2000008

The Effect of Cold Work on the Thermal Stability of Residual Compression in Surface Enhanced IN718

Paul S. Prevéy
Lambda Research, Cincinnati, OH

ABSTRACT

Surface enhancement, the creation of a layer of residual compression at the surface of a component, is widely used to improve the fatigue life in the automotive and aerospace industries. The compressive layer delays fatigue crack initiation and retards small crack propagation. The benefits of surface enhancement are lost if the compressive layer relaxes at the operating temperature of the component. Surface enhancement methods producing minimal cold work are shown to produce the most thermally stable compression.

The residual stress and cold work distributions developed in IN718 by shot peening, gravity peening, laser shock peening (LSP) and low plasticity burnishing (LPB) are compared. Estimation of cold work (equivalent true plastic strain) from x-ray diffraction line broadening is described. Thermal relaxation at temperatures ranging from 525C to 670C is correlated to the degree of cold working of the surface, independent of the method of surface enhancement. Highly cold worked (> 15%) shot peened surfaces are found to relax to half the initial level of compression in minutes at all temperatures investigated. The rapid initial relaxation is shown to be virtually independent of either time or temperature from 525C to 670C. The LPB process is described with application to IN718. High cycle fatigue performance after elevated temperature exposure is compared for surfaces treated by LPB and conventional (8A intensity) shot peening.

INTRODUCTION

The performance, life and cost of operating turbine engines are all dominated by the risk of high cycle fatigue (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 resists both crack initiation and small crack propagation, and 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 only be realized if the compressive residual stresses can be used to offset applied stresses in turbine 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 the three mechanisms for residual stress relaxation: thermal, overload, and cyclic, only thermal relaxation is significant for nickel base superalloys in typical hot section turbine applications.

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 nickel base superalloy, IN718. Initial thermal relaxation studies revealed the importance of cold work in thermal relaxation. Low plasticity burnishing (LPB), developed to improve retention of compression at elevated temperature by minimizing cold work, is compared to conventional shot peening in terms of both residual stress stability at turbine engine temperatures and HCF performance.

Proceedings: 20th ASM Materials Solutions Conference & Exposition
St. Louis, Missouri, October 10-12, 2000

Surface Enhancement Methods

All mechanical surface enhancement (SE) methods develop a layer of compressive residual stress following mechanical tensile deformation of the surface. The methods differ in how the surface is deformed, and the magnitude and form of the resulting residual stress and cold work (plastic deformation) distributions. The residual stress and cold work distributions developed by conventional shot peening (8A intensity, 200%), gravity peening, laser shock peening (LSP), and low plasticity burnishing (LPB) in IN718 are compared in Figure 1. The magnitude of compression at the surface is comparable, but the depth of the compressive layers differ by nearly an order of magnitude. The degree of cold working ranges from 40% for shot peening to a few percent for LPB.

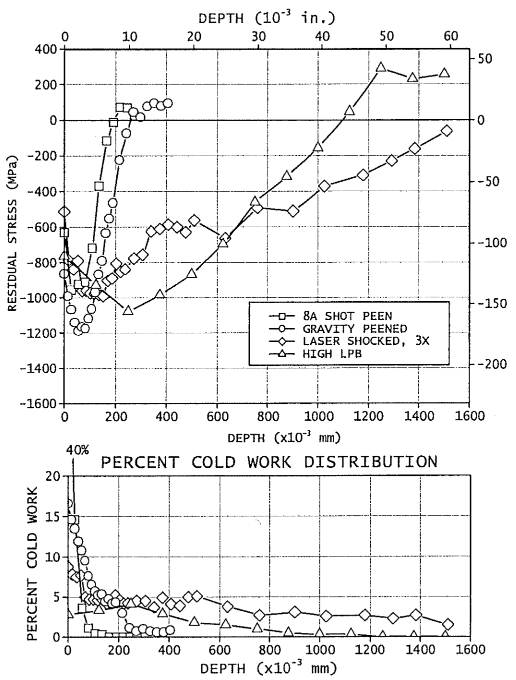

Figure 1 - Subsurface residual stress and cold work distributions produced by shot peeing (8A, 200%), gravity peening, LSP (3X), and LPB in IN718.

