Shot Peening in Shape Deposition Manufacturing

J.W. Zinn, J.L. Beuth

EDRC 24-121-95

Shot Peening in Shape Deposition Manufacturing

J. W. Zinn and XL. Beuth

Department of Mechanical Engineering and the
Engineering Design Research Center
Carnegie Mellon University

This work has been supported by the Engineering Design Research Center, a NSF Engineering Research Center

Abstract

Experimental results and their analysis are presented concerning the use of shot peening as a means of altering the geometries of residually stressed metals. The application of this research is to parts that are built up by the successive deposition of metal layers using shape deposition manufacturing. The goal of this work is to obtain qualitative and quantitative results which can be integrated into the design and planning of shape deposited parts. The results of shot peening experiments conducted on steel specimens arc presented along with a model of shot peening. This model enables the calculation of the stresses, strains, and curvatures induced by shot peening, based on the measured strains, as a function of the amount of peening. Using this model, two types of analyses of the peening tests have been conducted including an analytical beam-based analysis and a numerical finite element analysis. Quantitative and qualitative results are presented concerning the effectiveness of shot peening in producing shape changes in a manufactured part One of the primary conclusions drawn from these experiments is that the peening efficiency is a function of the thickness of the specimen, due to the manner in which compressive stresses develop in the shot peened portion of the part.

Introduction

Shape deposition manufacturing is a process in which three-dimensional parts are manufactured by successively depositing two-dimensional layers of molten material. The deposition process currently used is termed microcasting, which involves forming layers by the repeated deposition of molten metal droplets. Each layer is machined to shape after its deposition. The manufacturing process extends rapid prototyping concepts, linking manufacturing and computer aided design (see Merz et al., 1994). In parts made by depositing metals, several defects can occur such as the distortion of edge geometries, warping of the part, and dclamination between deposited layers. These part defects are the result of residual stresses that develop due to the thermal contraction of each deposited layer as it cools to room temperature from the molten state. The contraction of a newly deposited layer relative to previously deposited layers causes the edges of the lower layers to taper inwards and also produces a concave curvature in the part One of the primary applications of shape deposition manufacturing is the production injection molding tools which require very tight dimensional tolerances on edge geometries. Shot peening is investigated as a method of counteracting the thermal contraction of a layer by producing a compensating expansion in the top of that layer. Ideally, the expansion due to peening would exactly match the thermal contraction of each deposited layer eliminating edge defects and warping in the part The goal of this work is to quantify shape changes due to shot peening to allow shot peening to be incorporated into the planning and design of shape deposited parts.

Shot peening is a process in which small hardened steel balls are propelled with high velocities at the surface of a specimen. Two commonly used methods for propelling the shot include using a compressed air nozzle or a spinning wheel to accelerate the shot. When the shot impacts the surface of the peening specimen, high contact stresses develop locally beneath each ball (for a review of contact stress solutions see Johnson, 198S). The magnitude of the local stresses caused by the impact of the shot is a function of the diameter, velocity, mass, and hardness of the shot These stresses cause plastic deformation in the material, leaving a small dimple on the specimen. Based on the diameter of the dimple left by the shot, estimates of these stresses can be calculated. The dimple is due to the compression of the material beneath the point of impact, resulting in the radial displacement of material around the point of impact. Micro-level variations in the resulting residual stresses and strains will exist because of small variations in the individual impacts and also because of the random distribution of impact locations on the surface of the specimen.

A similar application of shot peening to produce shape changes is peen-forming, a process in which sheet metal is formed into complex curved geometries using controlled peening. Peen-forming has been developed as a method for manufacturing skin panels for aircraft In peen-forming, the amount of shape change which can be produced is limited by the thickness of the specimen being peenecl Peen-forming also uses an elastic stretching process in which a tensile pre-stress is placed on the specimen to provide a deeper plastic zone from peening and to produce a greater curvature in the direction of the pre-stress. More information about peen-forming and other applications of shot peening may be found in Meguid (1986) and Wohlfahrt, et al. (1987).

