FOD RESISTANCE AND FATIGUE CRACK ARREST IN LOW PLASTICITY BURNISHED IN718

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ABSTRACT

Surface enhancement methods induce a layer of residual compressive stress to improve fatigue life. Shot peening is inexpensive and widely used, but the associated cold work accelerates relaxation of the compressive layer at turbine temperatures and increases sensitivity to overload relaxation. "Deep rolling" burnishing methods produce deep compression, but with cold work comparable to shot peening. Laser shock peening (LSP) produces deep compression with minimal cold work and impressive FOD resistance, but is costly and presents logistical problems in manufacturing.

Low Plasticity Burnishing (LPB) has been investigated as a rapid, inexpensive surface enhancement method. Preliminary results indicate depth and magnitude of compression comparable to LSP. Compression reaching the alloy yield strength and extending to a depth of 1.2 mm (0.047 in.) is achievable with cold work of less than 4%. Excellent surface finish can be achieved with no detectable metallurgical damage. Ease of adaptation to CNC machine tools allows LPB processing at costs and speeds comparable to machining operations.

The LPB process is described with application to IN718. Thermal stability at engine temperatures is compared to conventional shot peening. Resistance to 0.13 and 0.25 mm (0.005 and .010 in.) deep sharp notch FOD was achieved, even after exposure to engine temperatures. Elevated temperature crack growth data are presented showing the arrest of existing 0.46 mm x 0.91 mm (0.018 x 0. 036 in.) fatigue cracks by the deep compressive layer.

INTRODUCTION

High cycle fatigue (HCF) ultimately limits the performance of critical turbine engine components. The risk of HCF failure increases maintenance costs, reduces the life of components and limits engine performance. Since the 1940's the HCF life of automotive and aerospace components has been improved by inducing a surface layer of compressive residual stress using a surface enhancement finishing treatment. The compressive layer resists both crack initiation and small crack propagation. The maximum subsurface residual stress has been correlated with HCF life **[1, 2].** Because the HCF life of turbine engine components depends primarily on the number of cycles to crack initiation, surface enhancement can extend component fatigue life by an order of magnitude in high strength structural alloys, including IN718 **[2].**

<u>Conventional Surface Enhancement Methods</u>:

All of the methods of surface enhancement (SE) currently available develop a layer of compressive residual stress following mechanical tensile deformation. The methods differ primarily in how the surface is deformed and in the magnitude and form of the resulting residual stress and cold work (plastic deformation) distributions developed in the surface layers.

Conventional air-blast shot peening is routinely applied to steel, titanium, and nickel alloy turbine engine components. High velocity impact of each particle of shot produces a dimple with a region of compression in the center. Typical 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.) The magnitude of compression achieved depends primarily upon the mechanical properties of the alloy. The depth of the compressive layer and the degree of cold working depend upon the peening parameters including shot size, velocity, coverage, impingement angle, etc. Because each shot impacts the surface at a random location, peening for sufficient time to achieve

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uniform surface coverage results in many multiple impacts producing a highly cold worked surface layer **[3]**.

Conventional shot peening produces from 10% to 50% cold work, more than grinding, machining, or other common surface finishing processes **[4]**. Cold work is accumulative, and repeated applications of shot peening can produce even more than 50% cold work. Both the depth and degree of cold working increase with peening intensity, with the most severe cold working at the surface. Surface compression often decreases during shot peening of work hardening materials as the yield strength of the surface increases with continued cold working.

Gravity shot peening utilizes the same mechanism as conventional air-blast or wheel shot peening but employs fewer impacts by larger shot, resulting in a less cold worked surface layer. Compression comparable to shot peening and a smoother surface finish are achieved with 5 to 10% cold work.

In split sleeve cold expansion (SSCE), an oversized mandrel is drawn through a hole, plastically expanding the hole diameter, to produce a deep layer of compression in one pass of the mandrel. A single deformation cycle can achieve 2% to 4% radial plastic strain and high magnitude, deep hoop compression with minimal cold working of the material.

