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Effect of Power Density and Pulse Repetition on Laser Shock Peening of Ti-6Al-4V

P.R. Smith, M. J. Shepard, P.S. Prevéy III, and A.H. Clauer

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Laser shock peening (LSP) was applied to Ti-6Al-4V (wt. %) simulated airfoil specimens using a Nd:Glass laser. Laser shock peening processing parameters examined in the present study included power density (5.5, 7, and 9 GW/cm^2) and number of laser pulses per spot (one and three pulses/spot). The LSP'd Ti-6Al-4V samples were examined using x-ray diffraction techniques to determine the residual stress distribution and percent cold work as a function of depth. It was found that the residual stress state and percent of cold work were relatively independent of LSP power density. However, the number of laser pulses per spot had a significant effect on both residual stress and percent of cold work for a given power density level. In addition, there was a strong correlation between the magnitude of residual compressive stresses generated and the percent cold work measured.

Keywords laser shock peening, LSP, residual stress, surface engineering, Ti-6Al-4V

1. Introduction

Rotating hardware, such as fan and compressor blades in gas turbine engines, are subject to foreign object damage (FOD), which can act to reduce their fatigue life. For years, engine manufacturers have used surface enhancement techniques such as shot peening to induce a state of residual compression into the surface of such components in an attempt to mitigate FOD effects on fatigue life. However, the depth to which the compressive stress state can be induced by shot peening is restricted to very near the component surface, thus limiting its effectiveness.[1] In addition, shot peening produces a rather high level of cold work (20 to 30%), which can be thermally relieved if the component is exposed to elevated temperatures in service or during secondary processing.[2]

More recently, a component surface enhancement technique called "laser shock peening" (LSP) has been successfully employed to improve the fatigue performance of gas turbine engine fan blades. In this process (Fig. 1), a laser vaporizes a thin opaque coating (usually black paint) applied to the surface of the component over the region to be treated. The vaporization of the paint produces a rapidly heated plasma that is confined against the surface of the component by a film of water. The pressure against the surface of the component increases rapidly, thereby causing a shock wave to travel into the surface of the material. If this shock wave is of sufficient magnitude, the process results in a residual state of compression in the treated area. Further details regarding the LSP process can be found elsewhere.[3,4]

Although the LSP process has been explored since the late 1970s, little work exists in the open literature regarding the optimization of LSP parameters. The subject study examines the effects of varying levels of LSP intensity on the residual stress state and percent cold work in simulated airfoil specimen made of Ti-6Al-4V. The different levels of LSP intensity were achieved by varying the power density and number of LSP pulses per spot.

2. Experimental Procedure

Simulated airfoil specimens were machined from Ti-6Al-4V hot-rolled bar by milling and subsequent low stress grinding. The material had been heat treated before machining as follows: vacuum treated at 705 °C for 2 h, static argon cooled to <149 °C, vacuum annealed at 549 °C for 2 h, static argon cooled to <149 °C. The resulting microstructure, shown in Fig. 2, consisted of approximately 90% platelike alpha (hcp) phase and approximately 10% intergranular beta (bcc) phase. The alpha phase is essentially equiaxed in the transverse section and somewhat elongated in the longitudinal section, along the longitudinal axis (rolling direction) of the bar.

The simulated airfoil specimens were specifically designed to approximate the leading edge geometry of a turbine engine airfoil with an edge thickness of 0.75 mm. Figure 3 shows a schematic of the specimen. The width of the specimen was tapered to provide a thin section along one edge (approximating a blade leading edge), which enabled through-thickness compressive residual stresses to be generated along this edge by LSP. Additional details regarding the development of this specimen geometry and rationale for its use in conjunction with LSP studies can be found elsewhere.[5]

The leading edge portion of the machined specimens was treated using three different levels of LSP power density: 5.5, 7, and 9 GW/cm^2. In addition, each power density level was applied using one or three pulses/spot to investigate the effects of shock repetition. Figure 4 shows the LSP pattern used for this study. The laser spot was essentially circular in geometry with a diameter of ~ 5.6 mm. Two sets of LSP parameters were applied

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P.R. Smith, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH 45433-7817; **M.J. Shepard,** Southwestern Ohio Council for High Education, Dayton, OH 45420-4014; **P.S. Prevéy III,** Lambda Research, Cincinnati, OH 45227-3401; and **A.H. Clauer,** LSP Technologies, Dublin, OH 43016-1272.

