid penetrant inspection process was evaluated by the writer to determine whether or not it met the five criteria set forth in the analysis of data section. The liquid penetrant inspection process met the criteria in the following ways.

Compatibility to Existing Industrial Education Programs

The writer believes that the justification for including non-destructive testing programs in the industrial education curriculum can best be stated by those who are knowledgeable in this area. David M. Goin (1968:33-34) stated that nondestructive methods of inspection could be incorporated into existing metalworking programs without disrupting them. He believes these methods could be integrated into the curriculum of the machine shop, welding shop, and general metals shop or they could be taught as a separate testing or metallurgy unit involving the different tests, heat treating, or the study of metals in general.

Bruce D. Tyler, Director of Training, Magnaflux Corporation

(1974: personal letter to the writer), made the following statement, ". . . I cannot give one good reason for not teaching nondestructive testing in the high school other than the mental laziness on the part of the instructor." Carl E. Betz, Nondestructive Test Consultant and past Vice-President to Magnaflux Corporation (1974:personal letter to the writer), sums up the need for including nondestructive testing processes in the high school program, ". . . for many years I have advocated the teaching of nondestructive testing at an early time in the education of young persons who are following a program leading to any branch of engineering or mechanics."

The inclusion of the liquid penetrant inspection process can, in the opinion of the writer, be justified by the goals and objectives (page 7) which the American Vocational Education Association set for industrial education (1968:9-11).

Ability to Satisfy One or More of
the Present Needs of Industry

Warren J. McGonnable (1961:vii) stated that ". . . one of the primary requirements for expanding the technology for the solution of tomorrow's problems is education in the field of nondestructive testing." Roy L. Odell, Western Manager, Automation Industrial Incorporated, Sperry Division (1974:personal letter to the writer), reaffirms this need by his statement that, ". . . as a salesman, I encounter many applications for nondestructive testing in industry

and it is extremely evident that there is currently a manpower shortage for trained and qualified personnel." The future for competent liquid penetrant inspectors looks encouraging when one considers the following statement by Betz (1967:59):

Today, the acceptance of nondestructive testing methods is practically universal and experience with these methods is now so extensive that complete confidence exists in these methods of inspection and in the ability of competent inspectors to interpret the test results.

Relative Simplicity and Broad
Encompassing Nature

The growth in the use of aluminum and other nonmagnetic metals created a serious situation in industry. What was desperately needed was a quick, easy, inexpensive, and reliable method of detecting discontinuities which are open to the surface. The liquid penetrant method met the criteria since there is no limitation on the size or shape of the part which can be inspected nor is there any limitation on the composition of the part as long as the surface is essentially nonporous in nature.

The liquid penetrant test requires three basic steps: (1) application of the penetrant, (2) removal of the excess penetrant, and (3) application of a suitable developer. No special equipment is required. Therefore, equipment and material costs are not a significant factor. Dye penetrant kits such as the DP-40, which contain a penetrant, cleaner-remover and a developer can be purchased

for \$3.95 from Sherwin Incorporated, 5007 East Washington Boulevard, Los Angeles, California 90040.

The relative simplicity of these methods of inspection is clearly stated by J. E. Hinkel, Manager of Application Engineering, Lincoln Electric Company (1974:personal letter to the writer), ". . . all of the processes used in nondestructive testing operate on sound and relatively simple principles of physics, electricity, and science." The ability of high school seniors to comprehend these testing concepts is reinforced by the statement by Carl E. Betz, Nondestructive Test Consultant and past Vice-President, Magnaflux Corporation (1974:personal letter to the writer), ". . . I believe the high school senior is quite capable of understanding the basic concepts of non-destructive testing if they are presented without the complex theoretical details."

Potential in Satisfying What the
Writer Believes to be a Weakness
of the Present Industrial
Education Program

Based upon an evaluation of the stated goals and objectives of industrial education as set forth by the American Vocational Education Association on page 7 (1968:9-11), the writer believes that industrial education teachers cannot be expected to satisfy the needs of their profession unless they have developed a certain measure of competency in liquid penetrant testing. This competency should include an

awareness and knowledge of: (1) the basic theories and principles, (2) the advantages and limitations, (3) the potential safety hazards, if any, and (4) the skills required to satisfactorily perform the liquid penetrant test.

Eckhart A. Jacobsen (1968:4) compliments the writer's belief with the following statement, "Industrial Education too often reflects the revolution of the past century rather than the technological evolution which has taken place since 1940. Much of the relevant content to which we must relate did not exist at this time." David M. Goin (1968: 33-34) reinforced this belief with the following statement:

. . . I sincerely hope that other industrial education teachers will see the need for nondestructive testing and will work to initiate it in different parts of our country, to try and get away from the old "manual training" concept of teaching metal-working in our high schools.

The Educational Requirements and
Competency Levels Expected of
Inspectors

Since this study is concerned with the development of entry-level competencies in the area of liquid penetrant testing, only those requirements which are essential to the development of this level of competency have been included in this study. Each entry-level inspector is expected to demonstrate, prior to being considered for certification in the field of liquid penetrant testing, that he has acquired (American Society for Nondestructive Testing, 1968:1-7): (1) sufficient education and experience to insure an understanding of the liquid

penetrant principles and procedures; (2) instruction in the processing of parts: under no circumstances should he be permitted to inspect parts prior to certification; and (3) sufficient knowledge to pass an examination which includes questions related to the equipment, operating procedures, and testing techniques. Prior to his certification, the entry level inspector should work at all times under the supervision of a certified inspector. He is directly responsible to this certified inspector for the proper performance of all liquid penetrant inspections.

According to Carl E. Betz (1963:125), the liquid penetrant inspector should have the following physical and natural competencies:

He should have good eyesight and should not be color blind. He must be alert, intelligent, conscientious and must be fully aware of and willing to accept the responsibilities of the job he is expected to do for the company.

Having met the five criteria as set forth in the analysis of data section, procedures for applying the liquid penetrant process in industrial education programs at the high school level have been described in depth.

PROCEDURES FOR APPLYING THE LIQUID PENETRANT PROCESS IN INDUSTRIAL EDUCATION

In theory, the liquid penetrant testing process is simple. Its effectiveness is based upon the infallible natural phenomenon of capillary action, one of the most powerful forces in nature (Sherwin,

1968:225).

In the liquid penetrant process, the penetrant does not seep into the discontinuity. It is literally pulled into the crack or discontinuity by capillary action. This force is the same force which draws sap to the top of tall trees or causes oil to rise through the wick of an oil lamp.

When the developer is applied, after the excess penetrant has been washed from the surface of the part, it acts like a blotter and draws the penetrant remaining in the crack or discontinuity to the surface of the part where it can be evaluated by the inspector.

To provide continuity in the inspection process, the following inspection steps are suggested:

1. Preparation of the parts
2. Application of the penetrant
3. Removal of the excess penetrant from the surface
4. Proper drying of the parts to be tested
5. Application of the developer
6. Inspection and evaluation of the parts
7. Establish acceptable inspection standards
8. Post-inspection cleaning of the parts prior to service

Preparation of the Parts

The preparation of the parts prior to the actual inspection is of utmost importance. The principle of all penetrant inspection

processes is the fact that the penetrant must be able to enter surface openings, if it is expected to identify cracks and discontinuities. Unless the parts are free of foreign materials, reliable inspections cannot be expected. There should be no paint, platings, scale, or grease on the surface of the part. All surfaces being inspected should be completely free of all extraneous materials. When a nonvolatile liquid is used to clean the parts, the surface should be heated or dried with hot air to insure the complete removal of the cleaning agent. As a final cleaning operation, each surface should be dipped, sprayed, wiped, or brushed with trichloroethylene, perchloroethylene, acetone, ethanol, or isopropanol.

Each part should then be thoroughly dried to remove the excess cleaner by wiping the part with a clean, dry cloth or absorbent paper and allowing the remainder to evaporate for a minimum of five minutes. Prior to the liquid penetrant inspection, the surface to be tested and any adjacent area within one inch of the area being inspected should be dry and free of all dirt, grease, scale, salts, or other extraneous materials which could obscure surface openings or otherwise interfere with the inspection process (Bureau of Naval Personnel, 1963:29).

Penetrants held on the surface of the part by dirt or other foreign materials can easily lead to false indications. Liquid solvents, vapor blasting, acid etching, and vapor degreasing can be used to prepare the surface. By far the most satisfactory method of cleaning

parts is the vapor degreasing process which cleans out cracks and other surface openings better than any hand process. The parts come from this process hot, so all solvent materials are driven out of the discontinuities. Any water that might have been lodged in a discontinuity is also driven out by the heat. There is no positive way to insure that discontinuities are free of water except by heating. For this reason, vapor degreasing as a step preparatory to any form of penetrant inspection is highly recommended (Betz, 1963:106).

Application of the Penetrant

Theoretically, all that is necessary in the penetrant inspection process is to cover the surface of the part with penetrant and leave it there long enough for the penetrant to be drawn into the discontinuity.

When the penetrant is in a tank of sufficient depth, however, the obvious method is to dip the part into the penetrant and then lay the part on a rack to drain. The recovery of the penetrant is of economic importance, but otherwise incidental. The principle thing to be concerned about is pockets of air which may have been trapped in openings, thus preventing the penetrant from entering the discontinuity.

When the parts are hot from the degreaser process, they should be allowed to cool to room temperature before they are dipped. If they are dipped while they are still hot, they should be allowed to remain in the penetrant bath until they have cooled sufficiently. If

the parts are removed from the penetrant while they are still hot, the heat will tend to dry the penetrant on the surface of the part causing a lack of proper penetration.

When the parts are too large to dip, penetrant tanks are often equipped with a pump and hose so the penetrant can be flowed over the surface of the part more easily. The inspector should make sure that all cavities have been thoroughly covered with penetrant. When automatic equipment is used, spray nozzles are incorporated to impinge penetration on the part from all directions. When the shape of the part permits, hosing or flooding of the part is permissible. In some cases, automatic dipping devices have been incorporated instead of sprays.

For field applications, both color contrast penetrants and fluorescent penetrants are available in small pressurized cans thus making the application of the penetrant for local or spot inspections relatively simple. For larger areas, such as blades of steam turbines, air pressure operated spray guns are used. In these circumstances, no effort is made to recover the excess penetrant. Control of the spray is such that only the amount of penetrant actually necessary to cover the part is used and no excess waste occurs. Color contrast penetrants are often supplied with a small brush to facilitate the application of penetrant. This is especially useful when the inspection takes place in small restricted areas (Betz, 1963:107-108).

When the penetrant pulls back in small droplets, the part should be recleaned by wiping it with a suitable cleaner, and the penetrant should be reapplied and allowed to remain on the part for the recommended period of time. Table 6, page 47, indicates the recommended penetration periods for liquid penetrants (McGonnagle, 1961:60-61).

Removal of the Surface Penetrant

After a suitable period of time, the surface film of penetrant should be removed. The removal of this film should be thorough so that the only penetrant remaining will be within the discontinuity. The inspector should be especially careful that all drilled holes and threads are rinsed out since penetrant remaining in these areas could cause nonrelevant indications. Since fluorescent penetrants are carefully compounded to make them completely emulsifiable by the physical action of water droplets, water main pressures of thirty pounds per square inch provide adequate pressure for rinsing operations.

The rinsing operation should be accomplished under a black light when fluorescent penetrants are being used, since the use of a black light makes it easier to see if any of the penetrant has been left on the surface of the part. Small parts can be rinsed individually or large quantities of parts can be placed in wire baskets. To avoid over-rinsing, the rinsing process should not be continued after the surface penetrant has been removed from the part.

Table 6

Typical Penetration Times for Dye Penetrants

Material	Type of defect	Penetration Time (Minutes)	
		Dy-Chek (60-90°F)	Zyglo
All	Heat treat cracks	3-5	2
	Grinding cracks	7-10	10
	Fatigue cracks	7-10	10
Plastics	Cracks	3-5	1-5
Ceramics	Cracks	3-5	1-5
	Porosity	3-5	1-5
Aluminum welds	Cracks and pores	7-10	20
Steel welds	Cracks and pores	7-10	10-20
Forgings	Cracks and laps	7-10	20
Metal rollings	Seams	7-10	10-20
Die castings	Surface porosity	3-5	3-10
	Cold shuts	3-5	10-20
Permanent mold castings	Shrinkage and porosity	3-5	3-10
Carbide tipped cutting tools	Poor braze	3-5	1-10
Cutting tools	Cracks in steel	3-5	1-10
	Cracks in tin	3-5	1-10

Since there is always the danger that hot water may remove some of the penetrant from larger or shallow discontinuities, care should be taken to keep from rinsing parts with water at temperatures higher than 110°F. In some cases, high temperature water is intentionally used in rinsing operations to reduce the sensitivity of the testing process.

Parts too large to wash in standard washing stations can be effectively washed with a hand nozzle on a common water hose. When large parts are washed, the inspector should start at the bottom and work up so that water running down does not separate oil from the emulsifier on lower areas before the spray reaches them. The emulsified water penetrant mixture from the upper areas will run off clearly over the sections which have already been washed.

Penetrant emulsifiers have one principal function: to emulsify the excess penetrant on the surface under examination so that it can be easily removed by water rinsing. To accomplish this task, several properties are necessary in a good emulsifier. These properties are: (1) it must be compatible with the penetrant; (2) it should mix readily with the penetrant in such a way that the excess penetrant is emulsified by subsequent water rinses; and (3) intermixing with the entrapped penetrant should be minimal to reduce its removal during rinsing and provide maximum retention of the penetrant for subsequent bleed back and indications.

Emulsifiers usually contain organic solvents, and some of them may be of a petroleum base. Fluorescent penetrant emulsifiers normally contain a dye which gives them a contrasting color and makes them easily distinguishable. It is common practice for this color to be red.

It is possible to remove post-emulsifiable penetrant to some extent by a water pressure rinse alone, without the benefit of an emulsifier. After the bulk of the excess penetrant has been removed, the emulsifier application is made and a final rinse performed. The emulsifier can be applied followed by rinsing, or an emulsifier may be injected into the rinse water to provide this function.

Penetrant removers are products used for the removal of the inspection penetrants by the hand wipe or solvent method. Removers are usually petroleum or chlorinated solvents, but they may be any solvent combination. Very often an emulsifier contains enough solvency to function as a remover or a product may be formulated for the express purpose of functioning as an emulsifier or a remover. Removers in use are subject to the same precautions described for emulsifiers.

Proper removal of all excess penetrant from the surface or parts is essential to the success of the inspection process. While water wash penetrants are designed to be completely removed with a water rinse, success in this operation depends upon the use of proper techniques: it is not achieved automatically. There is a correct

procedure for washing and rinsing parts. This procedure not only produces clean surfaces, but avoids over washing which could result in washing the penetrant out of discontinuities.

The most common method of washing parts is by means of a hand water spray. The character, pressure, and volume of this spray are all considered significant in the testing process. In general, a plentiful volume of water at moderate pressures (thirty to forty pounds per square inch) and coarse droplets which impinge on the surface of the part, will penetrate the film of an oil-emulsifier mixture and immediately flush it completely away from the surface of the part.

Higher water pressures are undesirable since mechanical pressure alone will tend to cause a penetration of the discontinuities and a possible washing out of some of the penetrant needed for the inspection process. Fine sprays, on the other hand, do not carry a sufficient volume of water for the flushing action needed. If the oil-water-emulsifier mixture is not washed away at once, some of the dye will separate out and stick to the surface. Further washing may not remove it. The use of a solid stream of water which produces a sufficient volume is not satisfactory, because the stream impinges on too small an area to achieve proper emulsification; and areas where the dye has separated and remained on the surface are usually the result.

Water at a temperature at which it comes from the water lines

is usually quite satisfactory. Washing with hot water makes the washing easier, but increases proportionately the hazard of removing penetrant from the discontinuities. Perhaps the optimum temperature for washing water is 110°F. However, heating the water is considered an additional expense and is generally not considered necessary.

The washing operation should be conducted under a black light when fluorescent penetrants are used. This operation should not be prolonged. As soon as the surface being inspected gives no indication of fluorescence (except at areas of porosity), the washing operation should be stopped to avoid over washing.

When large quantities of small parts are washed in metal baskets, care must be taken to insure that all surfaces of each part are reached, and that no areas are missed due to parts coming into contact with one another. When parts are shaped so that they cannot be placed in a basket without serious contact areas, spacers should be provided to keep the parts separate and accessible to the washing operation. Care should be taken that the baskets themselves are well washed. If the baskets retain some traces of penetrant, it could lead to contamination of the parts later in the inspection process, thus creating false or misleading indications. When this becomes a problem, it may be necessary to transfer the parts to clean baskets after they have been washed and prior to placing them in the dryer.

The wash tank and surrounding areas should be kept free from

fluorescent scum to avoid contaminating clean parts by creating fluorescent spots which tend to confuse or distract the inspector.

For quantities of small parts which are being processed in baskets, an automatic spray rinse has been devised which is far superior to the hand washing process. This procedure involves the use of a covered cabinet which has been equipped with spray nozzles which direct an abundant supply of water from all angles at the basket while it is being rotated. For most small parts, which have been properly placed in the basket to avoid undue contact between surfaces, this method does a very satisfactory job.

On automatic units, washing is accomplished with the spray nozzles placed according to the geometry of the parts being processed. In some instances, an oscillating spray is used instead of fixed nozzles. In some applications, where the parts are long and of a relatively uniform cross section, a traveling ring spray moves from one end of the piece to the other thoroughly cleaning all exposed surfaces in one pass.

Washing by simply immersing the penetrant coated part in a bath of warm water and moving it about while submerged is a method which has been used with some success under certain conditions. Since most penetrants have been formulated so that they will completely emulsify when they come into contact with water and disperse readily into the water bath, this particular method has the advantage of

simplicity. But, it has little value otherwise and is not recommended for general use.

In the inspection of steam turbine motors, washing is generally accomplished with a hose and spray nozzle. Other large parts which have been sprayed with penetrant may be similarly washed. Provisions for draining off the wash water should be made. In such washing operations, the inspector, once again, should start at the bottom and work up all sides of the part.

When spray washing is for any reason impracticable or not permissible, a good job can be accomplished on limited areas using a wet cloth. This cloth should be thoroughly wet with water and the wiping should be done rapidly. The first washing should be followed immediately with fresh water and rewiping with a clean rag. This particular method is obviously not suitable for large numbers of small parts or large and irregularly shaped parts. For the local inspection of limited areas, however, it is an acceptable cleaning alternate.

Adding detergents to wash water is a bad practice, although it has been tried with a certain measure of success by some companies. The proper amount of emulsifier has already been added to the penetrant. Adding detergents to the wash water may result in a clean surface, but it usually results in washing some of the penetrant out of the discontinuity in the process.

For average size installations, disposal presents no problem

since the actual amount of penetrant carried into the drain in the course of an hour is small in relation to the other wastes carried by the sewers. In some instances, especially for large operations, special precautions in disposing of the wash water may be required. Usually this consists of collecting rinse water in a tank and adding acid or other suitable substances to break down the emulsion. The oils containing the dyes will then rise to the surface where they may be skimmed off. The water, freed of the oily material and dye, may then be run safely into the drains.

Drying the Parts

Drying the parts after water washing is a necessary and important step in the processing of parts by the water wash penetrant method since the results can be materially affected by the method of drying, particularly the intensity and definition of the indication. Therefore, the sensitivity of the tests can be increased through a proper understanding and application of suitable drying techniques. In many instances, a simple air drying process is all that is needed. For most applications, however, special hot air dryers are utilized to dry the parts being tested. Precisely controlled heat and air circulation in a dryer will increase the efficiency of most penetrants. One acceptable method is to place them in a drying oven at a temperature of 180°F for a sufficient period of time to insure the drying of the part, but not so long that excessive degradation of the penetrant

occurs. Under no circumstances should the drying temperature exceed 250°F. Parts should be removed from the dryer as soon as they are dry. If they are allowed to remain in the dryer too long, the sensitivity of the test will be reduced as a direct result of dye degradation.

Wiping with cloth or paper towels is a simple and quite satisfactory method to dry the surfaces of parts. It is especially useful when local areas of large parts are being examined. After the parts are wiped dry, a short period of time should be allowed before dusting on the dry developer powder, to permit the last film of dampness to evaporate off the surface. The use of towels is obviously slow and would be clumsy on parts with complicated shapes. This procedure is considered impractical for production lines, since some of the advantages of sensitivity that result from the use of heat are lost when the hand wiping method of drying is used.

A strong blast of compressed air from the shop air system is sometimes convenient and often quite effective in removing large quantities of excess water from the parts. However, too strong or concentrated a jet of compressed air can blow some of the penetrant out of discontinuities or defects. This procedure does not leave the surface absolutely dry, and further drying time should be provided for the parts before the developer is applied.

When the part is too large, drying with heat may be impractical

or impossible. If the part is allowed to stand for a long period of time at room temperature, it will obviously dry; but this procedure is the slowest and possibly the poorest drying technique. On certain occasions, however, it may be the only possible solution. One specific drawback to this method of drying is that due to the prolonged period of time required, indications may have time to "bleed out" excessively. This is no disadvantage if the discontinuity is small and only a minimal amount of penetrant is in the discontinuity in the first place. However, defects holding a large reservoir of penetrant will have time to bleed excessively, and the indication will spread out thereby losing its definition. At room temperature, penetrants retain all their normal fluidity since the volatile constituents do not evaporate as rapidly as the water dries. This condition facilitates a spreading out of the penetrant.

Blowing warm air over the part by using a hair dryer type of blower is only slightly better than open air drying at room temperature. The air coming from such devices is seldom warmer than 130°F. when it reaches the surface of the part. Since the parts are cold, the increase in the rate of evaporation at the surface of the part is not considered great. The quantity of heat supplied by these methods is not great enough to warm the part very quickly and indications tend to spread out excessively as they do when open air drying is used. This method accomplishes little or nothing and is not usually worth the

trouble and expense of setting it up.

Placing parts in an oven which is maintained at 225°F. is a somewhat better approach to the drying problem, although it is still not considered an optimum procedure. If the power input of the oven is sufficiently large in relation to the mass of the metal represented by the load of parts, the part itself becomes heated. If there is no procedure for circulating air within the oven (this is the assumed condition of this discussion), absorption of heat and the removal of evaporated water vapor tends to be considerably slower and good control of both drying time and temperature becomes difficult. Temperature inside the oven varies considerably depending upon the disposition of the parts to be dried with respect to the heating element, resulting in uneven heating of the parts and thereby leading to the overheating of some parts. Since the recirculating hot air dryer overcomes most of these disadvantages, there is little reason to recommend the use of any other type of parts dryer.

The recirculating hot air dryer is a device used to dry parts properly and at the same time take advantage of all of the favorable effects which heat tends to have on the brilliance and the definition of indications, and therefore on the final results of the inspection. This dryer is basically an enclosed space consisting of two sections: (1) a heating section which consists of a bank of electric heaters, a fan, and a thermostat; and (2) a section in which the parts to be

heated are placed. After the hot air has been used to heat the parts, it is drawn back into the heating section to be reheated and reused. A certain amount of fresh air is constantly drawn into the system to reduce the moisture content of the air within the drying cabinet.

The temperature used for parts of normal size and thickness varies. For instance, with sections 1/4" or greater in thickness the temperature desired is 225°F. Air at this temperature heats the surface of the parts effectively and rapidly evaporating surface water and carrying away the water vapor. Parts should be removed as soon as they are dry, when they are still quite warm but not yet at the full 225°F temperature of the air within the dryer (Betz, 1963:149-157).

With the recirculating hot air dryer, several desirable effects are produced in addition to simply the drying of the parts. Wash water penetrants are composed of liquids, some of which are volatile and others which are nonvolatile and more viscous. When parts are placed in the dryer, penetrant begins to exude from the discontinuity. This process is aided by the heat absorbed by the surface of the part. In addition, as the penetrant reaches the surface of the part, the more volatile constituents tend to be carried away by the warm air. The more viscous nonvolatile constituents tend to concentrate near the edges of discontinuities producing maximum brilliance and definition of indications. Prolonged heating in the dryer or excessive temperatures will tend to increase the spreading of the viscous liquids thus

reducing this concentration. For this reason both time and temperature of the drying process should be closely controlled.

With most penetrants, the air thermostat should be set at 225°F. The temperature of the air in the dryer should not be allowed to exceed 250°F. However, with very small parts having a cross section of 1/4" or less, lower temperatures are most desirable. Depending upon the size and mass of the parts being tested, drying temperatures could range as low as 150°F to 175°F (Betz, 1963:149-157). Evaporation of the surface water may be somewhat slower on these occasions, but the parts will not reach temperatures high enough to produce distortions in the indications which could be caused by a rapid rise in temperature of parts having a small mass.

For proper drying, there must be a balance between the temperature of the air, the time the part is left in the dryer, and the size and character of the part being tested. The material of which the part is made is a prime factor in determining this balance. Aluminum and copper parts, because of their high heat conductivity, will transmit heat into the body of the part more rapidly than parts made from stainless steel. Surface temperatures of the latter, however, may rise more rapidly than in the case of aluminum or copper. An understanding of these factors and experience with the various drying methods are necessary if optimum test results are expected in a given set of circumstances.

Other methods and devices have been proposed and even tried for drying parts, but for the most part they have not been satisfactory. However, they do have some value as a substitute in the absence of suitable equipment. In judging such techniques, it should be remembered that the temperatures reached by the materials being tested are considered to be critical factors in the testing process.

Infrared lamps might appear to be a simple and convenient source of heat for the drying process. However, they are quite unsatisfactory since such lamps produce radiant heat which tends to heat the part itself rather than the air around the part. In the case of parts with highly polished surfaces, the radiant heat is reflected and neither the part nor the air around the part are heated. A rise in part temperature depends upon the mass of the metal involved. Thin sections will become heated quicker than thick sections and the part temperature may get too high before the entire surface is dry. With thick sections, the reverse is true. In addition, the time required to dry the part is usually longer than desired. This method is definitely inferior to the convection method of heating parts which is accomplished in the recirculating hot air dryer.

Heating the parts by induction, utilizing the heating effect of eddy currents, which can easily be accomplished by placing the part in a field of alternating current, has also been proposed. Once again, the part being tested is heated first and can therefore reach undesirable

temperatures before the surface of the part is properly dry.

High powered heaters blowing hot air at the parts have some advantages in drying very large parts, but this method is considered an uncontrolled and wasteful process when it is compared to the efficient, thermostatically controlled recirculating hot air dryer.

Application of the Developer

The purpose of the developer is to draw the penetrant which has been trapped in defects to the surface of the part. The developer exerts a combination of adsorptive-absorptive effect on the penetrant residues drawing them to the surface. As the penetrant disperses through the developer, it is observed by the inspector. In the case of nonaqueous wet and film type developers, solvent action plays an important part in promoting the withdrawal action, thus enhancing the indications. There are four common commercial developers in use today. They are: (1) wet, (2) dry, (3) nonaqueous wet, and (4) film developers.

The dry developers are easily distinguishable when they are compared to the wet types since they are fluffy in nature and have a high bulk density. In normal use, the dry developer is blown onto the surface after the penetrant has been removed and the part dried. The excess developer is removed by blowing it off with air pressure or tipping the part and shaking it off the surface. Dried parts may be dipped into the tank of developer or the dry powder may be brushed

lightly over the surface of the part. These fine, adhering particles tend to absorb residual penetrant and draw it from discontinuities. Indications appear in a few minutes as the penetrant bleeds back into the developer. These dry developers are generally employed with the fluorescent penetrants, but they may be used successfully with the visible types.

There are three types of wet developers produced commercially. They are: (1) developer powder suspended in water, (2) developer powders soluble in water, and (3) a liquid developer dilutable with water. These wet developers can be applied to the surface by dipping, spraying, or brushing, but care must be taken to insure that an excessive amount of developer is not applied since this will tend to obscure the indications. Wet developers may be applied to the surface after washing operations have been completed and prior to the drying operation, or they may be applied after the washing and drying operation have been completed. Normally, it is necessary following the application of the wet developer to accelerate the drying process by placing the parts in a hot air dryer.

Many companies prefer to dip or spray the wet developer on a wet surface which results from the post emulsification or water washable process. However, application to these wet surfaces by the spray method tends to develop runs since the developer has a tendency to leave voids on the surface of the part where the water drops or an accumulation of

water remained following the rinsing operation. When this occurs, a nonuniform developing action could occur.

The nonaqueous developers are similar to the wet developers, except for the fact that the developer solids come already suspended in a volatile solvent. This solvent tends to pull the penetrant from the indications by solvent action. This particular process accelerates the drying time, so that a supplementary drying action is not required. A thin film of nonaqueous wet developer is desirable to provide the ultimate in sensitivity. Spray applications utilizing a fine atomizing spray such as a paint spray gun will provide this fine film coverage. It is necessary, however, to agitate the nonaqueous wet developer prior to using it to insure that a proper mixture of the particles and the vehicle occurs. The use of the nonaqueous developers result in indications of a high order of sensitivity.

These solvent based developers are generally used with the visible dye penetrants, but they can also be used successfully with the fluorescent penetrants. The developer is usually applied to the surface of the part after the penetrant has been removed from the surface of the part and the part has been dried. This procedure will effectively enhance the penetrant sensitivity. The rapid drying action of these developers eliminates the necessity of oven drying the parts following the application of the developer.

The film type developers, as the name implies, forms a plastic

film over the penetrant as it dries. This developer is usually applied by the spray method and the action of the solvent carrier draws the penetrant into a film. As the film dries, the exposed penetrant indications are set in a pattern indicative of the discontinuity. This process provides a permanent record of the discontinuity since the film is peeled from the surface and retained for the records. Sensitivity of this type of developer is also of a high order, but its use is somewhat restricted to special applications since the cost of stripping the film from the part involves considerable labor. Film developers are usually applied to a dry surface and are applicable to fluorescent and visible penetrants alike (Betz, 1963:149-157).

To successfully carry out its function, a good developer should have certain properties or characteristics which can be clearly defined. Although all of the characteristics listed are not usually found to a maximum degree in any given material, they should be carefully considered in selecting the appropriate developer. Developers should have the following characteristics (Lomerson, 1972:2.9):

1. High absorption to secure maximum blotting
2. Easily dispersed to expose the discontinuity by a small amount of penetrant covering a large area
3. Provide a contrast background for indications
4. Easily, evenly, and readily applied
5. Form a thin coating over the surface

6. Easily wet to allow the developer to spread over the particle surface

7. Nonfluorescent, if they are used with a fluorescent penetrant

8. Easily removed once the inspection is completed

9. Inert to the material being inspected and to the equipment being used in the inspection process

10. Nontoxic and inexpensive

Developer powders consist of fine particles which are applied over the surface of the part being inspected, after the excess penetrant has been removed. Good developer powders should be expected to have these characteristics:

1. Have a blotting action which serves to draw the penetrant to the surface.

2. Provide a reflective base over which the penetrant can spread and disperse, thereby increasing the amount penetrant covered surface exposed to the human eye.

3. Help to cover up confusing backgrounds, and in some forms provides a complete background contrast layer over the surface of the part.

4. Increase to a high degree the sensitivity of the inspection method and at the same time shorten the time required for the indications to become visible to the inspector.

5. In addition to the blotting action of the developer powder, the solvent type developers should bring more penetrant out of a suspected discontinuity as a direct result of the solvent action of the suspending liquid.

The developing step is a critical part of the inspection process, since it could make visible borderline indications which might otherwise be missed. This step also reduces the inspection time by hastening the appearance of indications.

If these developers are expected to function properly, it should be emphasized to the inspectors that each developer was designed to work specifically with a certain penetrant. Developers which have been tuned to a specific penetrant should not be used with other penetrants since they may be totally ineffective. Penetrants and developers should be consistent and compatible. They must not, under any circumstance, repel each other.

Since developers play such an important role in securing successful inspection results, Table 7, page 67, has been included to help the inspector determine which type of developer to select for given types of surface conditions (Betz, 1963:103).

On very smooth or polished surfaces, dry powder developers do not adhere properly since they easily slip off the surface of the part. In this situation, wet developers or even solvent developers do a better job. On very rough surfaces, the dry powders on the other hand

Table 7

Selection of Developers Based Upon Surface Conditions

For Fluorescent Penetrants In the Order of Preference		
Very Smooth Surfaces	Very Rough Surfaces	All Other Surfaces
1. Wet	Dry-fluffy	Dry-fluffy or wet
2. Solvent	Dry-regular	Dry-fluffy or wet
3. Dry-fluffy	Wet	Solvent
4. Dry-regular	Solvent	Dry-regular

For Color Contrast Penetrants
All Types of Surfaces

1. Solvent
2. Wet
3. Dry-regular

provide far better results.

All of the dry powder developers should be used with caution to minimize the possibility of dust inhalation by the inspector and other personnel in the vicinity of the test. These extremely fine particles are easily airborne in high concentrations. Whenever possible these developers should be applied in well ventilated areas or under a hood which has been equipped with an exhaust fan to reduce the possibility of inhalation hazards.

Use of the nonaqueous wet developers also involves some personal hazards since the solvent carriers in which the developer particles are suspended are either flammable, toxic, or both. Precautions for the use of flammable or toxic solvents should be carefully observed when non-aqueous type developers are used.

The selection of the developer system to be used will depend upon the type of parts being inspected, the equipment available to the inspector and the sensitivity desired. Regardless of the type of developer used in the test, it should completely cover the surface of the part being tested. Dusting and spraying have the possibility of missing area, dipping the part into the developer powder has the tendency to contaminate the developer and dipping the part into the solution creates the possibility of trapping liquid in narrow openings causing uneven coating thickness and difficulty in drying the parts properly.

The developer should be allowed to remain on the part approximately one-half the penetrant dwell time, but in no case less than five minutes before the inspection takes place. This time is required to allow the developer time to draw the penetrant out of the discontinuity and to spread it out over the surface, thus magnifying small amounts of penetrant and increasing the reliability of the inspection process. Excessively long development times can cause over development or an excessive spread out of the penetrant. Development times are usually limited to one hour maximum.

Since the suspending liquid is water in many of the wet methods, the successful operation of the test equipment at temperatures below freezing becomes difficult. If the parts are not at freezing temperatures, heating units in the developer tanks will help prevent the suspension from freezing in the tank, but these heating units will not go far in preventing freezing from occurring on the surface of exceedingly cold parts. Fortunately, in many cases, the inspection process is carried out in warm shops. Castings on the other hand which may have been stored outside in near freezing weather can be brought into the shop and allowed to warm up before the inspection process begins.

At the other end of the scale, no serious limitations exist at temperatures above ambient except that the loss of water by evaporation is more rapid. To avoid having the bath concentration climb beyond safe limits at elevated temperatures, spot checks by the inspector are

necessary at frequent intervals. The addition of make-up water can be added as the occasions arise.

Inspection and Evaluation of Parts

After the proper developer time has passed, the part is ready for inspection and evaluation by the inspector. The lighting used in the test is predetermined by the process being used. A white light of sufficient intensity is required for the visible dye process, while a black light is necessary for the fluorescent penetrant process. The contrast of the penetrant to the background should easily indicate the size and shape of the discontinuity. Since it is necessary to verify that each indication is in fact a defect, a light brushing or wiping of the area in question with solvent on a dampened brush, redusting, and reinspection of the area is in order. Once the discontinuity has been located and its type, shape, location, and depth determined, the results of the test should be compared to acceptable test standards.

When the part does not meet the criteria of the test, it should be considered suspect. Suspect parts should, if possible, be repaired. When they cannot be repaired, they should be rejected. Quality inspections depend upon the ability of the inspector to locate discontinuities, evaluate the effect of the discontinuity on the part, and take action when necessary for repairing or disposing of unsuitable parts.

Establishing Acceptable Standards

Reference standards for liquid penetrant inspections are most difficult to manufacture since it is next to impossible to produce two or more samples with identical discontinuities. Since liquid penetrants have the ability to enter extremely small openings, manufacturing artificial flaws is also quite difficult. For the most part reference standards for the liquid penetrant tests do not exist, and quality level acceptance criteria is usually given in very general terms.

The United States Naval Experimental Laboratory at Annapolis, Maryland, has, however, developed a penetrant test block which is specifically designed to produce cracks and crack-like discontinuities of controlled width and depth for use in the comparison of penetrant specimens. An illustration of this test block is shown in Figure 4, page 72 (Betz, 1963:58). In this sample, two hardened surfaces have been ground and lapped to meet perfectly. They are forced together as sleeves on a shaft by screwing down on a nut to a specified torque. By varying the amount of torque, the size of the opening between the two surfaces can be varied. After the penetrants have been applied to the test part, the results of the test can be compared to the indications found on the test blocks. When the tests have been completed, the test blocks can be disassembled, cleaned, reassembled, and reused.

A second type of penetrant inspection standard could be manufactured from 2024-T3 aluminum alloy blocks. These blocks are heated

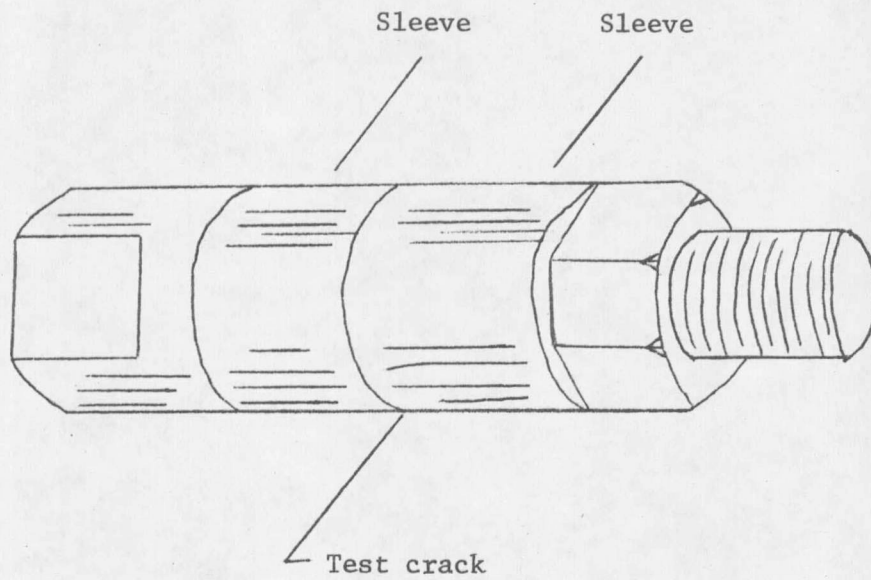


Figure 4

Typical Penetrant Test Block

to a temperature of 950°F and then they are quenched in cold water producing suitable cracks for use as a reference standard. This process produces a heat treating pattern which runs both around the hot spot and lengthwise on the test block. Using test blocks with known discontinuities, the knowledgeable inspector can demonstrate liquid penetrant testing procedures to novice inspectors at a relatively low cost (Betz, 1963:60).

Post Inspection Cleaning of Parts

Cleaning of the parts after the penetrant inspection should be accomplished as soon as possible. The use of a hot detergent wash is probably the most effective method of removing the developer from the part prior to its return to service. Critical parts such as those which are subjected to high temperatures should be carefully screened since residual penetrants can cause adverse reactions with the materials used to make the part if they are overlooked. When additional cleaning is required, the part in question should be dipped in a suitable solvent material, either liquid or vapor.

In the visible dye penetrant inspection process, as the developer dries to a smooth, even, white coating, minute red indications will begin to appear at the location of discontinuities. When no indications appear, there is good reason to believe that no discontinuities open to the surface are present. On the other hand, the depth of suspected discontinuities will be indicated by a richness of color

and speed of "bleed-out." Discontinuities located with the fluorescent penetrant process will show up as glowing yellow-green dots or lines against a dark background.

General Appearance of Liquid
Penetrant Indications

Figure 5, page 75, illustrates penetrant categories (McGonnagle, 1971:62-64). These categories include:

1. Cracks and similar openings
2. Pits and porosity
3. Tight cracks or partially welded laps
4. Large cracks or openings
5. Cracks and cold shuts
6. Fatigue cracks or laps
7. Porosity or pits

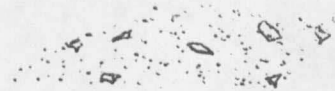
Since there are many characteristics which have similarities, the interpretation of liquid penetrant indications requires both training and experience. A cold shut, for example, can appear as a line of penetrant. Dots of penetrant, on the other hand, can indicate pits or porosity. A series of dots may be an indication of a tight crack, cold shut, or a partially welded lap.

Competent inspectors can accurately estimate the size and shape of a discontinuity by the spreading out of the penetrant on the developer or by estimating the bleed out from a discontinuity. The novice

1. A crack or similar opening



2. Pits or porosity



3. A tight crack or partially welded lap



4. A large crack or opening



5. A crack or cold shut

6. Fatigue crack or lap



7. Porosity or pits



Figure 5
Typical Penetrant Indications

inspector should not attempt to make this type of evaluation until he has gained a measurable amount of training and experience.

Time Required for Indications to Appear

A minimum of developing time is a basic requirement for all types of liquid penetrant inspection processes if the indications are expected to reach their maximum intensity. The actual time, however, may vary from a few minutes to an hour or more depending upon the characteristics of the materials being used and the types of discontinuities being sought. A good rule of thumb is a developing time of one-half the time required for the proper penetration of the liquid penetrant. Examples of proper developing times are provided in Table 8, page 77 (Betz, 1963:123-127).

Persistence of Indications

One method which can be used successfully to estimate the depth and size of a suspected defect is the persistence of the indication. If the indication continues to reappear after the developer has been removed and reapplied, it is an excellent indication that a reservoir of penetrant is present in the discontinuity. In the case of a weak or faint indication, where there is some doubt of the type or even the existence of an indication, it is considered good practice to repeat the penetrant inspection before making a final decision. If the indication reappears, it is most likely due to a small flaw rather than to the

Table 8

Development Times for Various Materials and Defects

Material	Type of Defect	Development Time (minutes)
1. Aluminum castings	Porosity and cold shuts	2-10
2. Magnesium forgings	Laps	5-15
3. Stainless steel forgings	Laps	5-30
4. All metals	Fatigue cracks	5-15
5. Glass	Cracks	2-15
6. Plastics	All	1-15

possibility of incomplete cleaning procedures (McMaster, 1959:8.4).

Factors Adversely Affecting
Penetrant Indications

A penetrant may become contaminated with foreign substances which unfavorably affect the action of the penetrant. If the penetrant is composed of several ingredients which have been balanced into a homogeneous whole, a little water or degreaser solvent may upset this critical balance causing the penetrant to separate into its several basic components. This actually happens with some penetrants when the amount of contamination becomes too large. Modern penetrants, however, have a relatively high tolerance to water, the most common contaminant, as well as for oil, grease, and degreasing solvents.

The inspector must practice constant cleanliness in the inspection area and use great care in the handling of parts if he expects to avoid contamination from: (1) spots of penetrant on the working bench, (2) penetrant on the hands of the inspector, (3) contamination of the wet or dry developer with the penetrant, and (4) penetrant rubbing off from an indication on one part to a clean portion of the surface of another part. These practices should also be observed with respect to the tanks of penetrants and other inspection materials in a continuous effort to exclude dirt and other foreign materials from the inspection area. Stray lint from wiping cloths may be held on the surface of the part. When this occurs, deceptive and meaningless indications will

result.

Acids and chromates. Acids and chromates should not be left on the surface of parts or within discontinuities at the time of the inspection since these chemicals adversely affect some penetrants. This is particularly true of the fluorescent penetrants, since such acids contaminate the fluorescence process creating poor or weak indications. For this reason, it is desirable to inspect aluminum castings very closely prior to anodizing, stainless steel parts prior to passivating, and magnesium parts prior to chromate treating.

Oil and grease. Oil and grease should be removed completely from the parts before any inspection process begins. Many oils are somewhat fluorescent, and are also good penetrants. When oil or grease is left on the parts, they may fill surface discontinuities and prevent the penetrant from entering. Oil and grease may also fluoresce under the black light. When this occurs, false indications result.

Scale and rust. Scale and rust should be removed completely from all parts prior to the inspection process since they tend to cover surface discontinuities and cause confusing indications by trapping or holding the penetrant on the surface of the part. The removal of such coatings should be accomplished by a method which does not affect any of the suspected discontinuities. In this case, methods such as sand blasting, shot blasting, wire brushing, metal scraping, or the

extensive use of emery cloth are not recommended. There is always the possibility with these methods of cleaning that discontinuities on the surface of the part will be covered up. This is particularly true for soft materials. Grit blasting with soft grit or a gentle brushing with a soft wire brush is not considered particularly objectionable on materials of Rockwell C-50 or greater hardness. Metals in this category would be most difficult to file with an ordinary metalworking file (Johnson, 1968:312).

Sulphur. The presence of sulphur in any developer is considered objectionable when certain types of metals are being tested, since these metals absorb sulphur and become very brittle if they are subjected to high temperatures with the developers still on the surface of the part. Sulphur is also objectionable on the surface of the part during fabrication, heat treatment, or during the part's service life. When the developer containing sulphur is removed immediately after the inspection, no embrittlement problems occur; but on highly critical components such as those used on high speed jet aircraft, it cannot be assumed that all of the developer has been thoroughly cleaned from fillets or holes of difficult access (McMaster, 1959:6.6).

Water. If the parts have been in contact with water, it is important that all traces of water be completely removed before the inspection process begins. Water must be removed, not only from the

surface of the part, but also from any discontinuities which may be present. Otherwise, the penetrant may be prevented from entering discontinuities. The drier usually associated with the fluorescent penetrants offers an excellent means of drying the parts before the inspection begins. When the visible method of inspection is used, the solvent cleaner usually supplied by the manufacturer to remove the excess penetrant can be used to preclean the parts before the inspection (Betz, 1963:102).

Types of Discontinuities Located with Penetrants

Penetrant inspections reveal discontinuities of what ever origin or significance in the surface of the material being tested. The indications produced may or may not be those of actual defects. Actually, the term "defect" is often loosely used, even by those who are fully aware of this distinction. This most usually occurs because the word "defect" is more easily said than the word "discontinuity." But, the fact remains, until a discontinuity has been determined to be an actual defect which impairs the future usefulness of the part, the term discontinuity is the only correct one to use (Betz, 1963:269).

Discontinuities and defects can be classified in many different ways and from different points of view. Each of these views would be useful for some purpose. Since this study is, however, limited to the detection of discontinuities and defects in metals, they have been

classified by their source of origin.

Discontinuities occurring during solidification. This category includes all discontinuities which occur while preparing the metal for its initial usable form, before any modifying operations of manufacture have taken place. Included in this category are casting and forging.

When metals are cast in molds and solidify from the molten state into substantially hardened shapes, they are generally subjected to a variety of discontinuities which are peculiar to the casting process. These discontinuities can occur regardless of the type of metal or the shape or size of the metal being cast. The principal types of discontinuities which occur are: (1) shrinkage cracks, (2) micro shrinkage, (3) porosity, (4) cold shuts, (5) sand inclusions on the surface, (6) blows and blowholes, (7) cracking from residual stresses, and (8) handling cracks.

Numerous types of metals are forged into a wide variety of parts for highly critical service in car engines, jet aircraft engines, aircraft structures, nuclear and space applications. Included in this category are aluminum and magnesium alloys, stainless steels, heat resistant alloys, and other alloys which were designed for high strength at elevated temperatures. Many types of discontinuities can occur, but the principal types occurring during solidification following forging are: (1) cracks, laps, and tears; (2) bursts, flakes, and seams; and (3) pipes, laminations, and cracks due to residual stresses.

Discontinuities occurring during processing. This category includes all of the classes of defects which were introduced during the manufacturing process. Four of these processing methods are: (1) forming, (2) heat treating, (3) machining and grinding, and (4) welding and brazing.

Various metal working processes are used to form metal into usable parts. These include the processes of extruding, explosive forming, spinning, stamping and drawing. The types of metal which can be formed by these methods include stainless steels, aluminum, brass, beryllium-copper, and others. The principal types of discontinuities occurring are seams, slivers, tears, and lamination cracks.

When metals are heat treated, they are subjected to high internal stresses which can and often do result in cracking. This is particularly true during the quenching operation when parts have a sharp radius between light and heavy sections.

Machining and grinding discontinuities may occur from improper control during the processing procedure. Poor machining practices, including the use of dull tools or improper machining speeds, may produce crack-like indications, tears, and chatter marks. Over heating during grinding can result in grinding cracks which are minute and often invisible to the unaided eye. On the other hand, while grinding cracks are extremely fine and shallow, they often occur in a definite network which is easily identified.

Aluminum, stainless steels, heat resistant, and corrosion resistant alloys are commonly joined by welding or brazing. During these joining operations, process cracks, lack of bond, and surface porosity can occur.

Discontinuities occurring during service. The most common cause of structural failure in machines and components is fatigue failure. Structural members which are subjected to numerous cycles or reversing and fluctuating stresses can under certain circumstances develop minute cracks. These gradually enlarge and spread through the cross section of the component until the remaining metal is no longer structurally sound. At this point, the structure fails. Since the penetrant method of inspection easily locates this type of discontinuity, periodic inspections for small fatigue cracks so that they can be located and dealt with before complete failure occurs is a most profitable and rewarding undertaking (Lomerson, 1972:2.17-2.21).

Nonrelevant Indications

The most common nonrelevant indications encountered during the inspection process are those which are a direct result of surface configuration variations. Excess penetrant tends to remain in sharp crevices such as roots, sharp changes in dimensional thickness, machined steps, and radical dimensional changes. It has been demonstrated that surface openings as small as thirteen micro-inches can be consistently

detected with standard penetrant inspection processes (Hellier, 1972: 14.2-14.3). Two-hundred and fifty times thirteen micro-inches is equivalent to the thickness of a single sheet of paper.

The most logical approach to the elimination of this type of indication is a careful masking of the surfaces surrounding the suspected crevice. Nonrelevant indications associated with surface configuration can also be minimized by employing special penetrant removal techniques for the area in question. Small cotton swabs or other appropriate items can be used in the penetrant removal process.

False indications are usually the direct result of improper processing techniques. The most common causes are improper or inadequate cleaning of the test surface prior to the application of the penetrant, inadequate removal of excess penetrant during the removal step, and surface roughness which is caused by scale or slag. Special care should be taken during the penetrant removal phase to prevent over cleaning, but proper surface cleaning is of prime concern in the inspection process, since it easily affects the clarity and size of the indications obtained. When there is a possibility that an indication is a false indication, the test procedures should be repeated with the inspector exercising the testing precaution stated earlier in this study.