Laser shock peening (LSP) **[5]** has been successfully applied for surface enhancement of titanium alloy fan blades, and demonstrated on nickel superalloys and steels **[6]**. LSP produces a layer of compression of comparable magnitude to shot peening, but much deeper with less cold work. Through-thickness compression can be achieved on the leading edges of Ti-6Al-4V blades providing impressive FOD resistance. Single shock LSP can produce high compression with less than 1% cold work. To achieve maximum depths of compression, multiple laser shock cycles are required. Because the cold work is accumulative, multiple LSP shock cycles used to achieve depths of compression exceeding 1 mm (0.04 in.) may produce an accumulation of 5-7% cold work **[7]**.

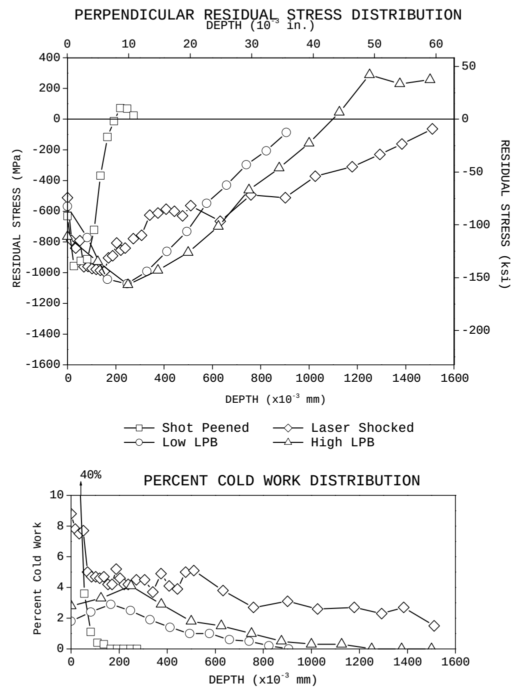


Figure 1 - Subsurface residual stress and cold work distributions produced by shot peeing (8A), LSP (3X) and two levels of LPB in IN718.

The residual stress and cold work distributions developed by conventional shot peening (8A intensity, 200%) and LPB in IN718 are compared in Figure 1. Shot peening produces 40% cold work at the surface.

The cold work associated with shot and gravity peening has been correlated with both the speed and magnitude of thermal relaxation of the compressive surface layer **[8, 9]**. Surface compression can relax to less than 50% of the initial value in only minutes at even low engine operating temperatures. Further, cold working the surface of work hardening alloys, such as IN718, increases the yield strength of the surface layers. The surface is then subject to overload relaxation in the event of subsequent plastic deformation. Because the cold worked surface yields at a higher stress level than the core material, even small plastic deformation can leave the previously compressive surface in high tension after a single loading cycle **[10]**. Surface compression created with minimal cold work is expected to be more stable both at high temperatures and with subsequent plastic deformation.

In conventional roller burnishing, a hard cylindrical roller is pressed into the surface of an axi-symmetric work piece with sufficient force to deform the near surface layers. Roller burnishing is performed with multiple passes usually under increasing load for improved surface finish and deliberate cold working of the surface. Fatigue enhancement is attributed to improved finish, increased yield strength, due to cold working, and the development of a compressive surface layer. In conventional ball burnishing, a fixed (non-rotating) ball is held in contact with the moving work piece surface under a normal force sufficient to deform the surface of the work piece. A smooth surface is achieved, but with extensive cold work and the potential for surface damage and residual tensile stress. The high friction and shear forces produced can cause surface damage even when lubricants are used.

Burnishing is used in the United States primarily for refinement of surface finish **[15-17]**. Although surface hardening and improvements in fatigue life are noted, no quantitative assessments exist. Residual stress distributions were measured in only one study **[18]** and compared to split sleeve cold expansion of holes in 7075 aluminum.

In Europe and Russia, roller burnishing is used on the inside or outside of cylindrical parts, usually with the tool positioned on a lathe, to improve fatigue life by both the introduction of surface compression and deliberate work hardening. Roller and ball burnishing have been studied in the USSR and Japan, and applied most extensively in the USSR in the 1970's **[19-23]**. Improvements in high cycle fatigue, corrosion-fatigue, and stress corrosion cracking are documented **[23-28]**. Optimum rolling parameters were established to minimize roughness and/or maximize surface hardening **[29-32]**. Models have been developed to predict the residual stresses from the deformation process in England **[33]** and in France **[34]**.

