THERMAL RESIDUAL STRESS RELAXATION AND DISTORTION IN SURFACE ENHANCED GAS TURBINE ENGINE COMPONENTS

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ABSTRACT

Compressive residual stresses are often deliberately induced in the surfaces of turbine engine components, using a variety of surface enhancement methods, to improve fatigue life. Thermal stress relaxation can occur in both the Ti and Ni alloys used in compressor and turbine stages. Nonuniform relaxation of the compressive layer can cause distortion of the critical aerodynamic shapes of thin blades, potentially effecting engine performance.

A detailed study of the thermal relaxation of the layer of compression induced by shot peening, gravity peening and laser shocking in Ti-6Al-4V and Inconel 718 at engine temperatures is summarized. Both the magnitude and rate of relaxation were found to depend primarily on the degree of cold working developed during processing. Compression in highly cold worked surfaces relaxed extremely rapidly in both alloys. Half the initial compression may be lost in less than 10 minutes even at moderate engine temperatures. Finite element estimates of the distortion resulting from nonuniform thermal relaxation in a hypothetical airfoil geometry is presented.

THE FATIGUE LIFE of titanium and nickel-base turbine engine alloys can be correlated with the maximum residual stress present in the shallow surface layer where cracking initiates (1,2). Manufacturing operations, such as turning and grinding, may leave the surface in tension. To improve the fatigue life of turbine engine components, various methods of surface enhancement (SE) are routinely applied to induce a layer of compressive residual stress at the surface after final machining. The layer of surface compression effectively impedes fatigue crack initiation in the low-load high-cycle fatigue regime. If the compression extends to sufficient depth, crack propagation can be retarded even under low-cycle fatigue loading.

Mechanical distortion is the result of either the introduction, redistribution or relaxation of residual stresses. If the shallow layer of high compressive stress induced by SE relaxes in service, fatigue life improvement will be lost. If the component is of sufficiently thin cross section, mechanical distortion will occur. The precise shape, specifically the camber and twist, of fan, compressor, and turbine blades strongly influences engine performance. Distortion of the airfoil shape of blades can reduce engine efficiency and change vibrational modes, effecting fatigue life (3).

A recent study of thermal stress relaxation in the compressive layer produced by different SE techniques in Ti-6Al-4V and Inconel 718 has revealed significant differences in the stability of the compressive layer produced (4). This paper summarizes the thermal relaxation observations and uses finite element modeling to explore the magnitude of the mechanical distortion which could be expected in a typical, but hypothetical, blade geometry.

Stress Relaxation in the Engine Environment. The relaxation of residual stresses is frequently observed, either by direct measurement or fatigue response, and is summarized in several survey papers (5,6). The three primary mechanisms for residual stress relaxation are: 1) tensile or compressive overload, 2) cyclic loading (near or above the endurance limit), and 3) thermal relaxation (5-12).

Because design stress levels are well below the endurance limit, in the absence of impact damage, thermal relaxation is the only mechanism causing significant loss of the protective compressive layer of residual stress in surface enhanced turbine engine components (6,12). Thermal relaxation of the compressive layer at the shot peened surface of actual engine components and fatigue test bars has been reported, but no detailed systematic study of thermal relaxation in Ti and Ni base alloys has been performed spanning the range of engine temperatures.

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Conventional Surface Enhancement Methods. All methods of surface enhancement (SE) currently available develop a layer of compressive residual stress as a result of mechanical tensile deformation of the surface. The methods differ primarily in how the surface is deformed and in the magnitude and form of the resulting residual stress and plastic deformation (cold work) distributions. Tumbling and shot or gravity peening are indiscriminate area covering methods, which produce local tensile deformation at the point of impact. Split-sleeve-cold-expansion (SSCE) stretches the material around the processed hole in tension, and is limited to through holes and similar prismatic geometries. In laser shock peening (LSP), tensile deformation is produced by a shock wave generated at the surface.

Conventional air-blast shot peening is routinely applied to a wide variety of titanium and nickel alloy turbine engine components. Small steel shot (S110) with a diameter of nominally 0.28 mm (0.011 in.) is commonly used to access tight radii. A small zone of compression is produced in the center of the dimple formed after tensile deformation of the surface upon the impact of each particle of shot. With sufficient impacts, the surface is completely covered, and a uniform layer of compression is formed. Typical compressive residual stress distributions reach a maximum on the order of the alloy yield strength, and extend to a depth of 0.05 to 0.5 mm (0.002 to 0.02 in.). The magnitude of compression achieved depends primarily upon the alloy yield strength and work hardening behavior. The depth of the compressive layer and the distribution of dislocation density caused by cold working of the surface layers depend upon the peening parameters such as shot size, velocity, coverage, impingement angle, etc.

The repeated dimpling of the surface results in a highly cold worked layer. The degree of cold work typically diminishes exponentially with depth. Conventional shot peening produces from 10% to 50% cold work, more than common grinding, machining, or surface finishing processes (13,14). The degree of cold working is accumulative, and repeated applications of shot peening can produce even more than 50% cold work. The most severe cold work occurs at the immediate surface, and both the depth and degree of cold working increase with peening intensity. In work hardening materials, compression at the surface is often reduced as the yield strength of the surface increases with cold work during shot peening.

Gravity peening utilizes the same mechanism as conventional air-blast or wheel shot peening but employs fewer impacts by larger shot, producing a less cold worked surface layer. Steel shot with a diameter of 2.38 mm (0.937 in.) was used to prepare samples for this study. Gravity peening is used for titanium alloy fan blades primarily for the smoother surface finish achieved.