SUMMARY

The forerunner of the present day liquid penetrant process was the oil and whiting method which was used by the railroad industry in the Nineteenth Century for the maintenance of steam locomotives. Parts to be inspected were dipped in a diluted solution of lubricating oil, dried, and then coated with a mixture of chalk and denatured alcohol. This mixture dried rapidly leaving a dead-white coating on the surface of the part. The oil entrapped in the discontinuity would seep out leaving a dark stain as an indication of a possible defect.

The penetrant process is used by industry to locate discontinuities which are open to the surface in solid and essentially nonporous materials. There is no limitation to the size or shape of the part, the process is applicable to magnetic and nonmagnetic materials, discontinuities which cannot be seen with the unaided eye become visible and the testing process is relatively low in cost.

The liquid penetrant process depends for its success upon the principle that a penetrating liquid entering a surface opening and remaining in that opening will be made visible when the proper developer is applied. In basic principle, the liquid penetrant process is simple. Its effectiveness is based upon the infallible natural phenomenon of capillary action, one of the most powerful forces in nature. The penetrant does not seep into a discontinuity, it is literally pulled into the discontinuity by capillary action. When the correct

developer is applied, it acts like a blotter drawing the penetrant remaining in the discontinuity to the surface.

Liquid penetrant tests are used in industry with three different philosophical points of view, each of which has a different principal purpose. These points of view are: (1) to locate flaws before the finished product goes to the consumer; (2) to reduce production costs by applying these tests at various stages of production thus permitting the removal of defective parts before additional production costs are incurred; and (3) to tabulate and analyze data resulting from these tests for the purpose of improving future products. All of these concepts are considered to be an integral part of the production process, and each is equally responsible for decreasing the cost of the part and increasing its service life.

The types of liquid penetrants commercially available can be divided into two categories: dye penetrants and fluorescent penetrants. In the case of dye penetrants, a special dye is selected which provides a high degree of contrast between the penetrant and the developer. In the fluorescent penetrants, the materials added require excitation by ultra violet radiation and observation under subdued light.

Generally speaking, no special equipment is required to perform the liquid penetrant tests when there are only a few parts to be tested, maximum sensitivity is not required, the part is too large to remove or place in the test equipment, or the proper test equipment is not

available. Color contrast penetrants and fluorescent penetrants can be applied by hand, the excess penetrant can be removed by hand cleaning, and the developer applied by hand. The only item of special equipment required is the ultra violet light for the fluorescent penetrant process.

On the other hand, when there are a large number of parts to be inspected on a production line, a high degree of sensitivity is required, large parts are to be inspected regularly, or consistent repetitive results are required as they are in production testing, certain industrial equipment is considered essential. Included in this category are: (1) precleaning and penetrating stations, (2) solvent remover and washing stations, and (3) drying and rinsing stations. Automated units are now available which have been designed to use prepunched computer cards which automatically program the various aspects of the liquid penetrant process.

Although many inspection problems can be solved using one or more of the penetrant test methods available, one testing process may be preferable for a specific material. When a choice exists, the selection of the testing method may be just as important as the procedures used in the testing process. Generally speaking, the penetrant inspection method is selected on the basis of its ability to locate open and shallow discontinuities, its sensitivity to very fine discontinuities and its relative brightness. Other criteria by which a method

is selected is primarily economic.

The liquid penetrant process was evaluated by the writer to determine whether or not it met the criteria set forth in the analysis of data section of this study. This criteria included an evaluation of the liquid penetrant process in terms of its: (1) compatibility to existing industrial education programs, (2) ability to satisfy one or more of the present needs of industry, (3) relative simplicity and broad encompassing nature, (4) potential in satisfying what the writer believes to be a weakness of the present industrial education program, and (5) educational requirements and competency levels expected of entry-level inspectors.

Since this evaluation could best be accomplished by those with expertise in the field of liquid penetrants, letters were written to those who had written books or articles about liquid penetrants, those who were currently employed in nondestructive testing positions in industry and others who were knowledgeable in the field of liquid penetrants. They were requested by the writer to evaluate the liquid penetrant process in terms of the five criteria selected for this study. Their statements indicated to the writer that liquid penetrant processes could be taught in industrial education courses at the high school level.

The preparation of the parts prior to the actual inspection is of utmost importance since the principle of all penetrant inspections

is the knowledge that penetrants must be able to enter surface openings if they are expected to locate discontinuities. Unless the parts are free from foreign materials, reliable inspections cannot be performed. Liquid solvents, vapor blasting, acid etching, and vapor degreasing can be used to clean the parts prior to the inspection, but the latter is considered the most satisfactory since it cleans out surface openings best and the parts come from this process hot. Solvent materials which could be trapped in discontinuities are driven out by the heat and any water that might have been lodged in the discontinuity is also driven out by the heat.

Theoretically, all that is necessary in the penetrant application procedure is to cover the surface of the part with penetrant and leave it there long enough for the penetrant to be drawn into the discontinuity. When the penetrant is available in a tank of sufficient size, the obvious method is to dip the part into the penetrant and then lay it on a suitable rack to drain and dry. When the parts being tested are too large to dip, they may be sprayed with penetrant from the penetrant tank or small pressurized cans may be purchased; these spray cans are most economical for field operations.

After a suitable period of time, the surface film of penetrant should be removed so that the only penetrant remaining is that which is contained within the discontinuity. Since most penetrants contain emulsifiers, this excess penetrant can be removed from the surface by

rinsing the part with water from a standard 30 p.s.i. water main.

Care should be taken in rinsing the part with hot water with a temperature in excess of 110°F, since there is a danger that the hot water will remove some of the penetrant from the discontinuity.

Drying the parts after they have been washed is a necessary and important step in the processing procedure since the results of the test may be affected by the method of drying. In many instances, a simple air drying process is all that is required. When there are a large number of parts to be inspected, a special hot air drier should be used, since it provides a means of controlling both the temperature and the circulation of air around the part. Under no circumstance should the drying temperature exceed 250°F. The parts should be removed from the drier as soon as possible since there is the possibility of reducing the sensitivity of the test due to dye degradation.

The developer draws the penetrant which has been entrapped in the discontinuity to the surface by a combination of adsorptive-absorptive effect on the penetrant residues, thus drawing them to the surface. As the penetrant disperses through the developer, the results can be seen and evaluated by the inspector. When fluorescent penetrants are used, an ultra violet light and a dark room are prerequisites to successful evaluations. The selection of the developer to use depends upon the type of penetrant being used, the type of parts being inspected, the equipment available, and the sensitivity desired.

Regardless of the type of developer being used, it should be allowed to remain on the part for approximately one-half of the time allowed for penetrant penetration, but in no case less than five minutes prior to the actual inspection.

Once the proper developing time has passed, the part is ready for inspection and evaluation. The lighting used in the test is predetermined by the type of test; a white light of sufficient intensity is required for the visible dye process, while a black light is necessary for fluorescent penetrant processes.

When a discontinuity has been located and its type, shape, and depth determined, the results of the test should be compared to acceptable test standards when they are available. For the most part, reference standards do not exist, since it is next to impossible to produce two or more samples with identical discontinuities. However, two types of test standards are available for penetrant processes. They are: (1) a penetrant test block which was designed by the United States Navy to produce crack-like discontinuities of controlled depth and length; and (2) a penetrant test standard which can be manufactured from a piece of 2024-T3 aluminum alloy. The latter are heated to 950°F and then quenched in cold water to produce comparable cracks.

The cleaning of the parts after the penetrant inspection process should be accomplished as soon as possible, since residual penetrants can cause adverse reactions with the materials used to manufacture the

partpart, if they are overlooked. The use of a hot detergent wash is probably the most effective method of removing developer from the parts prior to their return to the production line or to service.

-The liquid penetrant inspector should practice constant vigilance in the inspection area and use great care in the handling of test parts, if he expects to avoid contamination of the test results due to spots of penetrant on the test bench, penetrant on the hands of the inspector, mixing of the penetrant and developer or penetrant rubbing off from an indication on one part to a clean portion of the surface of another part. Other factors which cause meaningless indications and often add confusion to the testing process are acids, chromates, oil and grease, scale, rust, sulphur, and water.

The success and reliability of the liquid penetrant inspection process depends upon the thoroughness with which the knowledgeable inspector processes the parts. This begins with the precleaning of the parts and continues through the inspection process to the actual search for discontinuities or defects. In this study the term discontinuity is used until such a time when the discontinuity is determined to be an actual defect which impairs the future usefulness of the part. The liquid penetrant process is not a method of inspection where the parts to be inspected are thrown into a machine which quickly and efficiently separates the good parts from the bad parts. In this inspection process, the inspector carefully processes the parts, searches for indications,

and then makes a decision to accept or reject the parts. When the parts do not meet the criteria of the test, the inspector initiates procedures for repairing or disposing of the parts.

Chapter 3

MAGNETIC PARTICLE TEST

The magnetic particle process is a method of nondestructive testing which is used to locate both surface and subsurface discontinuities in ferromagnetic materials. It depends for its success on the knowledge that when a part is magnetized, discontinuities which lie in a direction transverse to the direction of the magnetic field will cause a leakage field to be formed at and above the surface of the part. The presence of this leakage field which indicates the possibility of a discontinuity is detected by using finely divided ferro-magnetic particles which are applied to the surface of the part after it has been magnetized. Some of these particles are gathered and held in place by this leakage field. This collection of magnetized particles form an outline of the discontinuity indicating its exact location, shape, size and extent (Betz, 1967:60).

Advancements in the art of magnetic testing have enabled it to provide the means for the critical inspection performance demanded by industry. To those who encounter the applications described in this chapter for the first time, the techniques may seem deceptively simple. The method is simple, but the tests must be applied with care, and within carefully prescribed guidelines which have been defined and developed through experience.

History of the Magnetic Particle Process

The first magnetic phenomena to be observed were those associated with the so-called natural magnets. These rough fragments of iron ore were found near the city of Magnesia. They had the ability to attract to themselves, unmagnetized iron. The effect of this magnetization was most apparent in the areas known as the poles which were located on the opposite ends of bar magnets. It was known by the Chinese as early as 121 A.D. that an iron rod, once it had been brought into the vicinity of a natural magnet, would acquire and retain this property of the natural magnet and that such a rod would, when it was freely suspended about a vertical axis, set itself approximately in a north-south direction. The use of these magnets as an aid to navigation can be traced back to the Eleventh Century (Sears, 1957:555-556)..

The study of magnetic phenomena was confined for years to magnets made in this manner. Not until 1819 was there shown to be any connection between electrical and magnetic phenomena. In that year, the Danish scientist Hans Christian Oersted (1770-1851) observed that a pivoted magnet, a compass needle, was deflected when it was placed in the vicinity of a wire carrying electrical current. Twelve years later, after attempts extending over a period of years, Faraday found that a momentary current existed in a circuit while the current in a nearby circuit was being started or stopped. Shortly afterward followed the discovery that the motion of a magnet toward or away from a circuit

would produce the same effect (Sears, 1957:555-556).

In the years prior to 1920, the term nondestructive testing, as we know it, had not yet acquired a meaning or found a place in the language of engineering. There were many testing methods, but nondestructive testing was not in effect at that time. In fact, none of the methods which are considered so essential today were even under consideration (Betz, 1967:47). Two developments in the days following World War I marked the birth of modern nondestructive testing: (1) work at the United States Bureau of Standards and at General Electric showed that X-rays could be used to make pictures of metallic articles thus revealing their internal conditions; and (2) William E. Hoke discovered data pertinent to the use of magnetic fields which could be used to develop processes to locate surface cracks in ferromagnetic materials (Betz, 1967:47). His discovery was predicated on the fact that metallic grindings from hardened steel parts which were being ground on a magnetic chuck often formed patterns on the surface of the part. These patterns corresponded to actual cracks in the part.

In 1928 and 1929, A. V. DeForest accomplished the work which actually resulted in the magnetic particle testing processes as we now know them (Betz, 1967:48). He realized that if discontinuities in any direction were to be located with reliability, the direction of the magnetic field could not be left to chance nor could the magnetic field be only longitudinal in direction. It was necessary to develop some

means of generating a magnetic field in any direction desired. To solve this problem, he proposed magnetizing a part by passing electrical current through the part. This was the first use of circular magnetization, the method so widely used in industry today. He also insisted on the use of magnetized powders of controlled shape, size, and magnetic properties as being essential to the success of the test. These initial contributions provided the impetus for the development of a truly practical and useful nondestructive testing process.

Description of the Magnetic Particle Process

A basic description of the magnetic particle method of testing is provided in Figure 6, page 99 (General Dynamics, 1967:7.5-7.6).

The equipment required, types of discontinuities detected with magnetic particles, and the advantages and limitations of this method of inspection are (Betz, 1967:66-67):

1. Equipment required: special commercial equipment, magnetic powders either wet, dry, or fluorescent, and a source of ultra violet light for the fluorescent method.
2. Enables detection of: surface and subsurface discontinuities in ferromagnetic materials.
3. Advantages: simple and rapid to operate, will detect discontinuities filled with foreign matter, no elaborate precleaning is required, operators can learn this method of testing without lengthy

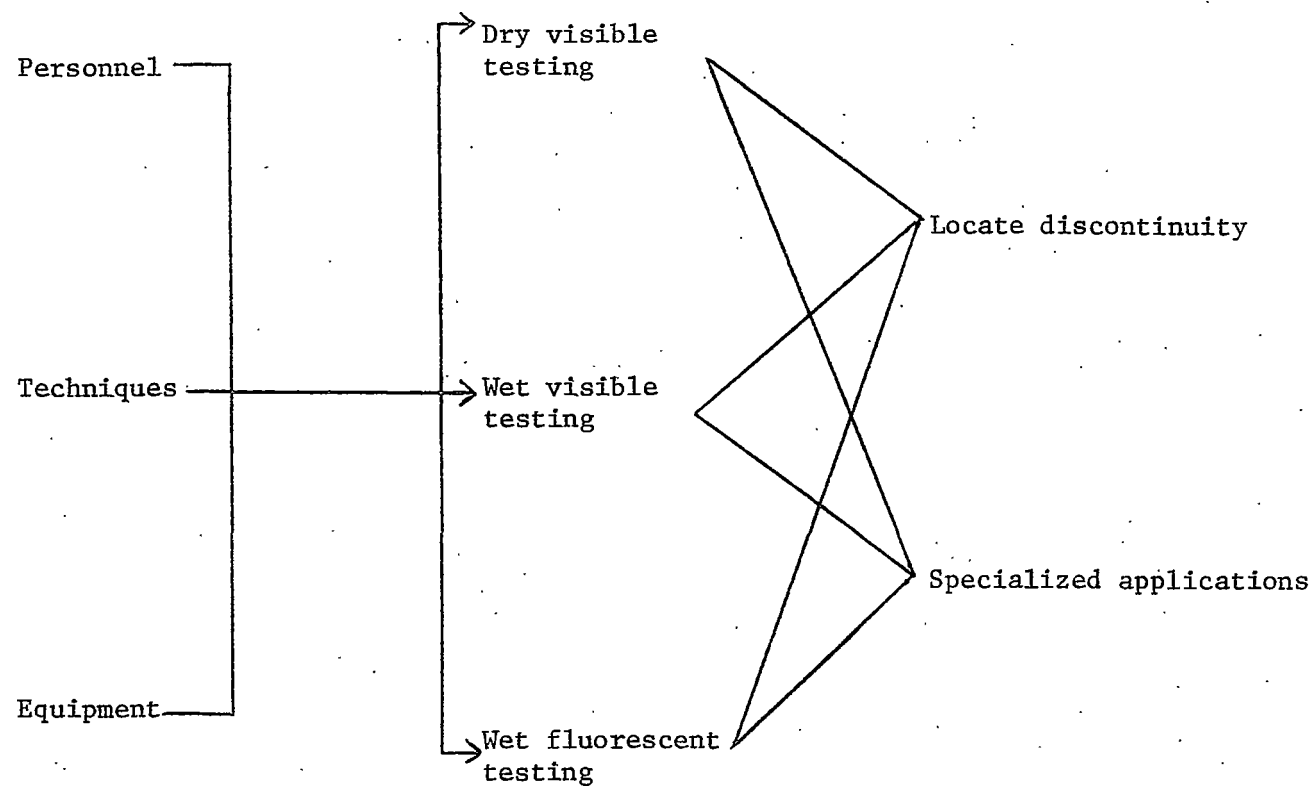


Figure 6

Magnetic Particle Testing

or highly technical training; this method of testing lends itself well to automated procedures and it is relatively inexpensive to operate.

4. Limitations: it will work only on ferromagnetic materials, it requires demagnetization on many occasions, it is not considered wholly reliable for subsurface discontinuities, odd shaped parts present some problems, and exceedingly high electrical currents may be required to perform the tests.

Having met the criteria set by the writer for this study, an indepth description of "how to apply" principles and procedures have been included for the magnetic particle testing process.

Principles of Magnetic Particle Testing

The magnetic particle test process depends for its success on the fact that ferromagnetic materials, when they have been properly magnetized, cause a leakage field to be formed above the surface of the part being tested, thus providing indications of discontinuities which lie in a direction transverse or nearly transverse to the direction of the magnetic field. The presence of this leakage field and therefore the presence of a discontinuity is detected by the use of finely divided ferromagnetic particles which are spread over the surface of the part after it has been magnetized. This magnetically held collection of particles forms an outline of the discontinuity and reliably indicates its shape, size, location, and extent (Betz, 1967:60).

Many of us remember the high school experiment which the instructor illustrated by placing iron filings on a sheet of paper over a bar magnet. When this piece of paper was tapped gently, the magnetic field aligned the particles with the magnetic lines of force (Betz, 1967:3). When this bar magnet was bent into the shape of a horseshoe, the particles would cling to the areas of the poles which were in close proximity. A further step could have been to weld halfway across the cross section of the horseshoe magnet, thus observing that the particles would cling only to the welded area, a simulated discontinuity. The basic principles of magnetic particle testing were easily observed by this simple high school experiment.

According to Betz (1967:60-61), there are many factors which affect the formation and appearance of magnetic particle indications. Some of these factors are:

1. The direction and strength of the magnetic field
2. The method of magnetization used
3. The size, shape, and direction of the discontinuity
4. The character of the magnetic particles used and the methods used to apply them
5. The magnetic characteristics of the parts being tested
6. The shape of the part, which affects the distribution of the magnetic field
7. The character of the surface of the part, whether it is

rough, smooth, plated, or painted

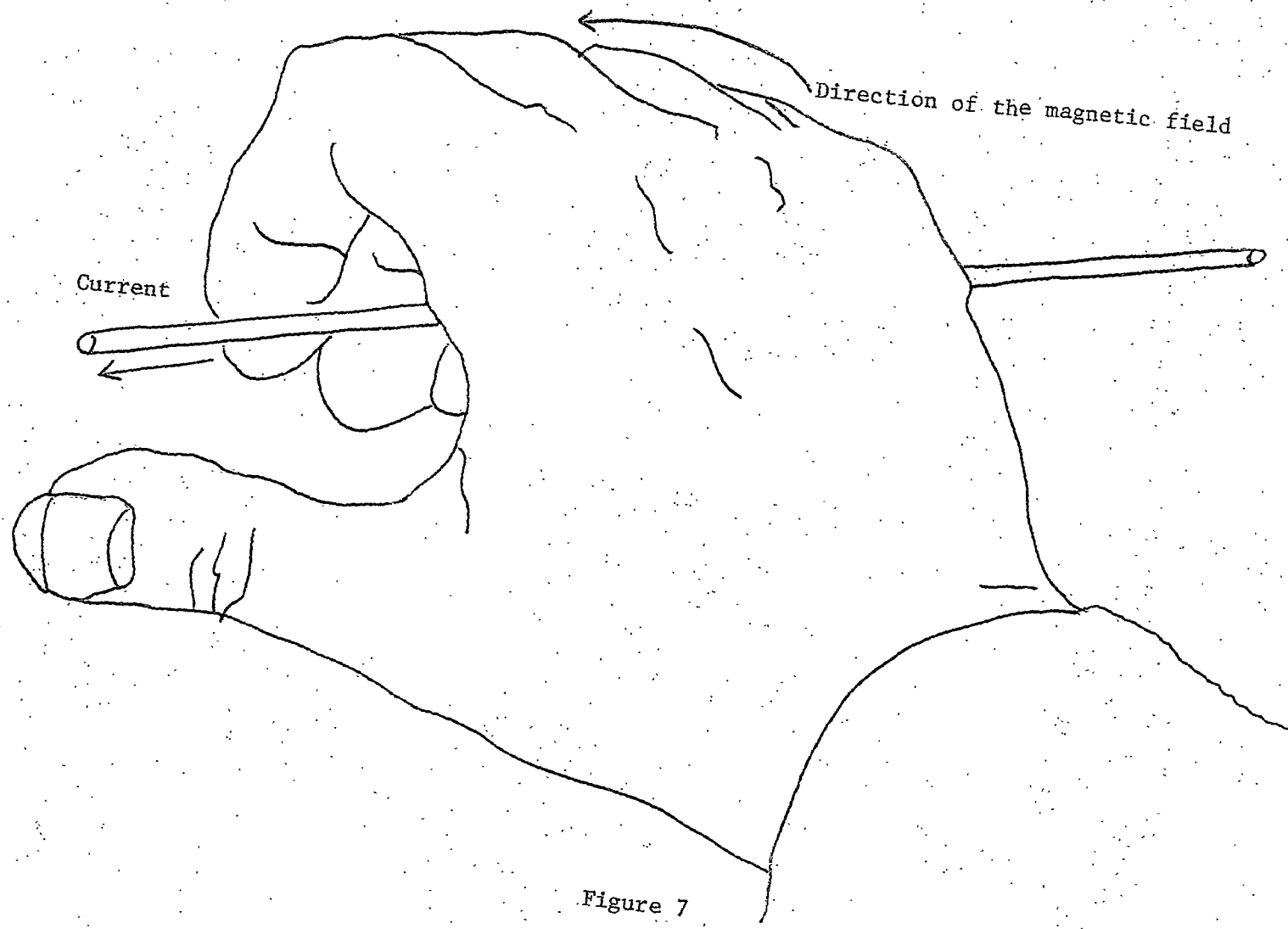
Theory of magnetism. One of the basic properties of permanent magnets is the fact that they can magnetize other ferromagnetic materials. This may be accomplished by placing the metal to be magnetized in the external field which surrounds a permanent magnet. But a more effective method is to touch or stroke the material to be magnetized with one pole of a permanent magnet. Under these conditions, soft iron will become temporarily magnetized, while hardened iron and steel become permanent magnets (Betz, 1967:141).

The earth is in effect a huge magnet having a north magnetic pole just north of the Prince of Wales Island in northern Canada and a south magnetic pole in the Antarctic Ocean south of Australia, just off the coast of Antarctica. The flux lines of the earth's field circles the globe in a generally north and south direction. Although there are many deviations on the way, these flux lines tend to concentrate at the magnetic poles. The earth's field is quite weak when it is compared to the strength of magnetic fields used in the magnetic particle testing process. However, long bars of iron and steel have been magnetized to an appreciable degree by placing them in a north-south direction (parallel to the earth's lines of force) for long periods of time. Magnetism in this case can be hastened by striking the bars with a hammer to make them vibrate (Betz, 1967:141). The natural lodestones mentioned earlier in this study derived their

magnetic properties from their location in the earth's magnetic field.

For magnetic particle testing purposes, permanent magnets can, and sometimes are, used to magnetize parts. This method of magnetization has many limitations, however, and should only be used when these limitations do not prevent the formation of suitable leakage fields at the discontinuity. The use of electrical currents to produce magnetic fields is by far the most effective and economical method (Betz, 1967: 143).

Theory of magnetic fields. Magnetic fields can be set up in ferromagnetic metals in one of three ways: (1) by passing an electrical current directly through all or a portion of the part, (2) by passing an electrical current through a conductor surrounding or in contact with the part, or (3) by using permanent magnets (McGonnagle, 1971: 306-307). Conductors carrying electrical current are surrounded by magnetic fields which form closed circles in a plane at right angles to the direction of current flow. A useful rule for determining the relative direction of the magnetic fields is the so-called "right hand" rule (McGonnagle (1971:306-307)). If one pretends to grasp a current carrying conductor with his right hand, so that the outstretched thumb points in the direction of current flow, the fingers will point in the direction of the magnetic field. This concept is illustrated in Figure 7, page 104 (Sears, 1957:550).



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Figure 7
Right Hand Thumb Rule

Characteristics of magnetic fields. More than forty-five years ago (1929) when magnetic particle testing processes were first put to use, remarkably little published data existed on those aspects of magnetism and magnetic fields which are now considered basic to the understanding and proper application of this method of nondestructive testing (Betz, 1967:130). The magnetic properties of iron and steel, and various other alloys were well known, but the use of magnets and magnetic fields was preponderantly in the area of power generation and use: generators, motors, transformers, switch gears, and relays. Very little had been done to analyze the behavior of magnetic fields inside of the ferromagnetic metals themselves. They were primarily concerned with the paths of magnetic fields external to the magnets. No attempt had been made to explain the theory of the nature of magnetism.

Since that time, however, our understanding of the atomic structure has resulted in theories of magnetism which have a sound basis, and new interest in its various uses and applications have stimulated both intensive and extensive studies in this area. The powerful magnetic fields used in our mammoth atom smashers are on one end of this line of interest, while the very faint fields involved in magnetic guidance systems for missiles are at the other end. Today, there is tremendous amount of literature available on this subject. Very little of the knowledge resulting from this research and

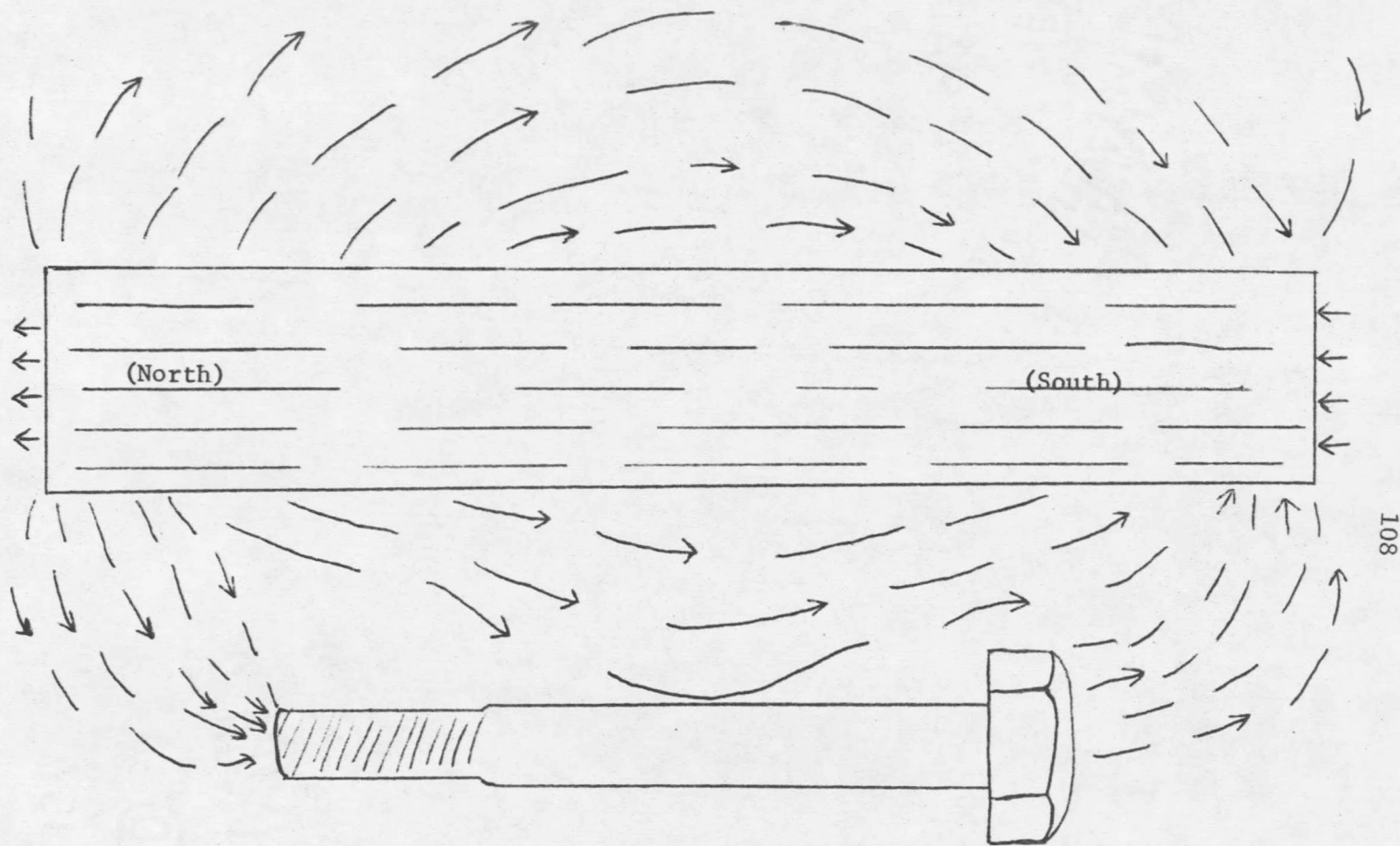
development, however, is of much direct value in the uses to which magnetism is used for magnetic particle tests. In this study, we are interested not so much in what magnetism is, but how it behaves with respect to discontinuity detection. We are further interested in the strength and direction of magnetic fields produced within ferromagnetic materials and how to create fields of suitable strength and direction. It is also important to know how these fields distribute themselves regarding their strengths and direction inside of the part being tested.

This interest stems from a single point of view: how to produce a suitable leakage field at discontinuities which is strong enough to produce readable indications with magnetic particles. To accomplish this, the magnetic fields produced should intersect the discontinuity at some appreciable angle, preferably one approaching 90° . Therefore, the direction of the magnetic fields must be predetermined and preset for reliable inspections (Betz, 1967:131). The second area of concern is knowledge of the strength of the magnetic field at the point where the discontinuity lies. This field must be strong enough to produce a leakage field above the threshold strength for reliable indications to appear. This field, on the other hand, could be too strong thus producing undesirable side effects. These elements will be considered from the point of view of defect detection, how they are produced, and how they distribute themselves in ferromagnetic materials.

Bar magnets. The simplest form of permanent magnet is the bar magnet which consists of a bar or rod of ferromagnetic material containing a south and north pole. The magnetic lines of force which exist outside of the magnet make up the magnetic field. These magnetic fields have lines of force with the following characteristics:

1. They form closed loops
2. They resemble rubber bands, since they stretch and change shape under the influence of any magnetic field present
3. They return upon themselves, once the magnetic field is removed, and once again form closed loops
4. They never cross
5. They seek the path of least resistance
6. They are most densely packed at the poles
7. They flow from south to north inside of ferromagnetic materials and from north to south outside of the magnet. These characteristics are illustrated in Figure 8, page 108 (Dunn, 1972:3.3).

When a bar magnet is bent into a circle so that the opposite ends are brought close together, the small space or air gap remaining between the ends will have a strong flux flowing across the gap and will, therefore, have a strong attraction for pieces of iron or ferromagnetic particles which are brought close to the magnet. This concept is essentially the common horseshoe magnet.



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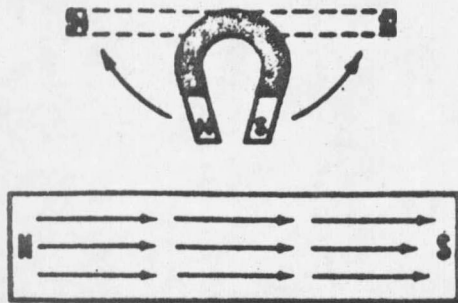
Figure 8
Magnet Lines of Force In and Around a Bar Magnet

Ring magnets. When a bar magnet is bent and the gap between the poles is completely closed so that there is no metallic discontinuity at all, there will be no leakage field or external poles. This is the concept of the ring magnet. The magnetic field which existed in the bar magnet will still exist in the ring magnet, but there will be no external evidence of its presence. In fact, the closed magnet will be much stronger than the bar magnet, since all metallic circuits have a low resistance and the high resistance air gap has been eliminated. There is no self-demagnetizing effect which is present in the bar magnet to limit the magnetic field. In this case, the ring magnet is considered to be circularly magnetized. This concept of using longitudinal magnetization utilizing a bar magnet and circular magnetization using a ring magnet are illustrated in Figures 9 and 10, pages 110 and 111, respectively, and should be carefully studied by novice inspectors (Magnaflux Corporation, 1952:1-9).

Purpose of Magnetic Particle Test

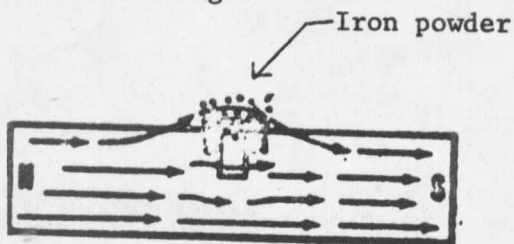
The primary function of the magnetic particle testing process is the detection of discontinuities in ferromagnetic materials. This particular method affords an excellent means of locating discontinuities which are too fine to be seen with the unaided eye on the surface of the part and those which are hidden from the human eye below the surface. It is not the purpose of these tests to determine whether or not such

Bar magnet



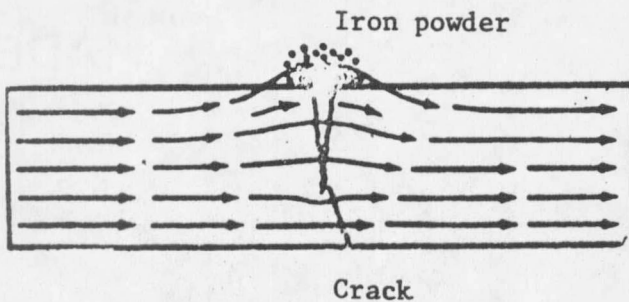
Straighten an open horse-shoe magnet, and it then becomes a bar magnet

Slit in bar magnet



A slit in a bar magnet creates magnetic poles at the slit which hold iron particles

Crack in a steel bar

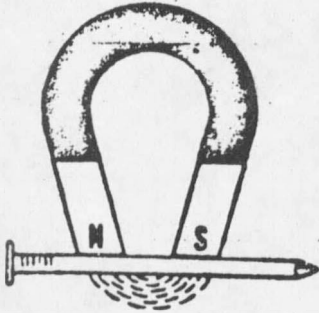


Cracks create a magnetic field outside of the part, to hold iron particles and build up as an indication of a crack

Figure 9

Longitudinal Magnetization

Open magnet



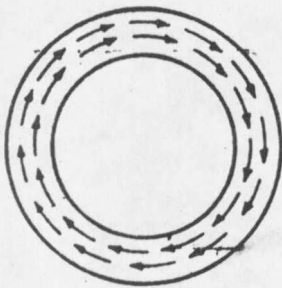
An open magnet has two poles. The magnetic field between the two poles will attract and hold a nail

Partially closed magnet



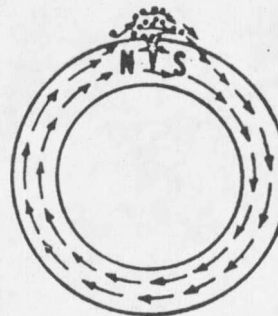
Bend the ends of an open magnet until they almost touch and the magnetic field between the poles will hold metallic particles

Completely closed magnet



Bend the magnet until it is completely closed and fuse the ends. The magnet will not attract iron particles

Cracked magnet



A crack part way through the magnet will cause polarity and a magnetic field at the crack which holds iron particles and builds up an indication

Figure 10

Circular Magnetization

discontinuities constitute harmful defects. How harmful these discontinuities are to the service life of the part must be determined by those who know the service requirements of the part. Each case must be evaluated on the basis of preset requirements and the magnitude of these discontinuities on those requirements.

Types of Test Equipment and Magnetic Particles Commercially Available

Commercial magnetic particle test units, both stationary and portable, are readily available for nearly every situation where this method of testing is applicable. A comprehensive listing of the various types of equipment available can be found in Welding Engineer, June, 1970. Emphasis should be placed upon the need for close adherence to the manufacturer's operating and maintenance instructions for each specific piece of equipment used in the testing process. Modern magnetic particle units can be purchased which produce a multi-directional magnetic field, thereby providing the inspector with the option of as many as three magnetic fields, each of which provides a magnetic field in a different direction. Using a rotational sequence, multi-directional magnetization can be accomplished with the inspection process being delayed until all of the magnetizing operations have been completed. While this method is not intended to provide a panacea for all of the problems related to magnetic particle testing, it does have many advantages (Eubanks, 1961:2).

Stationary units. A stationary, general purpose testing unit which can be used to conduct magnetic particle tests is illustrated in Figure 11, page 114 (Bureau of Naval Personnel, 1963:160-161). This type of testing unit can provide direct current for either the wet continuous method of inspection or the residual magnetization process. Circular magnetization or longitudinal magnetization can be used, and it may be powered with either rectified alternating or direct current. Contact heads have been provided to act as the electrical terminals for the magnetization process. One head is mounted in the fixed position, while the other head slides horizontally in fixed guides. Safety devices have been incorporated to prevent jamming on units which have electrically operated heads. Sufficient pressure should be maintained by the movable head to insure a good electrical connection. The magnetizing circuit is closed by depressing a push button which has been preset to open automatically after approximately one-half second. The strength of the magnetizing current is set manually by means of a rheostat, and the current used is indicated on an ammeter. Longitudinal magnetization is produced by a solenoid which moves along the same guides as the movable head and is connected to the electrical circuit by means of a switch.

The suspension is contained in a sump tank where it is continually agitated and circulated by an electrical driven pump. The suspension can be applied to the test parts by means of a flexible hose and

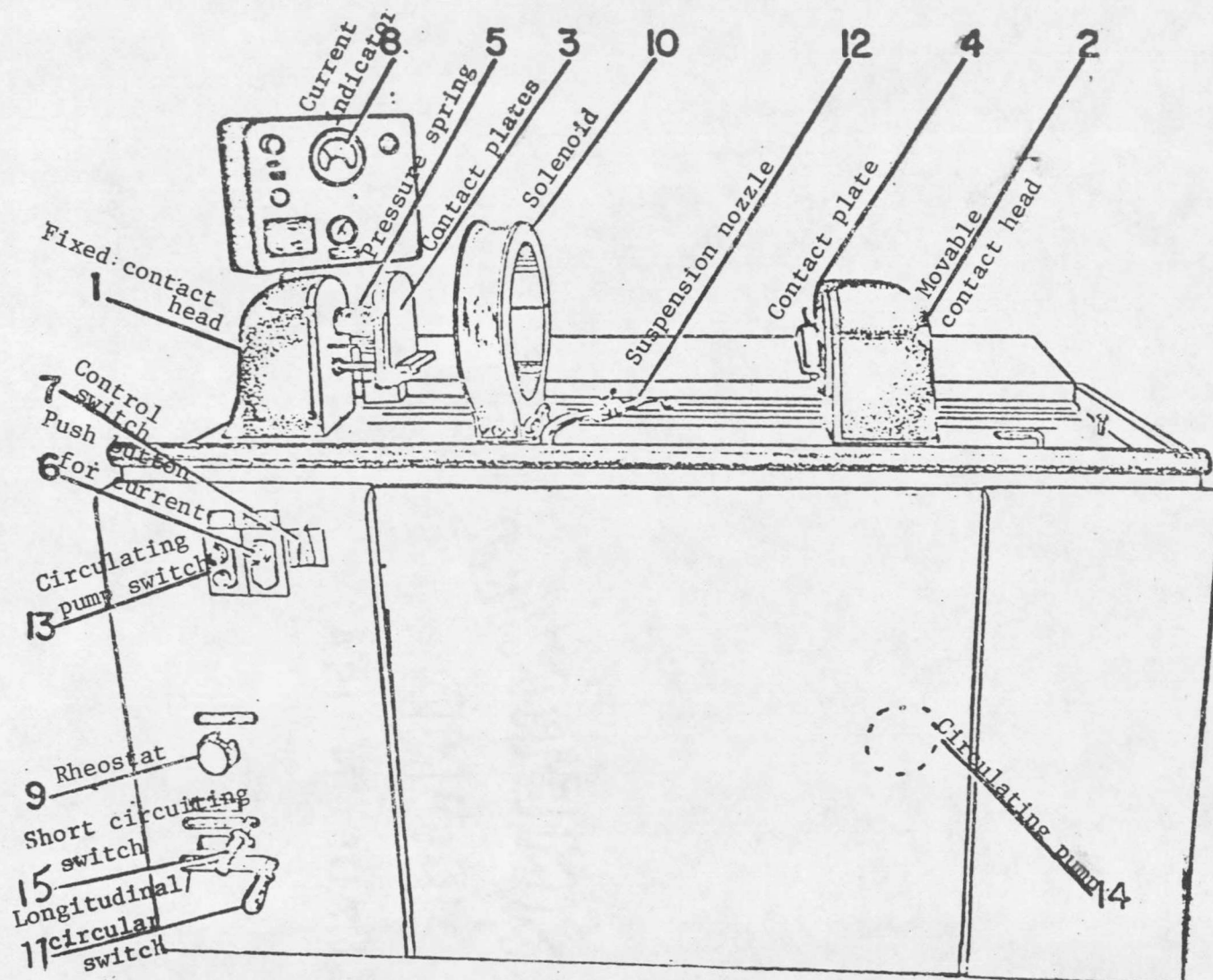


Figure 11
Standard General Purpose Magnetizing Unit

spray nozzle. Excess suspension drains from the work and passes through a wooden grill into a collecting pan at the bottom of the unit where it is filtered to prevent contamination. While some of the older models still have separate switches for the circulating operations, the newer models are connected to an on-off switch which provides for the automatic agitation of the suspension whenever the unit is in operation.

Without a thorough knowledge of the means of magnetizing parts, field strength and distribution, current distribution, and strength requirements, the inspector cannot expect to become proficient in magnetic particle methods of inspection. The following concepts should be clearly understood by all magnetic particle inspectors (Betz, 1967: 208):

1. Magnetic fields should be at 90° to the direction of the suspected discontinuity.
2. When magnetizing with electrical currents, the current should pass in a direction parallel to the direction of the suspected discontinuity. The magnetic field will then be at right angles to the current and therefore at right angles to the discontinuity.
3. Fields generated by an electrical current are at 90° to the direction of current flow.
4. Circular magnetization has the advantage over longitudinal magnetization since there are few, if any, local poles to cause confusion in the particle patterns. It is preferable when a choice of

methods is permissible.

5. For circular magnetization, 1,000 amperes should be used for each inch of part diameter. While this often produces too strong a magnetic field, the field produced will surely be strong enough.

6. When longitudinal magnetization is used, the following formula will provide the means of computing an adequate number of ampere turns for a given set of conditions:

$$NI = \frac{45,000}{L/D}$$

1. NI equals ampere turns

2. L/D equals length to diameter ratio of the part being tested

7. For prod magnetization with direct current, a minimum of 60 amperes per inch of prod spacing will produce a minimum magnetizing force of twenty Gersteds at the mid point of the prod line for parts three-fourths inch or less in thickness. A safer figure to use, however, is two-hundred amperes per inch, unless this current setting produces interfering surface powder patterns. Prod spacing for all practical inspection purposes is limited to a maximum of eight inches in part thickness, except in special cases.

Portable test equipment. Portable magnetic particle test equipment is available for field testing, and new methods of testing are taking this process out of the shop. Mobile units are especially desirable for locating defects which are open to the surface regardless of their depth, when surface indications are of primary concern, and

when the detection of subsurface indications may cause confusion or delay the testing process. Portable test units are particularly applicable to the inspection of ferromagnetic castings, forgings, and weldments. Evidence of the increasing acceptance of these units can be found in the field inspection of weldments.

The alternating current supplied by the portable units offer maximum sensitivity and speed in locating surface defects. Both circular and longitudinal magnetization are available. Contact prods are used to provide circular magnetization by passing the current directly through the part or by the use of a central conductor. Longitudinal magnetization is easily accomplished by forming a coil around the part with three or four turns of the cable. Current output in the portable units usually varies from 2,000-4,000 amperes.

When it is necessary to test components which cannot be removed, portable test equipment is a necessity. Although this unit provides for both a source of magnetization and the means for demagnetizing parts, it does not provide a means for supporting the work or applying the suspension. It usually operates on 220 volts, 60 cycles, alternating current, but each unit contains a rectifier for producing direct current when there is a need. The strength of the magnetizing current is controlled by an eight-point tap switch, and the length of time for which the current is applied is regulated by an automatic cut-off switch similar to the one used with the stationary unit.

Demagnetization is accomplished by passing alternating current through the part and gradually reducing the current with some type of current reducer (Bureau of Naval Personnel, 1963:160-161).

Magnetic particles. The magnetic particles used in the inspection process are in all cases finely divided ferromagnetic materials. Size, shape, density, mobility, and contrast should be carefully considered before a specific type of particle is selected, since the particle selected will affect the test patterns formed and will often determine whether or not a pattern is actually formed.

The basic choice in selecting magnetic particles is a choice between those used in the wet magnetic particle processes and those used in the dry magnetic particle processes, and secondarily between the various colors available, including the fluorescent particles. The final decision is influenced by one or more of the following factors (Betz, 1967:231):

1. Location: whether the defect to be located is on the surface of the part or completely below the surface. For deep lying discontinuities which are below the surface, the dry powders are usually more effective.

2. Size: the size of the defect, if it is on the surface. The wet method is usually more effective when it is used to locate very fine-shallow defects.

3. Convenience: dry powders used in conjunction with portable half-wave test units are relatively easy to use when large parts must be inspected in the field, foundry, or shop.

Dry particles. The magnetic particle inspection using the dry powders is usually used for the inspection of welds, large forgings, and castings, parts having rough surfaces, or where the location of subsurface discontinuities is expected. The dry powders used in this situation are available in red, gray, black, and yellow. The color selected will depend upon the particle characteristics listed previously. Dry powders are used extensively with portable test equipment, since they tend to offer maximum sensitivity when the inspector is searching for deep, subsurface, crack-like discontinuities.

The dry magnetic particles are heavier and individually have a greater mass than the very fine particles used in the wet magnetic particle processes. When the dry magnetic particles are applied to the surface of the test part with any appreciable velocity, the magnetic fields at the discontinuity may not be able to stop them or to hold them in place. This situation is especially true when vertical and overhead surfaces are being inspected. The dry powders should reach the surface as a cloud, with practically zero velocity, drifting to the surface where leakage fields can hold them in place. Actually, air acts as a suspension medium for the dry powders being applied and the magnetic field directs the path of the particles as they descend.

A common fault, when dry particles are used, is the application of too many particles. When this occurs, if the size of the particles permit, the part being tested can be tapped gently causing the excess particles to fall away and making the indication visible. The excess particles can also be removed by gently blowing them away with an air-stream which is not so strong that it blows away the particles which are forming the indication. When dry particles are compared to wet particles, the two most outstanding characteristics of the former are: (1) their more favorable shape, and (2) their permeability. The environment of the inspector is enhanced by the selection of the dry powders which are nontoxic in nature.

Wet particles. The wet particles are suspended in water or in a light petroleum distillate before they are applied to the parts being tested. Particles are available in either a paste or powder form, since both can be used effectively in water or oil. The basic requirements of the wet particles is similar to the requirements of the dry powders: both should produce suitable contrast for the inspection process and both should be nontoxic. The colors used most extensively for the wet method are black and red, with the latter producing an excellent contrast, especially on dark surfaces. Instant mix particles are available in a wide variety of highly visible colors.

The wet method is usually considered most effective for very fine, shallow defects. It is highly recommended for the inspection of

parts at various stages of their production and for most maintenance inspection processes. The wet method can be used successfully with direct current to locate small subsurface seams and inclusions a few thousandths of an inch below the surface. The use of wet particles has certain advantages and disadvantages. These advantages include (Betz, 1967:256):

1. It is the most sensitive method for very fine cracks
2. It is the most sensitive for very shallow surface cracks
3. It quickly and thoroughly covers the surface of irregular shaped parts, large or small
4. It is the fastest and most thorough method for the testing of large numbers of small parts
5. The particles used have excellent mobility in the liquid suspension
6. It is easy to measure and control the concentration of particles in the bath which results in uniform and accurate reproduction of test results
7. It is relatively easy to recover and reuse
8. It is well adapted to the short timed, shot technique of magnetization, which is used in the continuous method of inspection
9. It is readily adaptable to automatic unit operations

The disadvantages include:

1. It is not usually capable of locating defects lying

completely below the surface, if they are more than a few thousandths of an inch deep

2. They are messy to work with, especially when they are used with the expendable testing techniques or in field testing situations

3. When oil is used in the bath and direct current is used in the circular magnetization process, a potential fire hazard exists

4. A fairly critical recirculating system is required to keep the particles evenly distributed in the suspension

5. Occasionally, the wet particles present a post inspection cleaning problem since they tend to cling to the surface of the parts being tested

Although the exact amount of magnetic substance may vary from one bath to another, when new suspensions are being prepared, it is important that the correct amount of powder or paste be added to the suspension. A mixture of two ounces of concentration per gallon of liquid vehicle has been found to be generally acceptable for most testing processes. When questionable circumstances arise, it is best to follow closely the instructions furnished by the manufacturer.

The proper procedure in preparing the new suspension is to place the required amount of concentration in a suitable container and add small amounts of liquid vehicle, working the addition into the vehicle with a flat paddle until the concentration has been diluted into a uniform watery mixture which can be poured into the tank. The

concentration should not be poured into the liquid vehicle with the expectation that the agitating unit contained in the testing unit will mix it thoroughly. The total addition of all materials to the liquid vehicle should not raise the viscosity of the suspension above a maximum of 5.0 centistokes at any temperature at which the bath may be used (Department of Defense, 1965:3). It is important that new magnetic particle substances be used in the preparation of new suspensions.

One of the latest developments in the wet magnetic process is the use of these particles to test brazed joints in nonmagnetic stainless steels such as honey comb panels. This process depends for its success upon the fact that normally nonmagnetic stainless steels at temperatures of 2,000°F become magnetic. When this occurs, a solution of magnetic particles suspended in plastic are applied to the surface of the part being tested. The magnetic field produced causes the particles to migrate to transition regions between areas of different magnetic permeability. This plastic coating is then stripped off providing a permanent record for filing purposes, projecting as a lattem slide or for reproduction at a later date. This plastic solution dries in less than twenty-five minutes, and this drying time can be reduced considerably by the application of heat (Materials Testing Laboratories, 1968-1969:257-258).