Shot peening is routinely applied to many automotive and aerospace components and alloys. 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 and a highly cold worked surface layer.**[3]** The depth of the compressive layer and the degree of cold working depend upon the peening parameters: shot size, velocity, coverage, and impingement angle. Compressive residual stress distributions reach a maximum approaching the alloy yield strength, and extend to a depth of 0.05 to 0.5 mm (0.002 to 0.020 in.).

Conventional shot peening produces from 10% to 50% cold work.**[4]** Cold work is accumulative, 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. Surface compression may decrease during shot peening of work hardening materials as the yield strength of the surface increases with continued cold working.

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.

In conventional roller and ball burnishing, a hard cylindrical roller or fixed lubricated ball is pressed into the surface of an axisymmetric work piece with sufficient force to deform the near surface layers. Burnishing is performed with multiple passes, usually under increasing load, for improved surface finish and to deliberately cold work the surface. Fatigue enhancement is attributed to improved finish, the development of a compressive surface layer, and the increased yield strength of the cold worked surface.**[5-24]**

"Deep rolling" employs a hydrostatically supported burnishing ball similar to LPB, but is applied at higher loads. The processes differ in the method of use and the level of cold work generated, as well as the design of tooling and hydraulic controls. X-ray diffraction line broadening and micro-hardness distributions generated by deep rolling reveal cold work even greater than shot peening.**[25-27]** For low temperature applications, the increased yield strength may further improve fatigue life. In contrast, LPB produces cold working an order of magnitude lower.

Laser shock peening (LSP) **[28]** has been successfully applied for surface enhancement of a variety of alloys including titanium, nickel superalloys, and steels.**[29]** LSP produces a layer of compression of comparable magnitude to shot peening, but much deeper with less cold work. Single shock LSP can produce high compression with less than 1% cold work. Excellent thermal stability has been demonstrated in IN718.**[30]**. However, multiple laser shock cycles are required to produce compression to depths of 1mm, increasing the cold work to 5-7%.**[31]**

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.**[32]** 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 of 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 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.

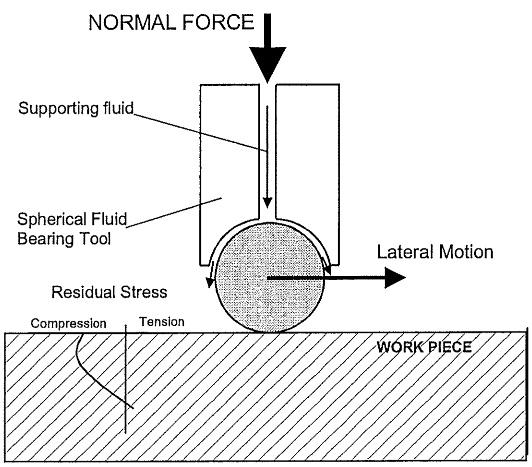

Figure 2 - Low Plasticity Burnishing (LPB) schematic.

EXPERIMENTAL TECHNIQUE

Material and Sample Fabrication

IN718 was acquired as 38 x 9.5mm (1.5 x 0.375 in.) bar stock in the mill annealed condition certified to AMS 5662J and AMS 5596G. The material was solution treated at 1800F and aged at 1350F/8h + 1125F/8h producing a hardness of 43 ± 2 HRC. The aged material had a tensile strength of 1,364 MPa (198 ksi), and a 0.2% yield strength of 1,109 MPa (161 ksi) with 23% elongation.

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. Initial thermal relaxation coupons were shot peened with S110 steel shot to a 10A intensity and 200% coverage. Peening was performed to an Almen intensity of 8A with CW14 shot at an impingement angle of 80 deg. for 400% coverage for later relaxation tests and HCF sample preparation. The peening parameters were chosen to be typical of shot peening practice used for superalloys in turbine engines.

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 19mm (0.75 in.) 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 IN718.