Laser shock peening (LSP) (15) has recently been applied for surface enhancement of titanium alloy fan blades and demonstrated on nickel superalloys and steels. The surface layer is deformed in tension by a shock wave formed by the rapid ablation of a coating at the surface (15). LSP produces a layer of surface compression of comparable magnitude to conventional shot peening, but deeper. The LSP residual stress distribution diminishes nearly linearly with depth, without the reduced surface compression typical of shot peening. LSP produces remarkably little cold working of the surface because only a single, or a few, deformation cycles are required.

The residual stress and cold work distributions produced by air-blast shot peening, gravity peening, and LSP in Ti-6Al-4V and Inconel 718 used in this study are shown in Figures 1 and 2.

Thermal Relaxation. Both magnitude and rate of thermal residual stress relaxation increase with the degree to which the material has been cold worked (10). The higher the dislocation density and internal energy of the material, the faster a given level of residual stress will relax at a fixed temperature.

Methods of SE which produce the least cold work in titanium and nickel alloys have been observed to suffer the least relaxation at engine temperatures. LSP, producing minimal cold working of the surface, has exhibited striking resistance to thermal relaxation. No detectable relaxation of the residual stress distribution produced by LSP was observed in Ti-8-1-1 after exposure for four hours at either 230 C (450 F) and 400 C (750 F) (16).

TECHNIQUE

X-ray Diffraction Measurement of Residual Stress and Cold Work. The macroscopic residual stress, of primary interest in design and life prediction, was determined in the conventional manner from the shift in the diffraction peak position (2, 17-22).

A method of quantifying the degree of cold working of metals, relating the diffraction peak broadening to the equivalent true plastic strain, has been developed by the authors (13,23). X-ray diffraction line broadening, measured along with the macroscopic residual stress, allows the amount of damage developed by SE methods to be quantified. The technique was applied to monitor the thermal relaxation of cold work in surface layers during macroscopic residual stress measurement.

The cold working of metals generates complex tangles of dislocations surrounding coherent crystalline regions strained elastically to different levels of microstress relative to the mean macroscopic stress in the material. Further cold working increases the dislocation density and the range of microstress, and reduces the size of the coherent crystalline regions, producing broadening of the diffraction peaks (24). The distribution of cold work as a function of depth into the deformed surface can be expressed in terms of the amount of true plastic strain that would be required to produce the same degree of peak broadening. If the degree of cold work is taken to be the equivalent amount of true plastic strain, the degree of cold work is accumulative and independent of the mode of deformation (13). The amount of cold work is estimated from empirical curves developed for each alloy by measuring the peak breadth in coupons deformed in compression to known true plastic strain.

Sample Preparation. Ti-6Al-4V and Inconel 718 were chosen as typical of the titanium and nickel-base superalloys used in aircraft turbine engines. Three SE methods in current use in the manufacture of aircraft turbine engines, LSP, gravity, and conventional air-blast shot peening, were selected. The SE processing parameters were chosen to represent low, nominal and high degrees of cold working while developing comparable levels of compression.

A coupon size of 63.5 x 25.4 x 19 mm (2.5 x 1.0 x 0.75 in.) with a 63.5 x 25.4 mm (2.5 x 1.0 in.) test face was selected. A total of 21 Inconel 718 coupons (7 by each SE method) and 27 Ti-6Al-4V coupons (9 by each method) were prepared. The material was solution heat treated, aged, and electropolished prior to SE processing to eliminate any residual stress and cold work from prior machining. One face of each coupon, sufficient to provide ten 12.7 x 12.7 mm (0.5 x 0.5 in.) measurement areas, was prepared by:

1) conventional air-blast shot peening with S110 shot to a 10A Almen intensity and 200% coverage,

2) gravity peening using 2.38 mm (3/32 in.) balls and a 1.62 m (64 in.) drop, to produce a 10A Almen intensity, and

3) LSP, performed with three repetitions at four overlapping 5 mm zones with 30% overlap at the center of each test area on the coupons.

The shot peening parameters were deliberately chosen to produce a high level of cold work. The residual stress distributions developed by the SE processes prior to thermal exposure are shown in Figures 1 and 2 for the Ti-6Al-4V and Inconel 718 samples, respectively.

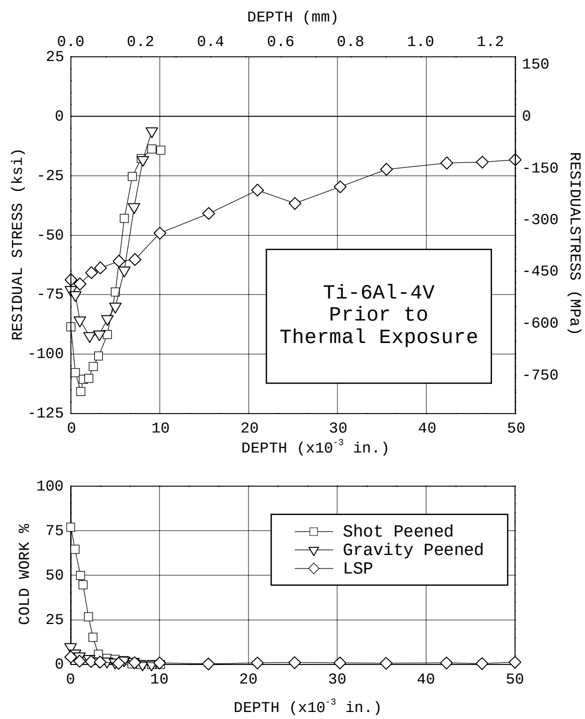

Fig. 1 – Residual stress and cold work distributions developed in Ti-6Al-4V coupons.