Fluorescent particles. Fluorescent particles which are used in conjunction with a black light are available for the fastest and most sensitive inspection available. The principle of fluorescence is not a new one for many substances have the property of fluorescence. These particular materials give off light when they are exposed to a light wave length shorter than that of the violet of the visible spectrum. The black or invisible light energy is absorbed by the fluorescent materials and re-emitted as light of a longer wave length in the visible spectrum. Different substances fluoresce in a variety of different colors from blue through green, yellow, and red. Many minerals fluoresce brilliantly under black or ultra violet light and prospecting for ores such as tungsten and vanadium is often done successfully at night with a portable black light.

The dyes used to treat the magnetic particles make them glow with a greenish-yellow color when they are exposed to a black light having a wave length of 3,650 angstrom units. True ultra violet of 3,000 angstrom units also activates many substances to make them become fluorescent, but this light with a shorter wave length is harmful, causing burns and permanent damage to the eyes. The black light of 3,650 angstrom units on the other hand is entirely harmless and is used successfully in thousands of inspection locations without any ill effect whatever on the inspectors (Betz, 1967:274-275).

Fluorescent particles can be used with success in either the

wet or dry magnetic particle processes. The use of these particles literally puts a spot light on every crack, making it glow with a vivid indication which is next to impossible to miss, even in a split second glance. This method is especially well adapted to the inspection of keyways, deep holes, and other similar locations. This process can be used with success in the testing of up to 2,500 parts each hour on an assembly line or production line.

Although success can be obtained with either the fluorescent wet or fluorescent dry particles, a suspension containing both fluorescent and nonfluorescent particles should not be used under any circumstances.

Liquid vehicle. The liquid vehicle used to carry the magnetic substance for the wet penetrant process should be a light oil such as kerosene conforming to VV-K-220 or a dry cleaning solvent conforming to the requirements set by the procuring activity. All vehicles used in the fluorescent inspection process should be essentially nonfluorescent (Department of Defense, 1962:1-4).

The liquid vehicle in which the particles are suspended performs the function of providing mobility for the suspended particles.

Although almost any vehicle will perform satisfactorily in a test, if the viscosity is comparable to kerosene, experience has indicated that an acceptable vehicle should fulfill other requirements. The vehicle should be of high permeability and low retentivity. The former insures

that a minimum of magnetic energy will be required to attract the particles to the flux leakage field, while the latter insures that the mobility of the particles will not be hindered by the particles becoming magnetized and attracting each other.

Petroleum distillates which have been used extensively as the particle vehicle in the past are not without disadvantages. They constitute a potential fire hazard and the distillate has been responsible for numerous skin reactions among allergic inspectors. Other disadvantages include a relatively high cost which can be increased even more by the expense of removing the liquid vehicle after the test has been completed. These removal processes tend to increase the possibility of the part rusting at a later date.

Water has often been tried as a liquid vehicle in the past, but it was never entirely satisfactory because of its inability to wet the part completely. Also, difficulties occurred in securing the proper dispersion of the iron oxide pastes in the bath and the water vehicle increased the possibility of rusting at a later date. These initial problems have been largely overcome by the inclusion of water soluble rust inhibitors and suitable anti-foaming agents. It is now considered practical to use clean tap water with the proper additives as a carrier for both the visible and the fluorescent particles. Acceptance of this medium can be evidenced by the success of the Griffin Wheel Company in Chicago which uses this technique to inspect wheel castings on their

production line (Panozzo, 1959:2).

When the suspension becomes discolored or contaminated with oil, dust, lint, or other foreign substances to the extent that the proper distribution and concentration or the integrity, character, or definition of the deposit of the magnetic substance is interfered with, the testing unit should be drained, thoroughly cleaned, and refilled with clean suspension. Suspensions should be tested at frequent intervals depending upon the frequency of use, discoloration, or contamination. Testing the suspension at least once a day is considered essential to the success of magnetic particle tests. Nonrecirculating systems should be tested for magnetic particle content once a week regardless of the frequency of use.

The following procedures have been found most helpful when it becomes necessary to test the suspension (Department of Defense, 1965: 25-26):

1. Fill a standard pear shaped 100 milliliter graduate to the 100 ml. mark with the suspension, directly from the hose or other device which is used to pour the suspension over the part being tested. When an immersion tank is being tested, the particles in the suspension should be thoroughly agitated. Let the graduate stand for thirty minutes to precipitate, or until all of the solid matter has settled to the bottom.
2. Decant the clean liquid as far as possible without losing

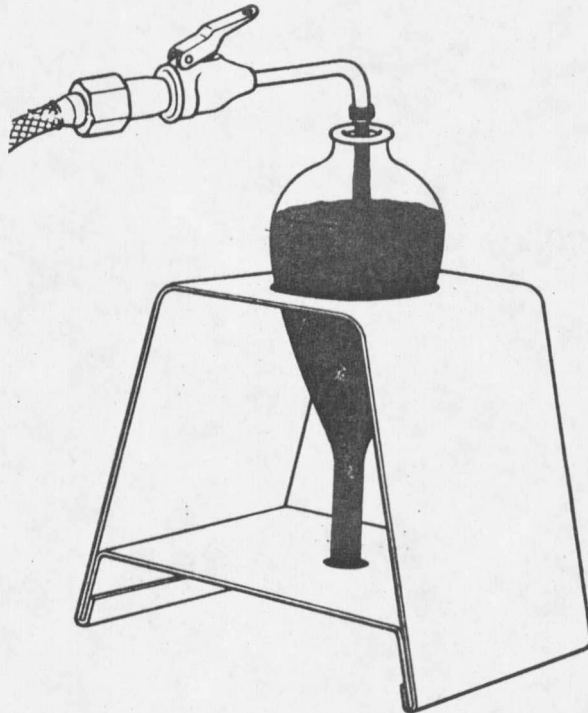
any of the magnetic substance

3. Refill the graduate above the magnetic substance with benzol, shake well, and let stand for one hour to allow the mixture to percipitate a second time

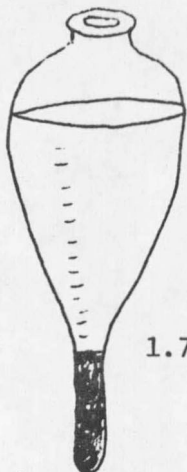
4. Read the height or volume of the percipitate in the graduate. The following amounts of magnetic particles are considered acceptable: (1) fluorescent magnetic particles, 0.3 to 1.3 ml., and (2) nonfluorescent magnetic particles, 1.7 to 2.4 ml. Figure 12, page 129 (Department of Defense, 1965:25-26), illustrates how to check magnetic particle baths for the proper amount of magnetic particles. Close adherence to the instructions provided by the manufacturer will effectively reduce the possibility of human error, thereby increasing the efficiency of the testing process.

When the inspector has made his decision regarding the most suitable type of test unit, type of current, test sensitivity required, direction of the magnetic field, and the sequence of procedures to be used in the test, there remains only the decision of which method of applying the particles is most appropriate. In this case, the choice is between the wet magnetic particles and the dry magnetic particles.

Black light. Since the black light used for the magnetic particle process is the same type as the one used for the liquid penetrant tests, data pertinent to the black light can be found in Chapter 2 of this study.

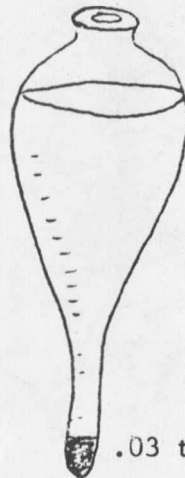


Standard Pear Shaped 100 Milleter Graduate



1.7 to 2.4 ml.

Black or red paste



.03 to 1.3 ml.

Fluorescent paste

Figure 12

Checking Bath Strength

Magnetization by Means of an Electrical Current

Since the use of electrical current is the most desirable method of magnetizing parts for the magnetic particle process, a brief description of the types of fields, types of current used in the testing process, and the availability of such current would, in the opinion of the writer, provide continuity in this chapter.

Either longitudinal or circular magnetic fields can be set up, the strength of the field varied, and by applying several types of current useful variations in field strength and distribution can be obtained. Electric current in one form or another is used for all but a very small percentage of the magnetic particle tests today.

There are two types of current in use, and both types are suitable for magnetic particle tests. They are: (1) direct current (DC), and (2) alternating current (AC). The strength, direction and distribution of the fields produced are greatly affected by the type of current selected. A complete and accurate knowledge of the basic characteristics of alternating current and direct current, and the various modifications possible in their application, is considered essential to the proper application of these characteristics in the magnetic particle process. The magnetic field produced by direct current usually penetrates the entire cross section of the part, while the field produced by alternating current is usually confined to the metal at or near the surface.

Commercial power is rarely furnished in the form of direct current and is therefore not considered as a practical source of power for stationary units. Other sources of power are the motor generator, storage batteries, and rectified alternating current. The latter is considered to be the most satisfactory source of power in this group. The advantages of rectified alternating current are readily apparent. Maintenance problems and corrosion characteristics associated with the use of storage batteries are eliminated, alternating current can be adjusted to deliver current on any work cycle, and variations of the current value is relatively simple to accomplish by using tapped transformers, saturable core reactors, or variable transformers in the alternating part of the circuit. There are many variations in the application of different types of rectified alternating current, which are highly useful in the magnetic particle testing process and could not be produced from other sources.

The exception to the use of electric current in the magnetic particle tests are those few cases where permanent magnets are used because electric current is not readily available. This situation usually occurs when the test must take place in a remote location or when the hazards from possible explosions exist. When these situations occur, the use of electric currents is prohibited.

The two most common types of magnetic fields produced with electric current are the circular method and the longitudinal method.

Figures 13 and 14, page 133, illustrate the basic concepts of circular magnetization and longitudinal magnetization (Magnaflux Corporation, 1952:1-9).

Circular magnetization is accomplished by placing the part to be tested between the poles of an electromagnet, while longitudinal magnetization is accomplished by placing the part in a solenoid coil. In either case, the magnetic field should be of sufficient intensity and direction to reveal all suspected discontinuities which could be cause for the repair or rejection of the part. In some cases, due to the size and shape of the part, it may be necessary to magnetize the part in sections to prevent the misrepresentation of resulting indications. The current should be such that saturation is considered a nonrelevant indication which can be easily recognized by the excessive amount of particles accumulated at slight changes of section or by pronounced indication of grain flow.

In some instances, it may be feasible to magnetize several parts simultaneously in the same magnetic field. This may be accomplished by placing the parts in a coil in the same position or by means of a central conductor which is placed through a hole in the parts. An example of the latter would be a large number of bolts, nuts, washers, or sleeves on a bar conductor.

Circular magnetization. This type of magnetization is the result of inducing a magnetic field consisting of concentric circles of

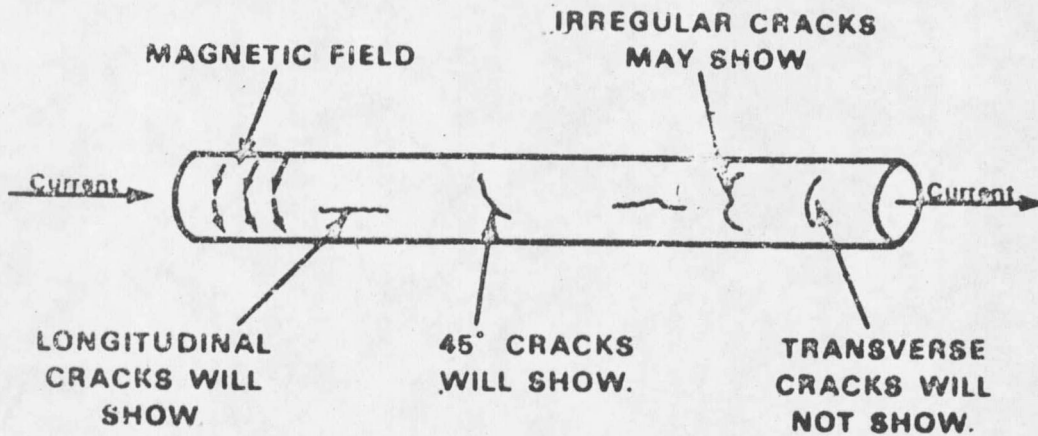


Figure 13

Detection of Cracks Using Circular Magnetization

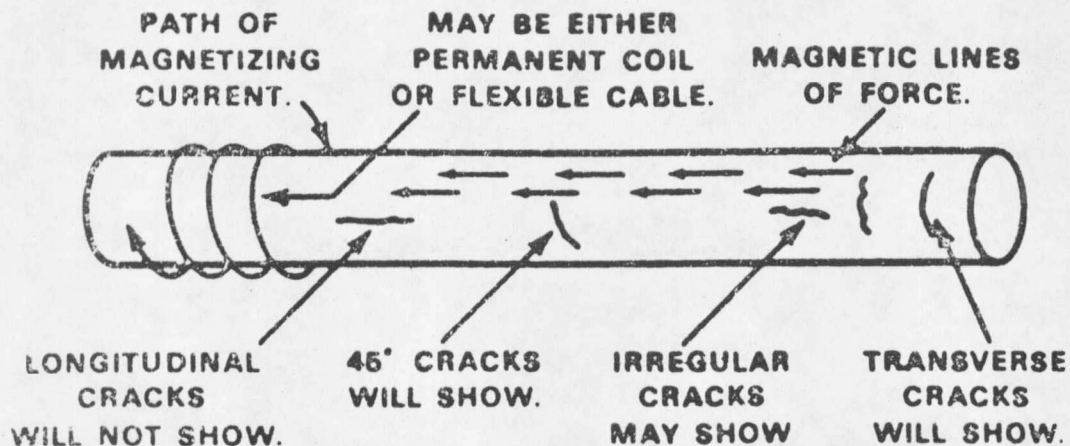


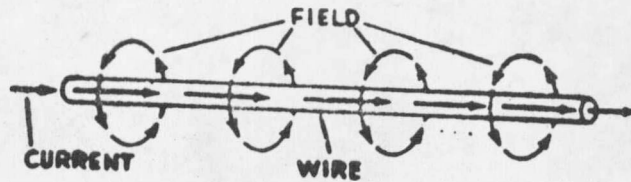
Figure 14

Detection of Cracks Using Longitudinal Magnetization

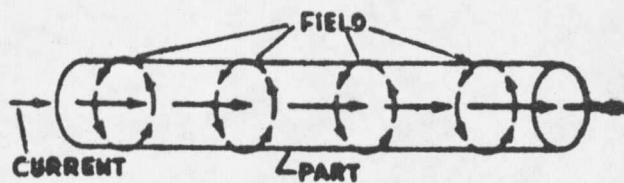
force about or within a part. It can be accomplished by running the current directly through the part or by using a central conductor in the case of hollow parts (Betz, 1967:135-136). Figure 15, page 135, illustrates the basic concepts of circular magnetization (Magnaflux Corporation, 1952:1-9).

The magnetizing force in circular magnetization should be 500-700 amperes per inch of part diameter. Either the inside diameter or the outside diameter can be used depending upon which surface of the part is being tested. When both the inside and the outside are being tested, the larger diameter should be used. For the magnetization of parts which are other than cylindrical in shape, a magnetizing current of 500-700 amperes per inch of maximum cross sectional area to the direction of the current flow should be used. A magnetic field indicator can be used to insure that a suitable flux has been established. When this type of indicator is used, a suitable flux is obtained when the indicator is laid copper side up in the area of interest and a clearly defined line of magnetic particles form across its face when the part is sprayed or immersed in the magnetic particle suspension (Department of the Navy, 1965:25).

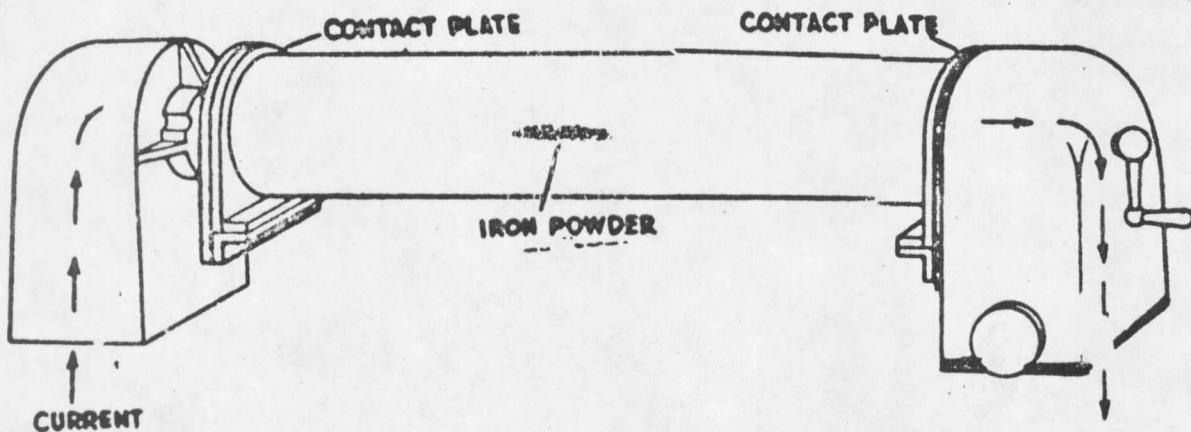
Longitudinal magnetization. This type of magnetization is produced in a direction parallel to the long axis of the part. This is accomplished by placing the part to be tested in a solenoid which has been excited by an electric current. In this situation, the metal part



Electric current passing through a wire creates a magnetic field around the wire. Direction of the field is 90° to the direction of the current.



Electric current passing through a part creates a magnetic field within the part. This is circular magnetization, a process used to detect lengthwise discontinuities



Magnetic particle indication of a lengthwise crack in a cylindrical part

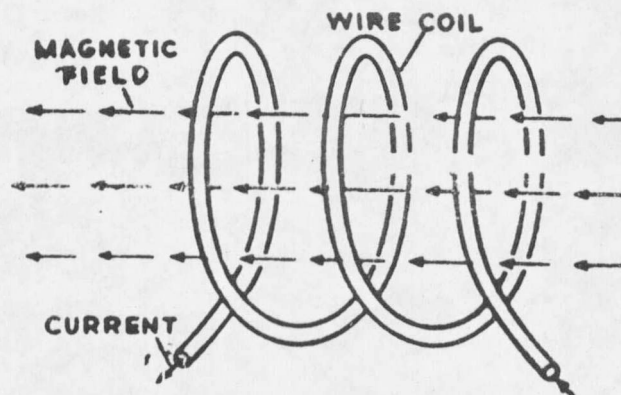
Figure 15

Circular Magnetization

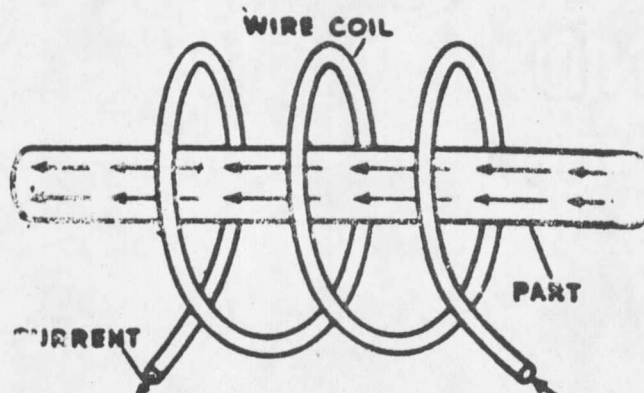
becomes the core of an electromagnet and is magnetized by induction from the magnetic field created within the solenoid. When this type of magnetization is used for long parts, the solenoid must be moved along the part to insure the proper magnetization of all areas being inspected. This procedure should be closely adhered to if sufficient field strength is to be expected throughout the part's length. Solenoids can be expected to produce effective magnetization for approximately twelve inches from either side of the coil. Therefore, these coils can accommodate parts which are approximately thirty inches in length without being moved along the part. Figures 16 and 17, pages 137 and 138, respectively, illustrate the concept of locating discontinuities using longitudinal magnetization (Magnaflux Corporation, 1952:1-9).

When a solenoid is used to magnetize parts, the solenoid should not be any longer than is considered necessary to accommodate the part being tested. The magnetizing force should be 3,000-4,000 ampere turns per inch of part diameter. Either the inside or the outside diameter can be used according to which surface is being tested. When both surfaces are being tested, the larger diameter should be used. A magnetic particle field indicator may be used to determine the flux strength.

Longitudinal magnetization equivalent to that which is obtained with a solenoid can be accomplished by wrapping a flexible electrical conductor around the part being tested. While this method is not



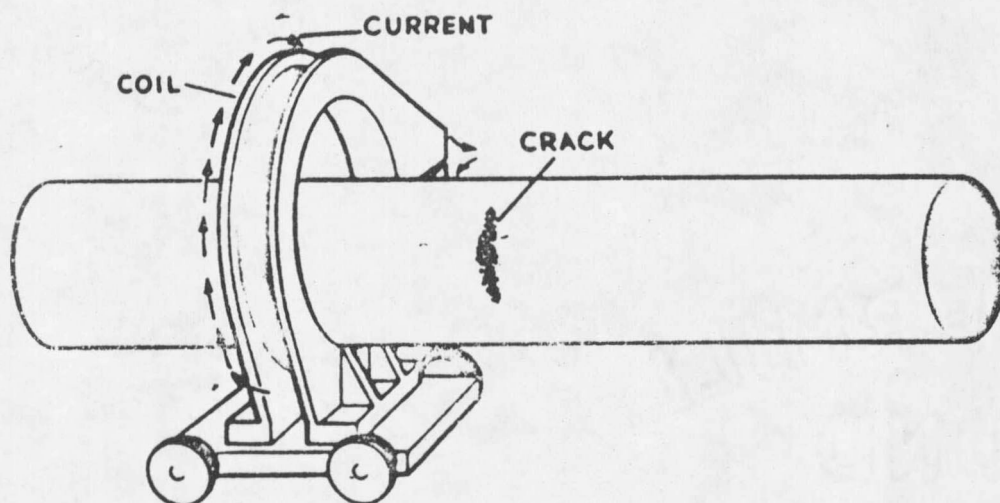
Electric current passing through a wire wound into a coil creates a magnetic field lengthwise inside the coil.



When a part is placed inside a coil carrying an electric current, a magnetic field running lengthwise in the part is created. This is longitudinal magnetization.

Figure 16

Longitudinal Magnetization



The part to be inspected using longitudinal magnetization is set up in a coil, and electric current is passed through the coil. Electricity is passed around the part, parallel to the discontinuities to be located. Small parts should not be centered within the coil, but held close to the coil where the field is the strongest.

Figure 17

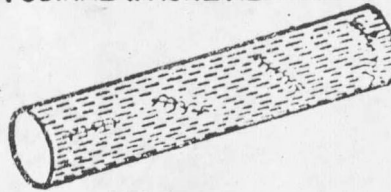
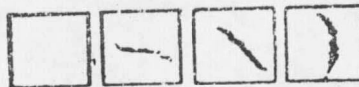
Longitudinal Magnetization

considered to be as effective as the solenoid method, it is convenient for field applications and it has the advantage of being able to produce coils which conform more closely to the actual shape of the part, thus producing a more uniform flux field. This method is especially well suited to the testing of parts which are irregularly shaped or too large to remove.

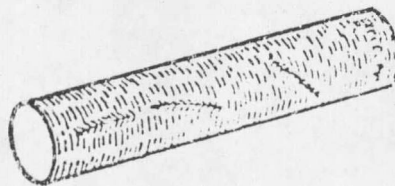
Effect of the direction of flux on the strength of indications.

In order to locate discontinuities, it is essential that the magnetic lines of force pass approximately perpendicular to the discontinuity. It is, therefore, necessary to be able to induce magnetic lines of flux in more than one direction, since the discontinuities are likely to exist at all possible angles to the major axis of the part. Figure 18, page 140, illustrates the effect of the direction of flux on the strength of indications (Caine, n.d.:3). To be positively certain that all discontinuities are located, it is advisable to apply the magnetic fields from two or more directions. Under ideal conditions, these fields should be at right angles to each other. A complete magnetic particle test should consist of one or more distinct operations so conducted that the magnetic lines of force will be transverse, insofar as possible, to any discontinuity which may be present in the part (Caine, n.d.:3).

The effectiveness of these tests depend upon the flux density or field strength at the surface of the part when the indicating medium

A. LONGITUDINAL MAGNETIZATION

ATTRACTION OF PARTICLES AT
DEFECTS

B. CIRCULAR MAGNETIZATION

ATTRACTION OF PARTICLES AT
DEFECTS

Figure 18

Effect of the Direction of Flux on
Strength of Indications

is applied. As the flux density is increased, the sensitivity of the test increases because of the greater flux leakage at the discontinuity and the resulting formation of magnetic particle patterns.

Excessively high flux densities may form nonrelevant indications which tend to interfere with the detection of magnetic particle patterns.

It is, therefore, necessary to use a field strength high enough to reveal all harmful discontinuities but one that is not so strong that it produces nonrelevant indications.

Selection of the Magnetic Particle Method

One of the most important steps in the magnetic particle test procedure is the actual selection of the most suitable process and steps of procedure for the part being tested. Many important factors are involved in this process and careful consideration should be given to the following items before a final selection is made. The considerations listed should be worked out in a matrix (Hagamier, 1972:15.24-15.25):

1. Whether the material is magnetic or nonmagnetic, metallic, or nonmetallis
2. Whether the part thickness is normal, ultra-thin, or thick
3. Whether the part geometry is symmetrical or complex
4. Whether the part size is microscopic, normal, or large
5. The material condition: is the material coarse or fine

grained, has it been annealed or heat treated

6. Whether the inspection will be manual, semi-automatic, or automatic

7. Whether the fabrication method was by casting, forging, weldment, adhesive, or braze bonded

8. Whether the surface condition is rough or normal, plated or unplated, bright or dull, clean or has scale

9. Whether the location of the suspected discontinuity is on the surface, near the surface, or subsurface

10. Whether the discontinuity orientation is axial, radial, longitudinal or traverse

11. Whether the size of the discontinuity sought is less or greater than the wave length of the probing medium, detectable, or undetectable

12. Whether reference standards are available or unavailable, simulated, or actual discontinuities and whether there is a need to fabricate these standards

13. What types of discontinuities are being sought: cracks, porosity, heat treatment, plating thickness, or bond quality

14. What type of test equipment and test method is available in the plant, at the contractors' facilities, in the research and development department, or not available

15. What is the test specification availability: routine

and available, use other supplier's specifications, or need to write them

16. What is the accessibility of the part: part is not accessible, part accessible but need to purchase or fabricate special probes or search units

17. What is the availability of the part: the part can be brought to the inspection area, portable equipment must be taken into the field or to the factory location

18. What is the acceptance criteria: it has been developed, it is or is not readily available

19. What test method will be used: routine, special, research and development necessary, or literature research necessary

20. What type of inspector qualifications are required: trained and certified, need public assistance, need training, none available

21. What test results can be expected: permanent, semi-permanent or no record, basic measurements or relative values, video or digital display, can or cannot be automated

22. What is the cost of the equipment required: expensive, normal, inexpensive

23. What is the nature or use of the part being tested: high or low stress, short or long fatigue life

24. What safety requirements need be met: need to protect

against radiation hazards or high voltages

This list appears to present a formidable barrier to the final selection of an applicable test method. In actual reality, however, most qualified inspectors can go through the mental gymnastics required to select the proper process in a matter of minutes. When the inspector is confronted with a new design or similar problem, he may be required to set up a matrix using the considerations listed before he makes a final decision. The applications, advantages, and limitations of liquid penetrants, magnetic particles, and eddy currents and what they are supposed to measure or detect are illustrated in Table 9, page 145 (Hagamier, 1972:15.24-15.25).

EVALUATION OF THE MAGNETIC PARTICLE TEST

The magnetic particle inspection process was evaluated by the writer to determine whether or not it met the five criteria set forth in the analysis of data section. The magnetic particle inspection process met the criteria in the following ways.

Compatibility to Existing Industrial Education Programs

The writer believes that the justification for including non-destructive testing programs in the industrial education curriculum can best be stated by those who are knowledgeable in this area.

Professor James P. Nagy, Materials Science Department, Erie Community

Table 9

Applications, Advantages, and Limitations of Nondestructive Tests

	Penetrants	Magnetic Particles	Eddy Currents
Measures or defects	Defects open to the surface, cracks, porosity	Surface and subsurface cracks, seams, porosity, and inclusions	Surface and subsurface cracks and seams Alloys Heat treatment Wall thickness, crack depth, and coating thickness
Applications	All parts with non-absorbing surfaces	Ferro-magnetic materials, bar forgings, weldments, and extrusions	Tubing, wire, ball bearings Spot checks on all types of surfaces
Advantages	Low cost, portable indications may be further examined visually	Relatively fast and economical. May be portable. Indicates inclusions open to the surface	No special operator skills required. High speed, low cost with automation possible for symmetrical parts
Limitations	Surface films such as coatings, scale, or smeared metals may prevent detection. Parts must be cleaned after the inspection	Alignment of the magnetic field may be difficult, demagnetization may be required and parts must be cleaned after the inspection Thick surface coatings	Conductive materials, depth of penetration, thin wall only. Masked or false indications caused by sensitivity to variations. Reference standards required.

College (1976:personal letter to the writer), made the following statement:

. . . I feel that the topics of nondestructive testing could very well be compatible with existing technical education programs at the high school level, especially in courses such as machine shop, metals casting, welding, and heat treating.

Dr. Richard R. Haugo, Professor, Industrial Education, Bemidji State University (1976:personal letter to the writer), stated that:

. . . it would appear that magnetic particle methods of inspection are compatible to what should exist in industrial education programs in my estimation. It is doubtful, however, that this much is being done.

L. J. Sparrowhawk, Instructor, Pinellas Vocational Technical School (1976:personal letter to the writer), gave his opinion of the compatibility of magnetic particle testing processes in the industrial education program in the following statement, ". . . magnetic particle processes and liquid penetrant processes can be taught to high school students without involving them in an extensive or intensive amount of technical preparation." Carl E. Betz, Nondestructive Test Consultant and past Vice-President, Magnaflux Corporation (1976:personal letter to the writer), reinforces this opinion with the following statement:

. . . there is no doubt in my mind of the need for a wider teaching of the fundamentals of nondestructive testing at an early time in the technical education of high school students who have an interest or inclination towards an engineering career.

Bruce D. Tyler, Director of Training, Magnaflux Corporation (1974:personal letter to the writer), sums up the need for including

nondestructive testing processes in the high school program, ". . . I cannot give one good reason for not teaching nondestructive testing processes in the high school, other than mental laziness on the part of the instructor."

The inclusion of magnetic particle inspection processes in the industrial education curriculum can, in the opinion of the writer, be justified by the goals and objectives (page 7) which the American Vocational Education Association set for industrial education (1968: 9-11).

Ability to Satisfy One or More
of the Present Needs of Industry

T. W. Judd, Assistant Division Head, Nondestructive Testing Division, Republic Steel Corporation (1976:personal letter to the writer), clearly indicates that there is at the present time a need for nondestructive test personnel in industry. He believes that, ". . . students graduating from high school with a knowledge of the practical applications of nondestructive testing could satisfy one or more of the needs of industry." This statement is reinforced by Glenn M. Thatcher, Coordinator of Industrial Technology, Kean College of New Jersey (1976: personal letter to the writer), who indicated that, ". . . people familiar with and trained in nondestructive testing techniques are greatly desired by industry at the present time."

Warren J. McGonnagle stated in 1961 in his book Nondestructive

Testing (1961:vii) that, ". . . one of the primary requirements for expanding the technology for the solution of tomorrow's problems is education in the field of nondestructive testing." In 1976, Robert T. Anderson, Technical Director, The American Society for Nondestructive Testing, Inc. (1976:personal letter to the writer), outlined the advantages education in the field of nondestructive testing:

. . . if high school students could be equipped with a knowledge of the practical applications of nondestructive testing (necessitating a familiarity with equipment), they would have knowledge that no other high school graduates would have. Hence, they would have an advantage over other such persons in entering the industrial labor market. Such knowledge would also serve to whet their interest for further education at the vocational-technical level or in one of the several junior colleges now offering fairly extensive course work in nondestructive testing.

The advantages of having high school experience in nondestructive testing is stated by James P. Nagy, Professor, Materials Science Department, Erie Community College (1976:personal letter to the writer), ". . . it would certainly be of help to industry to have high school students with a knowledge of nondestructive testing." Roy L. Odell, Western Manager, Automation Industries Incorporated, Sperry Division (1974:personal letter to the writer), made the following statement, ". . . it is extremely evident that there is currently a manpower shortage for trained and qualified nondestructive testing personnel."

Relative Simplicity and Broad
Encompassing Nature

Magnetic particle testing has grown from the original concept of acceptance or rejection of finished parts to become an integral part of the production line process. In many cases the "why" of the test results are given more significance than the "what" of these tests. Magnetic particle inspections have become part of the manufacturer's feedback-loop, constantly controlling quality through modifying operations which begin with the incoming materials and parts and continue through the shipping of the final product. These tests can be used to detect surface and subsurface defects, cracks, porosity, seams, cold-shuts, weld defects, inclusions, fatigue, and processing cracks with reliability. Magnetic particle tests can be used on all types of ferromagnetic materials regardless of the size or shape of the part. Portable equipment is available for the service testing of components in the field. The simplicity of the magnetic particle tests is clearly stated by J. E. Hinkel, Manager of Application Engineering, Lincoln Electric Company (1976:personal letter to the writer), "... all of the processes used in nondestructive testing operate on sound and relatively simple principles of physics, electricity, and science."

There are three essential steps to be considered in the application of the magnetic particle test. They are: (1) the proper magnetization of the part to be inspected, (2) application of suitable magnetic particles after the part has been magnetized, and (3) the inspection of

the part for the presence of indications.

George Pherigo, Chairman of the Educator's Division, The American Society for Nondestructive Testing (1976:personal letter to the writer), stated that, "... magnetic particle and liquid penetrant inspections are relatively simple in their application and could be taught successfully in the high schools." Carl E. Betz, Nondestructive Test Consultant and past Vice-President, Magnaflux Corporation (1976:personal letter to the writer), reaffirms this belief by stating, "... magnetic particle testing and liquid penetrant testing are relatively simple in theory and application. They require little in the way of technical preparation to be understood." Richard R. Haugo, Professor of Industrial Education, Bemidji State University (1976:personal letter to the writer), indicated that although these methods are simple enough, they should have a broad nature so as to develop interest in the student.

Glenn T. Thatcher, Coordinator of Industrial Technology, Kean College of New Jersey (1976:personal letter to the writer), sums up the relative simplicity and encompassing nature of these processes with the following statement, "... with the exception of ultrasonics and radiography, nondestructive testing processes are relatively simple in their application and they do have a broad encompassing nature."

Portable magnetic particle testing units can be purchased from Uresco Corporation or Magnaflux Corporation including cables and prods,

a field indicator, black light, and magnetic powders for less than \$2,000.

Potential in Satisfying What the
Writer Believes to be a Weakness
of the Present Industrial
Education Program

Based upon an evaluation of the stated goals and objectives of industrial education as set forth by the American Vocational Education Association on page 7 (1968:1-11), the writer believes that industrial education teachers cannot be expected to satisfy the needs of their profession until they have developed a certain measure of competency in magnetic particle testing. This competency should include an awareness and knowledge of: (1) the basic theories and principles, (2) the advantages and limitations, (3) the potential safety hazards, if any, and (4) the skills required to satisfactorily perform the magnetic particle test.

The statement by Eckhart A. Jacobsen (1968:4) that "... industrial education too often reflects the revolution of the past century rather than the evolution which has taken place since 1940. Much of the relevant content to which we must relate did not exist at that time" is reinforced by Joseph L. Rose, Mechanical Engineering Department, Drexel University (1976:personal letter to the writer), in the following statement, "... nondestructive testing processes have the potential to satisfy one of the current weaknesses of the present industrial

education program."

George Pherigo, Chairman of the Educator's Division, The American Society for Nondestructive Testing, Inc. (1976:personal letter to the writer), indicated that, ". . . there is a definite need for more information about nondestructive testing techniques in industrial education as they support industrial processes." Glenn M. Thatcher, Coordinator of Industrial Technology, Kean College of New Jersey (1976:personal letter to the writer), reaffirms the statement by Jacobsen (1968:4) in the following statement, ". . . I do feel that nondestructive testing is an area in which industrial education teachers might consider in making their programs more relevant."

James P. Nagy, Professor, Materials Science Department, Erie Community College (1976:personal letter to the writer), sums up the belief of the writer that a need for nondestructive testing in the present industrial education program currently exists in the following statement:

. . . many high school graduates are not aware of the various occupational areas of industry, especially nondestructive testing. A program of the sort suggested by this study could possibly encourage high school graduates to enter college level programs in materials science and nondestructive testing.

The Educational Requirements and Competency Levels Expected of Inspectors

Since this study is concerned with the development of entry-level competencies in the area of magnetic particle testing, only those

requirements which are essential to the development of this level of competency have been included in this study.

Each entry-level inspector is expected to demonstrate, prior to being considered for certification in the field of magnetic particle testing, that he has acquired (American Society for Nondestructive Testing, 1971:1-5): (1) sufficient education and experience to ensure an understanding of magnetic particle principles and procedures; (2) instruction in the processing of parts to the point where he is capable of demonstrating proficiency in performing specific tests on one or more samples; and (3) sufficient knowledge to pass a written examination which includes questions related to the equipment, operating procedures, and testing techniques. Prior to his certification, the entry-level inspector should work at all times under the direct supervision of a certified inspector. He is directly responsible to this inspector for the performance of all magnetic particle inspections.

According to Carl E. Betz (1966:396), the magnetic particle inspector should have the following physical and natural competencies:

He should possess good vision, be conscientious, and have a temperament which can be relied on not to become careless under possible monotony. If the inspector is sufficiently intelligent and alert, he should soon acquire the experience necessary to interpret most magnetic particle inspections. He should not be entrusted with the responsibility of working out new magnetizing procedures for new and widely differing classes of parts made of different types of steel until he has acquired sufficient knowledge and experience.

Having met the five criteria as set forth in the analysis of

data section, procedures for applying the magnetic particle process in industrial education programs at the high school level have been described in depth.

PROCEDURES FOR APPLYING THE MAGNETIC PARTICLE PROCESS IN INDUSTRIAL EDUCATION

Magnetic particle testing has become a standard testing practice in most sections of industry where iron and steel are made, fabricated, or used for important ends. Its applications are now so numerous and varied that it is difficult to give examples of all of its industrial uses (Betz, 1967:419).

Essentially, there are two basic components required for the successful completion of magnetic particle inspections. The first is the knowledge that the part must be magnetized with magnetic fields of suitable strength which have been applied in the correct direction for the detection of the particular type of defect being sought. The second ingredient of successful magnetic particle testing is the selection by the inspector of the correct type of magnetic particles to secure the best possible indications of the defects being sought under prevailing conditions in any given case (Betz, 1967:209).

Once the inspector has made these decisions the next step in the inspection process is the actual testing of the part by the method selected. To provide continuity in the inspection process, the following steps are suggested:

1. Surface preparation of the parts
2. Magnetizing parts
3. Application of the magnetic particles
4. Inspection and evaluation of parts
5. Establishing acceptable inspection standards
6. Principles of demagnetization
7. Marking parts and recording test results

Surface Preparation of the Parts

Prior to the application of the magnetic particles, all grease, oil, or other foreign materials should be removed from the part to prevent the formation of nonrelevant indications. One of the first prerequisites for successful magnetic particle inspections is cleanliness. All openings and oil holes leading to obscure passages or cavities should be plugged with paraffin or other suitable nonabrasive materials. The latter should not be used unless they are completely soluble in light engine oil. Parts containing small crevices should not be cleaned with chlorinated solvents, even though they have been previously plugged.

In general, the smoother the surface of the part and the more uniform its surface, the more favorable are the conditions for the formation and observation of the powder pattern. This applies particularly to tests being made on horizontal surfaces. For vertical and sloping surfaces, the dry powder may not be held on a smooth surface by

a weak leakage field. All surfaces should be clean, since the particles will stick to wet or oily surfaces and not be free to move over the surface to form the indications. The latter condition may completely prevent the detection of significant discontinuities. Since part surface roughness decreases the sensitivity of the test and tends to distort the magnetic field, it interferes mechanically with the formation of the powder pattern.

Any loose dirt, paint, scale, or rust should be removed with a wire brush, shot, or grit blasting or by some other acceptable means. On surfaces which have been cleaned of foreign materials by wiping them with a rag soaked in maptha, a thin film of oil often remains which is sufficient to interfere with the free movement of particles. This film can be removed by dusting the surface with chalk or talc from a shaker can and then wiping the surface with a clean, dry cloth. An initial application of the dry magnetic powder will often provide a surface over which a second application of magnetic particles will provide a dry, oil-free surface. It is not advisable to depend entirely upon the magnetic particle suspension to clean the parts. Attempts to clean by this method are not thorough, and the foreign materials removed from the parts will contaminate the bath, effectively reducing its ability to perform properly.

Primers, paints, enamel, and similar other nonmetallic coatings, as well as coatings of cadmium, copper, tin, and zinc, do not usually

interfere with the performance of the inspection process unless they are unusually heavy or the discontinuity to be detected is very small. Paint or plating on the surface of the part has the effect of making a surface defect behave like a subsurface defect. In this respect, the dry method is considered more effective in its ability to produce valid indications through such nonmagnetic coatings than is the wet method.

Chromium and nickel platings will not generally interfere with the formation of indications open to the surface, but they will prevent the formation of indications where very fine discontinuities are under consideration. Because it is more magnetic, nickel plating is more effective than chromium plating in preventing the formation of magnetic particle patterns. Most coatings of cadmium, nickel, and chromium are usually thinner than 0.005 inch and the plating thus serves as an excellent background for viewing the indications. When the possibility exists that a relatively heavy coating will interfere with the detection of harmful discontinuities, it is advisable to complete the necessary tests prior to the application of the plating (Aeronautical Standards Group, 1953:4). If very fine cracks are expected to be detected, the surface in question should always be stripped when the plating exceeds 0.005 inch in thickness.

Hot galvanized coatings are an example of the types of coatings which should be removed before the tests begin. The only exception to this would be a situation where only gross discontinuities are

considered significant. Broken or patchy layers of heavy scale also tend to interfere because of their tendency to hold magnetic particles around the edges of these breaks and patches. These coatings should be removed if there is any possibility that they are extensive enough to seriously interfere with the detection of genuine discontinuities (Betz, 1967:246-247).

Magnetizing Parts

In the continuous method of magnetizing parts, the part to be tested is magnetized and the magnetic particles are applied while the magnetizing force is maintained. The available flux density is thus maintained at maximum value: a factor which depends directly upon the magnetizing force, and the permeability of the material of which the part is made.

The continuous method of magnetizing parts may be used in practically all circular, longitudinal, wet, and dry magnetization processes. The excessive length of the solenoids in earlier days made it impractical to use the wet continuous method, but these difficulties have been eliminated and the application of the wet continuous method with these new solenoids is always a possibility.

Whenever a choice exists between the residual and the continuous method of application, the latter is always preferable. The advantage of this method is simple but basic. When the magnetizing force is applied to a ferromagnetic material, the field rises to a maximum on

the hysteresis curve, its value or intensity deriving from the field strength of the magnetizing force, and the material permeability of the part. When this magnetizing force is removed, the residual magnetism in the part is always less than the field present when the magnetizing force was acting. The actual amount of difference depends upon the retentivity of the material being tested. The continuous method, for a given value of magnetizing current, is always more sensitive than the residual method, at least so far as the sensitivity is determined by the strength of the field in the part. The continuous method is faster than the residual method due primarily to the fact that the particles are applied to the part while it is being magnetized. However, the continuous method will reveal more non-significant discontinuities than the residual method, and the interpretation and evaluation of the discontinuities discovered by this procedure requires careful observation on the part of the inspector.

The residual method should only be used on parts which have sufficient retentivity, since the magnetic field retained by the parts must be capable of attracting magnetic particles and thus producing an acceptable pattern of indications. The residual method is, in general, reliable only for the detection of surface discontinuities and is primarily used for the detection of discontinuities in steel parts which have been treated for stress applications.

Although the continuous method has the inherent advantage of

greater sensitivity, there are special circumstances which find the residual method more desirable. For example, the residual method is frequently used in special application and automatic testing equipment because the timing of the magnetization and the application of the particles is not critical and the entire process is more easily controlled.

Application of the Magnetic Particles

The application of the magnetic particles is a relatively simple process. By a combination of shaking, as one would do with a salt shaker, and applying pressure as one would on a typical squeeze bottle, the proper ejection of powder can be accomplished with a minimum velocity. A small amount of practice with a squeeze bottle and a sheet of paper will quickly enable the inspector to produce an even, gentle coverage. A more uniform distribution of the particles may be obtained by lightly vibrating the part while the excess powder is being removed. An excessive amount of powder can seriously impede the evaluation of indications. The use of these dry powders has certain advantages and disadvantages. The advantages include (Betz, 1967:245):

1. They are considered excellent for the location of defects below the surface, and deeper than a few thousandths of an inch
2. They are easy to use for large objects and with portable equipment

3. They have good mobility when they are used with alternating half-wave current
4. They are not as messy as the wet particles
5. The equipment is usually less expensive.

The disadvantages include:

1. They are not as sensitive as the wet method for locating fine and shallow cracks
2. It is not as easy to cover all of the surfaces properly, especially when the parts are large or irregularly shaped
3. They are slower than the wet method when large numbers of small parts are involved
4. They are not readily usable for short, timed-shot techniques using the continuous method
5. They are difficult to adapt to a mechanized test system

The application of the wet particles cannot in any sense be considered more difficult than the application of the dry particles. In the wet process, the particles are applied to the parts by hosing or immersing the part in the liquid vehicle containing the magnetic particles so that all of the surfaces to be tested are adequately covered.

When the continuous method of testing is used, the magnetizing circuit should be closed just before diverting the suspension or just before removing the part from the suspension if the inspection is

accomplished by the immersion process and allowed to remain closed for one-fifth to one-half of a second. This will result in insuring that the magnetizing current is applied while the part is still covered with a thin film of suspension which is sufficient to give satisfactory results.

When the residual method is used, the part should be magnetized by the application of current for at least one-fifth of a second, after which the magnetizing current should be shut off and the suspension applied by hosing or immersing the part. When the immersion technique is used, the part must be carefully removed from the suspension to avoid washing off the indications. In situations where the residual fluorescent process is used, the parts being tested should be rinsed in the vehicle used for the preparation of the suspension if it is felt that this procedure will enhance the indications.

Inspection and Evaluation of Parts

The magnetic particle method of testing produces indications of the possible presence of flaws. These indications are suggestive that something in the composition of the part is not normal, but they do not in themselves tell exactly what caused the indications. In this testing process, each pattern is the result of a disturbance created by a leakage field, but further knowledge and information is needed if the inspector is expected to state whether or not the pattern is significant.

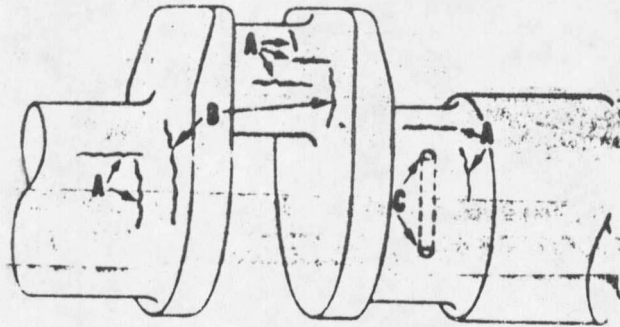
Given an indication of a magnetic disturbance which is evidenced by a magnetic pattern, the inspector should decide what the condition of the part is that has caused the pattern. In other words, he should interpret the indication in terms of its cause. For many years it has been customary to classify discontinuities in magnetic particle testing according to their source of origin in the various stages of production of the metal, its fabrication, and its uses. Before this can be accomplished, acceptable standards must be established.

Establishing Acceptable Inspection Standards

The need for an acceptable inspection standard in the field of magnetic particle testing becomes increasingly apparent as one considers the statements in Bulletin No. 87, Foundry, December, 1955, which states:

. . . magnetic particle inspection currently is the only major nondestructive testing process without standards of acceptance. At the present time, the only standard involves someone pounding on the desk and shouting, we want no cracks in our parts. At least one specification is being written which states that no magnetic particle indications regardless of length will be accepted (Caine, n.d.:2).

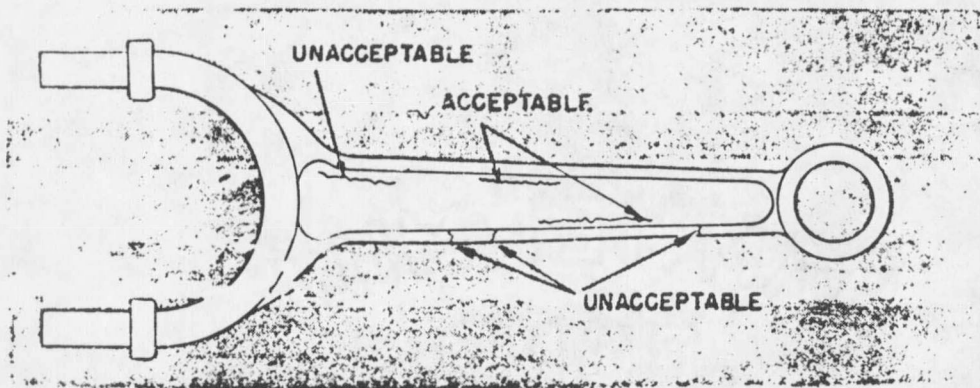
A few companies on the other hand have initiated private magnetic particle standards. Figures 19 and 20, pages 164 and 165, respectively (Caine, n.d.:3), illustrate acceptable and unacceptable types of discontinuities for crankshafts and connecting rods. It is most



- A. Longitudinal or transverse indications one inch to one and one-half inch long and one-sixteenth inch deep are acceptable away from fillets or oil holes. Up to four short indications per bearing are considered acceptable.
- B. Unless indications in fillets are under one-fourth inch in length, the crankshaft should be scrapped.
- C. Crankshafts should be scrapped when indications at the oil holes are less than one-half inch in length.

Figure 19

Standard for Crankshafts



Acceptance standards for indications on a connecting rod indicate that the acceptance or rejection of the part depends upon the location and orientation of the defect.

Figure 20

Standard for Connecting Rods

interesting to review these standards to see what is and what is not acceptable on the basis of actual performance.

The acceptable level of quality as illustrated in Figure 19, page 164, is applicable to large crankshafts: it would not be applicable to aircraft parts which have a high safety factor. However, this illustration serves to indicate what is lacking in many nondestructive testing specifications, namely, specific values on the sizes and shapes of indications which are acceptable. There is also ambiguity as to the disposition of parts which do not meet the criteria specified.