X-ray Diffraction Characterization

Apparatus developed at Lambda Research for fully automated measurement of subsurface residual stress and cold work distributions **[41]** was used in this study. The macroscopic residual stress was determined using a conventional sine-squared-psi (220)/Cr Kα technique **[33-35]** with correction for both penetration of the radiation into the subsurface stress gradient **[36]** and for stress relaxation caused by layer removal.**[37]**

The Kα1 peak breadth was calculated from the Pearson VII function fit used for peak location during macroscopic stress measurement.**[38]** 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.**[4, 33]** If the degree of cold work is taken to be the equivalent amount of true plastic strain, the degree of cold work is then accumulative and independent of the mode of deformation.**[4]**

The calibration data developed in this study for IN718 relating the (220) Cr $K\alpha 1$ peak breadth to cold work expressed as the equivalent amount of true plastic strain are shown in Figure 3. The half–breadth of the $K\alpha 1$ line separated form the $K\alpha$ doublet by fitting Pearson VII functions **[38]** was measured on the electropolished mid-plane of a series of 6.3mm (0.25 in.) 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.**[4]**

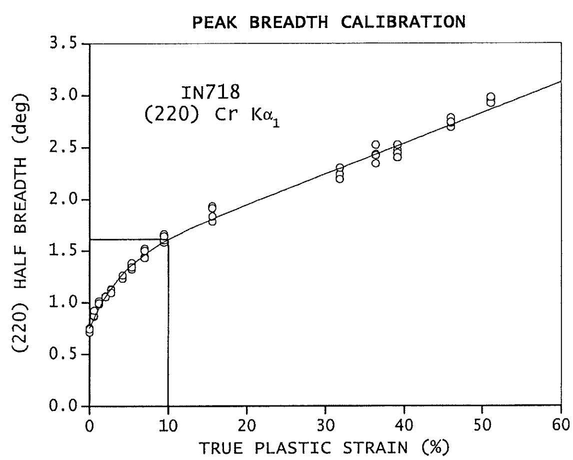

Figure 3 – Dependence of (220) peak breadth on "cold work" expressed as true plastic strain. Samples were prepared in compression with multiple measurements shown. The $K\alpha 1$ peak breadth corresponding to 10% cold work is indicated.

Thermal relaxation

Surface enhancement was applied to the previously electropolished surface of coupons, which 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 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.**[39]** 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 the highly compressive surface produced by surface enhancement methods. The test specimen provides a nominally 12.5mm (0.5 in.) wide by 25.4mm (1.0 in.) long gage surface under uniform applied stress to minimize scatter in fatigue testing. The original gage section thickness of nominally 9.5mm (0.375 in.) was chosen to provide adequate material under low magnitude tension to support a deep highly compressive layer on the test surface. The gage section thickness was then reduced to 6.3mm (0.25 in.) by milling the backside to insure failure in the compressive gage section.

Foreign Object Damage (FOD) Resistance

The influence of both dull and sharp notch FOD on the fatigue life of shot peened and LPB processed IN718 surfaces was tested using HCF specimens that were deliberately flawed in a controlled manner after surface enhancement. Sharp notch FOD was created using a 60 deg. thread cutting tool held in a fly cutter of a vertical milling machine. The tool was then indented to a depth of 0.25 mm (0.010 in.), machining a gouge of varying depth across the width in the center of the gage section. Dull FOD was simulated by pressing a diamond pointed brale hardness testing indenter into the surface to a depth of 0.25 mm (0.010 in.). To simulate FOD occurring during engine operation, the HCF samples were first given LPB or shot peening, and then exposed to 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 525C and 600C, respectively. The surface residual stress produced by shot peening has

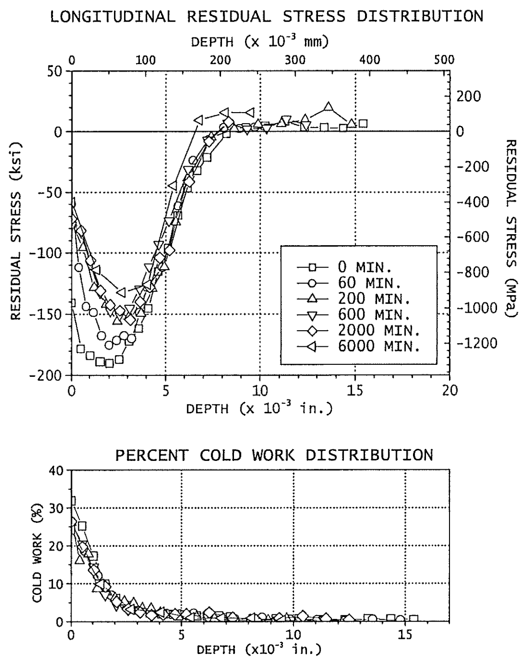

Figure 4 - Effect of exposure time at 525C on residual stress distributions in shot peened (10A, 200%) IN718.