In this application, the primary focus is on the net effects of shot peening, i.e. the macro-level effects which result from the superposition of all the micro-level impacts. On the macro-level, peening a specimen with a stream of shot produces a biaxial expansion on the surface of the specimen, relative to the rest of the specimen. This expansion is over a small finite depth which is based on the depth of plasticity caused by peening. The thin layer of expanding material, referred to in this work as the peened layer of the specimen, is loaded in residual compression by the rest of the specimen which resists the expansion due to peening. A bending moment is also produced by the peened layer causing a convex curvature in the specimen. Since the goal of this work is to produce large scale shape changes in the part, small scale variations in stresses and strains can be ignored.

Experiments

Initial experiments, aimed at measuring the effects of shot peening on stress free parts, were conducted on several stainless steel specimens with properties similar to those of the stainless steel used in shape deposited parts. For these tests, it was desired to determine the net in-plane expansion produced by peening and the stresses throughout the specimen as a function of the amount of peening. However, these values could not be directly measured with the available equipment Instead, the strain on the bottom of the specimen and the curvature of the specimen were measured after each pass of the peener. A model of the shot peening process was developed to estimate the expansion of the peened layer and the compressive stress in the peened layer, using the measured strains. The purpose of these tests was to determine if a limit existed to the strain which could be produced by shot peening and if so, to determine the number of passes needed to reach this limiting value of strain. Additionally, it was desired to know the change in strain as a function of the number of passes.

The specimens for these experiments were made of annealed 304 stainless steel because it is one of the primary materials used to make parts in shape deposition manufacturing. The specimens were 6.0 inches long by 0.75 inches wide with varying thicknesses, including: 0.185, 0.250, and 0.360 inches. These specimens were designed to be narrow enough so that they could be peened lengthwise by one pass of the peener. The specimens were attached to a hinge on one end and were free at the other end, allowing uniform strain and curvature along the specimen. Figure 1 shows the specimens and the method in which they were mounted.

In creating the specimens, a block of stainless steel was cut and machined to the size of the specimen. A tapped hole was placed on one end of the specimen and was used to bolt the specimen to the hinge (Figure 1). The specimens were then annealed at 1850 °F (1010 °C) for one hour per inch of thickness. After annealing, the specimens were quenched in water to provide a cooling rate similar to that of deposited material. Since they were not annealed in an inert atmosphere, oxidation developed on the surface of the specimens, which was removed using a belt sander. The specimens were then cleaned and prepared for attaching the strain gage. A biaxial strain gage was centered and mounted transversely on the bottom of the speci-

