



Tensile testing of metal/metal and ceramic/metal brazed joints
by Shreeram Raj

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Mechanical Engineering
Montana State University
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Abstract:

The current study focused on an increasingly important technological problem: strong and reliable brazed joints between dissimilar metals and between ceramics and metals. The influence of various joint component materials and other relevant variables on the joint strength of these systems was evaluated. The load required to cause separation usually gave clear information about the adhesion of the system of dissimilar materials. Strength data were also useful in ascertaining relative ranking of the adhesion between systems.

Various combinations of ceramics and metals were used to prepare braze coupons with Cusil ABA braze alloy. The evaluation of joint strengths was done using a butt joint geometry in an uni-axial tension test. The tensile tests were conducted on an Instron 8562 testing machine using a self-aligning fixture. This attachment aided in eliminating parasitic bending loads and in accommodating specimen misalignments, both of which are very critical to the tensile testing of brittle joint systems.

The results of these tests have led to a better understanding of the joint strengths of brazed dissimilar materials. Joints with high strengths were produced by an active filler metal process, the most economical of which utilized an active element forming a true alloy with the base filler metal. The results of the study provide an improved basis for material selection and joint design in non-shortening electrodes for use in Magneto-hydro-dynamic channels. This research also contributed to the general database on brazed joint strengths.

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**A thesis submitted in partial fulfillment
of the requirements for the degree**

of

Master of Science

in

Mechanical Engineering

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APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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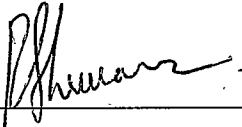
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ABSTRACT

The current study focused on an increasingly important technological problem: strong and reliable brazed joints between dissimilar metals and between ceramics and metals. The influence of various joint component materials and other relevant variables on the joint strength of these systems was evaluated. The load required to cause separation usually gave clear information about the adhesion of the system of dissimilar materials. Strength data were also useful in ascertaining relative ranking of the adhesion between systems.

Various combinations of ceramics and metals were used to prepare braze coupons with Cusil ABA braze alloy. The evaluation of joint strengths was done using a butt joint geometry in an uni-axial tension test. The tensile tests were conducted on an Instron 8562 testing machine using a self-aligning fixture. This attachment aided in eliminating parasitic bending loads and in accommodating specimen misalignments, both of which are very critical to the tensile testing of brittle joint systems.

The results of these tests have led to a better understanding of the joint strengths of brazed dissimilar materials. Joints with high strengths were produced by an active filler metal process, the most economical of which utilized an active element forming a true alloy with the base filler metal. The results of the study provide an improved basis for material selection and joint design in non-shortening electrodes for use in Magneto-hydro-dynamic channels. This research also contributed to the general database on brazed joint strengths.

CHAPTER ONE

INTRODUCTION

The use of ceramic/metal joints has assumed increasing importance in modern technology. One of the key technologies that will enhance or restrict the use of ceramics in high performance structural applications is the ability to reliably join them to metals. The earliest developments in the field of ceramic brazing began in the laboratories of Pulfrich and Vatter in the early 1930's [1]. Like other joining processes, the joining of ceramics was considered more an art than a science. Over the years, extensive research, development and refinement of techniques has improved ceramic/metal and ceramic/ceramic brazing. Efforts of late have been particularly focused on joining ceramics to metals for a wide range of industrial uses. Ceramics are generally brittle, more refractory and less thermally expansive or conductive when compared to metals. There are exceptions to this generalization, and this study dealt with some of those exceptions. Beryllium oxide and aluminum nitride, the ceramics used in this study, have high thermal conductivities. Tungsten and molybdenum, the metals used, are highly refractory. This leads to their use in special applications such as in cold electrodes for MHD channels.

The materials used in this study are metal/metal and ceramic/metal brazed joints for application with copper

electrodes. The ceramics are used as high thermal conductivity electrical insulators on the copper electrodes. The metals, in turn, are either used as intermediate layers in ceramic/metal joints or as wear resistant edges to the copper electrodes.

Brazing is a heterogeneous joining process in which materials are joined by a lower-melting material. As far as metals are concerned, brazing is a process of joining similar or dissimilar metals with a nonferrous filler metal that has a melting point below that of the metals being joined. The strength of a brazed joint is attributed to a variety of parameters discussed later. The brazing of ceramics is considerably more difficult than for metals. A major problem in successfully brazing ceramics with metal alloys is the well documented observation that liquid metals generally do not wet ceramic surfaces unless special provisions are made. The active filler metal process is used to overcome this problem in this study. Brazing is a very complex process with a number of different parameters simultaneously affecting the joint. To develop ceramic/metal brazed joints for demanding applications it is necessary to optimize the materials system, including the ceramic, the parent metal, the braze and the intermediate layers, if any. Also, the resistance of the joint materials to thermal shock, which depends heavily on the thermal expansion mismatch at the joint, is one of the more important factors in the formation of a reliable brazed joint.

Initially, to understand the system that was being

dealt with here, metal/metal brazed systems were tested for joint strength with different combinations of metals and braze alloys. Then, the ceramic/metal brazed systems were tested. The performance of electrical assemblies using ceramic/metal brazed systems under extreme conditions is directly traceable to the strength of the ceramic/metal joints in the system. Hence, the strength of the brazed joint is an important criterion for the evaluation of the performance of these systems. Systems having ceramic/metal brazed joints behaved in a brittle fashion, and so great care was needed in their testing.

CHAPTER TWO

BACKGROUND

Importance of Joining

Complex structures using structural ceramics which cannot be made in one piece require joining. Joined ceramic components can be made stronger and with shapes and tolerances not easily achieved in a single molding. The most important application of ceramic joining could well be the attachment of ceramic components to structural parts made of metals, where the purpose of the ceramic is to resist high temperature exposure. These assemblies must withstand stress or temperature gradients too great for ceramics alone. Cooling of the metal, and cyclic loading introduce complex stress and temperature gradients into the joints, and hence the design of such systems requires a great deal of information on the materials in the layers of the joint : thermal expansion, annealing effects, viscosity, elastic modulus, strength, fracture toughness, creep and fatigue, all as functions of temperature [1]. The availability of good joining techniques strongly influences the design of such systems.

Ceramic/metal components are joined by one of several primary techniques.

Mechanical Joining

These techniques use mechanical fasteners, hooks or

press and shrink fitting to join ceramic to metal. The latter method is usually employed in mass production processes.

Direct Joining

Achieved by pressing very flat mating surfaces at high temperatures to achieve diffusion bonding. Fusion welding using lasers and electron beams is employed for high melting temperature systems.

Indirect Joining

The most common method of achieving high-integrity joints using a wide variety of intermediate bonding materials. Metal intermediates are used as solid-state diffusion bonding agents or as brazes.

Adhesive Joining

In general, polymeric adhesives are not considered for ceramic applications where high temperatures and corrosive environments are present, due to deficiencies in the adhesive properties under these conditions.

Requirements for Strong Joints

Chemical bonding at the interface, low thermal expansion differential, low stress concentrations, and strong component materials are the basic requirements for strong bonded assemblies [1]. It is very difficult to characterize chemical bonding, especially at the interfaces; hence, it is generalized that two phases can form an acceptable assembly

with a chemical bond if they are at stable chemical thermodynamic equilibrium at the interface. This is irrespective of the bulk phases, provided they are physically compatible [2].

The formation of an intimate interface is the first requirement in joining. An intimate interface is one where atomic contact exists either as Van der Waals forces or primary bonding. In a solid/liquid combination an intimate interface is formed if the liquid wets or spreads and penetrates irregularities on the solid surface [1].

Stable chemical equilibrium at the interface is the next requirement. At metal/metal interfaces, solution reactions and saturation at the interfaces help achieve chemical equilibrium. At ceramic/metal interfaces, solution of oxide layer on pre-oxidized metal redox reactions, saturation at the interface with substrate oxide product redox reactions and the formation of compounds at the interface which are compatible with both phases help achieve chemical equilibrium [1].

In summary, for ceramic/metal joints the basic requirement is for chemical bonding across the interface and microstructures in the interfacial zone having favorable residual stress patterns [1]. Chemical bonding occurs when chemical reactions occur at the interfaces resulting in stable chemical equilibrium. Hence, the need for a liquid phase and favorable residual stress patterns has been the dominant

factor in the design of assemblies that use some intermediate material for joining [1].

Brazing

Despite recent advances in joining technology, brazing is still the foremost method of producing sound joints. Brazing is uniquely suited for the fabrication of ceramic/metal joints, and also lends itself to mass-production operations where small parts must be joined economically or large assemblies must be joined in a single operation.

The primary objective in brazing is to produce a mechanically acceptable bond between two surfaces without fusing the bulk materials. A liquid is made to flow into and to fill the space between the joint faces, and to then solidify. The liquid used has a lower solidification temperature than the bulk phases to be joined. Brazing filler metals are mainly copper, nickel, silver, gold or aluminum alloys. In brazing there exists a degree of intersolubility between the braze alloy and substrate, and hence interdiffusion at the substrate surface should occur [3].

The main factors which govern the effectiveness of joint filling by the braze alloy are the contact angles of the system, joint clearance (separation of joint faces), heating rate, uniformity, and temperature. Uneven heating results in irregular filling, and so circular joints are generally preferred to straight-edged joints in furnace brazing. Optimum

joint clearances range from approximately 0.002 in. to 0.005 in. for most brazing materials. However, copper is known to yield strongest joints with an approximately 0.003 in. joint clearance [4].

Brazing is also important in ceramic to metal joining, allowing complex assemblies to be joined in a stress free state. It also allows for differences in thickness and surface characteristics of joint members. Brazing permits additional members to be joined to a partially completed structure by using brazing filler metals with different melting temperatures. Another advantage here is the need for little or no finishing of the joint [1].

A good brazed joint depends on the braze and its compatibility with the brazing surfaces. The stresses produced in a joint due to geometry and thermal expansion mismatches between components also directly influence the integrity of a brazed joint [1]. The stresses produced in a brazed joint depend on the thermal expansion mismatch between joint components, the relative thickness of the components, the mechanical properties of the components, the geometry of the joint, and the brazing temperature. The strength of the brazed joint also depends on the residual stresses present at the joint, the individual properties of the joint components, and the integrity of the interfaces [1].

Brazing Methods

Brazing can be done by torch, resistance or induction

heating, by dipping, or in a furnace. Torch brazing is the common manual technique for brazing, using an oxy-acetylene or oxy-coal gas torch. Resistance or induction brazing is useful for repetitive work in open air conditions, with heating coils being designed for the specific application. Dip brazing is usually applied to sheet products formed to the desired shape, coated with braze alloy and then dipped in a flux bath [5].

Furnace brazing is preferred for batch or continuous processing of a large number of parts, generally at low unit costs. The equipment consists of a furnace that is electric, gas or oil fired with temperature and atmosphere controls. Filler metals are usually used as pre-placed preforms. A major advantage of this method is the ability to braze several joints simultaneously and to control surface oxidation by using a controlled atmosphere (vacuum or gas filled). The limitations of this method include high initial cost, floor space requirements and maintenance costs [6]. Also, the copper which is furnace brazed must be oxygen free or deoxidized, since regular copper is embrittled by hydrogen. Normally, copper, copper alloys and a few other metals are susceptible to intergranular penetration and cracking by the brazing material if residual or applied stresses are present during furnace brazing operation [3]. Hence, such combinations are stress relieved before furnace brazing, or else low-melting silver brazing alloys are used [3].

Brazing Procedure

First, care should be taken in designing the joint assembly so that the molten metal does not touch any part of the brazing fixture. Second, since the metal has a higher thermal conductivity than the ceramic, it heats faster, so that all the filler metal is drawn up by the metal. This effect is even more pronounced when the mass of the metal is small compared to that of the ceramic. Hence, the heating rate has to be controlled to minimize the temperature difference between the ceramic and the metal. This is usually achieved by initially holding the temperature below the solidus temperature of the braze, and then increasing the temperature at a controlled rate to the brazing temperature. Lastly, the rate at which the joint is cooled from the brazing temperature to room temperature is also critical. Slowing the cooling rate allows for the metals to plastically deform and, hence, reduce the thermal expansion mismatch stresses, resulting in a stronger joint [3].

The thermal expansion of both metal and ceramic play a very important role in brazing. A typical brazing cycle is summarized as follows [1]:

1. Heat the assembly to approximately 50 °C below the braze solidus temperature.
2. When melting begins, hold at that temperature for a given time such that all parts reach a uniform temperature.

3. Increase the temperature to about 50 °C above the liquidus temperature for complete braze melting.
4. Hold at this temperature for up to 10 minutes, then cool.

Brazing Ceramics

The major problem with brazing an oxide ceramic is the resistance to wetting caused by oxides on the surface of the ceramic. One way of rectifying this problem is by applying pressure to the braze filler metal to overcome the repelling surface tension forces of the oxides. Results of tests show that joint strength increases with increased applied pressure to a certain extent and then levels off [1]. Purer forms of oxide ceramics also tend to have lower joint strengths. Brazing in a vacuum also tends to yield higher joint strengths [1]. Active metal brazing using active braze alloys (ABA's), like Cusil ABA or Incusil 10 ABA, which contain an active metal to promote a redox reaction with the ceramic, also yield comparable joint strengths to other conventional metallizing-brazing techniques (like the Mo-Mn process) [7].

The braze system is dependent on the condition of the ceramic surface, with lapped surfaces resulting in much higher joint strengths compared to as-ground surfaces [8]. Metal coatings also help considerably in brazing oxide ceramics [1].

As far as ceramic/metal joining by active metal brazing is concerned, furnace brazing is accepted as the best technique. However, vacuum brazing or inert gas brazing are

the most economical methods [1].

Wetting and Adherence

The shape of a drop of molten braze metal on a solid ceramic surface (Figure 1) is determined by gravity and by the interacting forces of solid-liquid interfacial energy (γ_{SL}), solid-vapor interfacial energy (γ_{SV}) and liquid surface tension (γ_{LV}) [1]. Young's equation gives the relationship between these interfacial tensions as

$$\gamma_{SL} = \gamma_{SV} - \gamma_{LV} \cos\theta \quad (2.1)$$

The contact angle (θ) may vary from 0° to 180° . If γ_{SL} is high, the drop tends to form a ball with very small interface area, and if γ_{SV} is high then the drop tends to spread. Also, if only the liquid surface energy is decreased, the contact angle decreases for initially wetting drops ($\theta < 90^\circ$) but increases for initially non-wetting drops ($\theta > 90^\circ$) [1].

The contact angle is greater than 90 degrees when γ_{SL} is larger than γ_{SV} , and the liquid drop tends to spheroidize. Similarly, θ is less than 90 degrees when γ_{SV} is larger than γ_{SL} , and the liquid drop tends to flatten out and wet the solid surface.

Brazing filler metal should wet the solid in order to form a joint. The contact angle should be less than 90 degrees, i.e., γ_{SV} must be greater than γ_{SL} . From practical considerations a contact angle of about 70 degrees is found to be satisfactory [3]. Dupre [1] showed that the free energy

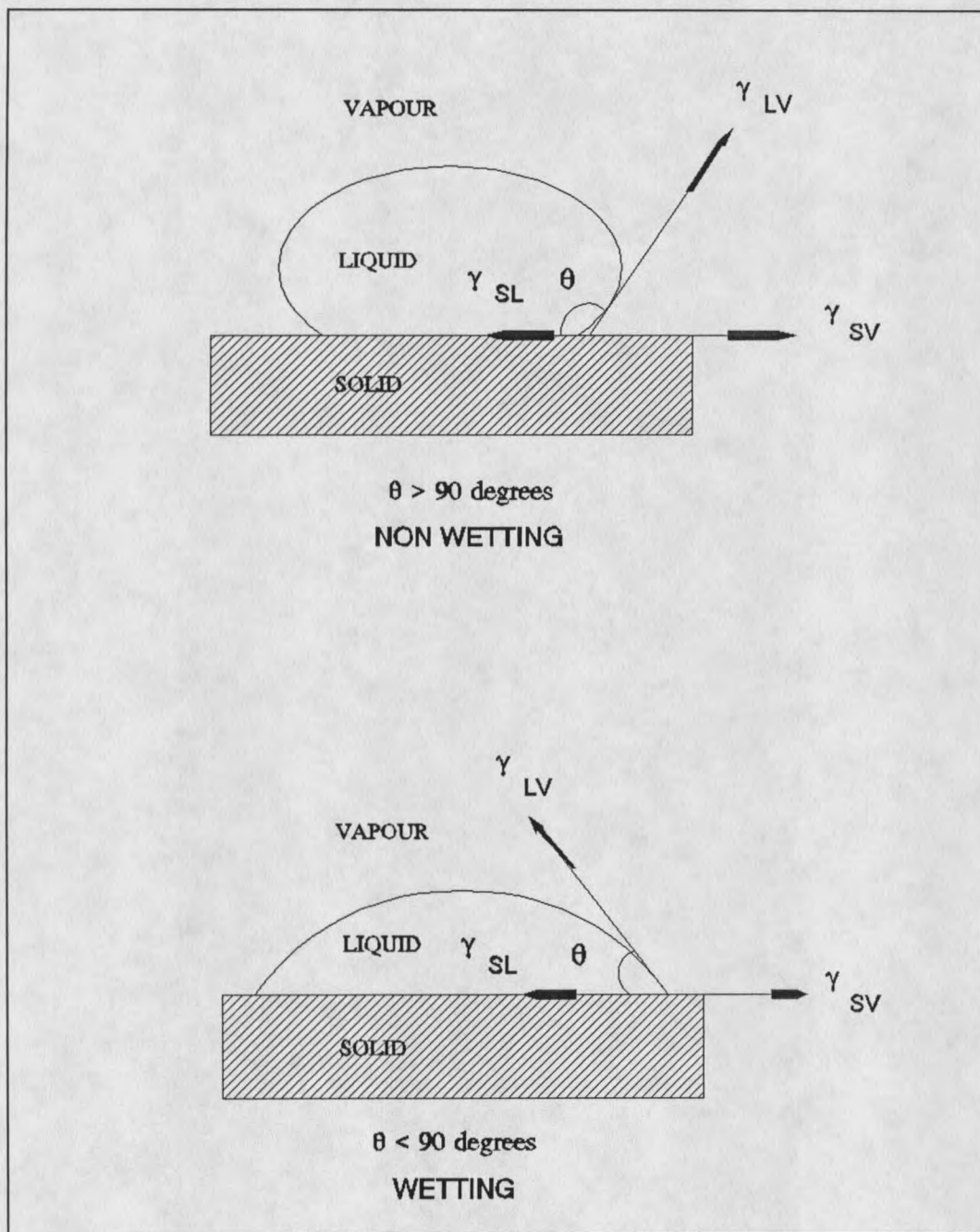


Figure 1. Wetting and contact angles.

change when solid and liquid are joined, combined with Young's equation, can be given in terms of the work of adhesion (W_A) as

$$W_A = \gamma_{SV} + \gamma_{LV} - \gamma_{SL} \quad (2.2)$$

This relates the adherence of the drop to the substrate, but not necessarily the adherence of the solidified drop. However, these equations assume the absence of any diffusion or reaction at the contact interface, which is not generally true, particularly with the use of active metals in braze filler metals [1].

It is important to analyze the factors that make wetting effective, including the effect surface cleanliness has on wetting. The effects of surface roughness versus smoothness and other methods to improve wetting are equally important. The contact angle should be such that the braze filler metal wets the ceramic but does not flow. However, if a low contact angle or flow on the ceramic is necessary, this can be achieved by using a high active metal content brazing alloy. Most high titanium content brazing alloys are very hard and brittle, thereby limiting their use in joining ceramic/metal systems with mismatched thermal expansions [1].

In general, the molten filler metal contact angle to the base metal ranges from 0 degrees, where the filler metal blushes or flows over the metal substrate surface, to 90 degrees (1.6 radians), where the molten metal stays where it melts [1].

The braze filler metal may alloy with the substrate to form a lower melting temperature alloy, which results in deep erosion followed by severe blushing of the newly formed composition. The opposite may also happen, with the braze filler metal readily alloying with base metal to form a higher melting temperature alloy, which then results in sluggish braze formation and no flow [1].

The joining of two materials with different brazing filler metal contact angles can be more difficult than that with same contact angles. In ceramic/metal systems this is due to the fact that in most cases the ceramic member mass is much greater than that of the metal member, and, hence, the metal becomes much hotter than ceramic at short times. This causes most of the braze filler metal to spread over the metal, leaving insufficient braze filler metal to wet the ceramic.

Braze Filler Metal

A braze filler metal works by melting, reacting and reaching chemical equilibrium at the interfaces with both the ceramic and metal components [1]. Unlike metal systems, the ceramic systems are not usually compatible, and wetting and subsequent bonding of the braze with the ceramic component becomes a problem. This is because the braze has a higher γ_{LV} and does not wet the ceramic. In joining AlN or BeO using a silver-copper eutectic braze alloy, no reaction occurs since the oxidation potentials of Cu and Ag are less than that of Al

or Be. Without stable chemical equilibrium, bonding does not occur at the braze/ceramic interface. Hence, Cu_xAg brazes usually have a small percentage of reactive metal, like Ti, added [9]. The high oxidation potential of Ti causes it to undergo a redox reaction with the ceramic, which causes spreading of the braze, and oxide formation at the interface compatible with both phases, resulting in bonding at the interface. Figure 2 shows the two cases of brazing with and without active metal additions. Table 1 compares a few silver-copper braze alloys.

Table 1. Some silver-copper braze alloys and their compositions [1].

	BRAZE ALLOY	COMPOSITION (wt %)
1	Cusil	72 Ag, 28 Cu
2	Ticusil	68.6 Ag, 26.7 Cu, 4.5 Ti
3	Cusil ABA	65 Ag, 33.5 Cu, 1.5 Ti
4	Cusiltin - 5	65 Ag, 30 Cu, 5 Sn

Most metal alloys used in brazing as braze filler metals do not wet ceramics easily unless their surfaces have been treated to promote wetting. Oxide ceramics (Al_2O_3 and BeO) are the most important of such structural ceramics. Even the slightest amount of Al or Ti present in a super-alloy can cause wetting problems due to the formation of oxides during heating (unless vacuum brazing is employed). Brazing of metals

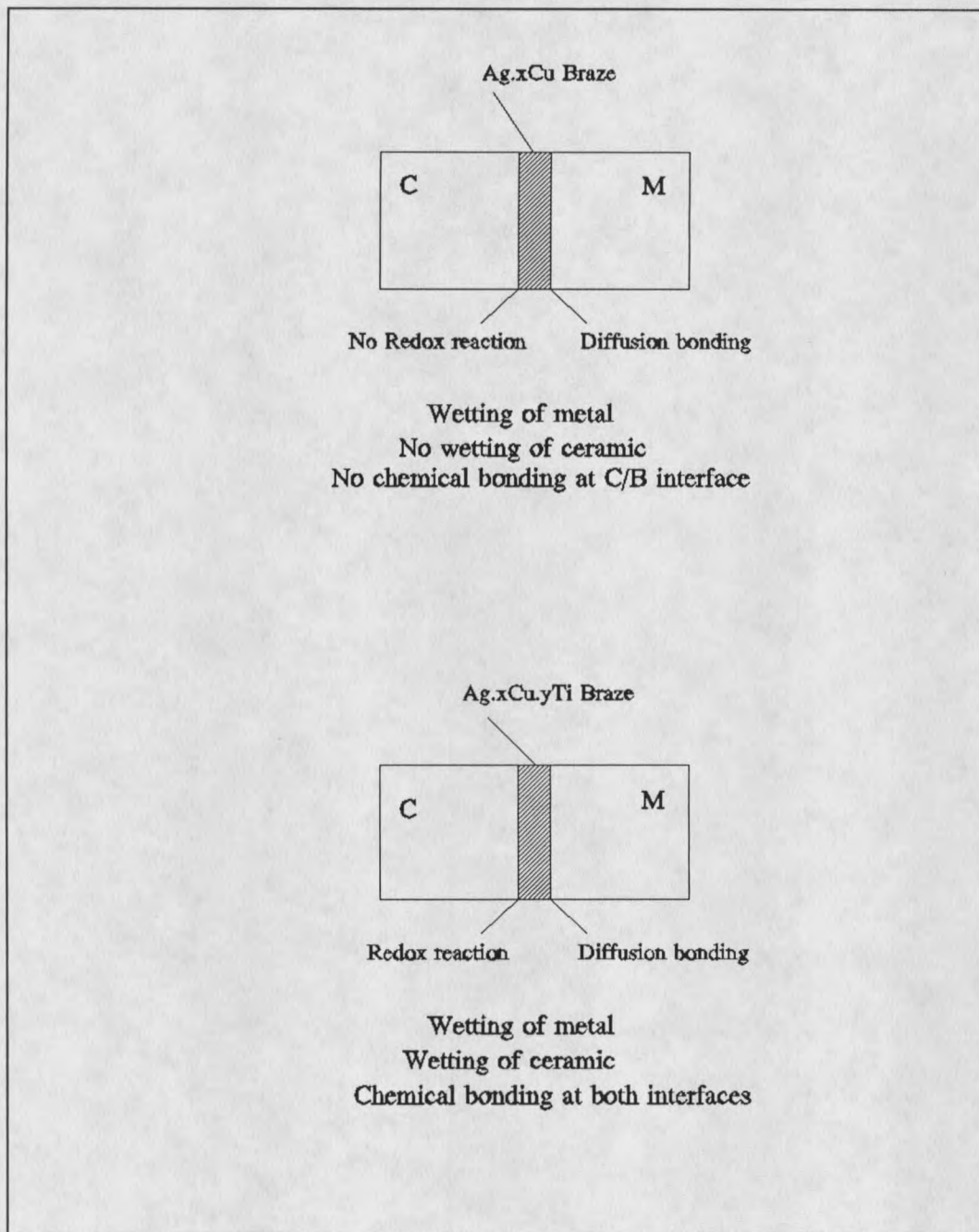


Figure 2. Brazing with and without active metal additions [1].

to metallized ceramic surfaces is easy because the metallized layer ensures wettability of the ceramic. However, metallizing is a costly and time consuming process and is also an additional step. Some metals and hydrides have the ability to wet ceramic surfaces that have not been metallized. Active Metal and Active Hydride processes are based upon these principles [10]. The use of active metals and hydrides to join ceramic to metal was first applied in the electronic industry.

One of the major factors in choosing a brazing filler metal is its liquidus temperature, which must be sufficiently below the solidus temperature of the base metal. Production methods also impose a major limitation. As regards a certain specific application, the properties that influence the choice of a certain filler metal are electrical conductivity, corrosion resistance, flow characteristics, cost and strength [6].

Brazing Alloys for Ceramics

The inability of conventional brazing alloys to wet ceramics because of low surface energies is a major concern. Hence, brazing alloys for direct brazing of ceramics often contain a reactive element, usually a metal like Ti or Zr, which promotes wetting by reacting with the ceramic and decomposing a thin layer of the ceramic.

Since these brazing filler metals contain reactive metals, they exhibit a high oxygen affinity and also poor corrosion resistance [11]. The oxidation resistance of

reactive metal brazing alloys is always very poor, but the addition of aluminum helps form an adherent protective oxide film without sacrificing wettability [12]. It is also known that the affinity of the filler metal, or elements in the filler metal, for oxygen plays a very important role in determining the strength of the brazed interface [13].

Active metal brazing has been used since 1940, but extensive use has not been attained due to inconsistent properties [1]. There are several methods of active metal brazing. One method involves a sheet of titanium clad by two sheets of braze alloy. Another method uses titanium hydride powders mixed with powders of conventional brazing metals. However, the most economical method uses a filler metal where the active element(s) forms a true alloy with the base filler metal.

According to Mizuhara and Huebel [9], there are currently four recognized active element joining processes. The first process uses titanium hydride powder mixed with a standard brazing filler metal powder. The ceramic surface is coated with the mixture and then the assembly is heated to brazing temperature. In the second process more than one layer is used. Titanium foil is stacked with brazing alloy foils between the ceramic and metal and then the assembly is heated to brazing temperature. The third process involves a commercially available clad product, which consists of an active element core that is protected from reacting with the

outgassing products until the melting of the silver-copper eutectic outerlayer. The final process uses a true alloy, having a controlled amount of titanium available for joining to the ceramic at melting. The main purpose of the active filler metal is to help wet the ceramic surface directly. Even though most filler metals have higher thermal expansions than ceramics, their low yield strength permits them to accommodate stresses and yield below the tensile strength of the ceramics [8].

The advantage in using a true alloy lies in the fact that the active element alloyed with the Ag-Cu eutectic stays protected until the alloy starts to melt, resulting in lower temperature requirement and greater utilization of the active element. During brazing the titanium migrates to the interface and reacts with oxygen in the ceramic or surroundings and also alloys with copper (Figure 3).

Thermodynamic calculations support the formation of an interface as shown in the model in Figure 3 [1]. The formation of Cu_xTi ($1.2 < x < 1.6$) and TiO_2 or TiN creates a graded seal effect with the TiO_2 or $\text{TiN}/\text{Cu}_x\text{Ti}$ ratio being greater next to the ceramic. However, it is not yet clear whether the interface is a mixture of small crystallites of the alloy Cu_xTi in TiO_2/TiN or a compound of copper, titanium and oxygen, where this compound varies in composition through the seal [1]. Thermodynamic calculations also support the formation of aluminum and calcium titanates on the ceramic side of the seal

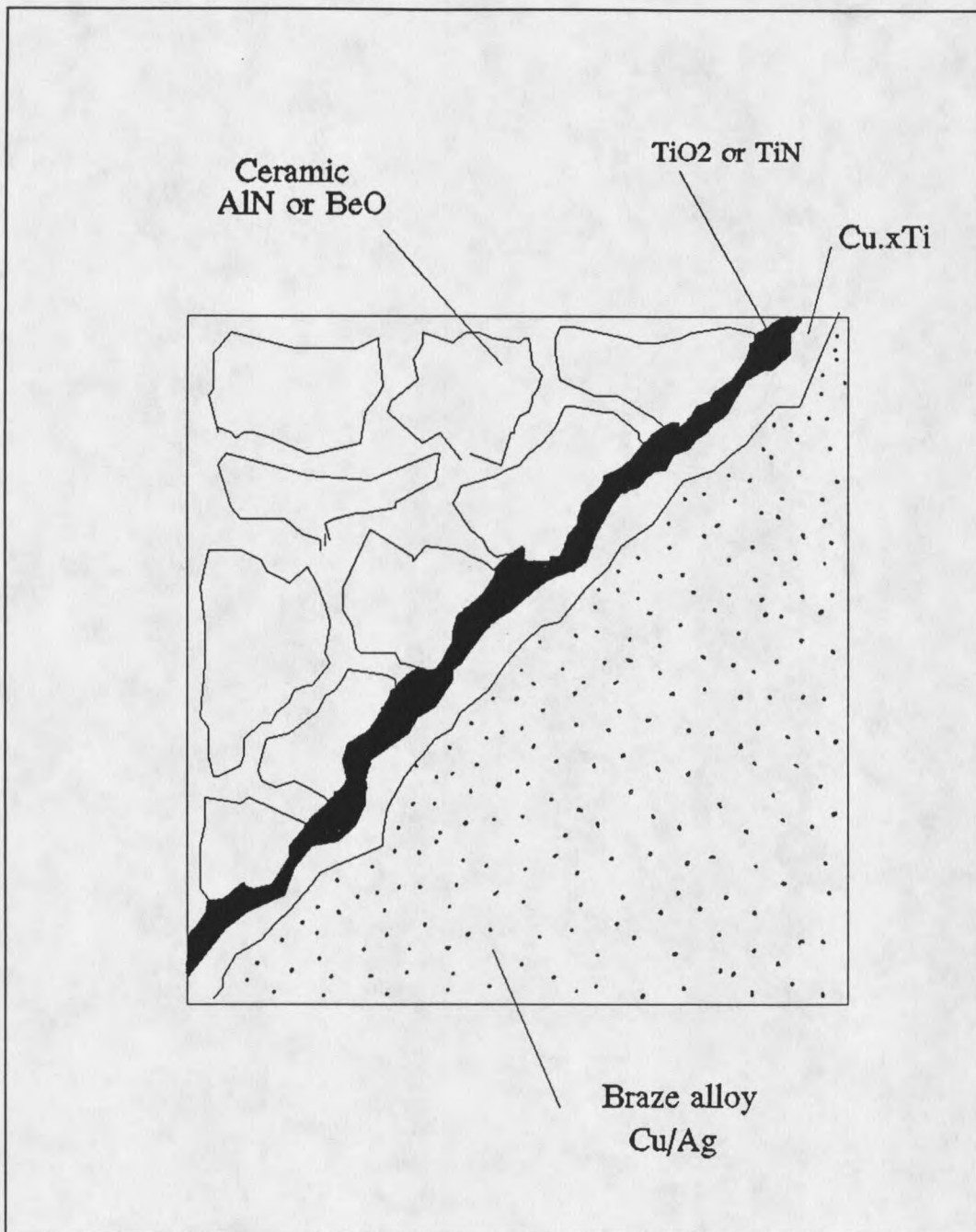


Figure 3. Interface of active braze alloy and ceramic [1].

and intermetallic compounds of copper and titanium on the braze side of the seal [1].

Ceramic/Metal Joining

Ceramic Versus Metal

Historically, ceramic materials predate metals. Archaeologists have found glass and brick to be among the earliest of man made materials. As a class, metallic materials are better electrical and thermal conductors than ceramics due to the comparative freedom of valence electrons in the metal, but ceramics have better dielectric properties. Ceramics are also more stable than most metals in both chemical and thermal environments. This is due to lower free energy of ceramics compared to metals [14]. Also, metals have comparable tensile and compressive strengths and are usually ductile, whereas ceramics are appreciably stronger in compression than in tension, and are brittle.

Characterization of Ceramic/Metal joints

Metal to ceramic joints are used in today's technology to exploit the advantages of structural ceramics with their excellent high temperature strength, their superior corrosion resistance, and their better wear resistance in comparison to metals.

Usually, service conditions involve complex mechanical and/or thermal loading. This necessitates strong ceramic/metal joints to build-up composite structural components in which

the optimum properties of both groups of materials can be properly used. Solid state (diffusion) bonding and liquid-phase (active metal) bonding are extensively used to join ceramics and metals [15].

Whereas much progress has been achieved in fabrication and application of ceramic/metal joints, much work remains to be done in the area of measurement and understanding of mechanical bond strength. Especially, research and development requires a reliable comparison of bond strength data for different brazed joints.

Initially, emphasis must be placed on the room temperature mechanical strength of the brazements as a function of processing conditions and filler metal composition. This helps in gaining a basic understanding of the relationship between the composition of the brazed interface and the properties of the joint. The creation of a strong interface is not always sufficient to ensure production of a useable brazed joint between ceramic and metal. Joint design and selection of work pieces with compatible physical properties can play a dominant role as well [1].

Usually, ceramic/metal brazed joints are best designed to have a sleeve configuration, putting the ceramic in compression on cooling from the brazing temperature [1]. However, most reactive metal brazes flow sluggishly when compared to conventional filler metals, and their spreading depends on reactions to render the ceramics wettable. Thus, in

practice, butt joints and pre-placed braze alloys are often employed. Since reactive metal brazes are also brittle, care must be taken to choose work pieces with similar thermal expansion coefficients [1].

Effective ceramic to metal joining techniques are important for the future of ceramics since they allow ceramic components to be incorporated into existing metal parts. The major problem here is that materials differ substantially in their mechanical and physical properties, especially in their coefficient of thermal expansion. This can lead to high stresses at the joint interfaces which can be destructive to the joint. The various methods available for joining ceramic to metal are as follows [1]:

Adhesives. This is a simple and inexpensive method of joining but its usefulness is severely restricted due to temperature limitations with organic adhesives [16].

Mechanical Fasteners. Bolting and interference fitting are used to constrain ceramic parts in a metallic structure. However, this method imposes severe design restrictions.

Welding. Welding ceramic to metal can be done with or without an intermediary. Diffusion bonding and friction welding are examples of welding without an intermediary. Diffusion bonding processes using a metallic interlayer have proven very useful and sometimes are even preferred over brazing [5].

Brazing. Brazing and metallizing of ceramics to form joints with metals find extensive use in electronic applications. The Moly-Manganese and the active metal processes are widely accepted.

Soldering. Metallized ceramics and metal parts are joined below 425 °C (800 °F) using a non-ferrous filler metal or solder in soldering. There are severe limitations to soldered metal-ceramic joints due to temperature restrictions. Usually a service temperature range limit around 200 °F is observed for soldered ceramic/metal joints.

Ceramic to metal bonding is the result of chemical and mechanical interactions between the materials. The chemical interactions may result in the formation of new compounds at the interface or adhesion due to secondary bonding forces. Mechanical bonding results from interlocking of surface roughness and asperities of one phase with the other. Lower bonding strengths can result from incomplete contact due to inhomogeneities at the surface of both materials, including surface roughness and impurities. There have been numerous theories explaining the requirements for good bonding [17].

Joint Properties

There are many different properties to be considered in ceramic to metal joints, including mechanical, electrical, and thermal. Depending on how the joint is to be used, some properties are more important than others. However, the

mechanical properties of a joint are by far the most important. For the evaluation of the joint properties, it is essential to establish proper testing methods with meaningful results [1].

One of the most important problems of joining ceramic to metal is the thermal expansion mismatch between the two. This difference can lead to very high stresses at the interfaces during cooling from braze temperatures. These thermal stresses should be accommodated to obtain reliable joints.

The various process variables that can be considered here include joining materials, joint design, braze alloys, braze temperature, etc [1]. The problem of thermal expansion mismatch is even more pronounced when the joints are subjected to thermal and/or mechanical stress cycling.

Joining Materials

Ceramic to metal brazing involves four major materials: ceramic, metal, cap-metal or interlayer and filler metal. Each of these greatly influence the resultant joint [3].

Ceramic Component. Because the ceramic is inherently brittle, it is the most critical material of the joint system. The base properties of the bulk ceramic are of great importance since, if not sufficient, the thermal stresses alone will fracture the ceramic on cooling from the brazing

temperature. The surface condition of the ceramic is equally important for joint reliability. Hence, sintered ceramic materials are always preferred to as-ground ceramic materials for obtaining highly reliable joints [3]. Extensive use of resintering and lapping processes is made with ground ceramics to obtain joints with the best properties.

Metal Component. The metal, being generally or comparatively ductile, does not easily fracture. However, it should produce low blushing (surface flow) of the filler metal. The parameters controlling the blushing behavior are the relative properties of the metal and filler metal. For example, Cusil ABA shows no blushing on 304 stainless steel, alumina or copper, whereas extensive blushing is seen on nickel [3]. Blushing can be eliminated by proper selection of metal-filler metal combinations or by applying stop-off paint on the metal prior to brazing [1].

Additionally, a method to reduce the thermal stress due to thermal expansion mismatch between the ceramic and metal is to closely match their thermal expansion coefficients. However, there are only a limited number of ceramic-metal combinations to satisfy this condition. Another method to reduce the thermal stress effects is to use a metal having low yield strength. Here, the thermal expansion mismatch is accommodated by the plastic deformation of the metal member. This also severely limits metal selection.

Capmetal and Interlayers. Internal stresses caused by thermal expansion mismatches must be compensated when joining dissimilar metals and ceramics to metals. When the joint is cooled to room temperature from the high joining temperatures, sometimes high stresses are introduced in the ceramic. This is due to the differential thermal contraction and is often responsible for causing catastrophic damage to the joint. Thermal cycling or thermal shock effects may also be introduced when the joint is used at high temperatures [18].

There are two approaches to avoiding these problems. The first method involves using a soft metal interlayer which undergoes elastic and plastic deformation to compensate for and accommodate the thermal expansion mismatches. The second method deals with an interlayer with intermediate expansion coefficient reducing the differences in thermal expansion coefficients across individual interfaces [18].

Filler Metal. The active filler metal should be able to wet and bond strongly with the ceramic. However, it should also not blush over the ceramic or metal. Another important requirement is that it should be ductile enough to accommodate the thermal stresses. It is also advantageous if the filler metal can be tailored for specific applications like melting temperature, density, corrosion resistance, etc [1].

Geometrical Considerations in Ceramic/Metal Joining

Since metals have a coefficient of thermal expansion greater than that of most ceramics, rigid joints between ceramics and metals are stressed on cooling. The magnitude of these residual stresses depends on [1]

- difference in coefficient of thermal expansion
- joint geometry
- relative thickness of ceramic and metal
- and the ability of metal and braze to relax stresses.