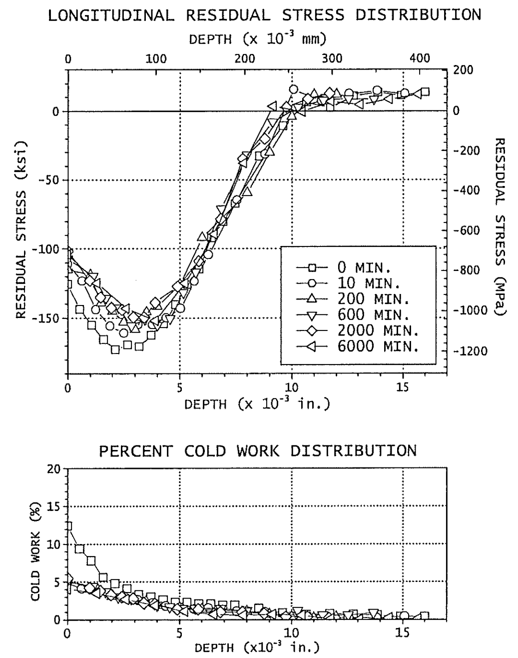

Figure 5 - Effect of exposure time on residual stress distributions in gravity peened IN718 at 525C.

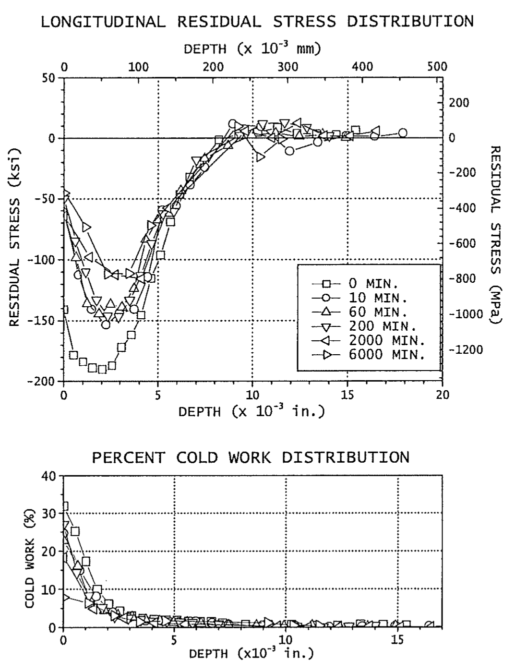

Figure 6 - Effect of exposure time on residual stress distributions in shot peened (10A, 200%) IN718 at 600C.

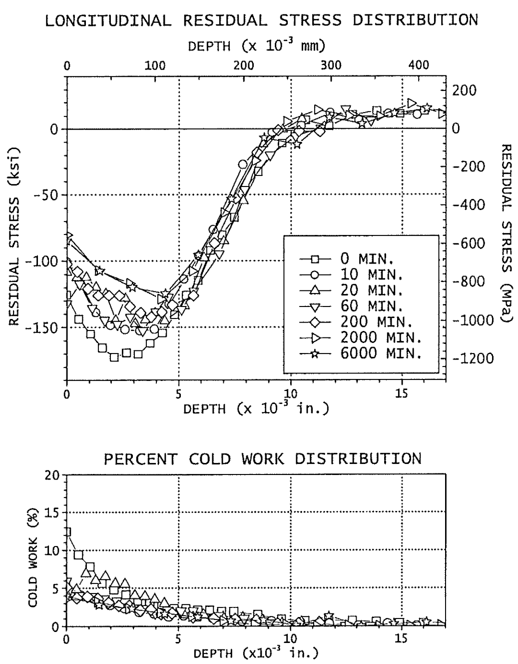

Figure 7 - Effect of exposure time on residual stress distributions in gravity peened IN718 at 600C.

been shown to relax rapidly initially and then predictably with time and temperature.**[40]** 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.**[30]** Surface compression in a highly cold worked surface can relax to less than 50% of the initial value in only minutes at even low engine operating temperatures.**[30]**