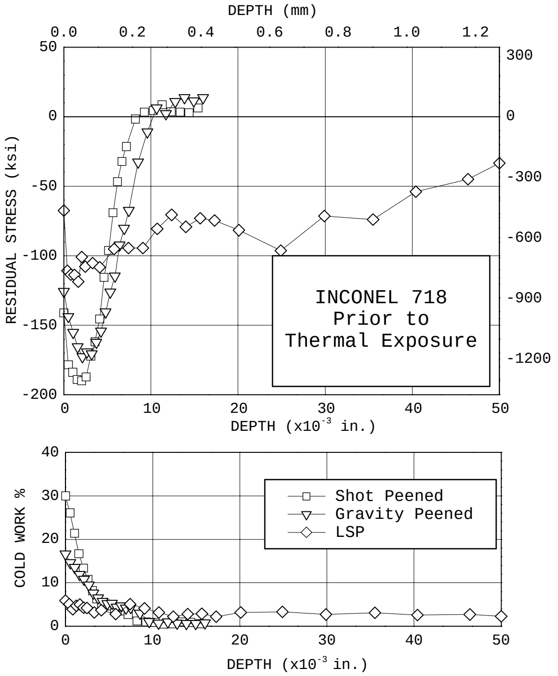

Fig. 2 - Residual stress and cold work distributions developed in Inconel 718 coupons.

The anticipated broad range of cold working is evident from the plots at the bottom of each of the figures. In each case, shot peening produced the highest degree of cold work due to the high number of impacts. Gravity peening, using fewer impacts with larger balls, produced an intermediate degree of cold work, and LSP, the least.

LSP was found to produce fluctuations in the residual stress distributions with depth, a feature not produced by the other SE methods. The stress developed at a given depth varied by nearly 250 MPa for samples which were presumably identically processed. The variation is attributed to the inherent non-uniformity of the LSP process, which was performed with three repetitions at four overlapping zones surrounding the center of each 12.7 x 12.7 mm (0.5 x 0.5 in.) test area on the coupons. The variation seen in the LSP residual stress distributions is attributed to the preparation of the original coupons and not the measurement or thermal relaxation.

Thermal Exposure and Data Acquisition. The thermal stress relaxation behavior of the surface enhanced Ti-6Al-4V and Inconel 718 coupons was investigated at temperatures bracketing typical turbine engine compressor and turbine conditions under which the alloys are used. For Ti-6Al-4V, coupons were exposed at 325, 375, 400, 425 and 475 C (617, 707, 752, 797 and 887 F). The Inconel 718 coupons were exposed at 525, 575, 600, 625 and 675 C (977, 1067, 1112, 1157 and 1247 F). The coupons were held at the selected temperatures in a molten salt bath for times of 10, 20, 60, 200, 600 and 2000 min., an approximately logarithmic time interval progression.

Residual stress and peak width distributions were measured as functions of depth after exposure for each time interval. One 12.7 x 12.7 mm (0.5 x 0.5 in.) test zone was alternately measured and electropolished to obtain the full subsurface residual stress distribution after each cycle of exposure. The residual stress and peak width distributions were obtained using automated x-ray diffraction apparatus developed by the authors (25). One coupon was used for each combination of SE method and temperature.

RESULTS AND DISCUSSION

Thermal Relaxation. Both the magnitude and rate of relaxation of the compressive layer developed by the SE processes were found to be highly dependent upon the degree of cold work induced during formation of the compressive layer. The volume of data generated prohibits presentation here, but the nature of the relaxation observed can be characterized by considering only selected exposure times at the minimum and maximum temperatures.

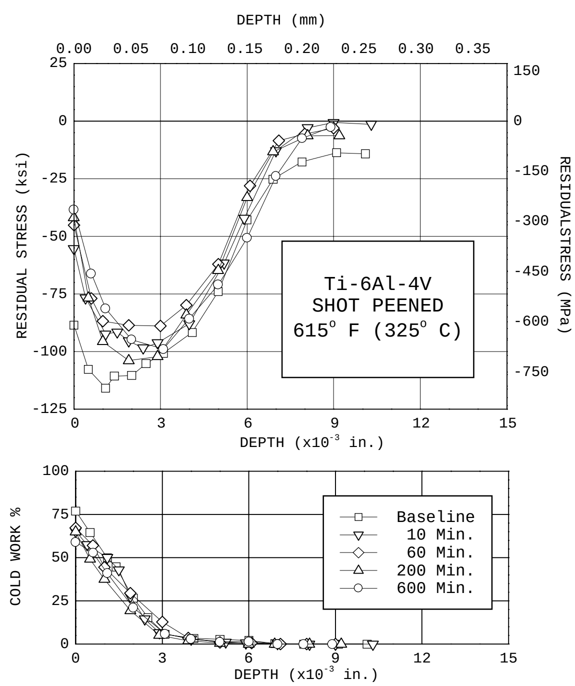

Fig. 3A – Thermal stress relaxation in shot peened Ti-6Al-4V at 325 C (615 F).