Figure 20, page 165 (Caine, n.d.:3), shows the acceptable criteria for connecting rods. This illustration does not indicate the specific dimensions on indication size, but it does point out the relative acceptable size in relation to the size of the part being tested. Of primary concern to the inspection is the fact that the discontinuity location and orientation, not the indication size, is the primary cause for rejection. It is also interesting to note that the specifications in each of these figures is applicable to a specific part. This is a feature common to the best nondestructive test specifications. The more general the specification, the more worthless it becomes.

Principles of Demagnetization

All ferromagnetic materials after magnetization will retain a residual field to some degree. This field may be quite negligible in

very soft materials but in harder materials it may be comparable to the intense fields associated with the special alloys used for making permanent magnets. The problem of demagnetization may be relatively simple or most difficult depending upon the type of material from which the part is made. Any ferromagnetic material subjected to magnetic particle tests may require demagnetization afterwards. Materials having a high coercive force are the most difficult to demagnetize. High retentivity is not necessarily related directly to the high coercive force. Therefore, the strength of the field retained is not always an accurate guide as to the probable ease or difficulty of the demagnetization process.

Reasons for demagnetizing. Demagnetization is considered necessary when the magnetization of the part (Office of the Secretary of the Navy, 1965:42):

1. May affect the operation or the accuracy of instruments when the part is placed in service
2. May interfere with the proper functioning of the component
3. Could cause particles to be attracted to or held on the surface of moving parts, particularly parts which are submersible in oil, thereby causing undue wear
4. Is likely to interfere with the inspection of the part at low field strengths

The inspector should be cautioned that it is not always necessary to demagnetize the parts and since the process involves both time and expense there is no need to do so unless there is a good reason for doing it. In the past demagnetizing was often carried out as a matter of course, without actually considering whether it was necessary. Today, it is considered essential to the success of the testing process that each inspector understand fully the reasons for demagnetizing as well as the problems involved and the means for solving them.

Methods of demagnetizing. Demagnetization may be accomplished in a number of different ways. Possibly the most convenient procedure to use for sensitive parts involves subjecting the part to a magnetizing force that is continually reversing its direction and at the same time gradually decreasing in field strength. As this decreasing magnetizing force is applied, first in one direction and then in another, the magnetization of the part will also decrease.

The simplest procedure for developing a reversing and gradually decreasing magnetizing force in a part involves the use of a solenoid energized by alternating current. As the part is moved away from the alternating field of the solenoid, the magnetic field in the part gradually decreases. A demagnetizer as near the actual size of the part as possible should be used. For maximum effectiveness small parts should be held as close as possible to the inner wall of the coil.

Parts that do not readily lose their magnetic fields should be passed slowly through the demagnetizing unit. This procedure may need to be repeated several times. During the demagnetizing process, the parts should be rotated or tumbled in various directions to insure their complete demagnetization. Allowing the part to remain in the demagnetizer with the current on accomplishes very little and should be discouraged. The most effective operation in the demagnetization process is accomplished by moving the part slowly out of the coil and away from the magnetizing field strength. As the part is withdrawn, it should be kept directly opposite the opening until it is one or two feet from the opening in the demagnetizing unit. The demagnetizing current should never be turned off until the part has been removed from the magnetic field, since this could result in the remagnetization of the part.

Although there are innumerable methods which could be used to successfully demagnetize parts and materials, the two most commonly used methods are demagnetization with an alternating current and demagnetization with direct current.

The most common method used to demagnetize small to moderate size parts is by passing them through a coil through which alternating current at a line frequency of 50-60 cycles per second are passing. Alternatively, the sixty cycle alternating current is passed through a coil with the part inside the coil and the current is gradually reduced

to zero. In the former, the reduction of strength of the reversing field is obtained by the withdrawal of the part axially from the coil or the coil from the part, and for some distance beyond the end of the coil or part along the axial line. In the latter, the gradual decay of the current in the coil accomplishes the same result.

There are several methods of demagnetizing with direct current. Although the direct current method of demagnetization is more effective, it is essentially identical in principal to the alternating current method described earlier in this study. By using reversing and decreasing direct current, lower frequency reversals are possible with more complete penetration of the demagnetizing force in parts with larger cross sections. Mechanical switching makes possible automatic reversals at a higher frequency per second than is commonly used in the manual process. Although this method requires special equipment, it is considered to be more practical and economical. In fact it is one of the most successful means of removing circular magnetic fields, especially when the current is passed directly through the part. Even parts having large cross sections can be demagnetized by this method. When a coil is used in conjunction with this method of demagnetizing, the part should remain within the coil for the duration of the entire cycle.

Some of the following suggestions could be quite helpful to the novice inspector in the demagnetization process (Betz, 1967:319-320):

1. When a short part is being demagnetized in an alternating

current coil by the process of withdrawing the part along the line of the axis of the coil, it is helpful to rotate the part both around axes parallel to and transverse to the coil's axis. This should be done while the part is in the coil and during the entire withdrawal time. This procedure is also effective in the demagnetization of hollow and cylindrical parts.

2. As a variant of the previous procedure, ring shaped parts may be rolled through the coil, a procedure which effectively helps to achieve a lower level of remnant magnetization.

3. A short part with a length-diameter ratio of one or less can often be more easily demagnetized by placing it between two-pole pieces of soft iron of a similar diameter, but longer than the part being tested. This combination is then passed through the coil as a unit. This procedure has the effect of increasing the length-diameter ratio and thus facilitates the removal of the magnetic field in the part.

4. For the demagnetization of ring shaped parts using a coil, the central conductor is energized with alternating current and the current caused to decay to zero by means of either a step-down switch or a stepless current control device. The latter method of decay can be reduced to a few seconds, thus providing a more effective method than the step-down method which requires about thirty seconds to complete its cycle.

5. Method (4) can also be used satisfactorily with reversing, decaying, or step-down direct current instead of alternating current.

6. For long parts, a direct current coil with the current on may be moved along the length of the part, the step-down of current is accomplished by one of the methods mentioned previously.

7. As a variant of (6), the operator may move the coil on "high current" along the length of the part with step-down being accomplished by one of the methods mentioned earlier.

8. For large hollow parts, a central conductor with high alternating current is passed through the close to the wall of the part, while the part is rotated 360° and the alternating current is caused to decay to zero.

Since demagnetizing methods vary widely in effectiveness when they are used on parts with different shapes, magnetic characteristics, hardness, and coercive force, it is often considered desirable to check the success of the test in some dependable manner. Although there is no way to check the degree of removal of circular magnetization without damaging the part by sawing it into two parts, it is relatively easy to check the effectiveness of demagnetization in the case of longitudinal fields since the external poles are always present. The simplest device used to check for demagnetization is a small hand-held field meter. This meter is brought close to the location of the suspected residual polarity with the meter in a position normal to the surface

and the dial and pointer farthest from it. If there is no residual field, the needle will remain stationary. On the other hand, if there is a residual field, the needle will move in a plus or minus direction depending upon the polarity of the field. The amount of movement indicates the strength of the field.

Some specifications use the field indicator to specify the degree of demagnetization desired. These specifications will often call for no more than two divisions (three cersteds) deviation of the needle in critical parts and less than five divisions (seven and one-half cersteds) of deviation in parts where a somewhat higher degree of residual magnetization can be tolerated.

When a field meter is not available, a simple substitute is a four or five inch length of tag wire balanced on the end of the operator's finger. When this piece of tag wire is brought near a part having a local magnetic pole, the end of the wire will deflect toward the magnetized area. If the wire is hard, tag wire is usually hard from cold drawing, it will retain a magnetic field and should be demagnetized before it is used so that its own remnant field will not be the cause of the deflection toward the part being tested. This method is not exact but an experienced inspector can use it effectively to judge quite closely the amount of remnant field remaining in the part.

Marking Parts and Recording
Test Results

Parts which have satisfactorily met the magnetic particle inspection criteria should be marked in accordance with applicable drawing specifications, purchase orders, contract specifications, or as specified herein. Unless otherwise specified, all materials tested for government controlled projects, which call for 100 per cent inspection by the magnetic particle inspection process, should be marked by the specifications listed in MIL-I-6870 (Aeronautical Standards Group, 1953:4). Markings should be applied in such a manner and location as to be harmless to the part and will preclude removal, smearing, or obliterating by subsequent handling. These parts should be marked with one of the following methods:

Etching. Unless otherwise specified, parts should be marked by etching employing fluids and application methods which are not considered detrimental to the parts.

Impression stamping. Impression stamping may be used when it is permitted by applicable specifications or drawings. Impressions should be located in areas adjacent to the part number. This method is not permissible on welded beads under any circumstances, since it could lead to fatigue cracks in weldments.

Dyeing. Where etching or impression stamping is not considered

appropriate, identification may be accomplished by dyeing.

Other means of identification. Other means of identification such as tagging may be used on parts such as completely ground and polished balls, rollers, pins, and bushings for which the construction, finish, or functional requirements preclude the use of etching, stamping, or dyeing. Bolts and nuts may be identified as having met the requirements of the magnetic particle test by conspicuously marking each package.

Whenever possible, the letter (M) should be legibly marked on all parts which have successfully passed the magnetic particle inspection. Each item which has been inspected and accepted should be marked as follows (Department of Defense, 1965:5):

1. When stamping or etching is applicable, the symbol (M) should be employed.
2. When dyeing is applicable, the letter (M) should be placed on the part with green dye.
3. When tagging or labeling is applicable, a statement that the part conforms to the magnetic particle inspection criteria should be included on the tag or label.

The results of the magnetic particle inspection should be appropriately recorded for permanent records, since the appearance and evaluation of these indications can be of great use for a number of purposes at a later date. Records showing the typical appearance of

acceptable or unacceptable indications are useful for the guidance of inspectors in testing large numbers of similar parts. A record of indications of discontinuities which are subsequently investigated by sectioning or other destructive means is considered an essential part of special reports. Occasionally a part is put back into service when experience has indicated that the defect will grow slowly. Comparison of indications obtained at a later date with the records of inspections performed earlier provide a positive means for checking such growth rate. These records may also prove useful in statistical studies of the occurrence of different types of discontinuities. Reports of unsatisfactory or defective materials should contain the following data (Bureau of Naval Personnel, 1963:164-165):

1. Complete identification of the part including the name and part number, model number, and the manufacturer's name.
2. Size, location, and shape of the indication by means of sketches, photographs, or transfers supplied with a written description.
3. An evaluation of the indication stating whether it discloses a crack, lap, seam, inclusion, or other discontinuity and whether the indication is open to the surface or subsurface. If possible, an evaluation should be made to determine the probable depth of subsurface discontinuities.
4. The procedures used in magnetizing the parts and the method used to apply the magnetic particles.

5. The strength of the magnetizing current for circular magnetization or the ampere turns for longitudinal magnetization.

When marking or dyeing the parts is considered to be impractical or when it is permitted by the purchaser in lieu of marking or dyeing, the vendor should report on an appropriate form the process used, the type of magnetic particles used, magnetizing procedures used, and the percentage of parts inspected. This special report should also include a statement that all parts included in the shipment conform to the standards set by the purchaser.

Factors Adversely Affecting Indications

Factors such as grease and oil, paints and primers, chrome and nickel platings, and galvanized coatings which may adversely affect magnetic indications were described in this chapter under the heading of surface preparation of the parts.

Types of Discontinuities Located with Magnetic Particles

Magnetic particles are useful in locating defects in ferromagnetic materials, materials which are attracted by a magnet. As a rule, this method of inspection can generally detect all surface discontinuities and under certain conditions subsurface discontinuities as well. Discontinuities can be classified in many different ways and from numerous points of view, each of which would be useful for some

purpose. Since this study is concerned with the study of metals, these discontinuities have been classified according to their source of origin. This classification includes: (1) discontinuities occurring during solidification, (2) discontinuities occurring during processing, and (3) discontinuities occurring during service.

Discontinuities occurring during solidification. This category includes all discontinuities which occur while preparing the metal for its initial usable form before any modifying operations of the manufacturer take place. Most commonly placed in this category are blow holes, casting cracks, segregations, ingot cracks, internal fissures, non-metallic inclusions, scabs, and pipes. Additional data on discontinuities occurring during solidification can be found in Chapters 2 and 4 of this study.

Blowholes. As the molten metal in the ingot mold solidifies, there is an evolution of the various gases. Some of these gaseous bubbles rise through the molten metal and escape while others are trapped in the metal as it solidifies. Some unusually small bubbles will appear on the surface of the metal, while the larger ones will often be found below the surface, deep within the metal. Air trapped in these bubbles can cause what is known as oxidation. When this occurs, complete fusion of the metal does not occur and this oxidation remains in the finished product as a defect or discontinuity.

Casting cracks. Surface discontinuities are formed in castings due to stresses resulting from cooling. These stresses are often associated with abrupt changes in cross section. The discontinuities which occur may be hot tears or they may be shrinkage cracks which occur as the metal cools. Sand from the mold which has been trapped by the hot metal may form sand inclusions at or near the top of these castings.

Ingot cracks. Surface cracking of ingots occurs due to stresses generated during the cooling of the ingot. These cracks may be either longitudinal or transverse, or both types may occur simultaneously. As the ingots are worked into billets by rolling, these cracks form long seams.

Internal fissures. Due to the stresses set up in the ingots as a result of shrinkage during cooling, internal ruptures occur which are quite large. Since no air normally reaches the surface as a result of these bursts, they may be completely welded shut during rolling or other working and therefore leave no sign of a discontinuity.

Nonmetallic inclusions. All steels contain more or less materials which are nonmetallic in nature. The origin of such matter is primarily the deoxidizing materials which have been added to the molten steel in the furnace, the ladle, or the ingot mold. Silicon oxides and sulphides constitute the bulk of these nonmetallic inclusions.

Scabs. When the liquid steel is first poured into the ingot mold, there is considerable splashing and spattering against the cool walls of the mold. These splashes solidify at once and become oxidized. As the molten steel rises and the mold becomes full, these splashes are reabsorbed to a large extent into the molten metal. In some cases, however, they will remain as scabs of oxidized metal adhering to the surface of the ingot. These may remain and appear on the surface of the rolled product. If they do not extend deeply into the surface, they may not constitute a defect since they can be easily removed by machining.

Segregations. This type of discontinuity takes place during the solidification of the molten metal, since there is a tendency for certain elements in the metal to concentrate in the last-to-solidify liquid. When this occurs, there is an uneven distribution of some of the chemical constituents of the steel between the outside and the center of the ingot.

Pipes. As the molten metal which has been poured into the ingots cools, it solidifies first at the bottom and at the walls of the mold. Solidification progresses gradually upward and outward. The solidified metal occupies a somewhat smaller volume than the liquid, so there is a progressive shrinkage as the cooling occurs and a depression or cavity is formed at the top of the ingot.

Discontinuities occurring during processing. This category includes all of the defects which were introduced into the metal during the manufacturing process. Most commonly placed in this category are burning, cooling cracks, cupping, etching, and pickling, grinding, flakes, flash tear lines, forging bursts, forging laps, heat treating cracks, laminations, machining tears, seams, straightening cracks, and weldments. A brief description of these categories is listed next. Additional data on processing discontinuities can be found in Chapters 2 and 4 of this study.

Burning. Overheating of forgings, to the point of incipient fusion, results in a condition which renders the forging unusable in most cases and is referred to as burning. Actual oxidation is not the real source of the damage. Rather, the partial liquidation of the material at the grain boundaries due to the heat causes the damage.

Cooling cracks. When alloy and tool steel bars are rolled and subsequently are run out onto a bed or table for cooling, stresses may be set up due to an uneven cooling which can be severe enough to crack the bars. Such cracks are usually longitudinal, but not necessarily straight. They may be quite long and they usually vary in depth along their length.

Cupping. This condition is created when, in drawing or extruding a bar or similar shape, the interior of the metal does not

flow as rapidly as the surface metal. Segregation in the center of the bar usually contributes to this occurrence. The end result is a series of internal ruptures which are severe defects.

Etching and pickling. Hardened surfaces which contain residual stresses may become cracked if they are pickled or etched with acids. Attack by the acid on the surface fibers of the metal gives the internal stresses a chance to be relieved by the formation of a crack. Before this action was fully understood, the heat treatment of the part was often blamed for the cracking which resulted, although such cracking usually occurred during the acid cleaning of the part prior to plating or for other purposes.

Grinding cracks. Surface cracks in hardened parts as the direct result of improper grinding techniques are frequently a source of trouble. Grinding cracks are essentially thermal cracks and directly related to quenching cracks in more ways than one. They are caused by stresses which occur as the direct result of local heating under a grinding wheel. They are in nearly all cases avoidable if proper wheels, proper cuts, and proper coolants are used, and if the wheels are properly dressed as required.

Flakes. Flakes are internal ruptures which occur in steel as the result of too rapid a cooling. It is believed that the release of hydrogen gas during the cooling process, after forging or otherwise

hot working, will effectively reduce their occurrence. Flaking ususally occurs in fairly heavy sections and certain alloys are more susceptible than others.

Flash line tears. Cracks or tears along the flash line of forgings are usually caused by improper trimming of the flash.

Forging bursts. When a steel part is worked at an improper temperature, it is subject to cracking or rupturing. Too rapid or too severe a reduction of part section can also cause bursts or cracks. Such ruptures may be internal bursts or they may occur as cracks on the surface.

Forging laps. As the name implies, forging laps or folds are formed when improper handling of the blank in the die during forging operations causes the metal to flow so that it forms a lap which is later squeezed tight. Since it is on the surface and is oxidized, the lap does not weld shut. This type of discontinuity is sometimes difficult to locate because it may be open to the surface, fairly shallow, and often may lie at only a very slight angle to the surface. In some cases, it may be solidly filled with magnetic oxides.

Heat treating cracks. When steel parts are heat treated and quenched to harden them or are otherwise heat treated to produce desired properties for wear or strength, cracking may occur if the

operation is not suitable to the material or the shape of the part.

Quenching cracks are most common and are caused when parts are heated to high temperatures and then suddenly cooled by immersing them in cool water, oil, or air. Such cracks often occur at locations where the part changes from a heavy cross section to a light cross section or at fillets or notches in the part.

Laminations. Laminations in rolled plate or strip materials are formed when blow holes or internal fissures are not welded tight during the rolling, but are enlarged and flattened into large areas of horizontal discontinuities.

Laps. A defect similar to a seam can occur in the rolling of an ingot into billets as the direct result of the overfilling of the rolls.

Machining tears. Machining tears are caused by the dragging of the metal under the tool when it is not cutting cleanly. Soft and ductile low carbon steels are more susceptible to this type of damage than are the harder high carbon or alloy steels.

Seams. Seams may originate from ingot cracks or they may be introduced by the rolling or drawing process. Seams are often caused by a lack of material during the rolling process.

Straightening cracks. The process of heat treating often causes some of the warping of the part due to slight unevenness in cooling during quenching operations. A hardened shaft, for example, may come from the heat treat operation not quite straight. In many cases, it can be straightened in a hydraulic press; but if the amount of bend is too great or the shaft is exceptionally hard, cracks may be formed.

Weldments. A number of discontinuities may be formed during the welding of thick and thin sections. Some are found at the surface of the part while others are located in the interior of the metal. Defects peculiar to weldments are a lack of penetration, a lack of fusion, undercutting, cracks in the weld metal, crater cracks, and cracks in the heat affected zone.

Discontinuities occurring during service. The most common cause of structural failure in machinery and parts is fatigue. Structural members which are subjected to numerous cycles of reversing or fluctuating stresses may under certain circumstances develop minute cracks. These gradually enlarge and propagate through the cross section until the remaining metal is no longer sound. At this point, the structure fails. Most commonly placed in this category are corrosion cracks and fatigue cracks. A brief description of these categories have been listed. Additional data on discontinuities occurring during

service can be found in Chapters 2 and 4 of this study.

Corrosion cracks. Parts which are under tension stress in service and are at the same time exposed to corrosion from whatever cause may develop cracks at the surface which are referred to as stress corrosion cracks. Such cracks under continuing corrosion and stress will progress through the section until failure occurs. When corrosion is added to fatigue producing service conditions, a type of service failure called corrosion fatigue occurs.

Fatigue cracks. Metals which are subjected to alternating or fluctuating stresses above a certain critical level will eventually develop cracks which eventually lead to failure of the part. Fatigue cracks almost invariably begin at the surface, induced by the presence of some stress raiser. They are most likely to occur in areas of high tension stress. Such areas include holes, notches, sharp changes of section, and stiffening members. The most likely places to look for fatigue cracks are at sharp changes of section such as fillets, keyways, splines, and roots of screw threads and gear teeth.

The discontinuities listed are no where near complete. An attempt has been made by the writer to provide inspectors with a description of the types of discontinuities which are of a recurring nature.

There is a striking difference between the interpretation of test results and the evaluation of test results. The primary purpose

of the former was to find the cause of discontinuities, while the primary problem of evaluation is the decision of whether a given discontinuity is of such magnitude, or shape, or is so located that it will endanger the satisfactory performance of the material in the service for which it was designed. Some of the considerations entering into the answer to these questions are (Betz, 1967:413-414):

1. What type of actual service stress is the part to be called upon to withstand, and what is the magnitude, direction, and duration of these stresses? Will these stresses be steady, or pulsating, or reversing? Have these stresses been positively and experimentally determined with reasonable accuracy?

2. Where do the defects lie with respect to the stresses? Is it in an area of high stress, or it is in an area of low stress? Is the stress parallel to or at some angle to the maximum stress direction?

3. What is the nature of the defect and how severe a stress raiser is it? How is it orientated with respect to other stress raisers which may be present due to the design or construction of the part?

4. What is the importance of the part to the entire structure or assembly and how serious would the result be if the part failed?

5. What is the history of similar parts in service? Have they a record of frequent or occasional failure? Do they never break? Have design or fabrication techniques changed to deteriorate or improve

these history records?

General rules for the evaluation of conditions revealed by the magnetic particle inspections cannot be laid down and such rules are not considered necessary when the inspector is equipped with adequate knowledge and experience. Nevertheless, inspectors are sometimes called upon to make decisions when they lack adequate information. As a guide for those inspectors, a few basic considerations, not rules, may be stated which even though they are more or less obvious after a thorough analysis of the subject may still be of some help when they are set forth in the following manner:

1. A defect of any type lying at the surface is more likely to be considered a harmful defect than a defect of the same size and shape which is lying below the surface. The deeper the defect lies below the surface, the less harmful it is.

2. Any defect having a principal dimension or a principal plane which lies at right angles or at a considerable angle to the direction of the principal tension stress, whether the defect is on the surface or subsurface, is more likely to be considered harmful than a defect of the same size, location, and shape which is lying parallel to the stress.

3. Any defect which occurs in an area of high tension stress must be more carefully considered than a defect of the same size and shape in an area where the tension stress is low.

4. Defects which are sharp at the bottom such as grinding cracks, for example, are severe stress raisers and are, therefore, more likely to be harmful in any location than rounded defects such as scratches.

5. Any defects which occur in a location close to a keyway or fillet, or other design stress raiser is likely to increase the effect of the latter and must be considered more harmful than a defect of the same size and shape which occurs away from such a location.

Nonrelevant Indications

Before the inspector has progressed very far in his experience with magnetic particle processes, he will become acutely aware of certain indications which are the direct result of component design or conditions which have no relevant bearing on the strength or usefulness of the component. Such indications are true particle patterns which are actually formed and held in place by magnetic leakage fields produced by the test. However, such patterns are not caused by conditions which are relevant to the strength or the usability of the part. The term nonrelevant has been accurately given to this type of pattern. Some of the more common nonrelevant indications include:

All over patterns. Many times surface patterns or all over patterns are produced when part are magnetized using circular magnetization. The indications formed are those of the flux lines of the

external field produced by the magnetizing current. The lines of these patterns will always appear at right angles to the direction of current flow and are usually formed only when too much current is being used.

Boundary zones in welds. In weld inspections, an indication is often formed at the boundary between the fused metal and the base metal. Other indications in the form of lines may appear at the edges of decarburized zones and these occurrences usually indicate an abrupt change of permeability in the path of the magnetic field, but they are not indicative of an objectionable condition. Many sound welds yield a powder line at the junction of the base and weld metal. Whenever there is the possibility of error, competent metallurgical evaluation should be obtained.

Brazed joints. When two pieces of ferromagnetic materials are jointed together by the brazing process, the thin film of brass joining them may form a discontinuity even though the joint may be structurally sound. A definite magnetic pattern will be produced outlining the joint. Since the brazed metal is not magnetic, local poles at the edges of the magnetic material will be formed as though there were no metallic junction at all.

Cold working. The type of plastic deformation called cold working produces a hardening in steel parts with a consequent change in permeability. When this cold working is very local, the abrupt

permeability change is often sufficient to cause a magnetic particle pattern. The indication produced is at times similar in appearance to magnetic writing. On demagnetizing and remagnetizing, however, the indications caused by cold working reappear while those attributed to magnetic writing do not.

Construction in the metal path. One of the most common non-relevant indications is the one which is caused by a constriction in the metal path through which the flux must pass. Such constrictions are caused by the shape and construction of the part. The crowding out of flux to produce a leakage field is exactly the same as that which produced indications over a subsurface defect.

Edge of scale. A rather obvious nonrelevant indication is that which can appear at the edge of a patch of tightly adherent mill scale. It is usually a patch of very thick scale which produces this indication. Since the mill scale is magnetic, but with a much lower permeability than the steel from which it was formed, this indication is really the result of a magnetic discontinuity.

External magnetic fields. Nonrelevant indications may appear on hardened steel parts due to residual local poles which have been caused by a proximity to magnetic fields from power lines, magnetic chucks, or permanent magnets of one type or another. These indications are similar in nature to those caused by magnetic writing.

External poles. Magnetic particles will adhere to local poles at sharp corners, sharp ridges, or at surface irregularities, but these effects are not usually confusing to the knowledgeable inspector. Such patterns are most likely to be encountered when longitudinal magnetization is too strong for the part being tested.

Flow lines. This type of magnetic pattern is similar to the grain flow in forgings. These lines have been caused as a direct result of deep etching, a pattern produced by these grain lines. This type of indication is caused by the high sensitivity required for some of the tests, and magnetization levels higher than those normally required for inspections.

Forced fits. When two members of an assembly are fitted together very tightly, as in a pressed fit between a shaft and a pinion gear, a magnetic particle pattern may be formed. When the fit is extremely tight, no indication may appear since the air gap between the two members may be almost zero. If no indication appears, it is never misleading unless the joint is completely hidden by paint or rust and the inspector is unaware of its existence. Usually a light polishing with fine emery cloth will easily reveal this line between the two members.

Grain boundaries. When the grain size is very large, the macrostructure showing the grain outlines may be found by the magnetic

particle inspection even though no metallic discontinuity exists. The pattern is due to sharply differing permeability between the grain and the boundary metal.

Joints between dissimilar magnetic materials. Sometimes a piece of hard steel is butt welded to a softer piece of steel by one of several possible methods. At the point of welding, there will be a sharp change of permeability, the soft steel having a high permeability and the hard steel a much lower one. When a magnetic field is set up and flows across this joint, there will be a concentrated leakage field and consequently a magnetic particle pattern.

Luder lines. Planes of slippage, called luder lines, in materials which have been stressed beyond the yield point are occasionally the cause of nonrelevant indications.

Magnetic writing. When two pieces of steel come into contact with each other, when either or both are in a permanently magnetized condition but not magnetized to the same degree, local poles are likely to be formed at the areas of contact. Since these areas are usually the result of one piece being rubbed against the other, they resemble lines and the local changes, influx density, or polarity also resemble lines. When the magnetic powder or suspension is applied, the particles tend to adhere along these lines. Their appearance occasionally resembles a scrawl. This scrawl is known as magnetic writing, whether it is

done intentionally or not.

Sharp fillets and thread roots. Similar in character to non-relevant indications which have just been described are indications which result from leakage fields at sharp roots or fillets or threads. Here the flux lines tend to bridge the air gap rather than follow the metal path exactly. Confusion is most likely to occur in locating the actual cracks at the roots of these threads, in sharp fillets, or in other places where discontinuities are likely to occur.

SUMMARY

Magnetic particle inspection processes can be used to determine the physical soundness and other characteristics of a metal without impairing its future usefulness in any way, shape, or form. The results of these tests have helped to make possible the manufacture of lighter and stronger materials and equipment, and the use of these materials and equipment with a high degree of safety to the consumer.

In the years prior to 1920, the term nondestructive testing had not yet acquired a meaning or found a place in the language of industry. There were many methods of testing, but magnetic particle testing was not one of them. In fact, none of the nondestructive testing methods which are considered essential to industry were even under consideration.

Two developments in the days following World War I marked the birth of modern nondestructive testing methods. These developments were:

(1) research at the United States Bureau of Standards and General Electric Corporation indicated that X-rays could be used to make pictures of metallic articles, thus revealing their internal conditions; and (2) William E. Hoke made the discovery that magnetic fields could be used to locate discontinuities in ferromagnetic metals. In 1928 and 1929, A. V. deForest completed the work which actually resulted in the magnetic particle methods as we now know them. These initial contributions provided the impetus for the development of a practical and useful testing process.

The magnetic particle inspection process is used to locate surface and subsurface discontinuities in ferromagnetic materials. Essentially, there are three basic steps in the application of this method of inspection. They are: (1) establishment of a magnetic field of suitable strength and direction; (2) application of the magnetic particles in such a way that they are free to move over the surface of the part, collecting at leakage fields which occur as the result of a discontinuity; and (3) inspecting and evaluating these indications in terms of part acceptance or rejection.

The magnetic particle process depends for its success upon the fact that ferromagnetic materials, once they have been magnetized, cause a strong leakage field to be formed at the surface when a discontinuity is present. This leakage field provides the means for locating discontinuities which lie in a direction transverse to the

direction of the magnetic field. The presence of this field and, therefore, the presence of a possible defect is accurately located by the application of finely divided ferromagnetic particles over the surface of the part. This magnetically held collection of particles forms an outline of the discontinuity and reliably indicates its exact location, shape, size, and extent.

Magnetic particle inspections are used to detect discontinuities in ferromagnetic materials which could constitute a defect thus necessitating repair of the part or rejection of the part. This process enables the inspector to locate discontinuities on the surface which are too fine to be seen with the unaided eye or those which are located beneath the surface. It should be clearly understood, however, that the primary purpose of the magnetic particle test is the detection of discontinuities. It is not the purpose of these tests to determine whether or not such discontinuities constitute harmful defects. How harmful a discontinuity is to the service life of a component must be determined by those who know the service requirements of the part.

Commercial test equipment, both portable and stationary, are readily available for nearly every situation where this method of inspection is applicable. Stationary equipment providing direct current for either the wet continuous or the residual, circular or longitudinal magnetization, rectified alternating current or direct current, electrically movable contact heads and safety devices satisfy the needs of

industry in the shop while portable units using contact prods for circular magnetization or cables in the form of looped-coils for longitudinal magnetization are used for field applications. The magnetic particles used in this process are in all cases finely divided ferromagnetic materials. Before a specific material is selected for the test, careful consideration should be given to particle size, shape, density, contrast, and mobility, since all of these factors affect the final test results. The basic choice in the selection of magnetic particles is between those used in the wet process and those used in the dry process, and secondarily between the various colors available, including fluorescent particles.

The magnetic particle process was evaluated by the writer to determine whether or not it met the criteria set forth in the analysis of data section of this study. This criteria included an evaluation of the magnetic particle process in terms of its: (1) compatibility to existing industrial education programs, (2) ability to satisfy one or more of the present needs of industry, (3) relative simplicity and broad encompassing nature, (4) potential in satisfying what the writer believes to be a weakness of the present industrial education program, and (5) the educational requirements and competency levels expected of entry-level inspectors.

Since an evaluation of this type could best be accomplished by those with expertise in the field of magnetic particle testing, letters

were written to those who had published books or articles, those who were currently employed in nondestructive testing positions in industry, and others who were considered to be knowledgeable in the field of magnetic particles. They were requested to evaluate magnetic particle processes in terms of the five criteria selected by the writer for this study. Their statements indicated to the writer that magnetic particle processes could be taught successfully in industrial education classes at the high school level.

To those who encounter the techniques of magnetic particles for the first time, the techniques may appear deceptively simple, but these inspection procedures must be applied with care and within carefully set guidelines which have been defined and developed through experience.

One of the prerequisites to effective magnetic particle inspections is cleanliness. All oil, grease, and other foreign materials should be removed from the surface of the part. This can be accomplished with a wire brush, shot, or grit blasting, or by wiping the part with a suitable solvent cleaner. All openings leading to obscure passages or cavities should be plugged or filled with paraffin to prevent the formation of nonrelevant indications. Primers, paints, enamels, and similar nonmetallic coatings as well as coating of cadmium, copper, tin, and zinc do not usually interfere with the performance of the test unless they are unusually heavy or the discontinuity to be detected is very small.

The parts to be tested may be magnetized by the continuous or residual method. In the continuous method, the part is magnetized and the indicating medium is applied while the magnetizing force is maintained. This procedure can be used in practically all circular, longitudinal, wet, and dry magnetization processes. The residual method, however, can only be used on parts which have sufficient retentivity since the magnetic field retained by the part must be capable of attracting magnetic particles and producing acceptable indications. Although the continuous method has the inherent advantage of greater sensitivity, there are special occasions such as special purpose and testing equipment where the timing of magnetization and application of particles is not considered critical and, therefore, the inspection process is more easily controlled. In these situations, the residual method is preferred.

The application of the particles in the dry method is relatively simple. By a combination of shaking as one would with an ordinary salt shaker and the application of pressure as one would normally apply on a typical squeeze bottle, the proper ejection of magnetic powder can be accomplished with a minimum velocity. A small amount of practice with a squeeze bottle and a sheet of paper will quickly enable the novice inspector to produce an even, gentle coverage. The application of the wet particles cannot in any sense be considered more difficult than the application of the dry particles, since the wet

particles are applied to the part by hosing the part with the liquid vehicle containing the particles or immersing them in the liquid vehicle containing the magnetic particles.

Given an indication of a magnetic disturbance which is evidenced by a magnetic pattern, the inspector must decide what the condition of the part is that has caused the pattern. In other words, he should interpret the indication in terms of its cause. For many years it has been customary to classify discontinuities according to their source of origin in the various stages of production, its fabrication, and its uses.

Once the inspection has been completed, the parts should be demagnetized since all ferromagnetic materials tend to retain a residual magnetic field to some degree. This field may be quite negligible in soft materials, but in harder materials it may be comparable to the intense magnetic fields associated with the special alloys used to make permanent magnets. The reasons for demagnetizing are the knowledge that it: (1) may interfere with the operation or accuracy of instruments, (2) may interfere with the proper functioning of a component, (3) could cause particles to be attracted and held on the surface of moving parts, and (4) these particles are likely to interfere with the inspection of parts when low field strengths are used.

Demagnetization can be accomplished in a number of different ways, but possibly the most convenient procedure to use involves

subjecting the part to be demagnetized to a magnetizing force which is continually reversing its direction and at the same time decreasing in field strength. To accomplish this process of demagnetization, the part is placed in a solenoid coil with alternating current. As the part is withdrawn from the coil, the current is reduced. It may be required to repeat this process several times before it is effectively demagnetized. A simple field meter may be used to check parts for complete demagnetization.

Parts which have satisfactorily met the magnetic particle inspection criteria should be marked in accordance with applicable drawing specifications. These markings should be applied in such a manner that they are harmless to the part and in such a manner that they will preclude removal, smearing, or obliterating by subsequent handling. Some of the more commonly used methods of marking these parts includes etching, impression stamping, dyeing, or tagging. Whenever possible, the letter (M) should be legibly marked on all parts which have successfully met the magnetic particle inspection requirements.

The importance of broad knowledge and experience on the part of the inspector is essential for the proper interpretation and evaluation of magnetic particle test results. Even in the case of electronic methods where the equipment has been precalibrated and set to provide for the automatic rejection of defective parts, setting the limits of

acceptability involves human judgment. This human factor cannot, in the opinion of the writer, be overemphasized.

The magnetic particle method of inspection is so readily applied and its results so essential to proving the integrity of ferromagnetic materials that it has grown to the point where it is today, the most widely used method of nondestructive testing in industry.

Chapter 4

EDDY CURRENT TEST

The principles of eddy current testing can be compared to a person rowing a boat. As he dips the oars and pulls, he forms little pools or whirlpools in the water. In nondestructive testing, these whirlpools are known as eddies. When these eddies hit something floating in the water, their shape changes. Similarly, a coil of wire carrying alternating current can induce a circulating electrical current within a mass of metal. This electrical whirlpool is known as an eddy current. The basic characteristics of eddy currents change according to the type of metal being tested, its mass, its ability to conduct electrical current, and other factors.

In the eddy current testing process, a coil is used to induce an eddy current in the part. The electrical characteristics of this coil are affected by the metal characteristics and by discontinuities in the metal. It is the careful electronic measure of coil changes which make the eddy current of testing unique among nondestructive testing in determining the composition or the accurate identification of metals in addition to locating defects (Rolfe, n.d.:2).

History of the Eddy Current Process

The use of electromagnetic waves for the nondestructive testing of metals outdates even the experimental proof of the reality of these waves. In 1879, the year of Maxwell's death when many people still

doubted his theories and eight years before Hertz demonstrated the existence of electromagnetic waves, D. E. Hughes was able to distinguish between different metals and alloys by means of induced eddy currents using an induction balance test process. An accurate account of these experiments was published in the Philosophical Magazine in 1879. This account is evidence of a study of surprising scope despite the crudeness of the electrical equipment then available. Lacking an electronic oscillator, Hughes used the ticking of a clock falling on a microphone to produce the excitation signals. The resultant electrical impulses passed through a pair of identical coils and induced eddy currents in objects which were placed within the coils. By listening to the ticks of the clock with a telephone receiver, Hughes adjusted his system of balancing coils until the sounds disappeared and noted the different adjustments needed for objects of different sizes, shapes, and composition (Sharpe, 1970:383).

In spite of this early beginning, the use of eddy currents as a practical nondestructive method of testing parts was not used extensively until the end of World War II. Most of the theoretical basis for their use was formulated by Freidrich Foerster in Germany during the 1930's and 1940's (Betz, 1972:10.1). In addition to his theoretical work, Foerster also helped to develop an extensive group of instruments for the performance of various nondestructive tests. It was the introduction of these instruments outside of Germany in the early 1950's

which helped to make the eddy current testing process what it is today.

Eddy current testing processes have since been developed to the stage where they can provide inexpensive, high-speed testing with a high degree of accuracy and reliability. Both of these factors are of primary concern to industry. The test equipment available today is compatible with most industrial specifications, and the process is often integrated into the manufacturing process to provide a completely automated inspection, qualification, or segregation of parts as they are being cast, formed, or machined.

Description of the Eddy Current Process

A basic description of the eddy current testing method is provided in Figure 21, page 206 (General Dynamics, 1967:7.5-7.6). The equipment required to perform these tests, the types of discontinuities detected with the eddy current test method, and the limitations of this method of inspection are (Betz, 1972:10.14-10.15):

1. Equipment required: commercial equipment containing test coils, probes, and instrumentation
2. Enables the detection of: flaw detection, material thickness coatings, alloy sorting, and monitoring of metallurgical conditions such as hardness, grain size, and heat treatment
3. Advantages: accurate measurement of conductivity, immediate indications, high speed testing, detection of small discontinuities,

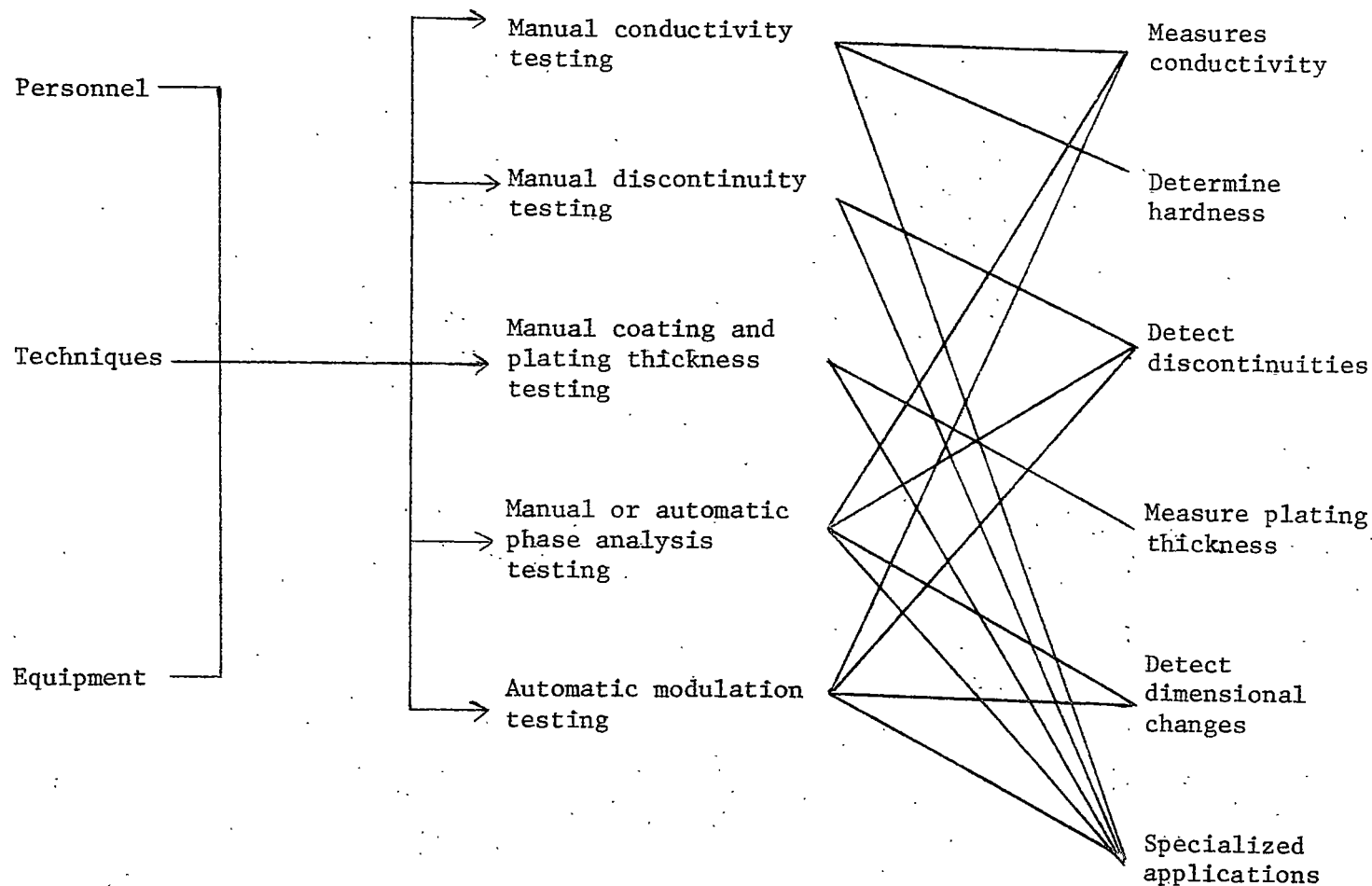


Figure 21
Eddy Current Testing

and noncontacting

4. Limitations: specific nature of the discontinuities is not clearly identified, depth of penetration restricts testing to less than one-quarter of an inch in most cases, testing of ferromagnetic materials can be difficult, and a permanent record of the discontinuity is often not available.

Principles of Eddy Current Testing

Eddy current testing may be defined as a method of nondestructive testing which requires the test part to be subjected to an alternating electromagnetic field. This test depends for its results upon the variations in the induced circulating currents which are commonly called eddy currents. When this test is used on nonmagnetic materials, the results of the test depend entirely upon the eddy current effects produced. When the test is used to test magnetic materials, both eddy currents and magnetic effects are encountered and it is nearly impossible to separate the two.

Whenever a coil carrying alternating current is brought into the vicinity of a metal specimen, eddy currents are induced in the metal by the process of electromagnetic induction. The magnitude of these induced eddy currents depend upon the magnitude and the frequency of the alternating current, the electrical conductivity, the relative position of the coil and the specimen, magnetic permeability, shape of

the specimen, and the presence of discontinuities or inhomogeneities in the part. Mechanical and thermal treatment of the part will affect the electrical conductivity of the part. In the case of austenitic stainless steels, mechanical and thermal treatments will affect the magnetic permeability of the part. The eddy currents induced in the part set up a magnetic field which opposes the original magnetic field. The impedance of the exciting coil or any pickup coil in close proximity to the part being tested is affected by the presence of these induced eddy currents. The path of these eddy currents is distorted by the presence of a defect or discontinuity. The apparent impedance of the test coil is changed by the presence of a discontinuity and this change in impedance can be measured and used to give an indication of defects or differences in the physical, chemical, or metallurgical structure of the part (McGonnagle, 1971:346).

Since the eddy current testing process sets up an opposing magnetic field, this process provides better results with nonmagnetic materials. For this very reason, early efforts by those working in the field of eddy currents were directed almost exclusively toward the development of processes applicable to the testing of nonmagnetic materials. Today, with the increasing demand by industry for both ferrous and nonferrous testing processes, the eddy current method of inspection has prospered.

Many conditions affect the magnitude and the distribution of

eddy currents within the test article. One of these factors is the electrical resistivity of the metal. This resistivity may be related to the strength, hardness, chemical purity, composition of the part, or heat treatment of the part. Because of this close relationship, the eddy current method of inspection can be made responsive to any or all of these properties. A second condition which influences these tests are the dimensions of the part being tested. This relationship has lead to the use of eddy currents to determine and control the dimensions of various products. Thickness measurements, for example, can be made from one side of the part, and these measurements can be as accurate as one micro-inch (Judd, n.d.:n.p.). Additionally, eddy currents are affected by discontinuities and boundary conditions. The detection of defects has been one of the principal fields of application for this method of testing, and it is in this area that the eddy current method of inspection has replaced such methods as the visual and magnetic particle methods of inspection. There are many factors which contribute to the widespread use of eddy current testing. Some of these factors are (Betz, 1972:10.1):

1. When eddy currents are properly applied, they can measure such diverse conditions as heat treatment, electrical conductivity, coating thickness, part dimensions, and hardness.
2. Eddy current testing can be applied to a wide range of products and fabricating methods such as rolled sheet stock, drawn

wire and tubing, and welded pipes and castings.

3. Eddy current methods of inspection are most effective on thin walled and relatively small items which must be tested in large quantities.

4. Eddy currents are unexcelled when they are used for the rapid detection of flaws, cracks and seams, or for the sorting of mixed items.

Purpose of Eddy Current Tests

In the field of eddy current testing, the word "flaw" has a much wider meaning than it does for other forms of nondestructive testing. The application of eddy current tests fall into three basic categories. They are (Magnaflux Corporation, 1965:2):

1. Detecting flaws in metal parts. Included in this category is the detection of cracks, voids, inclusions, laps, and seams.

2. Sorting parts according to alloy, conductivity, temper, or other metallurgical factors.

3. Gauging parts according to size, shape, plating thickness, or insulation thickness.

Fundamentals of Electromagnetic Theory

Early investigators of electricity discovered that an electric current flowing through a wire produced a magnetic field around the wire. The magnetic field produced is at all times perpendicular to the

flow of the current. When the wire is straight, the magnetic field produced is concentric. If on the other hand the wire is wound to form a solenoid, the magnetic field is parallel to the axis. These magnetic field concepts are illustrated in Figures 22 and 23, page 212 (Betz, 1972:10.2). In Figure 23, the magnetic field is composed of magnetic lines of force in closed loops. These type of coils are the most widely used in eddy current testing today.

An extremely important characteristic of magnetic fields and electrical currents was discovered by Michael Faraday in the 1830's (Betz, 1972:10.2). He discovered that when the current in one conductor was changing, as it did when he opened or closed a switch in a circuit, a current was caused to flow in another wire if it was located close to the first wire. He called this phenomenon electromagnetic induction and concluded that it occurred whenever the current and its associated magnetic fields were changing. This phenomenon, electromagnetic induction, is the basis for the operation of electric motors, generators, transformers, and of course the eddy current method of inspection.

Suppose we take the solenoid illustrated in Figure 23 and apply alternating current (AC) to it. In alternating current, the current flow starts at zero and builds up to some peak value. It then decreases to zero again, builds up to peak values in the other direction, and falls to zero again. This constitutes one cycle. Because the current is changing constantly, the magnetic fields created by an alternating

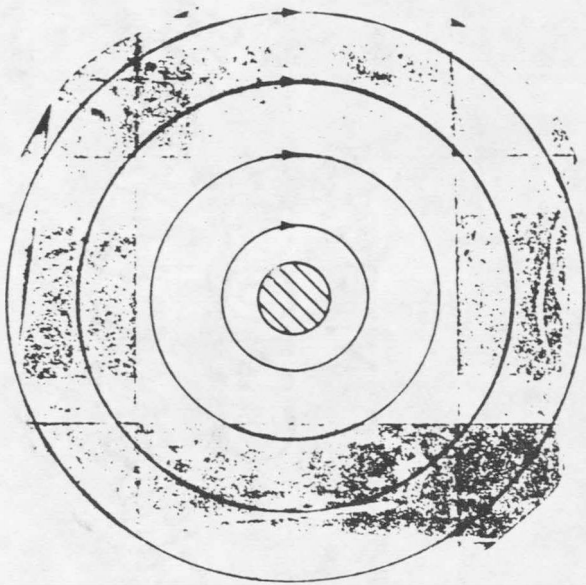


Figure 22

Magnetic Fields Around Current
Carrying Conductors Using the
Straight Wire Principle

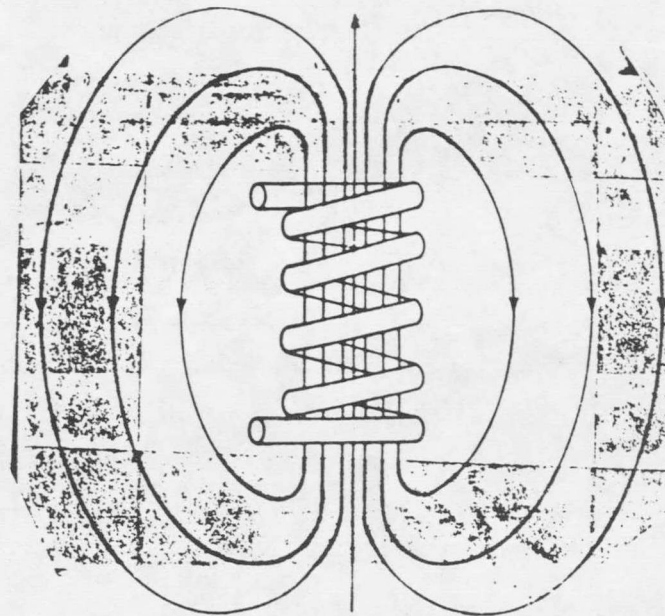


Figure 23

Magnetic Fields Around Current
Carrying Conductors Using the
Solenoid Coil Principle

current are alternately growing and collapsing at the same rate. When we bring a metal part close to the coil, we cause a current to flow in it by the process previously described as electromagnetic induction. The currents which are induced flow in closed paths which are perpendicular to the magnetic fields. This concept is illustrated in Figure 24, page 214 (Betz, 1972:10.2).