The fraction of compression remaining after thermal exposure to temperatures from 525C to 670C for times ranging from 10 to 2000 minutes is plotted for shot peened IN718 in Figure 8. The relaxation of a variety of different surface enhancement methods after just 10 min. at 670C is plotted vs. cold work in Figure 9. The compression remaining after thermal exposure for any of the shot peening methods is nearly independent of the temperature for the range examined and only slightly dependent upon the time of exposure. The loss of compressive residual stress depends primarily 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 between 525C and 600C, the data in Figures 8 and 9 seems to imply a threshold level of cold work, on the order of 3%, below which thermal relaxation is minimal for IN718.

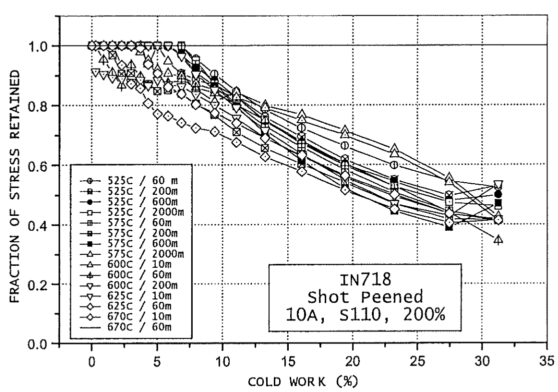

Figure 8 - Fraction of residual stress retained after exposures to temperatures from 525C to 670C for times ranging from 10 to 2000 minutes for shot peened (10A, 200%) IN718.

The subsurface residual stress and cold work distributions produced by 8A, 400% shot peening and LPB before and after exposure to 525C (977F) and 600C (1112F) for 100h are shown in Figures 10 and 11. The nearly complete relaxation of the highly cold worked shot peened surface at either temperature is evident. Below the cold worked surface the compression is largely retained. Virtually no relaxation occurs at the surface of the lightly worked LPB samples, and the subsurface maximum compressive level is reduced to the alloy yield strength at the exposure temperature.

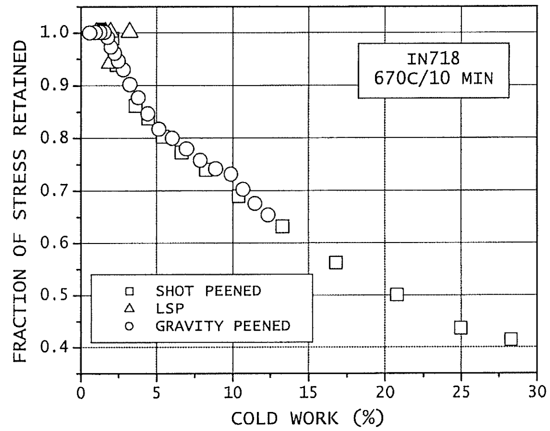

Figure 9 - Correlation of cold work and fraction of stress retained in shot peened, laser shock peened and gravity peened IN718 after 10 minutes at 670C.

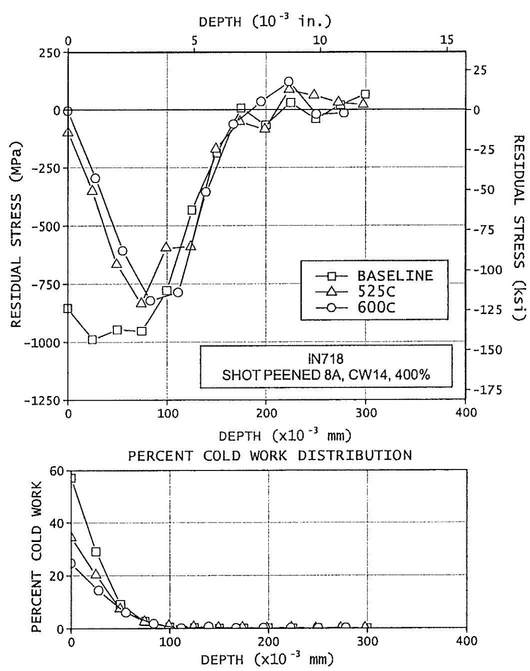

Figure 10 - Relaxation of residual stresses in IN718 shot peened to10A, 400% coverage with CW14 shot.

