Aircraft wing skin contouring as a result of residual stress distributions induced by shot peening

by Scot Edward Homer

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering Mechanics

Montana State University



Abstract:

Shot peening is a viable method for the forming of aircraft wing skins to aerodynamic contours. Presently, geometric methods used to calculate peening intensity patterns are approximate. These methods are based on simplifying assumptions which are not valid for complex contours. The scope of the work presented in this thesis is to develop a more accurate method of predicting peening intensity patterns.

The finite element is used to model the effects of shot peening. Inversion of the equations to determine an exact solution for the peening intensity pattern is impossible. An approximate solution is found through numerical methods taking into account contour accuracy and peening intensity magnitudes.

The resulting procedure produces accurate and reasonable results for the test cases presented, (computer simulations). Verification of the procedure will be completed when the system is field tested on an actual wing skin.

# AIRCRAFT WING SKIN CONTOURING AS A RESULT OF RESIDUAL STRESS DISTRIBUTIONS INDUCED BY SHOT PEENING

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APPROVAL

of a thesis submitted by

Scot Edward Homer

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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## ABSTRACT

Shot peening is a viable method for the forming of aircraft wing skins to aerodynamic contours. Presently, geometric methods used to calculate peening intensity patterns are approximate. These methods are based on simplifying assumptions which are not valid for complex contours. The scope of the work presented in this thesis is to develop a more accurate method of predicting peening intensity patterns.

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# CHAPTER I

# INTRODUCTION

Shot peening is a process whereby the surface of a metal part is treated by repeatedly impacting it with small particles or shot. The treated part has improved resistance to fatigue and to stress corrosion cracking as well as a hardened surface. These beneficial effects of shot peening are well documented and the process has been widely used for many years to extend the useful life and reliability of metal parts. [1-3]

More recently shot peening has become increasingly important as a metal forming process. The process, known as peen forming, has the same beneficial effects mentioned above. In addition, if applied to a part of relatively low stiffness such as a thin plate, peen forming has the effect of changing the shape of the part. The metal forming aspect of the shot peening process, specifically applied to aircraft wing skins, is the topic of this investigation.

In practice, shot peening is accomplished by forcing a stream of spherical particles, usually glass, cast iron, or steel, to strike the surface of a part at high velocity. The shot particles can be propelled through a nozzle by compressed air or thrown radially from the hub of a rotating hollow wheel with radial partitions. In some applications the shot particles are simply allowed to fall onto the part under the influence of gravity. Depending on the equipment, the shot velocity is controlled by varying the air pressure, wheel speed, or the height from which the shot particles fall. In wheel-type machines the shot velocity is almost entirely dependent on wheel speed. This allows for more precise process control than with air-type machines. Also, relatively high shot velocities can be achieved without the necessity of dropping the shot particles from excessive heights. Typical shot velocities range from 100 to 250 ft/sec (30.5 to 76.2 m/sec). Shot sizes typically range from 0.023 inches (0.058 cm) to 0.125 inches (0.318 cm) in diameter. [4]

## Mechanics of a Single Shot Impact

Each shot particle leaves a small spherical indentation after impact indicating that the surface of the material has undergone local plastic deformation. The plastic deformation of the material in the immediate vicinity of the impact is the mechanism by which shot peening is effective. Thus shot peening is usually only applied to ductile materials.

After a ductile material has been plastically deformed and all external loads are removed, it does not return to its original shape. The material is said to have a permanent "set" or plastic strain. Plastic deformation due to a single shot particle impact is a local effect and therefore the plastic strain is also local. Deformations are required to be continuous at the boundary between the plastically deformed zone and the surrounding elastic material. This causes strains in the elastic material. The elastic and plastic strains in the plastically deformed zone and the purely elastic strains in the surrounding elastic zone generate stresses that remain present after the shot particle has rebounded from the surface. Stresses that are present in a material that is not under the influence of any external loadings, including those produced by inertial and thermal effects, are called residual stresses. [11]

The plastically deformed zone extends radially in all directions around the indentation and into the material to a depth, $h_p$, as shown in Figure 1. The shape of the plastically deformed zone is given in references [6,7] and is based on a Hertz analysis of an elastic half-space using the Tresca maximum shear stress criteria for plastic yielding. [11,14] Al-Hassani, [6], states that experiments have shown a similar shape to that of the Hertz analysis.

