THE EFFECT OF LOW PLASTICITY BURNISHING (LPB) ON THE HCF PERFORMANCE AND FOD RESISTANCE OF Ti-6Al-4V

Paul S. Prevéy, Lambda Research
Michael J. Shepard and Paul R. Smith, AFRL/MLLMP

ABSTRACT

Low Plasticity Burnishing (LPB) has been developed as a rapid, inexpensive surface enhancement method adaptable to existing CNC machine tools. LPB produces a deep layer of compression with minimal cold work of the surface, comparable to laser shock peening (LSP), but can be incorporated into manufacturing operations at lower cost. Minimizing cold work during surface enhancement has been shown to improve both thermal stability at engine temperatures and resistance to overload relaxation accompanying foreign object damage (FOD).

Recent research leading to the development of a practical LPB demonstration facility and tooling is described. The mechanism for compressive residual stress development during LPB has been studied with elastic-plastic finite element modeling. DOE methods have been utilized to optimize compressive magnitude and depth with minimum cold work. Using optimum burnishing parameters, compression on the order of the material yield strength can be achieved to depths exceeding 0.040 in. (1mm) with low cold work.

Residual stress and cold work distributions developed by LPB in Ti-6Al-4V are compared to traditional shot peening and LSP. The compressive layer produced by LPB is shown to be resistant to both thermal and overload relaxation. After exposure to engine temperatures, the high cycle fatigue (HCF) strength at $2x10^6$ cycles after LPB is 40% higher than 8A shot peening. FOD 0.010 in. deep reduces the HCF strength of shot peened Ti-6Al-4V by 50% but has no significant effect on fatigue life after LPB. HCF life improvement and FOD tolerance are attributed to the deep compressive layer produced by LPB.

INTRODUCTION

The performance, life and cost of operating turbine engines are dominated by the risk of HCF failure. Since the introduction of shot peening, the HCF life of critical components has been improved by "surface enhancement" to induce a surface layer of compressive residual stress. The compressive layer both resists crack initiation and retards small crack propagation. The magnitude of the subsurface residual stress has long been correlated with HCF strength.**[1,2]** Because the HCF life depends primarily upon cycles to crack initiation, surface enhancement can significantly improve the endurance limit and extend component fatigue life by an order of magnitude in high strength structural alloys.**[2]**

The full benefits of surface enhancement can be realized only if the compressive residual stresses can be used to offset tensile applied stresses in turbine engine design. If the compressive layer relaxes during service at engine temperatures, the benefits of surface enhancement are lost. Risk of relaxation of the compressive layer during engine operation prevents designers from "taking credit" for the benefits of surface enhancement. Of three potential mechanisms for residual stress relaxation: thermal, overload, and cyclic, only thermal relaxation is significant in the absence of FOD. Thermal relaxation studies have revealed the importance of cold work in thermal relaxation. IN718**[19]** and Ti-6Al-4V**[3]** components, highly cold worked by shot peening, may lose most of the beneficial surface compression in minutes at even moderate engine operating temperatures.

This paper summarizes aspects of several research efforts in which x-ray diffraction methods were used to study thermal relaxation of compression induced by a variety of surface enhancement methods in a typical, well characterized titanium compressor alloy, Ti-6Al-4V. Low plasticity burnishing (LPB) is compared to conventional shot peening in terms of thermal stability of the compressive layer, HCF performance and damage tolerance.

Surface Enhancement Methods

Mechanical surface enhancement (SE) methods develop a layer of compressive residual stress following mechanical deformation of the surface. The methods differ in how the surface is deformed and in the magnitude and form of the resulting residual stress and cold work (plastic deformation) distributions developed. The residual stress and cold work distributions produced in Ti-6Al-4V by conventional shot peening (8A intensity, 200% coverage), gravity peening, laser shock peening (LSP), and two levels of low plasticity burnishing (LPB) are compared in Figure 1. The magnitude of compression at the surface is comparable, but the depths of the compressive layers differ by nearly an order of magnitude. The degree of cold working ranges from 100% for shot peening to only a few percent for LPB, and LSP.

Shot peening is routinely applied to critical engine components subject to HCF failure. High velocity impact of each particle of shot stretches the surface initially in tension and leaves a dimple with a region of compression in the center upon rebounding. Because shot impacts the surface randomly, peening to achieve uniform coverage results in many areas of multiple impact producing a highly cold worked surface layer.**[4]** The depth of the compressive layer and the degree of cold working depend upon the peening parameters including shot size, velocity, coverage, and impingement angle. Typical compressive residual stress distributions reach a maximum approaching the alloy yield strength, and extend to a depth of 0.002 to 0.020 in. (0.05 to 0.5 mm).

Titanium alloys cold work rapidly, generally to over 50% during conventional shot peening.**[5]** Cold work is cumulative and increases with coverage or repeated applications of shot peening, as during engine overhaul. The depth and degree of cold working increase with peening intensity, with the most severe cold working at the surface.