Development of Low Plasticity Burnishing (LPB):

The concept of low plasticity burnishing (LPB) originated as a means of producing a layer of compressive residual stress of high magnitude and depth with **minimal** cold work **[11]**. The process is characterized by a single pass of a smooth free rolling spherical ball under a normal force sufficient to deform the surface of the material in tension, creating a compressive layer of residual stress. A schematic diagram is given in Figure 2. The ball is supported in a fluid bearing with sufficient pressure to lift the ball off of the surface of the retaining spherical socket. The ball is in mechanical contact only with the surface to be burnished and free to roll on the surface of the work piece.

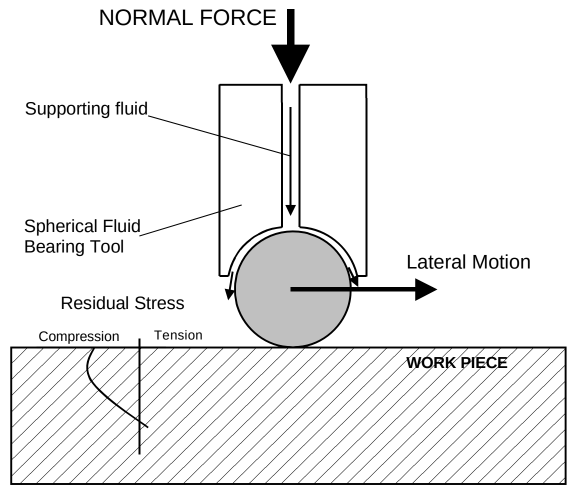
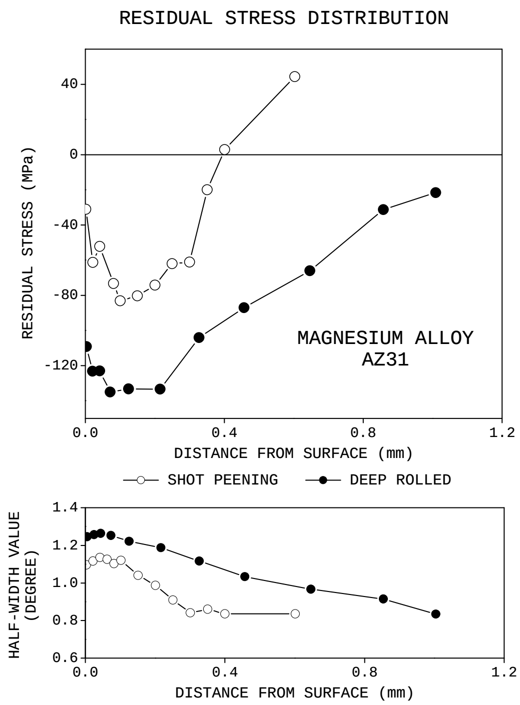


Figure 2 - Low Plasticity Burnishing schematic.

Although the tool designs and hydraulic systems differ, the LPB tooling is similar to “deep rolling” tools using a hydrostatically supported burnishing ball **[12-14].** The processes differ in the method of use and the level of cold work generated in developing the compressive layer. The line broadening and micro-hardness distributions generated by shot peening and deep rolling shown in Figure 3 reveal that deep rolling produces cold work greater than shot peening. In contrast, LPB produces cold working an order of magnitude lower than shot peening.

This paper describes the initial application of LPB to IN718. The characteristic residual stress and cold work distributions developed with the prototype tooling and limited HCF performance, FOD resistance and crack growth results are presented. Conventional shot peening is used as a bench mark for comparison.



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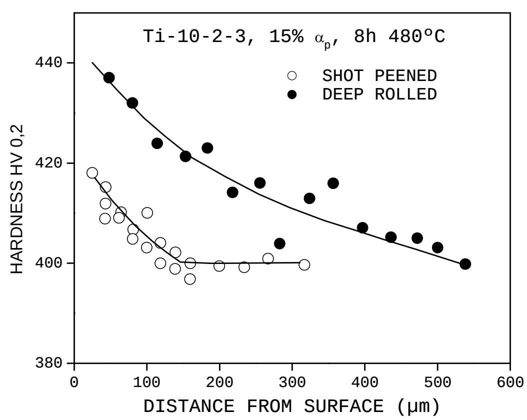

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Figure 3 - a) Residual stress and peak width distributions produced by shot peening and deep rolling magnesium alloy AZ31, after Zinn and Scholtes **[12]**, b) Micro hardness distributions produced by shot peening and deep rolling of Ti alloy Ti 10-2-3, after Drechsler... & Wagner **[14]**.