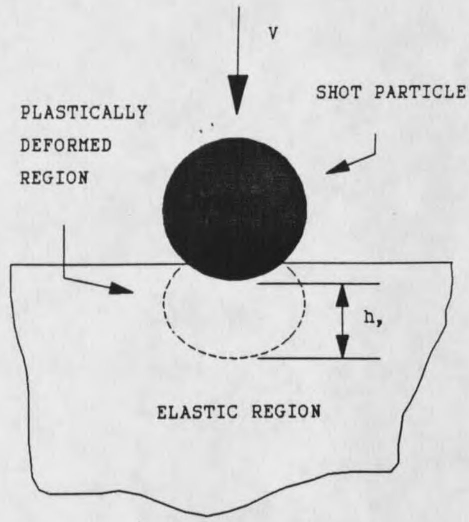


Figure 1. Plastically Deformed Zone.

The depth of the plastically deformed zone depends on the size, density, hardness, speed, and angle of incidence of the shot particle, and on the properties of the material being peened. When dynamical aspects are considered, $h_p$ is given by

$$h_p = 2.322R(\rho V^2/3Y)^{1/4} \qquad (1)$$

where $\rho$ is the shot density, V is the shot velocity, R is the shot radius, and Y is the material yield stress. [6] Typically, the value of $h_p$ is much less than both the diameter of the shot particle and the part thickness. Assuming an angle of incidence of 90 degrees and the following values for R, $\rho$, V, and Y, equation (1) yields a value of $h_p$ equal to 0.047 inches (0.119 cm).

R = 0.0625 in (0.1588 cm)

$\rho$ = 487 lb/ft$^3$ (76.5 kN/m$^3$) (steel)

V = 137.5 ft/sec (41.9 m/sec)

Y = 60 ksi (0.414 GPa) (aluminum)

References [1,2] present a general overview of the effect of these variables and process limitations. References [6,7] present a detailed analysis of the development of the plastic zone due to a single shot impact.

When a shot particle impacts the surface of the part, the material is compressed in the direction normal to the surface and stretched in the direction tangent to the surface. The tangential stretching places surface material in tension. As the elastic limits are exceeded, the material is forced to flow plastically in the direction tangent to the surface as shown in Figure 2. The plastic flow of the surface material is resisted by the underlying elastic material. Upon rebound of the shot particle, the stress in the plastically deformed zone reverses, leaving it in a state of residual compression. Static equilibrium is maintained as the surrounding elastic material is left in a state of residual tension. [1,2,6,7]

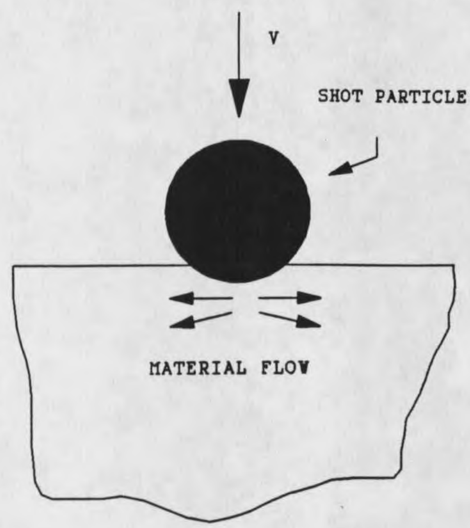

Figure 2. Material Flow Due to Impact.