Gravity peening utilizes the same mechanism as shot peening but employs fewer impacts by larger shot dropped onto the surface, producing less cold work and improved surface finish. Compression comparable to shot peening is achieved with 5 to 10% cold work.

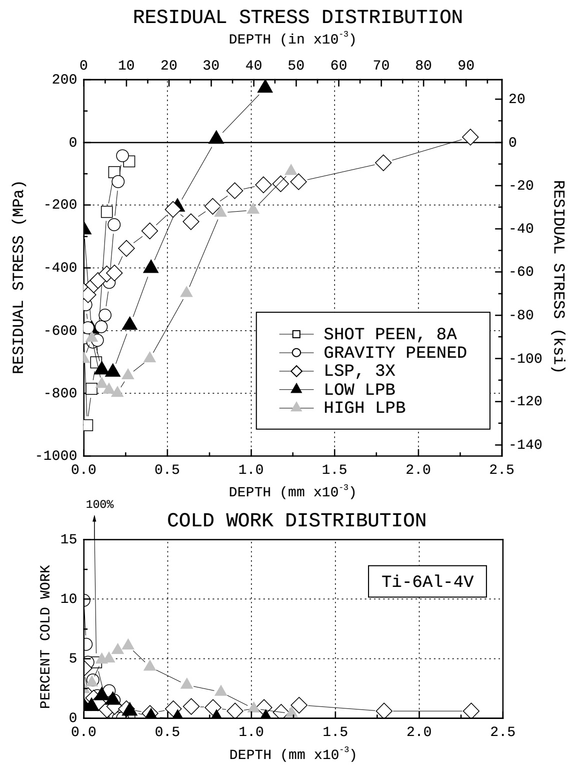

Figure 1 - Subsurface residual stress and cold work distributions produced by shot peeing (8A, 200%), gravity peening, LSP (3X), and two levels of LPB in Ti-6Al-4V.

Laser shock peening (LSP) **[6]** produces a layer of compression of comparable magnitude to shot peening but much deeper and with less cold work. LSP has been successfully applied for surface enhancement of a variety of alloys including titanium, nickel superalloys, and steels.**[7]** LSP performed with a single shock cycle can produce high compression with less than 1% cold work. Excellent thermal stability has been demonstrated in IN718 and Ti-6Al-4V.**[8]** However, multiple laser shock cycles are required to produce compression to depths of 1mm, increasing the cold work to 5 to 7%.**[9]**

Low plasticity burnishing (LPB) was developed to produce a deep layer of high compression, comparable to LSP, but with improved surface finish, lower cost, and **minimal** cold work.**[10]** The process is characterized by a single pass of a smooth free rolling spherical ball under a normal force just sufficient to deform the surface of the material in tension, creating a compressive layer of residual stress. The process is shown schematically in Figure 2. The ball is supported in a spherical fluid bearing with sufficient pressure to lift the ball off the surface of the retaining spherical socket. The ball is in solid contact only with the surface to be burnished, and is free to roll in any direction on the surface of the work piece. Surface deformation and damage caused by sliding of the tool in conventional burnishing is virtually eliminated. The normal force, pressure, and tool position are computer controlled in a multi-axis CNC machine tool or lathe.

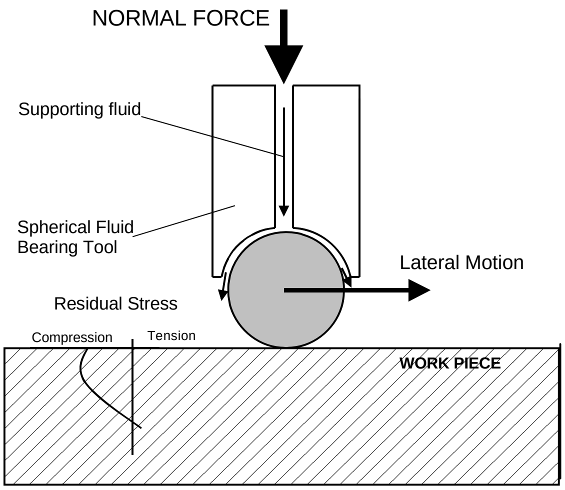

Figure 2 - Low Plasticity Burnishing (LPB) schematic.

EXPERIMENTAL TECHNIQUE

Material and Sample Fabrication

Ti-6Al-4V material was acquired as two nominally 16 x 6 x 0.8 in. forgings prepared for the PRDA V High Cycle Fatigue Initiative. Double VAR melted 2.5 in. diameter bar stock produced to AMS 4928 was forged at 1720F, solution treated at 1710F for 75 min. and air cooled. A final vacuum anneal at 1300F for 2 hr. produced a UTS of 142 ksi and yield strength of 135 ksi with a modulus of elasticity of 17.1 x 10^6 psi.