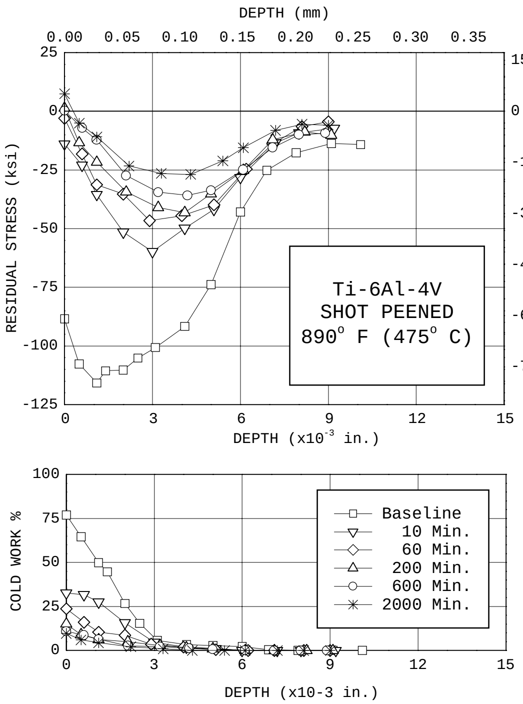

Fig. 3B – Thermal stress relaxation in shot peened Ti-6Al-4V at 475 C (890 F).

Conventional air-blast shot peening of TI-6Al-4V to a 10A intensity with small S110 shot produced severe cold working at the surface, exceeding 75%. Figures 3A and 3B show the stress distributions after exposures of shot peened Ti-6Al-4V ranging from 10 to 2000 min. at 325 C (615 F) and 475 C (890 F), respectively. The compressive residual stress at the surface drops to approximately 60% of the original value in only 10 min. at the low temperature and is virtually eliminated after only 10 min. at the higher temperature. Relaxation at all depths at the high temperature in the Ti alloy appears to follow a diffusion controlled Avrami model (7). At the low temperature, relaxation only appears to occur in the highly cold worked layers at the low temperature. Both the initial rate and magnitude of relaxation of the cold worked material were much faster than previously realized.

Gravity peening of Ti-6Al-4V produced substantially less cold work than air-blast shot peening, on the order of 10% at the surface. The layer of compression generated was comparable in magnitude to shot peening but relaxed less for the same temperature exposures, as shown in Figures 4A and 4B. Very little relaxation occurs at the surface at the low temperature, but even the gravity peened material has lost nearly half the compressive stress generated initially at the surface after only an hour at the higher temperature.

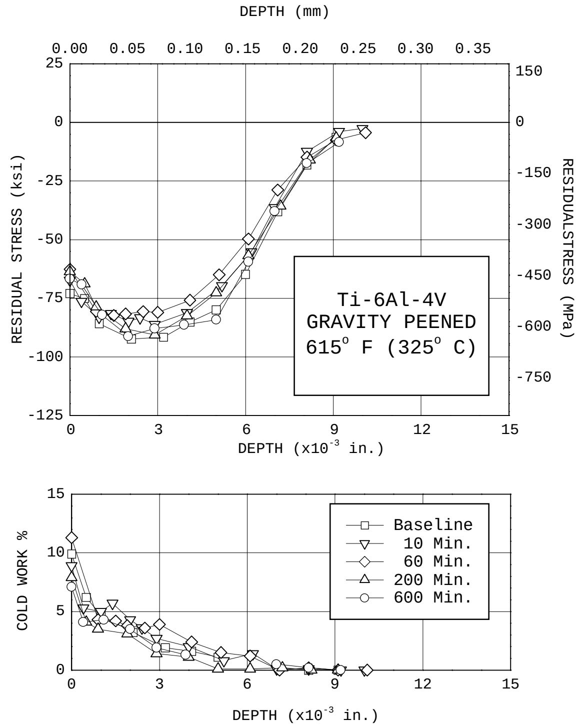

Fig. 4A – Thermal Stress relaxation in gravity peened Ti-6Al-4V at 325 C (615 F).

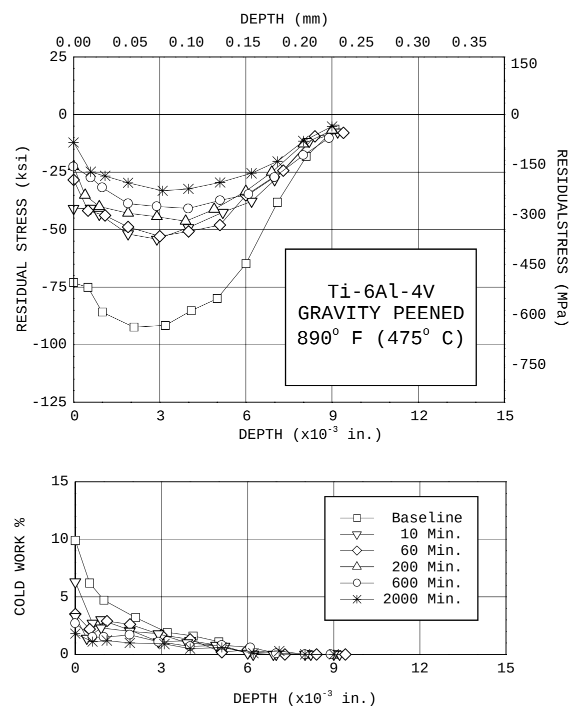

Fig. 4B – Stress relaxation in gravity peened Ti-6Al-4V at 475 C (890 F).