## Macroscopic Effects

When the part has been peened uniformly over the entire surface, the result is a uniform layer of surface material that has been plastically deformed. The layer of surface material is in a state of residual compression while the underlying elastic material is in a state of residual tension. [1,6,7] The residual stress distribution becomes a function of the depth only. Furthermore, the stress is invariant under rotations in the plane tangent to the surface.

At this point another process variable, that of percent coverage, may be introduced. Shot peening may be applied to a part in a uniform manner with unaffected areas between individual shot impacts. Percent coverage is defined as the percentage of total surface area that has been indented by individual shot particles. Percent coverage of a surface can be controlled by varying the time of exposure to the shot stream. The effects of percent coverage and methods of measurement are discussed in references [1,2,7,8].

Percent coverage and shot velocity are the two most easily controlled process variables. This allows for the precise control of peening intensity necessary to achieve a desired contour.

The stress due to shot peening has the effect of producing a net bending moment and net normal force on the cross section. Relatively stiff parts, (thick sections), will not show an appreciable deformation due to these forces. Parts of relatively low stiffness, (thin sections), however, will deform significantly. [6,7] Figure 3 shows a residual stress distribution typical of a plate that has been peened uniformly on both sides with the same intensity. [2]

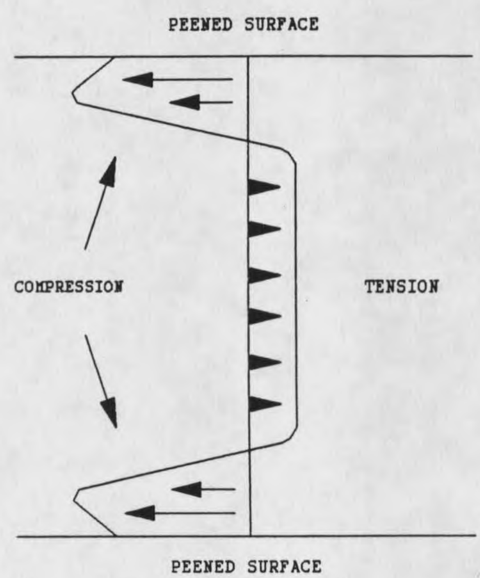


Figure 3. Residual Stress Distribution in a Uniformly Peened Plate.

The residual stress distribution of Figure 3 is based on several simplifying assumptions. The actual stress will vary in the plane tangent to the surface near individual shot particle impacts, especially if the coverage is less than 100%. Invariance of the stress under rotations in the plane tangent to the surface is due to the radial symmetry of the shot particles and an assumed 90 degree angle of incidence of the shot stream. Angles of incidence of individual shot particles will not, in general, be 90 degrees however. Collisions with shot particles rebounding from the surface will cause the angle of incidence to vary for individual shot particles. The fact that the normal stress on a free edge is zero implies that the residual stress distribution of Figure 3 is not valid near sharp edges or corners. This investigation is primarily concerned with the very thin plates used in the manufacture of commercial aircraft wing skins. Edge effects, as well as stresses in the direction normal to the plate, are therefore assumed to have a negligible effect on the overall deformation of the plate.

The assumptions of the preceding paragraph are accepted in this work allowing the residual stress at a specific point on the plate to be described by a scalar function of the depth. Other standard assumptions made in thin plate and shell theory such as "Straight lines normal to the neutral surface remain straight." are accepted as valid on a macroscopic scale as well. [12,13]

The author of references [6,7] questions the validity of these assumptions. Quoting Al-Hassani, [7] pp. 10:

> There has been a tendency in the shot peening literature to interpret the residual stress in the component as if it were the result of a stretching action, uniformly and instantaneously distributed over the surface followed by an elastic unloading action again distributed uniformly over the entire length of the specimen. Consequently, simple beam and plate bending theories are then used to explain the general features of the process. In addition to the neglect of the history of the residual stresses, such a concept