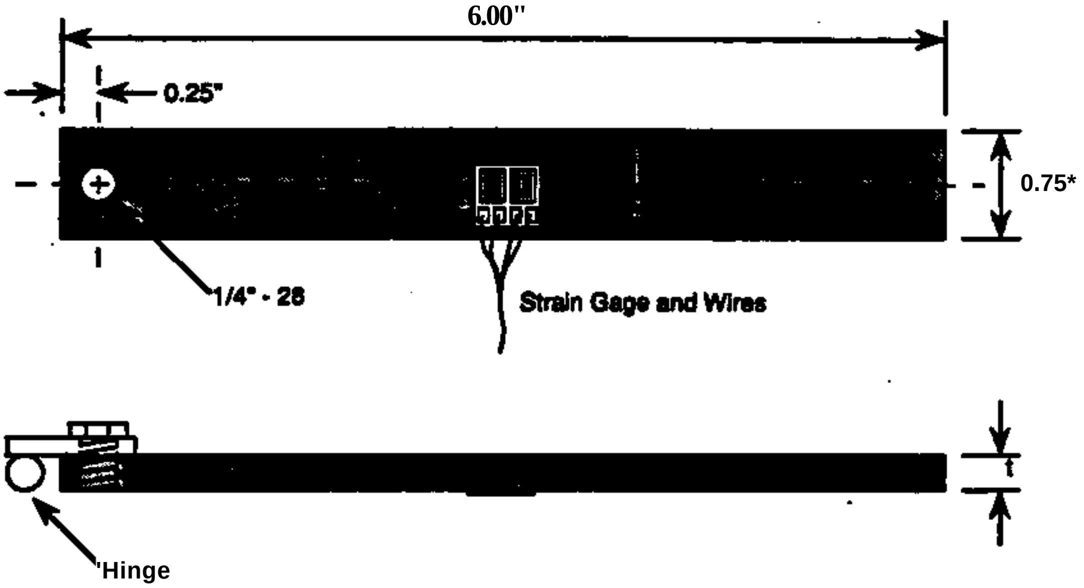

FIGURE 1: Diagram of the Specimens Used in the Free Peening Tests

men with the strain gage wires protruding from the side of the specimen. The strain gages were connected to a computer data acquisition system which monitored the strain during the peening process giving the change in strain on the bottom of the specimen per peening pass.

The shot peener was configured to peen the specimen lengthwise in one pass. The compressed air peener used for these tests set at a static pressure of 52 psi which provided an operating pressure of 32 psi. The shot had an average diameter of 0.065 inches. A robot with a pre-programmed path controlled the peener to insure uniform peening along the length of the specimen. The hinge to which the specimens were connected was mounted on a pallet that was placed in the peener. The alignment of the specimen with the programmed peening path was checked before each set of tests. Measurements of strain were made using the strain gage placed on the bottom of the specimen. In addition, the curvature was calculated after each pass of peening by measuring the height of the deformed specimen off of the top of the pallet

Model

To interpret the test results and to estimate the expansion of the peened layer using the measured strains on the bottom of the specimen, an elastic-plastic model has been developed in which the macro-level effects of shot peening are represented as the biaxial free strain (expansion) of a thin layer of material on top of a substrate, the peened layer (Figure 2). This free strain, denoted as Epeen* *^{s} analogous to a biaxial free thermal expansion given by aAT, a coefficient of thermal expansion times a change in temperature. The advantage of using this model of shot peening is that it lends itself to the analysis of the large scale effects of peening by allowing an estimation of the stresses and strains within the specimen after peening without requiring a precise knowledge of the development of plastic strains and stresses due to the individual impacts of shot In addition, the equations for the limiting case of strictly elastic beam behavior are easy to develop and may be compared against those presented by Tlmoshenko (1925) in his paper on the thermal expansion of bimetallic beams.

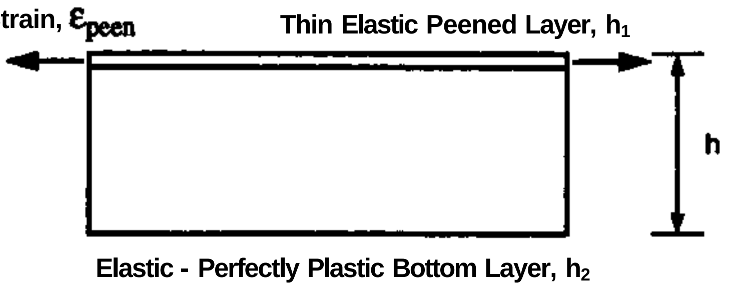

FIGURE 2: Model of Shot Peening as the Free Strain of A Thin Top Layer

This model contains several implicit assumptions. First, it assumes that the expansion in the peened layer is uniform over the length and width. This assumption is reasonable because small local variations in strain due to non-uniform expansion are minimal and are not reflected in the measurement of the strain on the bottom of the specimen. Secondly, it assumes that the depth of the peened layer is known and that it is constant Estimates of the depth of the peening have been made through physical inspection. In future work, it is desired to be able to determine more accurately the depth of the peened layer through methods such as X-ray diffraction. Third, it assumes that the expansion is constant over the depth of peening. Since the peened layer is thin, only the net force produced by the expansion is desired. Thus, the non-uniform expansion over the small depth can be approximated by an equivalent uniform expansion over the same depth. The error produced by such an approximation will be minimal and will result due to a slight difference in the moment produced in the specimen.