EXPERIMENTAL TECHNIQUE

Material and Sample Fabrication

IN718 was acquired as 38 x 9.5 mm (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 and room temperature tensile properties: UTS of 1,364 MPa (198 ksi), 0.2% YS of 1,109 MPa (161 ksi), 23% elongation, and 32% reduction in area.

Test coupons 101.6 mm (4 in.) long, 38.1 mm (1.5 in.) wide and 9.5 mm (0.375 in.) thick were used to establish the residual stress depth and magnitude attainable in IN718, assess surface damage, and perform thermal relaxation measurements. After heat treatment, the coupons were first mechanically polished and then electropolished to produce a flat surface free of residual stress and cold work. The gage sections of all of the HCF specimens were electropolished to remove the cold work and residual stress produced by finish grinding prior to either LPB or shot peening.

Two IN718 Kb bars and two manufactured from each of NASA developmental alloys E960 and E946, were provided by NASA, Glenn Research Center, for the purpose of investigating the effect of LPB on the growth of existing fatigue cracks. The Kb bars were burnished and returned to NASA for crack growth testing.

X-ray Diffraction Characterization:

Diffraction peak or line broadening, measured along with the residual stress, allows the amount of damage developed by SE methods to be accurately assessed. 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, 35]**. The distribution of cold work as a function of depth into the deformed surface can be expressed in terms of the equivalent true plastic strain. 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, and the subsurface yield strength distribution can then be estimated from true stress-strain curves **[4]**. The macroscopic residual stress, of primary interest in design and life prediction, is determined in the conventional manner from the shift in the diffraction peak position **[35-37]**.

Low Plasticity Burnishing (LPB) Apparatus

The LPB tool consists of a hardened sphere with a high modulus of elasticity and yield strength supported in a mating spherical socket of a fluid bearing, as shown schematically in Figure 2. The ball is supported by a continuous flow of fluid under sufficient pressure to force the ball off of the surface of the bearing during burnishing. Both hydraulic oil and water based cutting fluid have been used successfully. The freely turning burnishing ball makes solid contact only with the work piece surface and cannot support shear stresses at the work surface.

Using CNC positioning, the tool path is controlled so that the surface is covered with a series of passes at a separation maintained to achieve maximum compression with minimum cold working. The tool may be moved in any direction along the surface of a complex work piece, as in a typical multi-axis CNC machining operation.

The burnishing ball develops subsurface Hertzian contact stresses in the work piece acting parallel to the plane of the surface, which reach a maximum beneath the surface. With sufficient pressure applied normal to the surface, the subsurface stress exceeds the yield strength of the work piece material producing deep subsurface compression. The normal force required and the depth at which yielding first occurs depend upon the ball diameter.

The maximum subsurface residual stress magnitude can equal the material yield strength, and occurs below the surface. The depth of the compressive layer depends upon the burnishing ball diameter and normal force. The speed of burnishing has been found to have no effect upon the residual stress distribution produced up to 500 sfm, allowing application of the process at the highest practical CNC machining speeds.

The surface residual stress depends upon the normal force, feed and mechanical properties of both the ball and work piece. Lateral tensile deformation of the surface is necessary to achieve surface compression. Finite element modeling of the lateral surface deformation has proved to be complex, evidently due to limitations of the yield criteria. Therefore, processing parameters have been established empirically using Taguchi DOE methods. With a poor choice of processing parameters, the surface can be left nearly stress free or even in tension. Empirical optimization has been used successfully to select parameters that leave the surface in compression.

The LPB tool designed to fit a CAT-40 tool holder in a Haas HP vertical CNC mill is shown in Figure 4. The quill of the machine is not rotated during LPB. The swivel links in the hydraulic hose allow exchange of the tool to and from the tool holder so that LPB processing can be incorporated into standard machining sequences in existing CNC machine tools. Injection of the fluid through the quill of the mill is also possible in a suitably equipped machine. With minor modification, the apparatus can be adapted to most horizontal and multi-axis mills, or lathes.