In a similar manner, a solid bar placed inside of the coil will have eddy currents induced in it similar to those illustrated in Figure 25, page 214 (Betz, 1972:10.2). It should be clearly understood that the direction of these eddy currents change as the direction of current in the conductor changes. Once again, the eddy currents are closed loops which are perpendicular to the magnetic field. This relationship between the current and the magnetic field is important to remember, since this knowledge helps the inspector to determine which types of coil is needed to detect flaws with a given orientation.

The eddy currents caused to flow in a conductor adjacent to the coil also have a magnetic field associated with them. Furthermore, this field is exactly opposite in direction to the field which caused the currents to flow. The magnetic field created by eddy currents will induce a current in the coil which opposes the current flowing in the coil. The changes caused by this reaction are utilized in the eddy current inspection process. The relationship between the currents and the fields of the coil and the plate are illustrated in Figure 26, page 215 (Waidelich, 1970:n.p.).

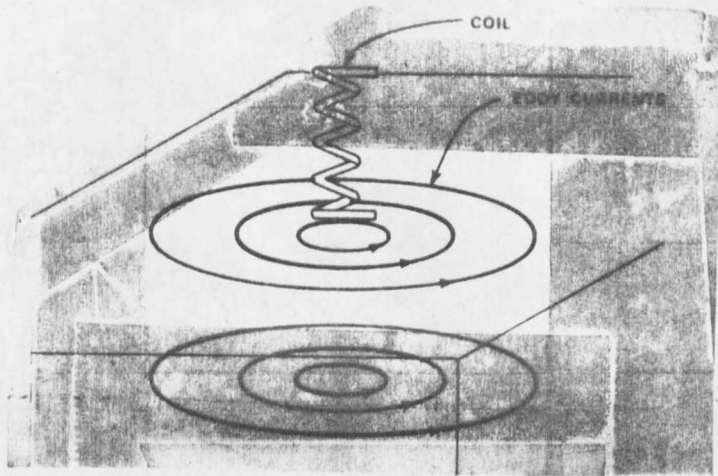


Figure 24

Flow of Eddy Currents in Conductors in the Vicinity of Solinoid Coils Utilizing a Flat Plate

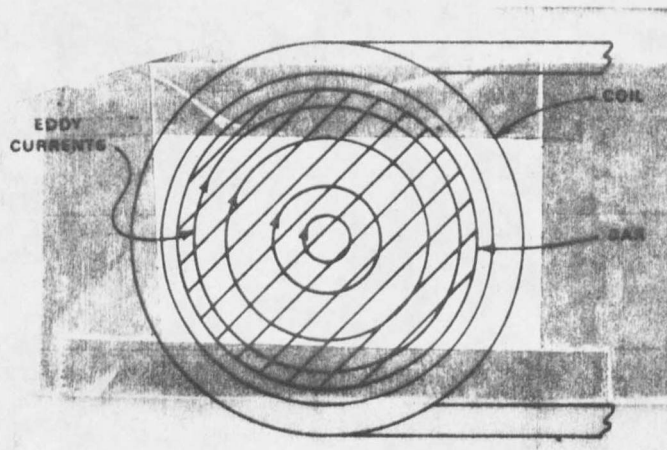


Figure 25

Flow of Eddy Currents in Conductors in the Vicinity of Solinoid Coils Utilizing a Solid Bar

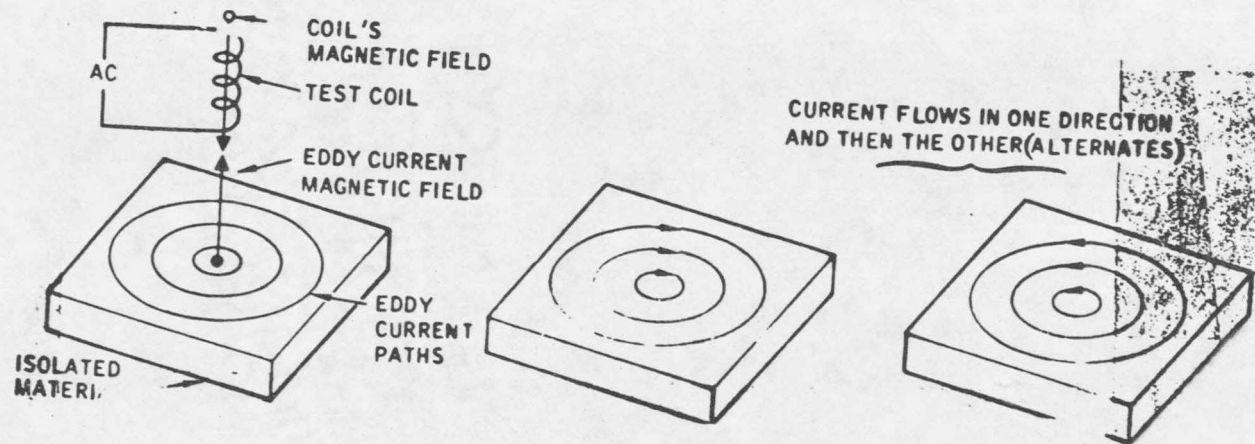


Figure 26

Relations Between Currents and the Magnetic Fields of
a Solenoid Coil Adjacent to a Flat Conductive Plate

Electrical conductivity. All materials have a characteristic resistance to the flow of electricity. In some materials which are known as insulators, this resistance is so high that virtually no current can flow in them. These nonconductors are of relatively little interest in eddy current testing. An intermediate class of materials which are known as semiconductors because their resistance is such that only a very small amount of current flows through them. The third class of materials are known as conductors. This class includes all metals and is the most significant from the point of eddy current testing. However, it should not be assumed that all of these metals are equally good as electrical conductors for such is not the case. For instance, copper is a much better conductor of electrical currents than lead.

How well a conductor will carry electrical currents can be measured in terms of: (1) its conductivity, or (2) its resistance. The unit of electrical resistance is known as the ohm centimeter, and the unit of conductivity is the mho per centimeter. The unit of measurement known as the mho is defined as the reciprocal of the ohm, a term used to measure resistance. Resistance and conductivity are reciprocals of each other, materials with a high conductivity have a low resistance. In eddy current testing, one frequently makes use of a simpler method of measuring which is accurately based upon the International Annealed Copper Standard (IACS). In this system, the

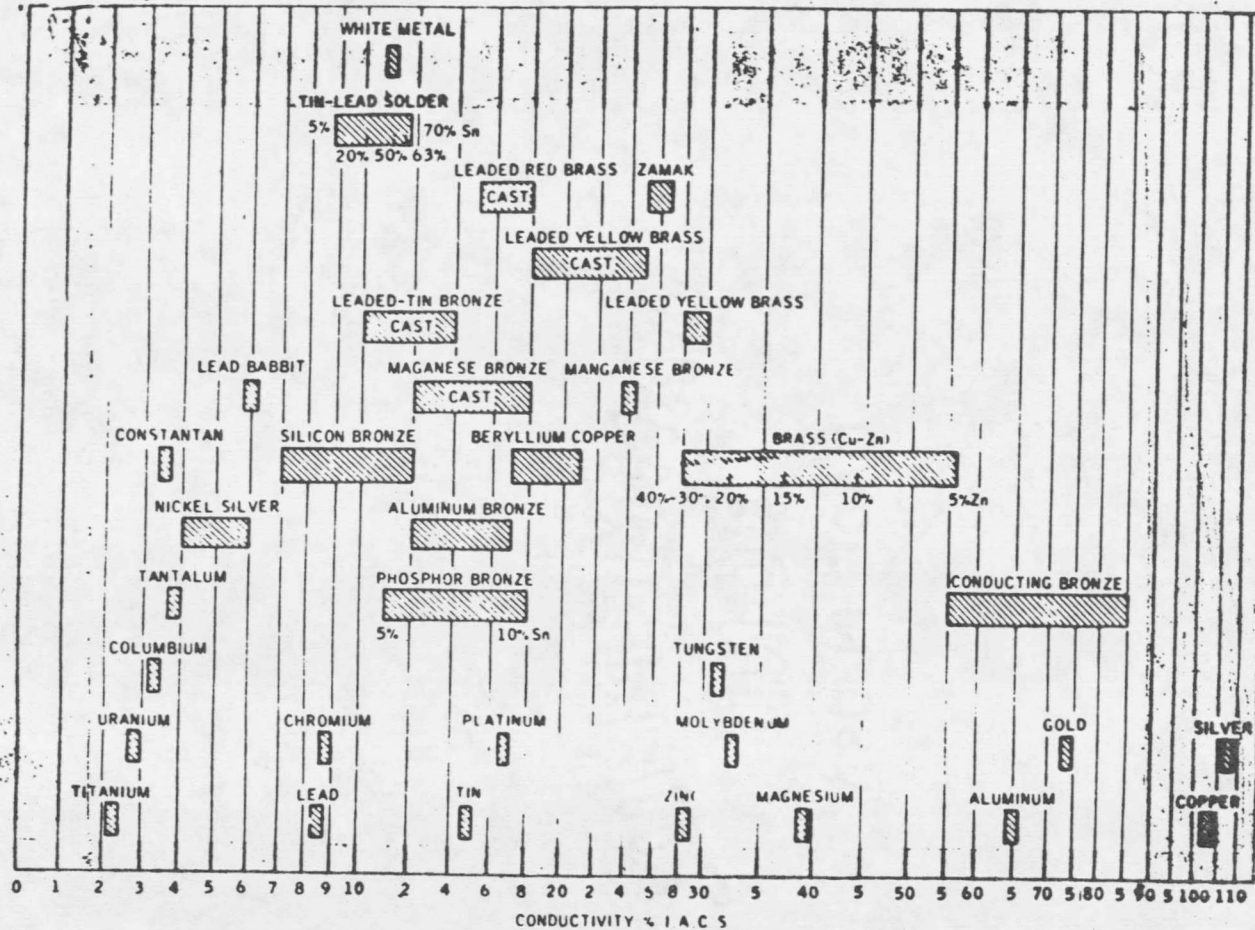
conductivity of annealed copper is arbitrarily taken to be 100 per cent and the conductivities of all other materials are given as a percentage of the conductivity of copper. Therefore, pure aluminum has a conductivity of 65 per cent IACS, or 65 per cent that of the copper standard. The conductivities of a number of metals are given in Table 10, page 218 (General Dynamics, 1967:3-9).

Many factors influence the conductivity of a metal. A pure metal may have a fixed conductivity, but as soon as other materials are added to it, either in the form of impurities or as alloying elements, the conductivity decreases. Because the conductivity of a metal is dependent upon its chemical composition, the values given in Table 10 must be considered approximates. Different batches or heats with the same nominal composition will vary somewhat from the given values in the table. This variation of conductivity with the chemical composition is the basis for the use of eddy currents to separate mixed lots of metals. It should be remembered, however, that such separation can only be made when the normal ranges of conductivity of these metals in the mix do not overlap.

In addition to chemical composition, electrical conductivity is influenced by a number of metallurgical conditions. Although they are not necessarily independent, such characteristics as heat treatment and the resultant grain structure, grain size, hardness, and residual stresses can change the conductivity of a metal. As with chemical

Table 10

International Annealed Copper Standards of
Some Common Metals and Alloys



composition, eddy currents can be used to monitor metals for one or more of the above metallurgical conditions as long as there is a sufficient difference in the conductivity between the two conditions. An excellent example of the use of eddy currents as a means of checking the metallurgical condition of a metal can be found in the aluminum industry. The hardness of aluminum alloys has a direct and pronounced effect on the conductivity of aluminum alloys. The effect of various stages of hardness are illustrated in Figure 27, page 220 (Government Printing Office, 1965:10).

Since all heat treatment processes are intended to provide a given hardness to a metal, it is possible to monitor aluminum alloys for heat treatment with eddy current instruments which have been designed to measure conductivity directly. Figure 27 illustrates how the conductivity changes of aluminum alloys follow an impedance plane. This illustration is considered to be a basic impedance plane, and most other curves will either start or end at this one. When nothing but the conductivity of a metal changes, the eddy current responses will move along this curve. When there are other condition changes such as the thickness of the part, the response will start at the conductivity curve and follow along some other characteristic curve.

Geometry and design. A test coil with no conductive material will give some indication when it is connected to a suitable test instrument. As the coil is moved closer to a conductor, the indication

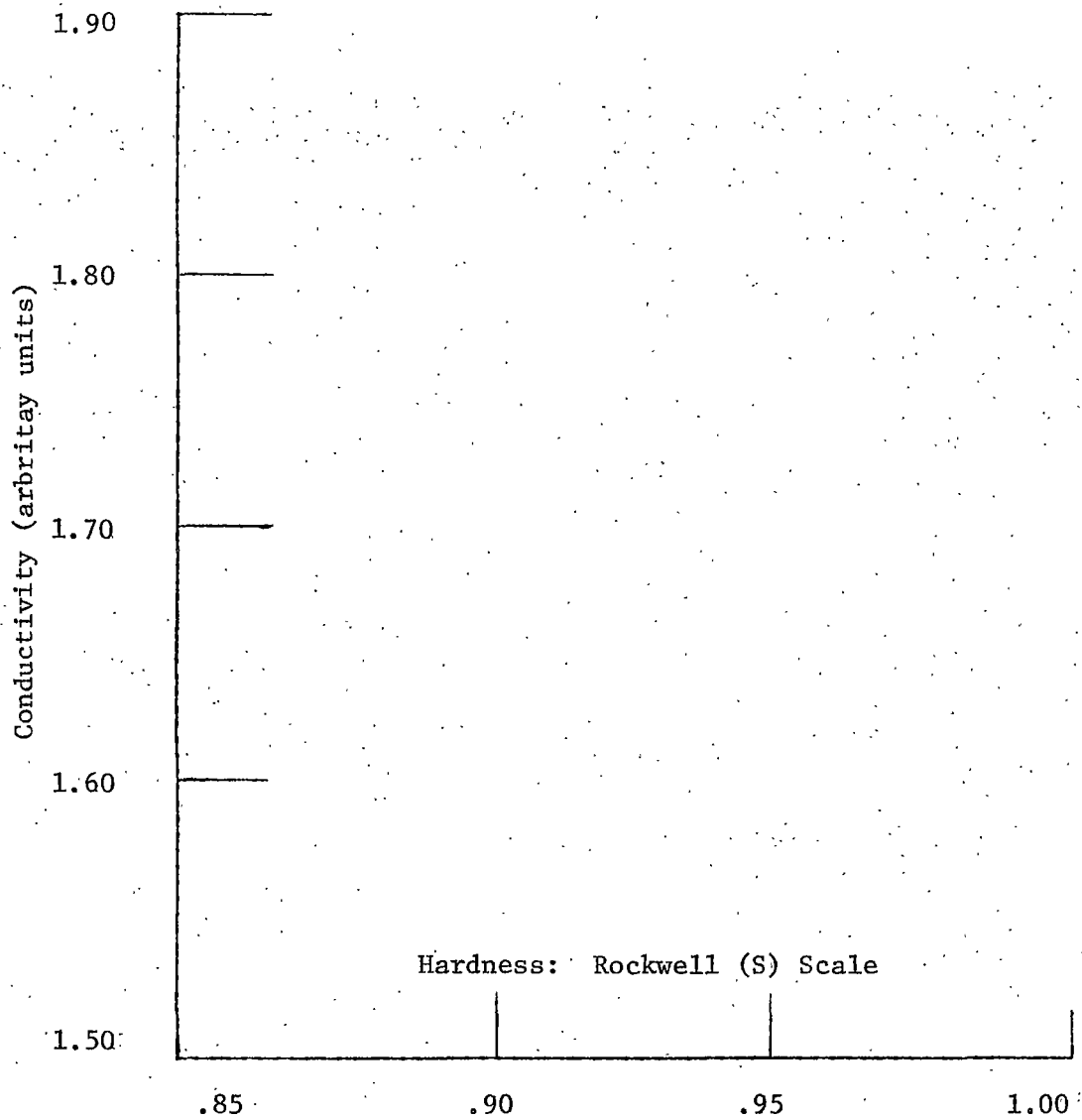


Figure 27

Variations of Electrical Conductivity with Hardness
of an Age Hardenable Aluminum Alloy

will begin to change. Since the field of the coil is strongest close to the coil, the indicated change on the instrument will continue to increase until the coil is directly on the conductor. These changes in indication with corresponding changes in the spacing between the coil and the test part are known as "lift off." This lift off effect is so pronounced that small indications in spacing can effectively mask many indications which are of significance to the inspector. For this reason, it is normally considered necessary to maintain a constant coil-to-test-part geometry. This lift off effect also makes it very difficult to perform eddy current tests which require the scanning of very complex shapes.

In spite of the fact that lift off can be quite troublesome in many test situations, it can also be quite helpful, since eddy current tests are considered an excellent means for determining the thickness of nonconductive coatings such as paint on conductive base materials, anodized coatings on aluminum and for many nonconductive hard surface coatings on a conductive base. A special thickness probe which is used to measure coating thickness is illustrated in Figure 28, page 222 (Government Printing Office, 1965:107).

When a test coil approaches the edge or end of a test piece, eddy currents tend to become distorted since they cannot flow beyond the edge of a test piece. This distortion results in an indication which is known as "edge effect." This edge effect effectively limits

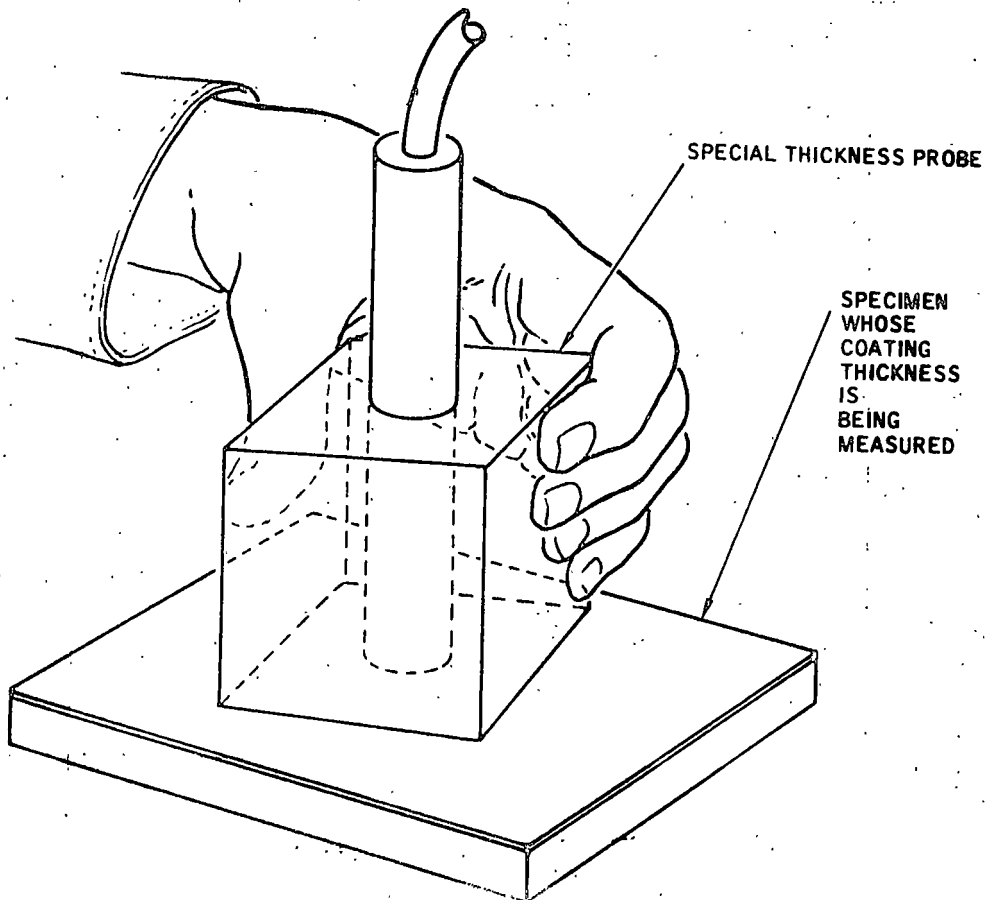


Figure 28

Typical Illustration of a Thickness Probe Which is Used
to Measure Coatings and Plating Thickness

the reliability of the testing process at or near the edge of parts since the magnitude of this effect is considerable. Unlike lift off, there is very little which can be done to eliminate edge effect.

Smaller coils will reduce this effect somewhat, but there are practical limitations to the sizes of coils. For the most part, the edge effect is at least one-eighth of an inch, and it is not considered practical to inspect closer than that to the edge of parts.

Impedance plane diagrams. When direct current (DC) is flowing in a coil, the magnetic field reaches a constant level and the only limitation to the current flow is the resistance of the wire. However, when an alternating current (AC) is flowing in a coil, there are two important factors to consider. They are: (1) the direct current resistance of the wire, and (2) a quality known as the inductive reactance. The latter is a measure of the reduction of current flow due to self-induced currents. The total resistance to the flow of alternating current in a coil is made up of the direct current resistance and the inductive reactance. This resistance is known as impedance.

It is common practice to plot impedance on an impedance plane diagram. In such a diagram, the direct current resistance is plotted along one axis, while the inductive reactance or inductance is plotted along the other axis. Since each specific condition in a material will result in a particular coil impedance, each condition will respond to a particular point on the impedance plane diagram. Suppose, for example,

that the test coil was placed on a series of thick pieces of metal, each with a different resistance. Each piece would cause a different coil impedance and would, therefore, correspond to a different point on the impedance plane. The line generated would have a shape similar to the one shown in Figure 29, page 225 (Government Printing Office, 1965:107). Other curves would be generated for material variables such as thickness, heat treatment, alloy, and various types of flaws.

Magnetic permeability. Certain metals and alloys tend to concentrate the flux of a magnetic field. These materials are known as ferromagnetic materials. The qualities and characteristics of this group of materials was thoroughly discussed in Chapter 3 of this study. The measure of this tendency to concentrate the flux of a magnetic field is known as magnetic permeability. For air and nonmagnetic materials, the permeability is very close to one. For ferromagnetic materials, such as iron or steel alloys, it may be several hundred. For special alloys, it may be even higher.

Magnetic permeability is not constant for a given material, since it depends upon the strength of the magnetic field acting upon it at a particular moment. Consider for example a piece of steel which has been completely demagnetized and placed in a solenoid coil. As the current increases, the magnetic field associated with the current will also increase. The magnetic flux within the steel, however, will increase rapidly at first, then tend to level off, so that a large

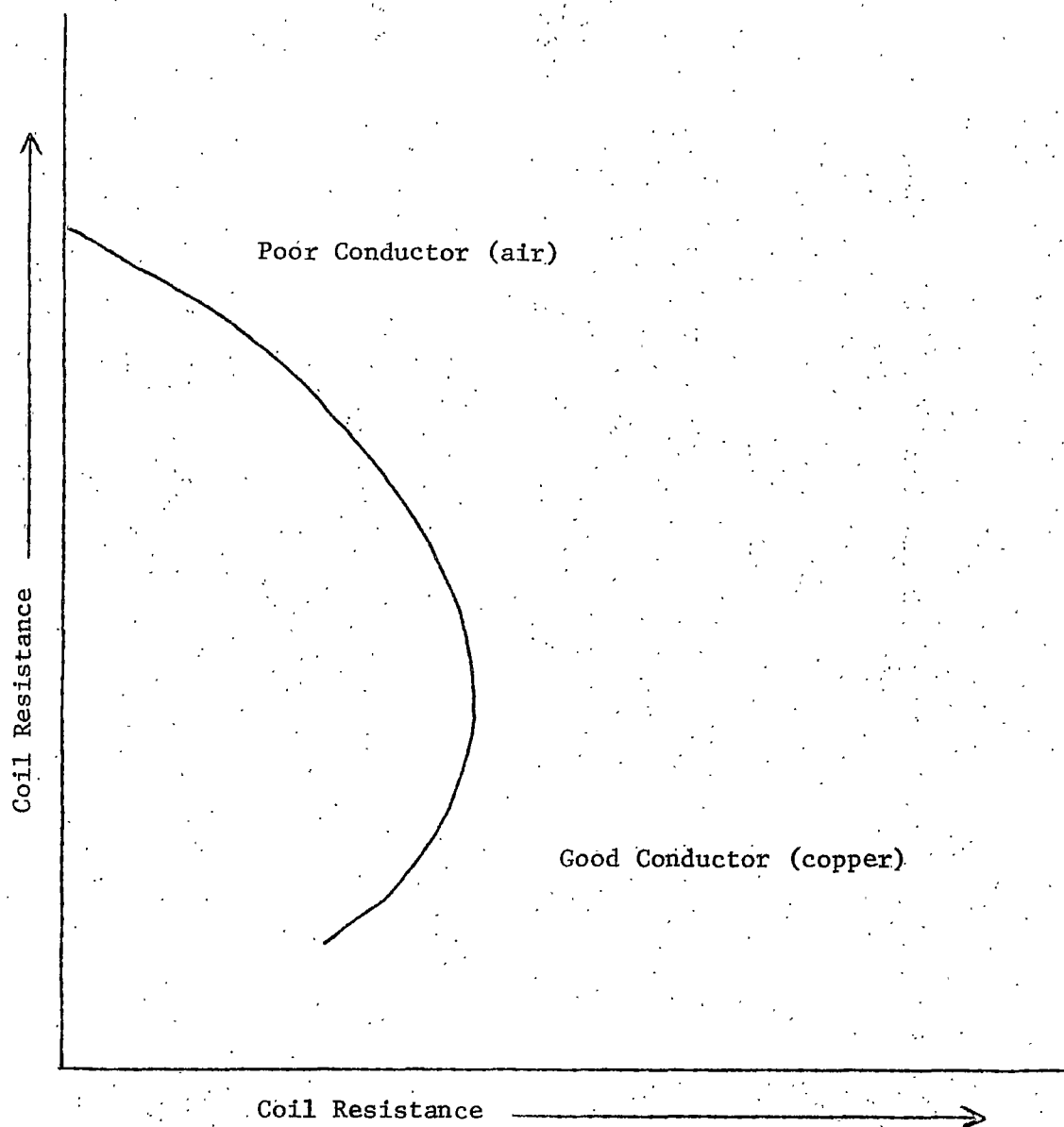


Figure 29

Typical Impedance Plane Representation Showing
Variations With Different Metallic Conductors

increase in the magnetic field will result in only a very small increase in the flux within the steel. This final situation is known as magnetic saturation, and the curve showing the relationship between the magnetic field intensity and the magnetic flux within the steel is commonly known as a magnetization curve. A typical magnetization curve is illustrated in Figure 30, page 227 (Betz, 1972:10.5). The magnetic permeability is the ratio between the strength of the magnetic field and the amount of flux within the material. Figure 30 indicates that at saturation where there is no appreciable change in the induced flux in the sample for a change in field strength, the permeability is nearly constant for small changes in field strength.

Since eddy current are induced by magnetic fields, the permeability of a material under test will have a strong influence on the eddy current response. For this reason, The techniques and parameters used for testing magnetic materials differ from those used to test nonmagnetic materials. However, the same factors which influence conductivity, chemical composition, hardness, alloy stresses, and flaws also influence magnetic permeability. For this reason, eddy current methods of inspection can be applied successfully to both magnetic and nonmagnetic materials. Magnetic materials also have an electrical conductivity but in general permeability changes have a much greater effect on eddy current response than conductivity variations have on them.

The fact that the permeability is constant when a ferromagnetic

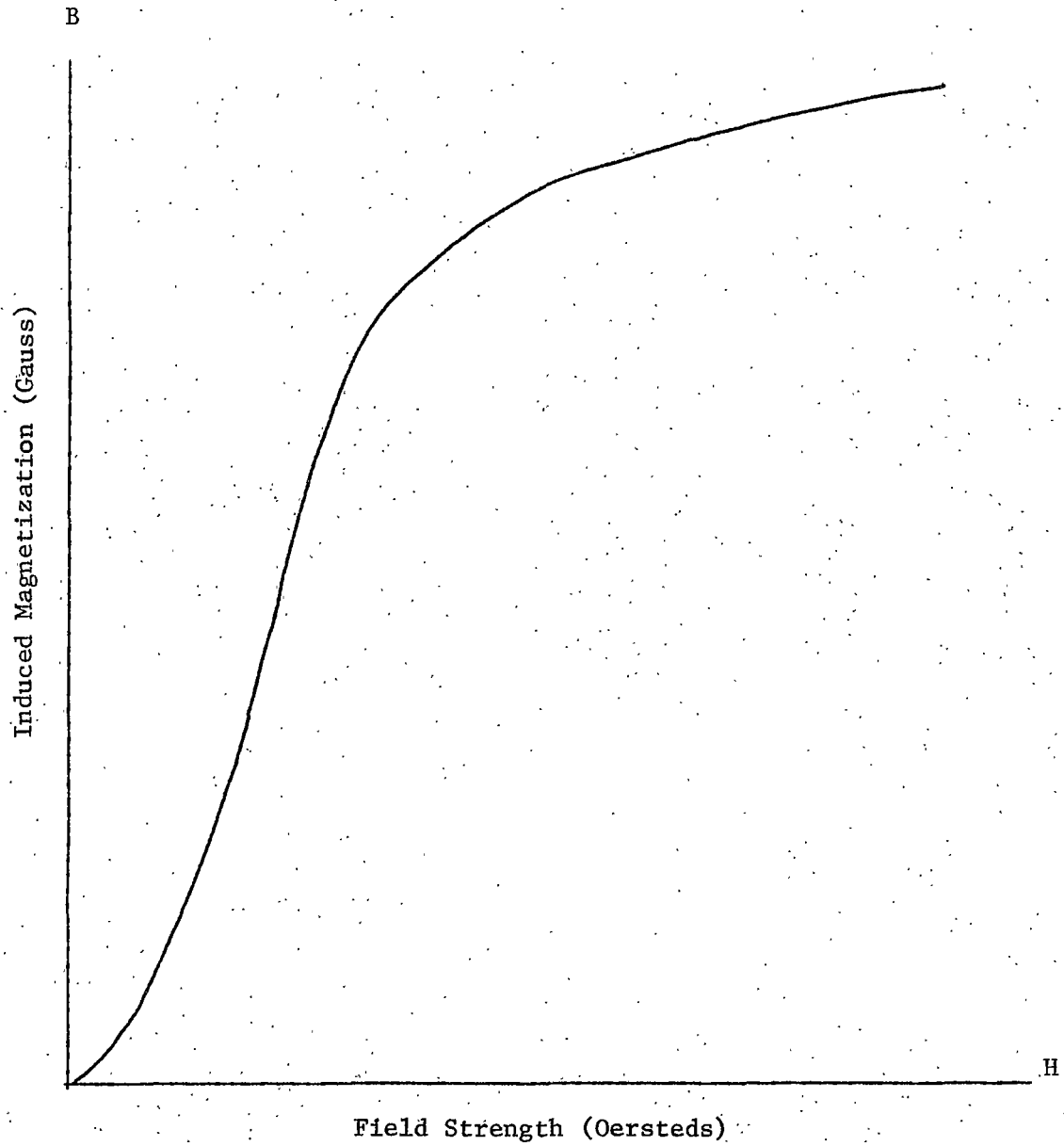


Figure 30

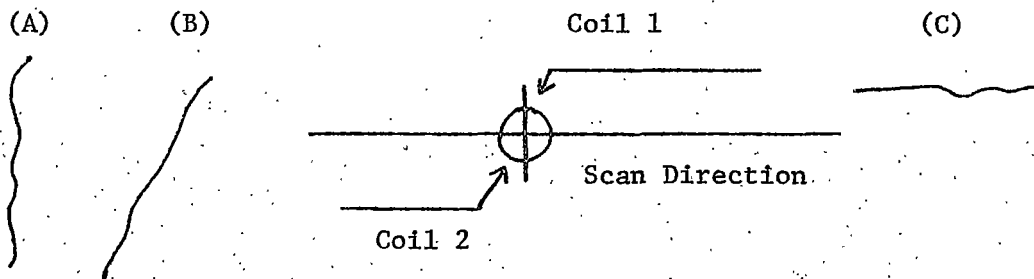
Typical Magnetization Curve for an Iron Alloy

material is saturated can be used to permit eddy current inspection of magnetic materials without being influenced by permeability variations. The parts to be inspected are placed in a coil in which direct current (DC) is flowing. The magnitude of the direct current (DC) used should be sufficient to drive the test material to saturation. The test coil is placed inside the saturation coil close to the part. This technique is generally used for the inspection of magnetic materials, since small variations in permeability are not generally of interest and could cause the rejection of acceptable materials.

Types of Test Equipment Commercially Available

The test coil is an essential part of all eddy current testing systems. The shape of the coil used depends to a considerable extent on the purpose of the test and the shape of the part being tested. When the primary purpose of the test is the detection of flaws such as cracks or seams, it is essential that the flow of eddy currents be as nearly perpendicular to the flaw as possible if maximum response to the discontinuity is to be expected. The significance of this concept is shown in Figure 31, page 229 (Ridder, 1972:11.6). When the flaw is parallel to the eddy current flow, there will be little or no distortion of the currents and, therefore, very little reaction on the test coil.

Since the test coil is considered to be the key element in the



- A. Not indicated
- B. Indicated
- C. Indicated

Figure 31

Probe Movement and Sensitivity to Crack Detection
in Eddy Current Tests Using a Differential Probe

eddy current testing process and since the materials to be tested come in various sizes and shapes, the discussion of the types of test coils available in this study will be divided into three basic categories. They are: (1) probe or surface coils, (2) encircling coils, and (3) inside coils. Each of these basic types of coils is illustrated in Figures 32, 33, and 34, pages 231, 232, and 233, respectively (General Dynamics, 1967:3.4-3.7).

Surface coils. Surface coils are designed for use on the surface of the test object. For maximum effect, the coil should fit the contour of the surface being tested. The coil can be the contacting or noncontacting type, operator held, or automatic. To minimize lift off, spring loaded coils such as the one in Figure 35, page 234, are used (General Dynamics, 1967:3.5).

Encircling coils. The encircling type of coil is used to enclose the part so that maximum effect is obtained from the test coil. The test coil should be shorter than the part being tested to reduce end effect. The shape of the test coil need not always be round, since an encircling coil produces maximum effect when it closely coincides with the surface of the part being tested.

Inside coils. The inside coil is identical to the encircling coil, except that it is placed inside of the part being tested to maximize sought-after effects. To localize discontinuities in tubular

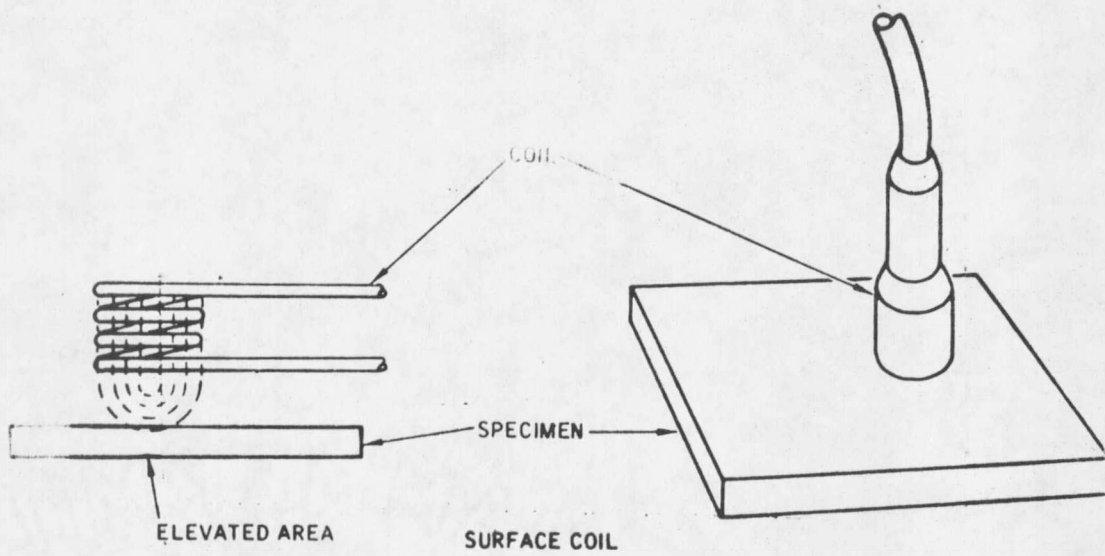


Figure 32
Typical Surface Coil

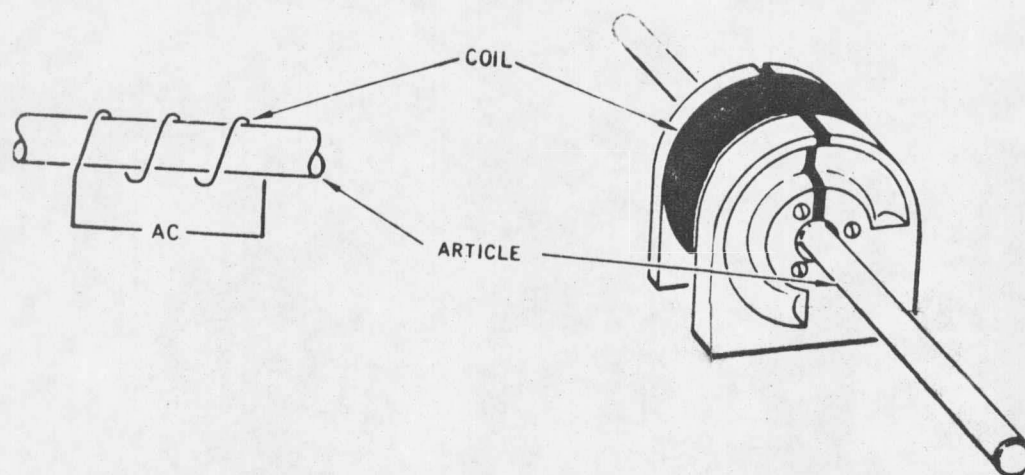


Figure 33
Typical Encircling Coil

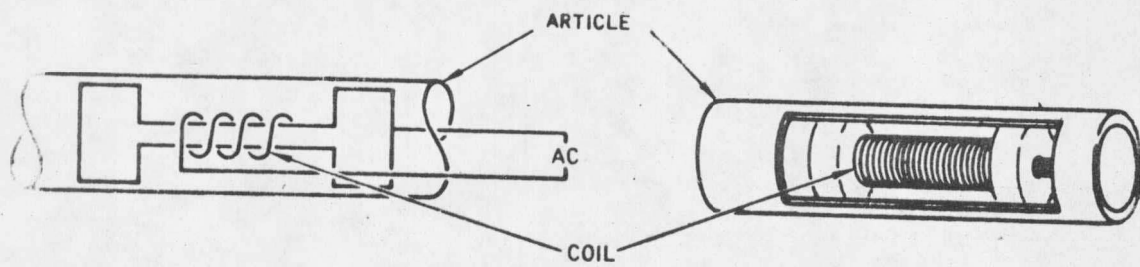


Figure 34
Typical Inside Coil

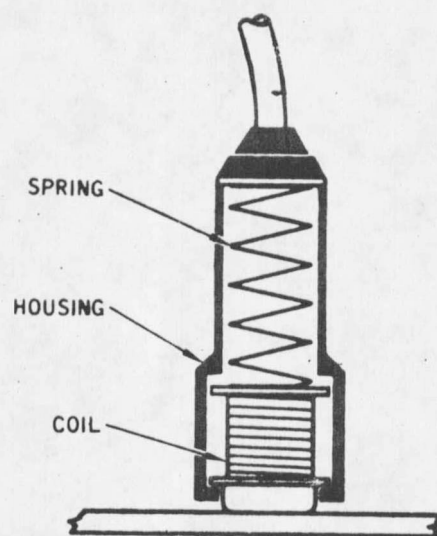


Figure 35

Typical Spring Loaded Surface Coil

shaped parts, for example, inside surface coils have been constructed with remote controls which permit the inspector to position the coil at specific places within the circumference of the tubing.

All of the coils mentioned can be used with a high degree of success, but the probe or surface coil and the encircling coil are by far the most often used today.

Test instruments. There is a wide selection of test instrumentation available for the eddy current testing process. Some of the instruments are very small and compact, while others are large and complex. Simple conductivity test units are illustrated in Figures 36 and 37, pages 236 and 237, respectively (General Dynamics, 1967: 4.4-4.13).

All eddy current test equipment contains certain basic elements in common. They are: (1) an oscillator, (2) a method of detecting impedance changes in the coil, and (3) a method of displaying the resultant data. In addition, some types of instruments include a means of analyzing the impedance changes while others provide a means of compensating for lift off.

Selection of the Eddy Current Method

A manual eddy current inspection is generally restricted to critical areas of the part. When 100 per cent inspections are required, it is best to use automatic methods of inspection. In some cases, a

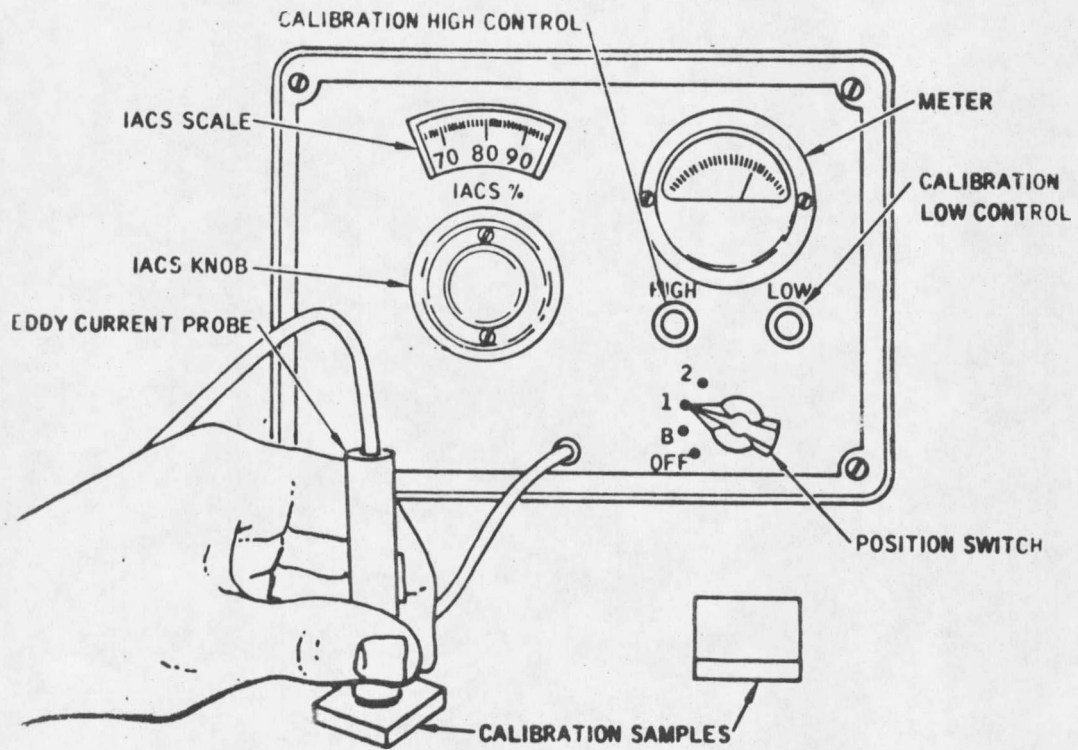


Figure 36
Typical Conductivity Tester

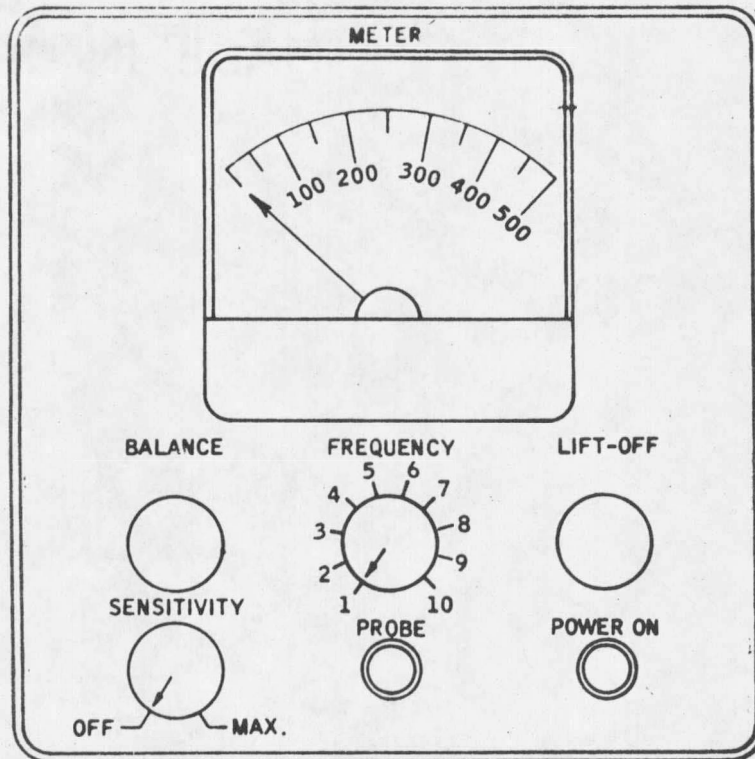


Figure 37

Typical Impedance (Discontinuity) Tester

different method of inspection such as magnetic particle testing or liquid penetrant testing may be required to provide the ultimate aim of all nondestructive testing processes: maximum reliability at the most reasonable cost.

Generally, a portable eddy current test instrument is used for the inspection of paramagnetic and diamagnetic materials. This category includes most of the nonferrous and some of the ferrous alloys. The instrument most commonly used operates in the following manner:

1. A variable oscillator generates a signal which is adjustable in frequency from 50-250 kilohertz.
2. This signal is applied in a modified Wheatstone bridge.
3. The sensing coil is part of this bridge. When the coil is placed on a sound piece of material, the bridge can be balanced by an outside control. When on the other hand the coil is passed over a discontinuity, a change occurs in the impedance of the coil.
4. This bridge unbalance is recorded on a microampere meter for the inspector.

A relatively simple diagram of an eddy current set up for paramagnetic and diamagnetic materials is illustrated in Figure 38, page 239 (Ridder, 1972:11.2). When the inspector uses this type of instrument only the magnitude of the impedance change is recorded. This instrument is relatively simple to operate, since there are only three control knobs. They are: (1) frequency, (2) balance, and (3) sensitivity.

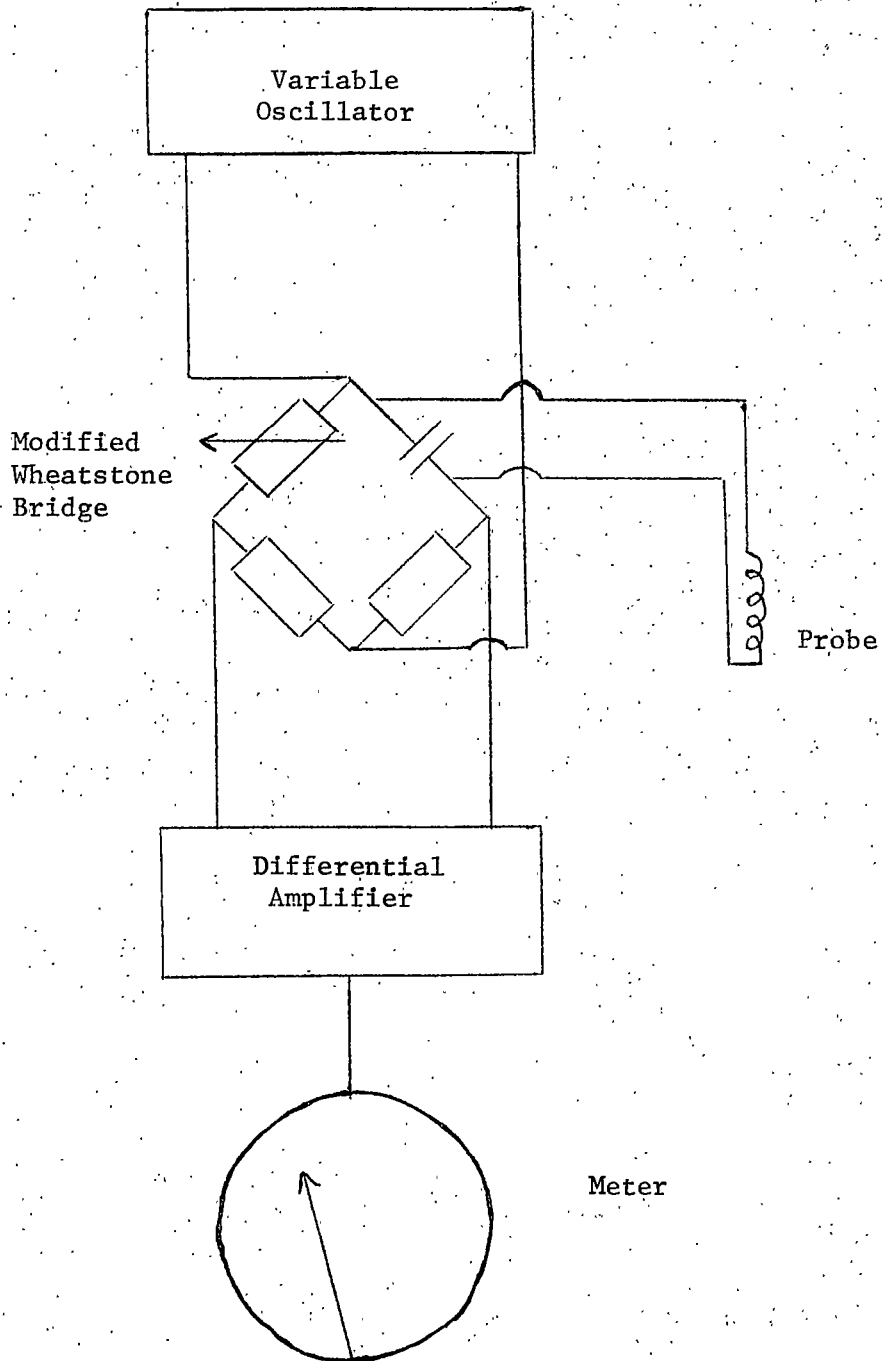


Figure 38

Block Diagram of an Eddy Current Setup for
Paramagnetic and Diamagnetic Materials

The proper selection of frequency is considered to be the most important step in the initial set up. This is accomplished by determining the lift off point. At this point, interference from a rough surface, a slight wobble of the probe, or a thin layer of paint does not interfere with the inspection process. Lift off is determined by using a common piece of paper or plastic approximately 0.004 inch thick between the probe and the material and adjusting the frequency control in such a way that there is no difference registered between the readings on the bare metal and the readings with the space in between. At this point, optimum frequency is achieved.