An analytical beam-based analysis of shot peening was developed assuming a thin elastic peened layer on top of the thick elastic-perfectly plastic bottom layer. Again, the biaxial free strain due to peening was modeled as being equivalent to a biaxial thermal expansion, aAT. Using the same procedure as Timoshenko (1925), the two layered specimen was decomposed into separate beams with an interfacial force/width, P, acting in compression on the bottom of the peened layer and in tension on the top of the bottom layer (Figure 3). The condition was then imposed that the strains at the interfaces must be equal. In this manner, the bottom layer was analyzed as a elastic-perfectly plastic beam with a load on the top for the following three individual cases: fully elastic, plastic deformation on the top of the bottom layer, and

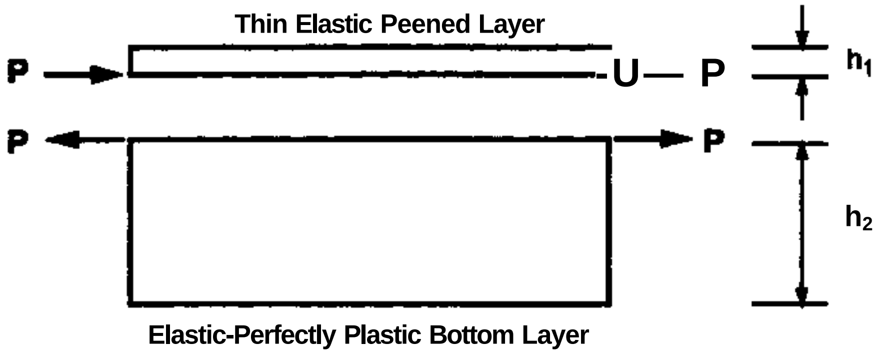

FIGURE 3: Decomposition of the Specimen into Two Beams

plastic on both the top and bottom of the lower layer. The range of the strain on the bottom of the specimen for each of these three cases was determined by evaluating the two limiting cases in which plastic deformation is just beginning. Next, a general elastic-perfectly plastic stress distribution with a yield stress of 45,000 psi (determined from tensile tests on the stainless steel used) was assumed for each case and was solved by integrating the stresses and requiring the net force/width to equal P and the net moment/width to equal $Ph_2/2$. Thus, the force/width, P, required to produce this stress distribution was determined and was expressed as a function of the strain on the bottom of the specimen. After obtaining P and matching the interfacial strains, the free strain of the peened layer, £peen> was determined as a function of the strain on the bottom of the specimen. Plots of P and £pee$_n$ versus the strain measured on the bottom of the specimen were made using this model for specimens with thicknesses of 0.185,0.250, and 0.360 inches. The thickness of the peened layer, h_t, used for this model was 0.01 inches, as determined by physical inspection of the test specimens after peening was completed.

A second analysis of shot peening, similar to the beam-based analysis, was solved using finite elements. The primary purpose of this analysis was to verify the results generated by the beam-based analysis. The same dimensions were used in both analyses. The top, peened layer was assumed to be elastic and the bottom layer was assumed to be elastic-perfectly plastic since these were the assumptions used in the beam based analysis. The specimens were meshed and analyzed in ABAQUS using axisymmetric, 8 noded, biquadratic elements. The free strain of the peened layer (Epccn) $^{w\,a\,s}$ modeled as a thermal free strain (ctAT). The strains on the bottom of the specimen were output for several step temperature loadings. In this manner, a point by point plot of $\pounds_{vetn}$ vs. the strain on the bottom of the specimen was obtained A plot of aAT vs. strain for the 0.250 in. thick specimen comparing results from the beam based analysis with data points from the axisymmetric finite element analysis is contained in Figure 4. The finite element results do correlate with those generated from the beam-based analysis verifying the validity of the beam-based analysis.