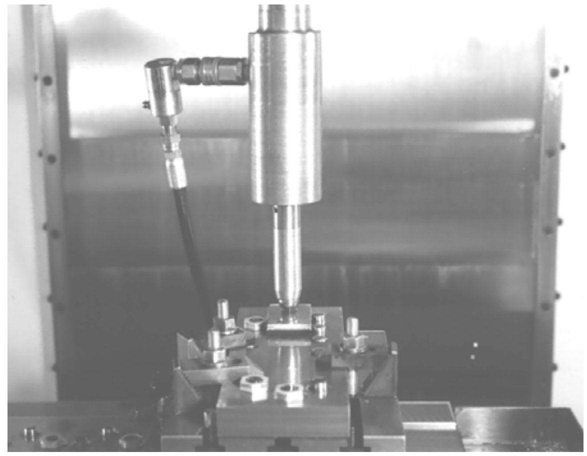

Figure 4 - LPB tool positioned for burnishing a coupon in a 20 HP vertical CNC mill.

The control apparatus for the hydraulic system provides a constant flow of fluid to support the burnishing ball and a computer controlled feedback system to maintain the desired normal force and fluid pressure. The computer control system uses direct numerical control to position the CNC machine tool and adjust the fluid pressure and burnishing force. The burnishing force and tool feed can be varied in order to "feather" the residual stress field providing a smooth transition at the perimeter of the burnished zone or to produce a distribution of residual stress appropriate for a specific application or applied stress field.

The burnishing ball is the only wear prone component of the LPB tooling. High chromium steel, beta-silicon nitride, and sintered tungsten carbide balls are readily available for ball bearing applications, and have been used successfully in the current apparatus. The surface finish achievable depends upon the finish of the ball which are commonly available with finishes of grade 25 (25 micro-inch), or better at costs less than cutting tool inserts.

Tool wear or damage has been observed only when abrasive grit has been introduced into the hydrostatic bearing socket causing scratches on the ball surface. The steel and WC balls can be retained by magnetic means for optimum clearance at the tool tip. Spring clips are used for non-magnetic ball materials. With either means of retention, the burnishing balls are easily and rapidly replaced.

High Cycle Fatigue Testing

Four-point bending was chosen as the loading mode for HCF testing to provide maximum sensitivity to the surface condition **[38]**. The bending fatigue specimen uniform gage cross section was 25.4 mm (1.0 in.) wide and 9.5 mm (0.375 in.) thick. The sample thickness was selected to allow compression from the surface to several mm without developing high internal tension. The 50.8 mm (2 in.) length of the gage section test surface provided a large surface area under uniform stress to minimize scatter in the fatigue data.

Fatigue testing was conducted at room temperature on a Sonntag SF-1U fatigue machine under constant stress sinusoidal loading at 30 Hz, R=0.01. The slightly positive R was used to prevent the mechanical bending fixture from traversing through zero load. Because R is essentially zero, the S/N curves are presented in terms of maximum stress at R=0.

FOD Resistance

The influence of sharp notch FOD on the fatigue life of both shot peened and LPB processed IN718 surfaces was tested using HCF specimens that were deliberately flawed in a controlled manner after surface enhancement. To simulate the introduction of a flaw in an existing engine component after operating temperature exposure, damage was introduced after shot peening or LPB processing and thermal exposure for 10h at 600C. Sharp notch FOD was created using a 60 deg. carbide thread cutting tool held in the spindle of a vertical milling machine. The tool was then indented to a depth of 0.12 mm or 0.25 mm (0.005 or 0.010 in.), and a gouge 6.3 mm (0.25 in.) long was cut across the width in the center of the gage section.

Two samples, one with each depth of flaw, were prepared for each of the three LPB process levels and for shot peening. The FOD specimens were tested at a fixed maximum stress of 724 MPa (105 ksi) and compared to the unflawed S/N curve.