In contrast, the laser shock peened Ti-6Al-4V coupons, which received minimum cold working on the order of

1 to 2%, did not relax at the lower temperature, as shown in Figure 5A. At the highest temperature investigated, 425 C (797 F) for the LSP coupons, only a small loss occurs near the surface where a slightly higher degree of cold working is evident in Figure 5B.

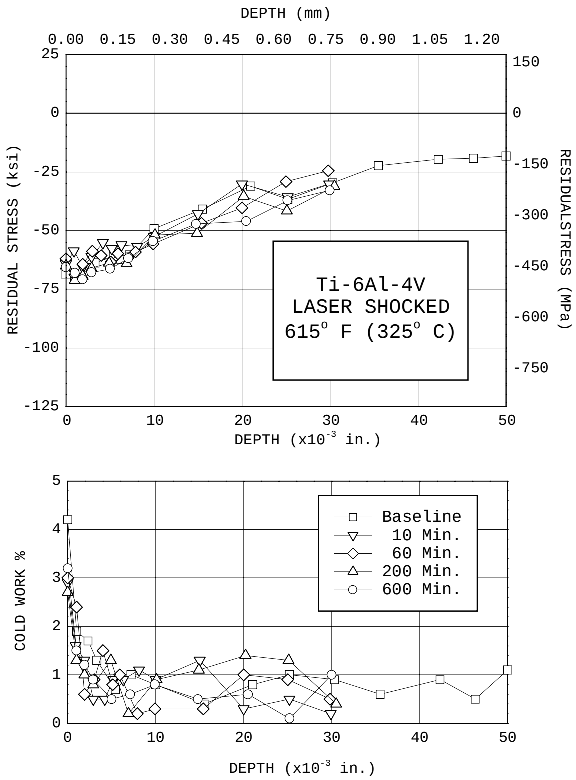

Fig. 5A – Thermal stress relaxation in laser shocked Ti-6Al-4V at 325 C (615 F).

Virtually identical trends are seen in the nickel-base superalloy, Inconel 718. However, even at the maximum temperature, the degree of cold work appears to correlate to the amount of relaxation. Exposures at the minimum and maximum ranges of 980 F (525 C) and 1240 F (670 C) are shown for shot peened, gravity peened, and laser peened samples in Figures 6 through 8.

The rate and magnitude of relaxation of the highly cold worked superalloy were also found to be much greater than anticipated. Figure 6A shows that the 30% cold worked surface of air-blast shot peened Inconel 718 loses nominally half the initial surface compression in the first 60 minutes at the low temperature. In Figure 6B, the fractional loss at the surface is nearly the same at the high temperature and is complete within only 10 minutes. The initial loss of compression appears to be essentially independent of the exposure time or temperature in the most highly cold worked layers within 0.08 mm (0.003 in.) of the surface.

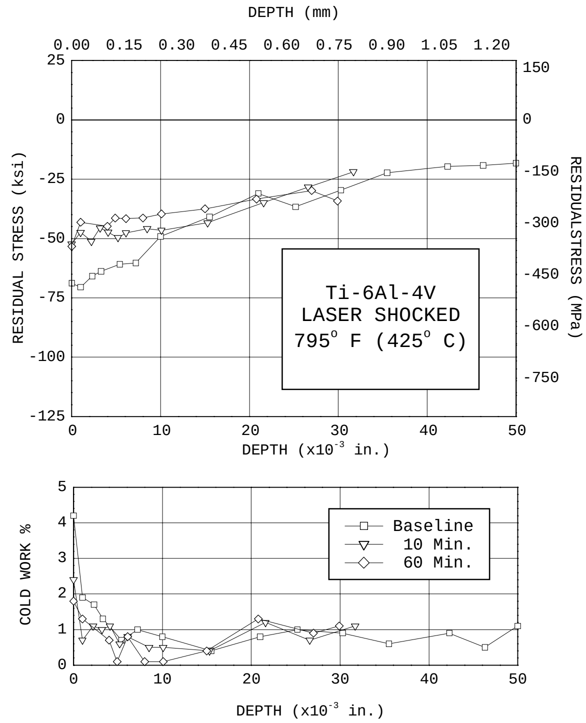

Fig. 5B – Thermal stress relaxation in laser shocked Ti-6Al-4V at 425 C (795 F).

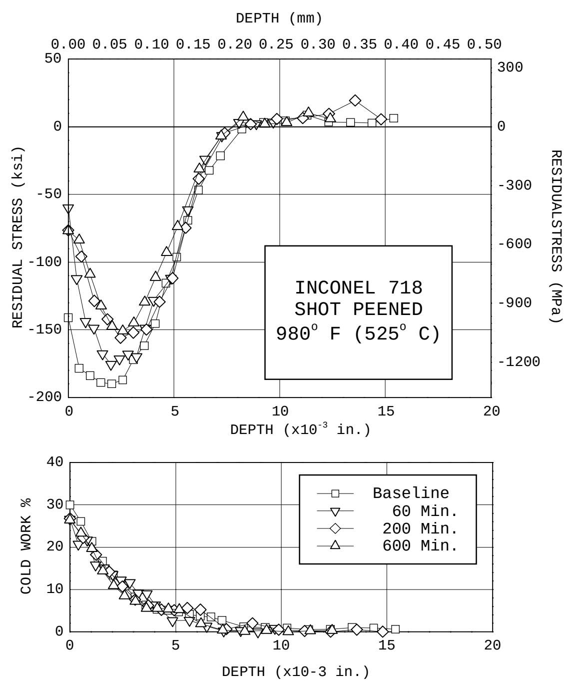

Fig. 6A – Thermal stress relaxation in shot peened Inconel 718 at 525 C (980 F).