It should be noted that shot peening is a strain controlled problem as modeled. In this model, there are no stresses directly applied to the specimen, all that is specified is a uniform free strain of the peened layer. Therefore, within the elastic range, the strains throughout the

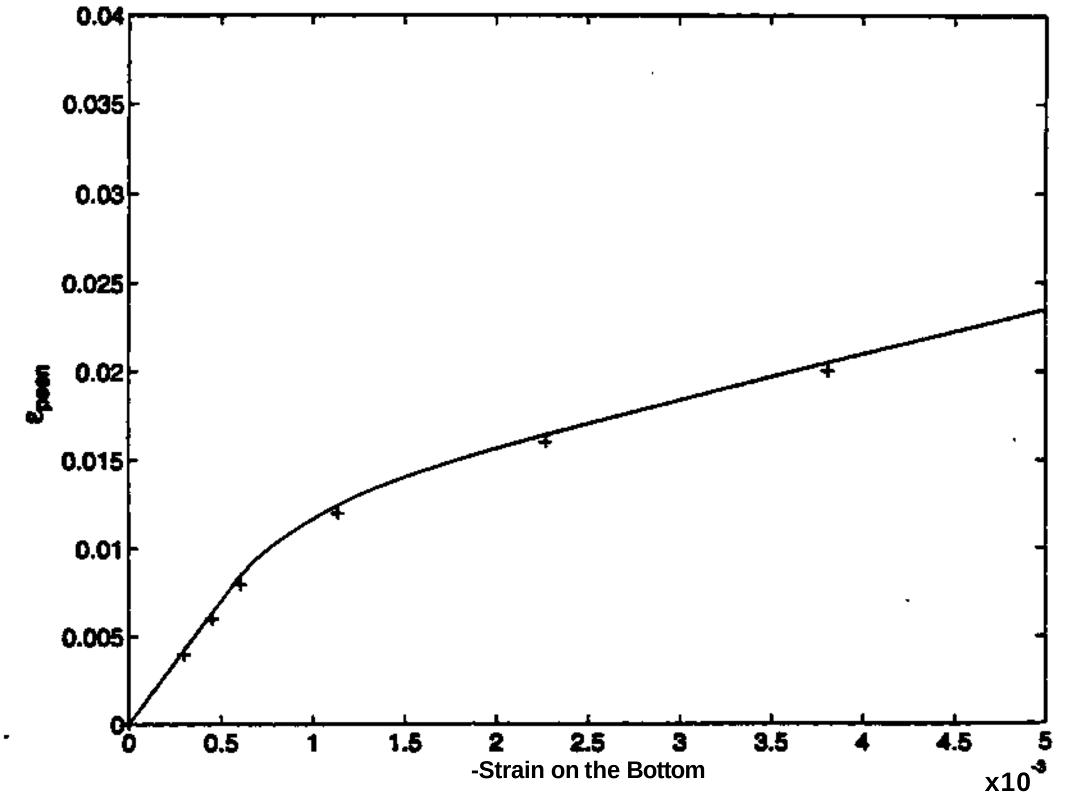

FIGURE 4: Comparison of Results from the Beam Based Analysis with Data Points from the Axisymmetric Finite Element Analysis

specimen are determined uniquely by the expansion of the peened layer independent of any constitutive relationships. The stresses then are determined from the strains using the constitutive relationships of the material. The beam-based analysis determined the S_{pccn} needed to produce an amount of strain on the bottom of the specimen. The above considerations were accounted for in this analysis when the stresses were determined from the strains. The biaxial stresses which resulted were calculated by multiplying the biaxial strain by E/(l-v). The finite element analysis accounted for the biaxial strains directly since axisymmetric elements were used.