It is desirable to match the thermal expansions of the ceramic and metal over the range from ambient to brazing temperature. Soft bars of copper can be used, but a low expansion metal like tungsten or molybdenum provide better joints. These contract less than most ceramics on cooling from brazing temperatures and may place the ceramic/metal interface in compression.

Thermal Expansion Mismatch

There are three points to be considered in obtaining good ceramic-metal joints: (1) bonding on the atomic scale, (2) lattice matching and (3) physical property matching (thermal expansion coefficient (α) and modulus (E)) [19]. Even if the bonds are good on the atomic scale, thermal expansion mismatches play a crucial role. Thermal expansion mismatches can be compensated for, either by using soft metals as interlayers or by the lamellar interlayer method [1] as shown

in Figure 4. Here, a number of interlayers with differing coefficient of thermal expansion are brazed such as to create a graded effect between the ceramic and the metal.

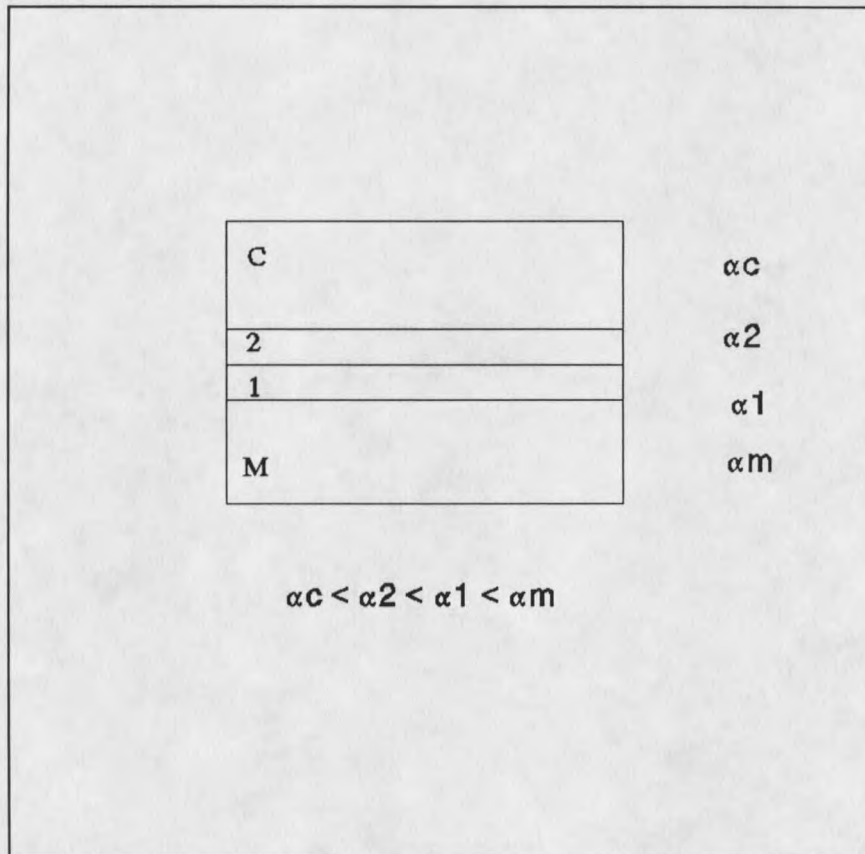


Figure 4. Graded technique to reduce the α mismatch between ceramics and metals [1].

The problem of how to compensate for thermal expansion mismatch can be a most serious one in ceramic to metal joining. Even if a strong interface can be achieved, joints with a high residual stress are easily broken. The most important stress in a ceramic-to-metal joint is the tensile residual stress perpendicular to the interface, which appears near or at the interface at the free surface in the ceramic

side [18]. Also, in specimens with square bond faces, the residual stresses are comparatively higher [18].

The strength of a bonded system is governed by a number of variables - the thermal and elastic mismatch, the plastic flow stress of the metal, the relative metal and ceramic layer thickness, the fracture resistance of the interface and the flaw distributions in the ceramic and at the interface [1].

Metallizing Processes

In this process a thin metallic layer is bonded to a ceramic substrate. It is usually an intermediate step before the main metal part is joined to the ceramic. Metallizing improves the wettability of the ceramic substrates for conventional braze filler metals and is now a widely used technique to produce good ceramic to metal seals. However, some active metals and their alloys or compounds also wet unmetallized ceramic substrates under certain conditions [1]. Hence, metallizing, is considered as a surface preparation for the ceramic and not as a part of the joining process. Metallized surfaces are usually coated with Ni, Cu or other metals. These metal coatings help in providing increased wetting for certain filler metals. They also eliminate adverse effects of the metallized surface on wetting and flow on the filler metal, and even act as a barrier to the penetration of the metallizing layer by the filler metal [9].

Metals used in ceramic to metal joints are also plated

to protect against oxidation of the metal surface, intergranular penetration by the filler metal, and to maintain cleanliness of the metal surface during storage [1].

Moly-Manganese Process. This is the most commonly used process to join ceramic to metal. It involves metallizing the ceramic followed by brazing, with the metallization of the ceramic conducted at high temperatures (1500°C) [9]. The process is well established and produces highly reliable joints, but it is time consuming since it is a two step process. Also, precise process control is required to ensure reliable joints [10].

Design Methodology

A significant research effort has been pursued into understanding the mechanical properties of ceramics and joined components. This involves finite element modelling down to a microscopic scale, studying the interfaces between ceramics and metals, and developing statistical representations for new design technologies [1]. Most structural ceramics contain flaws of random sizes, shapes and orientations, and, hence, material strength varies from part to part.

A reliable database which includes testing and design criteria must be available for advanced ceramic materials in order to evaluate ceramic-to-ceramic and ceramic-to-metal brazing. With the advent and commercial availability of Ag-Cu-Ti braze filler metals (eg. Cusil ABA from GTE WESGO), the one

step vacuum brazing of metals and ceramics has become practical. However, several criteria have to be met in selecting the right filler metal composition. Ductility, sufficient wetting and controlled flow are important. Also required are minimum surface flow (blushing) on both ceramic and metal. However, the degree of blushing also depends on the brazing temperature, metal-ceramic composition and brazing atmosphere [3].

Differential thermal expansion causes high thermal stresses in the joint region. As the size of the joint area increases it becomes more and more difficult to overcome thermal stresses by proper selection of joint materials. If the materials are already selected or the selection is limited, then this difficulty is overcome by using special joint designs. If design flexibility is present, then the choices are [7]:

Compliant Joint Design. Edge brazing is a familiar form of compliant joint design. Honeycomb structures or Feltmetal^R can also be used for such joints. The most popular of this type of joint design is the one using interlayers - both ductile metal interlayers and interlayers with intermediate thermal expansion coefficients. Such joints are also called gradient seals.

Compression Joint Design. In such joints the ceramic and the joint are forced into compressive stresses which improves the joint strength considerably. Here the thermal

expansion mismatch is utilized as an advantage to obtain a more reliable joint.

Stress-Distribution Joint Design. In this type of joint design backup materials are used to help increase the interface area which helps in distributing the thermal stresses over a larger area. Also, the stress distributions can be changed to a better advantage.

Ceramic/Metal Interface

The stability and strength of a ceramic/metal interface depends on the chemical and physical nature of the interface in a very complex way. The physical nature of the interface depends on the matching of the crystal lattices, thermal expansion of the involved phases and the presence of defects like pores, dislocations and grain boundaries [20]. Strength measurements of interfaces, like tensile tests, are useful for studying the effect of changes in the process conditions on the interface and are more representative of the strength of that particular test structure rather than the intrinsic interface strength. This makes it difficult to compare results from different studies.

High temperatures can sometimes help wetting, but attention has to be paid to factors such as environment quality, surface cleanliness, texture and flaws [21]. Reactive metal alloys change the chemistry, and hence the energy of the ceramic-metal interface. When Ti (active element) is present

in sufficient amounts it reacts with oxides to form TiO or, with other ceramics, TiN or TiC , which are wettable products. It is not practical to enhance wetting just by increasing Ti content since high concentrations of Ti can result in the formation of thick brittle layers at the interface [21].

It has also been shown that improved wettability can be obtained from Cu-Ti alloys with the addition of metals such as Sn and In, in which Ti is less soluble [1].

Since its formation is by liquid metal, the interface undergoes changes including solidification, thermal contraction and even phase changes. Chemical interactions on the microscopic scale resulting in the formation of new compounds at the interface have an effect on bond strength. These interactions are nucleated at discrete sites and proceed by further nucleation and growth of islands of the products bridging the interface [1]. The coverage of the interface increases with time, temperature and concentration of active metal, resulting in higher bond strengths.

Complete understanding of a ceramic-metal interface requires knowledge of the wetting and interface reactions, the microstructure and composition of interface compounds, the stress condition and atomic structure of the interface [12]. There are differences between interfaces being thermodynamically stable, mechanically stable and chemically stable. A thermodynamically stable interface is formed between two dissimilar materials if the interfacial free

energy of the bonded structure is less than the sum of free energies of the separate solid-vapor interfaces [12].

Failure Analysis of Ceramic Systems

Failure analysis is extremely important in ceramics or ceramic systems because it is the only means of isolating the failure-causing problem. It helps in differentiating between design deficiency failures and material deficiency failures. Fracture analysis is the examination of the fracture surfaces in an effort to reconstruct the sequence and cause of fracture [1]. Features on the fracture surface provide information like position at which fracture initiated (fracture origin), the cause of fracture initiation (impact, tensile overload, thermal shock, material flaw, etc.) and the local stresses that caused fracture.

A problem with testing ceramic systems in uniaxial tension is avoiding parasitic local stresses. Examination of the fracture surface for signs of cantilever curl (indicating bending) after tensile testing will help determine whether pure tension was achieved.

Again, if the part was pre-stressed or contained residual internal stresses, then the crack would not have passed straight through the thickness, but instead would have followed contours consistent with the stress fields it encountered [1]. Determining the cause of failure is very critical to defining specification requirements for material

and operating conditions [1].

Failure of Brazed Joints

Inclusions at the surface of the base metal, such as oxides, nitrides or sulfides can interfere with the flow of filler metal and, hence, result in low strength brazed joints. These inclusions also result from improper application of heat or excessive flux [22]. However, porosity of the brazed joint can result from improper cleaning of the brazing surfaces, vaporization of lower-melting constituents of the filler metal or the incomplete flow of the filler metal. Microporosity can result from shrinkage of filler metal or rapid cooling [22]. Incomplete brazing can also result from unsatisfactory cleaning, insufficient heating, improper fitting of brazing surfaces or surface contaminants [6].

Applications of Ceramic/Metal Joined Systems

Sometimes, excellent joint properties can be obtained by choosing the proper brazing technique, joint design and the right filler metal [1]. These brazed joints have better physical and mechanical properties than most welded joints. Their use with ceramic matrix composites also seems highly exploitable. Since the use of high performance structural ceramics is expected to grow in the near future, the growth of brazing as a major joining technique in these applications seems inevitable [1].

The major areas of current and potential applications

for structural ceramic systems are aerospace, automotive, nuclear and electronics. This means increased joining technique usage in production, prototypes and research and development in the following fields [1].

Aerospace

Gas turbines employ ceramic systems due to severe operating conditions and the need for higher operating temperatures for increased efficiency. Ceramics are used on parts such as bearings, shroud rings and turbine blades to enable higher temperature operation and allow tighter clearances due to low thermal expansion and improved wear resistance.

Automotive

Applications such as spark plug insulators, water pump seals, catalytic converter parts and piston crowns are where ceramic systems are already being used in this area. Reciprocating engines have many ceramic applications and, hence, joining requirements. These applications are related to two important advantages of ceramics - first, the wear resistance of high strength ceramics under high operating temperatures, and, second, the ability to provide a thermal barrier for higher efficiency engines. Examples include valves, valve seats and guides, tappets and fuel-injector nozzle pins.

Advanced structural ceramic systems have been

developed to operate at high temperatures with increased engine efficiency, but a major limitation becomes the reliability of the brazed or welded joint. The joint is, therefore, required to display the same qualities of high temperature service as the base material [23].

Electronics

Ceramic systems are being used for electronic components and packaging with high reliability. Plated copper thick film conductors are used in hybrid circuits on a number of new ceramic substrate materials [1]. Ceramics used in electronic components require metallization for electrode placements, surface creation for further bonding and other contact areas which involve extensive joining.

Another avenue for ceramic system use is heat dissipation associated with new integrated circuits (IC's). In these IC's the electrical current is forced through incredibly small (1 to 5 μm) conductors packed closely together. This generates heat which needs to be effectively dissipated. Most ceramics used as substrate materials have poor thermal conduction properties. BeO and AlN stand apart in their distinction of being suitable for hybrid packages and having good thermal and dielectric properties. The use of AlN improves thermal conduction by about ten times as compared to Al_2O_3 [24]. However, AlN is intrinsically difficult to bond with metals - a problem that does not exist with Al_2O_3 . New bonding techniques do offset the field in favor of AlN [25].

Nuclear

The reason for the potential use of ceramic systems in nuclear reactors is the possibility of operation at high temperatures in corrosive environments. Fuel element applications are where ceramic systems were applied and tested first. This involved brazing Al_2O_3 plates or BeO tubular brazed assemblies. Especially interesting is the fabrication of a Hall cell which involved a complicated ceramic brazing problem [24]. Another use for ceramics in fusion reactors is as insulating rings brazed to stainless steel rings. Ceramics like BeO-SiC have also been joined for use as wall materials [24]. They have high electrical resistivities and are brazed to stainless steel or copper using interlayers.

Miscellaneous

Every home has a joint between ceramic type material and metal in some form or the other. A common example would be an audio pickup which uses a diamond or sapphire brazed to a metal. In the steel industry, Al_2O_3 ladles are joined without removing the ladle from normal operating conditions using a technique for the hot repair of refractory materials [1].

Finally, development is on-going for the making of a whole series of brazing materials for ceramic to metal and ceramic to ceramic combinations.

As far as future potential of ceramic systems is concerned, for increased use a better understanding of joining

processes, especially at the ceramic/metal interface, by modelling wetting characteristics and chemical reactions becomes necessary [10]. With the ability to bond structural ceramics to high temperature alloys, the ceramic and metal field merge to provide the best combinations of both materials, and hence expand the markets for each [1].

Brazing and Fracture Mechanics

Adherence between similar or dissimilar materials is determined by the stress or load required to cause separation. This is useful in establishing a relative ranking of adherence between systems and also for quality control during production. Adherence in this context is considered to be the ability of the total joint system to resist fracture. However, since normally the failure stress of a brittle system depends both on the flaw size and the true adherence, a strength test by itself is not adequate to determine true adherence of the system [26]. Also, it becomes very difficult to relate adherence to material parameters in the region of failure - at the interface or in the bulk material.

Hence, selection of materials to form a joint or interface to achieve maximum adherence becomes the main problem. Fracture mechanics may be used to determine the adherence of brazed joints in a similar fashion to its use with the bulk behavior of brittle materials. In effect, either the stress intensity factor, K , or the strain energy release

rate, G , can be used to find the resistance to crack propagation along an interface or in an adjacent phase. The application of fracture mechanics to adherence of brazed joints can be quite complex [15]. Further, if the Young's modulus, E , and the Poisson's ratio, ν , of the two materials of the system are comparable, then the solution is the same as that for a crack in a single phase body. It may be that the adherence can be described in terms of K_{IC} under certain conditions of validity [26].

When considering experimental analysis, the use of the energy balance concept is far simpler, i.e., equating strain energy release rate, G_I , with the total energy required for crack propagation, R . The relationship is given by

$$K_I = \sigma Y(a)^{1/2} = (G_I E)^{1/2} \quad (2.3)$$

where a is the flaw size, σ is the applied tensile stress and Y is a geometric factor. Thus, G_I or K_I can be determined experimentally. Weibull related the probability of crack propagation as a function of flaw size, stress level and flaw frequency [1]. These are then related to a stress exponent.

Mechanical Testing

The mechanical testing of ceramic components is critical. The work of past years has resulted in the construction of databases. The reliability of ceramic structural components is becoming more and more critical, and methods to predict whether a component will fail under typical

operating conditions are gaining importance [27]. This requires a good description of stresses the component will be subjected to, along with the mechanical properties of the various parts of the component.

Mechanical testing is necessary to predict lifetime behavior. It is useful in assessing new materials, ranking materials for a specific application and also to predict failure [1]. Though mechanical testing gives a better idea of the failure characteristics when compared to non-destructive testing techniques (since critical flaws in ceramics are usually smaller than in metals), it usually does not take into account the effect of environmentally assisted crack growth [27].

A reliable database, which includes testing methods, test results and design criteria is required to evaluate brazed joints, especially metal-to-ceramic brazings. The major requirements of any testing methods used to evaluate ceramic-metal brazed joints are that they should [3]:

- lead to accurate and consistent results
- be capable of evaluating effects of processing variables on the joint properties
- provide meaningful results that can help in designing better joints.

There are many test methods for evaluating brazed joint strengths. However, the three frequently used tests are tensile tests, shear tests and peel tests.

Tensile Test

Bend tests cannot effectively detect randomly occurring defects in highly stressed parts due to the small material volumes which are highly stressed [27]. In tension tests, a larger material volume can be loaded. However, conventional tensile testing requires precision machined test specimens to minimize stress concentrations. Proper machining also minimizes uncontrollable bending when testing forces are applied. This results in higher costs per specimen, thus prohibiting extensive use of this method for process development and control [27].

Tensile tests provide bond strength data which are functions of specimen size and the testing mode employed. Another peculiarity to be considered in tensile tests is that fracture can occur far away from the interface when the bond strength is very high [28]. In most tensile tests on ceramic/metal joints, failure occurs predominantly in the ceramic and not the joint [3]. This is because the loading mechanism places the ceramic in tension. So, when the joint strength exceeds the tensile fracture strength of the ceramic, the tensile test becomes ineffective in evaluating the true ceramic/metal joint strength.

The term tension test usually refers to tests in which a prepared specimen is subjected to a gradually increasing uniaxial load until failure occurs. In a simple tension test this operation is accomplished by gripping opposite ends of a

piece of material and pulling it apart. The test specimen elongates in a direction parallel to the applied load until the material fails. Within the limits of practicality the resultant of the load is made to coincide with the longitudinal axis of the specimen. Usually, the test pieces or specimens are of approximately constant cross-section, since an attempt is made to obtain a uniform distribution of direct stress over a critical cross-section normal to the direction of applied load [29]. Tension tests may well be one of the simplest of all mechanical tests, but are not sufficient to enable the prediction of performance of materials under all loading conditions [23].

For brittle materials, only the fracture strength and the character of fracture are measured. It is also desirable to be able to predict the behavior of complex joined structures using the knowledge from accurate tests of simple specimens. One of the most important tests which has been used for many years to yield valid data has been the uni-axial tension test. This test has proven its effectiveness for metals and other ductile materials. Unfortunately, this test cannot be carried over to testing ceramic-metal brazed joints without some modifications.

In order to construct an accurate but simple tension test applicable to ceramic/metal brazed joints, those factors that contribute to error in testing must be eliminated or minimized (as an integral part of the system). The major

source of error that could be detrimental in uni-axial tension testing is caused by parasitic bending stresses. This, in turn, is reducible to an eccentric load induced within the specimen [29]. The eccentricity can be due to either the misalignment of the load device, misalignment of coupon or the misalignment of the load train. Unlike ductile materials, ceramics, being brittle in nature, do not deform locally and the eccentricity or misalignment is retained during the test, leading to gross errors [30].

The magnitude of error due to an eccentricity can be very high, and hence the primary prerequisite necessary for the attainment of accurate tensile joint strength data of ceramic/metal brazed joint specimens is the elimination or minimization of parasitic bending stresses. Thus, the ideal tension testing system is one which eliminates the eccentric load transfer to the uni-axial test specimen or, if this is not practical, at least minimizes it [23]. In the present study this is achieved by using a specialized fixture to hold the coupon, and a U-joint in the load train. There are also many new grips available for different testing machines which reduce the eccentric load problem [27,31].

This study covers the determination of the relative tensile strength of brazed joints by the use of bar butt joined specimens. Tension test specimens provide reasonably accurate information with regard to the tensile strength of these brazed joints. Tensile strength data may be suitable for

specification acceptance, service evaluation, manufacturing control and research and development. However, tension tests are not considered suitable for applications differing widely from the test in rate, direction and loading type [1].

Shear Test

This test yields the shear strength of the brazed joint. There are two commonly used shear tests. In the single brazed shear test, the shear strength measured depends on the compressive stresses at the joint. Hence the effect of the process variables cannot be properly evaluated [7].

In the double brazed shear test three blocks are butt brazed together and the center block is pushed relative to the end blocks, applying shear stress on two brazed joints simultaneously. This test yields the shear strength of the weaker of the two joints. The double brazed shear test has been shown to yield useful results despite potentially complex stress fields [7].

Peel Test

In this test, the load required to peel off a metal strip brazed onto a ceramic substrate is measured. It is a simple and economical test with fairly consistent results. However, the results obtained from this test cannot be easily translated into meaningful parameters for designing better joints [7].

CHAPTER THREE

MATERIALS AND METHODS

Materials

In this chapter the different materials used in this study are detailed with regard to their basic characteristics as related to their use in brazed joints. All materials used in this study were supplied in final form by the Avco Research Laboratories, Inc, a subsidiary of Textron, Inc.

Aluminum Nitride

Aluminum nitride (AlN) is a relatively new ceramic with a hexagonal crystalline structure. Its advantages are that it offers high thermal conductivity combined with good electrical insulating properties [25]. It is basically these properties that prompted its choice as the ceramic material to be used in electrodes with copper. In this study AlN is used in ceramic/metal brazed specimens. Table 2 summarizes some of the most important properties of AlN.

Although AlN is not suitable for high hardness wear applications, it could be an alternative to Al_2O_3 . Further important physical properties of AlN include resistance to water and thermal decomposition and stability in both oxidizing and reducing atmospheres [1]. As far as manufacturing is concerned, developments have allowed the production of 98% pure AlN, though pure AlN is difficult to

sinter and densify [1].

AlN is of great interest as a material for micro circuit substrates because of its high thermal conductivity, moderate dielectric constant and nearly exact coefficient of thermal expansion match with silicon [1]. Knowledge of AlN-metal interactions in bonding is useful for hermetic packing, metallizing and electroding of such substrates. Also, the contact angles for Ti containing alloys on AlN are known to be greater than zero at steady state [25].

Table 2. Selected properties of Aluminum nitride [1].

PROPERTY	VALUE
Density	3.26 gm/cm ³
Melting point	2400 °C
Dielectric loss	10 kV/mm
Thermal conductivity	170 W/m.K
Coeff. of thermal expansion	4.77x10 ⁻⁶ /°C
Hardness	Mohs 8
	Knoop 1200
Electrical resistivity	4x10 ²⁰ μΩcm

Aluminum nitride is a highly refractory ceramic with excellent thermal conductivity - higher than most metals - as well as good electrical insulation characteristics. Until

recently the predicted high thermal conductivity values for AlN were not achieved experimentally, possibly due to imperfections in the crystal, which has prevented its extensive use [25]. The thermal expansion coefficient of AlN is also fairly low, as shown in Table 3, which compares the properties of several ceramics.

Table 3. Comparative properties of several ceramics [25].

Property	Units	AlN	BeO	Al ₂ O ₃	SiC	Si ₃ N ₄
Density	g/cm ³	3.26	2.9	3.96	3.2	3.3
Thermal conductivity	W/m.K	140- 170	150- 250	10-35	90	10-40
Coeff. of thermal exp.	10 ⁻⁰⁶ /K	2.65	5.4	5.5	3.13	3.1
Electrical resistivity	μΩcm	4x10 ¹⁷	10 ²⁰	>10 ²⁰	>10 ⁰⁶	10 ¹⁵

Aluminum nitride also has moderate hardness and comparatively high rupture strength. As a consequence of high thermal conductivity and low thermal expansion coefficient, AlN has good thermal shock resistance. The chemical properties of AlN are also very attractive. The oxidation rate is rather slow in fully dense material even at high temperatures due to the formation of a protective oxide coating. Dissociation becomes prominent only after 1500°C in vacuum [32]. AlN is

also resistant to water and is very stable against molten metals (like Al, Ga, Ge, Si) and molten salts [32].

When AlN is brazed using an active metal brazing alloy (usually containing Ti), the titanium in the braze alloy migrates to the interface where it is found in a Cu containing phase. The Ti reacts with AlN to give TiN and with increasing time at temperature (above 900°C), the thickness of the TiN layer increases [12]. It has also been reported that the Al from the reaction $\text{Ti} + \text{AlN}$ appears to alloy with the metal remaining at the interface [25].

Aluminum nitride has been accepted as an attractive dielectric substrate material with high thermal conductivity. As far as electrical properties of AlN are concerned, it is typical of an insulating material [33].

In conclusion, AlN is a ceramic with high thermal conductivity, low coefficient of thermal expansion, high electrical breakdown strength, good resistance to thermal shock and fair mechanical properties. It is also highly resistant to thermal decomposition, is non-toxic and is stable in oxidizing and reducing atmospheres at elevated temperatures.

Beryllium Oxide

Beryllium oxide (BeO), like AlN, is also used as a ceramic insulator in cold copper electrodes. Hence, it is incorporated as a ceramic in the ceramic/metal brazed test specimens. It is the richest simple and stable oxide of all

metal oxides with respect to oxygen content [34]. BeO has oxygen atoms in close hexagonal packing, tightly linked together by means of small beryllium atoms between them. Among oxide ceramics beryllium oxide is special mainly due to its high melting point and exceptionally high thermal conductivity. In fact, BeO is a greater heat conductor than beryllium metal itself, and its extreme heat conductivity is a unique property [1]. However, its thermal conductivity decreases linearly with increased temperature. Pure BeO is also an excellent electrical insulator due to its high electrical resistivity, making it one of the best electric insulators, especially at elevated temperatures [1].

Some important properties of Beryllium oxide are given in Table 4.

Table 4. Selected properties of Beryllium oxide [34].

PROPERTY	VALUE
Density	3.0 gm/cm ³
Melting Point	2530 °C
Hardness	Mohs scale 9
Thermal conductivity	264 W/m.K
Coeff. of thermal expansion	5.8x10 ⁻⁰⁶ /°C from 0-200°C
Electrical resistivity	10 ¹⁴ μΩcm

BeO has a considerably higher thermal conductivity than Alumina (Al_2O_3), but its use has been restricted because of toxicity.

Tungsten

In this study tungsten (W) is used first in metal/metal brazed specimens with different braze alloys to understand its effectiveness when brazed with other materials. Tungsten has the lowest thermal expansion coefficient among metals, about $5 \times 10^{-6}/^\circ\text{K}$ up to 1000°K [35]. This property of tungsten is then taken advantage of in ceramic/metal brazed joints, as it is used as an interlayer or cap-metal to reduce the thermal expansion mismatch. Table 5 outlines important properties of tungsten.

Table 5. Selected properties of tungsten [35].

PROPERTY	VALUE
Density	19.3 g/cm ³ at 20°C
Melting point	3400°C
Coeff. of thermal expansion	$4.5 \times 10^{-6}/^\circ\text{C}$ from 0-100°C
Electrical resistivity	5.4 $\mu\Omega\text{cm}$ at 20°C
Thermal conductivity	174 W/m.K for 0-100°C

Tungsten also has a high melting point, high strength at high temperature, and high resistance to oxidation at high

temperatures. Tungsten is widely used in electrical equipment due to its hardness, melting point, resistance to wear, electrical conductivity and resistance to oxidation [1].

Molybdenum

Molybdenum (Mo), like tungsten is used in the metal/metal brazed joints with different braze alloys to study its effectiveness in being brazed with other metals. Then it is used as an interlayer or cap-metal in ceramic/metal brazed joints due to its lower thermal expansion compared to copper. Molybdenum is usually used as an alloying addition and for electrical and electronic parts. Selected properties are summarized in Table 6.

Table 6. Selected properties of molybdenum [35].

PROPERTY	VALUE
Density	10.2 g/cm ³ at 20°C
Melting point	2615°C
Coeff. of thermal expansion	5.1x10 ⁻⁶ /°C from 0-100°C
Electrical resistivity	5.7 μΩcm at 20°C
Thermal conductivity	137 W/m.K for 0-100°C

Some of the more important uses of molybdenum are in high-temperature furnace parts, thermocouples, corrosion resistant equipment and nuclear energy applications. It is not

suitable for continued service at temperatures above 500°C in an oxidizing atmosphere unless protected by an adequate coating [35].

Molybdenum has particularly good resistance to corrosion by mineral acids. It is also resistant to most liquid metals. It can be formed by most conventional methods but is not heat treated or joined mechanically. However, absolute cleanliness of the surface is essential in joining molybdenum [1].

O.F.H.C Copper

Oxygen free high conductivity (O.F.H.C) coppers like C10100 or C10200 in foil form are used in this study as ductile metal interlayers. Previous designations to this form of copper are oxygen-free electronic copper or oxygen free copper. Typical applications are as lead-in wires, bus bars, vacuum seals, glass to metal seals, etc. These are high conductivity electrolytic coppers produced without the use of metal or metalloids deoxidizers [35]. The only precaution when using them is to avoid prolonged heating in oxidizing atmospheres. These coppers have excellent resistance to atmospheric corrosion and to corrosion by water. They also show anodic and chemical passivity. They are readily formed by a wide variety of hot and cold methods, and can be readily soldered and brazed with hot working temperatures varying from 750°C to 875°C [35]. The preferred methods of brazing are furnace or torch brazing[1]. Selected properties of O.F.H.C

coppers are as given in Table 7.

Table 7. Selected properties of O.F.H.C copper foils [35].

PROPERTY	VALUE
Density	8.94 gm/cm ³ at 68 °C
Melting point	1083 °C
Electrical Resistivity	1.71 $\mu\Omega$ cm at 20°C
Thermal conductivity	391 W/m.K at 20°C
Coeff. of thermal expansion	14.98x10 ⁻⁰⁶ /°C

Copper

Copper has been an excellent choice for use as cold electrodes in M.H.D channels [36]. As a comparison with the other materials used in this study, selected properties of copper are given in Table 8.

Table 8. Selected properties of copper [35].

PROPERTY	VALUE
Density	8.96 g/cm ³
Melting point	1084°C
Thermal Conductivity	397 W/m.K for 0-100°C
Coeff. of thermal expansion	17x10 ⁻⁰⁶ /°C from 0-100°C
Electrical Resistivity	1.694 $\mu\Omega$ cm at 20°C

Hence, in this study, regular copper is used as an end material in the metal/metal brazed specimens as bars with dimensions of (0.45 x 0.45 x 1.00) inches and as pegs of dimensions (0.625 x 0.625 x 0.844) inches, with water holes for cooling the electrode in ceramic/metal brazed specimens.

Braze alloys

559. 559 is a commercial braze alloy. It is often called Handy harmon silver copper eutectic.

Au-Ni. Au-Ni is a gold nickel braze alloy, also used extensively commercially.

Cusil ABA. Cusil ABA (Active Braze Alloy) is a true alloy with titanium as the active element. The nominal composition of Cusil ABA is 63% silver, 1.75% titanium and the balance copper [37].

GTE-WESGO introduced Cusil ABA to help in the manufacture of protective devices such as surge arresters and many other similar applications. Cusil ABA is an active braze alloy that yields high strength, hermeticity and reliability in ceramic-metal and ceramic-ceramic bonds without prior metallization [1]. The various physical and electrical properties of Cusil ABA are listed in Table 9.

Furnace brazing is the recommended method for using Cusil ABA with a vacuum (10^{-5} torr) or inert gas (Argon or Helium) furnace atmosphere. The recommended brazing temperature is 830-850 °C [37]. It wets and bonds to nearly

all metallic and non-metallic surfaces, such as oxides, nitrides and carbides, and produces strong joints with ceramics upon adequate treatment of ceramic surfaces.

Table 9. Selected properties of Cusil ABA [37].

PROPERTY	VALUE
Liquidus temperature	1500°C
Solidus temperature	1435°C
Density	9.87 gm/cm ³
Thermal conductivity	180 W/m.K
Coeff. of thermal expansion	18.54x10 ⁻⁰⁶ /°C
Electrical resistivity	4.4 μΩcm

Preparation Of Specimens

The metal/metal brazed tensile test specimens were constructed with different combinations of center material sandwiched between end materials. Various combinations were brazed using different braze alloys. This was done mainly to generate a better understanding of the brazing properties of the various materials and the effectiveness of the braze alloys used. Aluminum nitride and beryllium oxide were the ceramic materials used for the tensile tests in ceramic-metal brazed joints. The specimens were prepared as compound bars

with the ceramic sandwiched between various combinations of cap-metals or interlayers, OFHC copper foils and copper pegs. The specimens were made symmetric through the midpoint of the ceramic so that there was no difference in the upper and lower section joints (Figure 5). The properties of two joints can be tested in a single test, but the joint strength of the weaker joint only is determined. The brazing alloy used was Cusil ABA which proved very effective in studies with metal/metal brazing. The compound specimen bars were then held in an alignment apparatus and fired in a furnace in vacuum to obtain strong bondings. Most of the brazing technique and surface preparation remain proprietary. Holes (0.188 in. dia) were drilled in the copper pegs as water holes to cool the electrode. These holes were in turn adapted to hold turn-buckle pins to help mount the specimens to the self-alignment fixture.

Surface Preparation

Joint surfaces prior to brazing must be clean and free from dirt, grease, oxides, scales and other foreign substances. Chemical de-greasers (solvent or alkali) and mechanical methods (sanding, wire-brushing, grinding, scraping or filing) are employed. Only chemical pickling solutions may remove oxide films completely. However, the actual methods used in the preparation of specimens for this study remain proprietary.

Metal/Metal Brazed Specimens

The metal/metal brazed specimens were made up of copper, molybdenum or stainless steel 446 as the end materials with different combinations of center materials (tungsten, molybdenum and platinum) and thicknesses (0.250 in., 0.375 in. and 0.010 in.). The choice of the braze filler metal and the corresponding brazing temperature (559 at 950 °C, Cusil ABA at 900 °C and Au-Ni at 1000 °C) also provide different combinations of specimens. Figure 5 shows the metal/metal brazed test coupon composition and dimensions. In particular, the combinations and dimensions of interest are summarized in Table 10.

Table 10. Metal/metal brazed test coupons and their composition.

Sample Group ID#	End Material	Center Material	Center Dim. (A)	Braze alloy & Temperature
MT 1	Cu	W	0.250in.	559 at 950 °C
MT 2	Cu	W	0.250in.	CusilABA at 900 °C
MT 3	Cu	Mo	0.250in.	559 at 950 °C
MT 4	Cu	Mo	0.250in.	CusilABA at 900 °C
MT 5	Mo	W	0.250in.	559 at 950 °C
MT 6	Mo	W	0.250in.	CusilABA at 900 °C
MT 7	Mo	W	0.250in.	AuNi at 1000 °C
MT 8	Cu	W	0.250in.	CusilABA & AuNi at 1000 °C
MP130 A	Cu	Pt	0.010in.	AuNi at 1000 °C
MP130 B	Cu	W	0.375in.	AuNi at 1000 °C
MP130 C	446 SS	Pt	0.010in.	AuNi at 1000 °C

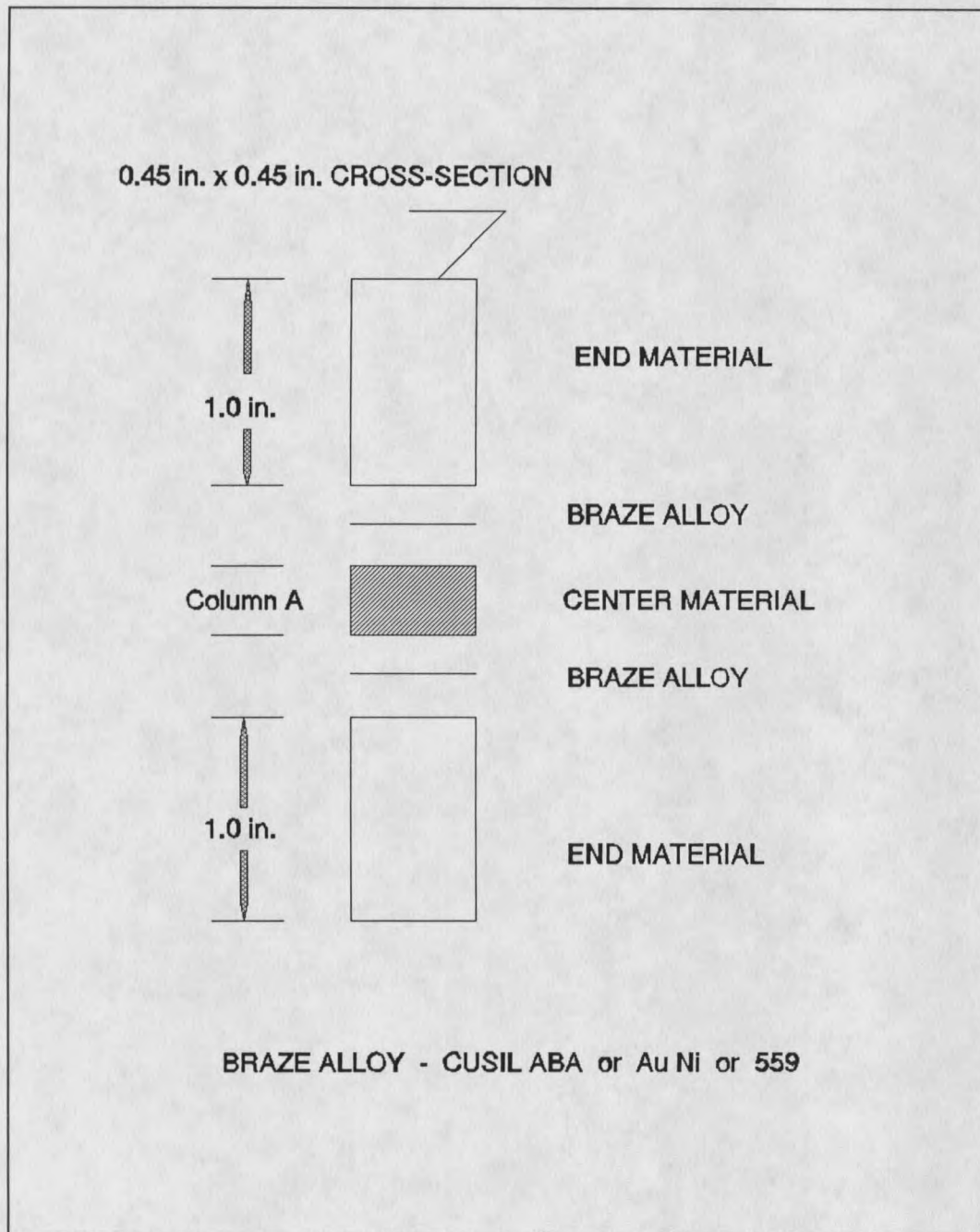


Figure 5. Exploded view of metal/metal brazed test coupon.

Ten specimens are tested for each of the above combinations. All the coupons have a constant square cross-sectional area of approximately 0.2025 in.².

Ceramic/Metal Brazed Specimens

The ceramic/metal brazed coupons are much more complex than the metal/metal ones. The choice of ceramic is limited to either aluminum nitride or beryllium oxide and their thicknesses are between 0.025 in. and 0.187 in.. Specimen symmetry is obtained by sandwiching the ceramic between the metal pieces. Copper pegs are used on both ends for gripping. These pegs are drilled with 0.188 in. diameter holes for water cooling. These holes are used with hardened steel dowel pins to help mount on the testing machine and to transmit tensile load to the joint. Cusil ABA is the active braze alloy used in all joints of this group. Molybdenum or tungsten are used as cap-metals on the upper and lower sides of the ceramic to help reduce residual thermal stresses on cooling from brazing temperatures. OFHC copper foils in different thicknesses (0.01 in. and 0.04 in.) are used as ductile metal interlayers and create different combinations of coupons to be tested. Figure 6 shows the various elements of a ceramic/metal brazed test coupon with dimensions. The various combinations and dimensions that were tested are summarized in Table 11. Since the coupons are symmetric about the ceramic in the middle, the composition of only one half of the coupon is given.

Table 11. Ceramic/metal brazed test coupon - composition (Coupon symmetric about ceramic).