Existing Crack Growth Testing

To assess the effect of the compressive layer produced by LPB on existing fatigue crack growth, LPB processing was applied to two pre-cracked Kb bars manufactured from each of the NASA developmental superalloys E946 and E960 and two IN718 bars. The bars were initially pre-cracked to produce fatigue cracks nominally 0.43 mm deep by 0.86 mm wide (0.017 x 0.034 in.) from a 0.18 mm deep by 0.35 mm wide (0.007 x 0.014 in.) semicircular EDM notch. After precracking, the E960 Kb bar was burnished in a rectangular zone nominally 6 by 12 mm (0.25 by 0.5 in.) centered on the crack using the high LPB processing parameters. The E946 and IN718 samples were first ground to remove the EDM notch leaving a 0.20 by 0.56 mm (0.007 x 0.014 in.) crack before LPB. The bars were returned to NASA for room temperature crack growth testing using potential drop crack length monitoring at constant stress amplitude. Heat tinting was used to record the crack front at several intervals during testing.

RESULTS AND DISCUSSION

Residual Stresses Developed

Using Taguchi DOE methods, processing parameters were selected to define three levels of LPB: low, medium and high. The subsurface residual stress and cold work distributions produced by 10A shot peening and LPB are shown before and after exposure to 600C in Figures 5 through 8.

The magnitude of compression achieved by LPB is comparable to shot peening. The depth of the compressive layer ranges from 5X to 8X that of shot peening for the range of LPB processing used in this study. The massive relaxation of the highly cold worked shot peened surface at 600C is evident in Figure 5. The surface of the medium and high LPB samples remains more compressive than the shot peened, even after 100 h at temperature.

Surface Damage Assessment

The metallographic examination at 500X showed no evidence of cracking, plastic deformation, or folds. The surface texture both parallel and perpendicular to the lay (direction of burnishing) was smooth, except for a wavy profile observed for the highest loads, on the order of 0.5 x 10^{-3} mm (20 x 10^{-6} in.).

High Cycle Fatigue Results

Baseline S/N curves were prepared for the untreated and shot peened conditions after exposure to 600C for 10 hours. Shot peening to a 10A intensity gave a fatigue strength of 570 MPa (82.7 ksi) at 10^6 cycles after thermal exposure, an improvement of nominally 100 MPa (14.5 ksi) over a residual stress free electropolished surface with the same thermal history. The least squares fit to the 10A shot peened + 600C/10h baseline is compared to the LPB processed samples in the S/N curves.

The high compressive residual stress on the surface of the LPB specimens forced virtually all of the failures to initiate at the edge of the gage section, just beyond the LPB zone, where the applied stress was slightly lower than at the gage section surface. When this failure mode was recognized, both the top test surface and sides of the remaining samples were burnished in an attempt to force failures to the test face. Samples burnished on both the top and sides frequently failed completely outside the gage section, beyond the end of the LPB zone, where the cross section was 20% larger than in the gage, and the stress in bending was correspondingly lower. Therefore, the fatigue strength of the LPB surface is evidently at least that indicated by the data presented here.

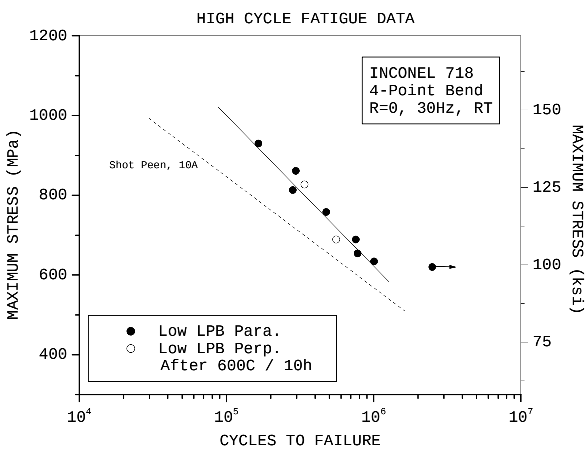

Figure 9 - Inconel 718, 4 point bend, R=0, 30Hz, RT.

The S/N curve for low level LPB processing both parallel and perpendicular to the specimen axis are shown in Figure 9. After 600C for 10h, low LPB provides substantial improvement in fatigue life relative to 10A shot peening, especially at higher stress levels. The low LPB fatigue life at 800 MPa (116 ksi) is five times the 10A shot peened life. No significant differences in fatigue strength were observed for samples burnished parallel and perpendicular to the applied stress.