HCF specimen gage sections and the coupons used for measuring residual stress distributions and thermal relaxation were first mechanically polished and then electropolished to produce a flat surface free of residual stress and cold work prior to surface enhancement.

Surface Enhancement

Shot peening was performed in a laboratory peening facility with a rotary stage, process timer, and a single nozzle held at a fixed impingement angle at constant air pressure. All samples were exposed to the constant shot stream for the same fixed time. Initially, thermal relaxation coupons were shot peened with S110 steel shot to a 10A intensity and 200% coverage. Peening for later relaxation tests and HCF samples was performed to an Almen intensity of 8A with CW14 shot at an impingement angle of 80 deg. for 400% coverage. The peening parameters were chosen to provide a high degree of cold working and yet to be typical of shot peening practice used for turbine engine components.

The low plasticity burnishing (LPB) single point tool was designed to fit a CAT-40 tool holder in a Haas 20 HP four-axis vertical CNC mill. LPB was performed in a raster pattern with a 0.75 in. (19mm) ball at a speed of 100 in. per min. The ball material, bearing pressure, normal force and feed per pass were developed empirically to optimize the magnitude of surface compression and the depth of the compressive layer in Ti-6Al-4V.

X-ray Diffraction Characterization

X-ray diffractometers developed at Lambda Research specifically for the measurement of subsurface residual stress and cold work distributions were used in this study. The macroscopic residual stress was determined using a conventional sine-squared-psi (21.3)/Cu K_α technique **[11-13]** with correction for both penetration of the radiation into the subsurface stress gradient **[14]** and for stress relaxation caused by layer removal.**[15]**

The $K_{\alpha}1$ peak breadth was calculated from the Pearson VII function fit used for peak location during macroscopic stress measurement.**[16]** The peak breadth increases as the crystallite size is reduced and microstrain increases with cold work during surface enhancement. The method of quantifying the degree of cold working of metals, by relating the x-ray diffraction peak broadening to the equivalent true plastic strain, has been described previously.**[5, 11]** When the degree of cold work is taken to be the equivalent amount of true plastic strain, the degree of cold work is then cumulative and independent of the mode of deformation.**[5]**

The calibration data relating the (21.3) Cu $K_{\alpha}1$ peak breadth to cold work expressed as the equivalent amount of true plastic strain for Ti-6Al-4V are shown in Figure 3. The half–breadth of the $K_{\alpha}1$ line separated from the K_α doublet by fitting Pearson VII functions **[16]** was measured on the electropolished mid-plane of a series of 0.25 in. (6.3mm) diameter cylinders compressed axially to the levels of true plastic strain indicated. Five repeat measurements are shown at each strain level. A linear plus exponential function is fitted by regression.**[5]**

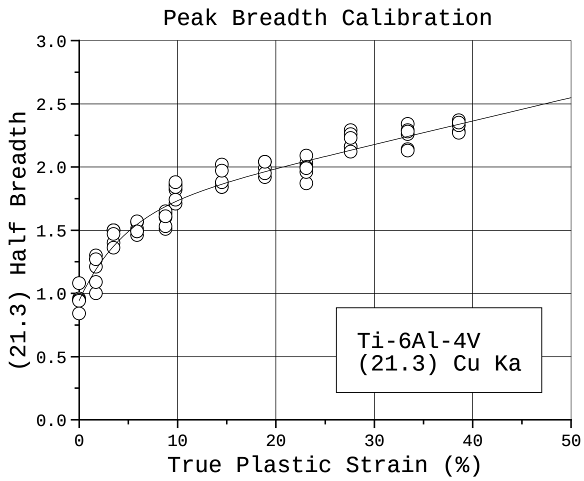

Figure 3 – Dependence of (21.3) peak breadth on "cold work" expressed as true plastic strain for Ti-6Al-4V. Samples were prepared in compression with multiple measurements shown. The $K\alpha 1$ peak breadth corresponding to 10% cold work is indicated.

Thermal relaxation

The different surface enhancement methods were applied to the previously electropolished surfaces of coupons. The coupons were then exposed to a fixed temperature for a series of times at nominally logarithmically increasing increments. Elevated temperature exposure was performed in molten salt baths held at fixed temperature for times less than 600 min. and in air in a heat treating furnace for longer exposures. The coupons were removed and 0.4 in. (1 cm) square areas were alternately measured and electropolished to determine the subsurface residual stress distribution at each time interval.

High Cycle Fatigue Testing

HCF testing was performed in four-point bending to provide maximum sensitivity to the surface condition.**[17]** Fatigue testing was conducted at room temperature on a Sonntag SF-1U fatigue machine under constant sinusoidal load amplitude at 30 Hz, R=0.1.