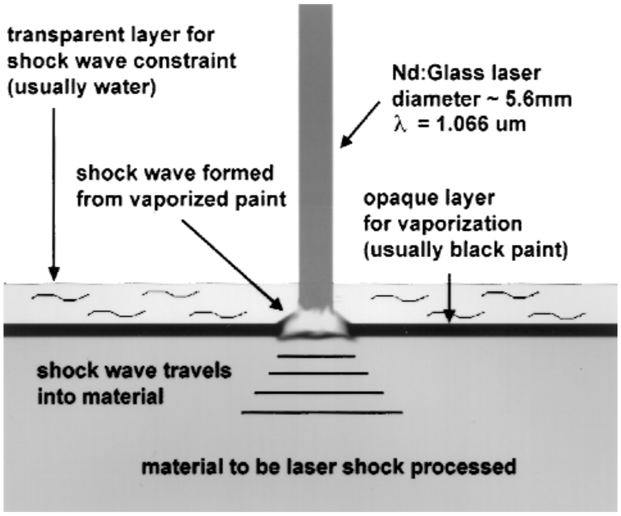

Fig. 1 Schematic of the LSP process

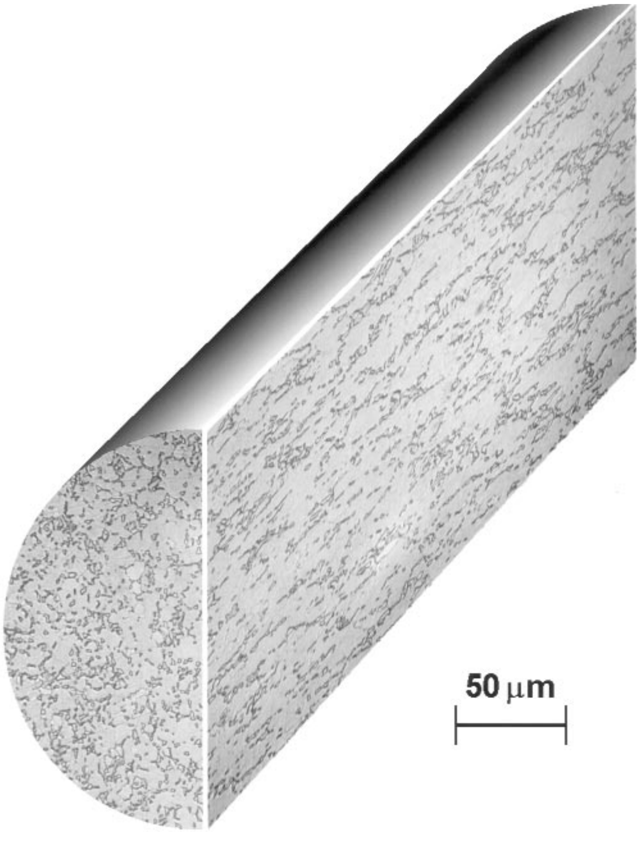

Fig. 2 Hot-rolled Ti-6AI-4V bar microstructure

per specimen, one in each of two independently treated zones. A finite element solution was developed to verify that the residual stress fields from each zone would not overlap. For each LSP parameter, two rows of spots were applied *via* LSP. One row nearest the leading edge contained four spots, and a second row contained three spots. The spots were overlapped ~30% in both the lateral (along the specimen) and vertical (across the specimen) directions. Both sides of the specimen were shocked simultaneously using a split beam.