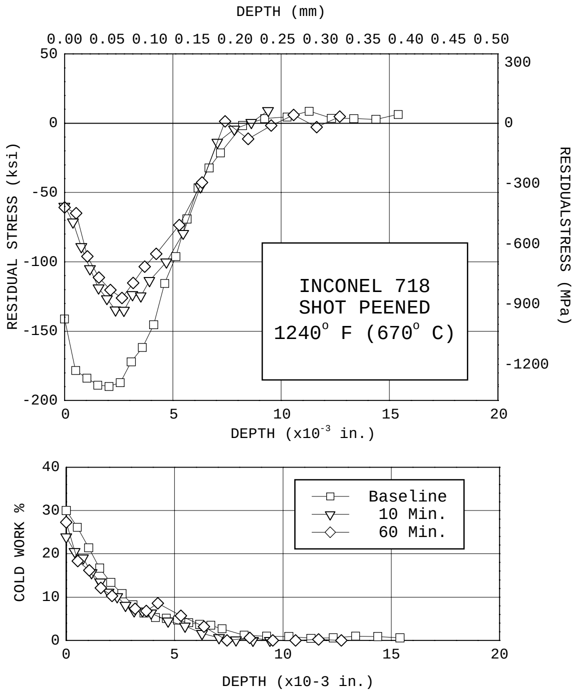

Fig. 6B – Thermal stress relaxation in shot peened Inconel 718 at 670 C (1240 F).

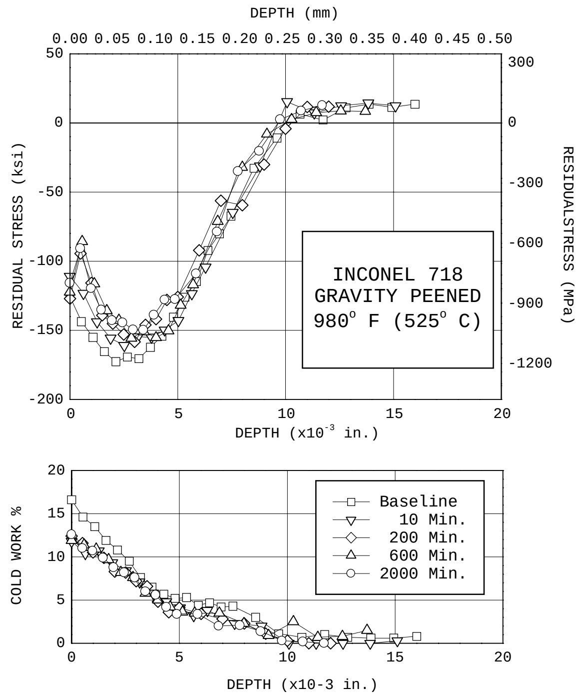

Fig 7A – Thermal stress relaxation in gravity peened Inconel 718 at 525 C (980 F).

Gravity peening of Inconel 718 results in less cold work, on the order of 15% at the surface, and very little loss at the surface at the low temperature, shown in Figure 7A. Comparison of Figures 7B and 6B reveals that, at the maximum anticipated engine temperatures, the less cold worked gravity peened surface retains compression better than the shot peened.

The residual stress distributions shown in Figures 8A and 8B reveal virtually no thermal stress relaxation in the LSP processed Inconel 718, which was cold worked only 3 to 6%, at any depth or exposure time at even the highest temperature. The variation in the stress distributions is attributed to non-uniform compression in the overlapping LSP zones.

The potential magnitude of mechanical distortion which could result from thermal stress relaxation of compressive layers induced by surface enhancement was investigated using finite element modeling. Distortion of the shape of airfoils could affect engine performance and fuel efficiency. Further, redistribution of residual stresses and subtle changes in the twist and camber of compressor and turbine blades could, in principle, alters the vibrational modes and, thus, the points of maximum stress, which, in turn, affects fatigue life prediction.

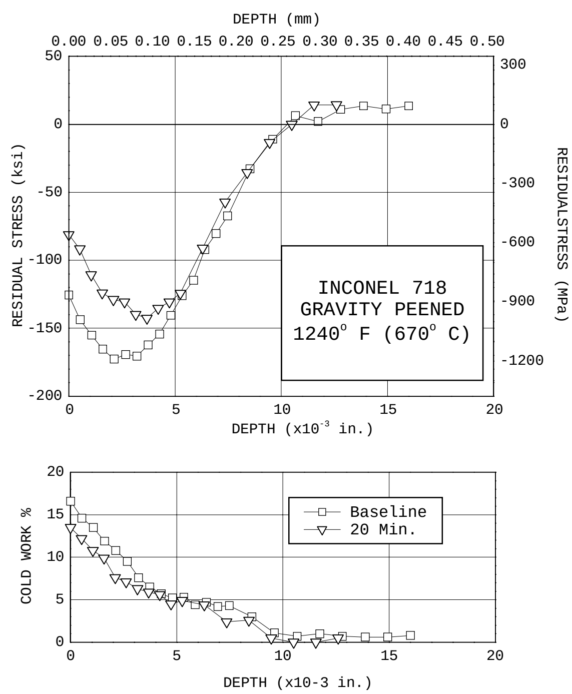

Fig. 7B – Thermal stress relaxation in gravity peened Inconel 718 at 670 C (1240 F).