Results

Results have been generated using the developed model of shot peening to analyze the experimental data obtained. The experimental measurements of the strain on the bottom of the specimen were input into the beam-based analysis to determine the free strain, £peen> needed to produce this measured strain and the corresponding force/width, P, which exists between the layers. Figures 5 and 6 contain respectively plots showing P vs. strain on the bottom of the specimen and E p ^ vs. strain on the bottom of the specimen for all three specimen thicknesses as predicted by the beam-based analysis with data points of actually measured strains for each pass of peening. These plots show that the initial pass of peening produces the largest change in £peen- They also show that the change in Bpeen decreases with successive passes for the 0.360 in. and 0.250 in. specimens. Together these plots demonstrate the "shakedown" effect in the 0.360 in. and 0.250 in. specimens. Shakedown occurs when additional peening produces less strain change until there is no further change in strain for additional peening. Shakedown results from the build up of compressive stresses in the peened layer. It is interesting to note that shakedown did not occur in the 0.185 in. specimen because the bottom layer of the specimen plastically deformed, reducing the stiffness of the specimen. Therefore, $£pee_n$ increases steadily without causing a large increase in P. The fact that shakedown occurs at lower strains for thicker specimens is due to the greater stiffness of the thicker specimens. It should also be noted that the same Epeen will result in larger P's for thicker specimens because of their higher stiffnesses.

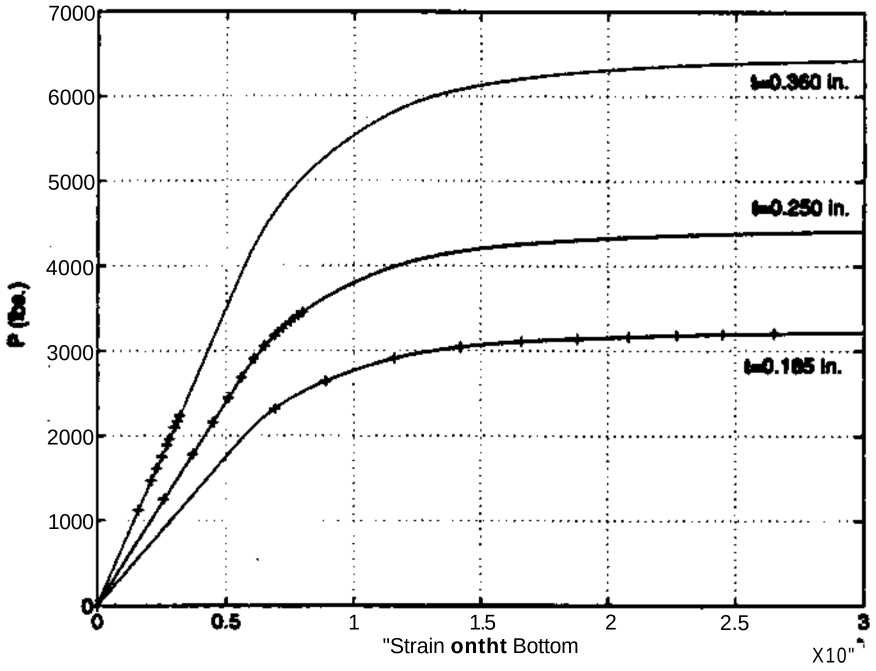

FIGURE 5: Plot Showing Values of P Predicted by the Beam-Based Analysis with the Strains Measured After Each Pass of Peening