Residual stress and percent of cold work measurements were made near the center of the LSP treated area using x-ray diffraction in accordance with recommendation SAE J784a and ASTM specifications E915 and E1426. Material was removed electrolytically for subsurface measurement in order to minimize alterations in the stress distributions that would be caused by machining or grinding. Residual stress results were corrected for penetration of the radiation into the stress gradient and for stress relaxation due to the material removal using a finite element model of the specimen geometry. The level of cold work produced during LSP was estimated by correlating the diffraction peak width to true plastic strain.[6] Assuming symmetry in the compressive residual stress state due to the simultaneous application of LSP to both sides of the specimen, residual stress and percent cold work measurements were made through half the nominal thickness.

3. Results and Discussion

Figure 5 shows the residual stress versus depth obtained for one pulse/spot for each of the three power densities investigated. The magnitude of the residual stresses is quite high at the specimen surface, most likely the result of specimen machining, but drops off with depth as would be expected. Although there appears to be some scatter in the data, there is no clear effect of LSP power density on the compressive residual stress state. In fact, the highest power density (9 GW/cm^2) actually produces the lowest level of compressive stress, up to ~0.3-mm deep. Figure 6 shows the corresponding percent of cold work versus depth data for the same conditions. There appears to be a relatively high level of cold work at the immediate surface, which again is likely the result of the milling process during specimen machining. The percent of cold work dropped off relatively quickly below the surface and was essentially constant at about 5 to 10% for depths >0.1 mm. Once again there was no clear effect of LSP power density on the level of cold work measured. Very similar results were found for residual stress and percent of cold work with varying power densities using three pulses/spot. Thus, there was no clear effect of LSP power density on either compressive residual stress state (Fig. 7) or percent of cold work (Fig. 8).

Figure 9 replots the above residual stress data versus depth at a constant power density (5.5 GW/cm^2) as a function of shock repetition. As before, the residual stress at and just below the surface is thought to be high due to machining stresses. It then drops off continuously with depth. However, notice that as the number of LSP pulses/spot increases from one to three, the magnitude of the compressive residual stress increases by ~100 MPa over the entire depth of measurement. As a result, at the midthickness of the specimen, the compressive stress for the single-shot condition drops to essentially zero, while for the three-shot condition, it is on the order of 100 MPa. Figure 10 shows the corresponding data for percent of cold work versus depth. Once again the percent of cold work is very high near the surface due to machining, but drops off to a steady-state condition at depths >0.04 mm. In addition, notice that the percent of cold work increases as the number of pulses increases from one to three, such that at one