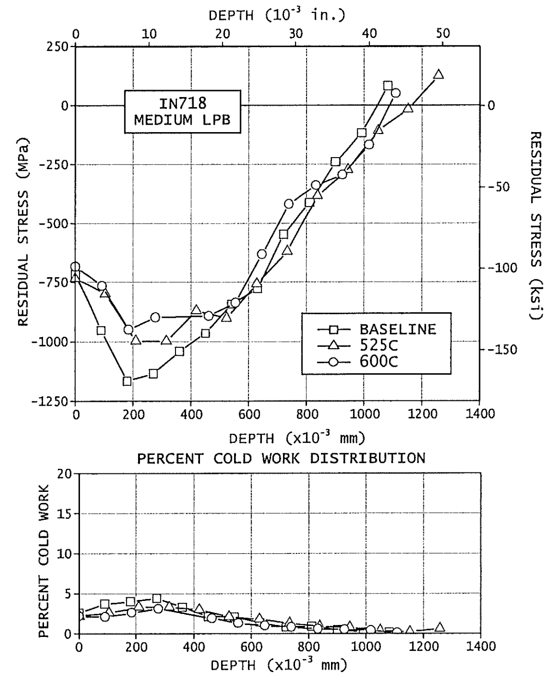

Figure 11 - Relaxation of residual stresses at 525C and 600C for LPB IN718.

High Cycle Fatigue Results

The high cycle fatigue results presented in Figure 12 show a substantial increase in the HCF endurance limit, or fatigue strength at 2 x 10^6 cycles for LPB over shot peening for either the 525C or 600C exposure for 100 hrs. The similar fatigue performance for shot peening followed by either 525C or 600C exposure is attributed to the near uniform relaxation of the surface compression seen in Figure 10 after exposure to either temperature. The endurance limit is typically associated with surface compression governing the initiation of fatigue cracks while fatigue strength in the finite life regime is dominated by crack growth through the compressive layer left by surface enhancement.

FOD Resistance

The difference in the ability of the two surface enhancement methods to resist foreign object damage (FOD) either in the form of a single indentation or a sharp notch is shown in Figure 13. The endurance limit or fatigue strength at 2 x 10^6 cycles is reduced from nominally 700 to 300 MPa by either form of damage. 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. Although considerable scatter is evident, which is attributed to variability in the FOD damage, all of the specimens treated by LPB have fatigue strengths and lives superior to that of shot peening even without FOD.

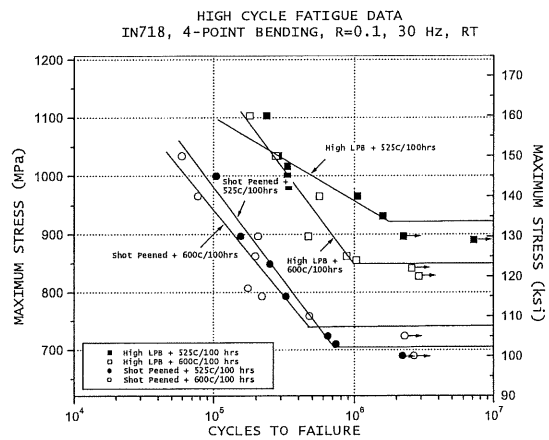

Figure 12 - High cycle fatigue performance of shot peened (8A, 400%) IN718 and LPB after 100 hr. exposures at 525 and 600C.

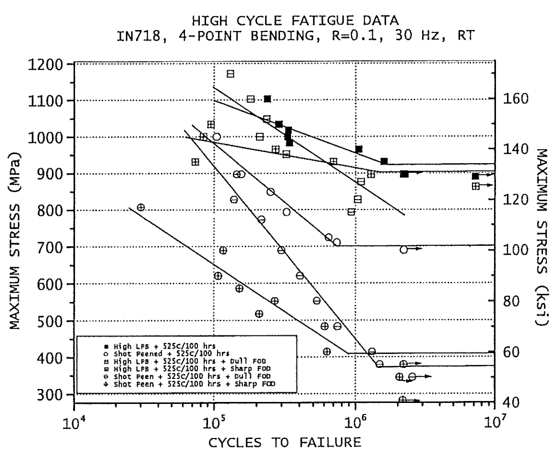

Figure 13 - High cycle fatigue resistance to foreign object damage (FOD) of either sharp or dull form (see text) for fatigue specimens previously shot peened (8A, 400%) or low plasticity burnished (LPB) prior to elevated temperature exposure simulating engine environments.