Copper Peg Dimensions (in.)	Cap Metal Type	Thick. (in.)	Cusil ABA Thick. (in.)	OFHC Foil Thick.(in.) (D & G)	Ceramic Type	Thick.(in.) (F)	No. of coupons	Coupon ID #
5/8 x 5/8 x 0.844	Mo	0.375	0.002	0.00	AlN	0.025	3	PA1-1,2,3
5/8 x 5/8 x 0.844	Mo	0.375	0.002	0.00	AlN	0.187	3	PA2-1,2,3
5/8 x 5/8 x 0.844	Mo	0.375	0.002	0.00	BeO	0.025	3	PB1-1,2,3
5/8 x 5/8 x 0.844	Mo	0.375	0.002	0.00	BeO	0.187	3	PB2-1,2,3
5/8 x 5/8 x 0.844	W	0.375	0.002	0.00	AlN	0.025	3	PA3-1,2,3
5/8 x 5/8 x 0.844	W	0.375	0.002	0.00	AlN	0.187	3	PA4-1,2,3
5/8 x 5/8 x 0.844	W	0.375	0.002	0.00	BeO	0.025	3	PB3-1,2,3
5/8 x 5/8 x 0.844	W	0.375	0.002	0.00	BeO	0.187	3	PB4-1,2,3
5/8 x 5/8 x 0.844	Mo	0.375	0.002	0.01	AlN	0.025	3	PA5-1,2,3
5/8 x 5/8 x 0.844	Mo	0.375	0.002	0.01	AlN	0.187	3	PA6-1,2,3
5/8 x 5/8 x 0.844	Mo	0.375	0.002	0.01	BeO	0.025	3	PB5-1,2,3
5/8 x 5/8 x 0.844	Mo	0.375	0.002	0.01	BeO	0.187	3	PB6-1,2,3
5/8 x 5/8 x 0.844	Mo	0.375	0.002	0.04	AlN	0.025	3	PA7-1,2,3
5/8 x 5/8 x 0.844	Mo	0.375	0.002	0.04	AlN	0.187	3	PA8-1,2,3
5/8 x 5/8 x 0.844	Mo	0.375	0.002	0.04	BeO	0.025	3	PB7-1,2,3
5/8 x 5/8 x 0.844	Mo	0.375	0.002	0.04	BeO	0.187	3	PB8-1,2,3

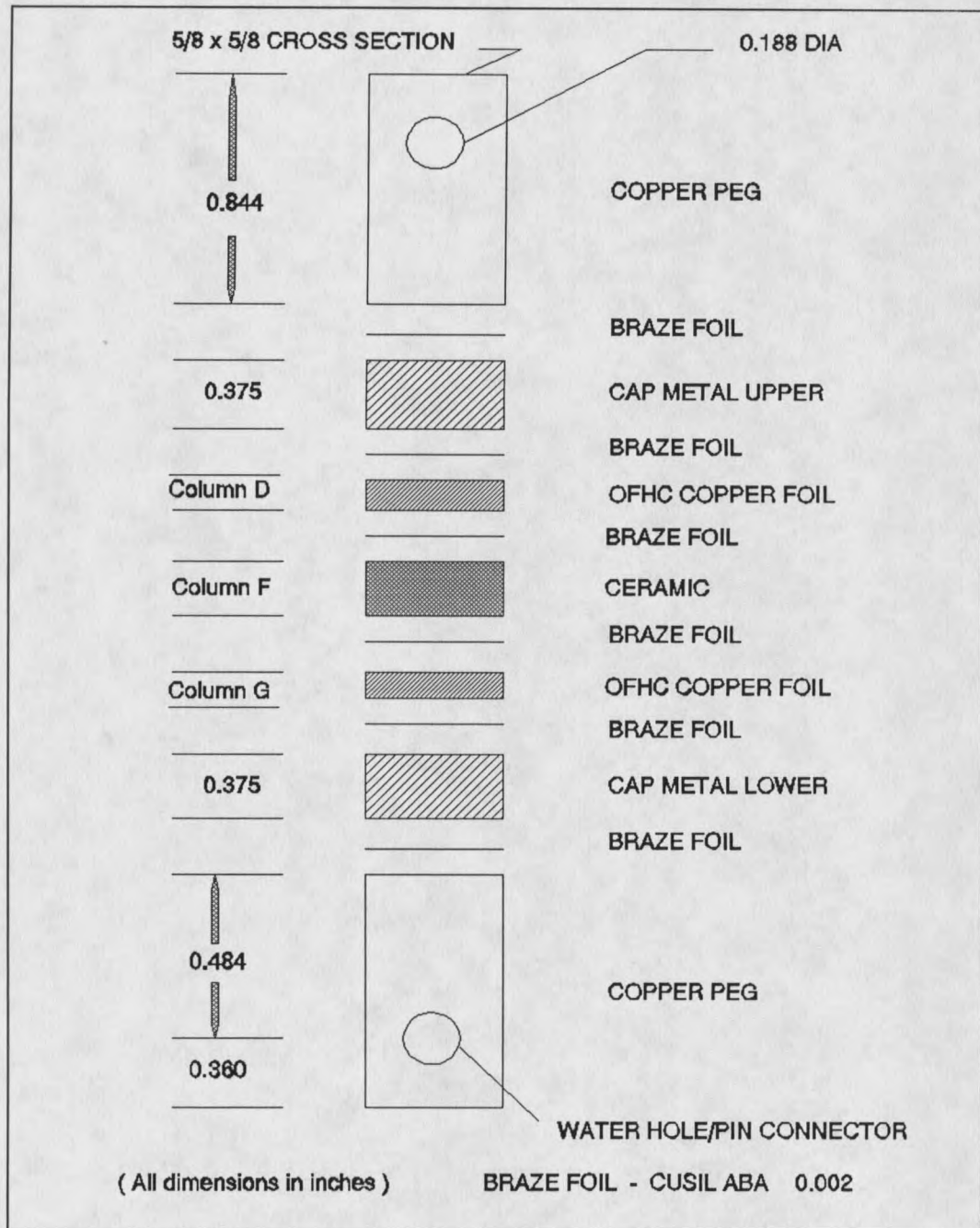


Figure 6. Exploded view of ceramic/metal brazed test coupon.

Gripping Devices

The function of the gripping devices is to transmit the load from the heads of the testing machine to the test specimen. The essential requirements are that the load be transmitted axially to the specimen, ie. the center of the grips be in alignment at the beginning and during the progress of a test, and that no bending or twisting be introduced to the specimen. Since only strength values are desired, a relatively short specimen length suffices. The advantage of having longer specimen lengths to adjust to incidental misalignments would be useful, but was not practical given the fabrication methods.

An attempt was made to isolate all bending forces using an attachment to hold the specimens. This attachment fixture is used to hold the specimen between the fixed member and the movable member of the testing machine. It consists of two separate fixtures - one attached to the lower movable head of the testing machine and the other attached to the fixed upper head, but with a U-joint introduced in the load train. The attachment was designed to be of the self-aligning type. The fixtures are attached to the fixed and movable members of the testing machine in such a way that they move into alignment as soon as the load is applied. The fixture is a clevis with holes to accommodate the specimen as shown in Figure 7. The specimen is attached to the fixture using

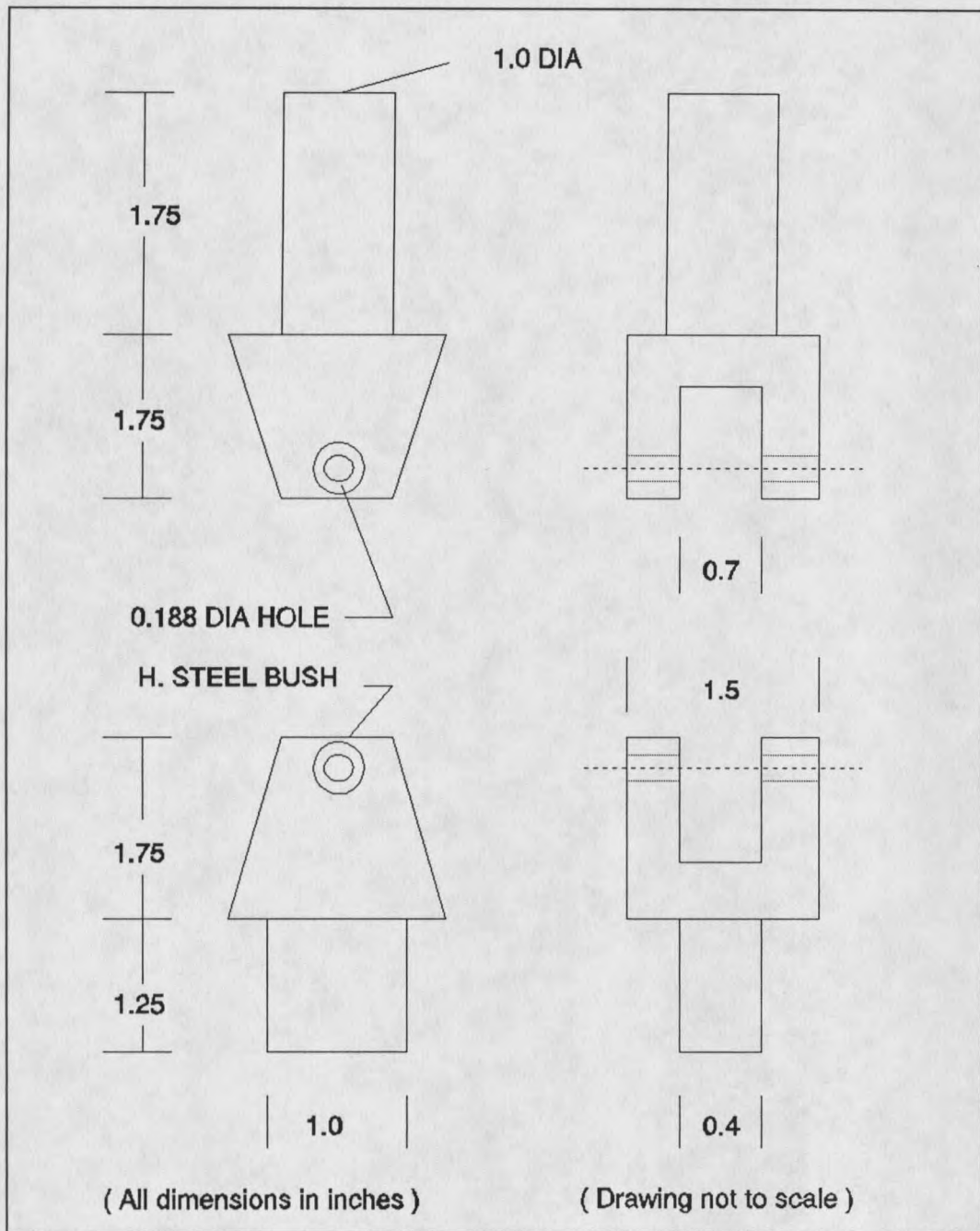


Figure 7. Clevis used to grip the test coupons.

hardened steel dowel pins. When loaded, the U-joint on the upper fixture ensures that the long axis of the test specimen coincides with the direction of the applied load.

Experimental Techniques

Initially, the specimen identification number and its upper end were marked with a permanent marker. The specimen was then checked for any serious misalignments and inherent flaws evident to the unaided eye. Measurements of length and cross-sectional area were also recorded for the specimen.

The specimen was then placed in the gripping fixture using hardened steel dowel pins. The upper end of the specimen was fixed to the upper fixture using the upper dowel pin. Then the lower grip fixture was moved into alignment so that the lower dowel pin could be inserted. Care was taken to ensure that no excessive load was applied on the specimen during mounting. The lower grip fixture was gently lowered to exert a small load on the specimen to remove slack on the load train; and the U-joint along with the clevis were adjusted to eliminate misalignments. The testing fixture setup with specimen is shown in Figure 8. The Instron 8562 servo electric test machine was switched to position control, and single ramp routine program (set up by Dr.J.Schutz, presently with Materials Research and Engineering, Boulder, Colorado) was run on computer control. The loading rate was specified on position control as 0.01 in./min or 0.05 in./min, and maximum

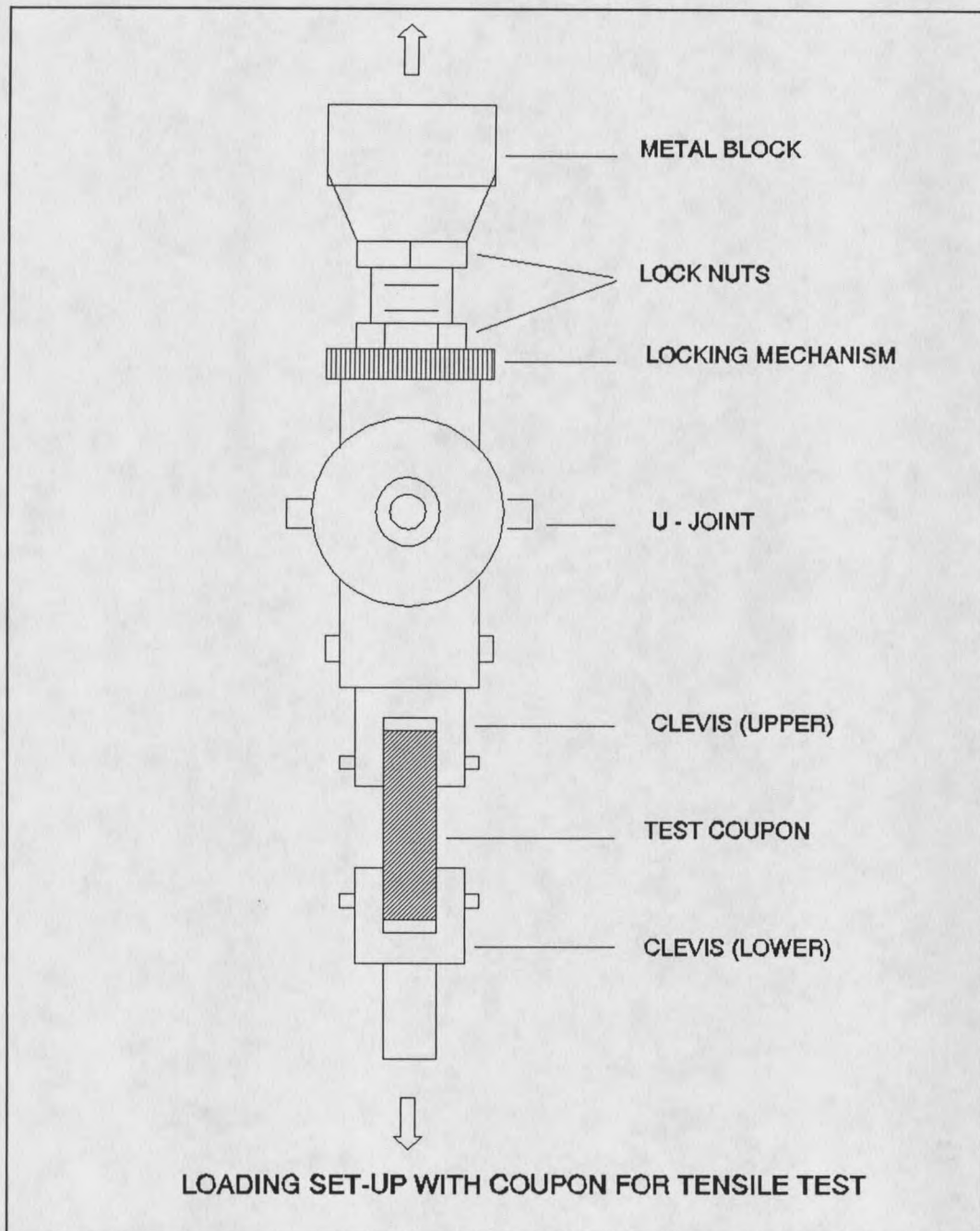


Figure 8. Testing fixture setup with test coupon.

limit was also set. Testing and data acquisition were controlled by the computer using a GPIB interface between the computer and the testing machine.

The specimen was loaded to failure and data were automatically stored in the appropriate file. The joint strength was taken from the maximum load on the display of the testing machine. Time to failure for the specific test was also recorded. The failed specimen was carefully removed from the fixture. The failure region and other immediately evident data were recorded. The failure stress on the joint was calculated using maximum force divided by the specimen cross-sectional area.

The average joint strength based on the individual strength values was computed. The standard deviation, S_F , of the joint strength was determined using the equation:

$$S_F = \sqrt{\frac{\sum_{i=1}^n (F_{Ji} - \bar{F}_J)^2}{n}}$$

where F_{Ji} is the individual specimen strength, and $\bar{F}_J$ is the average strength for the group of n specimens.

Specimens that fail due to some obvious flaw, like incomplete brazing, testing problem or abnormal behavior were not considered for analysis.

CHAPTER FOUR

RESULTS AND DISCUSSION

ResultsNomenclature

A broad range of component materials has been included in this study, as outlined in the preceding chapter. For convenience, an abbreviated nomenclature is used to refer to particular material combinations. For the metal/metal brazed specimens, a sample with copper as the end material, tungsten as the center material and Cusil ABA as the braze alloy at 900°C brazing temperature (refer to Figure 5) is represented as Cu/W(Cusil ABA, 900°C).

Ceramic/metal brazed specimens require a more complex representation. There are two groups - those with and without O.F.H.C copper foil (in two different thicknesses). Since all the specimens have copper pegs (both upper and lower), copper is not mentioned in the nomenclature. The same is true in the case of braze alloy Cusil ABA. Hence, a combination with tungsten as capmetal or interlayer and AlN ceramic of 0.025 in. thickness but without O.F.H.C copper foil is represented as W/AlN(0.025 in.). A combination with tungsten as capmetal, AlN ceramic of 0.025 in. thickness and O.F.H.C copper foil of 0.01 in. thickness (refer Figure 6) becomes W/Cf(0.01 in.)/AlN(0.025 in.). The use of this nomenclature is essential when comparing the effects of the various components.

Metal/Metal Brazed Specimens

Initial tensile tests were conducted on the metal/metal brazed test coupons to determine the optimum braze alloy for a particular combination of materials. These tests also helped in understanding the effectiveness of the different combinations of materials to form good brazed joints. Since these specimens were comparatively small compared with the ceramic/metal specimens, and since brittle behavior was not expected, the test fixture with the U-joint was not used in these tests. The test coupons were directly clamped in the testing machine hydraulic grips and loaded to failure. The gripping forces were high enough that the end material usually yielded, reducing any specimen misalignment. The results of the room temperature tensile tests conducted on the metal/metal brazed joints are summarized in Table 12. The complete test results are in Appendix A (Table 14).

Table 12 shows the number of specimens, average joint strength and standard deviations for each metal/metal material tested. The specimens failed at different locations - some along the lower bond, i.e., the joint between the center material and lower end material or along the upper bond, i.e., the joint between the upper end material and the center material. Some failures occurred through the center material and some predominantly along the center material but very close to either the lower or upper joints. Also noted was that most specimen groups had low mean values arising from rather

Table 12. Metal/metal brazed coupons - Tensile test results.

SAMPLE GROUP	MATERIAL (*)	No.	FAILURE FORCE (lbs)	
			MEAN	S.D
MT1	W/Cu (559, 950°C)	9	1083.51	512.42
MT2	W/Cu (Cusil ABA, 900°C)	10	1509.04	336.76
MT3	Mo/Cu (559, 950°C)	10	1298.01	450.21
MT4	Mo/Cu (Cusil ABA, 900°C)	10	1124.60	116.80
MT5	W/Mo (559, 950°C)	10	3188.75	794.04
MT6	W/Mo (Cusil ABA, 900°C)	8	4410.83	1931.77
MT7	W/Mo (Au-Ni, 1000°C)	9	1711.00	967.27
MT8	W/Cu (AuNi&CusilABA, 1000°C)	10	1375.90	348.53
P130-A	Pt/446 S.S (Au-Ni, 1000°C)	7	11063.40	2881.87
P130-B	W/Cu (Au-Ni, 1000°C)	10	1654.87	415.59
P130-C	Pt/Cu (Au-Ni, 1000°C)	10	5144.37	471.83

* See Table 10. for details of sample materials and construction.

high standard deviations.

Appendix B contains the representative load versus displacement curves for the different specimen groups. For those specimens where the failure did not occur at the interface (either lower or upper), it can be assumed that the joint strength was higher than the tensile failure strength for the material (either center or end). Hence, the tensile test did not measure the actual braze strength but merely provided a lower limit.

Failure sites in metal/metal coupons

Failure at the interface, either at the joint between the upper end material and center material or at the one between the center material and the lower end material is termed Type 1 (Type 1 in Figure 9). Fracture usually started from an inclusion or void at the interface and then propagated through the interface.

However, failure often occurred through the center material, very close to an interface or sometimes even partially through the interface. This was termed as the Type 2 failure (Type 2 in Figure 9). The third type of failure occurred through the center material, away from the interfaces (Type 3 in Figure 9). The fourth type of failure was through the center material, very close to the interface near the edges and corners and away from the interface at the center (Type 4 in Figure 9).

Considering the different combinations, for the

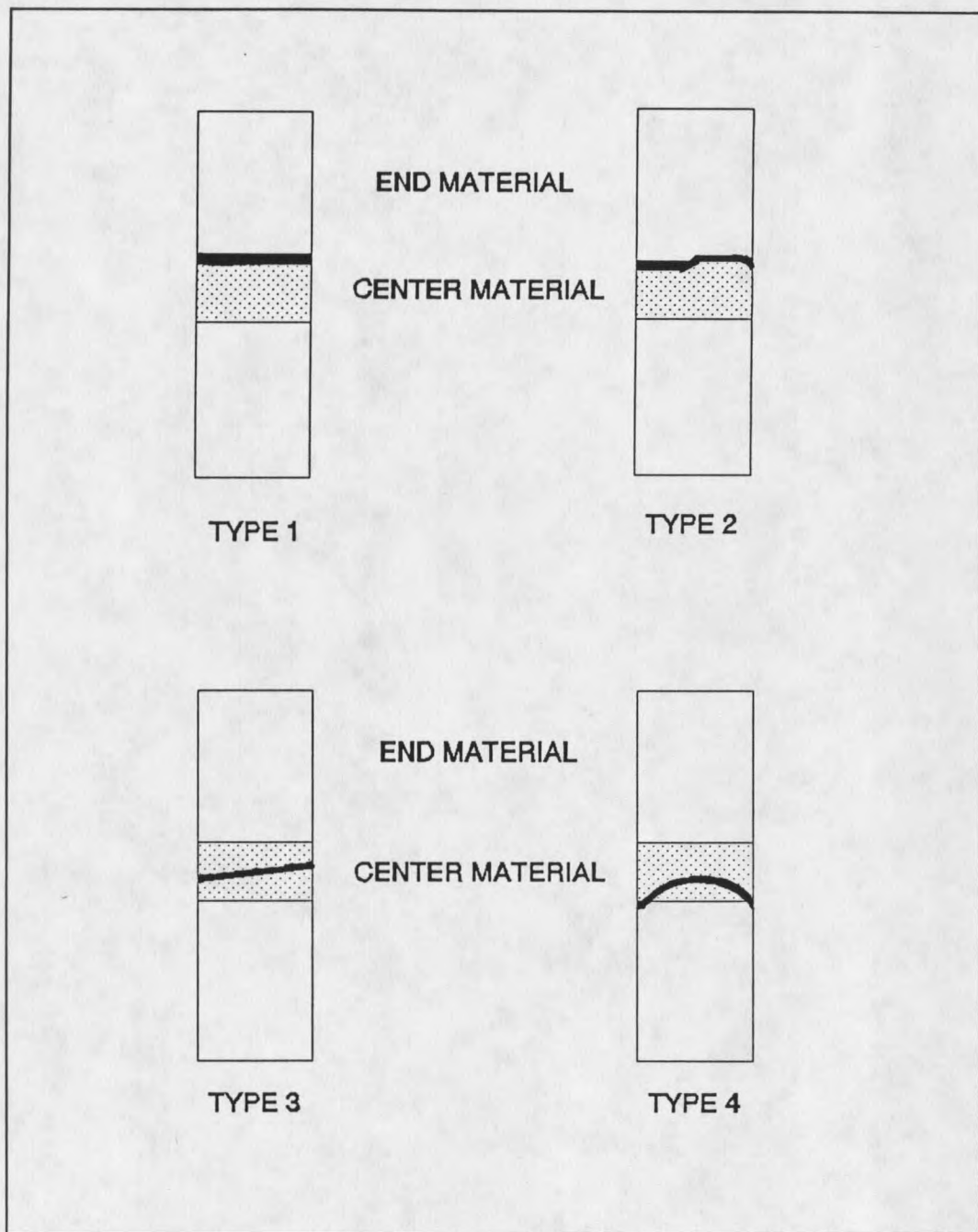


Figure 9. Failure types according to location in metal/metal brazed coupons.

W/Cu(559,950°C) combination failure was mostly of Type 1. However, these specimens also suffered from severe misalignment, which could have introduced parasitic bending stresses on gripping in the testing machine. Also evident in these specimens was extensive braze alloy flow and end material erosion on the sides (see Figure 10). This combination also had the lowest average joint strength value of all the combinations tested, only around 5 ksi. Failure was always at the interface between the center material (tungsten) and the braze alloy (559), suggesting that there was problem in the braze alloy wetting and bonding to tungsten. The W/Cu(Cusil ABA,900°C) combination had failures of Type 2, with slightly improved average joint strength value in the range of 7 ksi, possibly due to the better braze alloy for this combination. Here, the braze alloy seemed to be wetting and bonding to tungsten. However, most of the failures occurred through the braze alloy/center material interface.

The Mo/Cu(559,950°C) combination showed failure of Type 2, with a few exceptions. Again, braze alloy flow over the sides of the specimen was visible, and the average joint strength value was around 6.5 ksi. However, the Mo/Cu(Cusil ABA,900°C) combination also had Type 2 failure with not much of an improvement in joint strength from the previous combination, the average value being around 6.4 ksi.

The W/Mo(559,950°C) combination also showed Type 2 failures. Here, a marked increase in joint strength (average

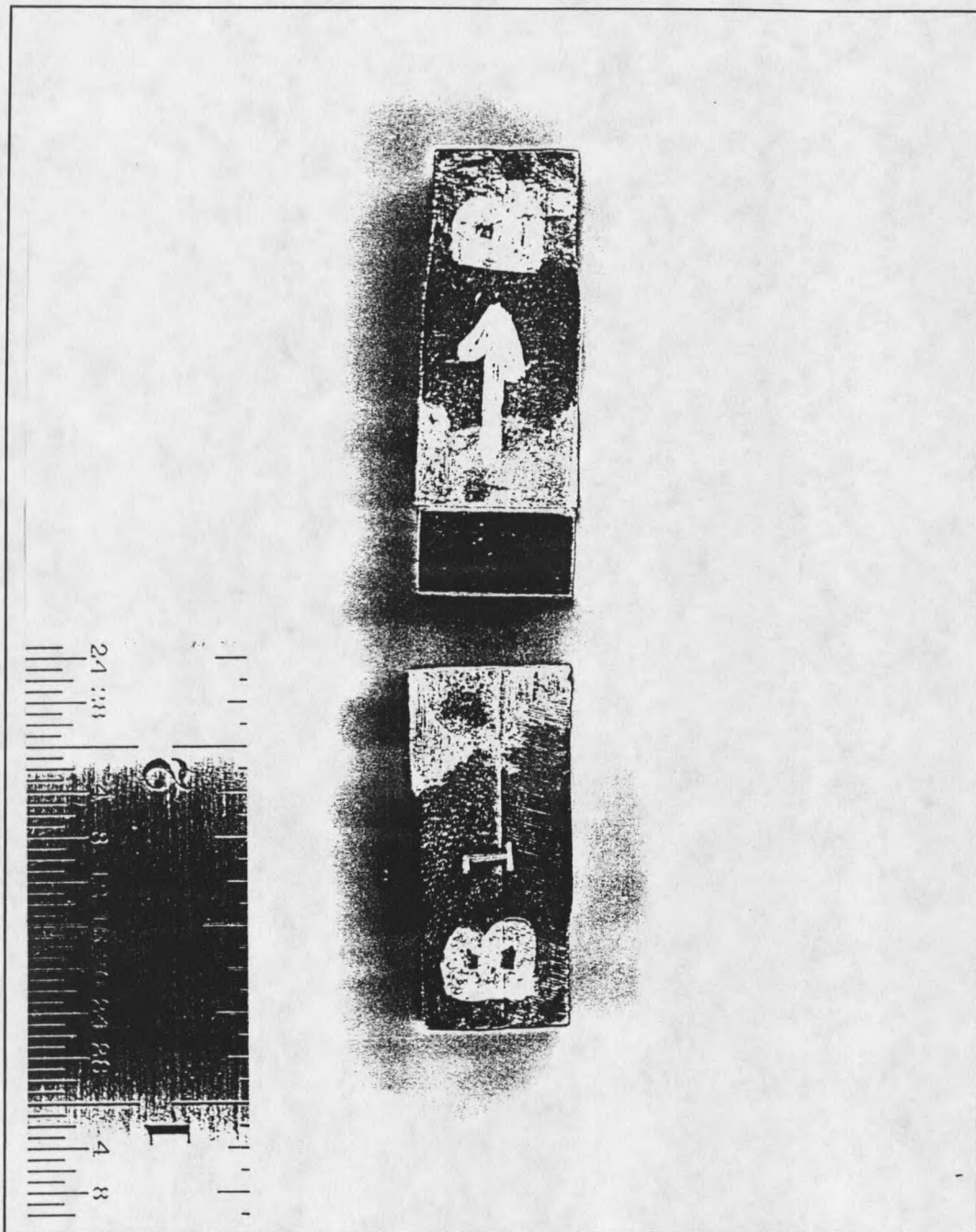


Figure 10. Braze alloy flow in W/Cu(559, 950°C).

value approximately 15 ksi) compared to the earlier combinations involving copper was achieved, which could be attributed to the matching thermal expansion coefficients of tungsten and molybdenum. These specimens also showed braze alloy flow over the sides, with extensive end material erosion. However, the W/Mo(Cusil ABA,900°C) combination further enhanced the effect of lesser thermal expansion mismatch with improved ductility of the active braze alloy. Failure was entirely Type 2, with an average joint strength value in the 20 ksi range. The W/Mo(Au-Ni,1000°C) combination always showed Type 4 failure with a comparatively reduced average joint strength of approximately 7.5 ksi.

The W/Cu(Cusil ABA and Au-Ni,1000°C) combination usually had Type 2 failure. However, some specimens did not separate, with the copper end materials yielding instead, with an average joint strength of approximately 6.5 ksi. Whereas, the W/Cu(Au-Ni,1000°C) combination failed entirely in Type 4 with considerable yielding in the copper end material and an average joint strength value in the 8 ksi range. Failure was always of the cup and cone type with the cup being formed in the center material (tungsten).

The Pt/446 S.S(Au-Ni,1000°C) combination showed impressive average joint strength of above 60 ksi. Only two of these specimens failed with Type 1 failure. The tests on a few of these specimens were not conducted due to the difficulty with high gripping pressure required and low grip surface area

available. However, the Pt/Cu(Au-Ni,1000°C) combination suffered from ductility of copper end materials, with most of the specimens failing to separate, suggesting an average joint strength value greater than 25 ksi (See Figure 11). It must also be mentioned that in the combinations with center material of only 0.010 in. thickness, it was difficult to distinguish between Type 2,3, and 4 failures.

Ceramic/Metal Brazed Specimens

After analyzing the results of the metal/metal brazed joint coupons, the ceramic/metal brazed coupons were prepared and tested. The test coupons were mounted with care using the U-joint attachment fixture, and loaded to failure. The results of the tensile tests are given in Table 13, consolidated for the specific sample groups. Table 13 shows the number of coupons tested, average joint failure strength and standard deviation for the various sample groups. Detailed results for each test specimen are shown in Table 15 in Appendix A. Appendix B also contains representative load versus displacement curves for these tests.

Failure sites in ceramic/metal coupons

Again, failure in these ceramic/metal brazed test coupons can be summarized to be of four different types according to location. Failure that occurred through the ceramic away from the interfaces was termed Type 1 (Type 1 in Figure 12). Often, failure occurred at the interface between

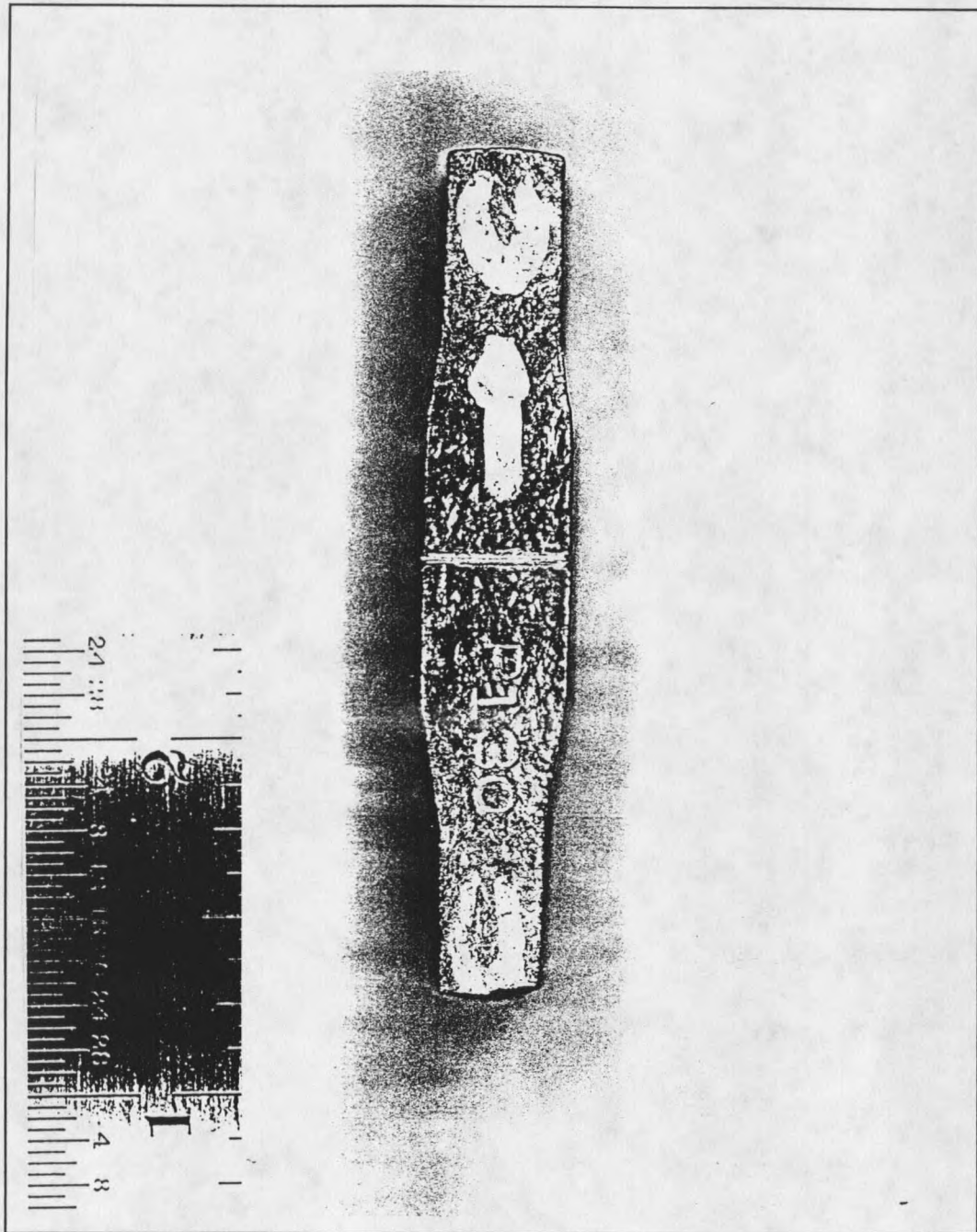


Figure 11. Excessive ductility of copper end material in Pt/Cu(Au-Ni, 1000°C).

Table 13. Ceramic-Metal brazed coupons - Tensile test results.

SAMPLE GROUP	MATERIAL (*)	No.	FAILURE LOAD (lbs)	
			MEAN	S.D
PA1	Mo/AlN(0.025in.)	2	1877.0	520.0
PA2	Mo/AlN(0.187in.)	3	1316.0	566.2
PA3	W/AlN(0.025in.)	3	2005.3	624.4
PA4	W/AlN(0.187in.)	3	2873.0	453.3
PA5	Mo/Cf(0.01in.)/AlN(0.025in.)	3	2320.3	1030.2
PA6	Mo/Cf(0.01in.)/AlN(0.187in.)	3	3028.6	411.8
PA7	Mo/Cf(0.04in.)/AlN(0.025in.)	3	3915.6	431.5
PA8	Mo/Cf(0.04in.)/AlN(0.187in.)	3	3261.0	785.2
PB1	Mo/BeO(0.025in.)	3	2734.0	463.6
PB2	Mo/BeO(0.187in.)	3	1442.0	248.5
PB3	W/BeO(0.025in.)	3	2117.6	181.3
PB4	W/BeO(0.187in.)	3	907.6	172.2
PB5	Mo/Cf(0.01in.)/BeO(0.025in.)	3	3297.3	915.7
PB6	Mo/Cf(0.01in.)/BeO(0.187in.)	2	3580.5	83.5
PB7	Mo/Cf(0.04in.)/BeO(0.025in.)	3	3745.6	284.0
PB8	Mo/Cf(0.04in.)/BeO(0.187in.)	3	3141.6	646.9

* See Table 11 for details of sample materials and construction.

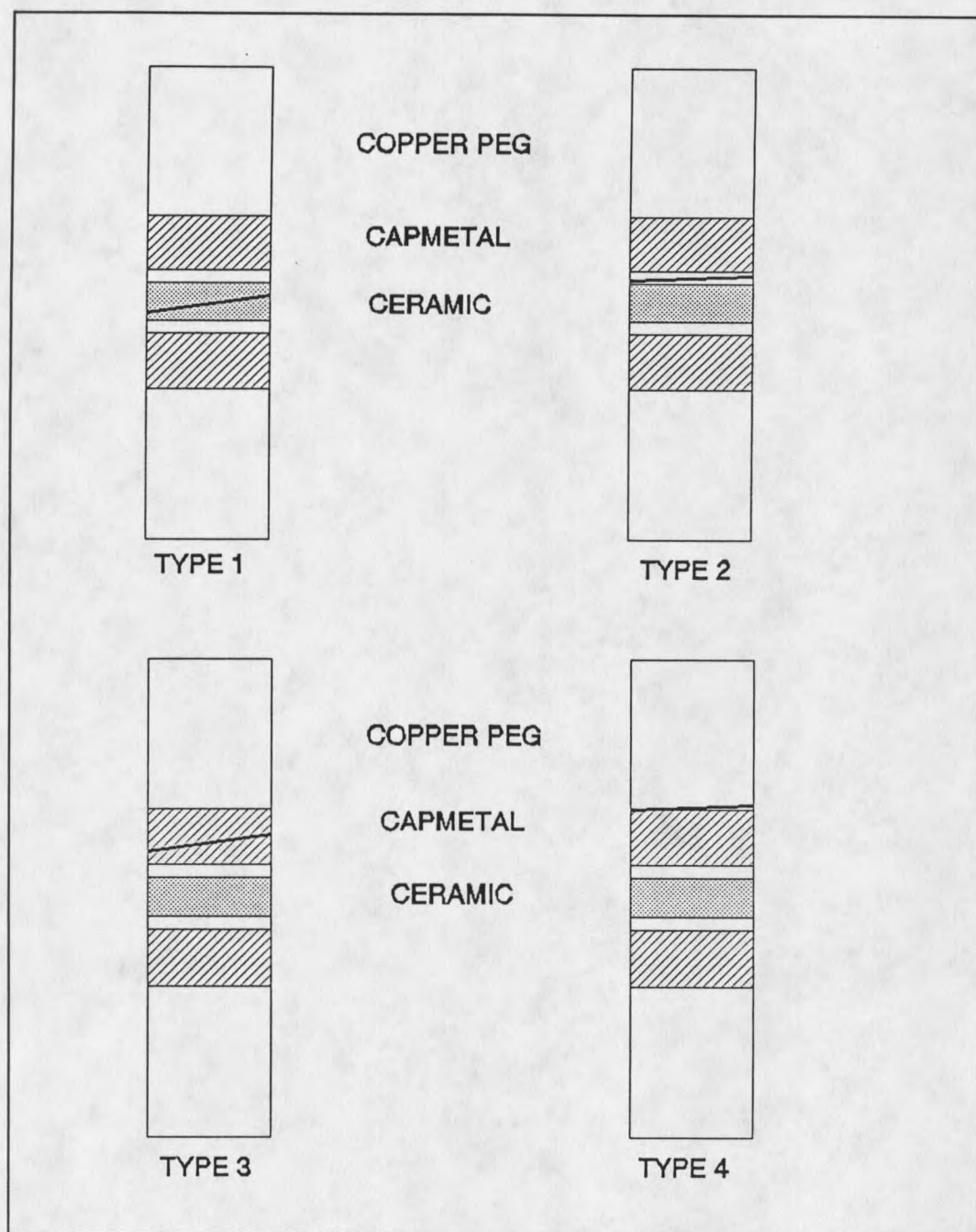


Figure 12. Failure types according to location in ceramic/metal brazed coupons.

the ceramic and the interlayer, either the upper or the lower interlayer. Sometimes, failure even propagated partially through interlayer or the ceramic. This has been identified as Type 2 failure (Type 2 in Figure 12). Failure occurred due to fracture that originated at an inclusion, void or insufficient braze region at the interface, and then propagated.