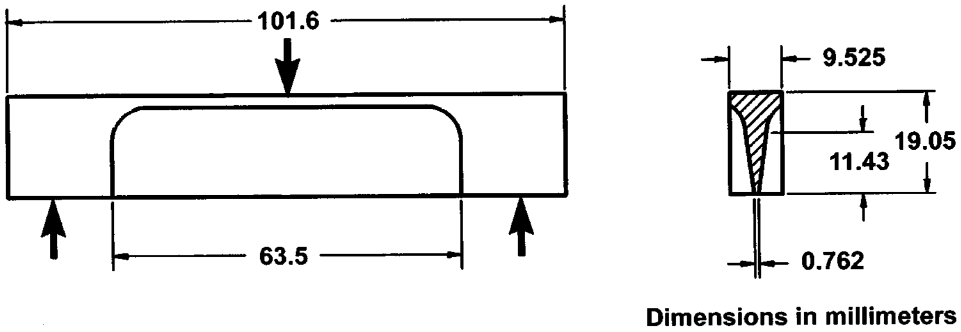

Fig. 3 Simulated airfoil specimen

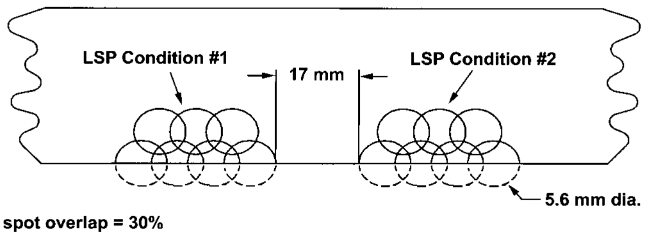

Fig. 4 LSP pattern

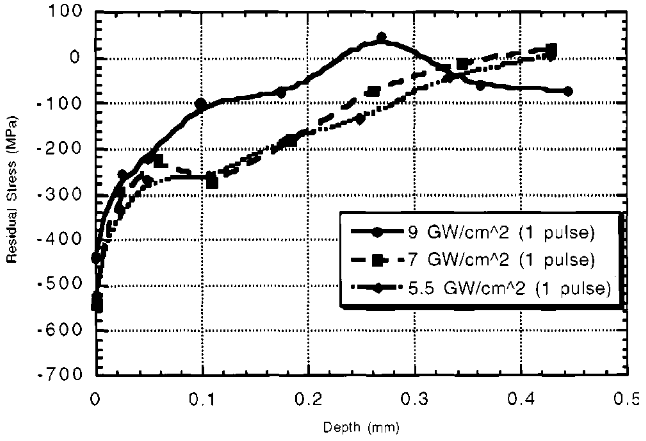

Fig. 5 Residual stress vs depth as a *f* (power density) at one pulse/spot

pulse/spot, the steady state of cold work is on the order of 6%, while for three pulses/spot, the steady state cold work is approximately 12%. Therefore, there is a correlation of increasing percent of cold work and increasing compressive residual stress with an increasing number of pulses. Similar trends for residual stress and percent of cold work versus depth at constant power density with one and three pulses were found for the 7 and 9 GW/cm^2 conditions (Figs. 11 to 14).

It should be noted, however, that although the percent of cold work appeared to reach a nominal steady-state condition with increasing depth, the magnitude of compressive residual stress continuously decreased. This was probably related to the observation that the percent of cold work determined from the x-ray diffraction analysis was related to the equivalent plastic strain, that is, the cumulative plastic strain, irrespective of whether this strain was induced in compression or tension. However, the

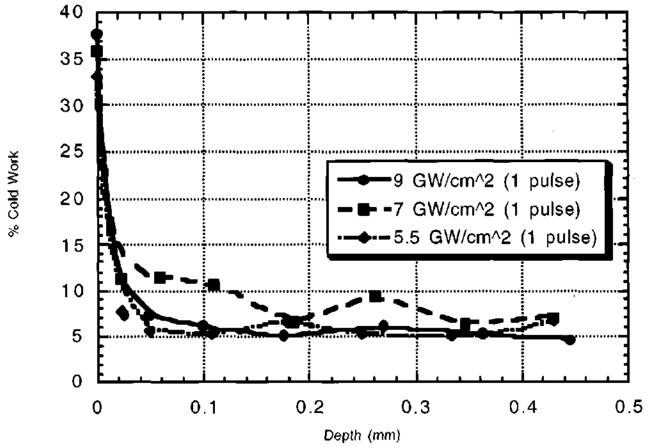

Fig. 6 Percent cold work vs depth as a *f* (power density) at one pulse/spot

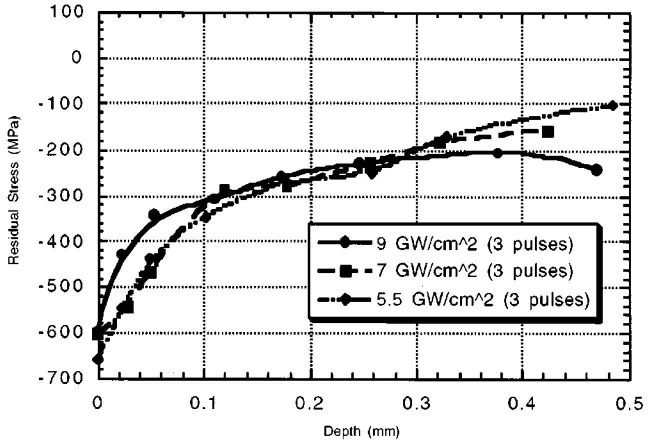

Fig. 7 Residual stress vs depth as a *f* (power density) at three pulses/spot

plastic strain along the through-thickness direction was created by both compression waves and tensile waves, and their interactions. The interplay of these stress waves creates a rather complex distribution of net radial plastic strain, which varies through the section thickness. It is the net radial plastic strain that plays the dominant role in determining the radial residual stress gradient. Correlations concerning the variations in the stress profiles