A bending fatigue specimen having a trapezoidal cross section was designed especially for testing surfaces in high residual compression. The test specimen provides a relatively large 0.5 in^2 (13 mm) gage surface area under uniform applied stress to reduce scatter in fatigue testing. The initial 0.375 in. (9.5 mm) gage section thickness was chosen to provide adequate material under low magnitude tension to support a deep highly compressive layer on the test surface without specimen distortion. The gage section thickness was then reduced to 0.25 in. (6.4 mm) by milling the backside to ensure failure in the compressive gage section after surface enhancement.

Foreign Object Damage (FOD) Tolerance

The damage tolerance afforded by shot peening and LPB were compared by introducing controlled FOD and observing the effect on the form of the HCF S/N curves and the endurance limit. To simulate FOD occurring after manufacture during engine operation, HCF specimens were deliberately flawed in a controlled manner after surface enhancement and elevated temperature exposure. "Dull" FOD was simulated by pressing a diamond tipped brale hardness testing indenter into the surface at the center of the uniformly stressed HCF sample gage section to a depth of 0.010 in. To simulate FOD occurring after exposure to the engine operating environment, the surface enhanced HCF samples were held at 600C for 100hr before damage was introduced.

RESULTS AND DISCUSSION

Thermal Relaxation

The rate and amount of stress relaxation for 10A, 200% shot peening and gravity peening processes which differ primarily in the amount of cold work developed, are shown in Figures 4 through 7 for exposures to 615F (325C) and 795F (425C), respectively. The surface residual stress produced by shot peening has been shown to relax rapidly initially **[19]** and then predictably with time and temperature**[18]**. Cold work associated with several surface enhancement methods including shot peening has been correlated with both the speed and magnitude of thermal relaxation of surface compression.**[8]** Surface compression in a highly cold worked surface can relax to less than 50% of the initial value in only minutes at even moderate engine operating temperatures.**[8]**

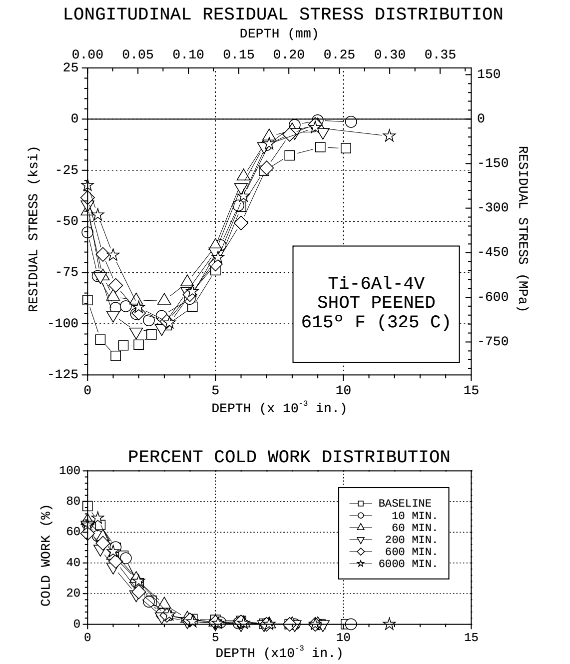

Figure 4 – Thermal relaxation of shot peened (10A, 200%) Ti-6Al-4V for various exposure times at 615F (325C).

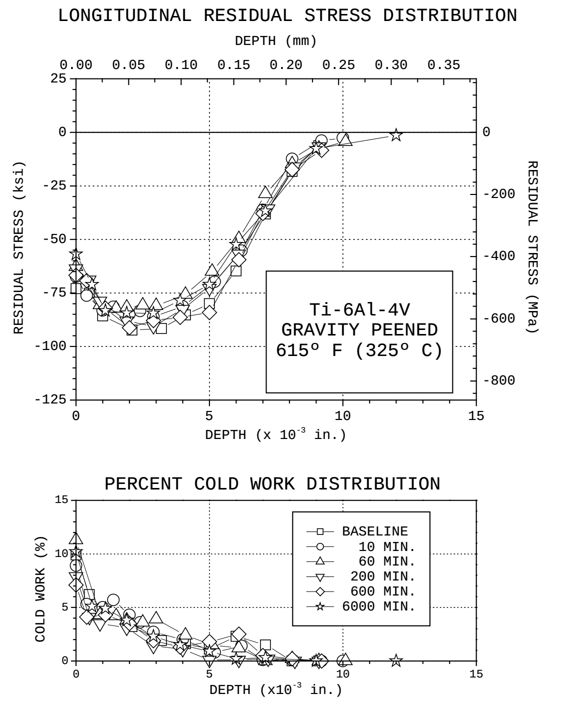

Figure 6 - Thermal relaxation of gravity peened Ti-6Al-4V for various exposure times at 615F (325C).