The third type of failure was the one through the interlayer away from the interfaces (Type 3 in Figure 12). However, failure at the interface between interlayer and the copper peg was also noticed and was termed Type 4 (Type 4 in Figure 12). Here again, failure often propagated partially through interlayer and partially through the copper pegs.

As regards the different specimen groups tested, both the Mo/AlN(0.025in.) and Mo/AlN(0.187in.) combinations showed predominantly Type 1 failure with the average joint strength in the 4 ksi range. However, the highest joint strength value obtained was often comparatively much higher than the lowest, yielding a high standard deviation for both cases. Both the Mo/BeO(0.025in.) and Mo/BeO(0.187in.) combinations showed failure entirely of Type 2. However, the Mo/BeO(0.025in.) combination yielded an average joint strength around 7 ksi, comparatively higher than Mo/BeO(0.187in.) with approximately 3.7 ksi.

The W/AlN(0.025in.) combination showed Type 2 and 4 failure with 5 ksi average joint strength, and the W/AlN(0.187in.) combination showed Type 4 failure with an

exception and approximately 6 ksi average joint strength. As far as the W/BeO(0.025in.) combination was concerned, Type 4 failures dominated entirely with an average joint strength value around 5.4 ksi. However, the W/BeO(0.187in.) combination had a lower average joint strength in the range of only 2.3 ksi and always had Type 2 failure.

As expected, the Mo/Cf(0.01in.)/AlN(0.025in.) combination showed great improvement in joint strength due to the presence of the ductile metal interlayer. The average joint strength was in the range of 5.9 ksi with failure mainly of Type 3. With increased ceramic thickness for the same combination, i.e., for Mo/Cf(0.01in.)/AlN(0.187in.), an average joint strength around 7.7 ksi was obtained with mainly Type 4 failure. However, for the Mo/Cf(0.01in.)/BeO(0.025in.) combination, an average joint strength value of about 8.4 ksi was obtained with no identifiable consistent failure type. For the Mo/Cf(0.01in.)/BeO(0.187in.) combination, increased ceramic thickness yielded increased joint strength, with an average value around 9.2 ksi and failure of Type 1.

Increasing the thickness of the ductile metal interlayer also yielded higher joint strengths as seen for both Mo/Cf(0.04in.)/AlN(0.025in.) and Mo/Cf(0.04in.)/AlN(0.187in.) combinations. Average joint strength was around 10 ksi with mainly Type 1 failure for the former and 8.3 ksi with mainly Type 4 failure for the latter (See Figure 13). For the latter combination, the specimen that yielded the highest

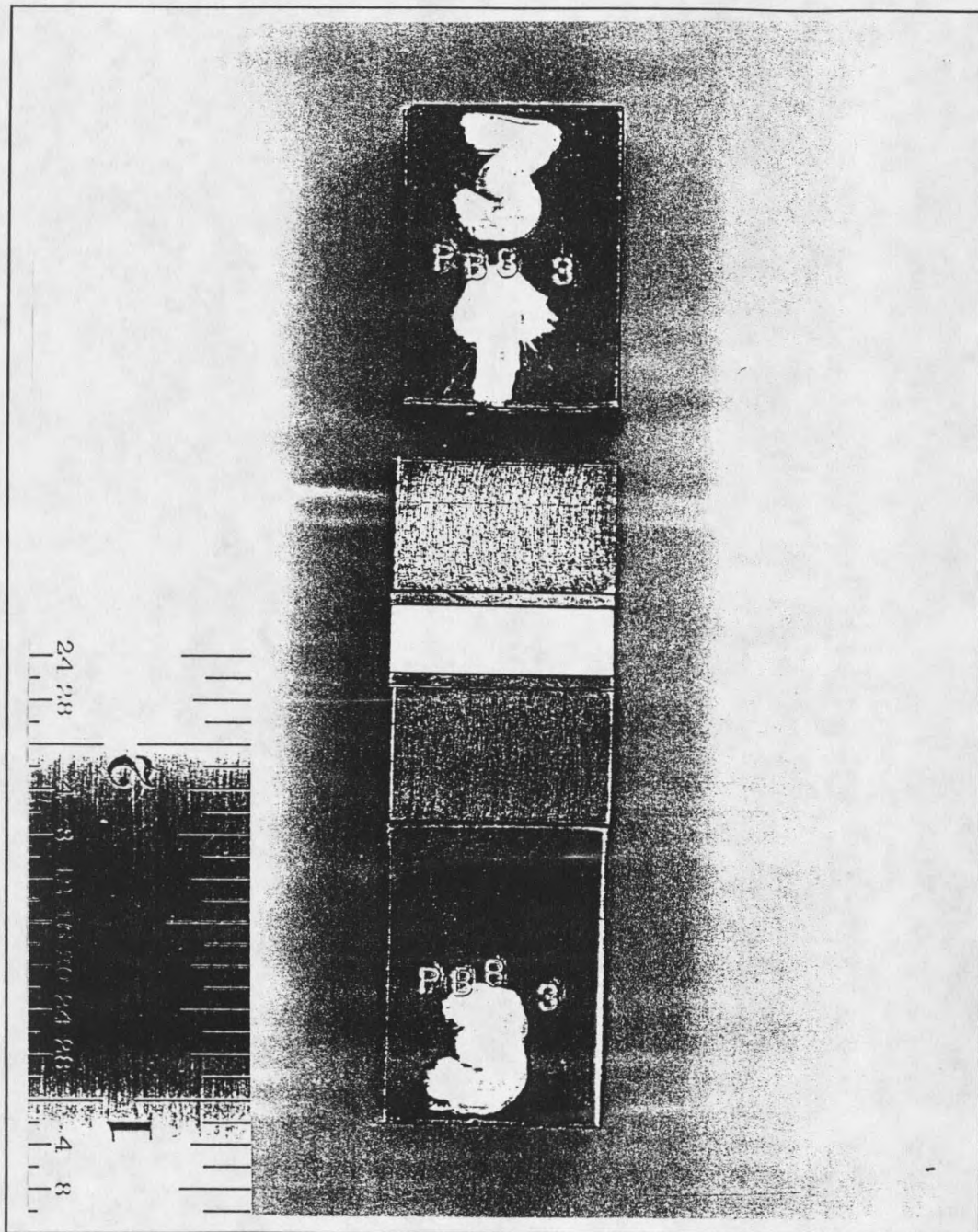


Figure 13. Type 4 failure in Mo/Cf(0.04in.)/AlN(0.187in.).

joint strength failed in Type 1. However, with BeO as the ceramic the effect of the thicker ductile metal interlayer was reduced, with the Mo/Cf(0.04in.)/BeO(0.025in.) combination yielding only marginally higher joint strength when compared to its counterpart with lower ductile interlayer thickness. The average joint strength was around 9.6 ksi with failure predominantly of Type 1 for this case, whereas the Mo/Cf(0.04in.)/BeO(0.187in.) combination even showed a reduction in average joint strength from its counterpart with lower ductile interlayer thickness, to about 8 ksi. Failure generally was of Type 4. However, the specimen that yielded the highest joint strength in this combination did fail in Type 1 (See Figure 14).

Analysis and Discussion

To clearly represent the effects of the various parameters, the results are represented on bar graphs. The bar graphs depict the average value of joint strength. However, many of the mean values are low, but some specimens of that group were much stronger, as indicated by higher standard deviation. It is of interest that the material combination can produce strong joints, even if some of the joints are weak due to the presence of some preparation flaws. Thus, the highest strength value is given along with the mean value as an indicator of the potential strength of the system.

The bar graphs show average joint strength with the

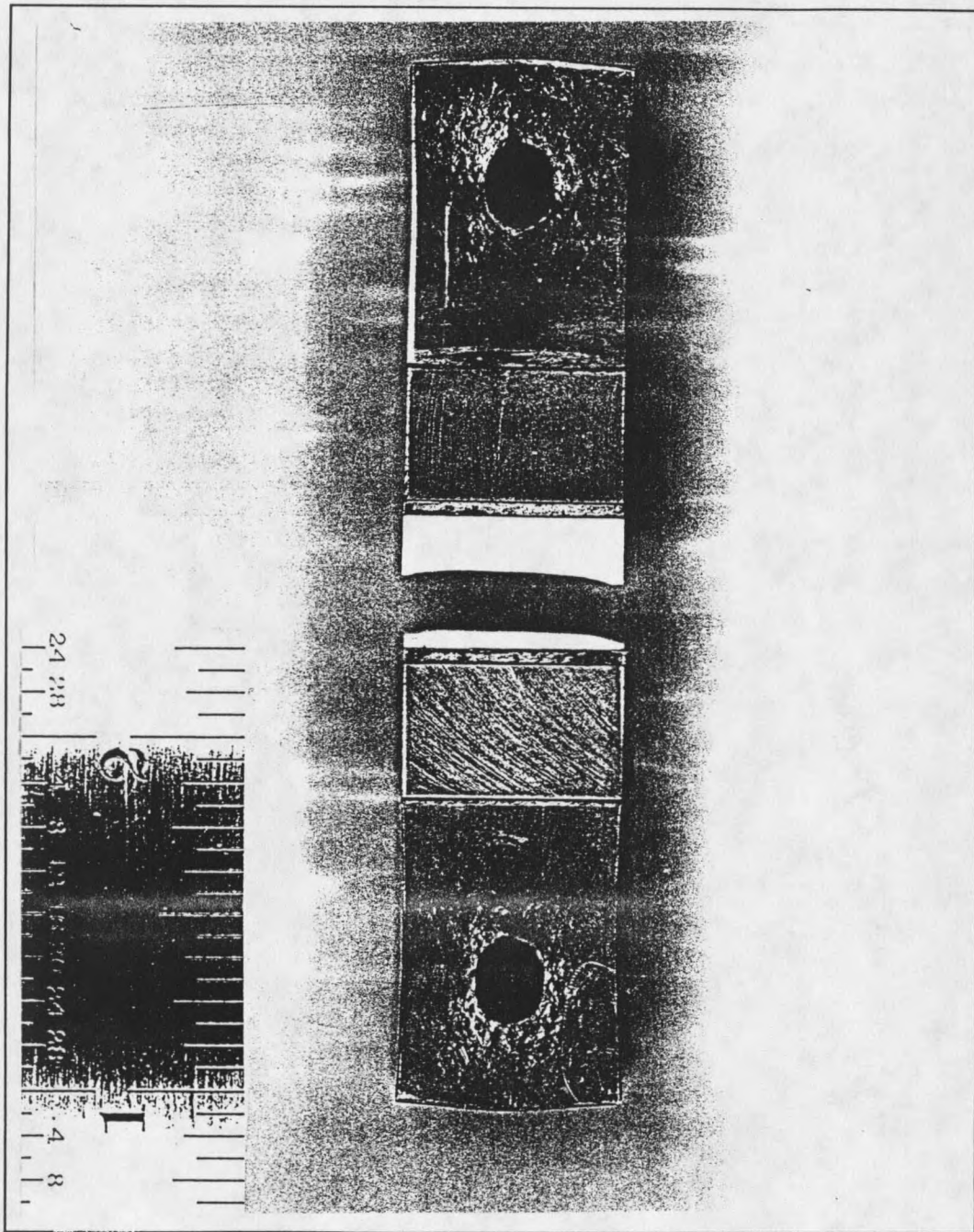


Figure 14. Type 1 failure in Mo/Cf(0.04in.)/BeO(0.187in.).

standard deviation in a box at the upper end, along with the highest strength value.

Metal/Metal Brazed Specimens

The results of the metal/metal brazed test coupons were grouped to find the effects of braze alloy, end material and center material for the different combinations possible. There was no reason to compare across different groups for the effect of a certain specific parameter, since, for example, comparing the joint strengths of Cu/W and Mo/W combinations does not give valuable information about the effectiveness of the braze alloy used, because the material combination itself varies.

Effect of Braze Alloy. Here the effects of different braze alloys on the joint strength for the various possible material combinations are discussed. All three braze alloys were tested for the Mo/W(0.025in.) combination, and Cusil ABA clearly had the edge over both 559 and Au-Ni (Figure 15). However, the combination using Cusil ABA as the braze alloy showed a high standard deviation.

Only two braze alloys, 559 and Cusil ABA, were used for the Cu/Mo(0.025in.) combination. In this case, 559 showed a slight edge over Cusil ABA in joint strength (Figure 16). The Cu/W(0.025in.) combination with 559 and Cusil ABA showed comparable results for both the braze alloys, but Cusil ABA had a higher average value (Figure 17). Thus, the

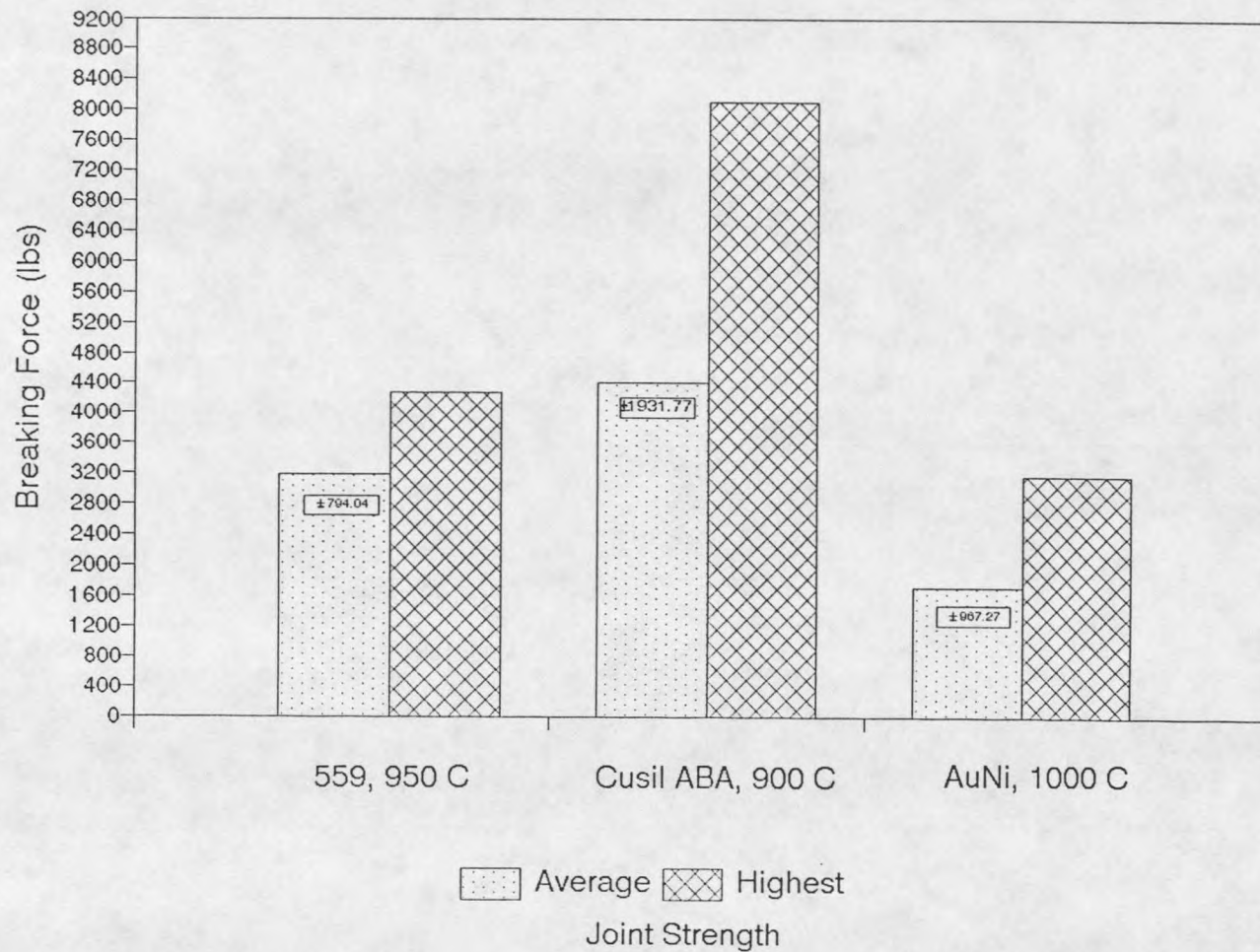


Figure 15. Effect of braze alloy on Mo/W (0.025in.) combination.

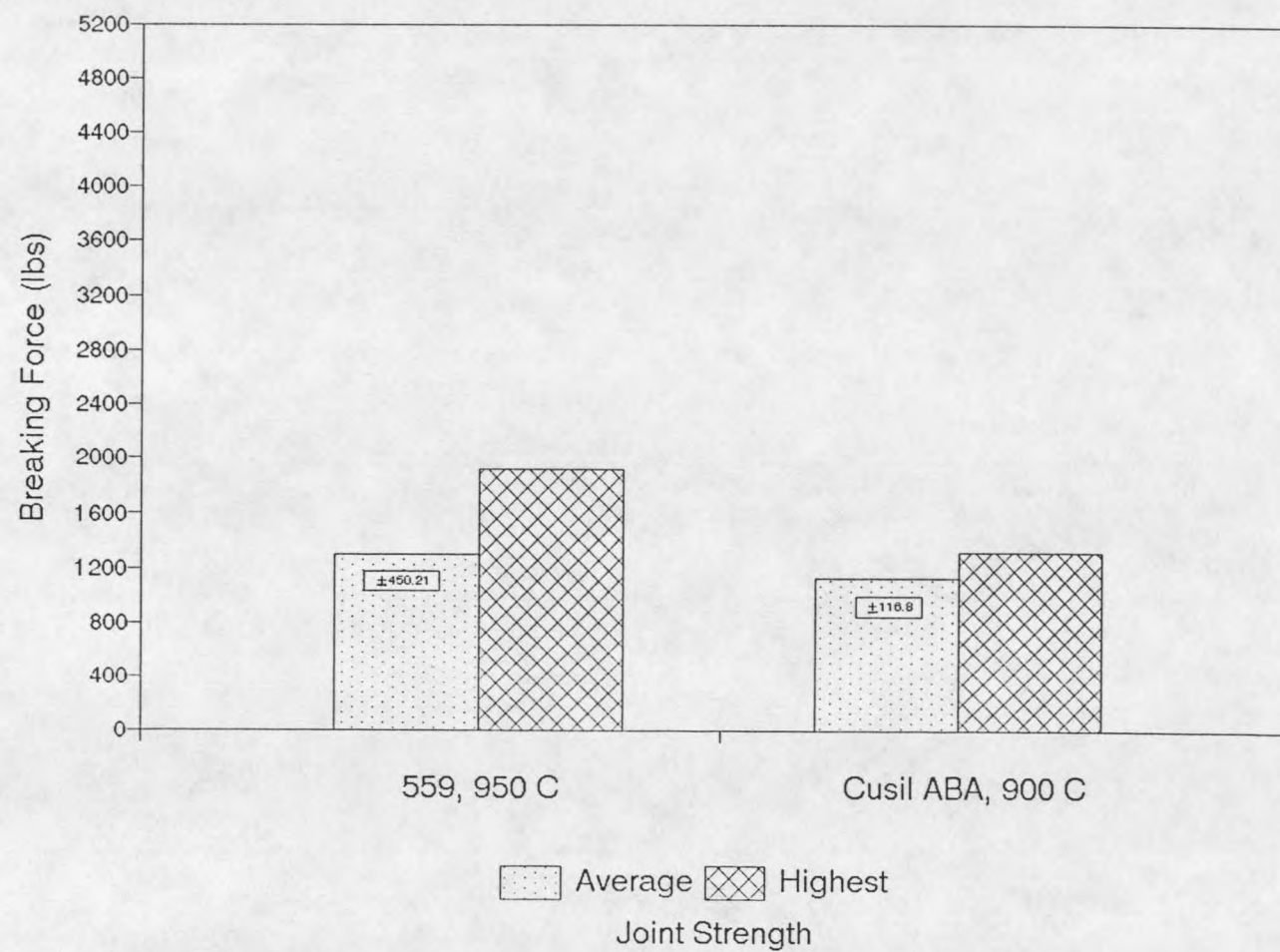


Figure 16. Effect of braze alloy on Cu/Mo (0.025in.) combination.

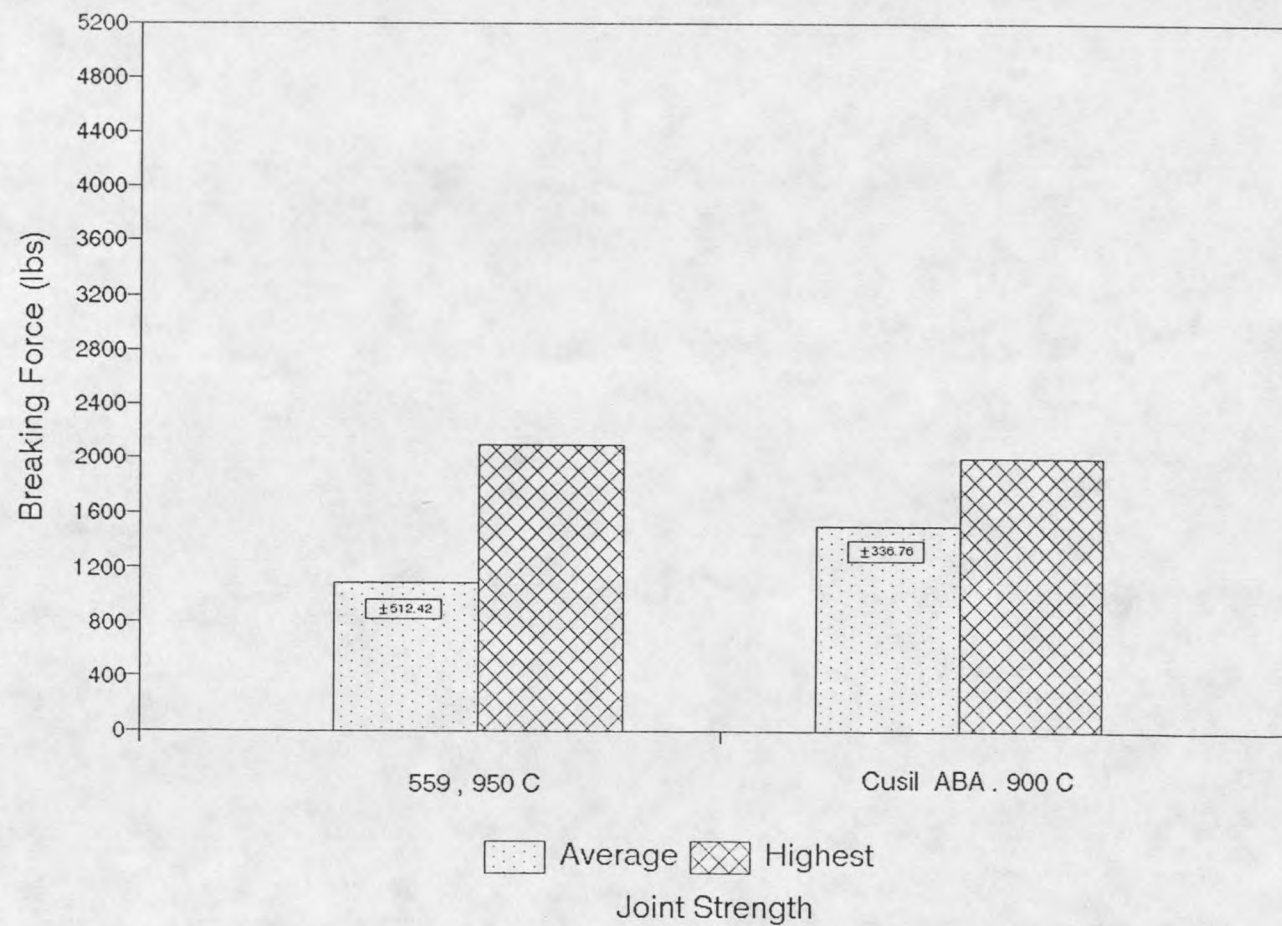


Figure 17. Effect of braze alloy on Cu/W (0.025in.) combination.

effectiveness of Cusil ABA in brazing materials other than copper is clear.

Effect of End Material. The effect of end material used for the different possible combinations was tested for each braze alloy. For 559 braze alloy, Mo/W(0.025in.) was the stronger combination when compared to Cu/W(0.025in.) (Figure 18). Whereas, for Au-Ni braze alloy, Pt/446 S.S(0.010in.) had a considerably higher joint strength than the Pt/Cu(0.010in.) combination (Figure 19). In fact Pt/446 S.S(0.010in.) gave the highest joint strength of all the metal/metal combinations tested, but with very high standard deviation. However, platinum is expensive and this combination was tested primarily for comparison. It should also be noted that these metal/metal brazed specimens with 0.01in. center material were considerably smaller in size (1.010 in. long) and hence gave problems with gripping in the testing machine. Thus, the low average value in some cases could be attributed to differences in testing setup. As far as the Cusil ABA braze alloy is concerned, of the combinations tested, Mo/W(0.025in.) again showed greater joint strength (Figure 20).

Effect of Center Material. This effect has been studied for only two braze alloys, 559 and Cusil ABA. For the 559 braze alloy both the Cu/W(0.025in.) and Cu/Mo(0.025in.) combinations showed comparable results, but with the average value for the former combination having a slight edge (Figure

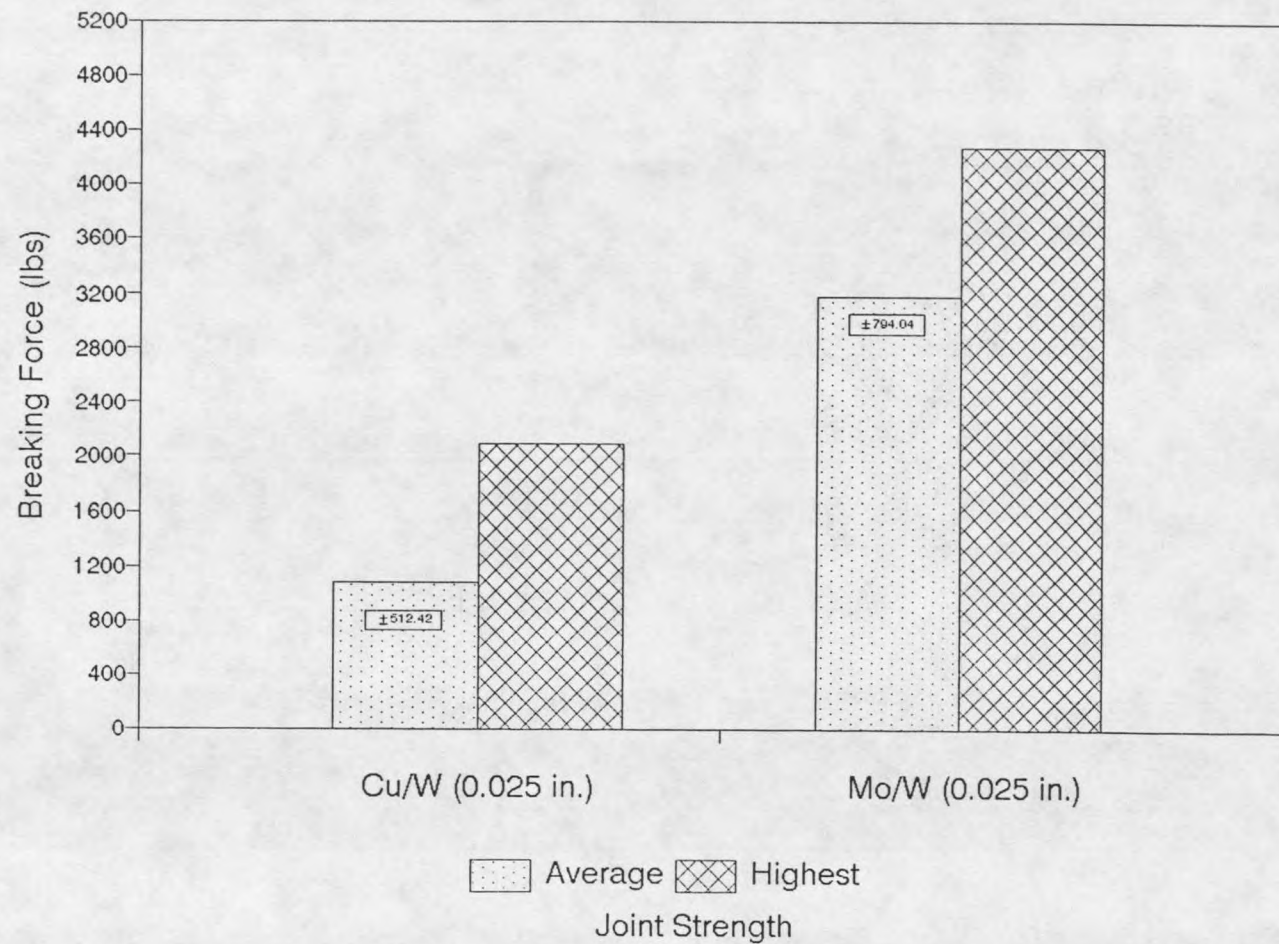


Figure 18. Effect of end material on braze alloy 559, 950°C.

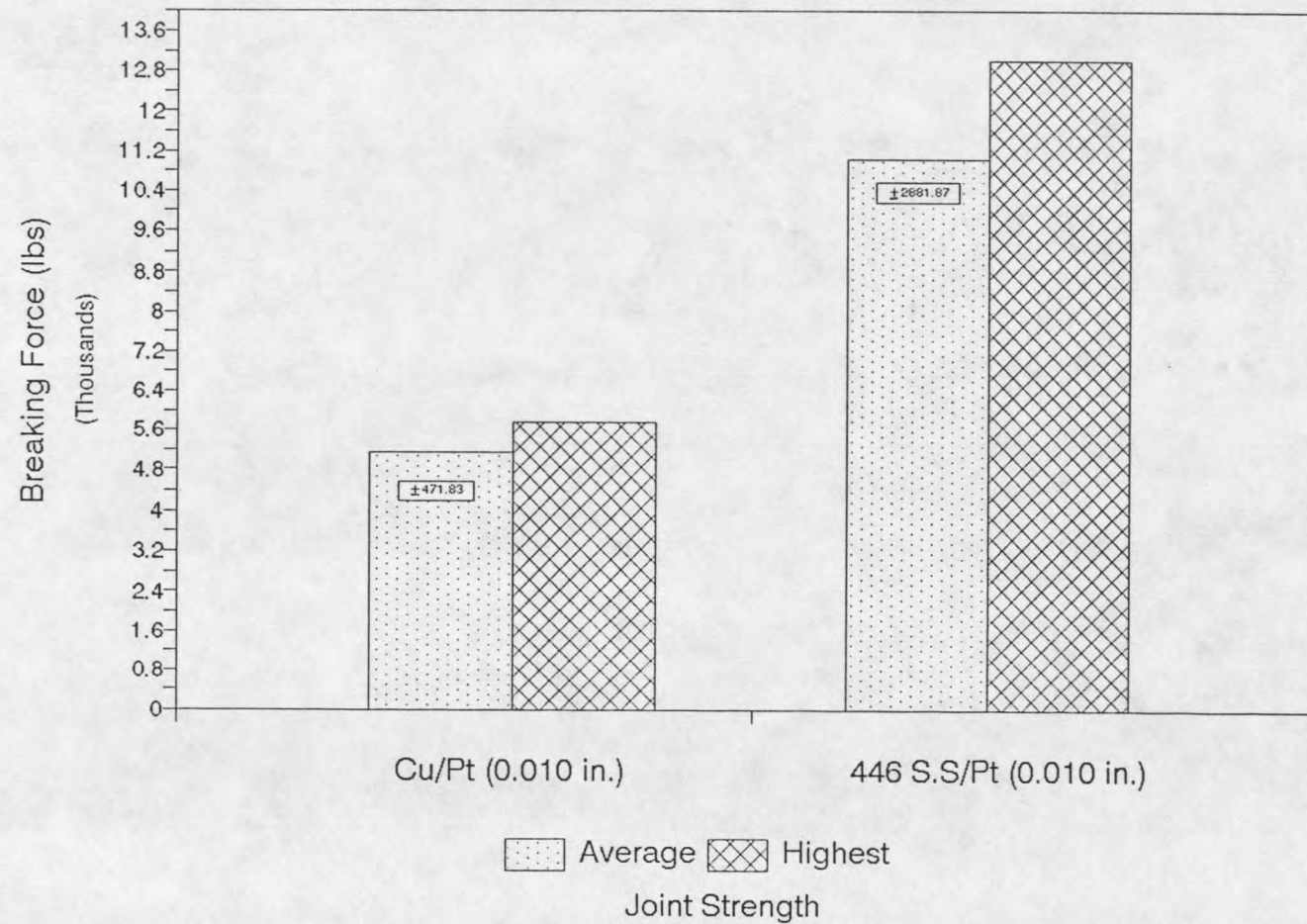


Figure 19. Effect of end material on braze alloy Au-Ni, 1000°C.

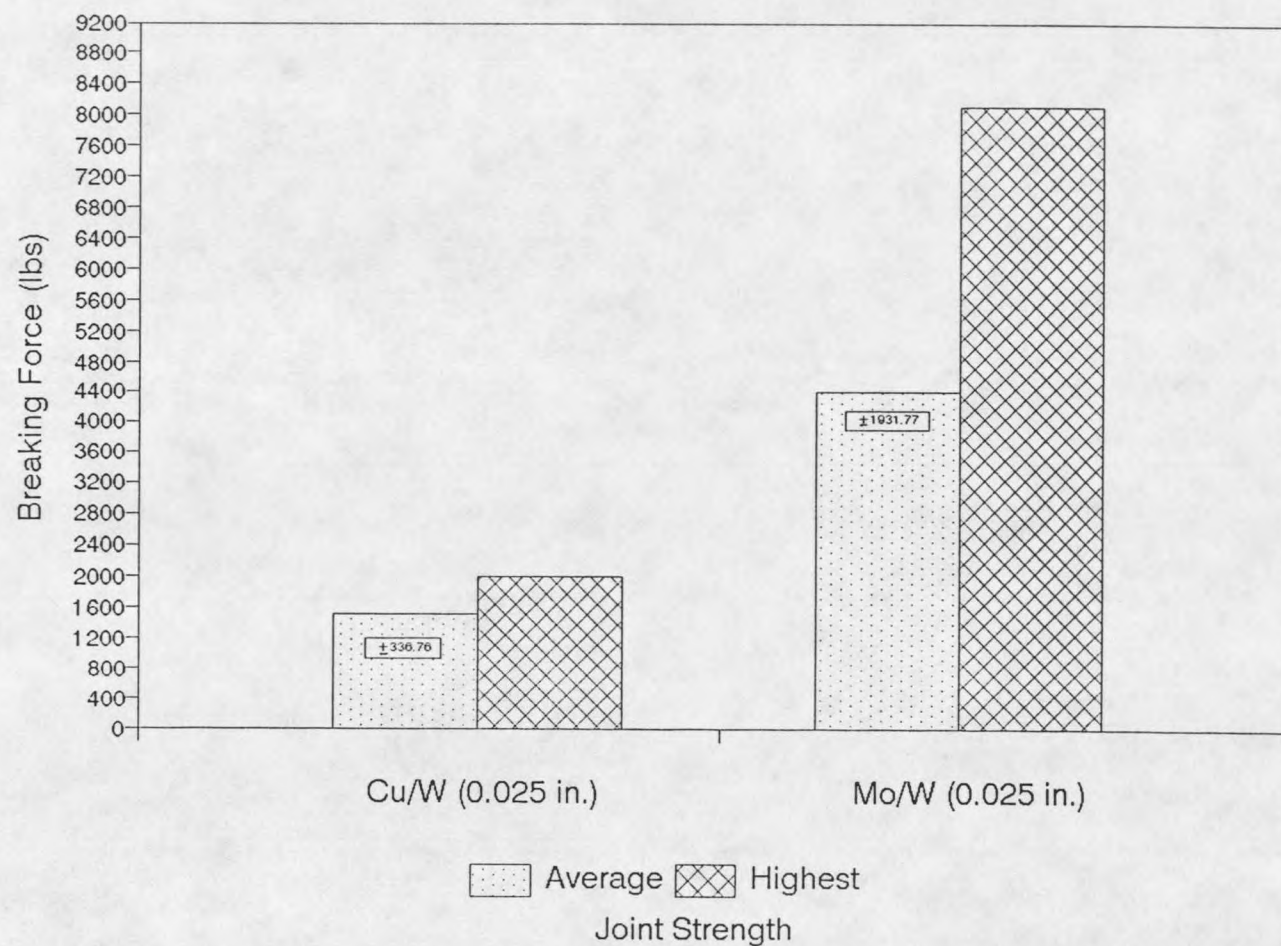


Figure 20. Effect of end material on braze alloy Cusil ABA, 900°C.

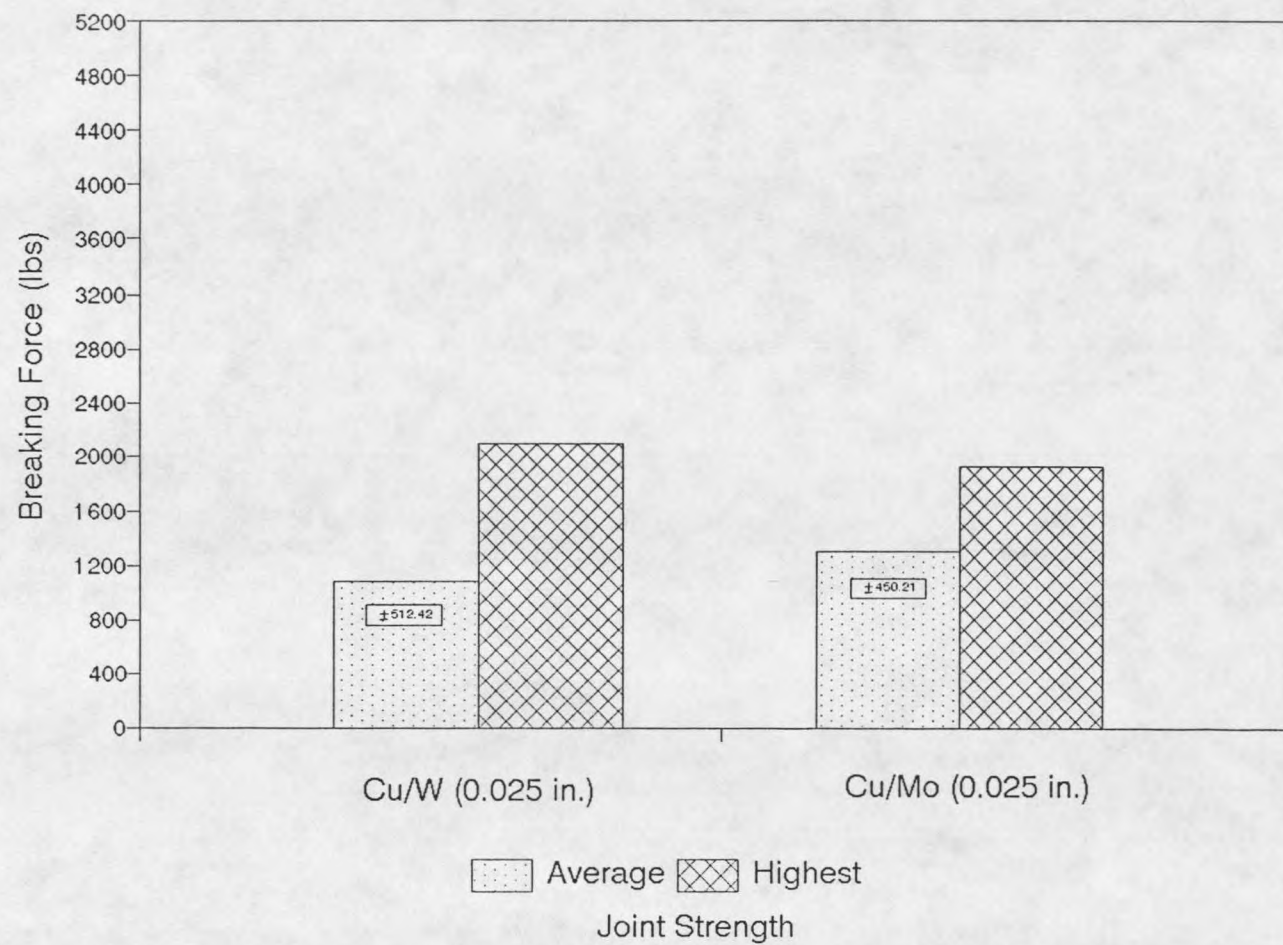


Figure 21. Effect of center material on braze alloy 559, 950°C.