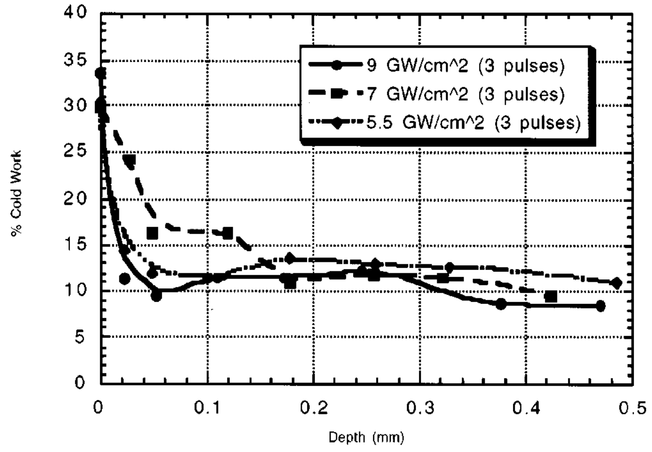

Fig. 8 Percent cold work vs depth as a *f*(power density) at three pulses/spot

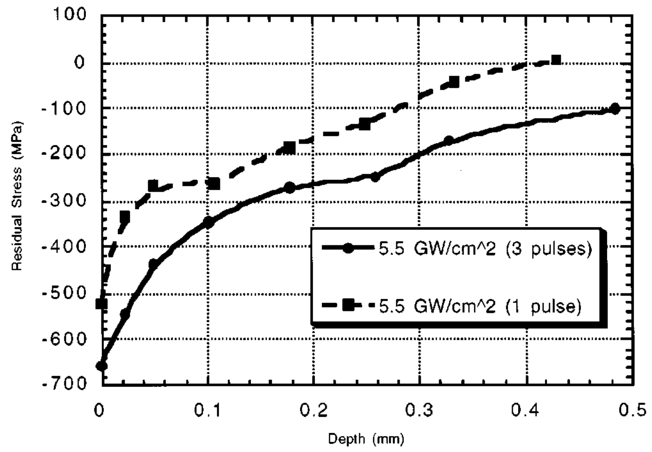

Fig. 9 Residual stress vs depth as a *f* (number of pulses per spot) at 5.5 GW/cm^2

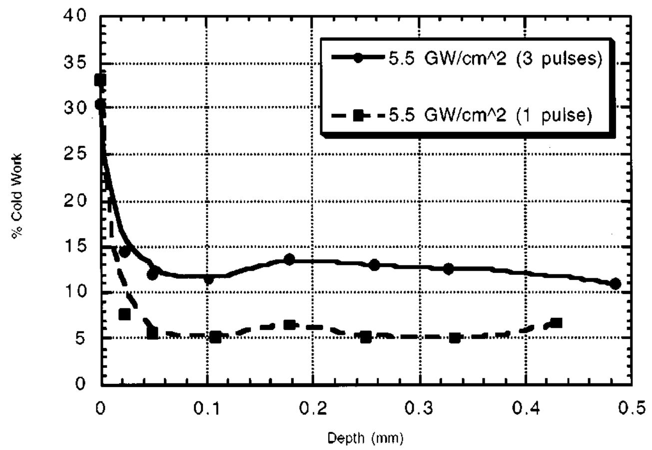

Fig. 10 Percent cold work vs depth as a *f* (number of pulses per spot) at 5.5 GW/cm^2

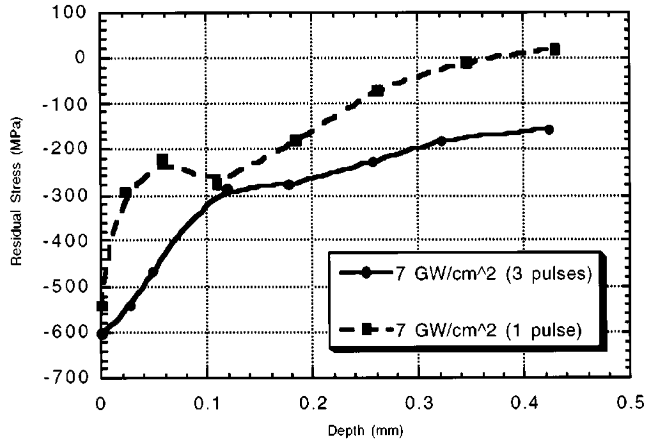

Fig. 11 Residual stress vs depth as a *f* (number of pulses per spot) at 7 GW/cm^2