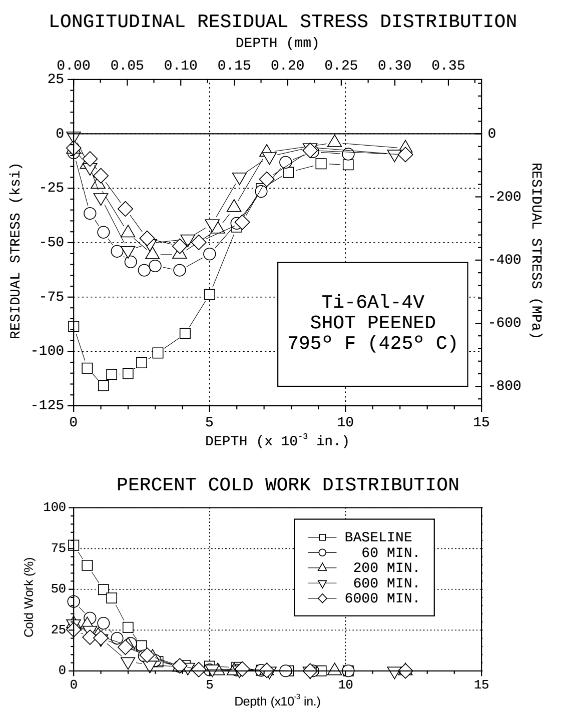

Figure 5 - Thermal relaxation of shot peened (10A, 200%) Ti-6Al-4V for various exposure times at 795F (425C).

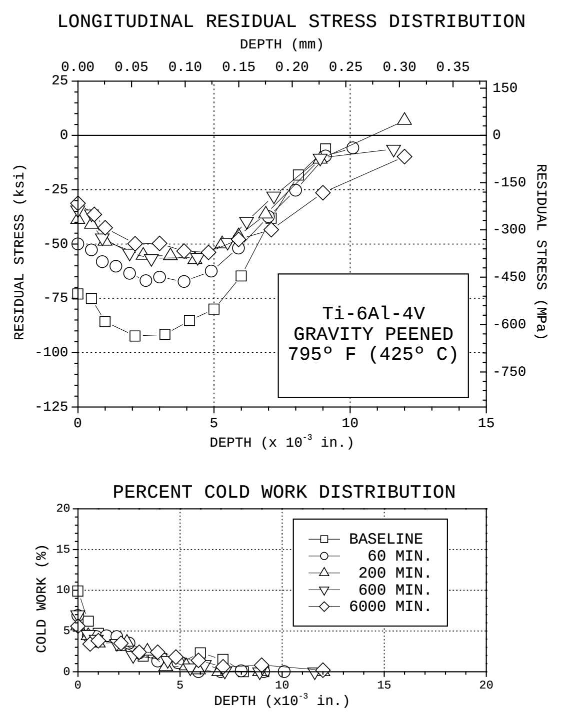

Figure 7 - Thermal relaxation of gravity peened Ti-6Al-4V for various exposure times at 795F (425C).

The fraction of compression remaining after thermal exposure to temperatures from 615F (325C) to 887F (475C) for times ranging from 10 to 200 minutes is plotted for shot peened Ti-6Al-4V in Figure 8. The loss of compressive residual stress is highly dependent upon the amount of cold work. The higher dislocation density associated with cold working appears to play a role, but the exact mechanism for the rapid initial relaxation of highly cold worked surfaces has not been identified. Surface compression created with minimal cold work is more stable at high temperatures. For exposures to 615F (325C), the data in Figure 8 indicate a threshold level of cold work may exist, below which thermal relaxation is minimal. A similar cold work threshold has been observed for IN718. **[19]**

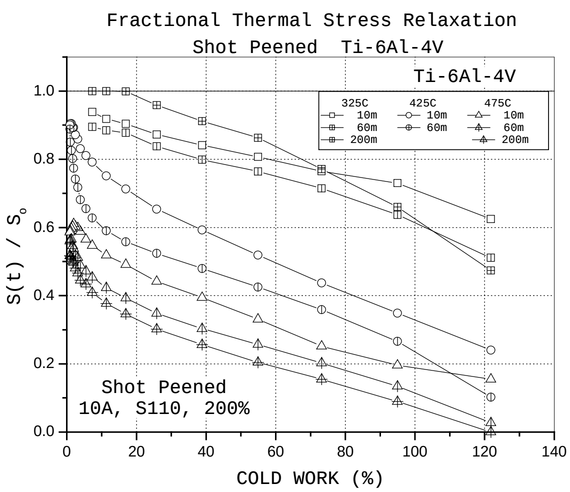

Figure 8 - Fraction of residual stress retained after exposures to temperatures from 615F to 887F for times ranging from 10 to 200 minutes for shot peened (10A, 200%) Ti-6Al-4V.

Thermal relaxation of shot peened (8A intensity, 400% coverage) and LPB processed Ti-6Al-4V after exposure to 795F (425C) for 10h is shown in Figure 9. The complete relaxation of the highly cold worked shot peened surface is evident. Relaxation at the surface of the lightly cold worked LPB sample is much less, and the subsurface maximum compressive level is simply reduced to the alloy yield strength at the exposure temperature.