21). For Cusil ABA braze alloy the Cu/W(0.025in.) combination definitely had an advantage over Cu/Mo(0.025in.) (Figure 22).

Ceramic/Metal Brazed Specimens

The results of the tensile tests on ceramic/metal brazed specimens are analyzed to understand the effects of the different parameters, using the joint strength values. The analysis included the effects of the type of interlayer or capmetal, type of ceramic, thickness of the ceramic and thickness of O.F.H.C Copper foil.

All ceramic/metal brazed specimens used Cusil ABA as the braze alloy. This was partly because of wetting problems commercial braze alloys like 559 and Au-Ni have with ceramics. Also, from the results of the analysis of the metal/metal brazed specimens, Cusil ABA was found to be an excellent braze alloy for some combinations and to be moderately effective for others.

Effect of Interlayer or Capmetal. The interlayer used with a particular ceramic/metal combination had a great effect on the braze joint strength. Capmetals are nothing but metal interlayers with intermediate thermal expansion coefficients. This helps reduce the thermal expansion mismatch between the ceramic and the metal in the ceramic/metal combination.

For the AlN ceramic, tungsten appears to be the best interlayer, since combinations with tungsten yielded much higher joint strengths. The effect was marginal in the case of

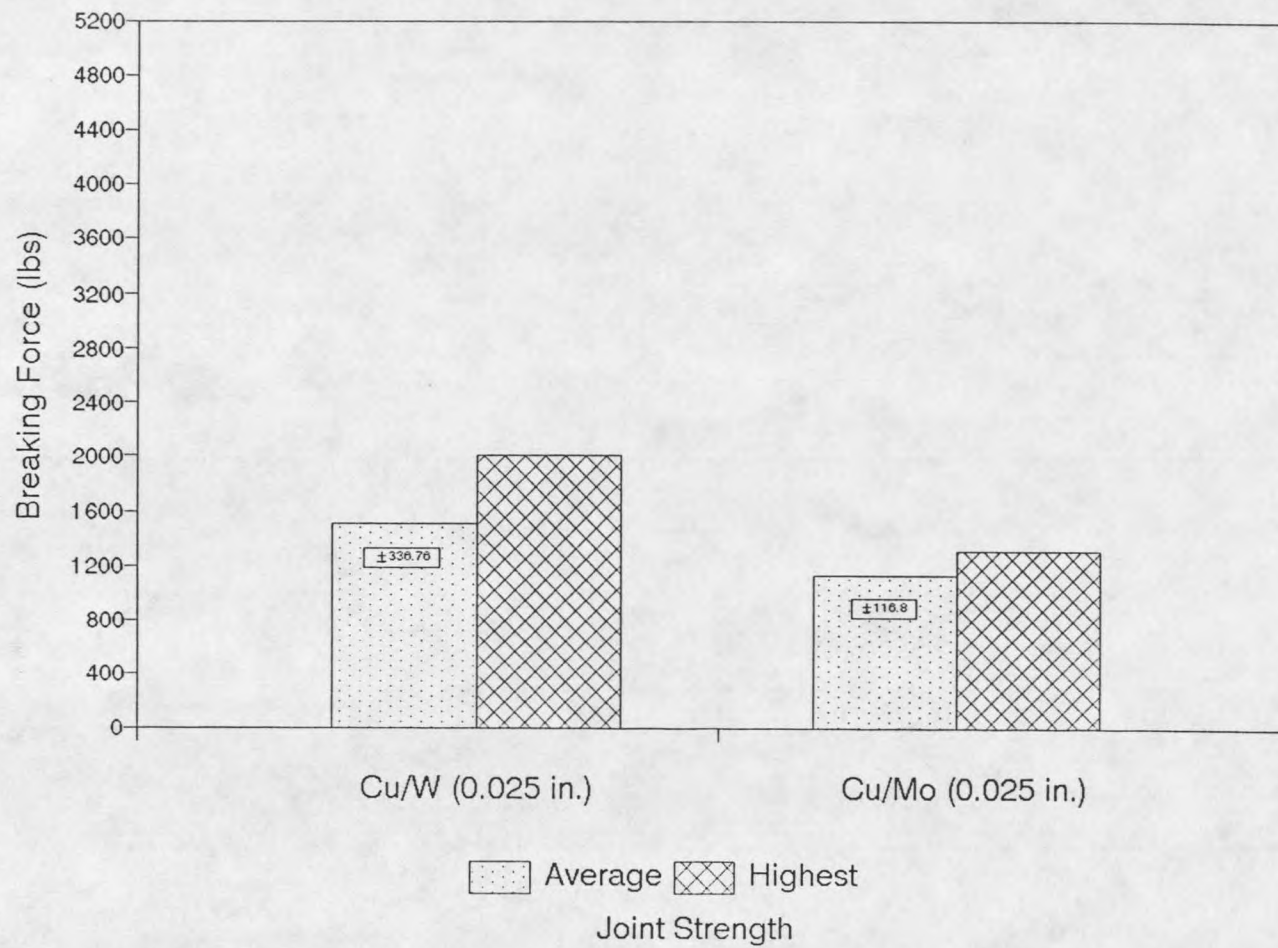


Figure 22. Effect of center material on braze alloy Cusil ABA, 900°C.

0.025 in. thick ceramic but more pronounced for thicker (0.187in.) ceramic combinations (Figure 23 and Figure 24). Conversely, for the BeO ceramic, molybdenum appears to be the better choice interlayer from the standpoint of higher joint strength. The effect is marginal in the case of 0.187 in. thick ceramic and more pronounced for the thinner ceramic (0.025 in.) combinations (Figure 25 and Figure 26). This is exactly opposite to the effect seen for the AlN ceramic. No explanation could be found for this behavior.

Of the different specimens tested, the W/AlN(0.187in.) combination and the Mo/BeO(0.025in.) combination showed the best joint strengths.

Effect of Ceramic Type. The effect of the ceramic type on the various combinations tested was quite complex. For the Mo/Ceramic combinations, BeO ceramic resulted in higher joint strengths for the 0.025in. ceramic thickness and lower joint strengths for 0.187in. ceramic thickness when compared to AlN combinations (Figure 27 and Figure 28).

For the W/Ceramic combinations, AlN ceramic yielded higher joint strengths for both ceramic thicknesses (Figure 29 and Figure 30). However, the effect of increased joint strength with the AlN ceramic was more pronounced in the thicker case. The difference was marginal for the 0.025in. thick ceramic, with a low average value indicated for the W/AlN combination.

For the Mo/Cf(0.01in.)/Ceramic combinations, BeO

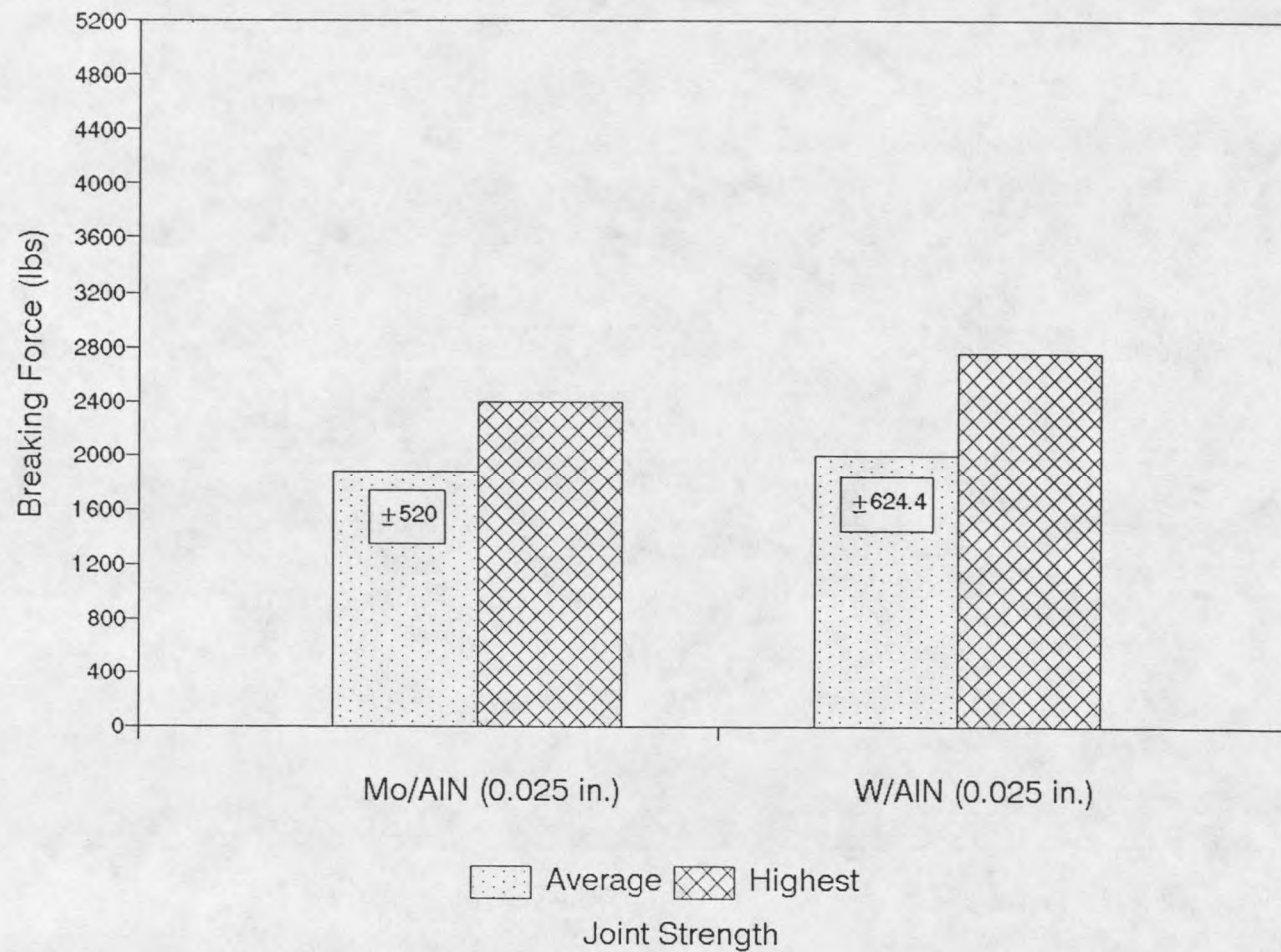


Figure 23. Effect of interlayer type on AlN (0.025in.) ceramic combinations.

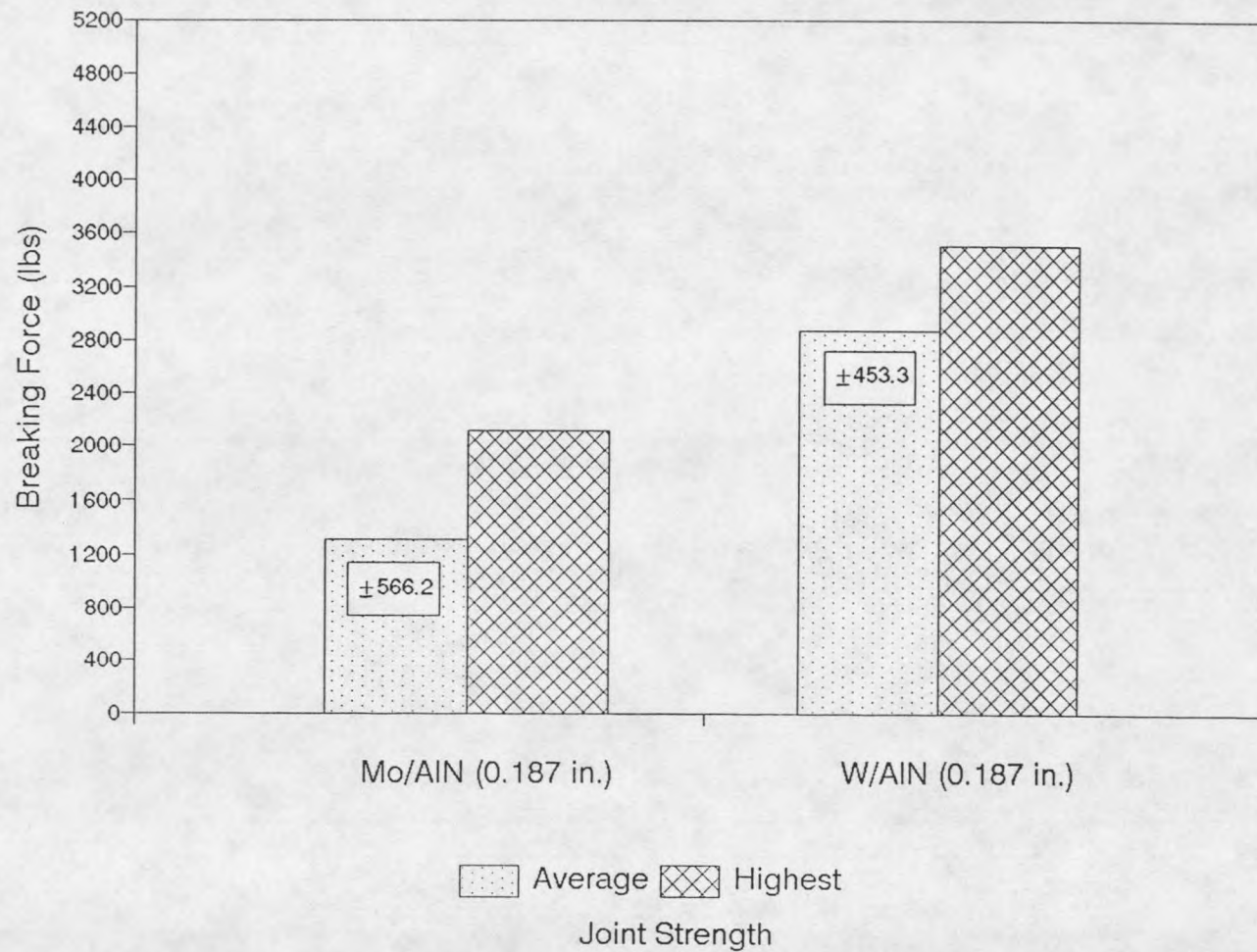


Figure 24. Effect of interlayer type on AlN (0.187in.) ceramic combinations.

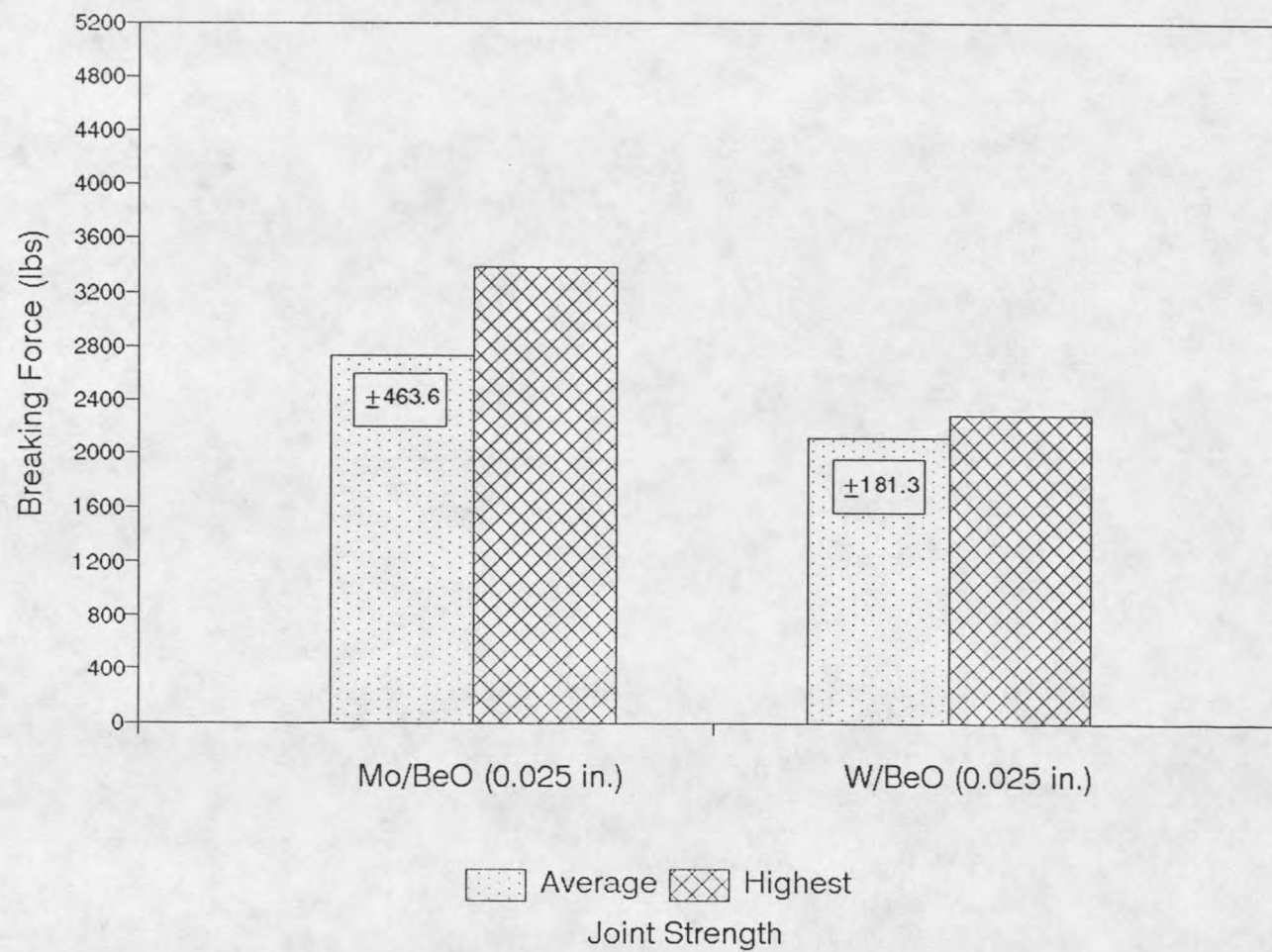


Figure 25. Effect of interlayer type on BeO (0.025in.) ceramic combinations.

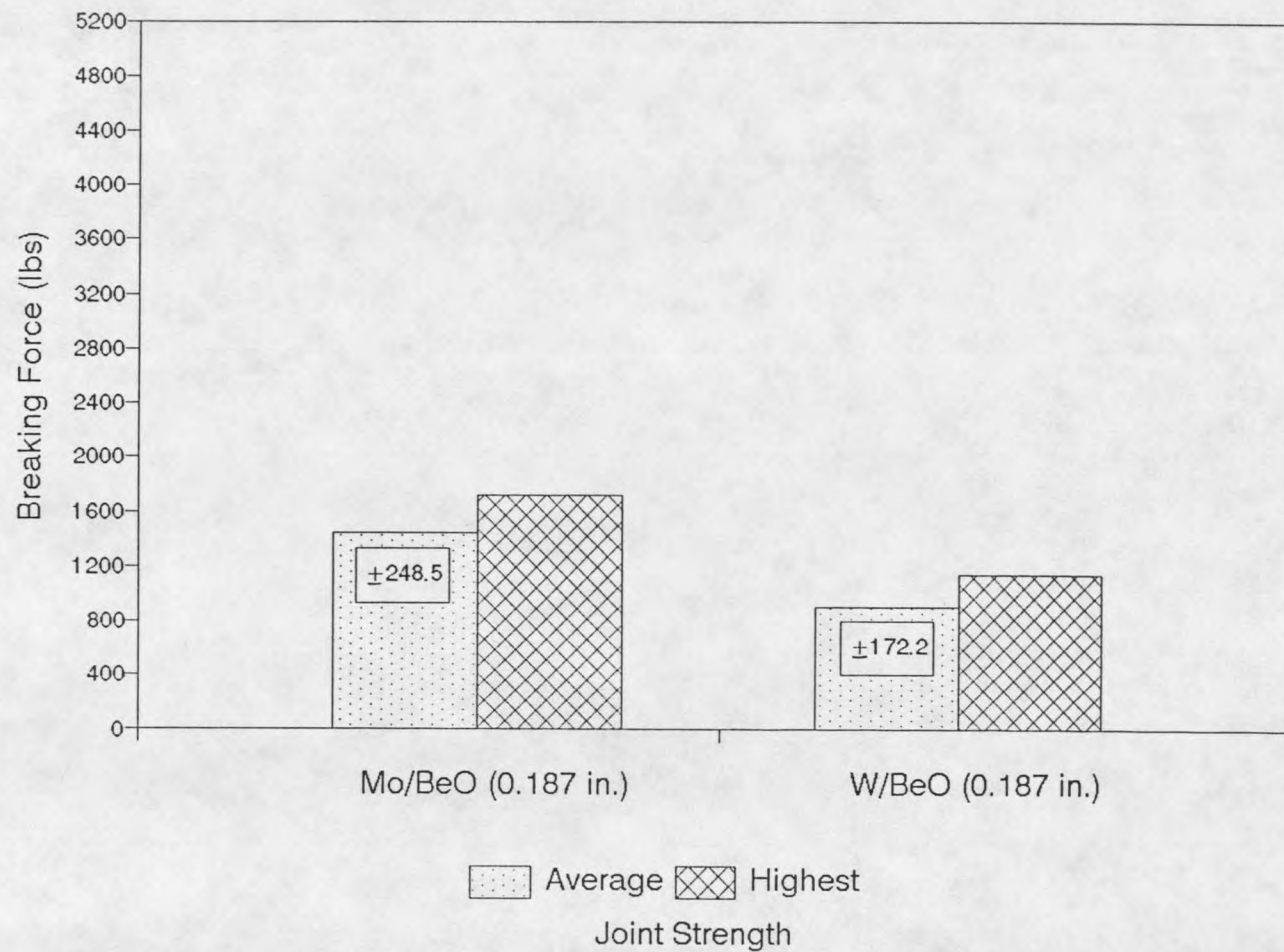


Figure 26. Effect of interlayer type on BeO (0.187in.) ceramic combinations.

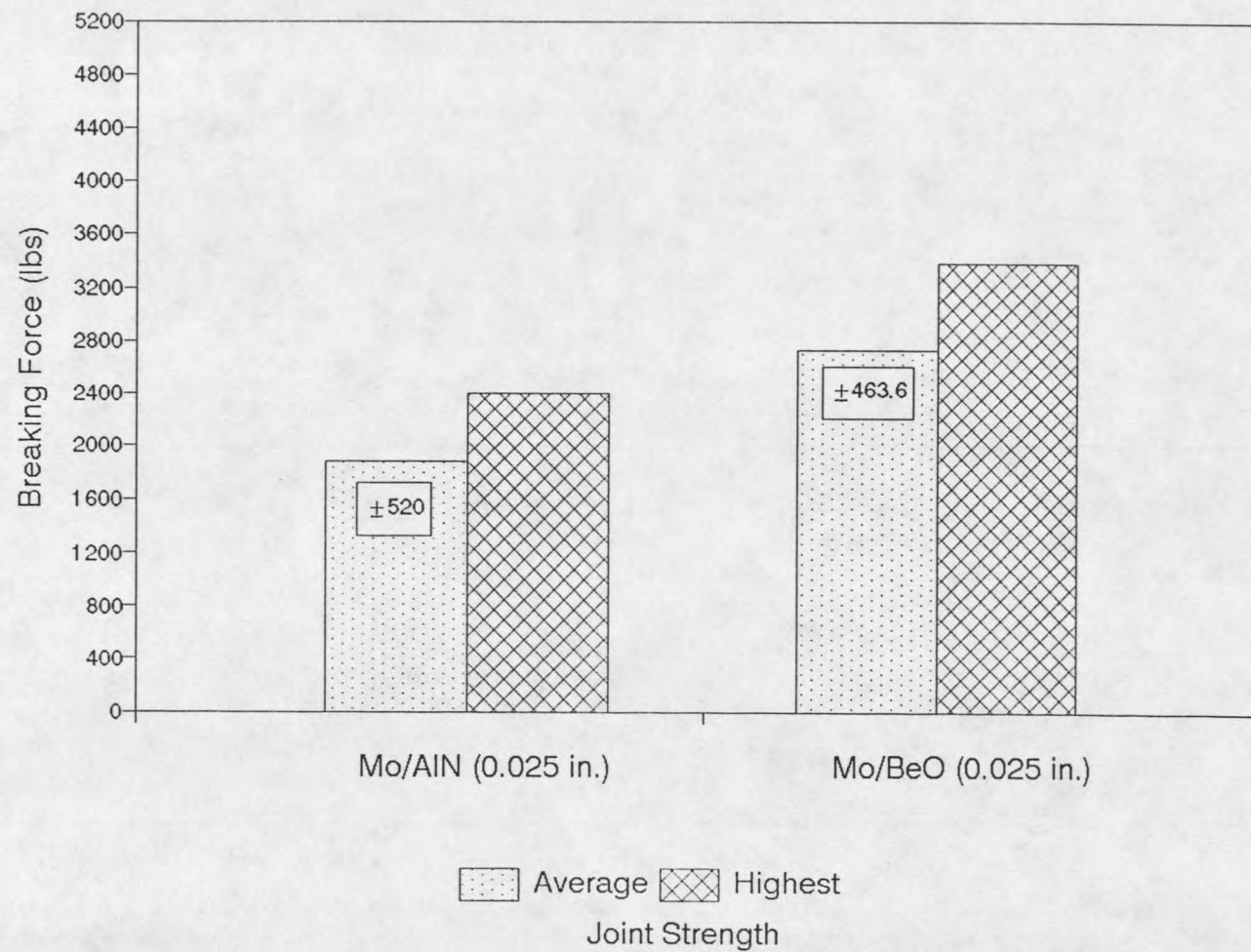


Figure 27. Effect of ceramic type on Mo/Ceramic (0.025in.) combinations.

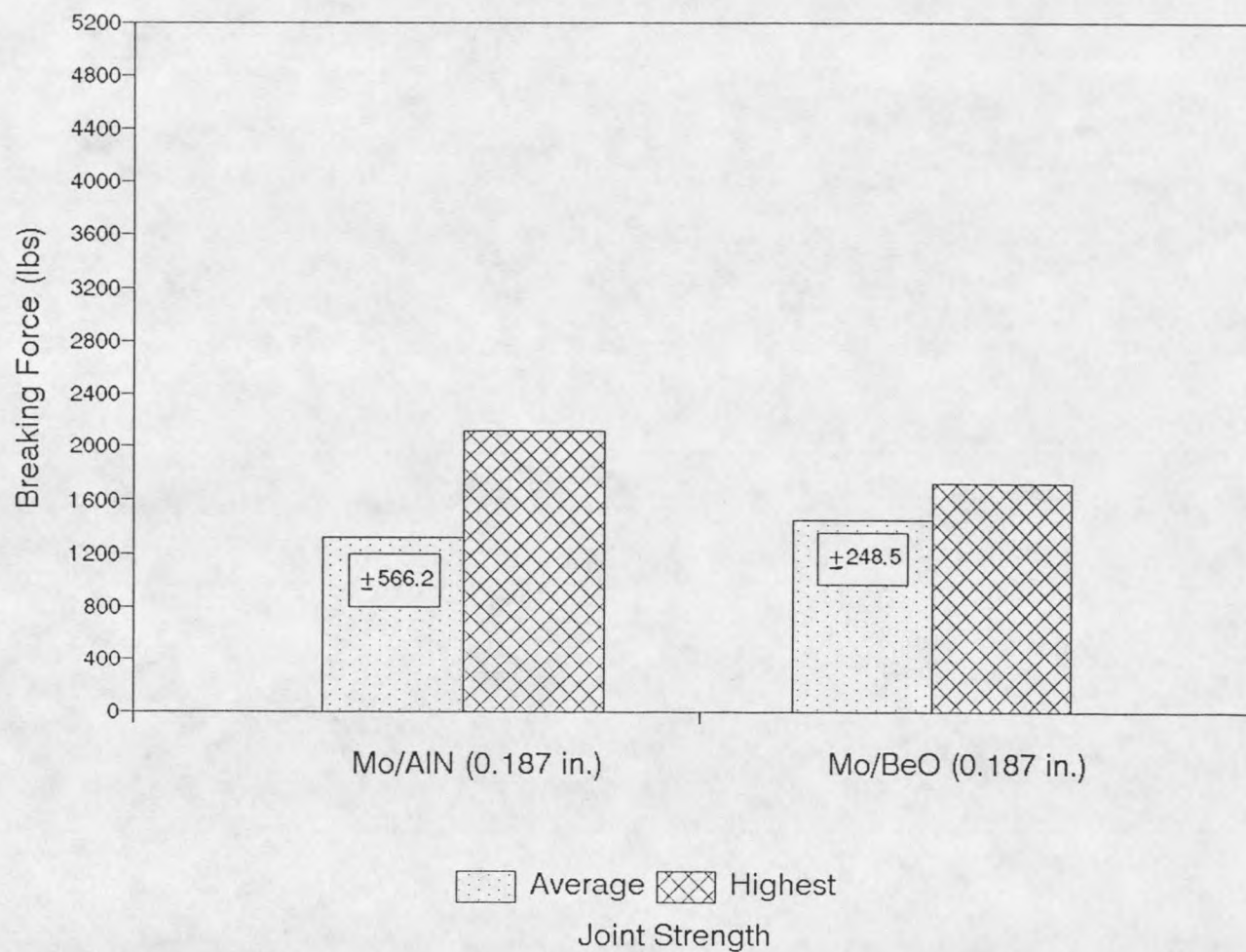


Figure 28. Effect of ceramic type on Mo/Ceramic (0.187in.) combinations.

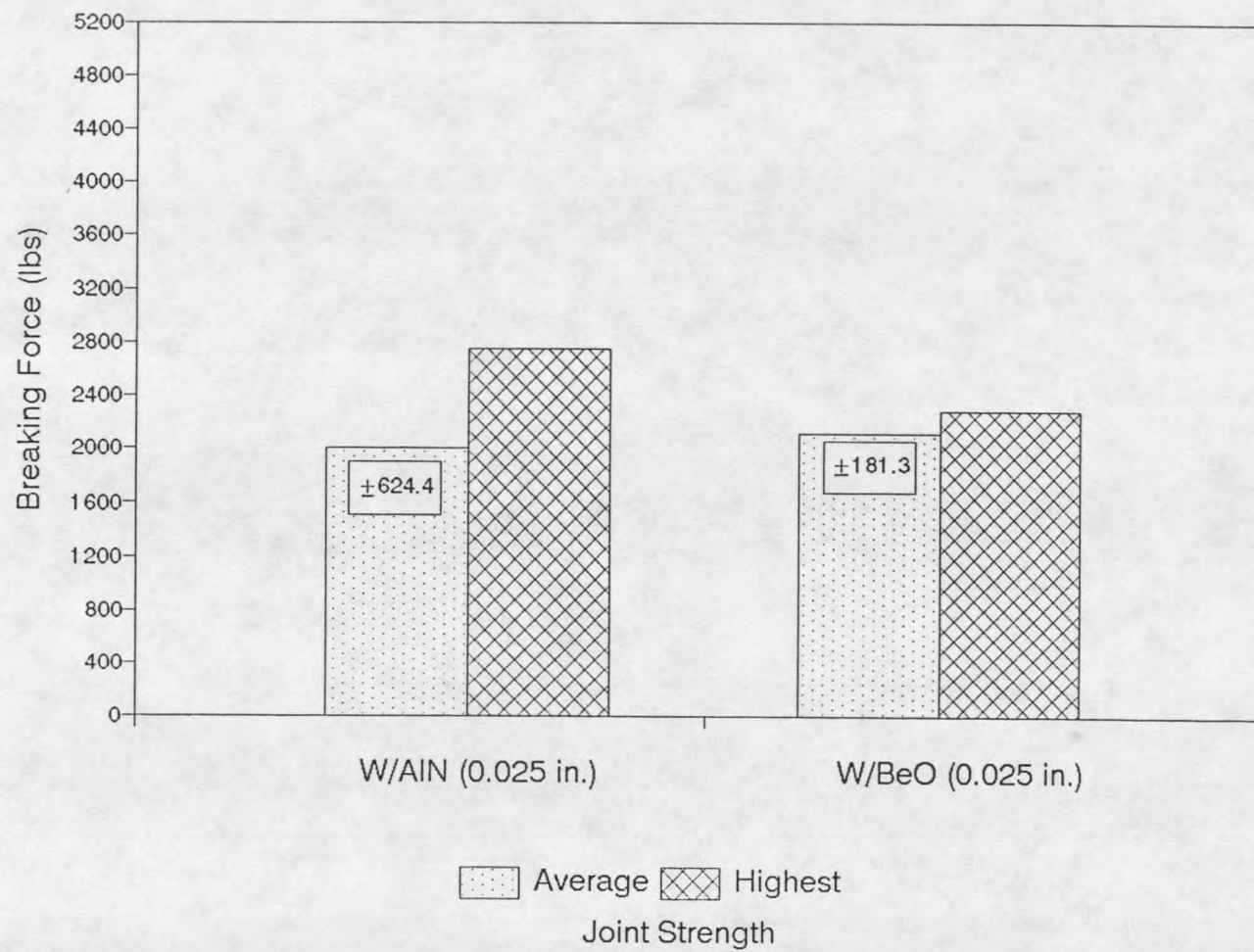


Figure 29. Effect of ceramic type on W/Ceramic (0.025in.) combinations.

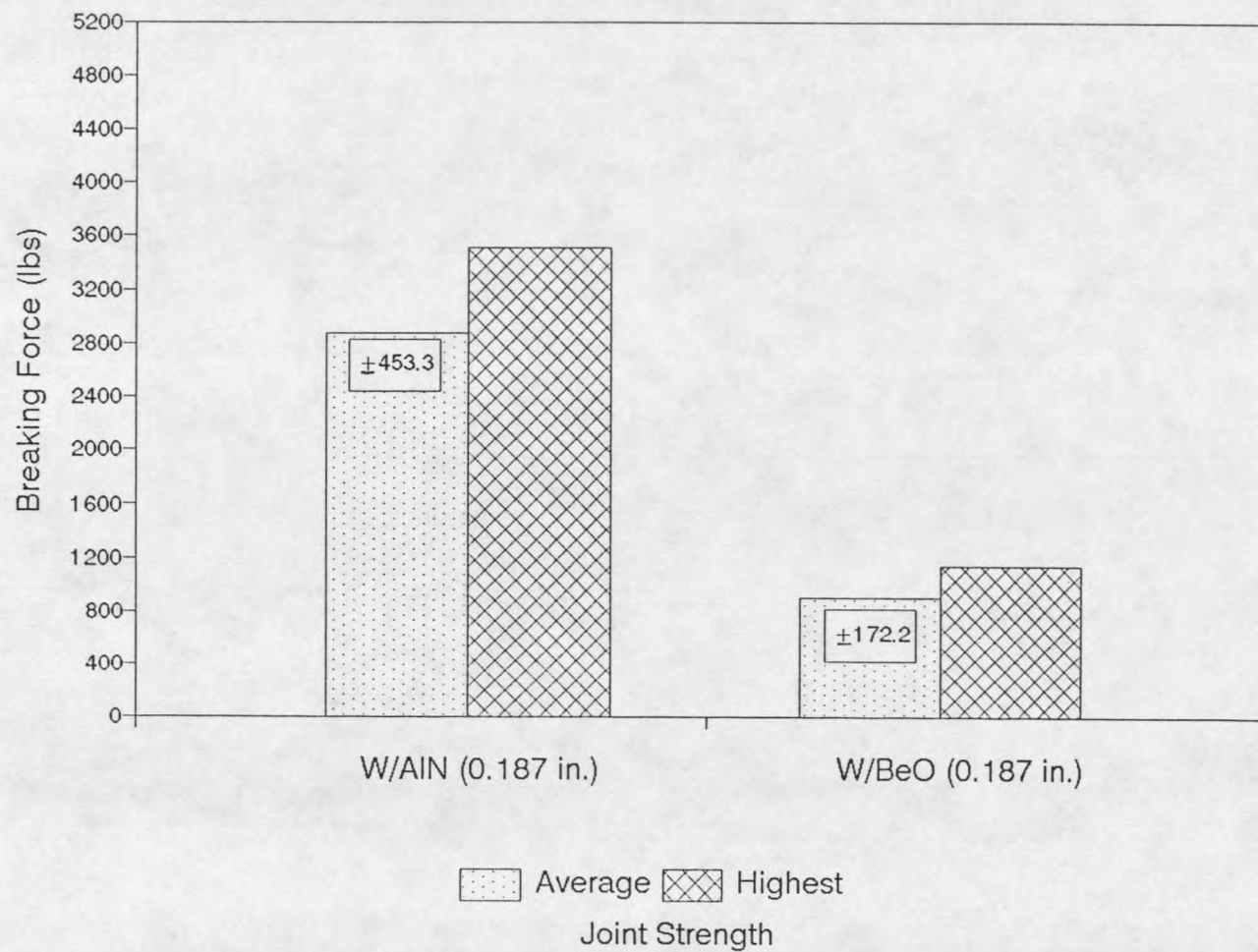


Figure 30. Effect of ceramic type on W/Ceramic (0.187in.) combinations.

resulted in marginally higher joint strengths for both ceramic thicknesses (Figure 31 and Figure 32). Also, for the Mo/Cf(0.04in.)/Ceramic combinations, AlN clearly dominated for both ceramic thicknesses (Figure 33 and Figure 34). With increased copper foil thickness the effect of the ceramic has been nullified by the presence of thicker ductile metal interlayer.

Effect of Ceramic Thickness. For both the Mo/AlN and Mo/BeO combinations, increased ceramic thickness resulted in lower joint strengths, with the effect being more marked for the Mo/BeO combination (Figure 35 and Figure 36). For the W/AlN combination, increased ceramic thickness combinations gave higher joint strengths, whereas, for the W/BeO combination, the opposite was true (Figure 37 and Figure 38).