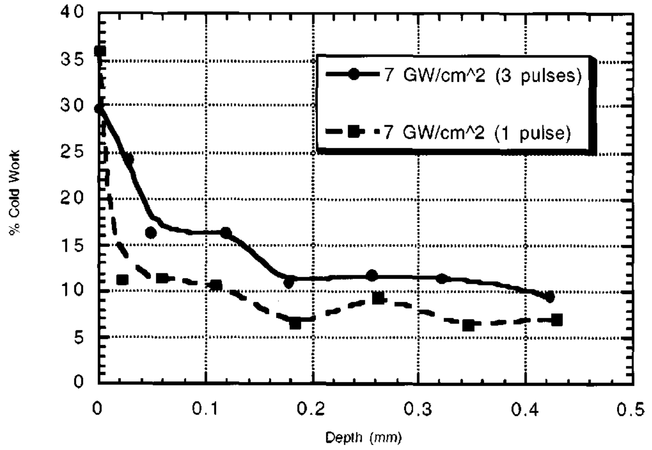

Fig. 12 Percent cold work vs depth as a *f* (number of pulses per spot) at 7 GW/cm^2

are further complicated by the necessary requirement that the x-ray diffraction spot used for making the measurements has a finite size and averages the measured residual stress over the area of the diffraction spot. In this study, a rectangular irradiated area, 2.5 by 10.0 mm, was used (long axis parallel to the blade edge), yielding residual stress values averaged over this irradiated area. In addition, because of the taper of the laser peened surfaces away from the leading edge (Fig. 3), the irradiated area spans a range of section thicknesses from 0.85 to 1.20 mm, with the midthickness ranging from 0.42 to 0.60 mm.

It is likely that much of the variation in the single shock data sets can be explained by the fact that there was some nonuniformity of the stress field generated by LSP as a result of the complex plastic strain distributions. These arose from both the factors mentioned above and the observation that the treatment relies on multiple shots patterned together to cover the desired area. Considering these combined effects, one would expect that multiple hits might act to smooth the plastic strain gradients somewhat and make the stress profile with depth more uniform. Such an effect can be seen

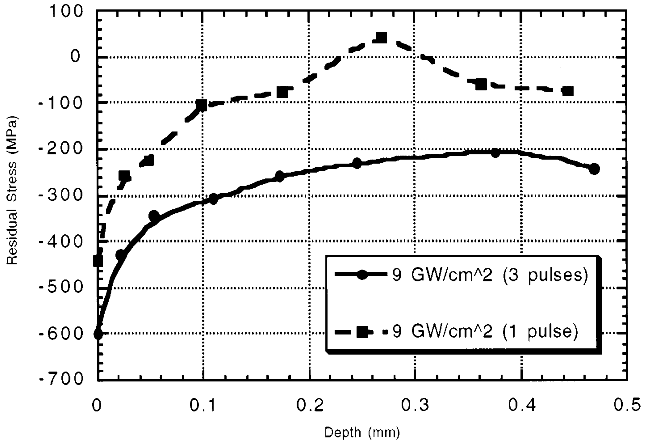

Fig. 13 Residual stress vs depth as a *f* (number of pulses per spot) at 9 GW/cm^2