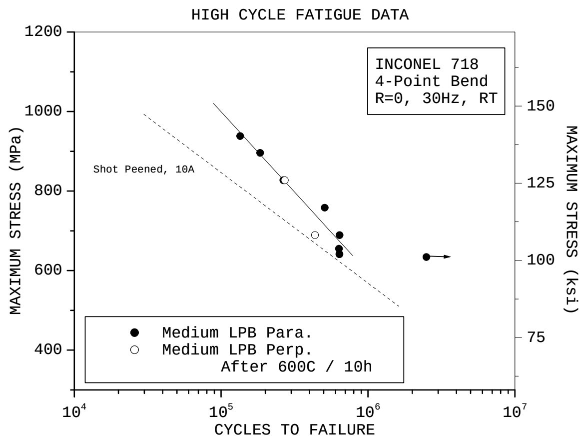

Figure 10 - Inconel 718, 4 point bend, R=0, 30 Hz, RT.

The results for the medium LPB processing, Figure 10, are comparable to the low LPB and again show improved performance over 10A shot peening especially at higher stress levels. No significant difference is evident between the parallel and perpendicular burnishing directions. All the failures were again from the edge of the LPB zone, yielding conservative estimates of the true fatigue strength.

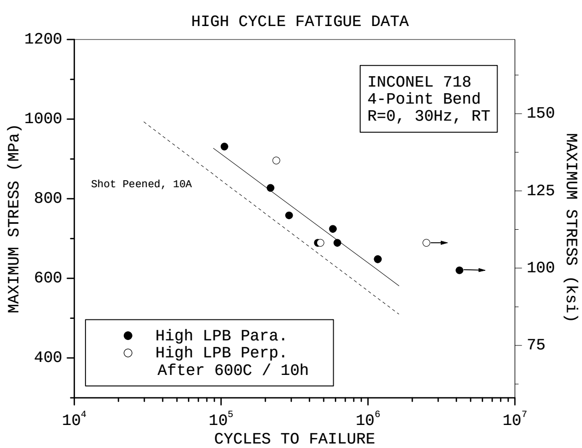

Figure 11 - Inconel 718, 4 point bend, R=0, 30 Hz, RT.

The highest level of LPB processing shows less of an improvement over simple shot peening, Figure 11. The majority of these failures again occurred at the very edge of the LPB zone; therefore, the fatigue strength is not indicative of the initiation of cracks from within the LPB processed region.

LPB processing at all three levels produced nominally twice the fatigue life of shot peened IN718 given the same thermal exposure. However, nearly all of the failures originated at the edges of the LPB zone, and do not represent nucleation in the LPB region. Additional testing is currently in process using a novel trapezoidal cross section bending fatigue sample designed to ensure failure in the highly compressive gage section.

FOD Resistance

Sharp FOD reduced the life of the shot peened specimens as shown in Figure 12. The fatigue crack originated out of the bottom of the FOD notch, and propagated through the center gage section for the shot peened 0.125 mm (0.005 in.) deep FOD sample.

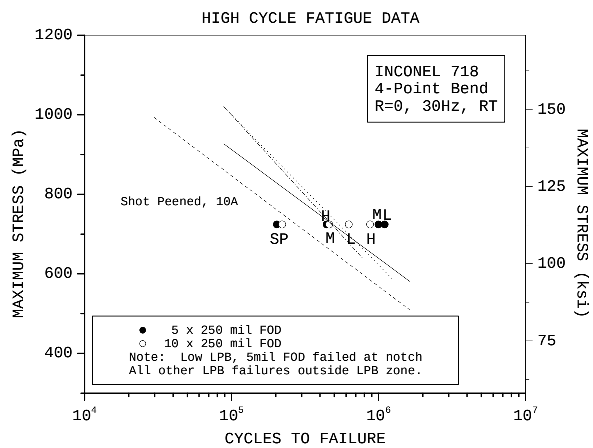

Figure 12 - Inconel 718, 4 point bend, R=0, 30Hz, RT.

All of the LPB processed specimens showed no reduction in fatigue life relative to un-flawed LPB surface, for either 0.125 or 0.250 mm (0.005 or 0.010 in.) deep flaws. As noted in Figure 12, all of the LPB processed specimens, except the low 0.125 mm (0.005 in.) specimen, failed completely out of the gage section beyond the LPB region, even in the presence of the 0.250 mm (0.010 in.) deep mechanical flaw.