CONCLUSIONS

The compressive layer induced by shot peening to improve fatigue life of IN718 has been found to relax extremely rapidly at moderate turbine engine temperatures.

Comparison of thermal relaxation for a variety of surface enhancement methods reveals a strong dependence of the amount of relaxation on the degree of cold working induced during creation of the compressive layer. Rapid short term relaxation is found for IN718 to be nearly independent of temperature or time and primarily a function of cold work above a few percent. 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.

After exposure to simulated engine environments at 525C and 600C for 100 hrs., LPB substantially improves high cycle fatigue (HCF) performance, which is attributed to retention of the surface compressive stress. Surface compression was completely lost after elevated temperature exposure in the highly deformed 8A, 400% shot peened material. The deep compressive layer produced by LPB is also found to provide superior resistance to 0.25 mm (0.010 in.) deep FOD, either formed as a sharp notch or rounded indentation.

The importance of minimizing cold work during surface enhancement for elevated temperature applications of super alloys is clearly demonstrated, and should be considered for any fatigue critical hot stage rotating turbine components. Surface enhancement methods which offer retention of compression at operating temperatures offer substantial fatigue life improvement.

ACKNOWLEDGMENTS

This work was supported in part by funding provided under DoD SBIR F33615-96-C-2667 and NASA SBIR's NAS3-98034 and NAS3-99116. The technical support and encouragement of Dr. Christopher Lykins of WPAFB and Dr. Timothy Gabb and Dr. Jack Telesman of NASA, Glenn Research Center are greatly appreciated. Engineering support for residual stress measurement, finite element modeling and fatigue testing were provided by Douglas Hornbach and Perry Mason and the staff of Lambda Research.

REFERENCES

[1] R., L. Mattson, and J.G. Roberts, "The Effect of Residual Stresses Induced by Strain Peening upon Fatigue Strength," Internal Stresses and Fatigue in Metals, G.M. Rassweiler and W.L. Grube ed., New York, NY: Elsevier Pub. Co., (1959), pp. 348-349.

[2] W.P. Koster, et al. (1970), AFML Report AFML-TR-70-11, AFML, WPAFB.

[3] D. Lombardo and P. Bailey, "The Reality of Shot Peen Coverage," The Sixth International Conference on Shot Peening, J. Champaign ed., CA, (1996), pp. 493-504.

[4] P. Prevey, (1987), Residual Stress in Design, Process & Material Selection, ASM, Metals Park, OH, 11-19.

[5] W. Walters, (1980), Cutting Tool Engineering, **32**, No. 5-6, pp. 15-16.

[6] Westerman, (1981), Proc. Deburring and Surface Conditioning 81, SME, Dearborn, MI, Report #MR81-401.

[7] G.R. Keessen, (1975), Cutting Tool Engineering, **27**, No. 5-6, pp. 12-13.

[8] Cassatt, Tenclay, (1982), Proc. 1982 Joint Conference Experimental Mechanics, Part 1-2, pp. 1138-1145.

[9] P.A. Chepa, V.A. Andrayshin, (1973), Russian Eng. J., **53**, No. 2, pp. 34-35.

[10] T. Nakamura, et al., (1993), JSME International Journal, **36**, No. 4, pp. 348-353.

[11] V.A. Pyshkin, et al., (1986), Chemical and Petroleum Engineering, **22**, No. 5-6, pp. 227-231.

[12] A.I. Lebedko, (1982), Met. Sci. Heat Treat., **24**, No. 3-4, pp. 295-297.

[13] V.V. Belozerov, et al., (1986), Met. Sci. Heat Treat., **28**, No. 7-8, pp. 565-569.

[14] V.T. Stepurenko, et al., (1976), Protection of Metals, **12**, No. 4, pp. 386-389.