In principle, any thin section component in the compressor and turbine region which is shot peened could be subject to distortion. The worse case distortion would occur for components with section thicknesses on the order of the depth of the compressive layer induced by surface enhancement. Further, the distortion would be most severe if the relaxation is nonuniform. The worse case would result from full relaxation on only one side of a blade. Such extremes could develop if severe temperature differences existed on opposing sides of a thin section, or more probably if one side was cold worked, perhaps by repeated applications of shot peening, more than the opposing side prior to exposure at a uniform temperature.

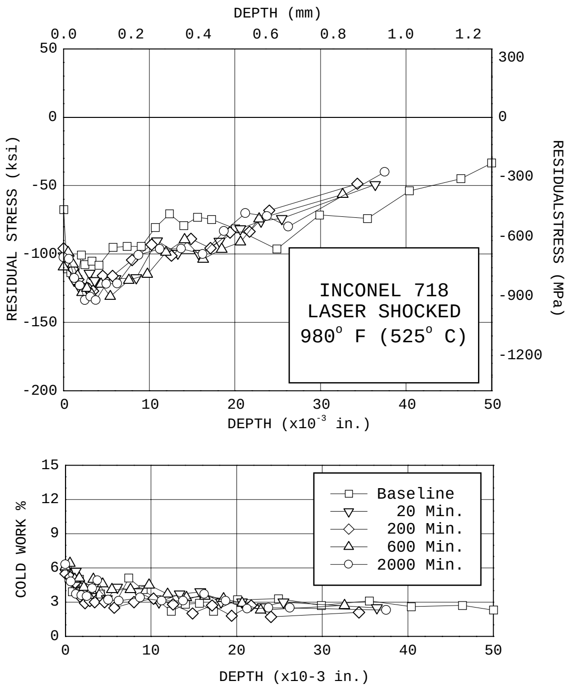

Fig. 8A – Thermal stress relaxation in laser shocked Inconel 718 at 525 C (980 F) (fluctuations attributed to original LSP processing).

A hypothetical blade model shown in Figure 9 was developed to allow estimation of the magnitude of distortion which could occur. Residual stress distributions equivalent to those produced by shot peening, gravity peening, and laser shocking of the Ti-6Al-4V and Inconel 718 were introduced into both the concave and convex surfaces of the blade model. The distributions were then allowed to relax to the maximum degree as shown at the higher temperature for each of the alloys in Figures 3-8. Two extreme scenarios were considered: uniform relaxation on both sides of the airfoil section and relaxation on the concave side only.

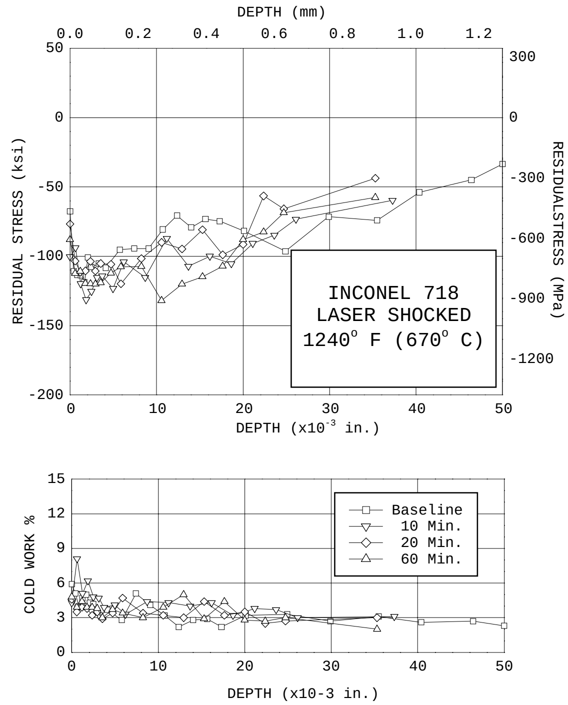

Fig. 8B – Thermal stress relaxation in laser shocked Inconel 718 at 670 C (1240 F) (fluctuations attributed to original LSP processing).

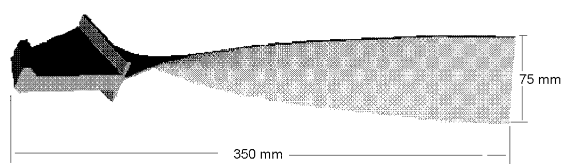

Fig. 9 – Finite element model of hypothetical blade used for distortion estimation.

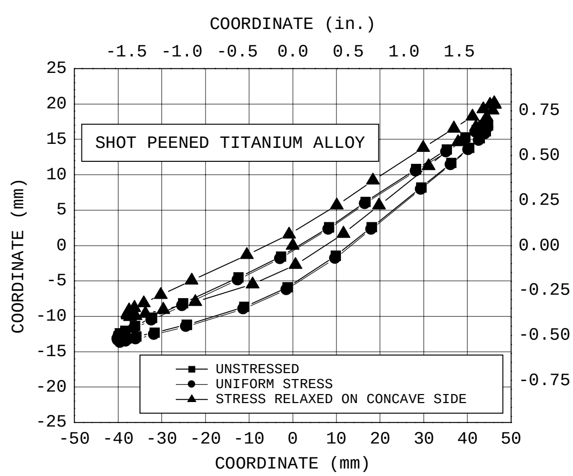

Fig. 10A – Airfoil tip cross-section distortion of shot peened Ti-6Al-4V model.