During the inspection, the meter should be watched constantly. In some instruments, an electronic switch is used to trigger a visual or audio alarm when a certain preselected meter reading is reached. When a crack or seam is encountered, a sudden sharp change in the current setting will be noticed. During the inspection process, minor or more gradual changes are often observed, but these are more likely to be caused by probe wobble or surface conditions even though the test instrument was adjusted for lift off compensation. A spring loaded surface probe similar to the one shown in Figure 35, page 234, tends to minimize these small variations. Changes in wall thickness of thin materials or in conductivity will also cause a change in meter reading. These are gradual changes, however, and can be readily distinguished from the sudden deflections caused by discontinuities

or defects.

Many types of probes are used with the eddy current method of inspection depending upon the type of application desired. The sensing coils are similar in inductance but for defect detection of simple cracks a coil with a ferrite or powder iron core is generally used to improve resolution. The size of these sensing coils can vary from one-eighth of an inch to one-quarter of an inch in diameter in order to better fit the physical shape of the probe being used in the test. The shape of the coil is determined by the application required, and three important factors should be kept in mind by the inspector. They are:

- (1) the core of the probe should pass directly over the critical area;
- (2) there should be minimum wear at the face of the coil; and (3) there should be maximum stability and ease of handling.

A second type of eddy current instrument has been developed for the detection of surface cracks. In sharp contrast to the sensing coil mentioned earlier in this study, this instrument was designed specifically to function as a differential probe. This probe contains two coils which have been balanced in such a way that their combined output is zero. When this probe is placed on an acceptable part, the impedance changes in both coils will be equal and the combined output remains zero. When the probe is moved over a part with a discontinuity, the impedance in one coil changes with respect to the other as soon as it is placed over the discontinuity.

This differential approach is very sensitive, especially when the parts being inspected are of low electrical conductivity such as stainless steel or titanium. For the inspection of ferromagnetic materials, the differential method is considered far superior to the probe inspection technique with a single coil.

The use of the single coil probe to detect surface discontinuities in ferromagnetic materials has been most difficult. In direct contrast to the inspection of nonferrous materials, obtaining a lift off condition for ferromagnetic materials without sacrificing sensitivity has not been possible. This failure is the direct result of the variations in the relative magnetic permeability at the surface of the material caused by stresses in the material which are residual from the manufacturing processes. Subsequent to the annealing treatment, minute stresses are left to cause equally minute variations in permeability. Since the eddy current testing equipment is quite sensitive even to those small variations, they can effectively mask indications which are of primary significance to the inspector.

In the automatic inspection process, it is possible to eliminate the effect of magnetic permeability. For the manual inspection process, the solution to this problem has been the development of eddy current techniques using the differential coil which has been built into a very small probe. In principle, the test coils should inspect areas which are very close to each other, since there is a minimum chance of

overlooking a discontinuity which is under both coils at the same time.

There are several types of signal detection systems in use today, but the most commonly used one is similar to the one illustrated in Figure 39, page 244 (Betz, 1972:10-14). This particular system contains four arms, each of which contains a possible combination of impedances. One of the arms contain the test coil. Prior to the test, the bridge is balanced with the probe on a sample of acceptable material by adjusting one or more of the elements in the other legs of the bridge. When the bridge is in balance, there is no current flowing through the amplifier. When the coil is placed on a test sample with different characteristics, the coil impedance indicator will change slightly, since a different current is flowing through the amplifier. By suitably amplifying the signal which occurs when the bridge is unbalanced, a very sensitive detection device is obtained.

Readout methods used for eddy current testing are as varied as most other parts of the testing system. By far the most common readout method used is the simple meter. Most instruments with meter readouts present only amplitude data about the signal. The second most common type is the cathode ray tube type. The manner of presenting data on the latter is generally a "flying spot," or some other type of lissajous (by using one sine wave signal to deflect the electron beam horizontally and the other sine wave to deflect the beam vertically, a pattern can be produced which provides a relationship between the two signals).

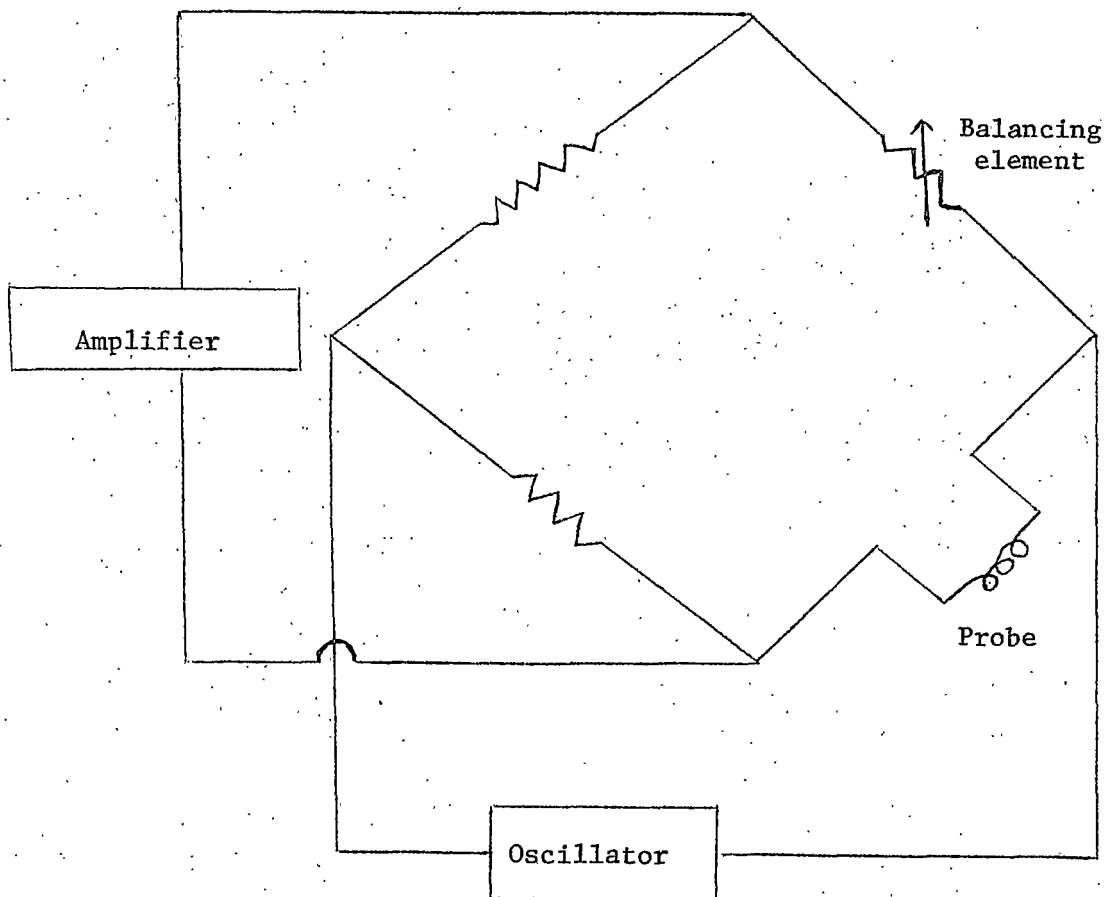


Figure 39

Schematic Diagram of a Simple Bridge Circuit

pattern. In the flying spot type of presentation, the screen represents the impedance plane and the spot of light is the location of the coil impedance on the plane. Instruments with this type of presentation present data on both amplitude and the phase of the signal. The spot that the dot follows is the impedance curve for the particular situation that the coil detects at the moment. The lissajous pattern also presents more amplitude data. The most common pattern used is the ellipse. Proper interpretation by the inspector of the tilt and the openings of the ellipse allow derivation of phase and amplitude information about the signal.

A feature found in many instruments is the lift off compensator. The primary function of this feature is the reduction of sensitivity to lift off so that only signals of interest to the inspector will appear on the instrument. In its most common form, lift off compensation is a means for varying frequency over a small range to locate the frequency at which the sensitivity to lift off is minimal. In any frequency range, there is a frequency for a given probe-material-conductivity combination at which the sensitivity to lift off is at a minimum. No lift off compensation scheme provides for infinite compensation although most systems can compensate to approximately 0.010 of an inch.

For many applications it is desirable to automate decision making to accept or reject a part on the basis of test results which

have been predetermined and preset. For this very reason, many test instruments contain some type of alarm circuit. These circuits provide an output whenever a signal exceeds a preselected amplitude. Once such a signal is available, it can be used to successfully activate all types of auxiliary equipment such as lights, audible alarms, or markers to identify defective materials or systems. The rejected parts can be shunted into separate bins for repairs or rejection at a later date.

Another useful type of eddy current instrumentation measures phase differences rather than the signal amplitude. Because there is a different time required for these currents to build up in a part, signals seen in the part due to eddy current tests lag behind the current used to induce them. This time difference is commonly known as phase shift between the two signals. Figure 40, page 247, illustrates this concept of phase difference (Betz, 1972:10-15). The phase shift between the oscillator output and the signal returned from the test piece varies with the type of material being tested. Other factors to be considered are material thickness, conductivity, crack size, and material composition. However, over a considerable range the phase shift does not vary considerably with lift off. Instrumentation of this type can be quite useful where it is necessary to inspect parts with sharp configurations and irregular shapes.

Some of the differences in eddy current instrumentation have been outlined in this study. To attempt to present data on all types

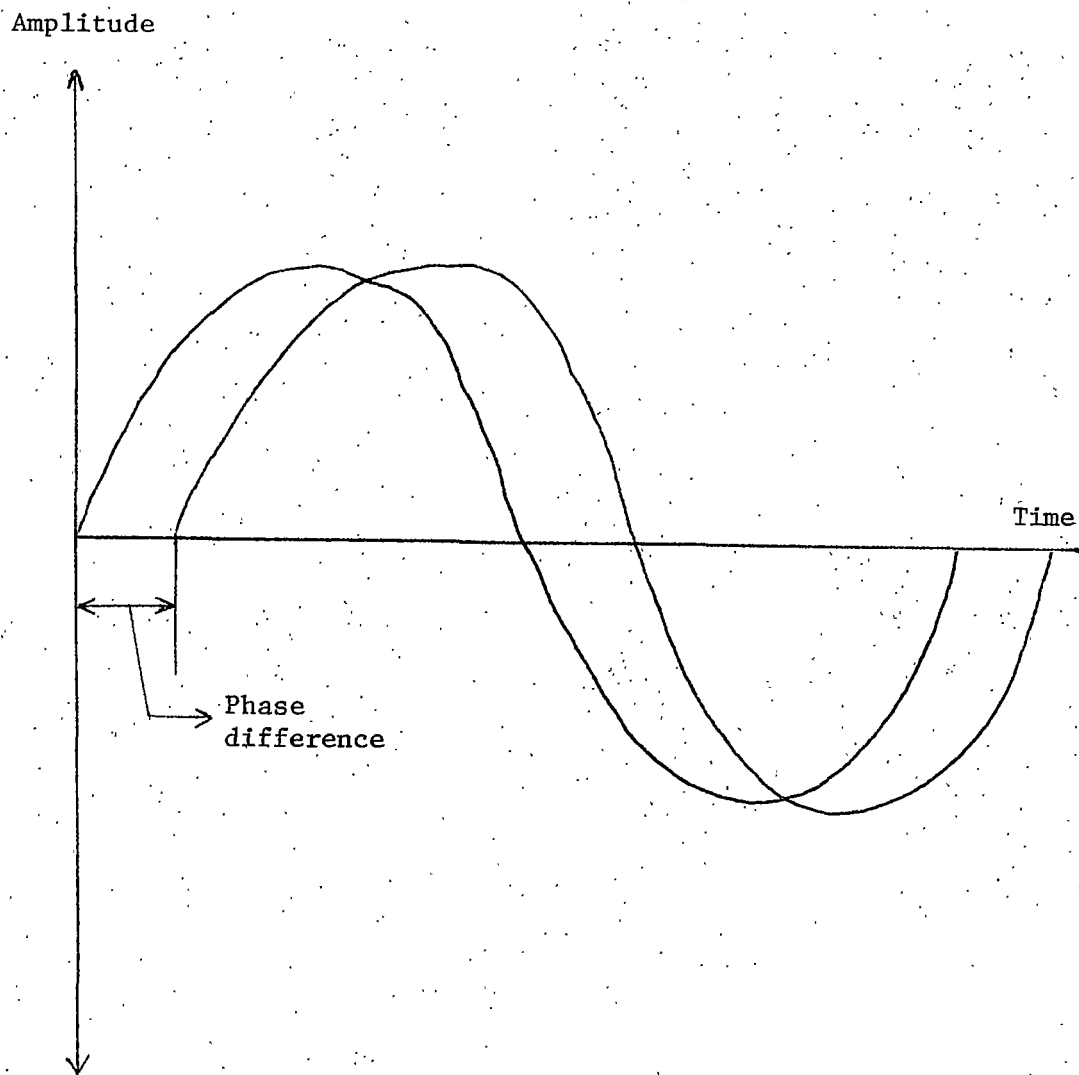


Figure 40

Phase Difference Between Two (AC) Signals

of instrumentation available to eddy current inspectors is considered by the writer to be beyond the scope of this study. There are probably more different types of instrumentation available for eddy current testing than there are for all of the other methods of nondestructive testing combined. For example, there are instruments designed primarily for measuring electrical conductivity, inspecting tubing, inspecting wire and rods, measuring coating thickness, and many other types of inspection which are used specifically for measuring the magnetic qualities of metals. This multiplicity of test instrumentation is a direct result of the variety of test parameters required by industry. To attempt to construct a single, all purpose eddy current test instrument would be considered impractical, since each test situation requires a different set of test parameters. To attempt to include a large number of possible situations would make the instrument too complex and too expensive. Therefore, there are numerous types of eddy current instruments available, each of which is intended primarily for a select and limited area of inspection.

EVALUATION OF THE EDDY CURRENT TEST

The eddy current inspection process was evaluated by the writer to determine whether or not it met the five criteria set forth in the analysis of data section. The eddy current inspection process met the criteria in the following ways.

Compatibility to Existing
Industrial Education Programs

The writer believes that the justification for including non-destructive testing programs in the industrial education curriculum can best be stated by those who are knowledgeable in this area.

Joseph L. Rose, Mechanical Engineering Department, Drexel University (1976:personal letter to the writer) concurs with the writer's belief that nondestructive testing programs are compatible with industrial education programs in the following statement, ". . . nondestructive testing methods are compatible to existing industrial education programs." In addition to the five methods selected by the writer for this study, Dr. Rose suggested that an awareness of holographic and acoustic emission testing methods would be desirable.

T. W. Judd, Assistant Division Head, Nondestructive Testing Division, Republic Steel Corporation (1976:personal letter to the writer), concurs with Dr. Rose in the following statement, ". . . I would think that the methods of nondestructive testing as suggested by this study would be compatible with existing industrial education programs and would be a desirable adjunct to them." These statements concur with the statements by David M. Goin (1968:33-34) that ". . . nondestructive testing methods could be incorporated into existing industrial education programs without disrupting them," and by Glenn M. Thatcher, Coordinator of Industrial Technology, Kean College of New Jersey (1976:personal letter to the writer), that ". . . nondestructive

testing methods would be compatible to industrial education programs if the support equipment was available."

Richard R. Haugo, Professor of Industrial Education, Bemidji State University (1976:personal letter to the writer), sums up the compatibility of nondestructive testing programs in the industrial education program with the following statement, ". . . it would appear that nondestructive testing methods are compatible with what should exist in industrial education programs in my opinion."

Ability to Satisfy One or More
of the Present Needs of Industry

Glenn M. Thatcher, Coordinator of Industrial Technology, Kean College of New Jersey (1976:personal letter to the writer), makes it quite clear that nondestructive methods of inspection can satisfy one of the present needs of industry in the following statement, ". . . people familiar with and trained in nondestructive testing techniques are greatly desired by industry at the present time." George L. Pherigo, Chairman of the Educator's Division, The American Society for Nondestructive Testing (1976:personal letter to the writer), concurs with the statement by Thatcher in the following statement, ". . . there is indeed a current need for personnel trained in nondestructive testing, and a knowledge of the basics in high school could be beneficial." Joseph L. Rose, Mechanical Engineering Department, Drexel University (1976:personal letter to the writer), agreed with Pherigo

and Thatcher in the following statement, ". . . nondestructive testing programs in the industrial education program could satisfy one or more of the present needs of industry."

Robert T. Anderson, Technical Director, The American Society for Nondestructive Testing, Inc. (1976:personal letter to the writer), sums up the ability of nondestructive testing methods to satisfy the needs of industry by providing high school graduates with competencies desired by industry in the following statement, ". . . high school students equipped with a knowledge of the practical applications of nondestructive testing would have an advantage that no other high school graduates would have."

Relative Simplicity and Broad
Encompassing Nature

Joseph L. Rose, Mechanical Engineering Department, Drexel University (1976:personal letter to the writer), indicated that, ". . . the nondestructive testing processes of liquid penetrants, magnetic particles, and eddy currents are relatively simple and do have a broad encompassing nature." This statement is reinforced by James P. Nagy, Professor, Materials Science Department, Erie Community College (1976:personal letter to the writer), who indicated that ". . . the methods of liquid penetrants, magnetic particles, and certain eddy current applications are relatively simple and require a minimum of equipment."

T. W. Judd, Assistant Division Head, Nondestructive Testing Division, Republic Steel Corporation (1976:personal letter to the writer), implied a note of caution in evaluating the simplicity of certain nondestructive testing techniques in the following statement, ". . . liquid penetrants and magnetic methods are relatively simple in their application. Eddy currents, radiography and ultrasonic tests may or may not be simply applied depending upon the nature of the test."

With the exception of eddy currents, Glenn M. Thatcher, Coordinator of Industrial Technology, Kean College of New Jersey (1976:personal letter to the writer), concurs with Judd in the following statement, ". . . with the exception of radiography and ultrasonics, the nondestructive testing processes selected by the writer for this study are relatively simple in their application and do have a broad encompassing nature."

Since the eddy current testing process depends upon measuring the changes in the impedance of a coil due to changes in the flow of eddy currents induced in a conductor, any material change which affects the flow of induced currents sufficiently can be detected. Since so many factors affect this flow, eddy current testing processes can be applied to a wider variety of test situations than any other of the nondestructive testing methods (Betz, 1972:10.15-10.16).

This broad encompassing nature is evident when one considers the fact that eddy current testing methods are applicable to: (1) a

wide range of products and fabricating methods such as rolled sheet stock, drawn wire and tubing, welded pipes, and castings; (2) the detection of flaws, cracks, seams, or for the sorting of mixed items; and (3) the inspection of thin-walled and relatively small items which must be tested in large quantities.

Eddy current testing in its simplest form is accomplished by using a probe or coil to induce eddy currents in the part being tested. The results of this test are indicated on a suitable test instrument. These results are immediate and can be compared to those of known quality. An acceptable eddy current testing unit can be purchased from Uresco Corporation or Magnaflux Corporation for approximately \$2,000.

Potential in Satisfying What the
Writer Believes to be a Weakness
of the Present Industrial
Education Program

Based upon an evaluation of the stated goals and objectives of industrial education as set forth by the American Vocational Education Association, on page 7 (1968:11), the writer believes that industrial education teachers cannot be expected to satisfy the needs of their profession unless they have developed a certain measure of competency in eddy current testing. This competency should include an awareness and knowledge of: (1) the basic theories and principles, (2) the advantages and limitations, (3) the potential safety hazards, if any,

and (4) the skills required to satisfactorily perform the eddy current test.

Joseph L. Rose, Mechanical Engineering Department, Drexel University (1976:personal letter to the writer), concurred with the beliefs of the writer in the following statement, ". . . nondestructive testing processes have the potential to satisfy one of the weaknesses of the present industrial education program." Oren J. Huber, Assistant Director, American Society for Metals (1976:personal letter to the writer), makes an interesting evaluation of the need for the development of nondestructive testing guidelines in the following statement, ". . . I may appear cynical, but it appears that secondary level school instructors do not generally want to expand much effort until there is a rather complete inspection package available."

Carl E. Betz and Richard R. Haugo sum up the belief that non-destructive testing processes should be included in the present industrial education program in the following statements, ". . . most technical and engineering schools have not appreciated the importance of nondestructive testing in today's industrial world, and that a wider acquaintance with this technology at an early level of education is highly desirable, (Betz, 1976:personal letter to the writer)," and ". . . I would agree that the inclusion of nondestructive testing processes would be a beginning to satisfy one of the weaknesses in industrial education (Haugo, 1976:personal letter to the writer)."

The Educational Requirements and
Competency Levels Expected of
Inspectors

Since this study is concerned with the development of entry-level competencies in the area of eddy current testing, only those requirements which are essential to the development of this level of competency have been included in this study. Each entry-level inspector is expected to demonstrate, prior to being considered for certification in the field of eddy current testing, that he has acquired (American Society for Nondestructive Testing, Supplement (E), 1968: 106): (1) sufficient education and experience to ensure an understanding of the principles and procedures of eddy current testing; (2) instruction in the processing of parts. Prior to his certification, the entry-level inspector should work at all times under the supervision of a certified inspector; (3) sufficient knowledge and experience to pass an examination which includes the basic test principles, types of equipment used in the tests, operating procedures, and testing techniques. Specific examinations should be included which cover the specifications and codes used by the employer in his nondestructive testing procedures.

In addition, each applicant should demonstrate that he is able to pass a physical examination which assures natural or corrected near-distance acuity such that the applicant is capable of reading J-1 letters on a standard Jaeger's test chart. Color vision tests may be

required in certain situations.

Having met the five criteria as set forth in the analysis of data section, procedures for applying the eddy current process in industrial education programs at the high school level have been described in depth.

PROCEDURES FOR APPLYING THE EDDY CURRENT PROCESS IN INDUSTRIAL EDUCATION

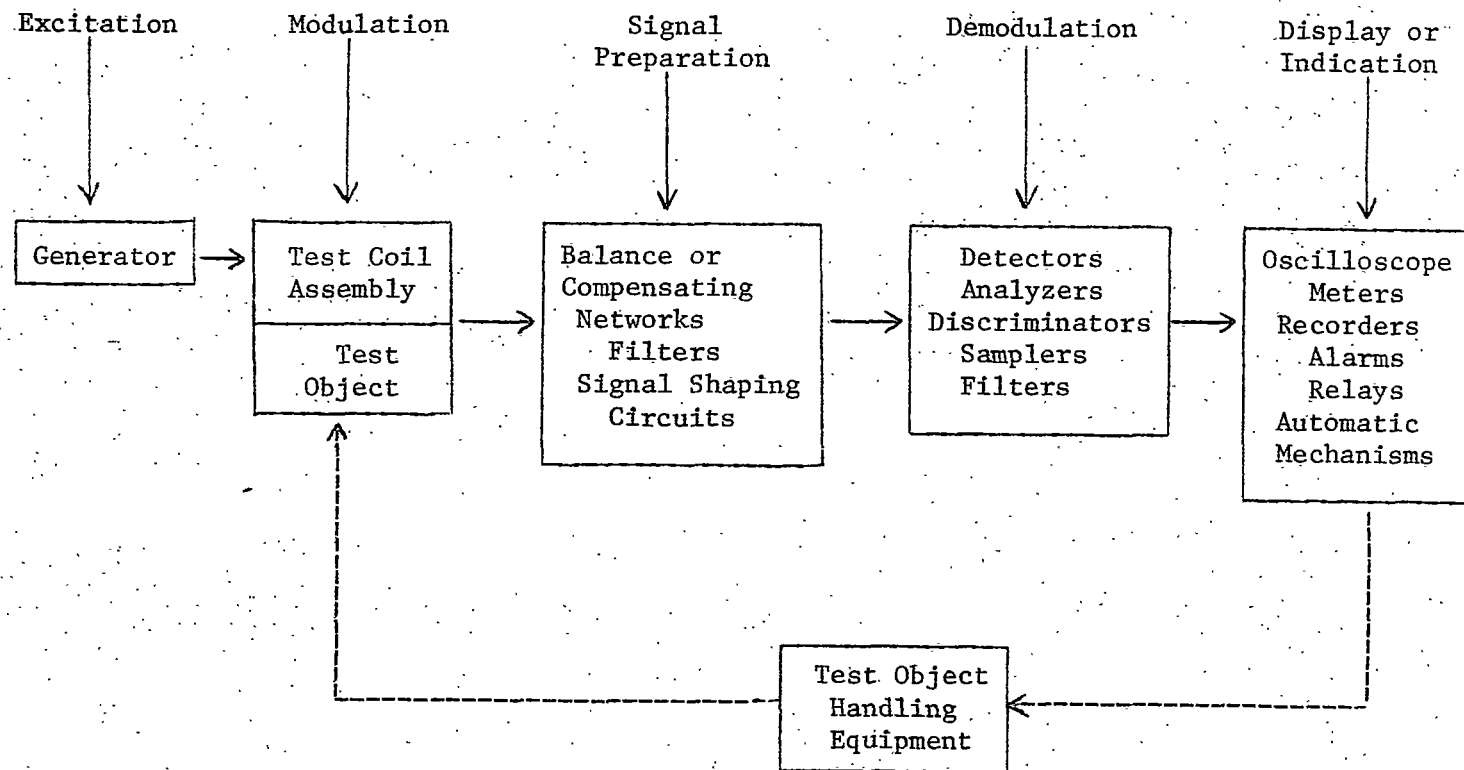
The test frequencies used in the eddy current testing processes range from 60 hertz to 6 megahertz or more. The majority of these tests are performed at a few hundred kilohertz. As a general rule, the lower frequencies up to approximately one kilohertz are used for the inspection of magnetic materials, while the higher frequencies are used for the inspection of nonmagnetic materials. These rules should be considered "thumb rules," since the actual frequencies used in any given situation will depend upon the thickness of the material being tested, desired penetration depth, sensitivity or resolution required, and the specific purpose of the test being performed.

The selection of a test frequency is usually a compromise. For example, sufficient penetration is required to reach suspected subsurface defects. Since the penetration is greater at the lower frequencies, this situation would seem to indicate that the inspector should use a frequency as low as possible. Unfortunately, as the frequency is lowered, the sensitivity to small flaws decreases. Therefore, the

inspector generally selects a test frequency as high as possible, yet one which is still considered to be compatible with the depth of penetration required. The choice is relatively simple when the detection of flaws is the primary concern. In this situation, frequencies up to several megahertz may be used successfully. When it is necessary to locate flaws which are below the surface and low frequencies are required, sensitivity is sacrificed and it is not possible to detect minute flaws.

When magnetic materials are being tested, quite low frequencies are in order, because of the relatively low penetration of these materials. As with the nonmagnetic materials, higher frequencies can only be used when it is necessary to inspect for surface discontinuities only. However, the higher frequencies used in this situation are still considerably below those selected for the inspection of nonmagnetic materials under similar conditions. According to Libby (1971:60-61), most eddy current test systems perform six internal functions. They are: (1) excitation, (2) modulation, (3) signal preparation, (4) signal demodulation and analysis, (5) signal display or indication, and (6) test object handling.

The test equipment used in the eddy current testing process can, therefore, be logically divided into sections which relate to each of these functions. Figure 41, page 258, illustrates the internal functions of the eddy current testing process (Libby, 1971:60). To provide



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Figure 41.

Internal Functions of the Eddy Current Method of Nondestructive Testing

continuity, each of these functions will be examined in depth.

Excitation

The generator which provides test coil assembly excitation signals can be developed from a single frequency sinusoidal generator and power amplifier, a multiple sinusoidal waveform generator and power amplifier, or a pulse generator delivering the desired pulse waveform. The signal may also be developed from a self-excited oscillator whose behavior is governed by the impedance of the test coil.

Modulation

The signal modulation occurs in the electromagnetic field of the test coil or coils. These test coils are labeled "test coil assemblies" because of the variety of configurations in which this part of the test equipment appears. The test coil assembly equipment is often related mechanically to the test object handling equipment which is discussed in detail in subsequent pages of this study.

Signal Preparation

The signal portion of the test equipment consists of the circuits which prepare the signal output of the test coil assemblies for the demodulation and analysis functions. These circuits consist of alternating current compensating or balance networks which subtract a steady alternating current component from the input signal so that the instrument amplifiers do not need as large a dynamic range as otherwise

would be the case. Filters are often included to improve the signal to noise ratio or to separate the different carrier signals in the case of multi-frequency tests. Signal shaping circuits are sometimes included. An important part of this portion of the equipment is the amplifiers which raise the signal to the desired level for demodulation and analysis.

Signal Demodulation and Analysis

The demodulation and analysis section of the test equipment is comprised of detectors and analyzers. These detectors range from simple amplitude detectors to amplitude phase detectors and more highly specialized electrical circuits. For the coherent detectors, a reference signal is provided from the generator section. Sampling circuits and discriminators may also be included in the analysis section. Various types of summing and comparison circuits may also be included in the test equipment at this point. Filters may be included for filtering the demodulated signal to accentuate or discriminate against certain characteristics of the signal.

Display or Indication

The signal display or indication portion of the test equipment is the real connecting link between the test equipment and its intended purpose. This indication of a discontinuity may be displayed by the use of meters, recorders, cathode ray oscilloscopes, visual or audible

alarm signals, relay outputs, automatic signaling, or reject equipment. Typical indicators were illustrated in Figures 36 and 37, pages 236 and 237, respectively.

Test Object Handling Equipment

Depending upon the nature of the tests, test object handling equipment needs may be minimal or they may require very complicated mechanical designs. In some test situations, the test coil assemblies are designed so that they can be positioned and held manually.

In this case, the demands of the handling equipment are considered minimal and all that is required is a place to set or hold the test object while the test is being performed. In many tests, however, mechanical feeders feed the test objects past test coil assemblies so that the test can be made rapidly under uniform conditions. Such equipment requires coordination in the design of the test coils and the feed equipment. Such tests are amenable to complete automatic operations. Additional data regarding these test functions can be found in the text, Introduction to Electromagnetic Nondestructive Test Methods, by Hugo L. Libby on pages 60-61.

Inspection and Evaluation of Parts

In the eddy current testing process, the four basic properties of electrical conductors should be kept constantly in the mind of the inspector. They are: (1) electrical conductivity, (2) magnetic

permeability, (3) object mass, and (4) the types of discontinuities to be located. In paramagnetic and diamagnetic materials, changes in electrical conductivity will be the major contributing factors when metallurgical factors are of prime concern to the inspector. This is in direct contrast to the group of metals classified as ferromagnetic where variations in hardness will cause changes in the magnetic permeability approximately 100 times greater than the electrical conductivity changes. The influence of a part's physical mass on eddy current readings is limited to the depth of penetration desired in the area surrounding the sensing coils. When thickness measurements are important, the other variables mentioned earlier in this chapter should be carefully considered.

The application of eddy current tests is dependent upon the following test variables:

1. The types of discontinuities to be detected
2. Which physical properties are to be measured
3. The thickness of conductive coatings such as foil, plating, or other nonconductive coatings
4. Whether the material to be tested is paramagnetic or diamagnetic
5. The rate of inspection desired

The use of an impedance detector such as the one illustrated in Figure 37, page 237, requires a simple two-step procedure: preparation

and detection. It is important for the inspector to know that the depth of penetration can be changed by adjusting the frequency control. Ten positions are available: number one is the lowest setting and the highest frequency (134 kilocycles), while number ten is the highest position and the lowest frequency (54 kilocycles) (General Dynamics, 1967:4-14). Rotating the control knob from the lowest position to the highest position represents an increase in the depth of penetration since the depth of penetration increases as the frequency is decreased. The lift off control is a fine frequency (vernier) control for any frequency selected by the frequency control. In normal practice, the frequency control is set to a position and the final frequency is selected through the lift off control. The frequency control is, therefore, a coarse frequency control while the lift off control is a fine frequency control.

Preparation for discontinuity detection is accomplished by completing the following steps (General Dynamics, 1967:4-14):

1. Make certain that the detector is turned on and the sensitivity control is rotated clockwise to the MAX position
2. Turn the balance control counter-clockwise to the maximum position
3. Turn the lift off control counter-clockwise to the maximum position
4. Set the frequency control to position number one or to a

specified position if it is known.

5. Press the probe on the surface of a reference part. Use a reference that has been previously found to be acceptable.

6. Adjust the balance control to obtain mid-range indication (approximately 250 microamperes on the meter scale).

7. Lift, then return the probe to the reference's surface noting the direction of meter deflection!

8. When the meter deflects down-scale toward the lower value, rotate the frequency control to position number two and repeat steps 6 and 7. If necessary, repeat the procedures using position number three (or the next highest number) until deflection in the up-scale direction is obtained.

9. Place a sheet of ordinary writing paper (0.002 to 0.004 inches in thickness) between the probe and the article being tested.

10. Slide the paper out from under the probe and note the direction of meter deflection.

11. Rotate the lift off control in a clockwise direction and note the direction of meter deflection.

12. Verify that the meter deflection in step 1 is the same as in step 10. If it is not the same, rotate the frequency control to the next highest position and adjust the balance control to obtain mid-range indication.

13. Repeat steps 9 through 12 until no meter deflection occurs

when the piece of paper is removed from under the probe.

14. If desired, the sensitivity can now be reduced by rotating the sensitivity control in a counter-clockwise direction. This will reduce the spread as displayed on the meter.

Eddy current discontinuity detection using the impedance method is a gross detection system which is based on the detection of changes from a reference standard. The test article through the regular eddy current patterns within the part is the reference. As the eddy current test coil probe is moved across the part's surface, a meter deflection indicates a change from a reference standard. The reason for the meter change cannot be determined by observing the meter deflection, but the inspector knows that something within the part has changed.

Since a number of factors within the part can affect the test coil, the significance of the deflection change depends upon the specific test application, the inspector's experience, and the availability of standard references with artificial or natural discontinuities. It is necessary to keep in mind that the depth of penetration varies with the test frequency. Therefore, the depth of testing is not constant. The inspector should also realize that eddy current testing is basically a surface testing technique which is limited by the depth of penetration. When the depth of the article is greater than the depth of penetration (the normal case), 100 per cent testing of the article is not being accomplished throughout all areas of the part.

Establishing Acceptable Standards

Over the years there has been an insistant demand for standards to govern the acceptance of components and materials on the basis of indications produced by nondestructive testing methods. Companies utilizing nondestructive methods of inspection were told to use a particular method of inspection, but they were not told what to do when they discovered discontinuities. Reflection on the part of the reader should make it apparent that broad, all-encompassing standards for this purpose are considered impossible.

Whether or not a discontinuity warrants rejection depends entirely upon factors which have little or no relation to the inspection method which produced the indication. The service requirements of the part in question are the controlling factors. Nature of the stresses in service, stress considerations, the critical nature and function of the part, and even the location and orientation of the defect should enter into the decision to accept or reject a part. These considerations cannot be generalized, but must be applied by those possessing knowledge relative to each specific testing situation. A given defect in one component may warrant rejection but have no significance if present in a different component.

The preparation of acceptable standards are the responsibility of the component designers and the quality control departments since these standards are most effective when they are included in the process

specifications. When such specifications are not available and the individual evaluating the part does not possess sufficient experience or knowledge, he should seek it from those who are responsible for the design and service performance of the part. Inspectors should not expect broad standards to be made available. A knowledge of the part material and its expected service life as well as the types of discontinuities expected and their effect on the strength and performance often enable the knowledgeable inspector, with the use of common sense, to arrive at an intelligent decision regarding the acceptance or rejection of the part (Sharpe, 1970:383).

There are three major sources of inspection requirements which the inspector can use in the development of acceptable levels of evaluation. They are: (1) theoretical consideration and/or stress analysis; (2) correlation of nondestructive test results with mechanical properties, destructive tests, or service life requirements; and (3) the quality level of similar parts which have been used with success in the past. In view of the difficulty of analyzing and using data from theoretical analysis or empirical test correlation results, one of the best sources of information for the establishment of suitable acceptance criteria is the test results from past experience. For example, suppose it was decided to inspect aluminum forgings with the eddy current inspection method in an attempt to locate a particular type of discontinuity. Past experience has shown that 90-95 per cent of the

aluminum forgings produced have been satisfactory in service. Therefore, it would not be logical to establish standards which reject 50 per cent of all the forgings inspected unless metallurgical analysis indicated that the forgings in this particular batch were abnormal.

An inspection acceptance level arrived at on this basis not only provides reasonable assurance that the parts accepted will provide satisfactory performance but also permits an acceptance level which is economically feasible. Naturally, the quality requirements cannot determine the design requirements, but it would be considered extravagant on the other hand to establish a level of quality beyond that which has proven to be satisfactory in the past.

When the inspector is dealing with a new design or material, past experience may provide very little assistance in establishing an acceptable design or performance criteria. In this case, the following procedures should be carefully considered:

1. Pilot parts should be fabricated and inspected for internal and external discontinuities by applicable destructive methods.
2. The frequency and severity of all flaws should be recorded.
3. The part containing the poorest quality should be subjected to mechanical or simulated service life tests. Should the part fail, the next poorest part should be tested. This procedure should be

continued until a part passes the test. The quality level of the part passing the test should be used as the minimum level of acceptance for qualifying.

4. Time permitting, the part should be identified and subjected to true service life conditions to ascertain that it will not fail due to overloading or cyclic fatigue. The part should be periodically inspected to see whether original discontinuities have grown in size and to make certain that the service life to which the part has been subjected is not inducing undesirable discontinuities which could lead to part failure at a later date.

Developing acceptance inspection criteria is not an insurmountable task, since standards and specifications which include acceptance levels are available for eddy current methods of inspection. Standards with seams of varying width and depth have been developed to establish a relationship between the test and the actual crack. Figure 42, page 270, illustrates a typical eddy current standard produced as the direct result of a destructive test (Ridder, 1972:11-7).

In ferromagnetic materials, the depth of penetration is not easily determined since the magnetic permeability is the major influencing factor and this factor is seldom accurately known. However, by using the differential coil approach, some practical experiments have shown a fairly good correlation up to approximately 0.026 of an inch. Beyond that depth there is no measurable increase in the meter reading.

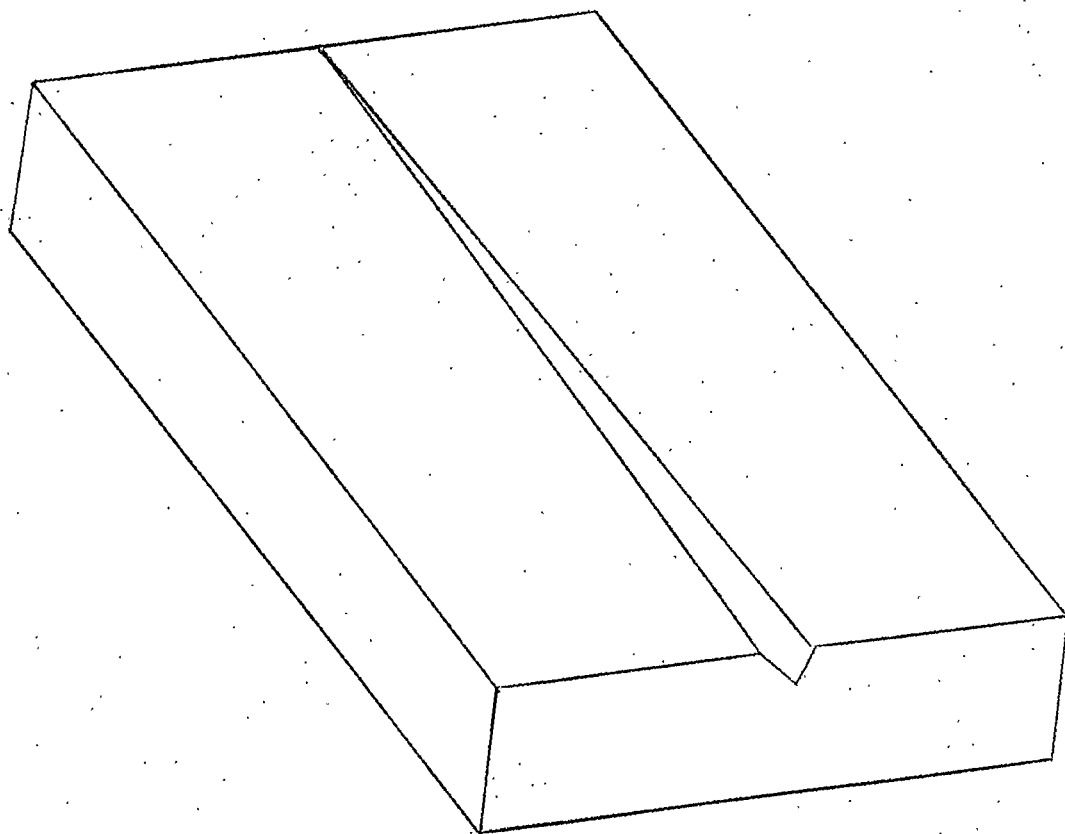


Figure 42
Typical Eddy Current Standard With a
Seam to 0.100 Inch in Depth

The relationship between the instrument values and the actual crack depth must be determined by procedures described earlier in this chapter.

In nonferrous materials, the depth of penetration is fairly accurately known and when the diameter of the probe exceeds the length of the discontinuity, the depth can be approximated. The width of the discontinuity, however, is not known and the accuracy to which this can be determined is limited to approximation. When the depth of the crack exceeds the depth of penetration, no measurable increase in meter reading results.

Since the study of eddy currents is applicable to such a wide variety of testing situations, the development of standards for broad applications is beyond the scope of this study. However, there are certain precautions and conditions which are generally applicable to the development acceptable eddy current standards. They are:

1. The standard should be of the same alloy and heat treat condition as the part to be inspected.
2. The standard should have the same shape and size as the part to be inspected.
3. No variation in plating, coatings, or surface finish is allowable between the standard and the part being tested.
4. Long parts such as rods or tubes should be long enough to compensate for end effect.

5. The standard should not be cold worked by bending or rubbing.

6. The standard should not be overheated.

Strict adherence to the principles listed above will enable the inspector to develop an eddy current compensation curve using a test block similar to the one shown in Figure 43, page 273 (Ridder, 1972:11-19).

Chapters 2, 3, and 4 of this study have reviewed some of the basic requirements of nondestructive testing specifications and some of the test elements considered basic and essential to the success of these testing processes. Basically, there are three major sources of nondestructive testing specifications. They are: (1) military sources, (2) technical societies, and (3) industrial sources. Considering the vast number of specifications available, it is not practical in the opinion of the writer to attempt to list all of them in a study of this scope. However, a brief listing of specifications applicable to liquid penetrants, magnetic particles, and eddy current testing have been included in Appendix A, pages 358-363.

Factors Adversely Affecting Indications

Some test problems arise due to the indirect nature of the eddy current test. Eddy currents are caused to flow in the test specimen by placing it in the alternating current magnetic field of the induction coil. The flow of currents is affected by the electrical properties and

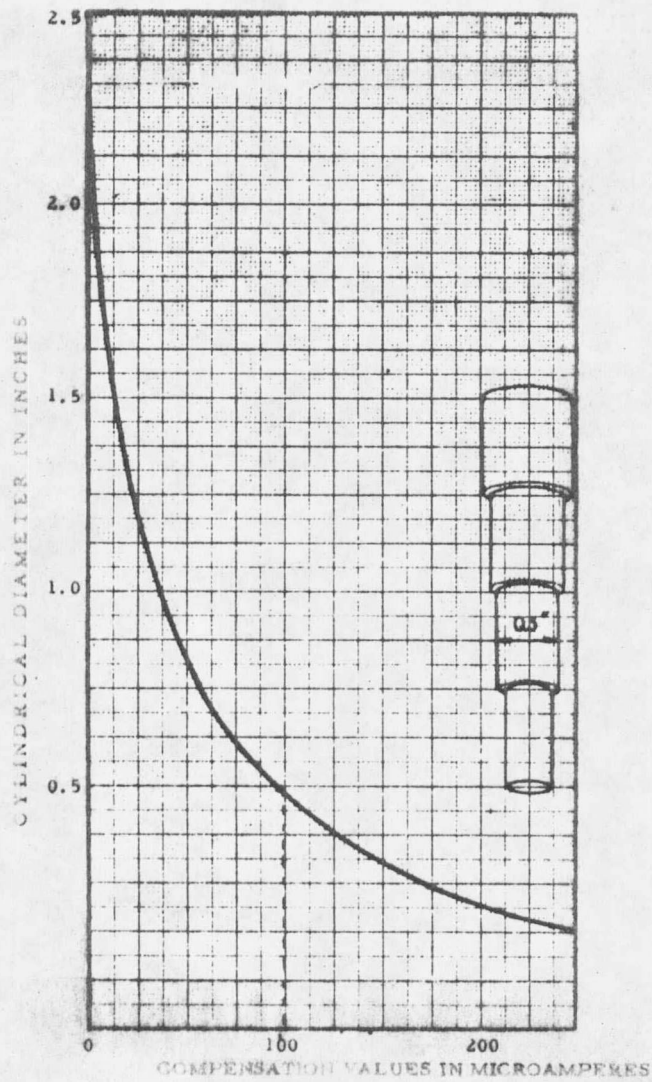


Figure 43

Typical Test Block for Developing Eddy
Current Test Curves

the shape of the test part or by the presence of discontinuities or defects. The current flow, in turn, makes its effect observable by affecting the electrical impedance of the exciting coil or by the related affect of altering the induced voltage of the coil. These effects may be observed by monitoring the test coil impedance. The eddy current test is indirect in that it does not measure directly any specific characteristic of the part being tested. It does, however, respond to some weighted function of the current flow which is indirectly related to the test specimen's condition. This weighted function depends on the test coil design, the operating frequency, and the test specimen. The result is that if several test conditions vary it becomes difficult or perhaps impossible to identify the individual test conditions by observing the test signal in the conventional test. The effectiveness of the conventional single frequency eddy current test is limited to the identification of one or two test conditions only.

Edge effect. When a test coil approaches the edge or end of a test piece, the eddy currents are distorted, because they cannot flow beyond the edge of the part. This distortion results in an indication which is known as "edge effect." Edge effect limits testing near the edges of parts, since the magnitude of this effect is very large. Unlike lift off, there is very little that can be done to eliminate this effect. Smaller coils will reduce the effect somewhat, but there are practical limits to the sizes of coils. For the most part, edge effect is at

least one-eighth of an inch, and it is not normally considered practical to inspect any closer to the edge of a part.

Fill factor. Another condition comparable to lift off which is known as fill factor occurs when an encircling coil is used. This is a measure of how well the test part fills the coil. Changes in fill factor result from outside diameter variations and must be watched carefully since small changes can give large indications. The lift off curves in Figure 44, page 277, are very similar to those used to indicate changes in fill factor. For a given fixed lift off or fill factor, the conductivity curve will shift to a new position as indicated in Figure 44. Use can sometimes be made of the fill factor, because it makes a rapid method for checking the outside diameter variations in bars and rods.

Geometry of part. In addition to the geometrical relation between the part and the test coil, the geometry of the part itself will effect eddy current response. Eddy currents are not uniformly distributed throughout the conductor. Instead, they are most dense at the surface of the part and become progressively less dense with increasing distance below the surface. This phenomenon is known as "skin effect." At some point below the surface of thick parts, there will be essentially no eddy currents flowing at all.

Lift off. A test coil with no conductive materials in the vicinity will give some indications when they are attached to a suitable instrument. As the test coil is moved closer to a conductor, the indication will begin to change. Because the field of the coil is strongest close to the coil, the indicated change on the instrument will continue to increase until the coil is directly on the conductor. These changes in indication with changes in spacing between the coil and the test piece are known as "lift off." The lift off effect is so pronounced that small variations in spacing can mask many indications resulting from conditions of interest. For this reason, it is normally necessary to maintain a constant coil-to-test-part geometry. The lift off effect also makes it very difficult to perform a test that requires the scanning of a part with a complex shape.

The changes of coil impedance with lift off can be seen in the impedance plane diagram in Figure 44, page 277 (Betz, 1972:10-6). When the coil is in air, the impedance is at a point at the upper end of the diagram. As the coil approaches the conductor, the impedance moves in the direction indicated by the dotted lines until the coil is in contact with the conductor. The impedance is then at a point corresponding to the impedance of the test part, in this case its conductivity. The fact that the lift off curve approaches the conductivity curve at an angle can be utilized in some instruments to separate the lift off signals from those resulting from variations in conductivity or some

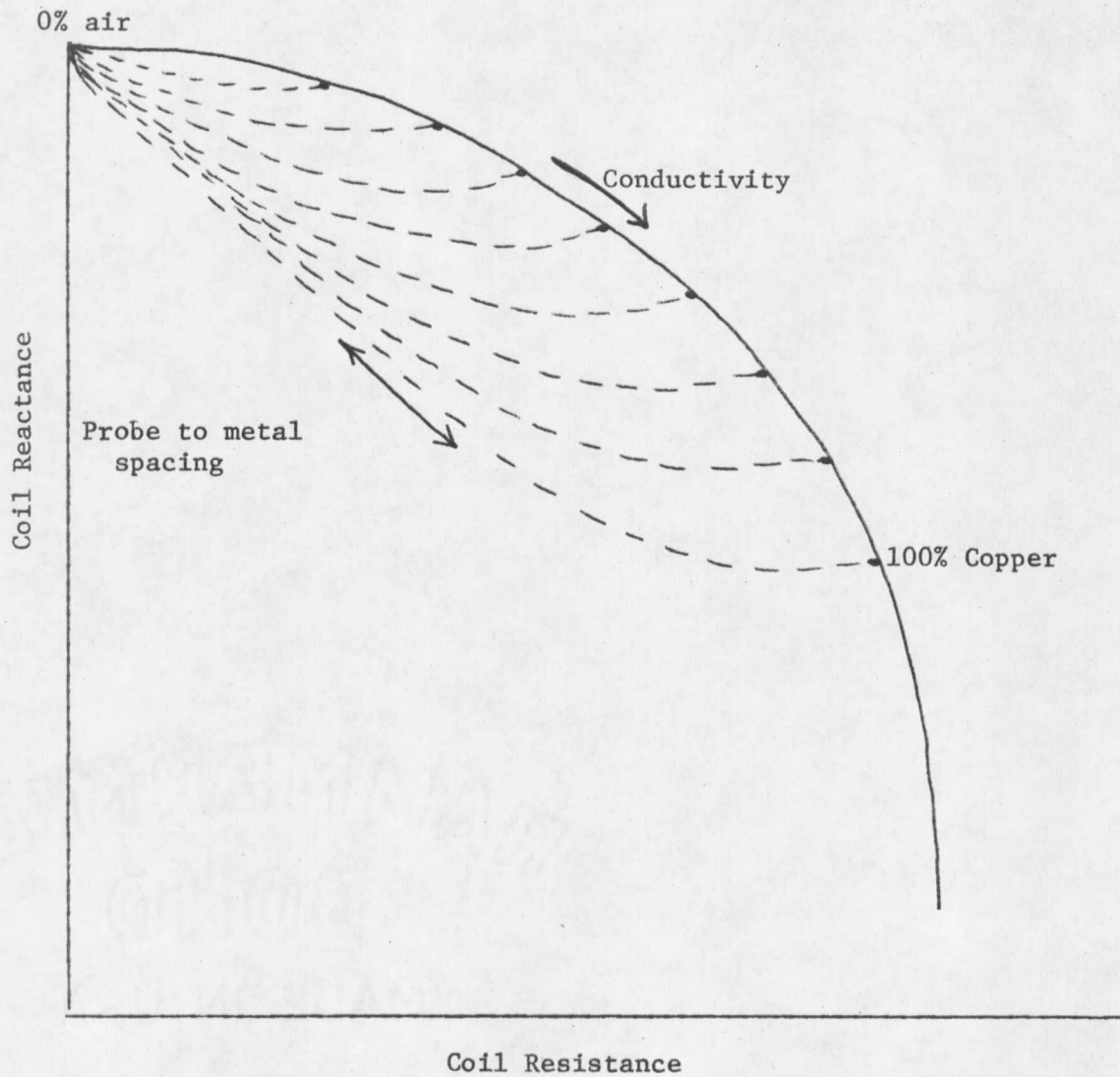


Figure 44

Impedance Plane Diagram Showing Conductivity
and Lift Off Curves--Test Frequency 100kHz.

other parameter of interest.