[15] D.D. Papshev, Yu G. Golubev, (1972), Russian Engineering Journal, **52**, No. 4, pp. 48-51.

[16] M. K. Freid, et al., (1994), Protection of Metals, **20**, No. 2, pp. 263-265.

[17] L.M. Belkin, et al, (1984), Soviet Engineering Research, **4**, No. 9, pp. 30-32.

[18] L.M. Belkin, (1983), Soviet Materials Science, **19**, No. 3, pp. 225-228.

[19] M. Fattouh, et al., (1988), Wear, **127**, pp. 123-137.

[20] N.H. Loh, et al., (1989), Wear **129**, No. 2, pp. 235-243.

[21] N.H. Loh, et al., (1993), Precision Engineering, **15**, No. 2, pp. 100-105.

[22] B. Kotiveerachari, R.L. Murty, (1985), International Journal of Production Research, **23**, No. 3, pp. 499-521.

[23] D.A. Hills, et al., (1979), Proc. Int'l Conference on Wear of Materials, ASME, New York, NY, pp. 396-402.

[24] S. Braham, J. Frelat, (1993),Proc. Computer Methods and Exp. Meas. for Surface Treatment Effects, Computational Mechanics Publications, Southampton, U.K., pp. 255-264.

[25] W. Zinn and B. Scholtes, "Mechanical Surface Treatments of Lightweight Materials - Effects on Fatigue Strength and Near-Surface Microstructures," Journal of Materials Engineering and Performance, Volume 8(2), April 1999, pp. 145-151.

[26] I. Altenberger, et.al., "Cyclic Deformation and Near Surface Microstructures of Shot Peened or Deep Rolled Austenitic Stainless Steel AISI 304," Materials Science and Engineering, A264, 1999, pp. 1-16.

[27] A. Drechsler, et.al., "Mechanical Surface Treatments of Ti-10V-2Fe-3Al for Improved Fatigue Resistance", Materials Science and Engineering, A243, 1998, pp.

217-220.
[28] P. Foget, et al. (1990), Materials and Manufacturing Processes, **5**, No. 4, 501-528.
[29] A.H. Clauer, "Laser Shock Peening for Fatigue Resistance," Surface Performance of Titanium, J. K. Gregory et.al. eds., TMS, Warrendale, PA, (1996), pp. 217-230.
[30] P. Prevey, et al., (1997), Proc. ASM/TMS Materials Week, Indianapolis, IN, Sept 15-18, 1997, pp. 3-12.
[31] P.R. Smith, M.J. Shepard et.al., "Effect of Laser Shock Processing (LSP) Power Density and Shot Repetition on Residual Stress Distributions and % Cold Work in Ti-6Al-4V," Proceedings of the 5th Nat. Turbine Eng. HCF Conference, Chandler, AZ, 2000.
[32] U.S. Patent 5,826,453 (Oct. 1998), other patents pending.
[33] P.S. Prevey, (1986), Metals Handbook, Vol 10, ASM, Metals Park, OH, 380-392.
[34] M.E. Hilley, ed. (1971) Residual Stress Measurement by XRD, SAE J784a, SAE, Warrendale, PA.
[35] Noyan & Cohen (1987) Residual Stress Measurement by Diffraction & Interpretation, Springer-Verlag, NY.
[36] D.P. Koistinen and R.E. Marburger, Transactions of the ASM, Vol. 67, 1964.
[37] M.G. Moore and W.P. Evans, "Mathematical Correction for Stress in Removed Layers in X-Ray Diffraction Residual Stress Analysis,"SAE Transactions, Vol. 66, 1958, pp. 340-345.
[38] P.S. Prevéy, "The Use of Pearson VII Distribution Functions in X-Ray Diffraction Residual Stress Measurement," Advances in X-Ray Analysis, Vol. 29, 1986, pp. 103-111.
[39] P.Prevey, W.P. Koster, (1972) "Effect of Surface Integrity on Fatigue of Standard Alloys at Elevated Temperatures," Fatigue at Elevated Temperatures, ASTM STP520, ASTM, Phil., PA., pp. 522-531.
[40] B. Eigenmann, V. Schulze, and O. Vöhringer, (1994), Proceeding ICRS IV, pp. 598-607.
[41] U.S. Patent 5,737,385 (Apr. 1998).