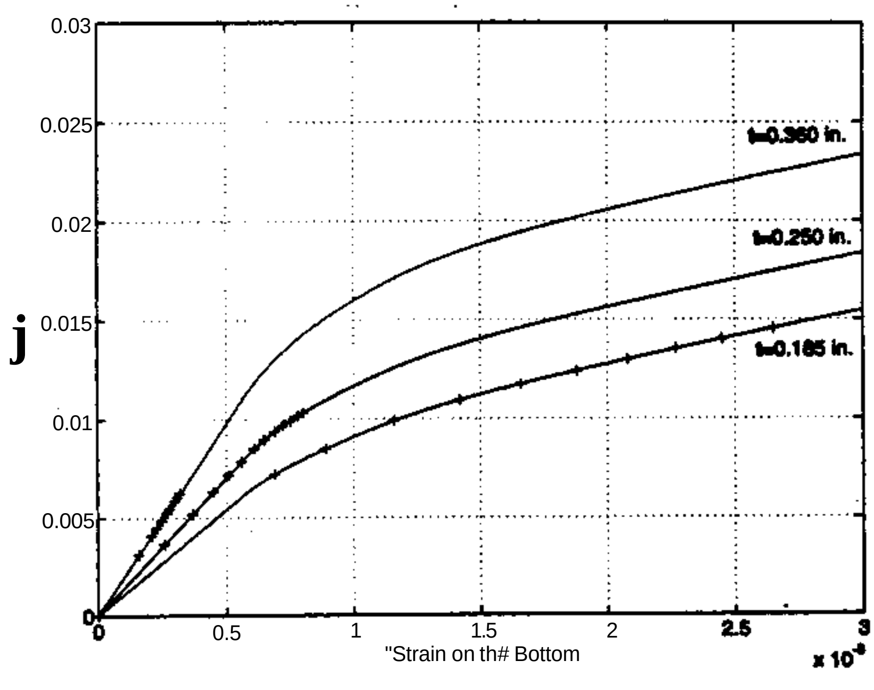

FIGURE 6: Plot Showing Values of £pe$_{en}$ Predicted by the Beam-Based Analysis with the Strains Measured After Each Pass of Peening

Conclusions

Based on the results of the tests conducted on stress free specimens, several qualitative conclusions can be drawn concerning the effectiveness of using shot peening to produce shape changes in shape deposition manufacturing. First, it is evident that the first pass of peening is the most effective in producing shape change since the build up of compressive stresses in the peened layer inhibits free strains due to peening in subsequent passes. Second, initial peening of deposited layers in shape deposited parts will be more effective than peening stress free specimens due to the residual tension on the surface of the deposited layer. Finally, peening of shape deposited parts should be self-correcting. Because deposited parts are built on a laige, stiff pallet, they are significantly constrained form bending deformation. The resulting rapid build-up of residual compressive stresses will lead to shakedown and will prevent overpeening, the case where excessive peening causes shape changes that are greater than those due to the thermal contraction of the deposited layer. In this manner, peening can correct the shape changes due to cooling without itself inducing excessive shape changes. These conclusions indicate that shot peening will be an effective method for producing shape changes to correct the thermal contraction of deposited layers in shape deposition manufacturing.

These initial sets of tests suggest the need for more extensive testing on the shot peening process. Future test will be conducted to more specifically determine the effects of specimen constraint. In addition, the stresses on the top and bottom of the specimen will be measured using X-ray diffraction and will be compared to the values predicted by the model.

Acknowledgment

The authors gratefully acknowledge the support of the Engineering Design Research Center, and Engineering Research Center of the National Science Foundation, under Grant No. EEC-8943164. The authors would also like to thank Lee Weiss and Fritz Prinz for their thoughts and insights related to this research.

References

Johnson, K.L. (1985) *Contact Mechanics,* Cambridge University Press.

Mcguid, S.A. ed. (1986) *Impact Surface Treatment,* Proc. Second Int. Conf. Impact Treatment Processes, Cranfield Institute of Technology (Bedford, UK).

Mere, R., Prinz, F.B., Ramaswami, K., Terk, M., and Weiss, L.E. (1994) "Shape Deposition Manufacturing," *Proceedings Solid Freeform Fabrication Symposium,* H. Marcus, JJ. Beaman, J.W. Barlow, D.L. Bourell and R.H. Crawford eds., The University of Texas at Austin, pp. 1-8.

limoshenko, S. (1925) "Bending and Buckling of Bimetal Strips," J. Optical Soc. Am., Vol. 11, pp. 233-255.

Wohlfahrt, H., Kopp, R., Vohringer, O. eds. (1987) *Shot Peening: science, technology, application,* Proc. Third Int. Conf. Shot Peening, Garmisch-Partenkirchen (FRG).