Overload Relaxation

Overload or mechanical relaxation can result in the loss of compression or even inversion of the residual stress field into tension.**[18]** The cold work distribution developed during surface enhancement results in a corresponding yield strength distribution varying with depth through the deformed layers. High cold work at the surface will produce a significant increase in yield strength compared to the undeformed interior in work hardening alloys.

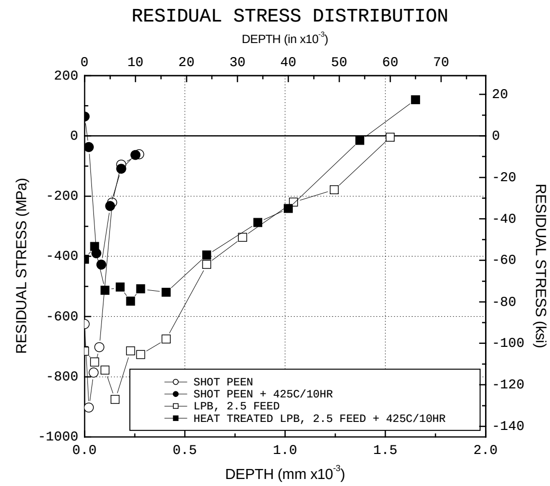

Figure 9 – Thermal relaxation of shot peened (8A, 400%) Ti-4Al-4V and LPB Ti-6Al-4V after 795F (425C) for 10 hr.

The subsurface residual stress, cold work and corresponding yield strength distributions produced by shot peening and LPB of Ti-6Al-4V are shown in Figure 10. The effect of a single cycle of 2% plastic deformation on the residual stress distributions is modeled by finite element analysis including the yield strength gradient measured by x-ray diffraction. Although the compression is lost in the LPB surface, the high yield strength gradient in the shot peened surface causes an inversion of the initially –80 ksi compressive surface to +90 ksi tension in a single deformation cycle.

The FEA model of overload relaxation in Ti-6Al-4V has not yet been confirmed by experiment. However, the same inversion has been both accurately predicted by including the yield strength gradient in a finite element model and measured for IN718.**[20]** Overload relaxation and inversion of compressive shot peened surfaces into tension has been observed at Lambda Research in a variety of actual components experiencing plastic deformation including disk bores, helicopter rotor components, dovetail slots and high pressure pump housings. Single high stress events such as FOD impact can create a local area of lowered compression or even tension that will degrade HCF performance.

Surface enhancement processes that produce minimal cold working to develop the compressive layer will be less prone to loss of compression or inversion to tension by subsequent deformation.

<u>High Cycle Fatigue Performance</u>

The high cycle fatigue results presented in Figure 11 show a 38% increase in the HCF endurance limit for LPB (>90ksi) compared to shot peening (~65 ksi) after exposure to 795F (425C) for 10 hrs. The endurance limit increase after surface enhancement is generally associated with surface compression delaying the initiation of fatigue cracks. The reduced HCF strength of the highly cold worked shot peened surface is attributed to the complete loss of surface compression after even a brief elevated temperature exposure.

Fatigue strength in the finite life regime between 10^5 and 10^6 cycles is considered to be determined by the rate of crack growth through the layer of subsurface compression left by surface enhancement. The much deeper compressive layer produced by LPB provides over an order of magnitude increase in fatigue life compared to the current shot peening practice, at any stress level tested.

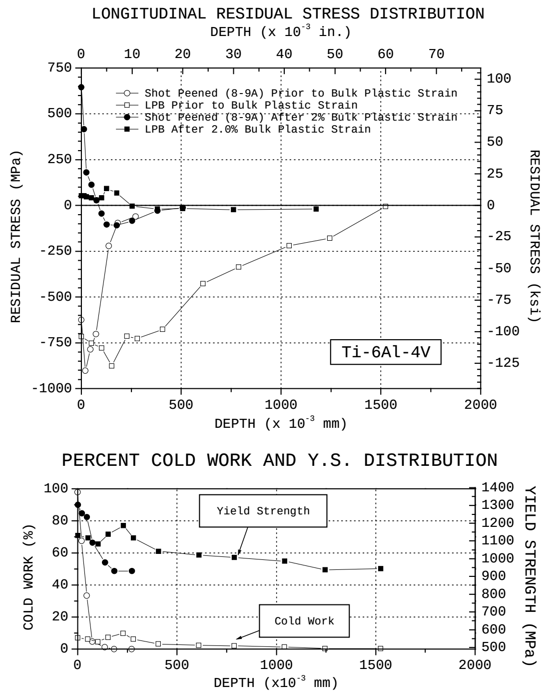

Figure 10 – Finite element model comparing overload relaxation and inversion of compression in LPB and shot peened Ti-6Al-4V.