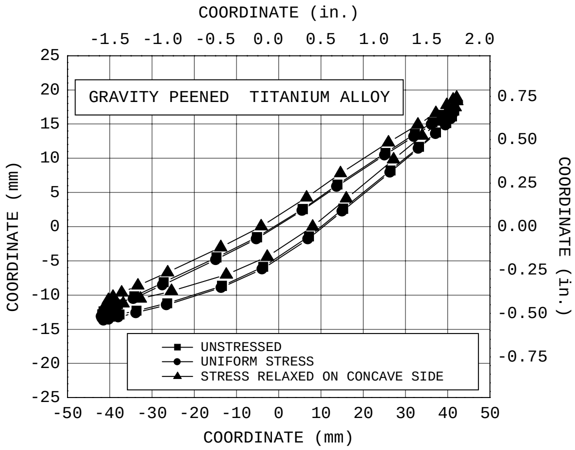

Fig. 10B – Airfoil Tip cross section distortion of gravity peened Ti-6Al-4V model.

The depth of the compressive layer induced by LSP was too great for simulation in the thin uniform airfoil section. The thermal relaxation data had indicated nearly negligible relaxation of the low cold work LSP generated stress profiles. Therefore, only the shot peened and gravity peened stress and cold work distributions were considered for the uniform coverage FEA model.

The complex distortion possible in the blade geometry was quantified by considering simply the cross-section of the airfoil tip. Assuming a cantilever gripping of the blade at the dovetail, the form and displacement of the cross-section of the airfoil tip are shown in Figures 10A and 10B for the shot peened and gravity peened titanium alloy model and in Figures 11A and 11B for the shot peened and gravity peened nickel-base model, respectively.

Uniform relaxation of either stress distribution from both sides of the airfoil produced nearly negligible distortion, on the order of only 0.1 mm, primarily at the leading edge. Relaxation on the concave side only, of course, produces maximum distortion. Because of the lower modulus and lower compressive stress level developed by the surface enhancement methods in the titanium alloy, the distortions resulting from thermal relaxation are nearly identical for a given surface enhancement method regardless of the material properties. The gravity peened model exhibits approximately one-third the distortion of the shot peened model for either alloy.

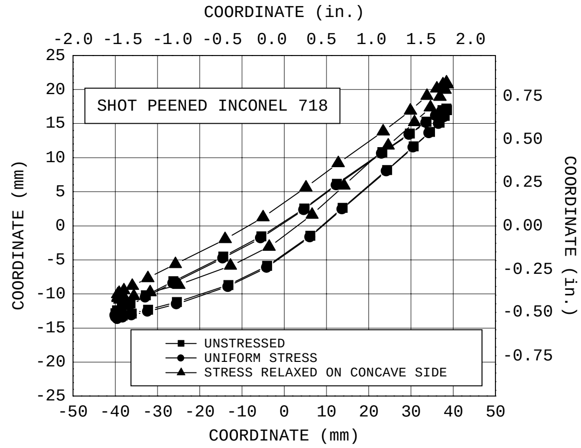

Fig. 11A – Airfoil cross section distortion of shot peened Inconel 718 FEA model.

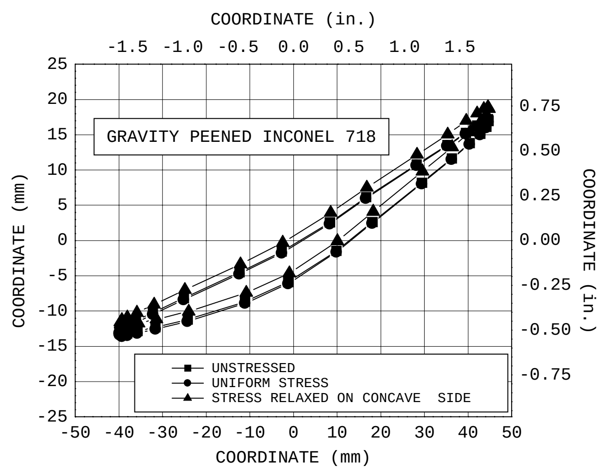

Fig. 11B – Airfoil tip cross section distortion of gravity peened Inconel 718 model.

CONCLUSIONS

The thermal residual stress relaxation which occurs at turbine engine temperatures in the compressive layer induced by surface enhancement of Ti-6Al-4V and Inconel 718 has been characterized.

Initial thermal relaxation of highly cold worked surfaces can be far more rapid than previously realized, and can result in 50% loss in 10 minutes even at relatively low engine temperatures for either the titanium or nickel-base alloy.

Thermal relaxation appears to progress in two stages: a primary stage, which is extremely rapid, and a secondary stage, which appears to follow the Avrami diffusion model (5,7). The Avrami model appears to best describe the relaxation for long exposures at the higher temperatures in these alloys.

The rate and amount of relaxation is directly correlated to the degree of cold work measured by diffraction peak broadening.

Compression induced by surface enhancement processes which produce the least cold work will be retained for the longest time and at higher engine temperatures.

Distortion of thin section Ti and Ni alloy components, such as compressor and turbine blades, may be anticipated even at moderate engine temperatures if the surfaces are highly cold worked during surface enhancement.

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