For the Mo/Cf(0.01in.)/AlN combination, the average joint strength increased with ceramic thickness, but the standard deviation values for the 0.025in. thick ceramic combination resulted in a low average value (Figure 39). For the Mo/Cf(0.01in.)/BeO combination, the joint strength decreased with increased ceramic thickness, and a low average value was indicated for the 0.025in. thick ceramic combination (Figure 40). Whereas, for the Mo/Cf(0.04in.)/AlN and Mo/Cf(0.04in.)/BeO combinations, the joint strength decreased with increased ceramic thickness, but with suspect average values for the 0.187in. thick combination (Figure 41 and Figure 42). Generally speaking, it could be safely assumed

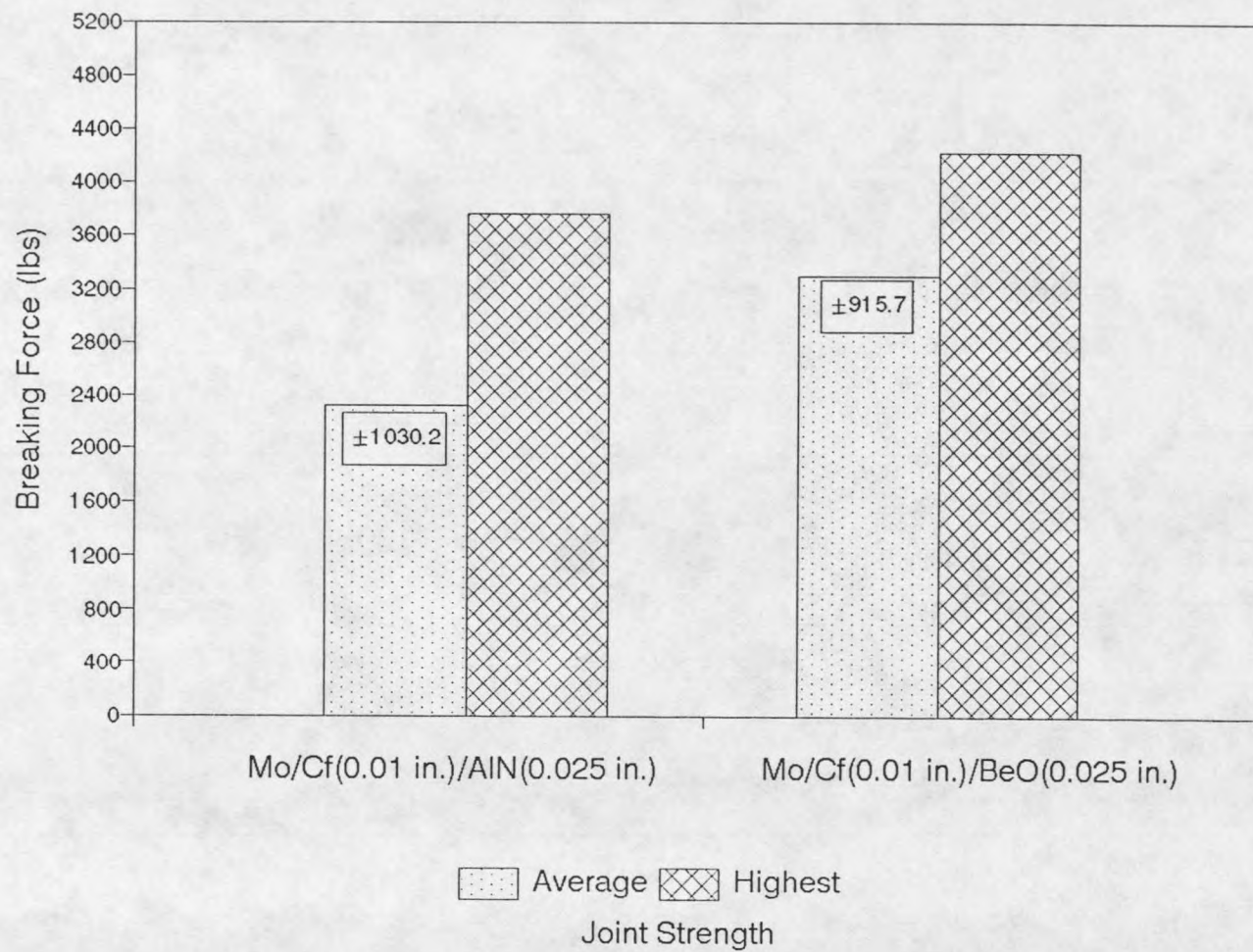


Figure 31. Effect of ceramic type on Mo/Cf(0.01in.)/Ceramic(0.025in.) combinations.

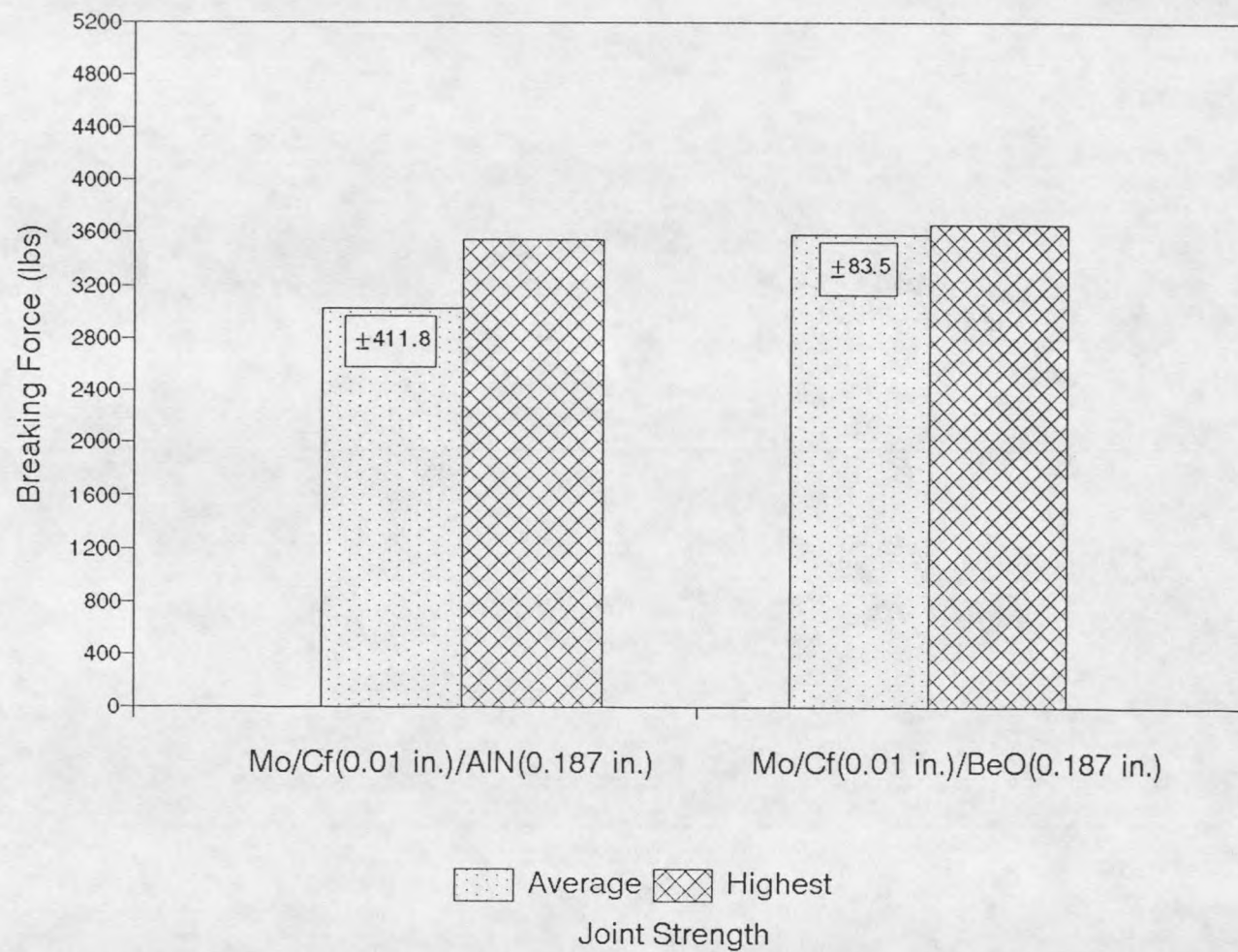


Figure 32. Effect of ceramic type on Mo/Cf(0.01in.)/Ceramic(0.187in.) combinations.

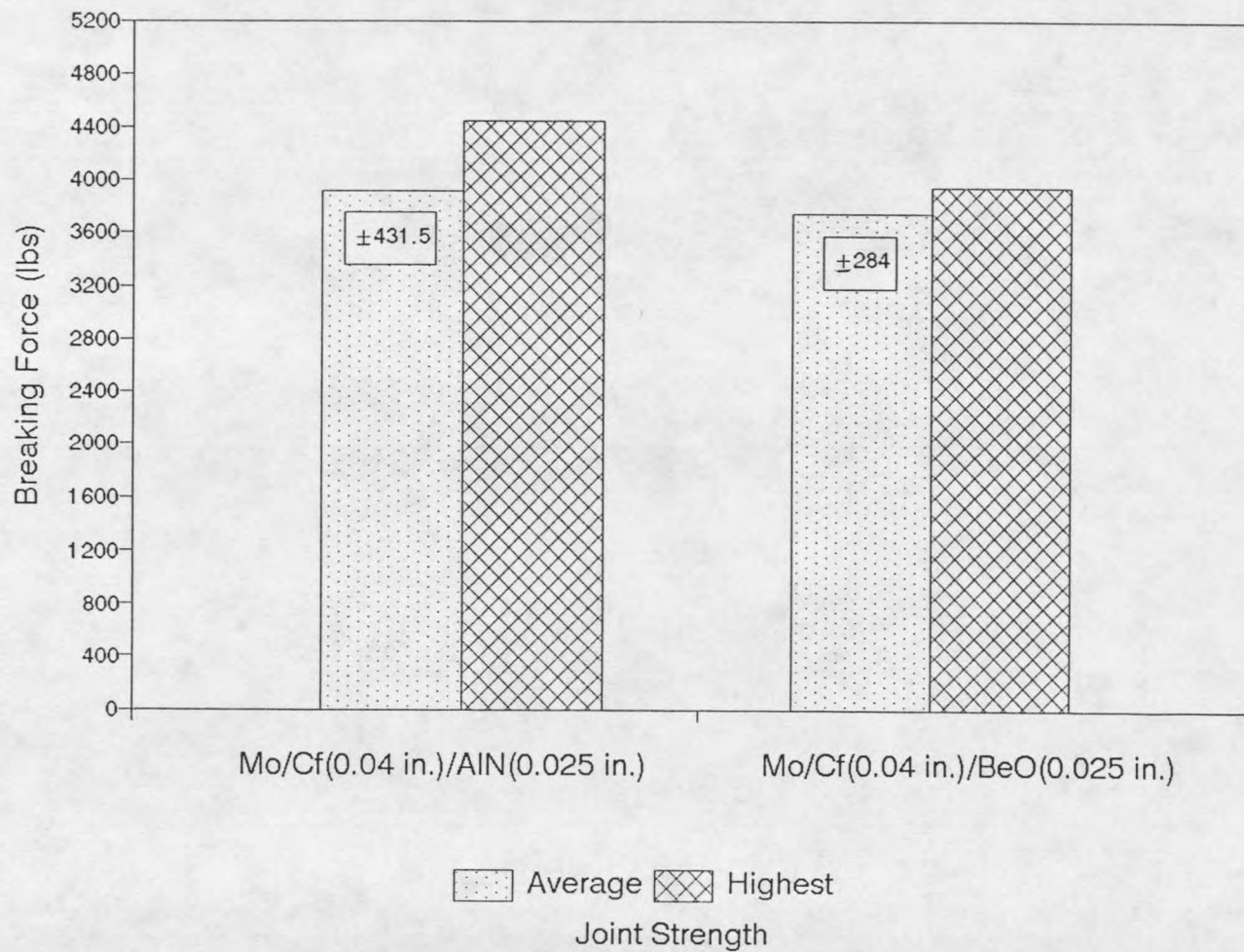


Figure 33. Effect of ceramic type on Mo/Cf(0.04in.)/Ceramic(0.025in.) combinations.

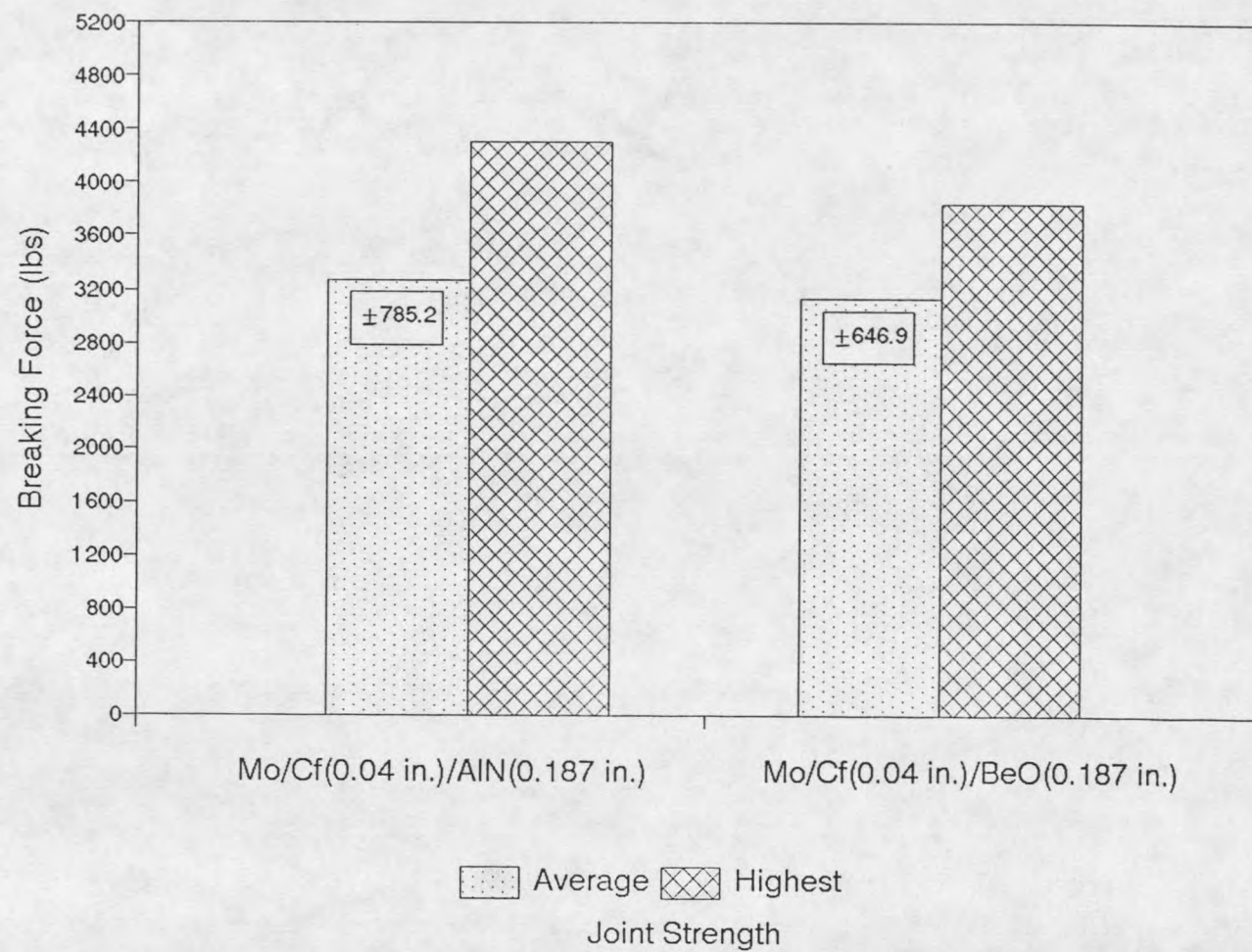


Figure 34. Effect of ceramic type on Mo/Cf(0.04in.)/Ceramic(0.187in.) combinations.

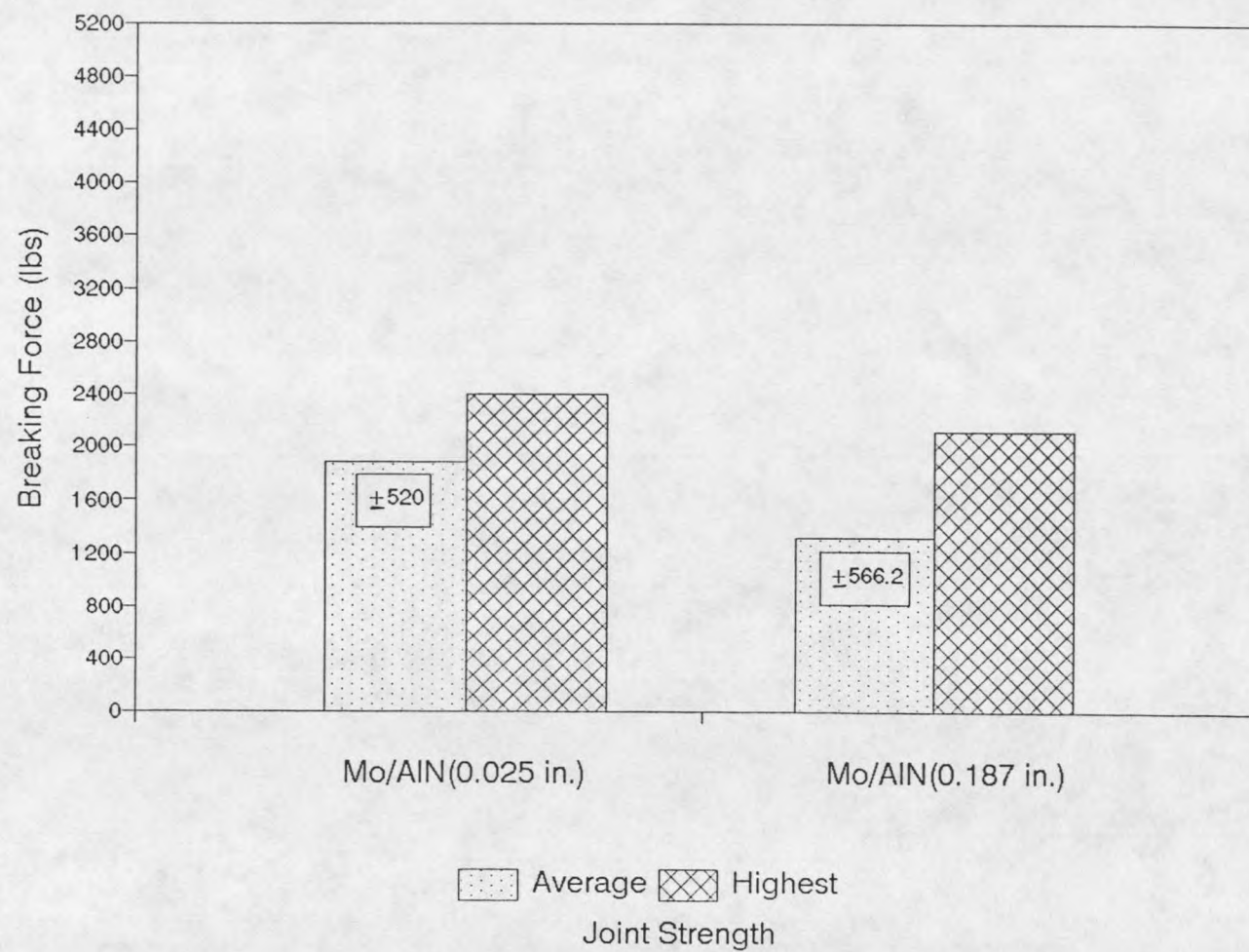


Figure 35. Effect of ceramic thickness on Mo/AlN combinations.

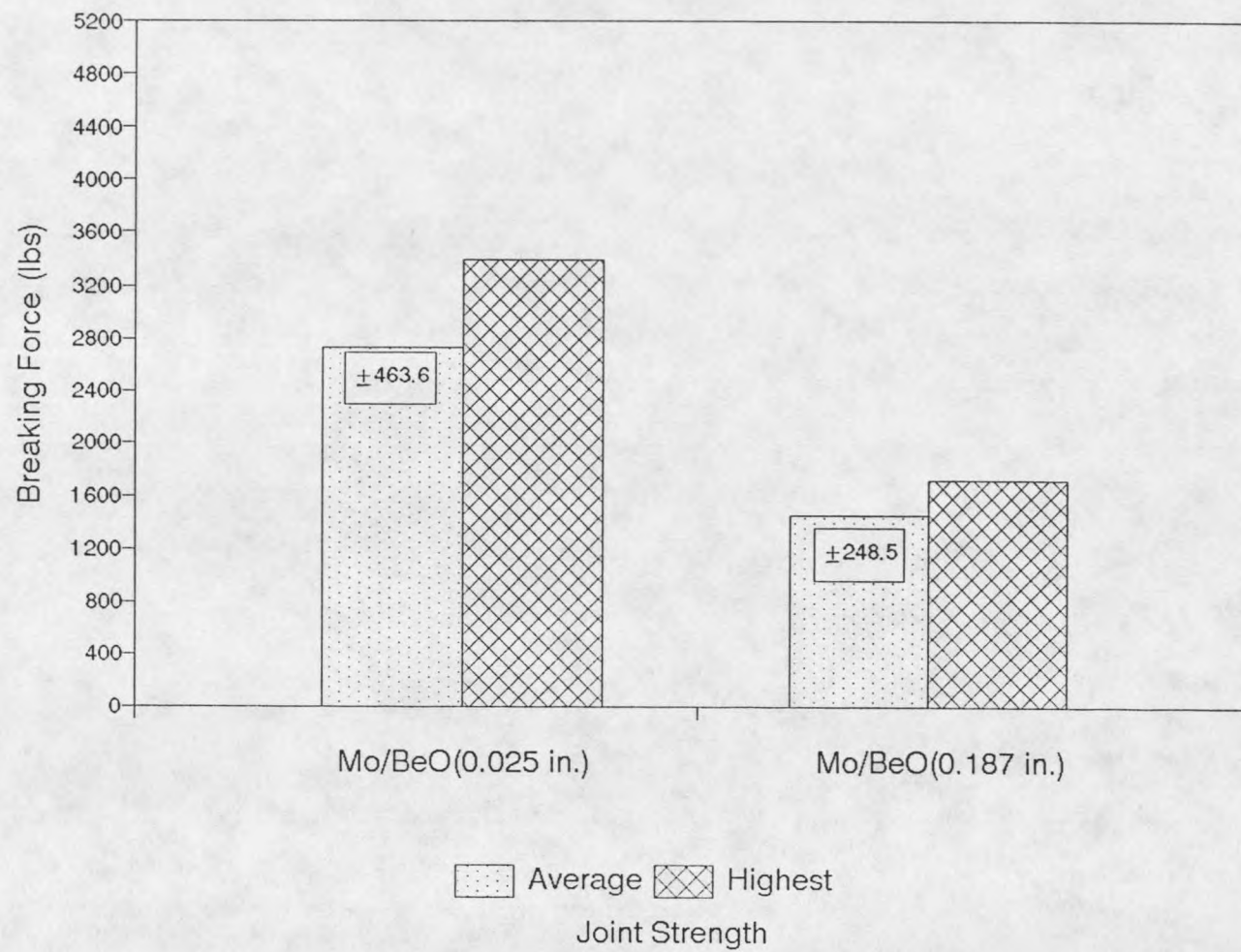


Figure 36. Effect of ceramic thickness on Mo/BeO combinations.

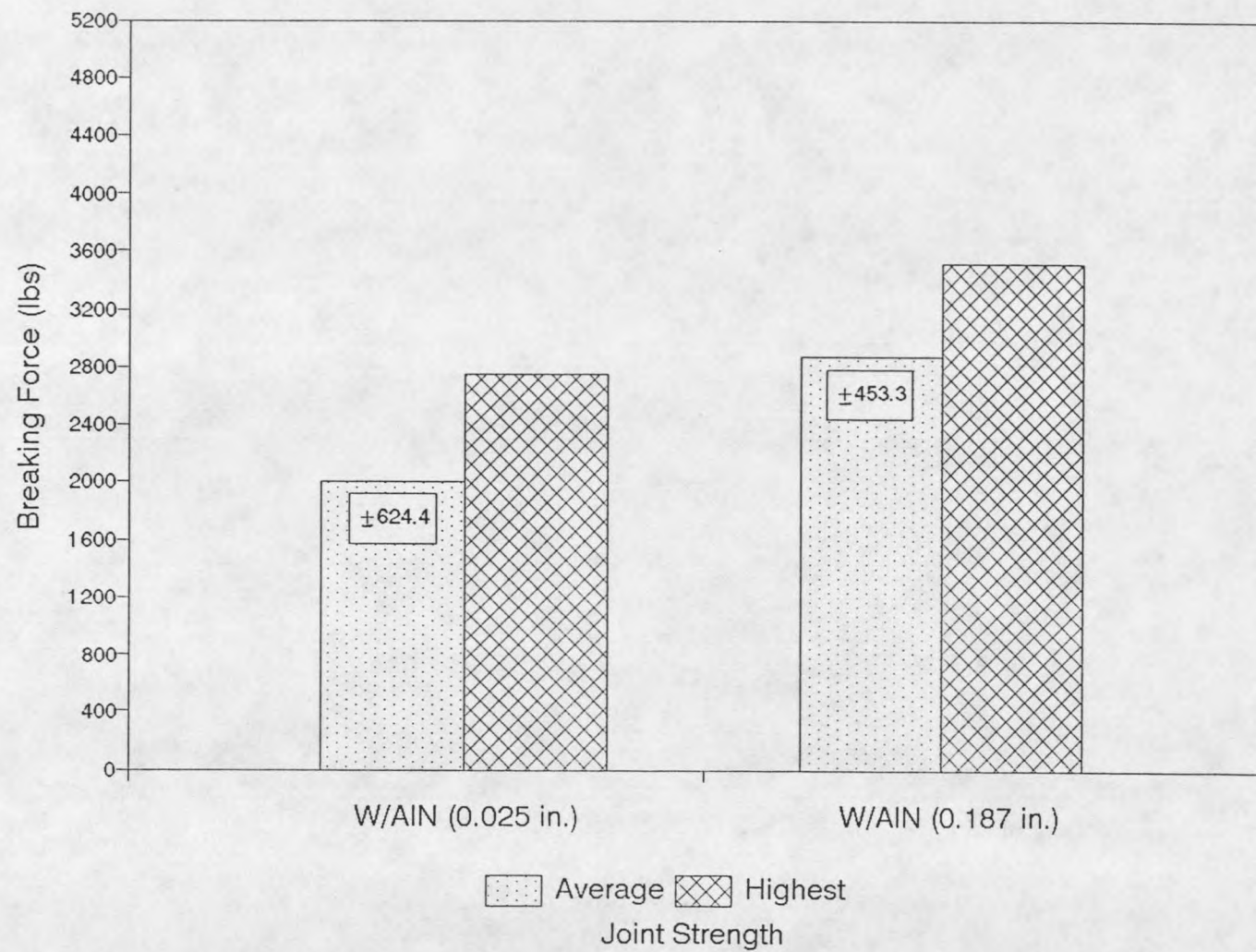


Figure 37. Effect of ceramic thickness on W/AlN combinations.

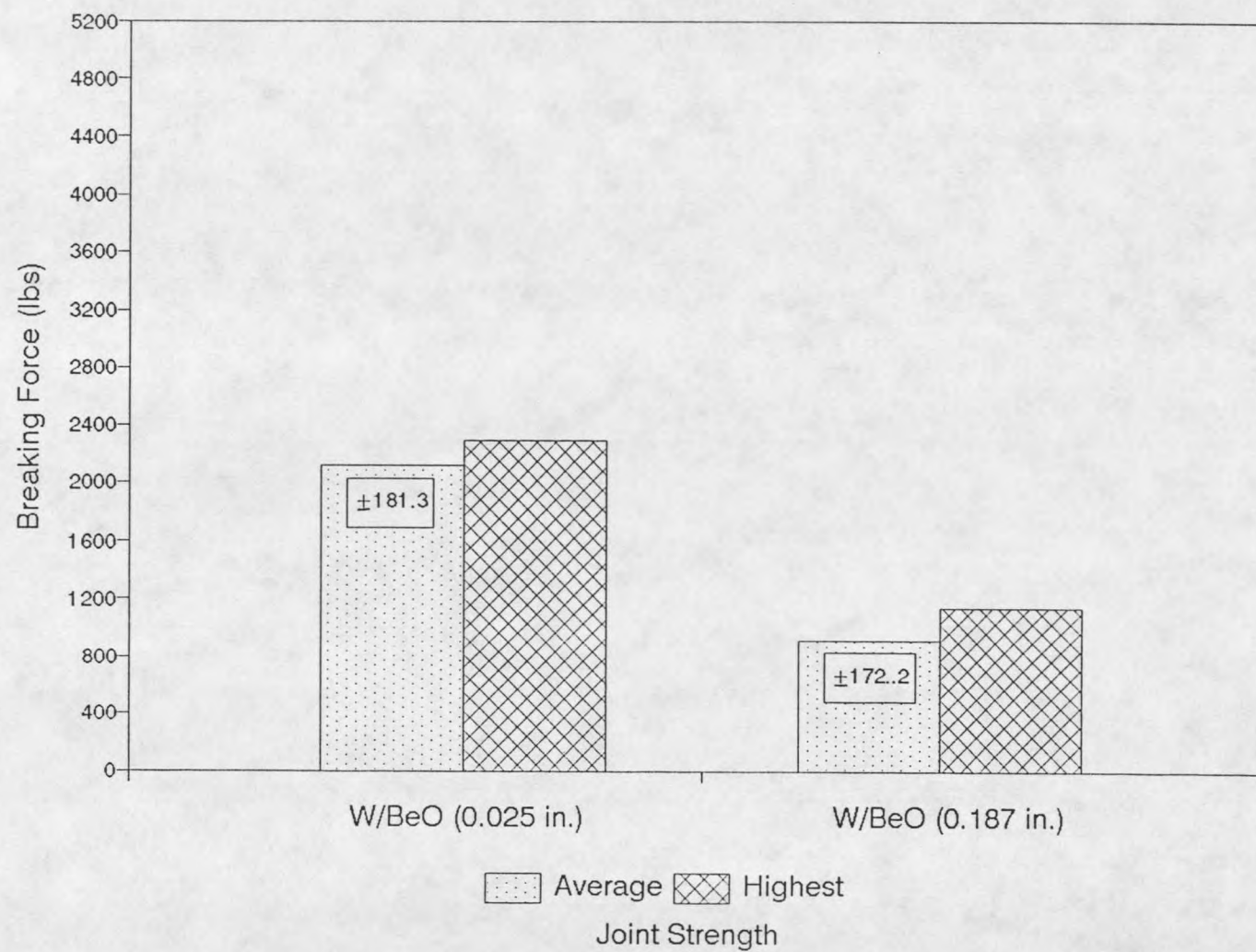


Figure 38. Effect of ceramic thickness on W/BeO combinations.

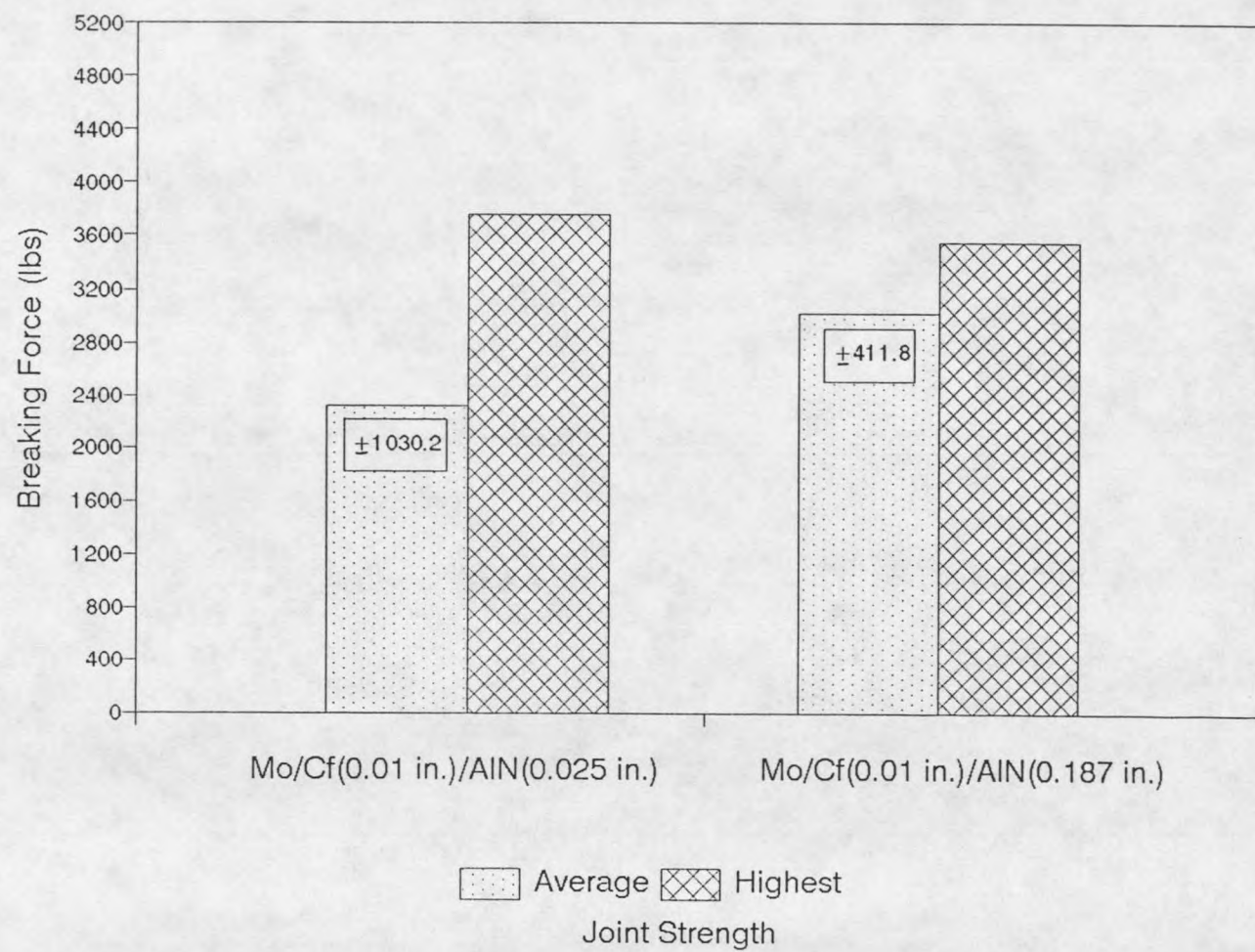


Figure 39. Effect of ceramic thickness on Mo/Cf(0.01in.)/AlN combinations.

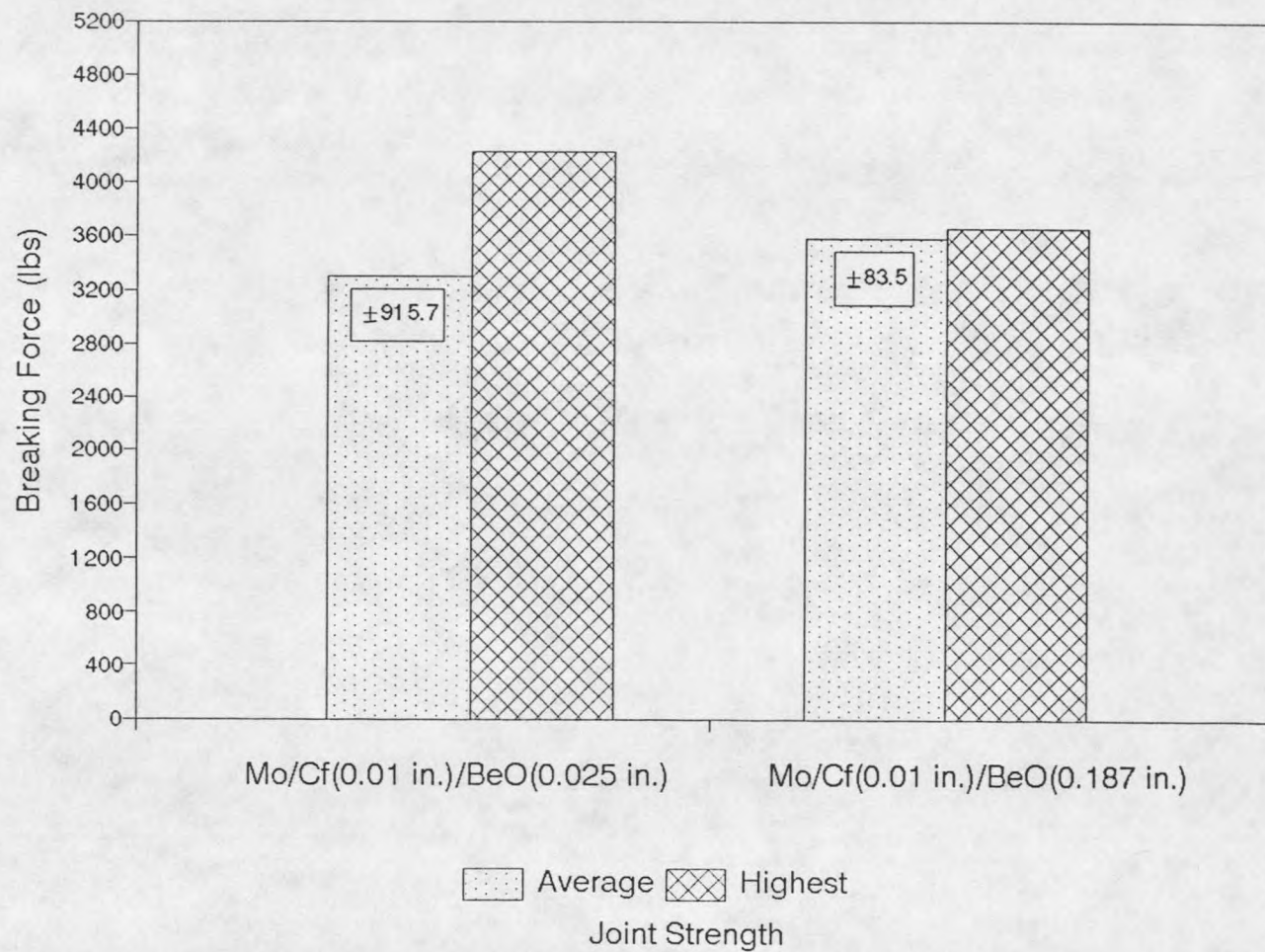


Figure 40. Effect of ceramic thickness on Mo/Cf(0.01in.)/BeO combinations.

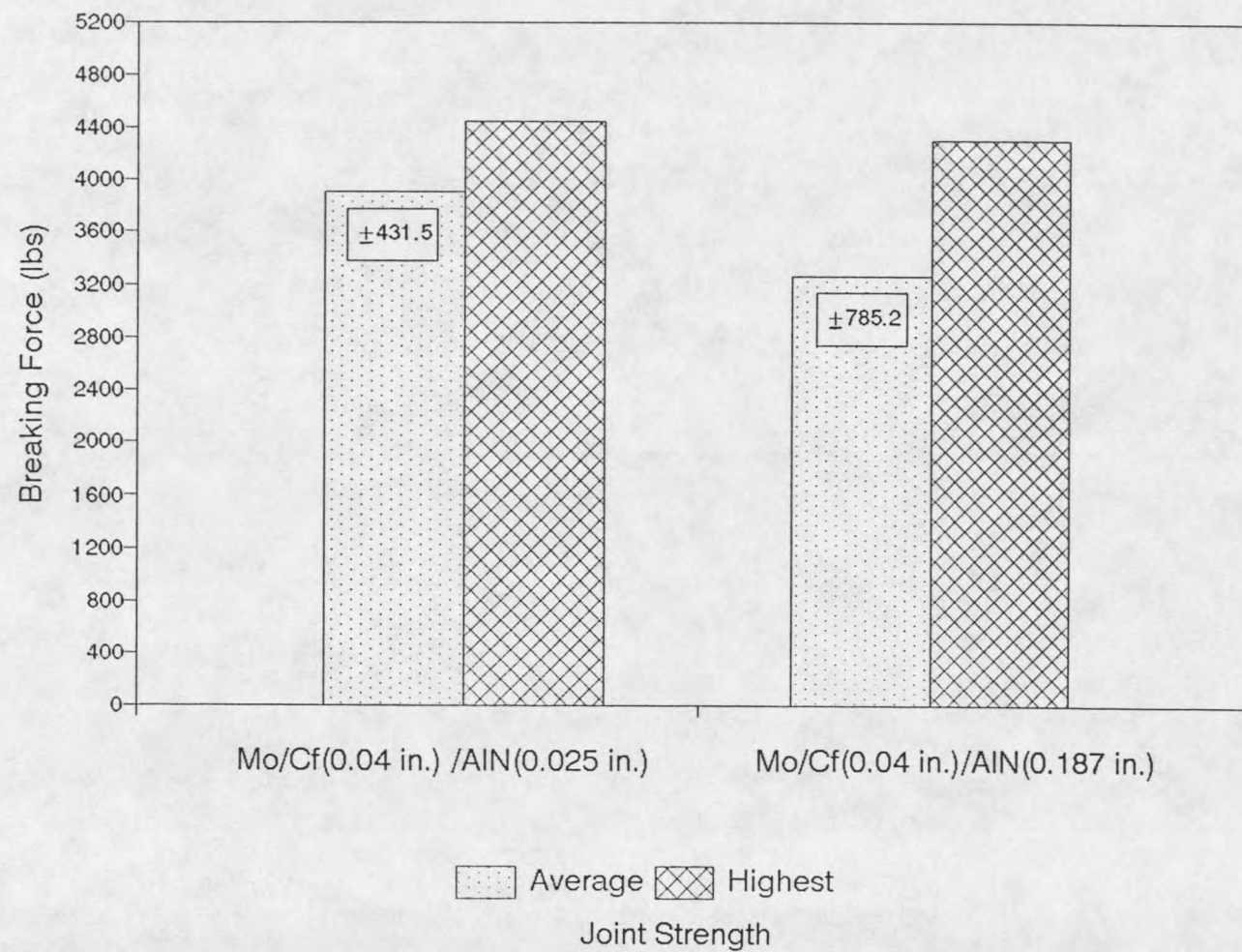


Figure 41. Effect of ceramic thickness on Mo/Cf(0.04in.)/AlN combinations.