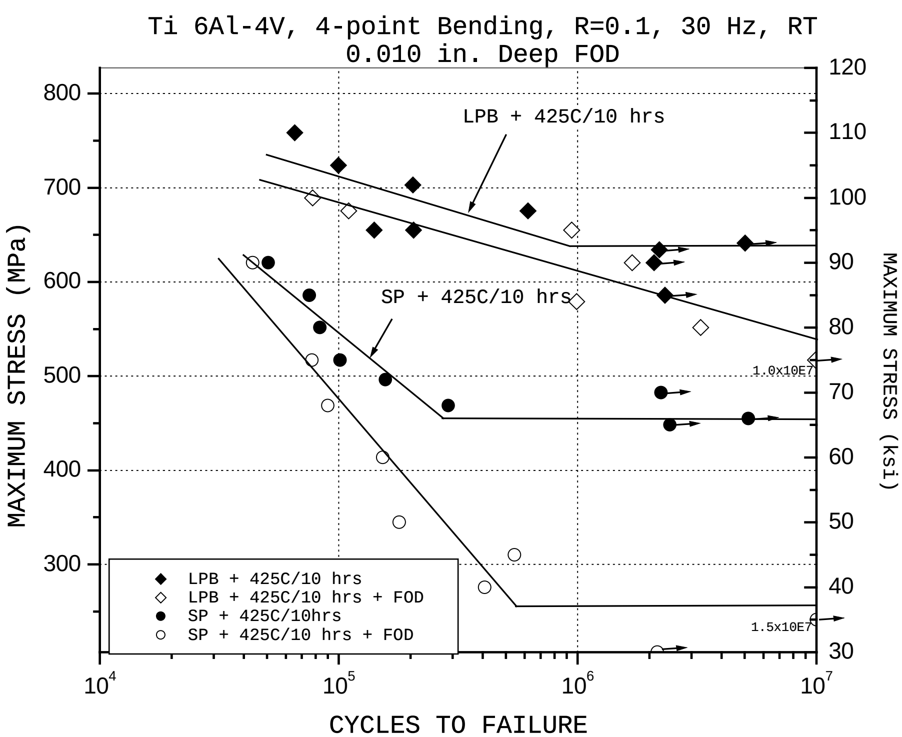

Figure 11 - High cycle fatigue performance and tolerance to 0.010 in. deep damage for shot peened and LPB processed Ti-6Al-4V after exposures to 795F (425C) for 10 hours.

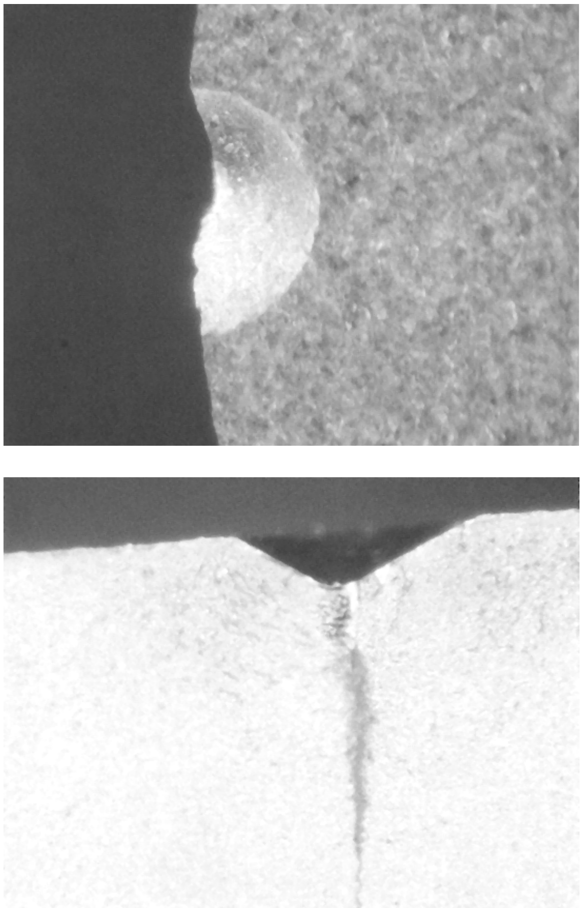

Figure 12 – Fatigue initiation site in shot peened Ti-6Al-4V heat treated at 425C (797F) for 10 hours with 0.010 in. FOD.