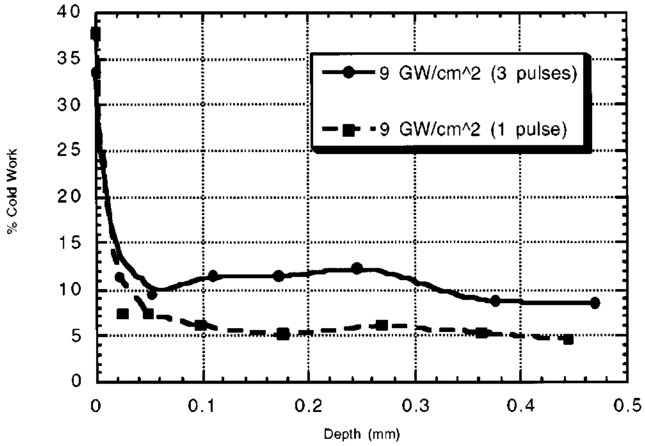

Fig. 14 Percent cold work vs depth as a *f* (number of pulses per spot) at 9 GW/cm^2

by comparing the residual stress versus depth curves for the triple and single shock experiments (Fig. 5 versus Fig. 7).

As can be seen in Figs. 5 and 7, the shocked region was in a compressive residual stress state through essentially its entire thickness. This feature occurred because the thin sections were laser shot peened from both sides simultaneously. As a result, the shock waves traveled into the material from opposite surfaces at the same time. When they met at the midthickness of the material the shock stresses doubled, causing an increase in plastic deformation or cold work at midthickness. This was clearly shown in aluminum alloys, where the hardness increased at midthickness in thin sections, and this effect became more pronounced as the section thickness decreased.[3] This localized plastic strain contributed to increasing the compressive residual stress at midthickness in thin sections. As section thickness decreased, the compressive residual stress began to extend all the way through the thickness. It is interesting to note that whereas the aluminum results[3] showed a pronounced peak in hardness at midthickness (0.9-mm thick), the percent of cold work in this study was relatively constant through most of the thickness.

4. Conclusions

The following conclusions can be drawn.

- Neither the magnitude of compressive residual stress state nor the percent cold work generated by LSP appears to be dependent on with the laser power density under the conditions investigated in this study. This could be the result of the thin section thickness, the taper of the opposing surfaces, the properties of the material, and/or the laser beam conditions.
- The magnitude of the compressive residual stress state was very high (550 to 650 MPa) at, and just below, the surface (most likely the result of machining stresses) and decayed to a minimum value (0 to 250 MPa) at the nominal midthickness of the section (*i.e.,* ~0.40 mm).
- The magnitude of compressive residual stress generated by LSP appeared to be proportional to the number of pulses per spot for a given power density, such that as shock repetition increased, so did the magnitude of compressive stress.
- The percent of cold work generated by LSP appears to be proportional to the number of pulses per spot for a given power density, such that as shock repetition increased, the percent of cold work increased.
- The percent of cold work reached a steady-state condition at depths = 0.04 to 0.06 mm.
- The compressive residual stress generated by LSP appears to be related to the percent of cold work induced, such that as the amount of cold work increased, the magnitude of the compressive residual stress increased.

References

1. P.S. Prevéy: *Optimization of Surface Enhancement Methods to Improve the Fatigue Life of Turbine Engine Components,* Lambda Research, Cincinnati, OH, 1996.
2. P.S. Prevéy, D. Hornbach, and P. Mason: *Thermal Residual Stress Relaxation and Distortion in Surface Enhanced Gas Turbine Components,* ASM/TMS Materials Week, Indianapolis, IN, 1997.
3. A.H. Clauer, J.H. Holbrook, and B.P. Fairand: in *Shock Waves and High-Strain-Rate Phenomena in Metals,* M. A. Meyers and L.E. Murr, eds., Plenum Publishing Corp., New York, NY, 1981, pp. 675-702.
4. P. Peyre and R. Fabbro: *Optical Quantum Electronics,* 1995, vol. 27, pp. 1213-29.
5. J.J. Ruschau, R. John, S. Thompson, and T. Nicholas: *J. Mater. Technol.* 1999, vol. 121.
6. P.S. Prevéy: *The Measurement of Subsurface Residual Stress and Cold Work Distribution in Nickel Base Alloys in Residual Stress in Design, Process and Materials Selection.* Ed. W. B. Young, ASM, Metals Park, OH.