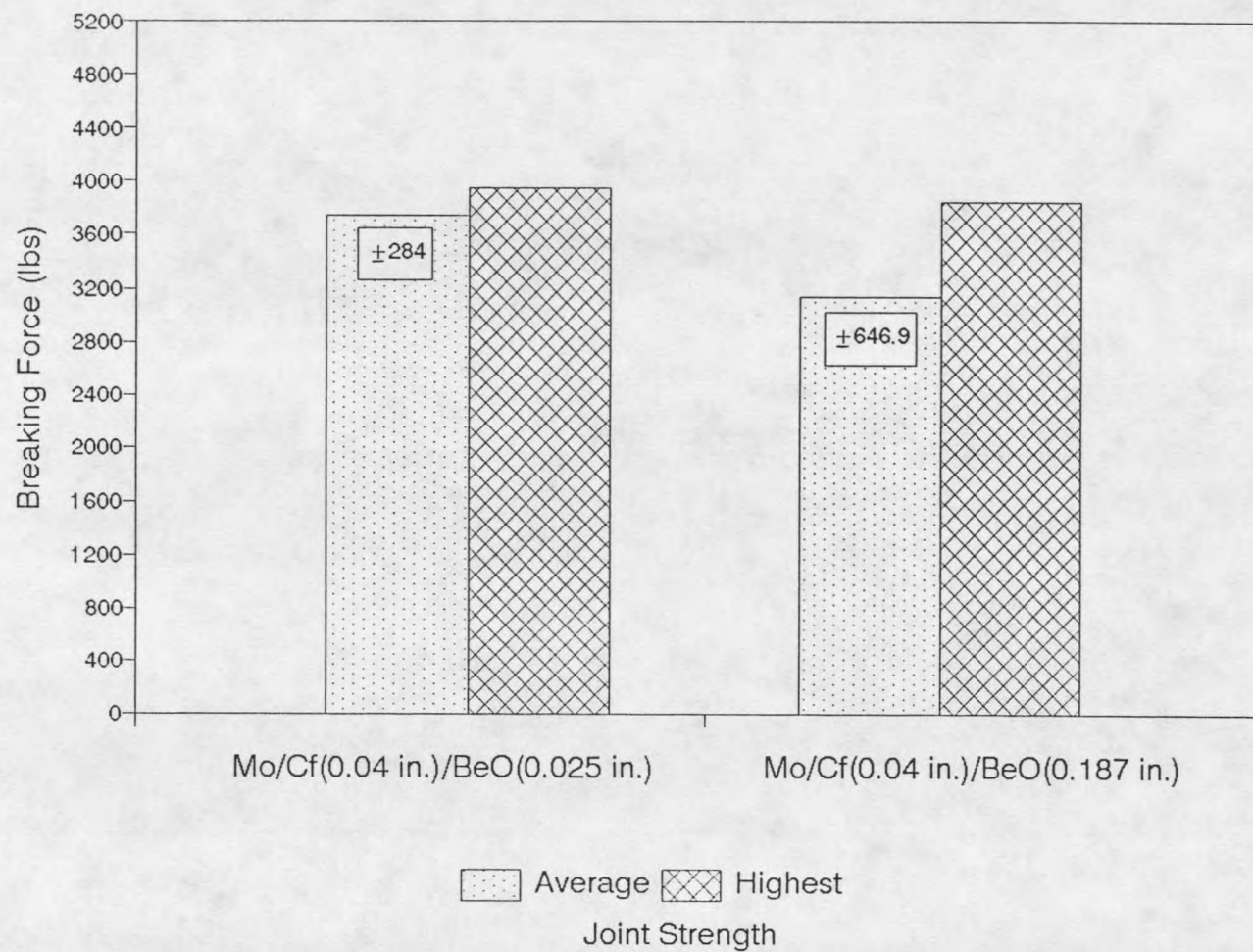


Figure 42. Effect of ceramic thickness on Mo/Cf(0.04in.)/BeO combinations.

that increased ceramic thickness led to reduced joint strength values in most cases, since combinations with thicker ceramics are prone to failure in the ceramic.

Effect of Ductile Interlayer Thickness. In general, the presence of the O.F.H.C copper foil, which was a ductile metal interlayer, seemed to considerably improve the joint strength. The bar graphs for no copper foil versus those with copper foil clearly showed the marked improvement in joint strength in the latter. However, as far as the thickness of the O.F.H.C copper foil affecting the joint strength, increased copper foil thickness resulted in increased joint strength for the Mo/Cf/AlN combinations (Figure 43 and Figure 44), but not that much of an improvement for the Mo/Cf/BeO combinations (Figure 45 and Figure 46). In fact, the highest values of joint strength showed a decrease for the Mo/Cf/BeO(0.025in.) combination, but the average value showed the opposite trend.

Considering each case separately, the joint strength steadily improved with increased copper foil thickness for the Mo/Cf/AlN combination for both ceramic thicknesses. Only the Mo/Cf/BeO(0.025in.) combination showed a deviation from this pattern, with the joint strength dropping a little for the highest copper foil thickness.

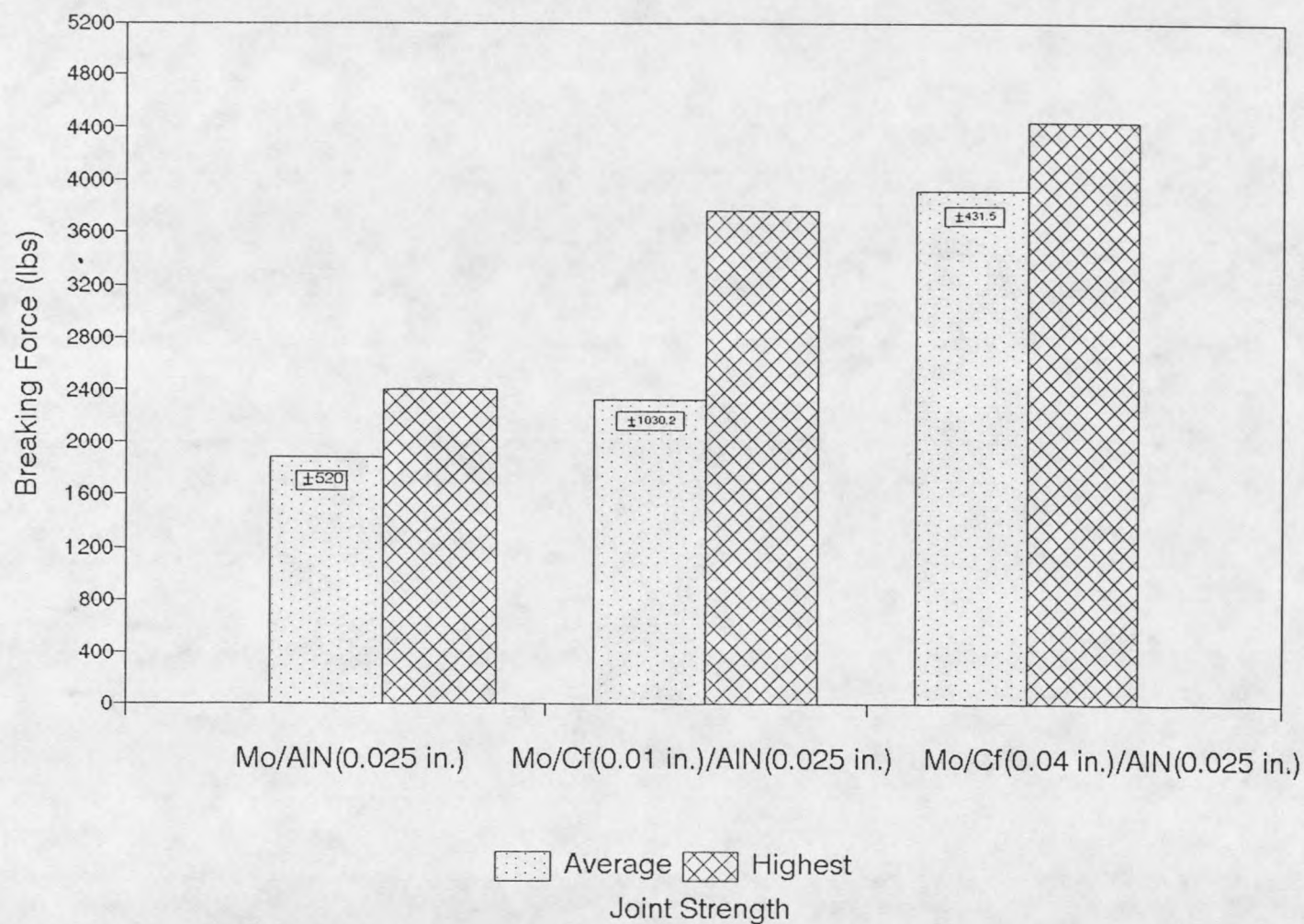


Figure 43. Effect of ductile interlayer thickness on Mo/Cf/AlN(0.025in.) combinations.

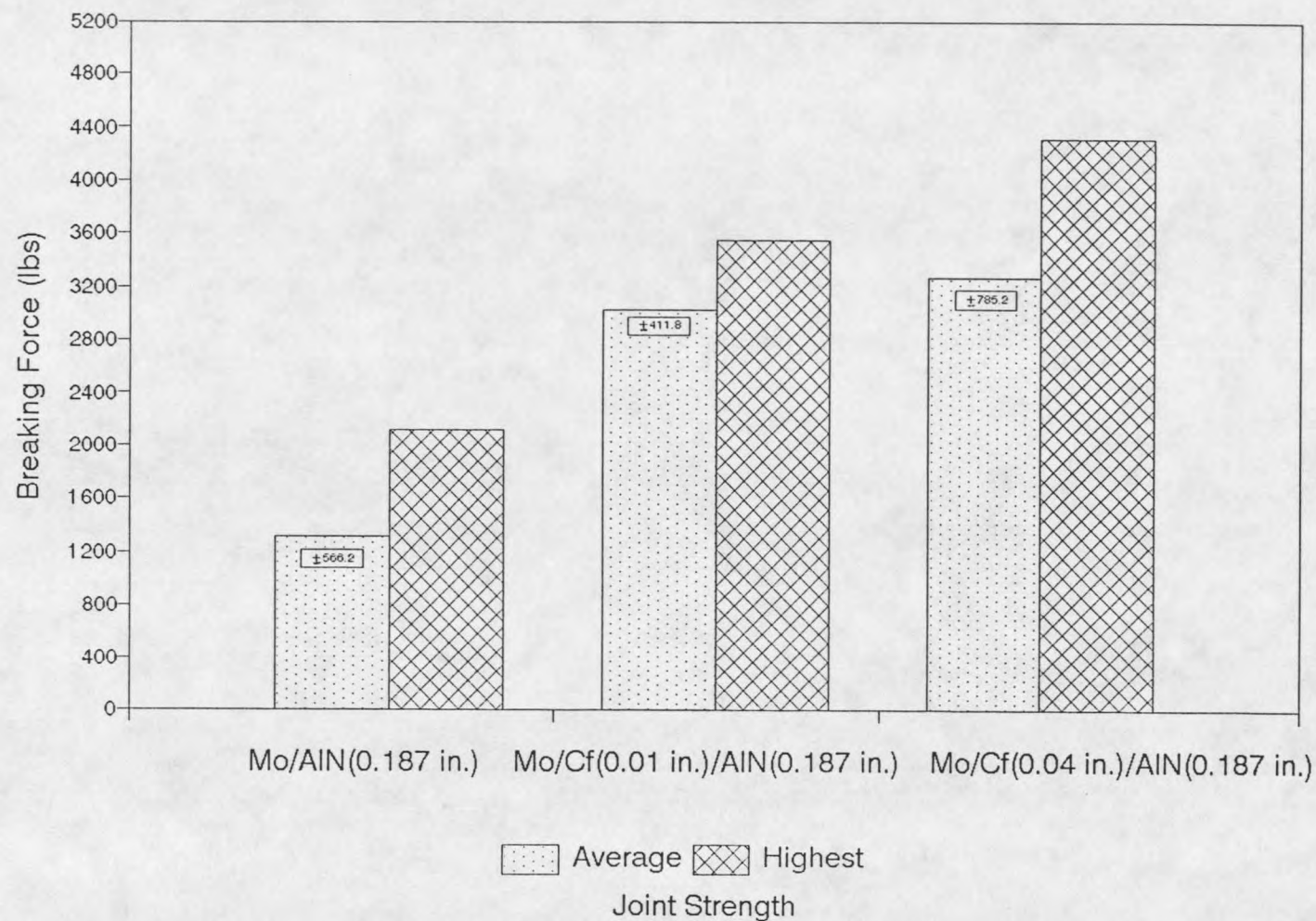


Figure 44. Effect of ductile interlayer thickness on Mo/Cf/AlN(0.187in.) combinations.

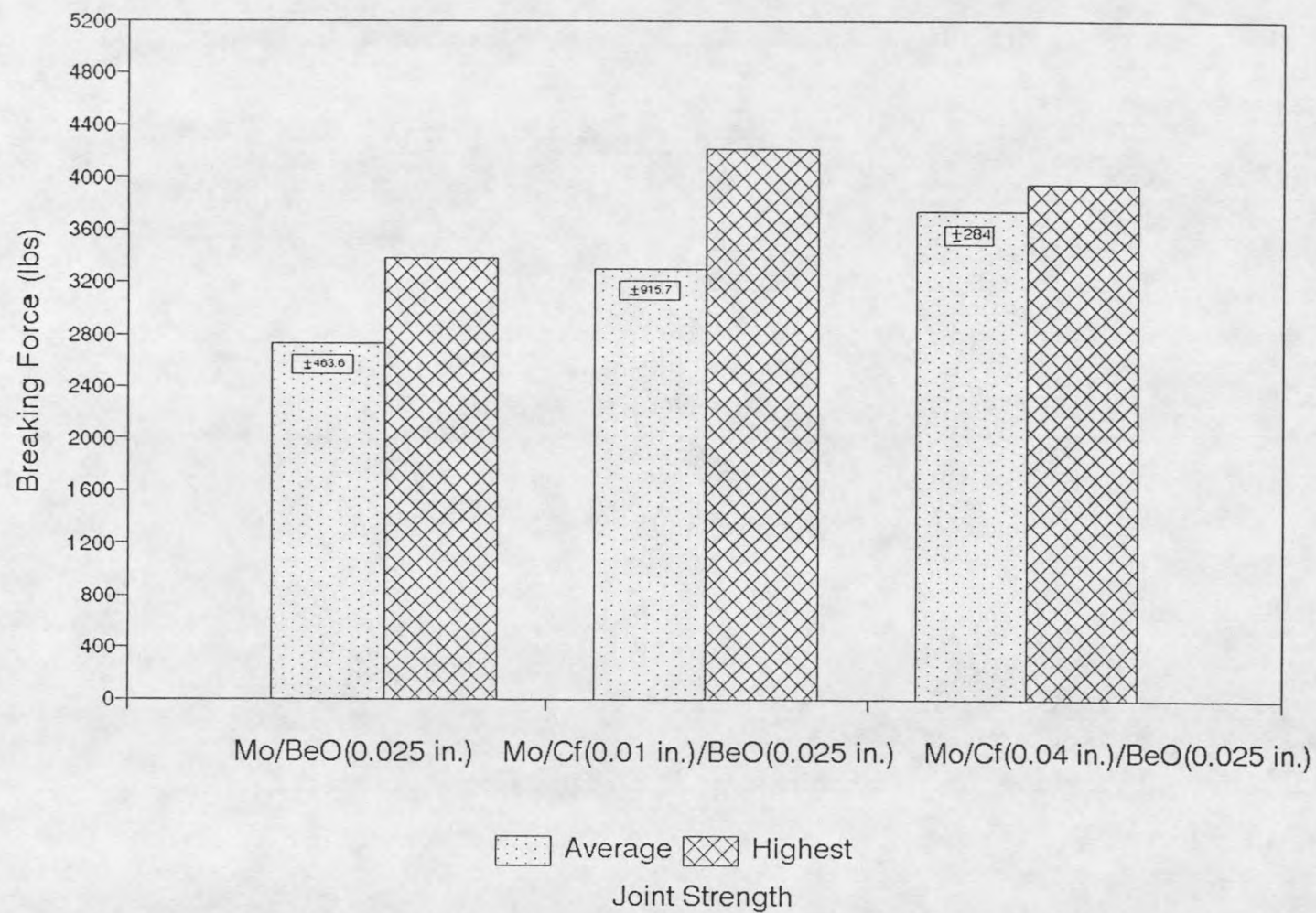


Figure 45. Effect of ductile interlayer thickness on Mo/Cf/BeO(0.025in.) combinations.

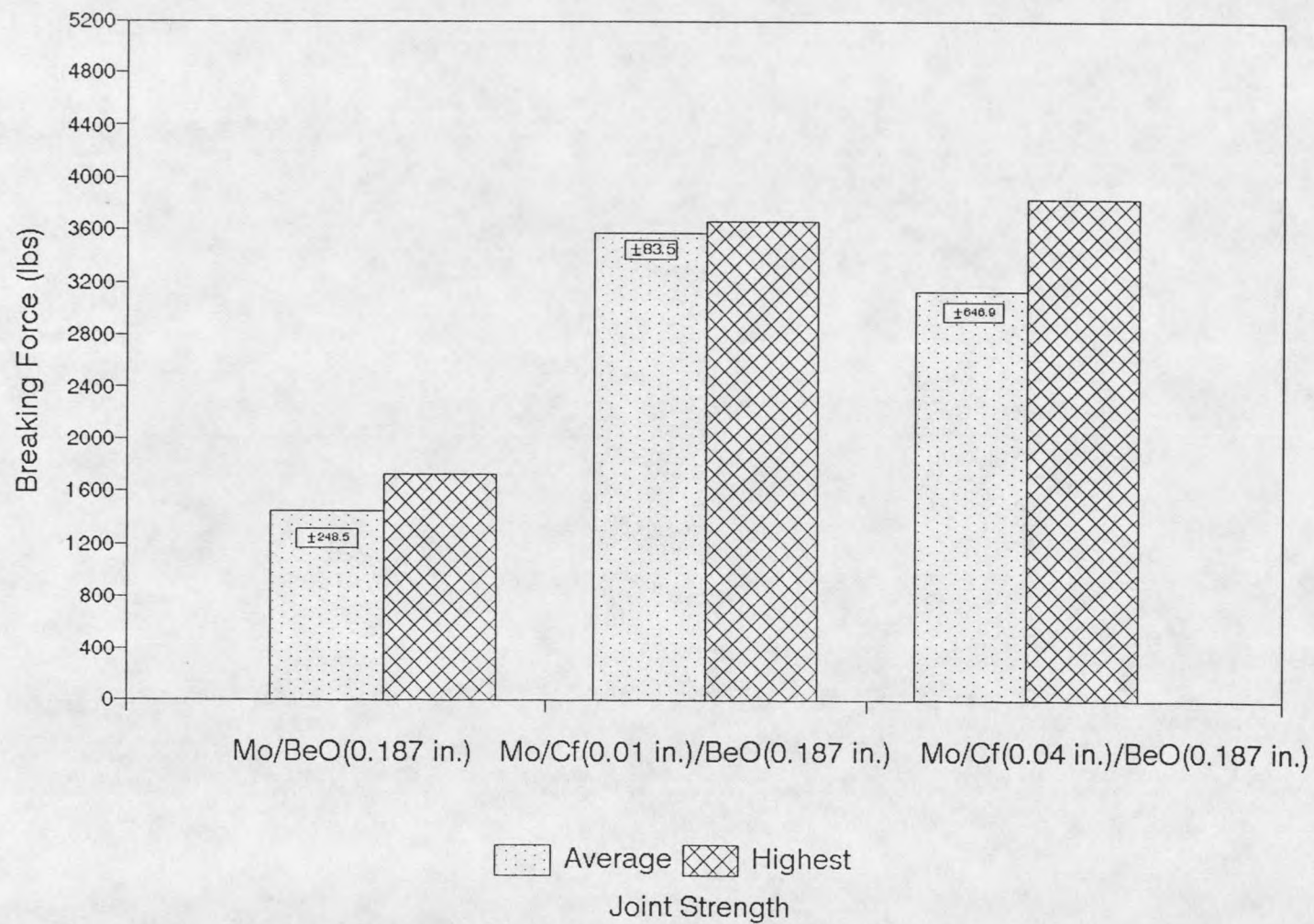


Figure 46. Effect of ductile interlayer thickness on Mo/Cf/BeO(0.187in.) combinations.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The ductile active brazing filler metal formed reliable mechanical joints in both metal/metal and ceramic/metal joints. As far as the metal/metal brazed joints are concerned, Cusil ABA proved quite effective for brazing the different combinations of metals. Use of Cusil ABA resulted in improved joint strengths in most cases. Thermal expansion mismatch played an important role in the resultant joint strengths, with the combinations with matching thermal expansion coefficients yielding comparatively higher joint strengths. However, combinations with platinum yielded the highest joint strength values of all the systems tested.

The tensile testing technique developed for the joint strength of ceramic/metal brazed systems proved to be very effective. This modified test was effective in studying variations in the different process variables, giving meaningful and consistent results in most cases. It has been demonstrated that the modified tension test can be used to determine the joint strength of ceramic/metal brazements effectively. The normal care used in preparing ceramic systems for all mechanical property testing must be used, but, other than that, the alignment fixture used during testing should not pose any problem for others seeking to apply this test.

The system could use further investigation of stress concentration effects at the corners, and more detailed study of misalignment effect for brittle systems.

For the ceramic/metal brazed systems, active metal brazing using Cusil ABA did achieve sufficient joint strength, i.e., no failures occurred on cooling from the brazing temperature itself, due to residual stresses. Interlayer materials with either low yield stress, such as O.F.H.C Copper, or low thermal expansion coefficients, such as tungsten and molybdenum, were shown to be effective in improving the joint performance by reducing the residual stresses. Also noticeable was the effect of an increase in ductile metal interlayer thickness, resulting in higher joint strength irrespective of the combination tested.

This study has also demonstrated that the combinations using thicker ceramics were generally less strong and more prone to failure in the ceramic, either clear through the ceramic or through the ceramic but close to an interface. Generally, each of the ceramics gave particularly strong joints with a certain metal interlayer, tungsten for aluminum nitride and molybdenum for beryllium oxide. Their closely matching thermal expansions could explain this effect. However, the use of both ductile metal interlayers and intermediate expansion interlayers did offset this trend to some extent. Whereas, the strongest combination tested was Mo/Cf(0.04in.)/AlN(0.025in.) and the weakest was

W/BeO(0.187in.)

Recommendations for Future Work

The results of this study are part of the database for joint strengths of metal/metal and ceramic/metal brazed butt joints, found using tensile tests. As mentioned earlier, such results are extremely sensitive to the geometry of the test specimen and the test method employed. Thus, extreme caution should be used in correlating the results of this study with future work.

More samples of each combination of materials need to be tested under similar conditions. This would give more meaningful average values and statistics, which could then validate the conclusions drawn here.

As an empirical extension of this study, more combinations of different materials could be tested. The influence of other ceramic thicknesses on joint strength would be interesting to investigate. The effectiveness of other active metal braze alloys (like Incusil from GTE WESGO) could also be tested for different brazed combinations. The effect of different ductile metal interlayers and their thicknesses on these combinations could also be tested. Another interesting aspect to investigate would be the effect of the thickness of the intermediate expansion interlayer. Also, the effect of the braze joint thickness - a critical variable in the strength of any brazement, on the joint strength could be

studied. A particularly strong need is for new and detailed nonlinear modelling of these combinations to better understand differences in behavior and fracture details. A well validated modelling procedure would allow a more rational choice of parameters for further study, as well as give an indication of geometric effects in real joint applications.

Finally and most importantly, since these metal/metal and ceramic/metal brazed joints are to be used at elevated temperatures (up to 600°K), elevated temperature testing of these combinations could lead to interesting results and hence should be investigated at length.

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REFERENCES CITED

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APPENDICES

APPENDIX A
COMPLETE TENSILE TEST RESULTS

Table 14. Metal/metal brazed coupons - Complete tensile test results.

COUPON ID #	FAILURE LOAD (lbs)	FAILURE STRESS (lbs/sq.in.)	FAILURE LOCATION & COMMENTS
MT1A	-	-	Deformed while gripping
MT1B	1083	5290.7	LJ
MT1C	950	4650.0	LJ
MT1D	2096	10259.4	UJ
MT1E	1502	7287.7	UJ
MT1F	657	3226.7	Alignment doubt
MT1G	820	4013.7	Alignment doubt
MT1H	476	2366.9	Alignment doubt
MT2A	1630	7855.4	UJ
MT2B	2001	9925.6	CM(L)
MT2C	939	4638.5	CM(U)
MT2D	1324	6468.0	CM(U)
MT2E	1429	7025.5	Still carried 750 lbs load
MT2F	1713	8384.7	CM(U)
MT2G	1867	9178.9	-
MT2H	1169	5696.8	-
MT3A	825	4038.6	UJ
MT3B	1462	7156.1	CM(U)
MT3C	500	2475.2	CM
MT3D	1633	8048.3	LJ
MT3E	965	4697.9	CM(U)
MT3F	1571	7574.7	CM(U)
MT3G	1499	7337.2	CM(L)
MT3H	1928	9377.4	CM(U)

Table 14. Metal/metal brazed coupons - Complete tensile test results (continued).

COUPON ID #	FAILURE LOAD (lbs)	FAILURE STRESS (lbs/sq.in.)	FAILURE LOCATION & COMMENTS
MT4A	1154	5550.7	UJ
MT4B	1003	4909.4	CM(L)
MT4C	1081	5257.8	LJ
MT4D	1272	6253.7	CM(L)
MT4E	1317	6377.7	CM(L)
MT4F	1123	5584.3	CM & LJ
MT4G	1102	5455.4	CM(L)
MT4H	945	4719.3	CM(L)
MT5A	3900	19174.0	CM(L)
MT5B	4270	21128.1	CM(L)
MT5C	2560	12698.4	CM & UJ
MT5D	3155	15480.8	CM(L)
MT5E	2784	13782.2	CM(U)
MT5F	1773	8777.2	Alignment doubt
MT5G	3002	14890.8	CM(L)
MT5H	4066	20168.6	CM(L)
MT6A	1830	9077.4	CM
MT6B	3716	18598.6	CM(L)
MT6C	4728	23348.1	CM(L)
MT6D	8103	40393.8	CM(L)
MT6E	3255	16145.8	CM(L)
MT6F	-	-	Failed while gripping
MT6G	-	-	Failed while gripping
MT6H	4833	23866.7	CM(L)

Table 14. Metal/metal brazed coupons - Complete tensile test results (continued).

COUPON ID#	FAILURE LOAD (lbs)	FAILURE STRESS (lbs/sq.in.)	FAILURE LOCATION & COMMENTS
MT7A	1556	7737.4	CM(L)
MT7B	2073	10262.4	CM
MT7C	91	451.0	CM
MT7D	3173	15669.1	CM(L)
MT7E	574	2822.0	CM
MT7F	2748	13603.9	CM
MT7G	1500	7392.8	CM
MT7H	353	1758.8	CM(L)
MT8A	877	4313.2	CM(U)
MT8B	835	4122.9	CM
MT8C	> 1530	> 7456.1	Not seperated
MT8D	1844	9088.2	CM(L)
MT8E	1788	8851.5	CM(L)
MT8F	1271	6087.2	CM(L)
MT8G	> 1450	> 6885.1	Not seperated
MT8H	1412	6911.4	CM(U)
P130AA	> 5337	> 26238.9	Not seperated
P130AB	> 13000	> 64197.5	Not seperated
P130AC	11980	59014.8	LJ
P130AD	12410	61283.9	LJ
P130AE	> 12590	> 62730.4	Not seperated
P130AF	-	-	Not conducted
P130AG	-	-	Not conducted
P130AH	-	-	Not conducted

Table 14. Metal/metal brazed coupons - Complete tensile test results (continued).

COUPON ID #	FAILURE LOAD (lbs)	FAILURE STRESS (lbs/sq.in.)	FAILURE LOCATION & COMMENTS
P130BA	2238	11024.6	CM
P130BB	1434	7064.0	CM
P130BC	> 1581	> 7738.6	Not seperated
P130BD	1966	9756.8	CM
P130BE	2226	10943.9	CM
P130BF	1272	6198.8	CM
P130BG	1029	5049.1	CM
P130BH	1493	7325.8	CM
P130CA	> 4476	> 22202.4	Not seperated
P130CB	> 5427	> 26986.6	Not seperated
P130CC	> 5002	> 24591.9	Not seperated
P130CD	> 5397	> 26533.9	Not seperated
P130CE	> 4391	> 21492.9	Not seperated
P130CF	5091	24870.5	CM
P130CG	> 5770	> 28493.8	Not seperated
P130CH	5601	27295.3	UJ

Legend: UJ - Between upper end material and center material
 LJ - Between lower end material and center material
 CM - Through center material
 CM(L) - Through center material(Close to lower joint)
 CM(U) - Through center material(Close to upper joint)

Table 15. Ceramic/metal brazed coupons - Complete tensile test results.

COUPON ID #	FAILURE LOAD (lbs)	FAILURE STRESS (lbs/sq.in.)	FAILURE LOCATION & COMMENTS
PA1-1	1357	3473.9	Through ceramic
PA1-2	2397	6116.7	Through ceramic
PA1-3	352	900.1	U.capmetal/Ceramic
PA2-1	2113	5366.2	Through ceramic
PA2-2	850	2169.0	Through ceramic
PA2-3	985	2501.5	Through ceramic
PA3-1	2044	5224.3	U.capmetal/Ceramic
PA3-2	2750	7040.0	Ceramic/L.capmetal
PA3-3	1222	3128.3	Copper/U.capmetal
PA4-1	2499	6397.4	L.capmetal/Copper
PA4-2	3511	8988.2	Copper/U.capmetal
PA4-3	2609	6679.0	L.capmetal/Copper
PA5-1	1417	3627.5	Thro' U.capmetal
PA5-2	1782	4561.9	Thro' U.capmetal
PA5-3	3762	9630.7	L.capmetal/Copper
PA6-1	2993	7662.1	Through ceramic
PA6-2	3550	9088.0	Copper/U.capmetal
PA6-3	2543	6510.1	Copper/U.capmetal
PA7-1	3385	8665.6	Thro' U.capmetal
PA7-2	3920	10035.2	Through ceramic
PA7-3	4442	11371.5	Through ceramic
PA8-1	4312	11038.7	Through ceramic
PA8-2	3046	7797.7	Copper/U.capmetal
PA8-3	2425	6208.0	Copper/U.capmetal

Table 15. Ceramic/metal brazed coupons - Complete tensile test results (continued).

COUPON ID #	FAILURE LOAD (lbs)	FAILURE STRESS (lbs/sq.in.)	FAILURE LOCATION & COMMENTS
PB1-1	2356	6031.4	U.capmetal/Ceramic
PB1-2	2459	6295.0	Ceramic/L.capmetal
PB1-3	3387	8670.7	Through ceramic
PB2-1	1120	2867.2	Ceramic/L.capmetal
PB2-2	1481	3791.4	U.capmetal/Ceramic
PB2-3	1725	4416.0	Through ceramic
PB3-1	2290	5862.4	L.capmetal/Copper
PB3-2	1867	4779.5	L.capmetal/Copper
PB3-3	2196	5621.8	L.capmetal/Copper
PB4-1	864	2211.8	U.capmetal/Ceramic
PB4-2	1137	2910.7	Ceramic/L.capmetal
PB4-3	722	1848.3	Ceramic/L.capmetal
PB5-1	4225	10816.0	Through ceramic
PB5-2	2051	5250.6	Thro' L.capmetal
PB5-3	3616	9257.0	L.capmetal/Copper
PB6-1	-	-	-
PB6-2	3497	8952.3	U.capmetal/Ceramic
PB6-3	3664	9379.8	U.capmetal/Ceramic
PB7-1	3344	8560.6	Copper/U.capmetal
PB7-2	3944	10096.6	Through ceramic
PB7-3	3949	10109.4	Through ceramic
PB8-1	3839	9827.8	Through ceramic
PB8-2	2280	5836.8	U.capmetal/Copper
PB8-3	3306	8463.4	U.capmetal/Copper

APPENDIX B
LOAD VERSUS DISPLACEMENT CURVES

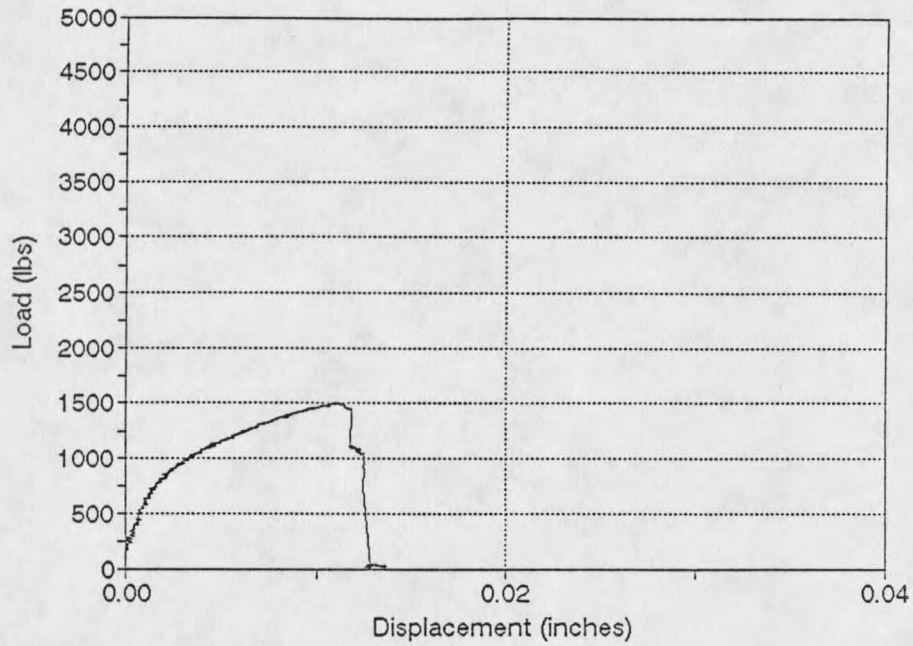


Figure 47. Load versus displacement curve for MT1E tensile test.

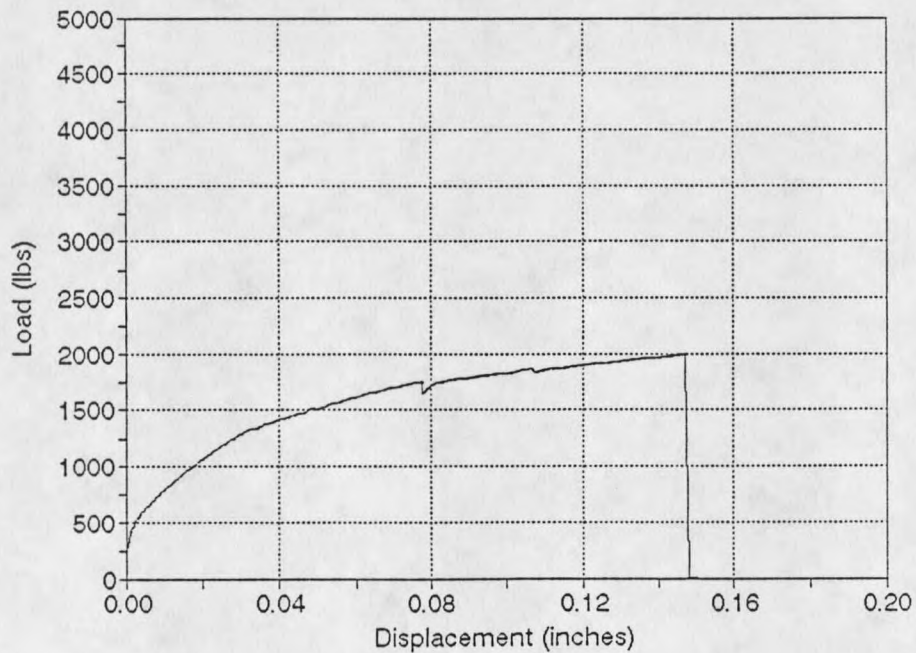


Figure 48. Load versus displacement curve for MT2B tensile test.

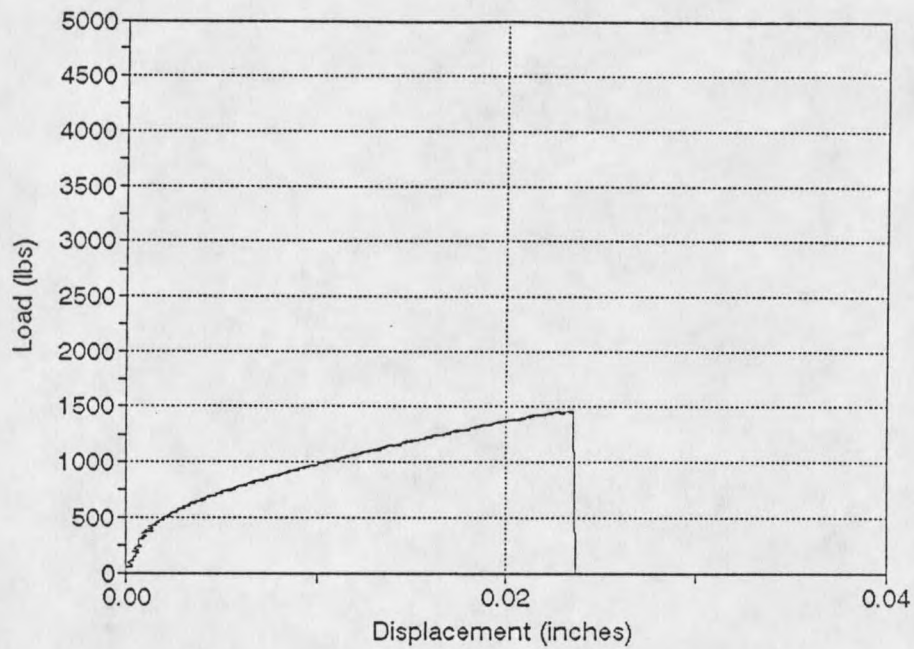


Figure 49. Load versus displacement curve for MT3B tensile test.

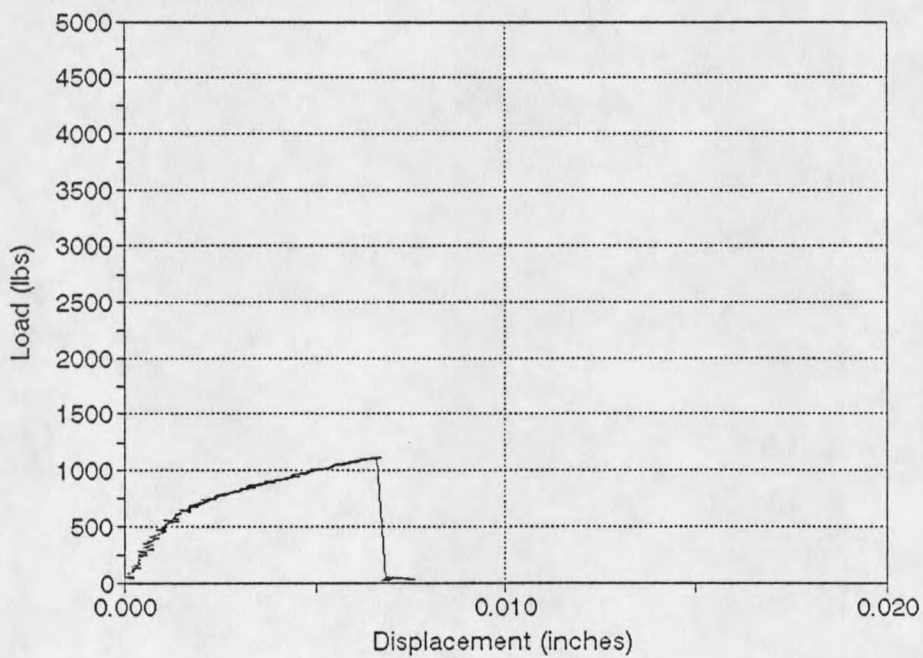


Figure 50. Load versus displacement curve for MT4F tensile test.