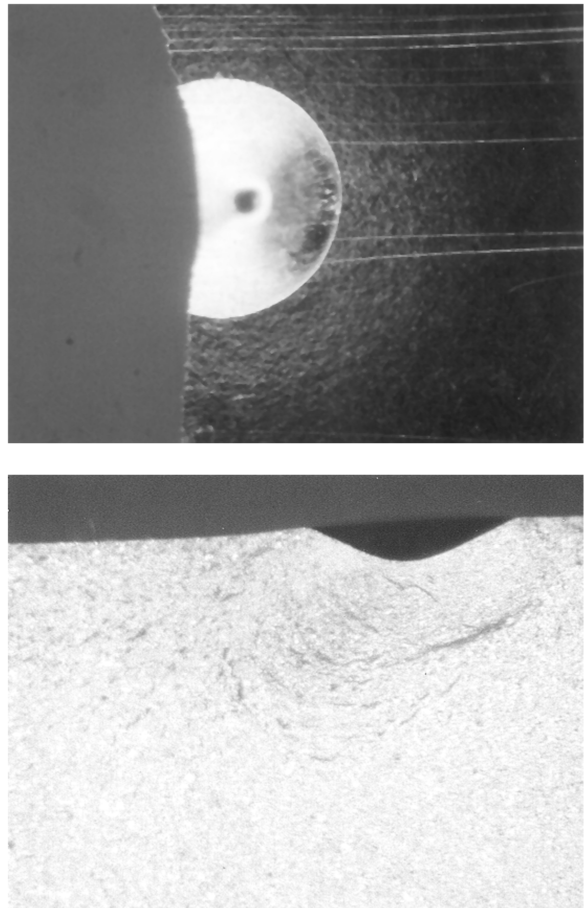

Figure 13 – Fatigue initiation site in LPB processed Ti-6Al-4V heat treated at 425C (797F) for 10 hours with 0.010 in. FOD.

Damage Tolerance

The damage tolerance of Ti-6Al-4V after conventional shot peening and LPB are compared in Figure 11. FOD in the form of a single 0.010 in. deep indentation reduces the HCF endurance limit of the shot peened surface over 40%, from nominally 65 ksi to less than 40 ksi. In contrast, the endurance limit for the LPB surface is only nominally 15% lower after FOD. The deep compressive layer produced by LPB is far more effective in retarding crack growth, even after thermal exposure, because of the minimal stress relaxation and the greater depth of the compressive layer.

The failure mode out of the FOD zone was found to be consistently different for the shot peened and LPB surfaces. Figures 12 and 13 show views of the top and fracture faces of FOD crack initiation sites in shot peened and LPB HCF samples, respectively. Failures in the shot peened samples consistently originated from the bottom of the conical FOD depression, as shown in the bottom of Figure 12. All of the failures from the LPB samples originated from the mounded material forced up from the surface on either side of the FOD depression, and not from the bottom of the depression. The surface curvature after FOD deformation supports the conclusion that the initiation sites are in areas of local residual tension. The stress intensity is highest at the vertex of the depression, and failures were expected to originate there for either surface treatment. However, the high compression at the depth of the FOD vertex in the LPB samples appears to force the fatigue origin to the regions of surface tension assumed present in the mounded material at the edges of the FOD depression.

The fatigue data presented in Figure 11 support an observation of potential importance to the effort to improve the HCF life of turbine engines: All of the specimens treated by LPB have fatigue strengths and lives **after** FOD that are significantly superior to that of shot peened surfaces **before** FOD. The use of surface enhancement methods that produce deep thermally stable compression to substantially improve the HCF performance and damage tolerance of Ti-6Al-4V has been demonstrated.

CONCLUSIONS

The compressive layer induced by shot peening to improve fatigue life of Ti-6Al-4V has been found to relax extremely rapidly at turbine engine operating temperatures. Subsurface thermal relaxation data show a strong dependence of the amount of relaxation on the degree of cold working induced during creation of the compressive layer. Surface compression was completely lost after elevated temperature exposure in the highly deformed 8A intensity, 400% coverage, shot peened material. Surface enhancement methods such as laser shock peening (LSP) and low plasticity burnishing (LPB), which produce minimal cold work, offer the greatest resistance to thermal relaxation at elevated temperatures.

Cold work developed during surface enhancement increases the yield strength of the deformed layer. The compressive surface is then susceptible to mechanical relaxation or even inversion into high tension if plastically deformed in service, even locally at FOD sites. Surface enhancement methods that generate minimal cold work reduce the detrimental effects of overload relaxation and should be considered for components subject to even single event momentary plastic deformation.

LPB provides 38% greater HCF strength than conventional shot peening after even brief exposure to engine temperatures because the compressive layer produced by LPB is both deeper and more stable at elevated temperatures. The deep compressive layer produced by LPB provides more than twice the HCF fatigue strength than that from shot peening after 0.010 in. deep FOD. LPB surfaces **with** FOD are stronger in high cycle fatigue than shot peened samples **without** FOD.

The importance of minimizing cold work during surface enhancement of Ti-6Al-4V for elevated temperature applications has been demonstrated, and should be considered for any fatigue critical turbine engine components operated at even moderate temperatures. Surface enhancement methods which provide deep, stable compression at elevated temperatures offer substantially improved high cycle fatigue life and damage tolerance.

ACKNOWLEDGMENTS

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