In spite of the fact that lift off can be quite troublesome in many applications, it can also be quite useful. Eddy current instruments are excellent for measuring the thickness of nonconductive coatings such as paint on conductive base materials or anodized coatings on aluminum or magnesium alloys, and for many nonconductive hard surface coatings on a conducting base.

Types of Discontinuities Located with Eddy Currents

When eddy current tests are properly applied, they can be used to measure such diverse conditions and properties as electrical conductivity, grain size, heat treatment, coating thickness, part dimensions, and hardness. This testing process can also be applied to a wide range of types of products and fabricating methods. Rolled sheet stock, drawn wire and tubing, bar stock, welded pipe, and castings are all being tested for one type of discontinuity or another with the eddy current method of inspection. Eddy currents tend to be most effective on thin or small items where other methods of nondestructive testing are considered to be of little or no value. They are, therefore, the best method for testing such things as hypodermic tubing and fine wires. For the rapid detection of flaws, cracks, seams, and the sorting of mixed materials they are unexcelled. In addition to their versatility, one of the biggest advantages of the eddy current method of testing is

their speed. In the case of long, uniform shapes such as tubing, inspection speeds up to 500 feet per minute are not considered uncommon. For the sorting or testing of small items such as nuts and bolts, inspection rates of 200 pieces per minute can be achieved (Betz, 1972: 10-1).

Since the use of eddy currents depends upon the development of acceptable standards which have been discussed in depth earlier in this chapter and since the solidification, processing, and service categories of discontinuities are not in the opinion of the writer relevant to the eddy current testing process, these categories of discontinuities will not be included in this chapter. An extensive discussion of types of nondestructive testing discontinuities can be found in Chapters 2 and 3 of this study.

SUMMARY

Electromagnetic inspection processes are generally referred to as eddy current testing because the basic principle behind such inspections are derived from the eddy current phenomenon. When a mass of conducting material is moved in a magnetic field or is subject to a changing magnetic flux, eddy currents circulate within this mass. These eddy currents are closed loops of induced current circulating in planes perpendicular to the magnetic field.

The use of eddy currents as a practical method of nondestructive

testing was not used extensively until the end of World War II. Most of the theoretical basis for the use of eddy current testing was formulated by Freidrich Foerster, in Germany, during the period 1930-1950. In addition to his theoretical work, Foerster also helped to develop an extensive group of instruments for the performance of various non-destructive tests. It was the introduction of these instruments outside of Germany in the early 1950's which helped to make eddy current testing significant in modern industrial processes. Today, eddy current testing equipment is compatible with most industrial specifications, and these testing processes are often integrated into the manufacturing process to provide a completely automated inspection of parts as they are being cast, formed, or machined.

The eddy current testing process may be defined as a method of nondestructive testing which requires the part being tested to be subjected to an alternating electromagnetic field. This testing process can be compared with a person rowing a boat. As he dips and pulls on the oars, little whirlpools (eddies) are formed in the water. When these whirlpools hit something floating in the water, their shape changes. Similarly, a coil carrying an alternating current can induce a circulating electrical current within a mass of metal. This electrical whirlpool is known as an eddy current. Its basic characteristics change according to the type of material being tested, the ability of the metal to conduct electrical current, and other factors directly

related to the material being tested.

In the field of eddy current testing, the word "flaw" has a much wider meaning than it does in other forms of nondestructive testing, since the eddy current process is applicable to more than the detection of discontinuities. Eddy current applications fall into three basic categories. They are: (1) detecting flaws in parts, this includes the detection of cracks, voids, inclusions, laps, and seams; (2) sorting of parts according to their alloy, conductivity, temper, or other metallurgical conditions; and (3) gauging parts according to their size, shape, plating thickness, or insulation thickness.

The detection of discontinuities, however, has been one of the principal areas of application for this method of inspection, and it is in this area that the eddy current method has replaced such methods as the visual and magnetic particle methods of inspection.

In the eddy current testing process, a coil is used to induce eddy currents in the part being tested. The electrical characteristics of the coil are affected by any discontinuity or defect. It is the careful electronic measurement of coil changes which make the eddy current method of inspection unique among nondestructive test methods in the determination of part composition or the accurate identification of materials in addition to locating discontinuities.

There are many factors which contribute to the widespread use of eddy currents. Some of these factors are: (1) when eddy currents

are properly applied, they can be used to measure such diverse conditions as heat treatment, electrical conductivity, coating thickness, part dimensions, and hardness; (2) they can be applied to a wide range of products and fabricating methods such as rolled sheet stock, drawn wire and tubing, welded pipes, and castings; (3) this method of inspection is excellent when it is used for the rapid detection of flaws, cracks, and seams or for the sorting of mixed items; and (4) they are most effective on thin-walled and relatively small items which must be tested in large quantities.

A variety of test probes, frequencies, and instruments are available. Generally speaking, the term "test probe" refers to an electromagnetic transducer placed on the surface of a test object, while the term "test coil" is used to designate a transducer which encircles the test object. In any case, the test equipment used in the eddy current testing processes should include the following elements: (1) an oscillator, (2) a method of detecting impedance changes in the coil, and (3) a method of displaying the test results. Probes and coils vary in inspection area dimensions from 16 by 16 inches to 0.020 by 0.030 inch to 0.001 inch in diameter.

The test coil or probe is usually a coil of wire with electrical properties which match the instruments with which they are used. In addition to this coil of wire, there is often a piece of ferrite material associated with the test probe which is designed to shape and

focus the electromagnetic field. By using such a core material, it is possible to direct the electromagnetic field from the coil of the wire to the specific area of the test object which is to be inspected and thereby increasing the resolution and sensitivity of the test. Some types of test equipment include a means of analyzing impedance changes while others provide a means of compensating for lift-off.

While there are many different test frequencies, coils, and probes available from manufacturers of eddy current test equipment, there are basically two types of instruments. The number of test probes associated with an instrument is indicative of its type. A dual differential instrument has two identical test probes which are electrically opposed. Metallurgical differences within a sample or between samples are detected and displayed by this type of instrument. An absolute test instrument, on the other hand, has only one test coil or probe associated with it. In this situation, the metallurgical or geometrical differences between test objects, or the presence of a flaw or defect, changes the properties of the test coil and thereby produces an indication on the instruments display system.

Most of the eddy current testing systems perform six internal functions. They are: (1) excitation, (2) modulation, (3) signal preparation, (4) signal demodulation and analysis, (5) signal display, and (6) test object handling.

The eddy current data signals obtained from the coils are

usually displayed in one of four ways. The simplest of these is the meter display which provides a numerical indication of the differences between the part being tested and a part of known quality. The other three basic oscilloscope displays are: the line trace, the ellipse, and the flying spot. The former provides a numerical indication which can be calibrated to indicate the depth of a defect while the latter provide the data necessary to separate test variables or to analyze the properties of the test object.

The eddy current testing process was evaluated by the writer to determine whether or not it met the criteria set forth in the analysis of data section of this study. This criteria included an evaluation of the eddy current testing process in terms of its: (1) compatibility to existing industrial education programs, (2) ability to satisfy one or more of the present needs of industry, (3) relative simplicity and broad encompassing nature, (4) potential in satisfying what the writer believes to be a weakness of the present industrial education program, and (5) the educational requirements and competency levels required of entry-level inspectors.

Since an evaluation of this type could best be accomplished by those with expertise in the field of eddy current testing, letters were written to those who had published books or articles, those who were currently employed in nondestructive testing positions in industry and others who were considered to be knowledgeable in the field of eddy

current testing. They were requested to evaluate eddy current testing processes in terms of the five criteria selected by the writer for this study. Their statements indicated to the writer that the eddy current processes could be taught successfully in industrial education classes at the high school level.

Today, electromagnetic testing has been developed to the point where it can provide inexpensive, high speed nondestructive testing with the accuracy and stability required to meet industrial needs. Eddy current testing has often served to speed up testing and in some cases has offered 100 per cent inspection where only a destructive sampling was previously possible. The excellence of this method of testing is evidenced in the inspection of space vehicle materials. In the space vehicle, eddy current tests are performed on thousands of feet of small diameter tubing, thin sheet metal, and numerous other items with high safety requirements. The safety of flight personnel requires complete reliability in each and every component.

Chapter 5

RADIOGRAPHIC TEST

Radiographic testing is a method of nondestructive testing which provides for the internal inspection of a material by a procedure which utilizes X-rays or gamma rays. The results of this test are accomplished by recording the effects of the penetrating radiation on a sensitive film. It is considered to be one of the oldest types of nondestructive testing. The radiographic method of inspection has undergone continuous improvement, and today it is readily applicable to both the mechanical testing field and the area of quality control.

History of the Radiographic Process

Many of the spectacular scientific and engineering achievements of the past few years can be traced to nondestructive testing methods which, by determining the internal soundness without destroying the usefulness of the product, assume the satisfactory performance for which the product was intended. Perhaps the oldest of the modern non-destructive testing methods is radiography.

In 1895, while using a Crooke's tube in the course of his cathode ray studies, Wilhelm Conrad Roentgen discovered that this tube, when energized, gave off a new ray which caused a piece of paper, accidentally covered with platinocyanide crystals, to glow. Further investigation revealed that this invisible radiation penetrated paper,

wood, books, the human hand, and certain light metals, but not lead. Roentgen, assuming that this new ray was a form of invisible light, made the first human radiograph of Mrs. Roentgen's hand on a photographic plate. He called this mysterious ray "x" for the unknown quantity and the term "X-ray" came into being. During the following year, 1896, Becquerel discovered that certain uranium bearing ores also emitted a similar, but more penetrating type of radiation. This lead to the discovery of another similar natural radiation emitter: the new element radium by Madame Curie and her husband. The radiation produced by these natural emissions seemed similar to Roentgen's X-rays but also seemed to be more penetrating. The term "gamma rays" was eventually applied to these natural emissions to distinguish them from X-rays (Aman and others, 1973:1).

It was not until 1922 that the first commercial use of industrial radiographic testing was pioneered by Colonel Jenks and Dr. Lester at the Watertown Arsenal in Massachusetts (Rasor, 1976:unpublished data sent to the writer).

In 1927, the aluminum industry began to use radiographic testing processes to insure that only sound materials were being used in the construction of aircraft. About ten years later, the makers of high pressure boilers began to use radiographic testing methods for the inspection of welds. Since then, industrial radiographic techniques have been developed for the inspection of woods, plastics, ceramics,

and for quality control inspections using electronic equipment.

Description of the Radiographic Process

A basic description of the radiographic method of inspection is provided in Figure 45, page 289 (General Dynamics, 1967:7.5-7.6). The equipment required, types of discontinuities detected with the radiographic test method, and the advantages and limitations of this method of inspection are (Materials Selector, 1970:489):

1. Equipment required: commercial equipment containing X-ray or gamma units, film processing facilities, and fluoreoscopic viewing equipment.
2. Enables the detection of: interior microscopic flaws, cracks, nonmetallic inclusions, incomplete root penetration, undercutting, icicles, and burn-through.
3. Advantages: positive flaw detection, inspection standards are usually available, surface roughness is not a problem, irregular contours can be inspected, high sensitivity to flaws in the path of the X-rays or gamma rays, and the method provides a permanent record of the test results.
4. Limitations: the test sensitivity is limited, test thickness is limited, flaw orientation is critical, flaw depth requires highly specialized equipment and inspection techniques, radiation hazards are present, high equipment and testing costs, and the test

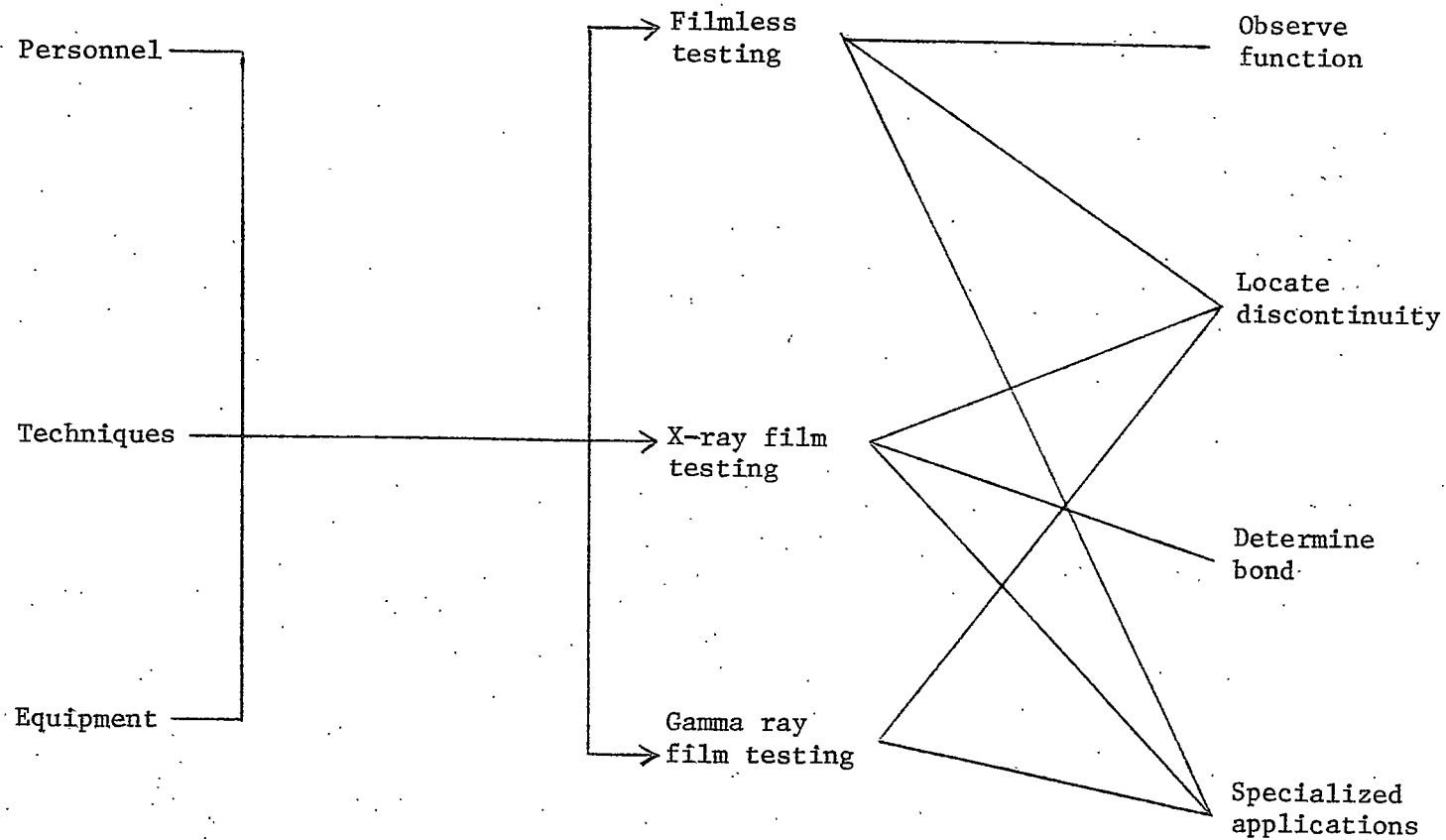


Figure 45
Radiographic Testing

equipment is not usually portable.

Principles of Radiographic Testing

Just as the doctor peers inside of the human body with X-rays, radiographic testing processes utilize these same X-rays to inspect industrial materials and products. A radiographic test in its simplest form is the interpretation of a photographic record which has been produced by the passage of X-rays or gamma rays through an object onto a film. When this film is exposed to X-rays, gamma rays, or light, a change is produced in the film emulsion. Gamma rays are similar to X-rays and show the same similarities to, and differences from, visible light as to the X-rays. They are distinguished from X-rays by their source of origin rather than by their nature (Eastman Kodak, 1969:7-8).

In the radiographic testing process, a beam of gamma rays or X-rays are directed toward the part being tested. Some of this beam is absorbed as the ray passes through the part while some of the ray is scattered. The absorption of this beam depends upon the thickness of the part, its physical density, and its composition. The part of the beam which passes through the part is recorded on a special photographic film for interpretation and evaluation by the inspector. Radiographic tests can be applied to organic materials, inorganic materials, solids, liquids, and even gasses (Aman, 1973:8.2-8.3).

Purpose of Radiographic Tests

Radiographic testing processes are used to discover the presence and the nature of microscopic discontinuities located beneath the surface in metals. This testing process is based upon the ability of X-rays and gamma rays to penetrate metals and other opaque materials, thus producing an image on sensitized film or on a fluorescent screen. The term "X-ray quality" widely used by industry to infer high quality welds, arised from the method of inspection used to guarantee this quality (Hinkel, n.d.:7-8).

Since the radiographic testing process utilizes both X-rays and gamma rays, a brief description of these types of rays has been included.

1. X-rays, which have a wave length $1/10,000$ that of visible light, are produced by high voltage generators. The depth to which a material can be penetrated depends upon the power of this generator. Today, portable testing equipment, rated up to 2,000 kilovolts, is used in the inspection of welds. The higher power units, operating between 1,000-2,000 kilovolts, will penetrate from five to nine inches of steel and produce reliable indications.

2. Gamma rays are produced by the atomic disintegration of radioisotopes. They are similar to X-rays, except that the wave-length is usually shorter than the X-rays produced with low voltage equipment. X-rays generated at 1,000 kilovolts or higher, for all practical

purposes, appear to be identical to the gamma rays produced by radioisotopes. While the short wave lengths of gamma rays allow penetration to considerable depth, the exposure times required to obtain an acceptable picture are usually many times greater than the time required for X-rays because of the lower intensity of the radiation. The level of radiation is directly proportional to the amount of radioisotope used in the test.

When the X-rays or gamma rays used in the radiographic test are directed at a part being tested, not all of the radiation gets through the metal and to the film located behind the part. Some of the rays are absorbed, and the denser or thicker the material being tested the greater this rate of absorption. Should there be a discontinuity in the interior of the part, such as a blow-hole or internal crack, the radiation will have less material to pass through than it would in a sound part. Consequently, there will be less absorption in the area where the discontinuity is located and a greater amount of radiation striking the film. After the film has been developed, the size and shape of the discontinuity will be indicated on the film as a black or darker area.

The film image is known as a radiograph. Radiographs made with X-rays are referred to as exographs, while those made with gamma rays are called gammagraphs.

The ultimate purpose of radiographic testing is to provide

visual information upon where judgments can be based concerning the disposition of the part. It must be remembered that radiography as effective as it is does not guarantee that all discontinuities will show up as indications on the radiograph nor does the level of acceptable discontinuity assure the servicibility of the part. It is always wise in the practice of nondestructive testing to confirm the presence or absence of flaws, particularly in critical parts, by another test method if possible. Therefore, radiography or any other nondestructive test method should be used to compliment or supplement another method or methods (McBride and others, 1973:9.36).

EVALUATION OF THE RADIOGRAPHIC TEST

The radiographic inspection process was evaluated by the writer to determine whether or not it met the five criteria set forth in the analysis of data section. The radiographic inspection process did not meet four of the five criteria in the following ways.

Compatibility to Existing Industrial Education Programs

Whether or not radiation in the radiographic testing process is dangerous depends upon several factors: time, distance, and shielding. When the correct safety precautions are utilized, radiation is no more dangerous than driving a car on today's highways. On the other hand, inspectors and other personnel in the vicinity of radiographic

tests may be getting "zapped" by radiation without knowing that it is actually happening. If the testing process is either the X-ray or the isotopic type, and the proper safety precautions have not been strictly adhered to, there is a high probability that radiation hazards exist (Welding Engineer, 1970:55).

It is the use of these rays and the gamma rays specifically which present a radiation hazard to those engaged in the radiographic testing process. The primary beam of this testing equipment will be of a higher intensity and, therefore, more dangerous than the scatter or background radiation mentioned earlier in this chapter. However, this scatter radiation is far more difficult to measure, thus presenting a more difficult shielding or personal protection problem. By definition, scatter radiation is a type of radiation which "bounces" off test parts in such a fashion that it can reach places where direct radiation cannot: behind a thick wall, for example (Welding Engineer, 1970:55).

This problem with scatter radiation is complex and can be calculated with a great deal of difficulty under the various testing conditions which exist in radiographic testing. Although this scatter radiation may be of a much lower intensity than the radiation of the primary beam, its affects are cumulative and its after effects can be just as hazardous over an extended period of time.

The writer gave special consideration to the statements in

Materials Selector (1970:489), which indicated that prospective users of radiographic equipment should be aware of the following limitations:

1. Specialized testing equipment and operating techniques are required
2. Radiation hazards are present
3. Test equipment and application costs are relatively high
4. The test equipment used in the radiographic testing process is not usually portable.

Hugo L. Libby, Physics and Instrumentation Department, Pacific Northwest Laboratories (1974:personal letter to the writer), emphasized the need for special consideration of the problems related to radiation hazards in the following statement:

. . . the field of nondestructive testing involves a wide range of disciplines and I am sure that the attempt to teach these processes in the high schools will present some special safety problems. Among these is that of personal safety which is especially important in X-ray and other radiation inspection processes.

James P. Nagy, Professor, Materials Science Department, Erie Community College (1976:personal letter to the writer), indicated concern for those involved in the radiography tests in the following statement, ". . . care must be exercised in using X-rays or gamma rays with students under the age of eighteen, because of the low allowable radiation requirements."

Ability to Satisfy One or More
of the Present Needs of Industry

John B. Rasor, Department Chairman of Nondestructive Testing, Don Bosco Technical Institute (1976:personal letter to the writer), indicated that, ". . . we at the Don Bosco Technical Institute have been teaching nondestructive testing to students between the ages of fifteen and sixteen for the past twenty years."

Wesley P. Winter, past professor of Nondestructive Testing, Pennsylvania State University (1976:personal letter to the writer), indicated that, ". . . nondestructive testing methods could satisfy one or more of the present needs of industry." He indicated a concern for the fact that the newer methods of teaching industrial education--broad concepts of manufacturing and construction--could easily by-pass nondestructive testing. Professor Winter made the following statement, "I am, in general, in complete sympathy with the hypothesis of the writer. Nondestructive testing could and should be taught at the high school level." He indicated, however, that the inclusion of radiographic testing could present radiation hazards, and the cost of existing equipment is quite expensive.

George L. Pherigo, Chairman of the Educator's Division, The American Society for Nondestructive Testing (1976:personal letter to the writer), sums up the present need for nondestructive test personnel in industry in the following statement, ". . . there is a current need for technically trained personnel in nondestructive testing, and a knowledge

of the basics in high school could be beneficial."

Relative Simplicity and Broad
Encompassing Nature

Kanji Ono, Professor, School of Engineering and Applied Science, University of California, Los Angeles (1976:personal letter to the writer), made the following statement regarding the simplicity of non-destructive testing processes. In his opinion, "the basic principles are simple, but not necessarily their application." This opinion was shared by George L. Pherigo, Chairman of the Educator's Division, The American Society for Nondestructive Testing (1976:personal letter to the writer), in the following statement:

. . . only the liquid penetrant and magnetic particle processes are simple enough to include in the high school program with more than a theoretical approach and only the liquid penetrant and magnetic particle processes can be taught to high school students without involving them in an extensive and intensive amount of technical preparation.

Robert T. Anderson, Technical Director, The American Society for Nondestructive Testing (1976:personal letter to the writer), concurred with the opinions of Pherigo and Ono by making the following statement, ". . . some of the nondestructive testing processes are simple while others are complicated. A good working knowledge of radiography, ultra sonics, and eddy currents require significant training and experience."

Glenn M. Thatcher, Coordinator of Industrial Technology, Kean College of New Jersey (1976:personal letter to the writer), sums up the

evaluation of radiographic testing in relation to its relative simplicity and broad encompassing nature in the following statement:

. . . the nondestructive testing processes suggested by the writer for this study are relatively simple and do have a broad encompassing nature with the exception of radiography and ultra sonics which require both sophisticated equipment and licensing to adequately familiarize students with their principles.

Potential in Satisfying What the
Writer Believes to be a Weakness
of the Present Industrial Education
Program

Based upon an evaluation of the stated goals and objectives of industrial education as set forth by the American Vocational Education Association (1968:9-11) on page 7, the writer believes that industrial education teachers cannot be expected to satisfy the needs of their profession unless they have developed a certain measure of competency in radiographic testing. This competency should include an awareness and knowledge of: (1) the basic theories and principles, (2) the advantages and limitations, (3) the potential safety hazards, if any, and (4) the skills required to satisfactorily perform the radiographic test.

The potential of the radiographic testing process to satisfy these needs is, however, offset by evidence presented by those who were considered to be knowledgeable in the field of nondestructive testing. In their opinion the radiographic method of inspection was not: (1) compatible to existing industrial education programs, or

(2) relatively simple in either theory or application. The radiographic method of inspection required both an extensive and intensive amount of technical preparation.

The Educational Requirements and
Competency Levels Expected
of Inspectors

Since this study is concerned with the development of entry-level competencies in the area of radiographic testing, only those requirements which are essential to the development of this level of competency have been included in this study. Each entry-level inspector is expected to demonstrate, prior to being considered for certification in the field of radiographic testing, that he has acquired (American Society for Nondestructive Testing, 1971:1-10): (1) sufficient education and experience to insure an understanding of the radiographic principles and procedures; (2) instruction in the processing of parts: under no circumstances should he be permitted to inspect parts prior to certification; and (3) sufficient knowledge to pass an examination which includes questions related to the theory of radiographic testing, operating procedures and techniques, and test equipment. Prior to his certification, the entry-level inspector should work at all times under the supervision of a certified inspector. He is directly responsible to this inspector for the proper performance of all radiographic inspections.

It may appear to those who are unfamiliar with the process of radiographic inspection that the requirements are no more stringent than they are for the nondestructive test methods evaluated earlier in this study. Without going into extensive detail, some of the technical preparation required of these inspectors have been listed. Each inspector is expected to have an awareness of:

1. The history of industrial radiography, its principles and theories, the relationship of penetrating radiation, radiography and radiometry, and the general areas in which this method of inspection is applicable.

2. The physical principles of radiography including the nature of particles, wave properties, electromagnetic waves, electrical theory of matter, the fundamentals of radiation physics, and sources of radiation.

If one is expected to apply radiographic methods of inspection, it is the opinion of the writer, that he should understand just what radiation is, how it is formed, how it interacts with matter, and how the images are produced.

Since the radiographic method of inspection did not meet the criteria as set forth in the analysis of data section, procedures for applying the radiographic process in industrial education programs at the high school level have not been included in this study.

SUMMARY

Radiographic testing is a method of nondestructive testing which provides for the internal inspection of a material by a procedure which utilizes x-rays or gamma rays. The results of this test are accomplished by recording the effects of the penetrating radiation on a sensitive film. This method of inspection is considered to be one of the oldest types of nondestructive testing. The early methods of radiographic inspection have undergone continuous improvement and are, today, readily applicable to both the mechanical testing field and the area of quality control.

In 1895, while using a Crooke's tube in the course of his cathode ray studies, Wilhelm Conrad Roentgen discovered that this tube, when energized, gave off a new ray which caused a piece of paper, accidentally covered with platinocyanide crystals, to glow. Further investigation revealed that this invisible radiation penetrated wood, paper, books, the human hand, and certain light metals, but not lead. Roentgen, assuming that this new ray was a form of invisible light, made the first human radiograph of Mrs. Roentgen's hand on a photographic plate. He called this mysterious ray "x" for the unknown quality, and the term x-ray came into being. During the following year, Becquerel discovered that certain uranium bearing ores also emitted a similar, but more penetrating, type of radiation. This led to the discovery of another similar natural radiation emitter: the new

element radium by Madame Currie and her husband. The radiation produced by these natural emissions seemed similar to Roentgen's x-rays, but they also appeared to be more penetrating. The term "gamma rays" was eventually applied to these natural emissions to distinguish them from x-rays.

The first commercial use of industrial radiography was pioneered by Colonel Jenks and Lester in 1922 at the Watertown Arsenal in Massachusetts. The aluminum industry in 1927 began to use this method of testing to insure that only sound materials were being used in the construction of aircraft. Approximately ten years later, the makers of high pressure boilers began to use radiographic testing methods for the inspection of welds. Since then, industrial radiographic techniques have been developed for the inspection of wood, plastic, ceramics, and for quality control inspections using electronic equipment.

Just as a doctor peers inside of the human body with x-rays, radiographic testing processes utilize these rays to inspect materials and products. A radiographic test in its simplest form is the interpretation of a photographic record which has been produced by the passage of x-rays or gamma rays through an object onto a film. When this film is exposed to gamma rays, x-rays, or light, a change is produced in the film emulsion. Although gamma rays are similar to x-rays and show the same similarities to and differences from visible light as do the x-rays, they are distinguished from x-rays by their

source of origin rather than by their nature..

In the radiographic testing process, a beam of gamma rays or x-rays are directed toward the part being tested. Some of this beam is absorbed as the rays pass through the part while some of the rays are scattered. The absorption of this beam depends upon the thickness of the part, its physical density, and its composition. The part of the beam which passes through the part is recorded on a special photographic film for interpretation and evaluation by the inspector. These tests can be applied to organic materials, inorganic materials, solids, liquids, and gases.

Radiographic tests are used to discover the presence and nature of discontinuities located below the surface. The testing process is based upon the ability of x-rays and gamma rays to penetrate metals or other opaque materials, thus producing an image on sensitized film or on a fluorescent screen. The term "x-ray quality" widely used by industry to infer high quality welds, arises from the method of inspection used to guarantee this quality.

Chapter 6

ULTRASONIC TEST

The ultrasonic process of nondestructive testing is a physical test. It finds its main application in the location of subsurface discontinuities. With the ultrasonic method of inspection, it is possible to locate flaws in metal parts which cannot be detected by other nondestructive means and also to determine the actual flaw geometry, size, and position. The need for industrial quality in various materials is increasing, and new applications are being developed for ultrasonic inspection processes.

History of the Ultrasonic Process

The first use of sound in nondestructive testing could have been the result of an accident centuries ago when a man noted that, when tapped, a cracked bowl emitted a different tone than an uncracked one. Many variations of this method have been used in an attempt to ascertain the internal quality of material. The sensitivity and accuracy of these tests are obviously operator sensitive and depend primarily upon the ear of the inspector.

Although certain laboratory experiments in the late Nineteenth Century indicated that sound could be generated with frequency above the human hearing range, it was not until the 1930's that the possibility of using ultrasonic waves for nondestructive testing was recognized. At this time, O. Muhlhauser, A. Trost, and R. Pohlman of Germany and S.

Sokolof of Russia investigated various continuous wave techniques. The inspection methods developed from their studies were a giant step forward, but depended upon a gross flaw obstructing the transmission of sound through the test piece from one transducer to another. This process is now known as the through transmission method. This test process was limited because of the need for access to two opposite surfaces on the test part and the limitations in locating minute defects and determining their locations below the surface (Smith, 1972:1).

Those shortcomings were overcome in the early 1940's when Fred Firestone of the University of Michigan developed an instrument that utilized pulsed ultrasonic wave trains to determine the depth and relative extent of small flaws. Access to only one side was necessary because the system was monitoring reflected energy, not the loss of transmitted energy (Smith, 1972:1).

From that time on, pulse echo ultrasonics has been developed into a reliable and efficient nondestructive testing tool with uses in such widely varying, and many times complex, systems that it is considered by the writer to be out of the scope of this study to discuss many of them.

Description of the Ultrasonic Process

A basic description of the ultrasonic method of testing is provided in Figure 46, page 306 (General Dynamics, 1967:7.5-7.6). The

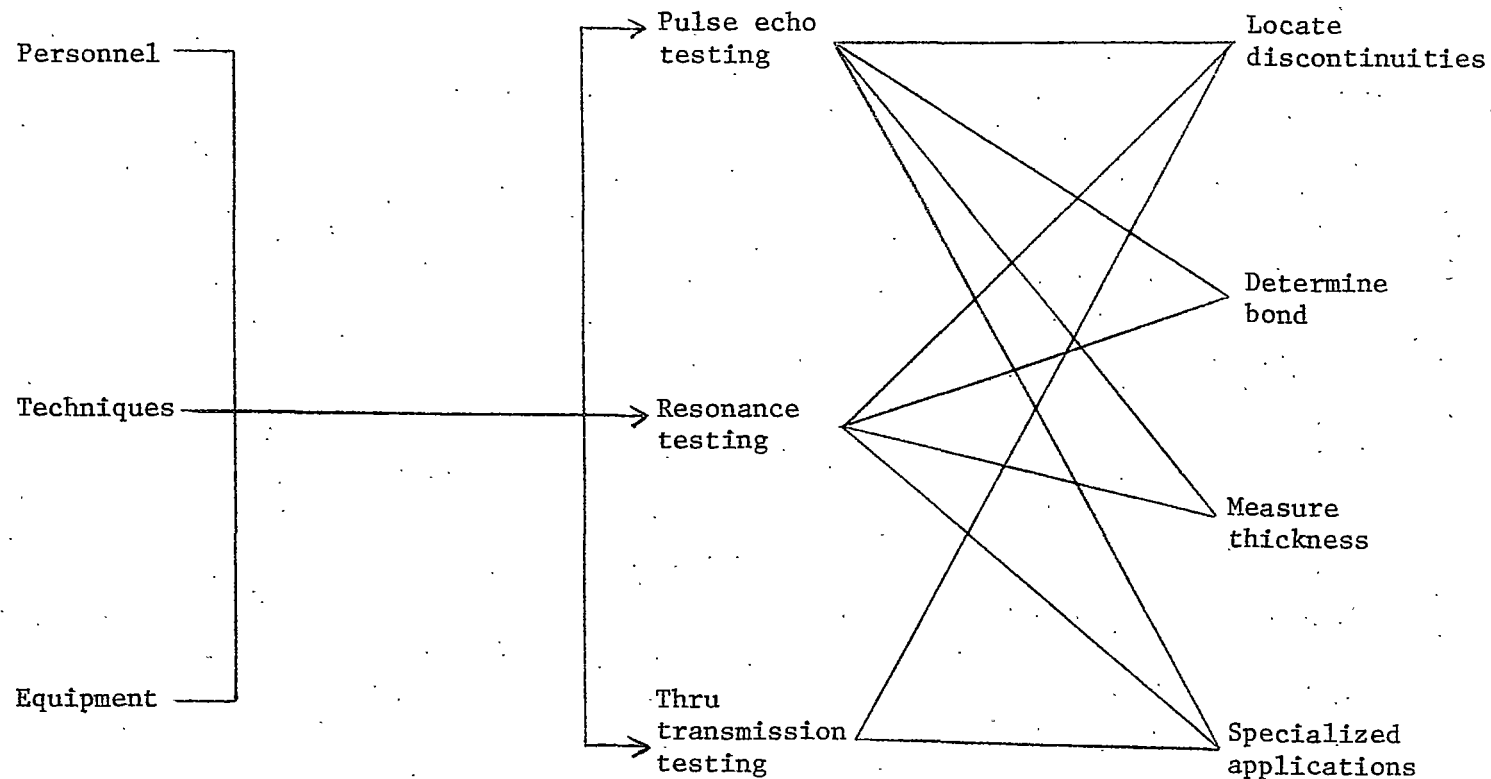


Figure 46
Ultrasonic Testing

equipment required, types of discontinuities located with ultrasonic testing processes, and the advantages and limitations of this method are (Materials Selector, 1970:489):

1. Equipment required: special commercial equipment of either the pulse-echo or transmission type is required, standard reference patterns are required to accurately interpret (RF) or video patterns.

2. Enables the detection of: surface and subsurface flaws, including those which are too small to be detected by other nondestructive tests; it is especially good for the detection of subsurface discontinuities in laminations.

3. Advantages: high test sensitivity, beam direction can be varied, flaw depth can be accurately pin-pointed, there is no limit to casting thickness, flaw thickness is normally not a factor, test equipment is inexpensive, and portable and test results are immediately available.

4. Limitations: As-cast surfaces are sometimes unacceptable to this method of testing, coarse grained castings are difficult to test, the nature of the flaw is not identified, highly skilled inspectors are required, acceptance standards are not available, and permanent records are not normally obtained.

Principles of Ultrasonic Testing

During World War II, submarines were tracked with sonar, sound navigation, and ranging. By accurately measuring the time it took for

sound pulses to go out and come back, sonar instruments were able to indicate how far away a submarine was from the ship. The same thing happens on a smaller scale in ultrasonic testing. Instead of looking for enemy submarines, the ultrasonic inspector attempts to locate discontinuities inside of steel parts, tank walls, welds, and concrete cissions. Inspectors can determine how thick a piece of metal is without seeing the other side of it.

In the ultrasonic testing process, pulses of sound energy are created by electrically exciting a crystal, known as a transducer, which has piezo-electric properties, causing the crystal to vibrate. Sound energy is transmitted into the material being tested through a couplant; this couplant can be water, oil, or glycerine. Sound which returns to the crystal as reflected energy is converted into electrical signals by a transducer. These signals can be shown on an oscilloscope. The time and amplitude relation of these reflected signals can be interpreted to show the location of internal reflecting surfaces in three-dimensions for accurate location (Materials Selector, 1970:490).

Ultrasonic testing equipment generates ultrasonic pulses which are converted into a beam of ultrasonic waves by a transducer which is a combination microphone and loud-speaker. The waves travel through the part being tested and discontinuities and the opposite side of the part reflect these pulses back to the transducer where they can be interpreted and evaluated by the inspector. The amount of time it takes

between the starting pulse and the reflection is indicated on a cathode-ray tube. The picture on this tube looks like a line with "spikes" on it. The distance between these spikes and their relative height accurately pinpoints the discontinuity and indicates how bad it is. Using the ultrasonic method of inspection, discontinuities as far as thirty feet below the surface can be located (Rolfe, n.d.:2).

Purpose of Ultrasonic Tests

Ultrasonic testing processes are used for the nondestructive detection of discontinuities within materials. The ultrasonic test equipment requires access to only one surface of the material being inspected and can be used successfully with either straight or angle-beam testing techniques.

The test instrument electronically generates ultrasonic vibrations and sends them in a pulsed beam through the part being tested. Any discontinuity within the part, or the opposite end, will reflect the vibration back to the test instrument which measures the elapsed time between the initial pulse and the return of all reflections, and indicates such time lapse on a cathode-ray indicator. In the testing process, the searching unit is caused to vibrate while sending out an initial pulse, then stops until the pulse reaches the other end of the piece or a discontinuity and is reflected back. The return signal is amplified and appears as a pip or mark on the cathode-ray tube. This return pulse is timed so that it appears on the tube in the same

relation to the front and back pulse as the discontinuity is to the front and back of the part being tested.

The differences between ultrasonic testing processes and other nondestructive testing processes, such as liquid penetrants and magnetic particles, are obvious because the latter two are sensitive to surface or very shallow subsurface discontinuities only. While ultrasonics can be tailored to detect the same type of discontinuities, it is primarily used for the inspection of the area beyond the successful depth of penetration of magnetic particle inspections.

EVALUATION OF THE ULTRASONIC TEST

The ultrasonic inspection process was evaluated by the writer to determine whether or not it met the five criteria set forth in the analysis of data section. The ultrasonic inspection process did not meet four of the five criteria in the following ways.

Compatibility to Existing Industrial Education Programs

The statement by Ostrofsky (1965:9) that ". . . at the present time ultrasonic testing processes require highly trained and experienced inspectors" is reinforced by the following statement by Betz, Nondestructive Test Consultant, and past vice-president to Magnaflux Corporation (1974:personal letter to the writer), stating that:

One must not lose sight of the fact that the principles underlying many of the nondestructive testing processes are very

sophisticated, and for their full understanding require a wide familiarity with many phenomena of physics. I do not believe that attempt to teach such methods as ultrasonics or radiography would be very fruitful. On the other hand, this is not equally true of the magnetic particle or liquid penetrant testing processes since these processes require very little theory for their complete understanding. Their concepts can be easily taught without going very far into their theory.

The beliefs of Ostrofsky and Betz are summed up in the following statement in Materials Selector (1970:489); which indicated to the writer the definite limitations of ultrasonic testing, ". . . the ultrasonic testing method of inspection requires highly skilled inspectors."

Ability to Satisfy One or More
of the Present Needs of Industry

John B. Rasor, Department Chairman, Don Bosco Technical Institute (1976:personal letter to the writer), made the following statement regarding the ability of ultrasonic testing, ". . . although the processes of ultrasonics and radiographic testing require the most technical preparation, they do have the ability to satisfy one or more of the needs of industry." Rasor's concern regarding the amount of preparation required for ultrasonic testing processes is reinforced by the following statement by Kanji Ono, School of Applied Engineering Professor, University of California, Los Angeles (1976:personal letter to the writer). Ono indicated that, ". . . not much depth appears to be possible in the teaching of ultrasonics at the high school level."

The opinion of the writer concerning the ability of ultrasonic

testing processes to satisfy one or more of the needs of industry is reinforced by the statements made by Wesley P. Winter, past professor of Nondestructive Testing, Pennsylvania State University (1976:personal letter to the writer) and Joseph L. Rose, Mechanical Engineering Department, Drexel University (1976:personal letter to the writer). They stated that, ". . . the nondestructive testing processes suggested by the writer for this study do have the potential to satisfy one or more of the present needs of industry."

Glenn B. Thatcher, Coordinator of Industrial Technology, Kean College of New Jersey (1976:personal letter to the writer), in the following statement, "Yes, people familiar with and trained in nondestructive testing techniques are greatly desired by industry at the present time."

Relative Simplicity and Broad
Encompassing Nature

An evaluation of the ultrasonic testing process in Materials Selector (1970:489) indicated the following limitation: highly skilled inspectors are required for the ultrasonic method of inspection.

Robert T. Anderson, Technical Director, American Society for Nondestructive Testing (1976:personal letter to the writer), concurred with the statement in Materials Selector in the following statement, ". . . in ultrasonic testing, students must be fundamentally founded in the principles of acoustics or the propagation of sound." J. E. Hinkel,

Application Engineering, The Lincoln Electric Company (1976:personal letter to the writer), made the following statement concerning the relative simplicity of ultrasonic testing processes. He stated that ". . . the ultrasonic method of inspection is not simple." Glenn M. Thatcher, Coordinator of Industrial Technology, Kean College of New Jersey (1976:personal letter to the writer), points out that, ". . . sophisticated equipment is required for ultrasonic testing and radiographic testing processes, and that licensing is necessary to adequately familiarize students with their principles."

Joseph L. Rose, Mechanical Engineering Department, Drexel University (1976:personal letter to the writer), sums up the need for both intensive and extensive technical preparation for those interested in becoming an inspector in the area of ultrasonic testing in the following statement, ". . . ultrasonic theory is not simple. Very few people understand wave propagation theory and inspectors using ultrasonic testing either don't know why it works or thinks he knows why, but he probably doesn't."

Potential in Satisfying What the
Writer Believes to be a Weakness
of the Present Industrial
Education Program

Based upon an evaluation of the stated goals and objectives of industrial education as set forth by the American Vocational Education Association (1968:9-11) on page 7, the writer believes that industrial

education teachers cannot be expected to satisfy the needs of their profession unless they have developed a certain measure of competency in ultrasonic testing. This competency should include an awareness and knowledge of: (1) the basic theories and principles, (2) the advantages and limitations, (3) the potential safety hazards, if any, and (4) the skills required to satisfactorily perform the ultrasonic test.

The potential of the ultrasonic testing process to satisfy these needs is, however, offset by the evidence presented by those who were considered knowledgeable in the field of nondestructive testing. In their opinion, the ultrasonic method of inspection was not: (1) compatible to existing industrial education programs, or (2) relatively simple in either theory or application. The ultrasonic method of inspection required both an extensive and intensive amount of technical preparation.

The Educational Requirements and Competency Levels Expected of Inspectors

Since this study is primarily concerned with the development of entry-level competencies in the area of ultrasonic testing, only those requirements which are essential to the development of this level of competency have been included in this study. Each entry-level inspector is expected to demonstrate, prior to being considered for certification in the field of ultrasonic testing, that he has acquired (American

Society for Nondestructive Testing, 1971, Supplement (C):1-9):

(1) sufficient education and experience to insure an understanding of the ultrasonic principles and procedures; (2) instruction in the processing of parts: under no circumstances should he be permitted to inspect parts prior to certification; and (3) sufficient knowledge to pass an examination which includes questions related to the theory of ultrasonic testing, operating procedures and techniques, and test equipment. Prior to his certification, the entry-level inspector should work at all times under the supervision of a certified inspector. He is directly responsible to this inspector for the proper performance of all ultrasonic inspections.

It may appear to those who are unfamiliar with the process of ultrasonic testing that the requirements are no more stringent than they are for the nondestructive methods evaluated earlier in this study. Without going into extensive detail, some of the technical preparation required of these inspectors have been listed. Each inspector is expected to have an awareness of:

1. The fundamental properties of sound, including frequency, velocity, and wave length; the definition of ultrasonic vibrations and its general applications.
2. The principles of wave propagation and the generation of ultrasonic waves.
3. Ultrasonic testing methods including: contact testing,

immersion testing, and modified immersion testing.

4. Ultrasonic testing equipment including: a description of basic pulse-echo instruments, special test instruments, and scanning equipment.

If one is expected to apply the ultrasonic methods of inspection, it is the opinion of the writer that he should understand how test parameters are selected, tests are standardized, test results are interpreted, and the variables of the ultrasonic testing processes.

Since the ultrasonic method of inspection did not meet the criteria as set forth in the analysis of data section, procedures for applying the ultrasonic process in industrial education programs at the high school level have not been included in this study.

SUMMARY

The ultrasonic method of nondestructive testing is a physical test. It finds its main application in the location of subsurface discontinuities. It is possible, with the ultrasonic method of inspection, to locate flaws in metal parts which cannot be detected with other nondestructive means. It is also possible to determine the actual flaw geometry, size, and position. The need for industrial quality in various materials is growing and new applications are being developed for the ultrasonic inspection processes.

The first use of sound in nondestructive testing could have

been the result of an accident centuries ago, when a man noted that a cracked bowl emitted a different tone than an uncracked one. Many variations of this method of inspection have been used in an attempt to ascertain the internal qualities of materials. The sensitivity and accuracy of these tests are operator sensitive and depend primarily upon the ear of the inspector.

Although certain laboratory experiments in the latter part of the Nineteenth Century indicated that sound could be generated with frequency above the human hearing range, it was not until the 1930's that the possibility of using ultrasonic waves for nondestructive testing was recognized. At this time, O. Muhlhauser, A. Trost, and R. Pohlman of Germany and S. Sokolof of Russia investigated various continuous wave techniques. The inspection methods developed from their studies were considered a giant step forward, but depended upon a gross flow obstructing the transmission of sound through the test piece from one transducer to another. This process is now known as the "through transmission" method. This particular process was limited, because of the need for access to both sides of the test part and the limitations in locating minute defects and determining their exact location below the surface.

These shortcomings were overcome in the early 1940's when Fred Firestone of the University of Michigan developed an instrument which utilized pulsed ultrasonic wave trains to determine the depth and

relative extent of small flaws. Access to only one side of the part was necessary, since this system of testing was monitoring reflected energy, not the loss of transmitted energy.

Submarines were tracked during World War II with sonar, sound navigation and ranging. By accurately measuring the time it took for these sound pulses to go out and to come back, sonar instruments were able to indicate how far away a submarine was from the ship. The same thing happens on a smaller scale in ultrasonic testing. The ultrasonic inspector, instead of looking for a submarine, attempts to locate discontinuities inside of steel parts, tank walls, welds, and concrete ciissions. Inspectors can now determine how thick a piece of metal is without seeing the other side of it.

Pulses of sound in the ultrasonic testing process are created by electrically exciting a crystal, known as a transducer, which has piezo-electric properties thus causing the crystal to vibrate. Sound energy is transmitted into the material being tested through a couplant; this couplant can be water, oil, or glycerine. Sound which returns to the crystal as reflected energy is converted into electrical signals by a transducer. These signals can be shown on an oscilloscope. The time and amplitude relation of these reflected signals can be interpreted to show the location of internal reflecting surfaces in three dimensions for accurate location.

Ultrasonic test equipment generates ultrasonic pulses, which

are converted into a beam of ultrasonic waves by a transducer which is a combination microphone and loud-speaker. These waves travel through the part being tested and discontinuities on the other side of the part reflect these pulses back to the transducer where they can be interpreted and evaluated by the inspector. The amount of time it takes between the starting pulse and the reflection is indicated on a cathode-ray tube. The picture on this cathode-ray tube looks like a line with "spikes" on it. The distance between these spikes and their relative height accurately pinpoints the discontinuity and indicates the extent of the discontinuity. Discontinuities as far as thirty feet below the surface can be located with the ultrasonic method of inspection.