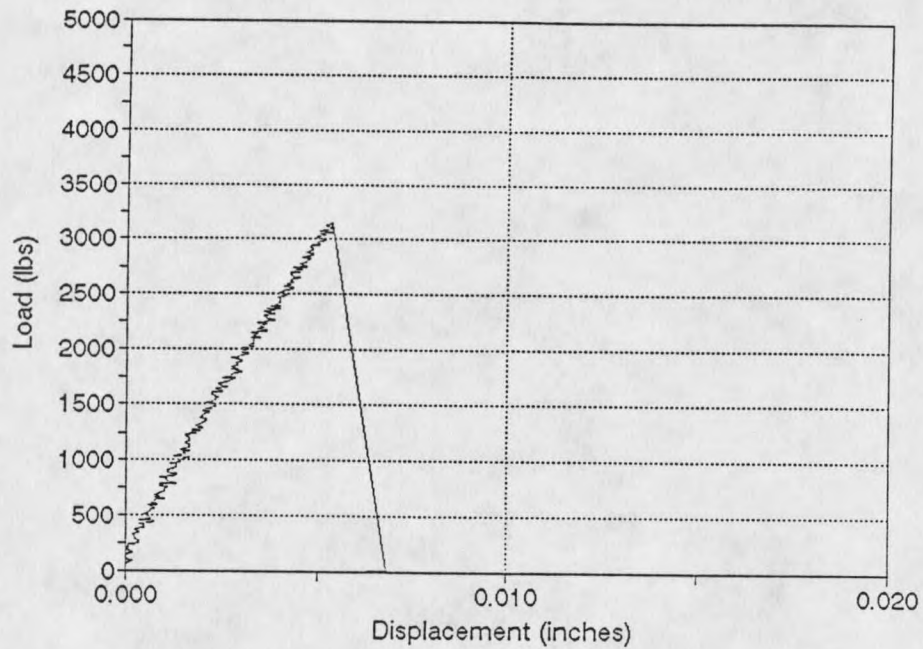


Figure 51. Load versus displacement curve for MT5D tensile test.

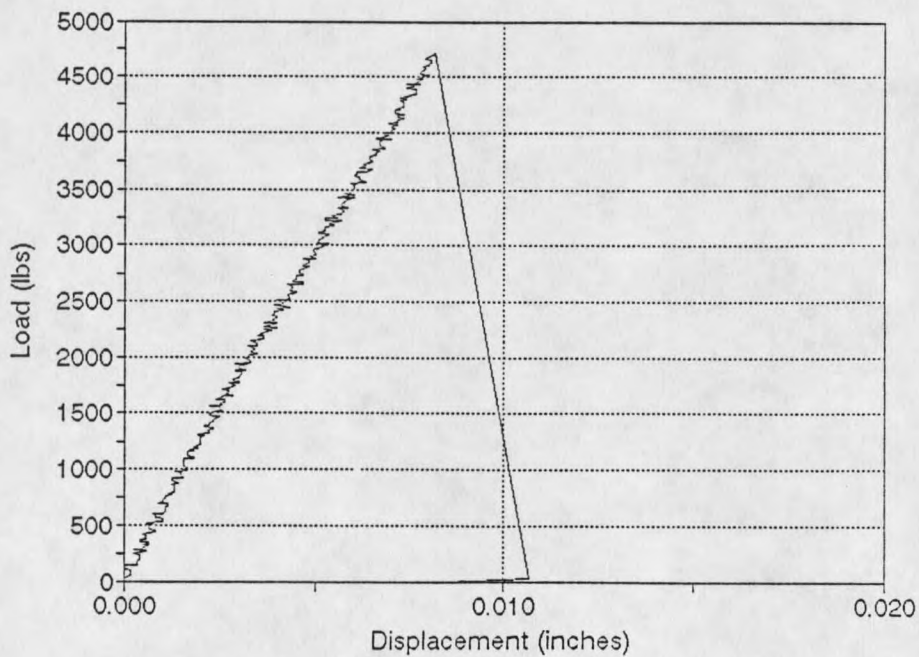


Figure 52. Load versus displacement curve for MT6C tensile test.

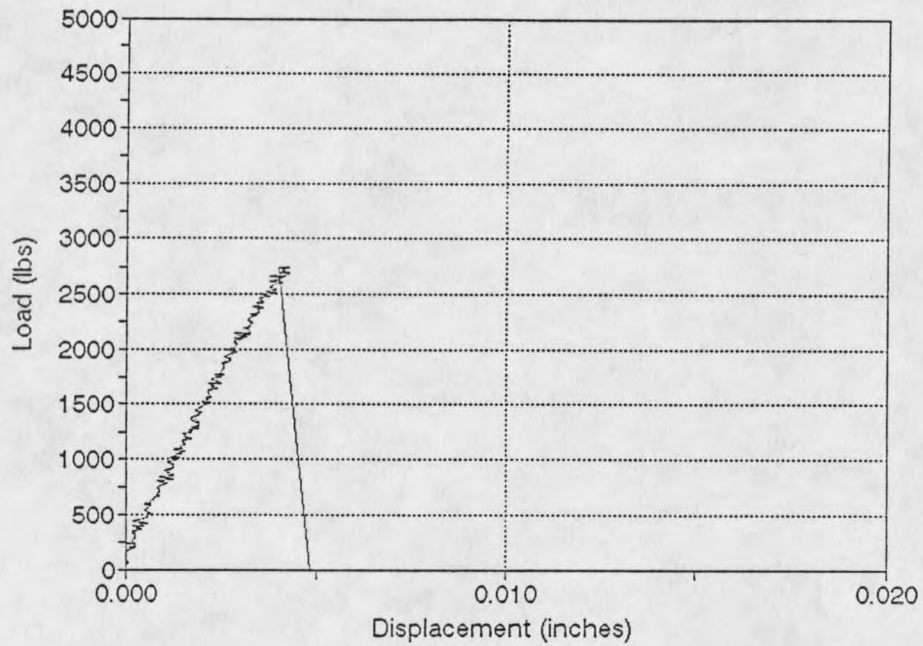


Figure 53. Load versus displacement curve for MT7F tensile test.

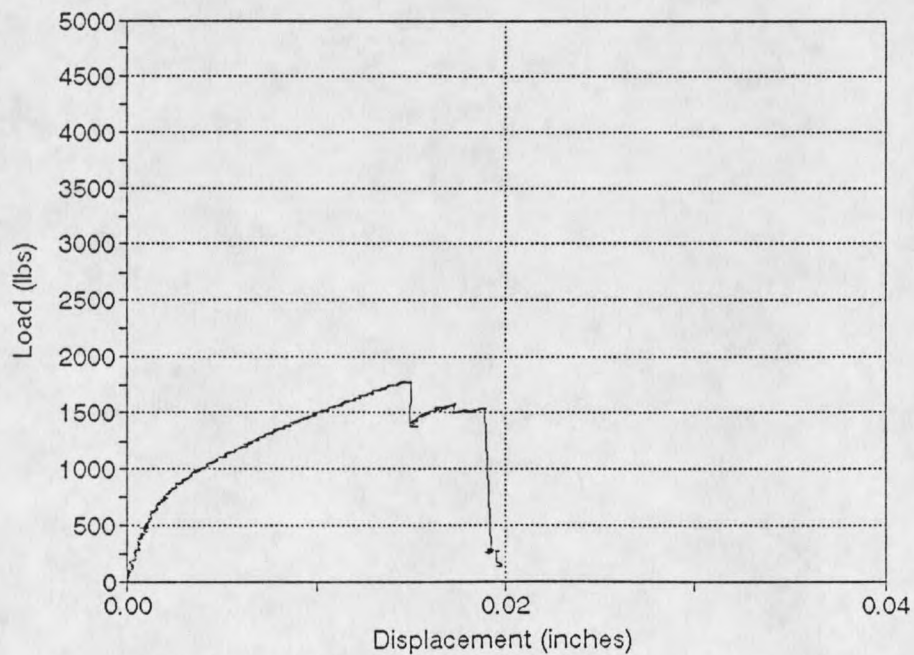


Figure 54. Load versus displacement curve for MT8E tensile test.

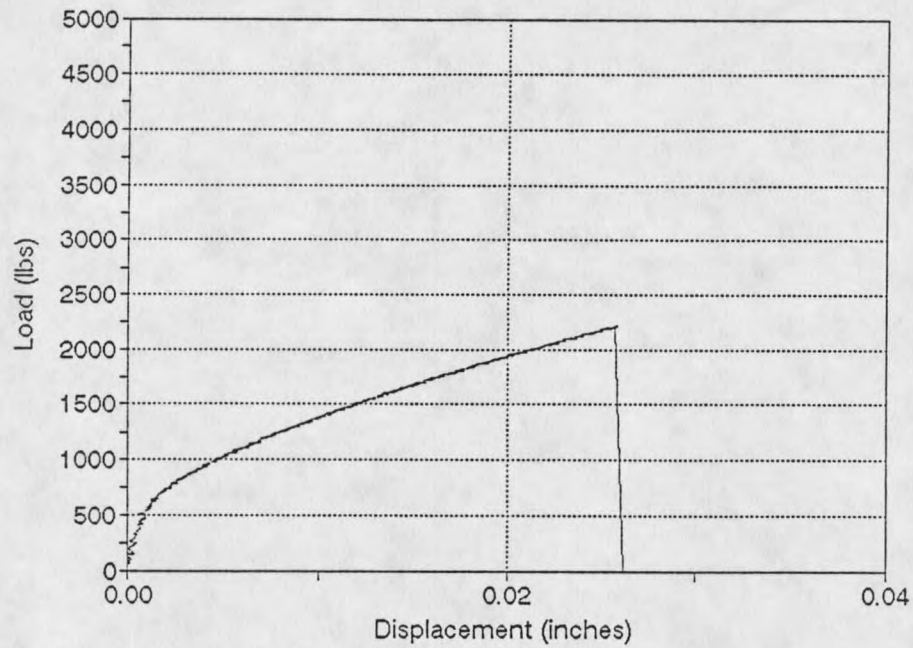


Figure 55. Load versus displacement curve for P130-BE tensile test.

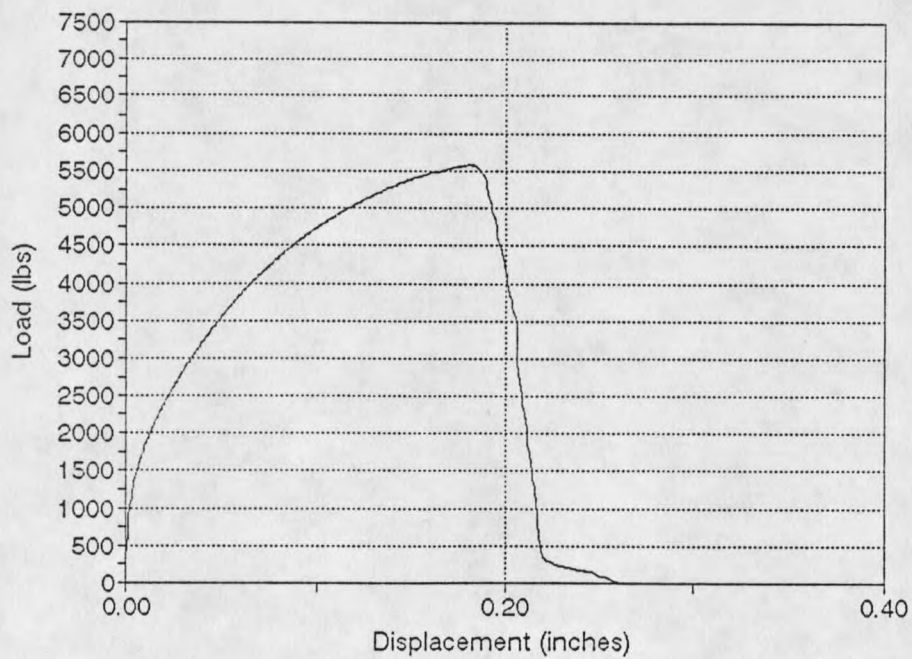


Figure 56. Load versus displacement curve for P130-CH tensile test.

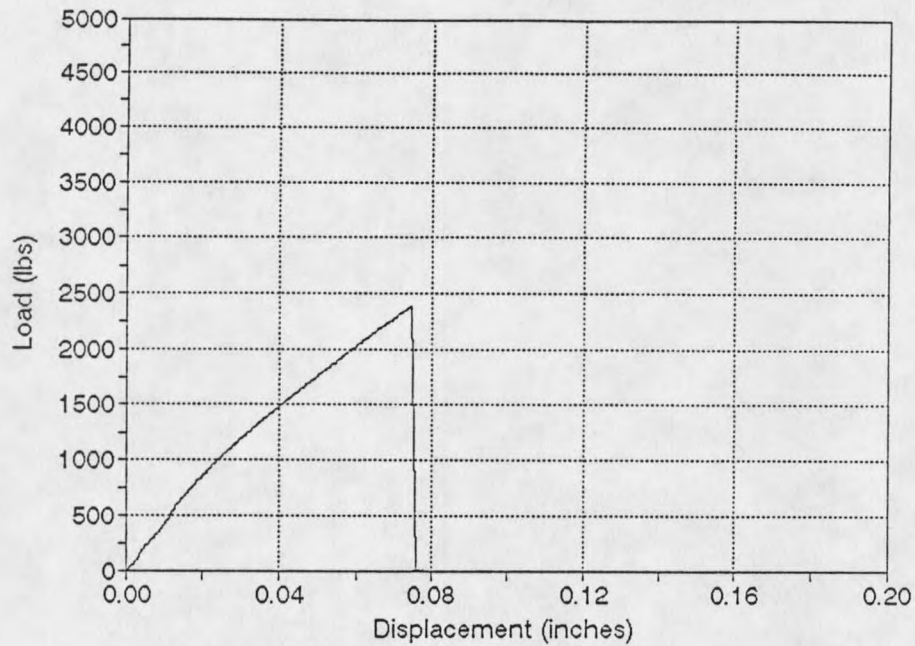


Figure 57. Load versus displacement curve for PA1-2 tensile test.

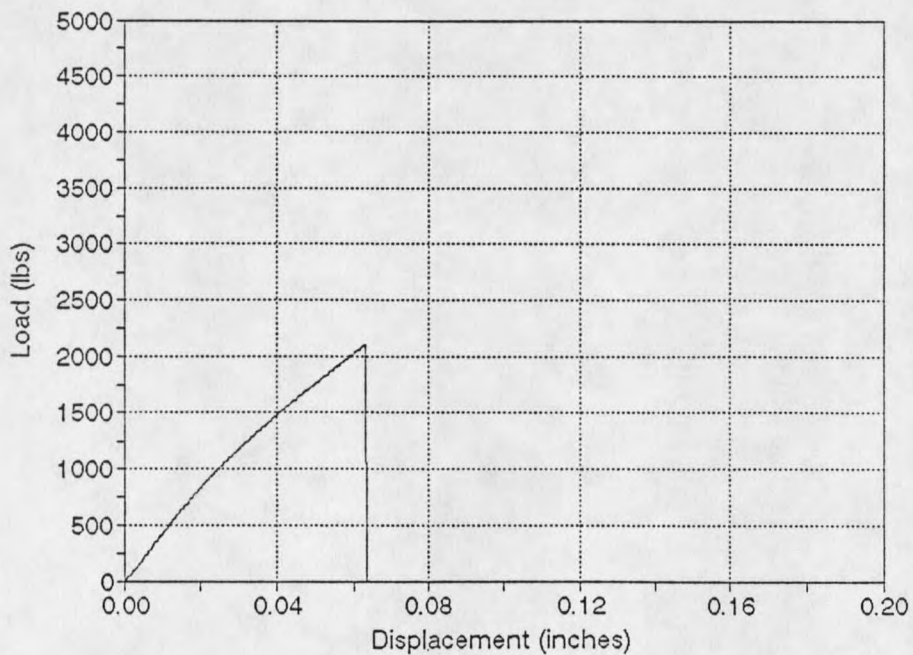


Figure 58. Load versus displacement curve for PA2-1 tensile test.

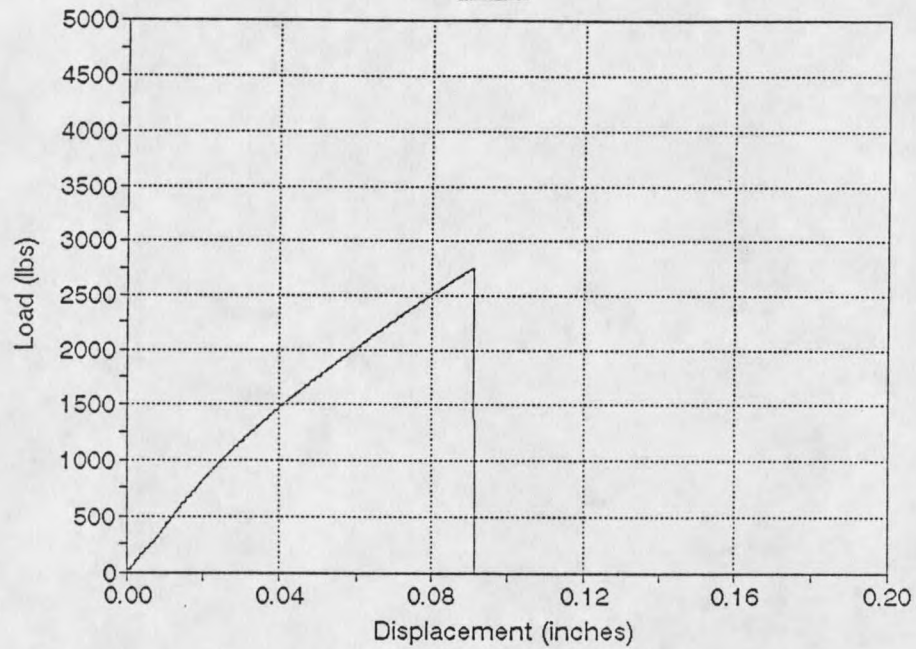


Figure 59. Load versus displacement curve for PA3-2 tensile test.

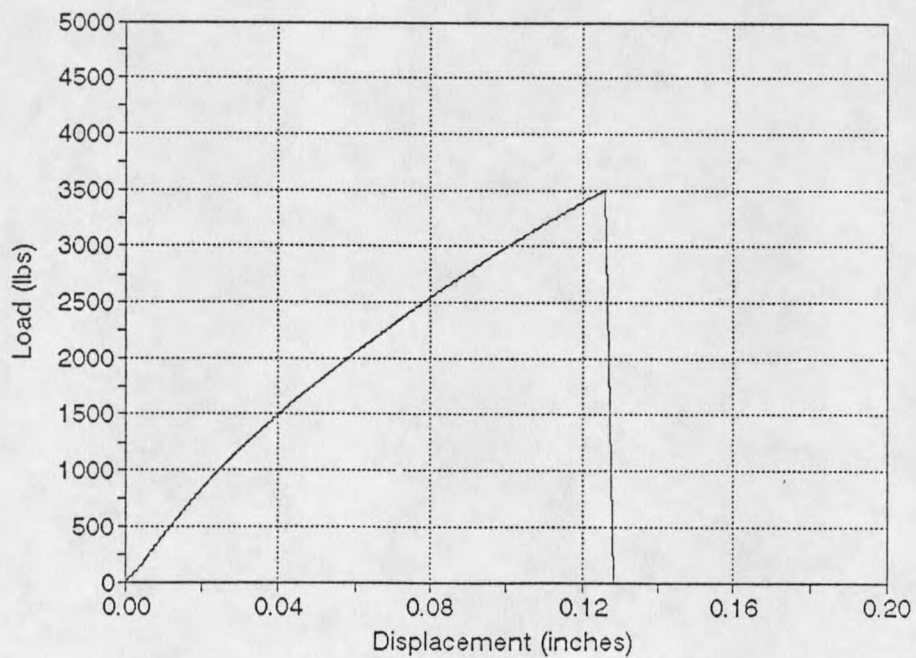


Figure 60. Load versus displacement curve for PA4-2 tensile test.

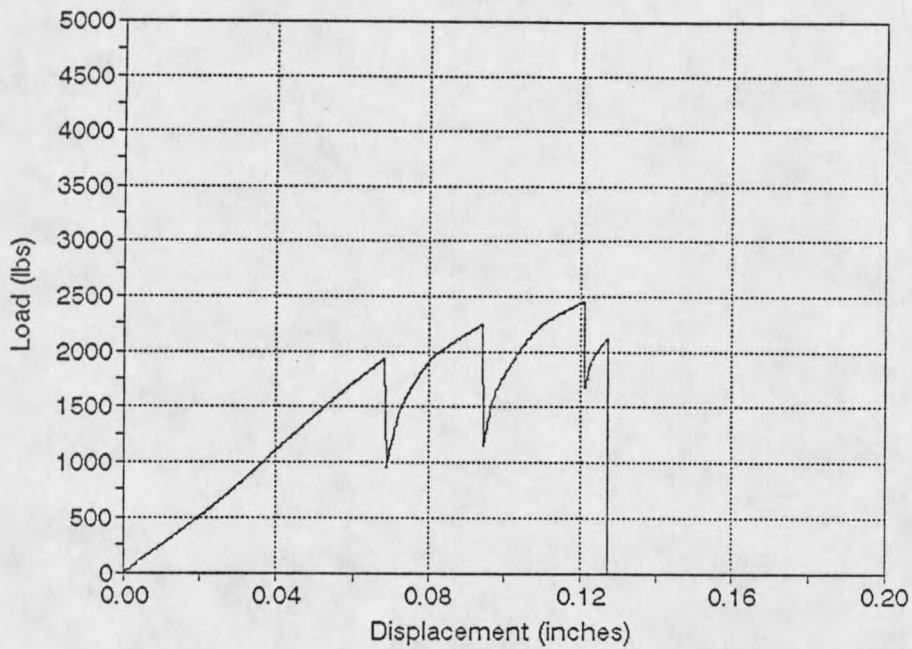


Figure 61. Load versus displacement curve for PA5-3 tensile test.

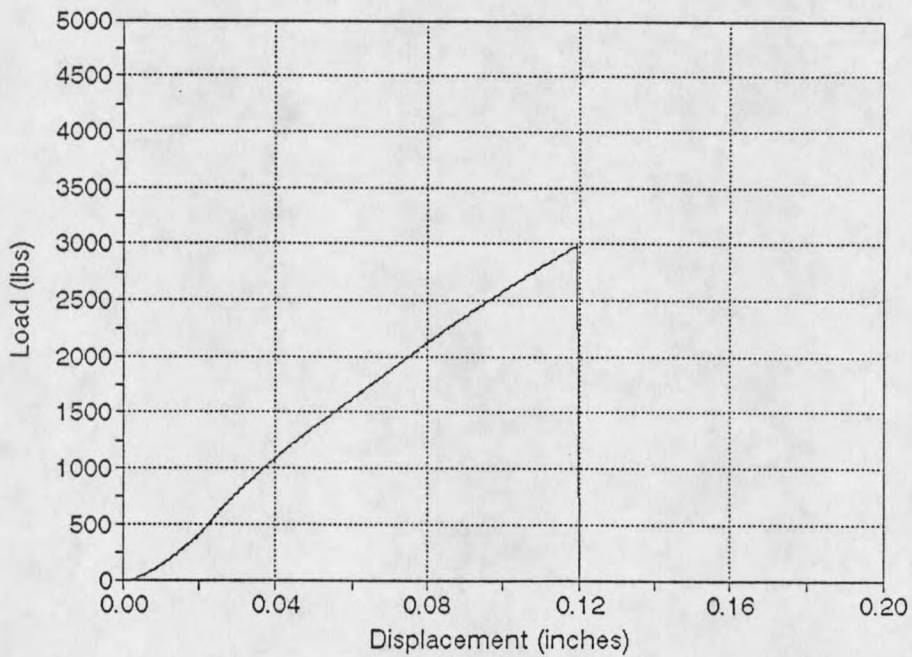


Figure 62. Load versus displacement curve for PA6-1 tensile test.

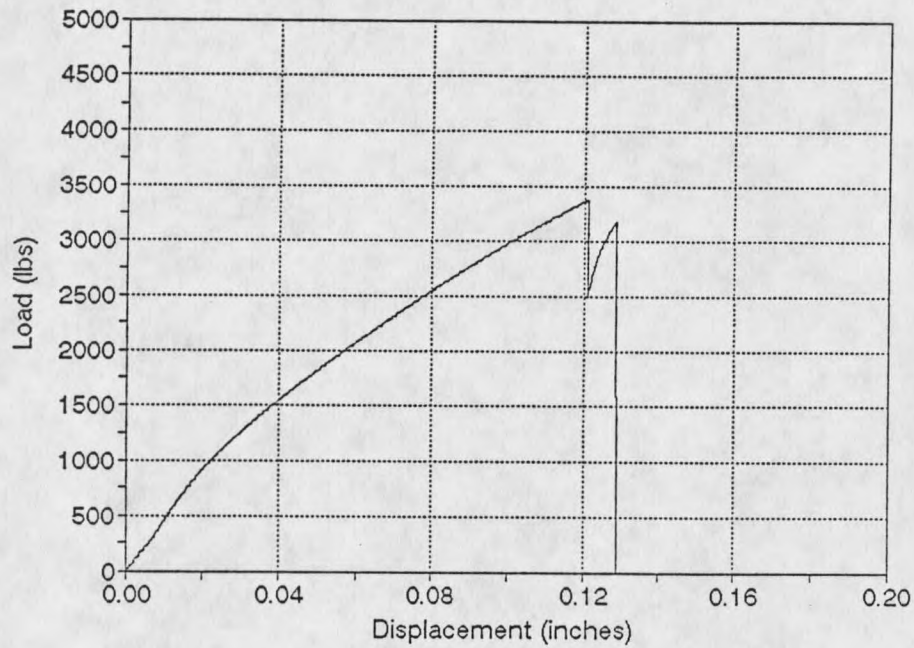


Figure 63. Load versus displacement curve for PB1-3 tensile test.

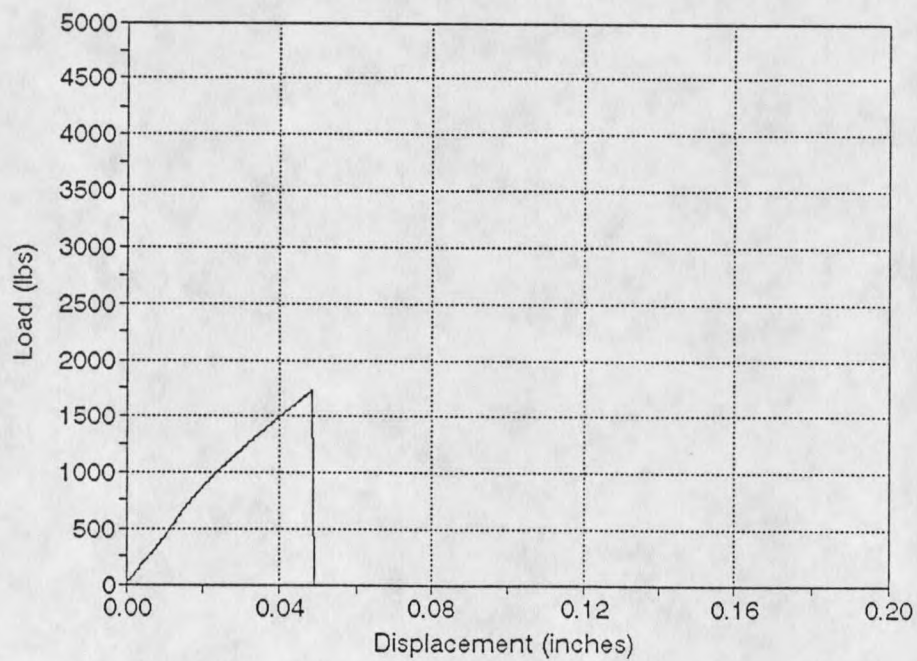


Figure 64. Load versus displacement curve for PB2-3 tensile test.

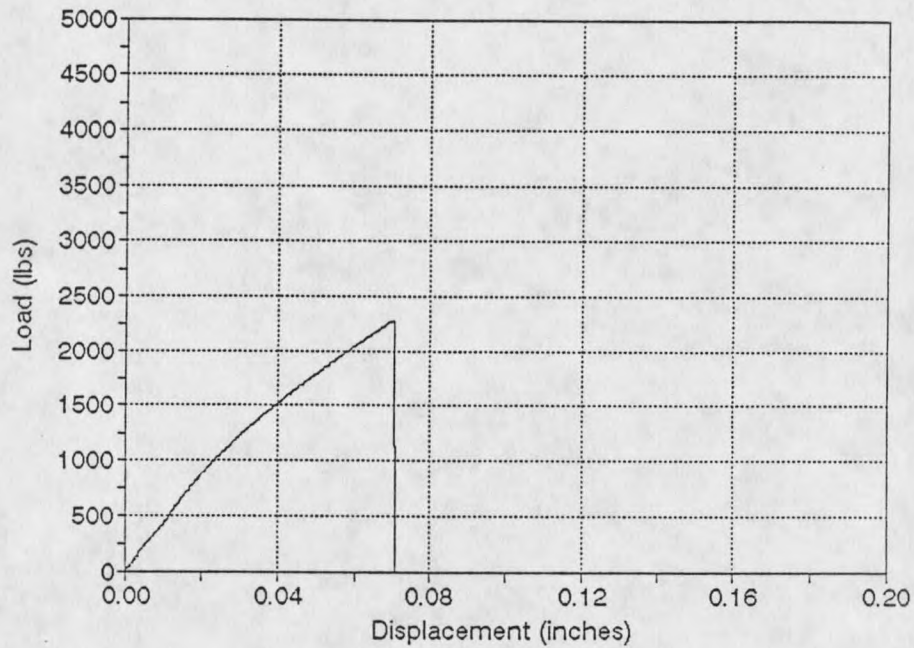


Figure 65. Load versus displacement curve for PB3-1 tensile test.

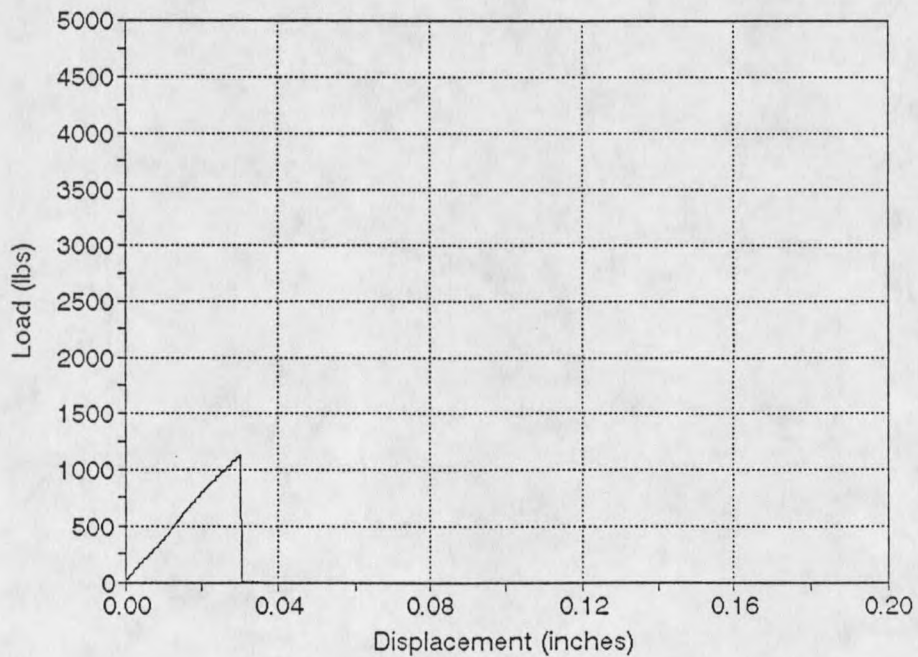


Figure 66. Load versus displacement curve for PB4-2 tensile test.

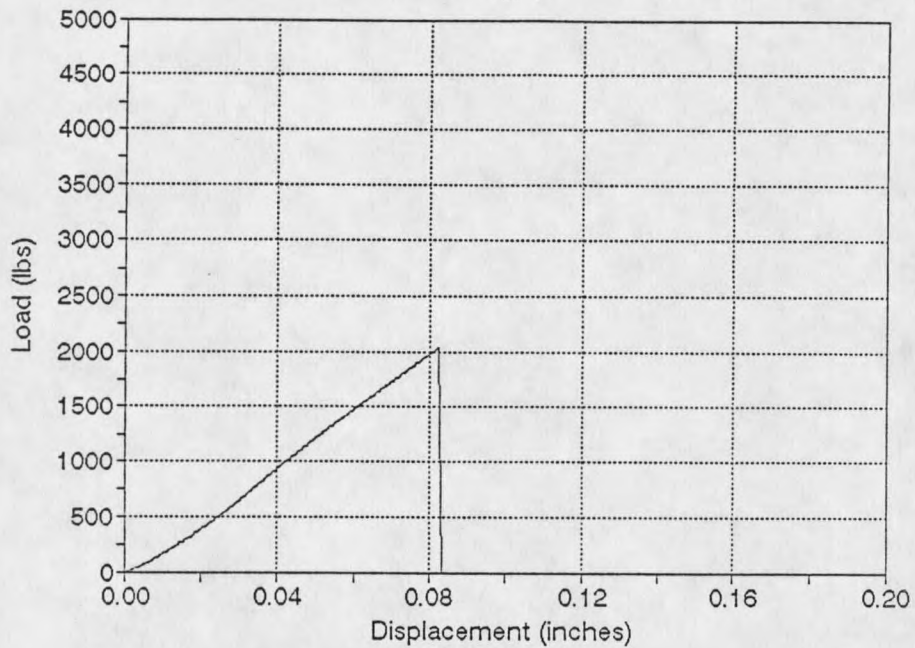


Figure 67. Load versus displacement curve for PB5-2 tensile test.

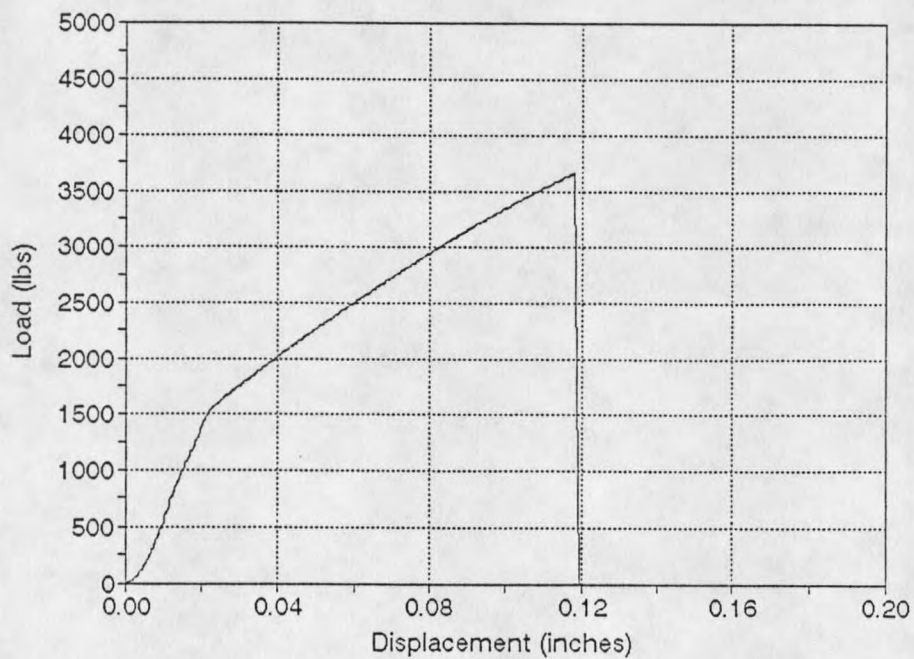


Figure 68. Load versus displacement curve for PB6-3 tensile test.

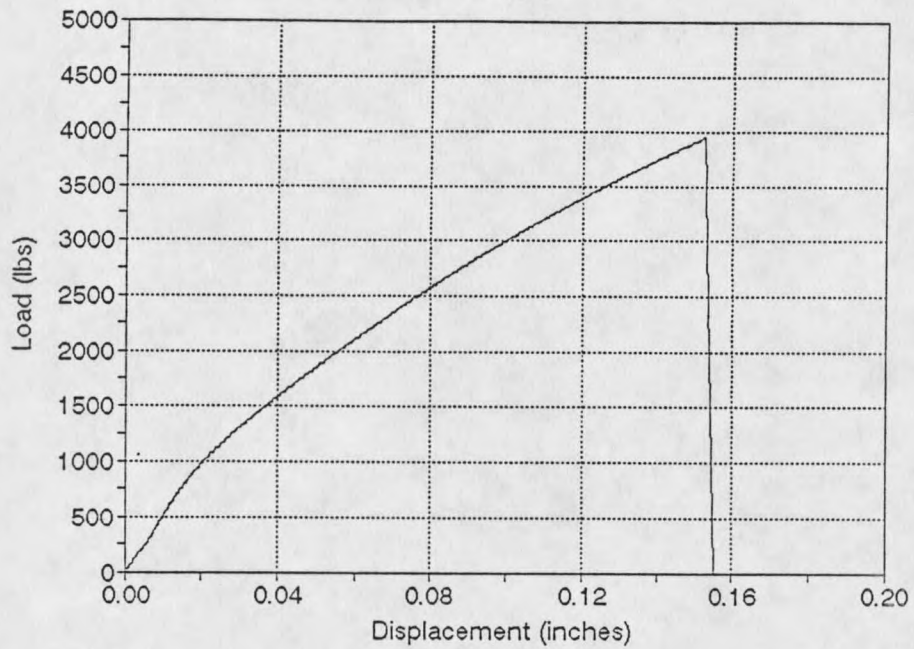


Figure 69. Load versus displacement curve for PB7-3 tensile test.

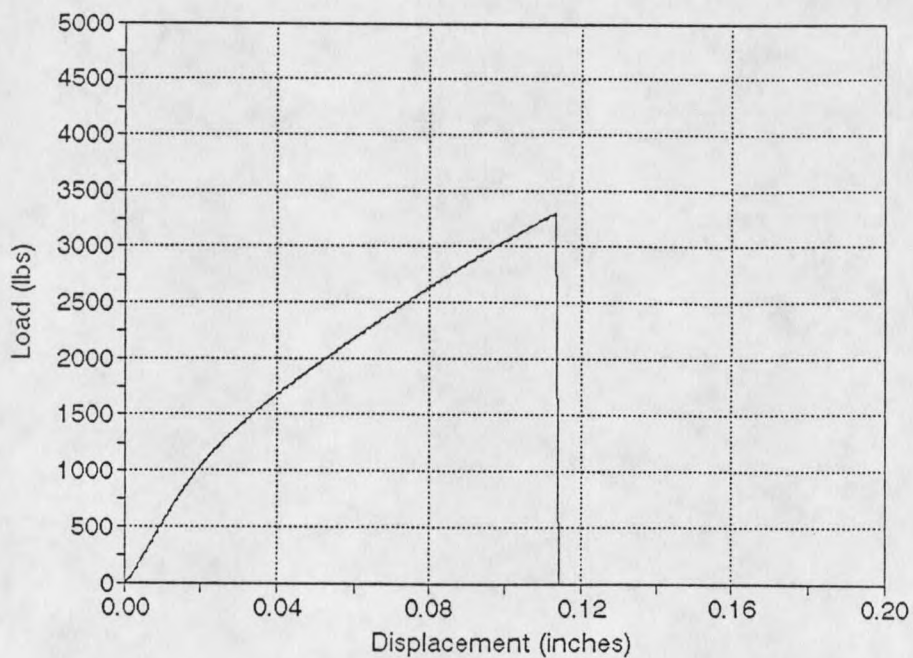


Figure 70. Load versus displacement curve for PB8-3 tensile test.

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