In the testing process, the searching unit is caused to vibrate while sending out an initial pulse, then stops until the pulse reaches the other end of the piece or detects a discontinuity and is reflected back. This return signal is amplified and appears as a pip or mark on the cathode-ray tube. The return pulse is timed so that it appears back on the tube in the same relation to the front and back pulse as the discontinuity is to the front and back of the part being tested.

The differences between ultrasonic testing and other methods of nondestructive testing, such as liquid penetrant and magnetic particle testing, are obvious since the latter are sensitive only to surface or very shallow subsurface discontinuities. Although the ultrasonic method of inspection can be tailored to detect surface discontinuities,

it is used primarily to detect discontinuities beyond the successful depth of penetration of either the liquid penetrant or the magnetic particle method.

Chapter 7

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

The term nondestructive testing as it is used in this study is a general term given to all methods of testing which permit the inspection and evaluation of a metal without impairing its future usefulness in any way, shape, or form.

With all of our advanced technology and all of the devices industry has developed for quality control, our nation is still unable to produce materials which possess the high degree from imperfection that our highly complicated machines and demanding services require. The acceptance of nondestructive testing by industry is practically universal today, and experience with these methods is now so extensive that complete confidence exists in these testing processes and in the ability of competent inspectors to interpret the results.

Statements by Betz, Goin, Stern, and Tyler indicated a growing awareness on the part of industry and education--an awareness of the need to include nondestructive testing methods as an integral part of the industrial education program at the secondary level. In their opinion, it is the responsibility of the schools to initiate methods of instruction and to provide the means for the practical application of these methods of testing.

Numerous volumes have been written on the subject of nondestructive testing, but it is the opinion of the writer that large amounts of this data was not available in a form easily understood by industrial education teachers.

The problem of this study was twofold: (1) to evaluate the five major methods of nondestructive testing according to the criteria set by the writer for inclusion in the industrial education program; and (2) to describe procedures for applying those testing processes found acceptable to the industrial education program in a form more easily understood by teachers. Once the data had been collected and organized, each of the testing processes was evaluated in terms of five criteria:

1. Compatibility to existing industrial education programs
2. Ability to satisfy one or more of the present needs of industry
3. Relative simplicity of the test and its broad encompassing nature
4. Potential in satisfying what the writer believes to be a weakness of the present industrial education program: the exclusion of nondestructive testing methods from the industrial education program
5. The educational requirements and competency levels expected of entry-level inspectors

An indepth description for applying these tests in the

industrial education program was included only when a test satisfactorily met the five criteria set by the writer. The premise of the writer was that once suitable guidelines had been developed, industrial education teachers would be encouraged by the availability of these guidelines to include these testing processes in their program.

No attempt was made by the writer to provide the reader with data pertinent to the development of test equipment or materials. Emphasis was placed on the description of "need to know" data in a form more easily understood by industrial education teachers.

Liquid Penetrant Test

The forerunner of the present day liquid penetrant inspection process was the oil and whiting method which was used by the railroad industry in the Nineteenth Century for the maintenance of steam locomotives. Parts to be inspected were dipped in a diluted solution of lubricating oil, dried, and then coated with a mixture of chalk and denatured alcohol. This mixture dried rapidly leaving a dead-white coating on the surface of the part. The oil entrapped in the discontinuity would seep out leaving a dark stain as an indication of a possible defect.

The liquid penetrant process is used by industry to locate discontinuities which are open to the surface in solid and essentially nonporous materials. There is no limitation to the size or shape of the part, the process is applicable to magnetic and nonmagnetic materials,

discontinuities which cannot be seen with the unaided eye become visible, and the testing process is relatively low in cost.

The liquid penetrant process depends for its success upon the principle that a penetrating liquid entering a surface opening and remaining in that opening will be made visible when the proper developer is applied. In basic principle, the liquid penetrant process is simple. Its effectiveness is based upon the natural phenomenon of capillary action, one of the most powerful forces in nature. The penetrant does not seep into a discontinuity, it is literally pulled into the discontinuity by capillary action. When the correct developer is applied, it acts like a blotter drawing the penetrant remaining in a discontinuity to the surface.

Liquid penetrant tests are used by industry with three different philosophical points of view, each of which has a different principal purpose. These points of view are: (1) to locate flaws before the finished product goes to the consumer, (2) to reduce production costs by applying these tests at various stages of production thus permitting the removal of defective parts before additional production costs are incurred, and (3) to tabulate and analyze data resulting from these tests for the purpose of improving future products. All of these concepts are considered to be an integral part of the production process and each is equally responsible for decreasing the cost of the part and increasing its service life.

The types of liquid penetrants commercially available can be divided into two categories: dye penetrants and fluorescent penetrants. In the case of the dye penetrants, a special dye is selected which provides a high degree of contrast between the penetrant and the developer. When the fluorescent penetrants are used, the materials added require excitation by ultra violet radiation and observation under subdued light.

Usually, no special equipment is required to perform the liquid penetrant tests when there are only a few parts to be tested, maximum sensitivity is not required, the part is too large to remove or place in the test equipment, or the proper test equipment is not available. Color contrast penetrants and fluorescent penetrants can be applied by hand, the excess penetrant can be removed by hand cleaning, and the developer applied by hand. The only item of special equipment required is the ultra violet light for the fluorescent process.

On the other hand, when there are a large number of parts to be inspected on a production line, a high degree of sensitivity is required, large parts are to be inspected regularly, or consistent repetitive results are required as they are in production testing, certain industrial equipment is considered essential. Included in this category are: (1) precleaning and penetrating stations, (2) solvent remover and washing stations, and (3) drying and rinsing stations. Automated testing units are now available which have been

designed to use prepunched computer cards which automatically program the various aspects of the liquid penetrant process.

Although many inspection problems can be solved using one or more of the penetrant test methods available, one testing process may be preferable for a specific material. When a choice exists, the selection of the testing method may be just as important as the procedures used in the testing process. The penetrant inspection method is usually selected on the basis of its ability to locate open and shallow discontinuities, its sensitivity to very fine discontinuities, and its relative brightness. Other criteria by which a method is selected are primarily economic.

Since there are other methods of inspection classified as nondestructive which are capable of locating discontinuities in non-magnetic materials, a quick comparison should provide continuity in the analysis of these inspection processes. This comparison indicated that the penetrant process:

1. Is more flexible than the eddy current method and is not restricted by part geometry or size. Eddy currents are considerably faster on bars and tubing for certain classes of defects, but they cannot locate as wide a variety of discontinuities with regard to width, depth, or direction.
2. Yields to the method above in the detection of internal defects. In this respect, the penetrant method also yields to the

magnetic particle method (on parts which can be magnetized) but are practically the equal of the latter in all applications where the suspected discontinuity is open to the surface and is not filled with some type of blocking contamination.

3. Excels eddy currents and magnetic particles in the location of fine, short, or shallow discontinuities which are open to the surface. The liquid penetrant method is the most effective method available for the detection of fatigue cracks in nonmagnetic materials. The magnetic particle method is, however, its equal in this respect when the discontinuity has become filled with a foreign substance.

Fatigue cracks almost invariably begin at the surface of parts which have been subjected to high stresses in service and spread through the cross section until a complete failure of the part occurs. When these defects are discovered in their early stages, they can be prevented and the part saved. Because of its special ability in locating surface discontinuities, the penetrant inspection method is considered superior to all other methods, in most instances, for the upkeep and maintenance of all types of machinery.

The liquid penetrant method of inspection was evaluated by the writer to determine whether or not it met the five criteria set forth in the analysis of data section of this study. Since this evaluation could best be accomplished by those with expertise in the field of liquid penetrants, letters were written to those who had published

books or articles, those who were currently employed in nondestructive testing positions in industry, and others who were considered knowledgeable in the field of liquid penetrants. They were requested by the writer to evaluate the liquid penetrant process in terms of the five criteria selected for this study. Their statements indicated to the writer that the liquid penetrant method could be taught successfully in the industrial education program at the high school level.

Magnetic Particle Test

Magnetic particle inspection processes can be used to determine the physical soundness and other characteristics of a metal without impairing its future usefulness in any way, shape, or form. The results of these tests have helped to make possible the manufacture of lighter and stronger materials and equipment, and the use of these materials and equipment with a high degree of safety to the consumer.

In the years prior to 1920, the term nondestructive testing had not yet acquired a meaning or found a place in the language of industry. There were many methods of testing, but magnetic particle testing was not one of them. In fact, none of the nondestructive testing methods which are considered essential to industry were even under consideration.

Two developments in the days following World War I marked the birth of modern nondestructive testing methods. These developments were: (1) research at the United States Bureau of Standards and General Electric Corporation indicated that X-rays could be used to make

pictures of metallic articles thus revealing their internal conditions; and (2) William E. Hoke made the discovery that magnetic fields could be used to locate discontinuities in ferromagnetic metals. In 1928 and 1929, A. V. deForest completed the work which actually resulted in the magnetic particle methods as we now know them. These initial contributions provided the impetus for the development of a practical and useful testing process.

The magnetic particle inspection process can be used to locate surface and subsurface discontinuities in ferromagnetic materials. Essentially, there are three basic steps in the application of this method of inspection. They are: (1) establishment of a magnetic field of suitable strength and direction; (2) application of the magnetic particles in such a way that they are free to move over the surface of the part, collecting at leakage fields which occur as the result of a discontinuity; and (3) inspecting and evaluating these indications in terms of part acceptance or rejection.

The magnetic particle process depends for its success upon the fact that ferromagnetic materials, once they have been magnetized, cause a strong leakage field to be formed at the surface when a discontinuity is present. This leakage field provides a means for locating discontinuities which lie in a direction transverse to the direction of the magnetic field. The presence of this field and, therefore, the presence of a possible defect is accurately located by the application

of finely divided ferromagnetic particles over the surface of the part. This magnetically held collection of particles forms an outline of the discontinuity and reliably indicates its exact location, shape, size, and extent.

Magnetic particle inspections are used to detect discontinuities in ferromagnetic materials which could constitute a defect, thus necessitating repair of the part or rejection of the part. The inspector is able to locate discontinuities on the surface which are too fine to be seen with the unaided eye or those which are located beneath the surface. It should be clearly understood, however, that the primary purpose of the magnetic particle test is the detection of discontinuities. It is not the purpose of these tests to determine whether or not such discontinuities constitute harmful defects. How harmful a defect is to the service life of a component should be determined by those who know the service requirements of the part.

Commercial test equipment, both portable and stationary, are readily available for nearly every inspection situation where this method is applicable. Stationary equipment providing direct current for either the wet continuous or the residual, circular, or longitudinal magnetization, rectified alternating or direct current, electrically movable contact heads and safety devices satisfy the needs of industry in the shop, while portable equipment using contact prods for circular magnetization or cables in the form of looped-coils for

longitudinal magnetization are used for field applications. The magnetic particles used in these processes are in all cases finely divided ferromagnetic materials. Before a specific material is selected for the test, careful consideration should be given to particle size, shape, density, contrast, and mobility since all of these factors affect the final test results. The basic choice in the selection of magnetic particles is between those used in the wet process and those used in the dry process, and secondarily between the various colors available, including fluorescent particles.

The magnetic particle process has the following characteristics when it is compared to the liquid penetrant and eddy current processes.

1. When magnetic particles are compared to liquid penetrants, the liquid penetrants are their equal for the location of surface discontinuities, provided the discontinuities are not already filled with a foreign substance. Because of this factor and the knowledge that the penetrant method is slower, the magnetic particle method of inspection is preferable on magnetic materials for the location of surface discontinuities. Penetrants are unsuitable for locating discontinuities below the surface, but magnetic particles can do a remarkably good job under favorable circumstances and controlled conditions.

2. When magnetic particles are compared to eddy currents, it was found that eddy currents were better adapted to the detection of

discontinuities in nonmagnetic materials. Eddy current testing, when it is used in conjunction with magnetic saturating bias fields, are sometimes better for the location of subsurface discontinuities.

However, eddy currents are more limited in the depth they can penetrate effectively. Eddy current usually indicate only those discontinuities lying close to the surface. Magnetic particle tests are less hampered by part size and shape.

Since the magnetic particles process excels all others in the location of very shallow discontinuities in ferromagnetic materials, it is considered the best method to use in the detection of fatigue cracks. The magnetic particle process is preferable to eddy currents and liquid penetrants in the overhaul and maintenance of machinery because of its tremendous ability to locate very fine surface discontinuities.

Advancements in the art of magnetic particle testing have enabled it to provide the means for the critical inspection performance demanded by industry. To those who encounter these techniques for the first time, they may appear deceptively simple, but the magnetic particle inspection processes must be applied with care and within carefully set guidelines which have been carefully defined and developed through experience. Even in the case of electronic methods, where the equipment has been precalibrated and set to provide for the automatic rejection of unsatisfactory parts, setting these limits involves human judgment. Broad knowledge and experience on the part of the inspector is essential

for the proper interpretation and evaluation of magnetic particle tests.

The magnetic particle method of inspection was evaluated by the writer to determine whether or not it met the five criteria set forth in the analysis of data section of this study. Since this evaluation could best be accomplished by those with expertise in the field of magnetic particles, letters were written to those who had published books or articles, those who were employed in nondestructive testing positions in industry, and others who were considered to be knowledgeable in the field of magnetic particles. They were requested by the writer to evaluate the magnetic particle process in terms of the five criteria selected for this study. Their statements indicated to the writer that the magnetic particle method could be taught successfully in the industrial education program at the high school level.

Eddy Current Test

Electromagnetic inspection processes are generally referred to as eddy current testing, because the basic principles behind such inspections are derived from the eddy current phenomenon. When a mass of conducting material is moved in a magnetic field or is subject to a changing magnetic flux, eddy currents circulate within this mass. These eddy currents are closed loops of induced current circulating in planes perpendicular to the magnetic field.

The use of eddy currents as a practical method of nondestructive testing was not used extensively until the end of World War II. Most of the theoretical basis for the use of eddy current testing was formulated by Freidrich Foerster, in Germany, during the period 1930-1950. In addition to his theoretical work, Foerster also helped to develop an extensive group of instruments for the performance of various nondestructive tests. It was the introduction of these instruments outside of Germany in the early 1950's which helped to make eddy current testing significant in modern industrial processes. Today, eddy current testing equipment is compatible with most industrial specifications, and these testing processes are often integrated into the manufacturing process to provide a completely automated inspection of parts as they are being cast, formed, or machined.

The eddy current testing process may be defined as a method of nondestructive testing which requires the part being tested to be subjected to an alternating electromagnetic field. This process can be compared with a person rowing a boat. As he dips the oars, little whirlpools (eddies) are formed in the water. When these whirlpools hit something floating in the water, their shape changes. Similarly, a coil carrying alternating current can induce a circulating electrical current within a mass of metal. This electrical whirlpool is known as an eddy current. Its basic characteristics change according to the type of metal being tested, the ability of the metal to conduct

electrical current, and other factors directly related to the material being tested.

In the field of eddy current testing, the word "flaw" has a much wider meaning than it does in other forms of nondestructive testing, since the eddy current process is applicable to more than the detection of discontinuities. Eddy current applications fall into three basic categories. They are: (1) detecting flaws in parts; this includes the detection of cracks, voids, inclusions, laps, and seams; (2) sorting of parts according to their alloy, conductivity, temper, or other metallurgical conditions; and (3) gauging parts according to their size, shape, plating thickness, or insulation thickness.

The detection of discontinuities, however, has been one of the principle areas of application for the eddy current method, and it is in this area that the eddy current method of inspection has replaced such methods as the visual and magnetic particle methods of inspection.

In the eddy current testing process, a coil is used to induce eddy currents in the part being tested. The electrical characteristics of the coil are affected by any discontinuity or defect. It is the careful measurement of coil changes which make the eddy current method of inspection unique among other nondestructive test methods in the determination of part composition or the accurate identification of materials in addition to locating discontinuities.

There are many factors which contribute to the widespread use

of eddy currents. Some of these factors are: (1) when eddy currents are properly applied, they can be used to measure such diverse conditions as heat treatment, electrical conductivity, coating thickness, part dimensions, and hardness; (2) they can be applied to a wide range of products and fabricating methods such as rolled sheet stock, drawn wire and tubing, welded pipes, and castings; (3) this method of inspection is excellent when it is used for the rapid detection of flaws, cracks and seams, or for the sorting of mixed items; and (4) they are most effective on thin-walled and relatively small items which must be tested in large quantities.

A variety of test probes, frequencies, and test instruments are commercially available. Generally speaking, the term "test probe" refers to an electromagnetic transducer which is placed on the surface of a test object while the term "test coil" is used to designate a transducer which encircles the test object. In any case, the test equipment used in the eddy current testing process should include the following elements: (1) an oscillator, (2) a method of detecting impedance changes in the coil, and (3) a method of displaying the test results.

While there are many different types of test frequencies, coils, and probes available, there are two basic types. They are: (1) a dual differential test instrument which has two identical test probes which are electrically opposed, and (2) an absolute type of test

instrument. The number of test probes associated with an instrument is indicative of its type. A dual differential instrument has two identical test probes which are electrically opposed. Metallurgical differences within a sample or between samples are detected and displayed by this type of instrument. An absolute instrument, on the other hand, has only one test coil or probe associated with it. In this situation, the metallurgical or geometrical differences between test objects, or the presence of a flaw or defect, changes the properties and thereby produces an indication on the test instruments display system.

Most of the eddy current testing systems perform six internal functions. They are: (1) excitation, (2) modulation, (3) signal preparation, (4) signal demodulation and analysis, (5) signal display, and (6) test object handling.

The eddy current data signals obtained from the test coils are usually displayed in one of four ways. The simplest of these is a simple display which provides a numerical indication of the differences between the part being tested and a part of known quality. The other three are basic oscilloscope displays which include the line trace, the ellipse, and the flying spot. The former provides a numerical indication which can be calibrated to indicate the depth of a defect, while the latter provides the data necessary to separate test variables or to analyze properties of the test object.

The eddy current process has the following characteristics when it is compared to the magnetic particle and ultrasonic processes.

1. Eddy currents are subject to limitations similar to ultrasonics for the location of surface cracks, since a finite depth is required to unbalance the impedance bridge and secure reliable indications.
2. Eddy current methods, in general, are better adapted to the testing of nonmagnetic than magnetic materials.
3. Eddy currents used in conjunction with magnetic saturating bias fields are sometimes better for the location of below the surface discontinuities than magnetic particles, but they are more limited in the depth they can penetrate.
4. Eddy current tests can usually indicate only discontinuities lying close to the surface.

Today, electromagnetic testing has developed to the point where it can provide inexpensive, high speed nondestructive testing with the accuracy and stability required by industry. Eddy current testing processes have helped to speed up testing, and in some cases has provided 100 per cent inspection where only a destructive sampling was previously possible. The excellence of this method of testing is evidenced in the inspection of space vehicles where thousands of feet of small diameter tubing, thin sheet metal, and numerous other items with high safety requirements. In this situation, the safety of flight

personnel requires complete reliability in each and every component.

The eddy current method of inspection was evaluated by the writer to determine whether or not it met the five criteria set forth in the analysis of data section of this study. Since this evaluation could best be accomplished by those with expertise in the field of eddy current testing, letters were written to those who had published books or articles, those who were employed in nondestructive testing positions in industry, and others who were considered to be knowledgeable in the field of eddy current testing. They were requested by the writer to evaluate the eddy current process in terms of the five criteria selected for this study. Their statements indicated to the writer that the eddy current testing process could be taught successfully in the industrial education program at the high school level.

Radiographic Test

Radiographic testing is a method of nondestructive testing which provides for the internal inspection of a material by a procedure which utilizes X-rays or gamma rays. The results of this test are accomplished by recording the effects of the penetrating radiation on a sensitive film. This method of inspection is considered to be one of the oldest types of nondestructive testing. The early methods of radiographic inspection have undergone continuous improvement, and today these methods of inspection are readily applicable to both the mechanical testing field and the area of quality control.

In 1895, while using a Crooke's tube in the course of his cathode ray studies, Wilhelm Conrad Roentgen discovered that this tube, when energized, gave off a new ray which caused a piece of paper, accidentally covered with platinocyanide crystals, to glow. Further investigation revealed that this invisible radiation penetrated paper, wood, books, the human hand, and certain light metals, but not lead. Roentgen, assuming that this new ray was a form of invisible light, made the first human radiograph of Mrs. Roentgen's hand on a photographic plate. He called this mysterious ray "x" for the unknown quality, and the term X-ray came into being. During the following year, 1896, Becquerel discovered that certain uranium bearing ores also emitted a similar, but more penetrating, type of radiation. This led to the discovery of another similar natural radiation emitter: the new element radium by Madame Currie and her husband. The radiation produced by these natural emissions seemed similar to Roentgen's X-rays, but they also appeared to be more penetrating. The term "gamma rays" was eventually applied to these natural emissions to distinguish them from X-rays.

It was not until 1922 that the first commercial use of industrial radiography was pioneered by Jenks and Lester at the Watertown Arsenal in Massachusetts. In 1927, the aluminum industry began to use radiographic testing processes to insure that only sound materials were being used in the construction of aircraft. About ten years later, the

makers of high pressure boilers began to use radiographic testing methods for the inspection of welds. Since then, industrial radiographic techniques have been developed for the inspection of woods, plastics, ceramics, and for quality control inspections using electronic equipment.

Just as the doctor peers inside of the human body with X-rays, radiographic testing processes utilize these same X-rays to inspect materials and products. A radiographic test in its simplest form is the interpretation of a photographic record which has been produced by the passage of X-rays or gamma rays through an object onto a film. When this film is exposed to these gamma rays, X-rays, or light, a change is produced in the film emulsion. Although gamma rays are similar to X-rays and show the same similarities to and differences from visible light as do the X-rays, they are distinguished from X-rays by their source of origin rather than by their nature.

In the radiographic test, a beam of gamma rays or X-rays are directed toward the part being tested. Some of this beam is absorbed as the ray passes through the part, while some of the ray is scattered. The absorption of this beam depends upon the thickness of the part, its physical density, and its composition. The part of the beam which passes through the part is recorded on a special photographic film for interpretation and evaluation by the inspector. These tests can be applied to organic materials, inorganic materials, solids, liquids, and

even gases.

Radiographic tests are used to discover the presence and nature of discontinuities located below the surface. This testing process is based upon the ability of X-rays and gamma rays to penetrate metals or other opaque materials, thus producing an image on sensitized film or on a fluorescent screen. The term "X-ray quality" widely used by industry to infer high quality welds, arises from the method of inspection used to guarantee this quality.

When the radiographic inspection process is compared to the magnetic particle process, the radiographic process is:

1. Superior to the magnetic particle testing process in most cases for the location of discontinuities which lie wholly below the surface.
2. Not nearly so effective, however, for the location of surface cracks, in which magnetic particle tests excel all other methods, on magnetic materials.
3. Slower and more expensive to apply than the magnetic particle process, especially when 100 per cent inspection of large quantities of parts is required, and the results are immediate.
4. The magnetic particle inspection method is less hampered by the shape of the part than is the radiographic method.

The ultimate purpose of radiographic testing is to provide visual information upon which judgments can be based concerning the

disposition of the part. It should be remembered that the radiography inspection process, as effective as it is, does not guarantee that all discontinuities will show up as indications on the radiograph nor does the level of acceptable discontinuity assure the servicibility of the part. It is always considered prudent in the field of nondestructive testing to confirm the presence or absence of flaws, particularly in critical parts, by another test method, if possible. Therefore, the radiography test or any other nondestructive testing process should be used to supplement or compliment another method or methods.

The radiographic method of inspection was evaluated by the writer to determine whether or not it met the five criteria set forth in the analysis of data section of this study. Since this evaluation could best be accomplished by those with expertise in the field of radiography, letters were written to those who had published books or articles, those who were currently employed in nondestructive testing positions in industry, and others who were considered knowledgeable in the field of radiography. They were requested by the writer to evaluate the radiographic inspection method in terms of the five criteria selected for this study. Their statements indicated to the writer that the radiographic inspection method could not be taught successfully in the industrial education program at the high school level.

Ultrasonic Test

The ultrasonic method of nondestructive testing is a physical test. It finds its main application in the location of subsurface discontinuities. With the ultrasonic method of inspection, it is possible to locate flaws in metal parts which cannot be detected with other nondestructive means and also to determine the actual flaw geometry, size, and position. The need for industrial quality in various materials is growing, and new applications are being developed for the ultrasonic inspection processes.

The first use of sound in nondestructive testing could have been the result of an accident centuries ago, when a man noted that a cracked bowl emitted a different tone than an uncracked one. Many variations of this method of inspection have been used in an attempt to ascertain the internal qualities of a material. The sensitivity and accuracy of these tests are obviously operator sensitive and depend primarily upon the ear of the inspector.

Although certain laboratory experiments in the late Nineteenth Century indicated that sound could be generated with frequency above the human hearing range, it was not until the 1930's that the possibility of using ultrasonic waves for nondestructive testing was recognized. At this time, O. Muhlhauser, A. Trost, and R. Pohlman of Germany and S. Sokolof of Russia investigated various continuous wave techniques. The inspection methods developed from their studies were a giant step

forward, but depended upon a gross flaw obstructing the transmission of sound through the test piece from one transducer to another. This process is now known as the through transmission method. This particular test process was limited because of the need for access to two opposite surfaces on the test part and the limitations in locating minute defects and determining their location below the surface.

These shortcomings were overcome in the early 1940's when Fred Firestone of the University of Michigan developed an instrument that utilized pulsed ultrasonic wave trains to determine the depth and relative extent of small flaws. Access to only one side was necessary, because the system was monitoring reflected energy, not the loss of transmitted energy.

From that time on, pulse echo ultrasonics has been developed into a reliable and efficient nondestructive testing tool with uses in such widely varying, and many times complex, systems that it is considered by the writer to be beyond the scope of this study to discuss many of them.

During World War II, submarines were tracked with sonar, sound navigation, and ranging. By accurately measuring the time it took for sound pulses to go out and come back, sonar instruments were able to indicate how far away a submarine was from the ship. The same thing happens on a smaller scale in ultrasonic testing. Instead of looking for a submarine, however, the ultrasonic inspector attempts to locate

discontinuities inside of steel parts, tank walls, welds, and concrete cissions. Inspectors can now determine how thick a piece of metal is without seeing the other side of it.

In the ultrasonic testing process, pulses of sound are created by electrically exciting a crystal, known as a transducer, which has piezo-electric properties, causing the crystal to vibrate. Sound energy is transmitted into the material being tested through a couplant; this couplant can be water, oil, or glycerine. Sound which returned to the crystal as reflected energy is converted into electrical signals by a transducer. These signals can be shown on an oscilloscope. The time and amplitude relation of these reflected signals can be interpreted to show the location of internal reflecting surfaces in three-dimensions for accurate location.

Ultrasonic equipment generates ultrasonic pulses which are converted into a beam of ultrasonic waves by a transducer which is a combination microphone and loudspeaker. These waves travel through the part being tested and discontinuities or the other side of the part reflect these pulses back to the transducer where they can be interpreted and evaluated by the inspector. The amount of time it takes between the starting pulse and the reflection is indicated on a cathode-ray tube. The picture on this tube looks like a line with "spikes" on it. The distance between these spikes and their relative height accurately pinpoints the discontinuity and indicates how bad it is.

Using the ultrasonic method of inspection, discontinuities as far as thirty feet below the surface can be located.

In the testing process, the searching unit is caused to vibrate while sending out an initial pulse, then stops until the pulse reaches the other end of the piece or detects a discontinuity and is reflected back. The return signal is amplified and appears as a pip or mark on the cathode-ray tube. This return pulse is timed so that it appears back on the tube in the same relation to the front and back pulse as the discontinuity is to the front and back of the part being tested.

The differences between ultrasonic testing processes and other nondestructive testing processes, such as liquid penetrants and magnetic particles, are obvious because the latter are sensitive only to surface or very shallow subsurface discontinuities. While the ultrasonic processes can be tailored to detect the same type of discontinuities, it is primarily used for the inspection of an area beyond the successful depth of penetration of magnetic particle inspections.

When the ultrasonic method of inspection is compared to the magnetic particle process, the ultrasonic process:

1. Is inferior to the magnetic particle inspection process for the location of exceedingly shallow surface cracks, since there is no known minimum limit to the depth of cracks magnetic particles will detect, provided the proper materials and techniques are used.
2. Requires a certain minimum depth, although this is very

small, in order to obtain sound wave reflection.

3. Is in general superior to magnetic particle processes in the case of below the surface discontinuities at great depths below the surface.

4. Is inferior to the magnetic particle process when irregular shaped parts are being inspected.

The ultrasonic method of inspection was evaluated by the writer to determine whether or not it met the five criteria set forth in the analysis of data section of this study. Since this evaluation could best be accomplished by those with expertise in the field of ultrasonic testing, letters were written to those who had published books or articles, those who were currently employed in nondestructive testing positions in industry, and those who were considered knowledgeable in the field of ultrasonic testing. They were requested by the writer to evaluate the ultrasonic testing process in terms of the five criteria selected for this study. Their statements indicated to the writer that the ultrasonic method of inspection could not be taught successfully in the industrial education program at the high school level.

During the past decade, public attention has increasingly focused on the schools and their difficulties in providing an adequate education for all segments of the nation's population. This is especially true in the area of industrial education where one of the

basic educational objectives has been an attempt to satisfy an individual's vocational needs as he prepared to enter the world of work. The development of vocational competencies is a tremendous challenge when one stops to consider the rapid changes which occur almost daily in American industry. The responsibility of fulfilling this mandate ultimately falls upon the teachers. Teachers are expected to develop an adequate foundation for learning: a foundation which will be of use to their students throughout their entire lives.

In the decade ahead, teachers will be held increasingly responsible and accountable for the behavior of students in the schools. It was stated by the American Vocational Education Association in their report, A Guide to Improving Instruction in Industrial Education (1968:9-11), that there was a need for a closer correlation between the needs of industry and the goals and objectives of education. This is especially true in the area of industrial and technical education. This movement toward behavioral accountability has arisen partly from the conviction that desired educational outcomes can be specified and measured with reasonable precision, and partly from the increase in parent-community concern and involvement in not only the direction of education but also in the operation of public education. The teaching profession while working steadily toward public recognition of its professional status has found that it must deal realistically with the issues of accountability. In the case of industrial education, there

is a growing awareness on the part of both educators and men of industry that the curriculum of industrial and technical education should be closely related to the needs of the nation.

In an attempt to improve industrial education and assist teachers to meet these needs, educators should be involved in a continual search for alternative means to improve the educational curriculum as well as teacher competence and accountability. The inclusion of these methods of testing could, in the opinion of the writer, enhance the future of industrial education.

The adoption of these processes will not simplify the lives of those responsible for the preparation of industrial education teachers nor is it intended to simplify the lives of students who are preparing to enter teaching or technical professions. The decision to implement these testing processes will require considerable effort on the part of teachers and students alike, since this type of program will tend to create an atmosphere of anxiety and concern on their part. These feelings are considered to be a normal reaction when one is faced with the uncertainty of a novel program. To the extent that the people and institutions involved are adaptable, there is hope for success.

The justification for including nondestructive testing processes in the industrial education program lies primarily in the knowledge that:

1. Nondestructive testing processes and procedures permit an

effective integration of industrial theory and practice.

2. There is an immediate need in industry for individuals with nondestructive testing competencies.

Certain advantages could be derived as a direct result of initiating a program of nondestructive testing in the industrial education program at the high school level. Among the most promising are its attention to an individual's vocational needs, its focus on educational objectives, its accountability features and its efficiency which is enhanced by the use of feedback. These advantages would appear to warrant and insure a strong and viable movement toward strengthening teacher preparation in the field of industrial education through the development of individual strengths in specific areas of nondestructive testing.

CONCLUSIONS

Based upon this study, the following conclusions were made:

1. In spite of the changes which have occurred in industrial education in the past twenty years, the gap between what is being taught in the present industrial education nondestructive testing program and what is needed by individuals preparing to enter the world of work appears to be widening.

2. Based upon the opinions of selected authorities, nondestructive testing processes and procedures can be made an integral part

of existing industrial education programs or integrated into existing programs of science, chemistry, or metals testing.

3. It is the opinion of selected authorities in the field of nondestructive testing that high schools can develop levels of competency in nondestructive testing which are comparable to those developed by industry.

4. There is a willingness on the part of members of industry to assist teachers in the development of nondestructive testing programs.

5. The nondestructive testing processes of eddy currents, liquid penetrants, and magnetic particles met the criteria selected by the writer for this study. Radiography and ultrasonic testing processes did not meet the criteria of this study.

RECOMMENDATIONS

Utilizing the findings and conclusions of this study as a basis, the following recommendations are made:

1. Industrial education should provide for the acquisition and demonstration of technical and occupational competencies in nondestructive testing.

2. The nondestructive testing processes and procedures included in this study should be continually updated to keep abreast of new developments and technological changes in the field of

nondestructive testing.

3. The Departments of Industrial Education in universities and colleges should conduct a study to determine the feasibility of developing a program of nondestructive testing to be added to the present curriculum.

4. The administration at teacher education institutions with industrial education programs should provide release time for faculty members who are conducting the feasibility study.

If the Department of Industrial Education at these universities and colleges, based upon the results of the feasibility study, decide to implement a nondestructive testing program into their present curriculum, the following recommendations are made:

1. A standing committee should develop a continuous communication system. This system should include the means for feedback from members of the university faculty, members of secondary school faculties, members of industry who are currently engaged in nondestructive testing, and students who are interested in nondestructive testing processes and procedures.

2. Key teaching personnel should be encouraged by financial support to enroll in nondestructive testing programs similar to those offered by Magnaflux Corporation for the development of competencies in the areas of eddy currents, liquid penetrants and magnetic particles.

3. The faculty should become involved in current research

dealing with the subject of nondestructive testing.

4. The faculty should develop an on-going evaluation of the nondestructive testing program to determine the degree to which the stated goals and objectives of the program are being met.

5. The writer believes that nondestructive testing curriculum guidelines should be developed for industrial educators in the areas of eddy currents, liquid penetrants and magnetic particles utilizing the processes and procedures found in Chapters 2, 3 and 4 of this study.

APPENDICES

APPENDIX A

Commonly Used Specifications and Standards for Nondestructive Testing

Title	Number	Date	Issued By
<u>Liquid Penetrant Methods</u>			
Method for Inspection, Liquid Penetrant Inspection	E165-63	1960	ASTM
Method of Liquid Penetrant Inspection	A462-62T	1962	ASTM
Fluorescent Penetrant Inspection	AMS-2645E	n.d.	SAE
Contrast Dye Penetrant Inspection	AMS-2446A	n.d.	SAE
Oil, Fluorescent Penetrant Solution Soluble	AMS-3155A	1964	SAE
Oil, Fluorescent Penetrant Water Soluble	AMS-3156A	1964	SAE
Solution Fluorescent Penetrant, Water Base	AMS-3158	1964	SAE
Inspection Penetrant Method	MIL-I-6866A (FSC-6850)	1953	Naval Supply Depot
Inspection Materials Penetrant	MIL-I-25135C	1961	Naval Supply Depot

Appendix A (continued)

Title	Number	Date	Issued By
Qualification of Inspection Personnel, Magnetic Particle and Penetrants	MIL-STD-410A	1962	Naval Supply Depot
Inspection Penetrants, Non-destructive Testing	MIL-I-19864 (FSC-6850)	1957	Naval Supply Depot
Inspection of Materials, Fluorescent Dye Penetrant Method	T.O. 42C-1-10	1955	Naval Supply Depot
Inspection Unit, Fluorescent Penetrant Type, MA-2	MIL-I-25105	1955	Naval Supply Depot
Inspection Unit, Fluorescent Penetrant Type, MA-3	MIL-I-25106	1955	Naval Supply Depot
<u>Magnetic Particle Methods</u>			
Dry Powder, Magnetic Particle Inspection	E109-63	n.d.	ASTM
Methods and Specifications for Magnetic Particle Inspections of Large Crankshafts	A456-61T	n.d.	ASTM
Reference Photographs for Magnetic Particle Testing of Ferrous Castings	E125-63	n.d.	ASTM
Steel Forgings, Heavy Magnetic Particle Testing and Inspection	A275-61	n.d.	ASTM

Appendix A (continued)

Title	Number	Date	Issued By
Wet Magnetic Particle Inspection	E138-63	n.d.	ASTM
Magnetic Particle Inspection, Premium Aircraft Wuality Steel Cleanliness	AMS-2300A	n.d.	SAE
Magnetic Particle Inspection	AMS-2640G	n.d.	SAE
Magnetic Inspection Unit, Portable	MIL-M-19698A (FSC-6635)	1958	Naval Supply Depot
Magnetic Particle Inspection Process for Ferro Magnetic Materials	MIL-M-11472	1952	Naval Supply Depot
Magnetic Particle Inspection Soundness Requirements for Weldments	MIL-M-11473	1951	Naval Supply Depot
Qualification of Inspection Personnel, Magnetic Particle and Penetrants	MIL-STD-410A	1962	Naval Supply Depot
Inspection Process, Magnetic Particle, General Requirements	MIL-I-6868C	1965	Naval Supply Depot
Technical Inspection Manual, Volume 3, Section 4, Magnetic Particle Inspections	NAVAER 00-15PC-503	n.d.	Naval Supply Depot

Appendix A (continued)

Title	Number	Date	Issued By
Inspection of Materials, Magnetic Particle Method	T.O. 33-B2-1-1	1963	Naval Supply Depot
Inspection, Magnetic Particle Requirements for Processes Applicable to Overhaul of Airframes, Propellers and Accessories	MIL-I-18620	1955	Naval Supply Depot
Inspection Procedures for Determining Magnetic Permeability of Wrought Iron-Austenite Steels	MIL-STD-288(1)	1957	Naval Supply Depot
Magnetic Particle Inspection Unit, Lightweight	MIL-M-23527	1962	Naval Supply Depot
Magnetic Inspection Unit	MIL-M-6867B	1961	Naval Supply Depot
Magnetic Particle Inspections on Steel Parts	MS-17980A	1963	Naval Supply Depot
<u>Eddy Current Methods</u>			
Methods of Test for Electrical Conductivity Using Eddy Currents	B342-61T	1961	ASTM
Determination of Aluminum Alloy Tempers Through Electrical Conductivity Measurement	Proposed Aero- space Recommended Practice	1964	SAE

Appendix A (continued)

Title	Number	Date	Issued By
Electromagnetic Testing of Seamless Aluminum Alloy Tubing	E-215-63T	1963	ASTM
Welding, High Pressure and Cryogenic Systems	T.O. 00-25-224	1964	Naval Supply Depot
<u>General Nondestructive Methods</u>			
Index to ASTM Standards	none	Annually	ASTM
Nondestructive Testing, Personnel Qualifications and Recommended Practices	SNT-TC-1	1963	Society for Non-destructive Testing
Castings, Classification and Inspection of	MIL-C-6021F	n.d.	Naval Supply Depot
Inspection Requirements, Non-destructive, For Aircraft Materials and Parts	MIL-I-6870A	1960	Naval Supply Depot
Nondestructive Test Symbols	MIL-STD-23A	1950	Naval Supply Depot
Military Standard Nondestructive Testing Requirements for Metals	MIL-STD-271D	1965	Naval Supply Depot
Standards for Welding of Reactor Conduit Coolant and Associated Systems	NAVSHIPS 250-1500-1	1964	Restricted by Navy Technical Orders
Fourth Edition, American Welding Society Handbook	none	n.d.	American Welding Society

Appendix A (continued)

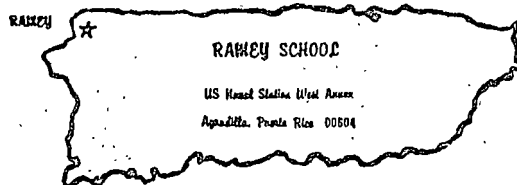
Note: Addresses of References Cited

- A. ATSM, 1916 Race Street, Philadelphia, Pennsylvania
- B. SAE, Society of Automotive Engineers, 485 Lexington Avenue, New York, New York
- C. Naval Supply Depot, Commanding Officer Naval Supply Depot, 5801 Tabor Avenue, Philadelphia, Pennsylvania
- D. American Welding Society, United Engineering Center, 345 East 47th Street, New York, New York

** The specification and standards used in this appendix were obtained from the text, Electromagnetic Testing, which was published by the Government Printing Office, Washington, D.C. 1965, pp. 147-150.

APPENDIX B

Permission to Copy Letters



Mr. Herbie Thomas, Head
Industrial Arts Department

15 July, 1975

Addison-Wesley Publishing Company, Inc.
Reading, Maine # 01867

Dear Sirs:

I am presently in the process of writing my doctoral thesis in industrial education. The area I have selected to research is the development of guidelines for prospective teachers in the area of nondestructive testing. To accomplish this task, I have attempted to collect the most easily understood data pertinent to this field.

With this in mind I would be most appreciable if your company would give me permission to use data in the text, University Physics by Francis W. Sears with the following limitations:

- A. Data will only be used in my doctoral thesis and the thesis will not be published.
- B. Copyright regulations will not be circumvented and appropriate footnotes and references will be given for all data used.

Specifically, I am interested in data found on pages 555-556 which relate to the phenomena of magnetism; and the right hand rule figure on page 550.

I sincerely hope that I will be granted permission to include this useful data in my thesis.

Dear Professor Thomas:
Permission is hereby given to use the material noted in this letter in the manner explicitly stated above.

Mary Loiko
Mary Loiko - Permissions Department
Science and Mathematics Division
August 22, 1975

Respectfully,

M. Thomas
Merle C. Thomas



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DR. WILLIAM M. MUELLER
DIRECTOR OF EDUCATION

19 April 1974
MEI-sb-18

Mr. Merle C. Thomas
Rt. 1 Box 66BB
Ronan, Montana 59864

Dear Mr. Thomas:

RE: Your letter of 8 April 1974

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I hope you have found the MEI course useful and I want to extend my congratulations and best wishes for your project.

Cordially,

METALS ENGINEERING INSTITUTE

Orén J. Huber
Assistant Director

OJH/SBurnett
cc: Dr. Mueller

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EDWARD J. MYERS
DIRECTOR OF EDUCATION

30 July 1975
MEI-sb-7

Mr. Merle C. Thomas
Ramey School
U.S. Naval Station West Annex
Aquadilla, Puerto Rico 00604.

Dear Mr. Thomas:

RE: Your letter of 15 July 1975

This letter grants you permission to use selected data, figures, and tables from the MEI course, "Fundamentals of Nondestructive Testing", in your thesis. The source of the individual items used should be acknowledged in appropriate footnotes or references.

We are pleased to learn that you find our materials useful and would appreciate an opportunity to see your finished thesis.

Cordially,

METALS ENGINEERING INSTITUTE



Oren J. Huber
Assistant Director

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8 May 1974

Mr. Merle C. Thomas
 St. Ignatius High School
 St. Ignatius, Montana 59865

Dear Mr. Thomas:

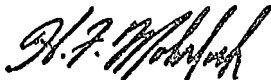
Your letter of April 28, 1974, requesting permission to reproduce certain pages from the Convair NDT handbook P1-4-5 on Eddy Current Testing has been referred to me for consideration and reply.

We are willing to grant permission to reproduce portions of that book, subject to the following limitations.

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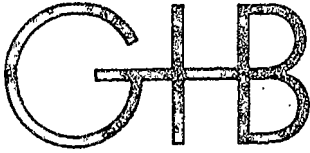
My best wishes on your endeavor.

Sincerely,



H. F. Mohrlock
 Patent Department

HFM:mb



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Mr. Merle C. Thomas, Head
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RAMEY SCHOOL
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Dear Mr. Thomas:

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We hereby grant you permission to use this abovementioned material in your thesis, under the proviso that the thesis is not published, and that should our copyrighted material should appear in a published form, that permission be re-requested.

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Reference: Our #815-1152

Gentlemen:

Thank you very much for your letter of September 22, 1975. We have no objection to your using certain data from the "Principles of Penetrants" and "Principles of Magnetic Particle Testing" as long as credit is given to Magnaflux Corporation. It would be of interest to us to receive a copy of your doctoral thesis.

We take this opportunity to extend our best wishes to you in your NDT project.

Sincerely yours,

MAGNAFLUX CORPORATION


A.N. Zelaya
Asst. Manager-International Marketing

ANZ:lc



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WASHINGTON, D. C. 20301

24 APR 1974

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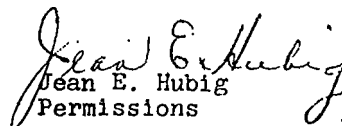
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JEH/m



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Ramey High School
U. S. Naval Station-West Annex
Aguadilla, Puerto Rico 00604

Dear Mr. Thomas:

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The article to which you refer was published in Volume XXVIII, Number 12, December 1970, pp 262-266. The author was:

Dr. Donald L. Waldelich
University of Missouri
Department of Electrical Engineering
Columbia, Missouri 65201

I share your opinion that this article is quite explicit and useful as educational background material. I presume that you are familiar with the programmed instruction manuals and audio-visual materials that we supply. In case you are not, I have enclosed a copy of our most recent Book Mart.

Thank you for your comments and interest in NDT technology. Please let me know if ASNT can be of further service to you.

Very truly yours,

Robert T. Anderson
Robert T. Anderson
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Mr. Merle C. Thomas
Raney High School
U.S. Naval Station-West Annex
Aguiadilla, Puerto Rico 00604

Dear Mr. Thomas :

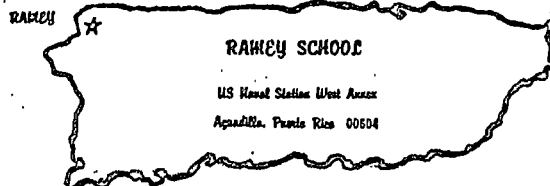
This is in reply to your letter of September 22 concerning the use of certain data from my paper "The Role of Theory in Eddy Current Testing". You have my permission to use this data in your thesis. It is understood that no publication of the material will occur.

I would be interested in seeing a copy of your thesis when it is completed. Would this be possible?

Sincerely yours,

Donald L. Waidelich
Professor

DW/lw



Mr. Merle Thomas, Head
Industrial Arts Department

15 July, 1975

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Dear Sirs:

I am presently in the process of writing my doctoral thesis in the area of nondestructive testing; the development of guidelines for prospective teachers in the field of Industrial Education.

With this in mind it would be appreciated if your company would give me permission to use data, figures and tables from the text Introduction to Electromagnetic Nondestructive Testing by Hugo L. Libby, 1971, with the following limitations:

- A. Data will be used only in my doctoral thesis and the thesis will not be published.
- B. Copyright regulations will not be circumvented and appropriate footnotes and references will be given for all data used.

I sincerely believe that once these guidelines are developed industrial education teachers will be more willing to include this subject in their curriculum.

Your consideration of this request at an early date is appreciated.

Permission granted. JUL 17 1975
Proper credit must be given
to our publication.

Joan E. Lince
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Permissions Manager
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Merle C. Thomas
Merle C. Thomas

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APPENDIX C

Letter Sent to Selected Specialists in the Field
of Nondestructive Testing

Gentlemen:

It has been my objective as part of the requirements for my doctorate in education to develop nondestructive testing guidelines which could be used at the high school level to develop entry level nondestructive testing competencies for interested students. My hypothesis is that there is not only justification for including NDT principles in the industrial education curriculum, but also the sincere hope that other industrial education teachers would be encouraged to include these methods of testing in their programs, once suitable guidelines had been developed. This study has been limited to the five major methods of nondestructive testing: (1) eddy currents, (2) liquid penetrants, (3) magnetic particles, (4) radiography, and (5) ultrasonics.

With the above in mind, it would be appreciated if you would jot down your thoughts regarding the following:

A. Are the methods selected compatible to existing industrial education programs?

B. Could a knowledge of the testing methods satisfy one of the present needs of industry: students graduating from high school with a knowledge of the practical applications of nondestructive testing?

C. Are the methods selected for this study relatively simple in their application and do they have a broad encompassing nature?

D. Do the methods selected have the potential to satisfy one of the present weaknesses of industrial education: the exclusion of NDT processes in the curriculum?

E. Which of the methods selected can be taught to high school students without involving them in an extensive or intensive amount of technical preparation?

Your consideration of this request at an early date would be appreciated.

Respectfully,

Merle C. Thomas

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LITERATURE CITED

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1. The first part of the document is a list of names and addresses of the persons who have been in contact with the subject.

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GEOMETRY OPINIONNAIRE

name _____ School _____ Period _____ Date _____
 last first middle

Directions: Each of the statements on this opinionnaire expresses a feeling which a particular person has toward geometry. You are to express on a five-point scale, the extent of agreement between the feeling expressed in each statement and your own personal feeling. The five points are: Strongly Disagree (SD), Disagree (D), Undecided (U), Agree (A), and Strongly Agree (SA). You are to circle the letter which best indicates how closely you agree or disagree with the feeling expressed to each statement as it concerns you.

1. I do not like geometry. I am always under a terrible strain in the geometry class. SD D U A SA
2. I do not like geometry, and it scares me to have to take it. SD D U A SA
3. Geometry is very interesting to me. I enjoy this geometry course. SD D U A SA
4. Geometry is fascinating and fun. SD D U A SA
5. Geometry makes me feel secure, and at the same time it is stimulating. SD D U A SA
6. I do not like geometry. My mind goes blank and I am unable to think clearly when doing geometry. SD D U A SA
7. I feel a sense of insecurity when attempting geometry. SD D U A SA
8. Geometry makes me feel uncomfortable, restless, irritable, and impatient. SD D U A SA
9. The feeling that I have toward geometry is a good feeling. SD D U A SA
10. Geometry makes me feel as though I'm lost in a jungle of numbers and figures and I can't find my way out. SD D U A SA
11. Geometry is something which I enjoy a great deal. SD D U A SA
12. When I hear the word geometry, I have a feeling of dislike. SD D U A SA
13. I approach geometry with a feeling of hesitation--hesitation resulting from a fear of not being to do geometry. SD D U A SA
14. I really like geometry. SD D U A SA
15. Geometry is a course in school which I now like and enjoy studying. SD D U A SA
16. I don't like geometry. It makes me nervous to even think about having to do a geometry problem. SD D U A SA
17. I do not like geometry, and it is my most dreaded subject. SD D U A SA
18. I love geometry. I am happier in the geometry class than in any other class. SD D U A SA
19. I feel at ease in geometry, and I like it very much SD D U A SA
20. I feel a definite positive reaction to geometry; it is enjoyable. SD D U A SA

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