LPB processing appears to suppress FOD producing flaws shallower than the depth of the compressive layer. Confirmation testing is in process with the revised trapezoidal cross section fatigue sample designed to force failures into the treated gage section.

Existing Crack GrowthTesting

The crack growth history and crack front for the E960 specimen are shown in Figure 13**.** Prior to burnishing, the crack grew to 0.43 mm (0.017 in.) in 4000 cycles under a 6.1 *KIP* cyclic load. Following LPB processing, crack growth was effectively arrested at a depth of 0.43 mm (0.017 in.) even with the cyclic load increased 18%. Crack growth resumed at 30,000 cycles when the applied load was increased to 7.9 *KIP* but again arrested after growing only 0.025 mm (0.001 in.). After increasing the load to 8 *KIP*, 31% higher than the initial load required for crack growth, the crack again grew to failure.

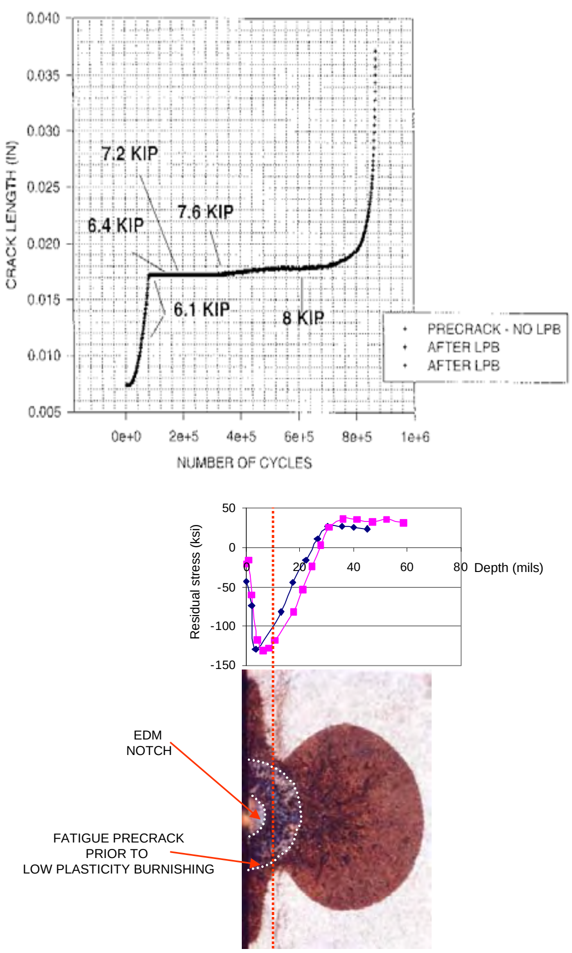

Figure 13. Effect of LPB on crack growth in E960 specimen precrack not removed.

The crack front preserved by heat tinting is shown in Figure 13. The remarkable shape of the crack front appears to be consequence of the residual stress field through which it was forced to grow. Comparison of the crack shape with the residual stress distribution measured in the LPB zone after fracture indicates that the zone of high compression occurring below the surface has caused the crack growth rate to vary with direction and depth. The original semicircular crack front has been severely distorted. Low compression on the surface has allowed the crack to grow laterally along the surface. At the depth of maximum compression, the crack growth arrested laterally, and only broke through to the lower compressive region with increased load. The crack then expanded outward behind the layer of high compression.

The E946 Kb bar was precracked to a depth of 0.43 mm (0.017 in.) The EDM notch was ground away prior to LPB processing a region nominally 6.35 mm (0.25 in.) square centered on the pre-crack leaving a crack 0.20 mm deep and 0.55 mm (0.008 x 0.022 in.) wide. The crack growth history is shown in Figure 14. Initial rapid pre-cracking occurred at 6.1 *KIP*. Following LPB processing, the crack arrested at nominally 0.25 mm (0.010 in.) under a 6.2 *KIP* load, and again at 6.4 *KIP*. The test was finally stopped by overload failure at 10 *KIP*.

Examination of the fracture face shown in Figure 14 reveals that the layer of high compression produced in the E946 material completely arrested crack growth into the material and forced the crack to grow laterally along the surface to the entire width of the LPB processed region. The apparent depths indicated by potential drop were evidently distorted by the extreme crack aspect ratio. The surface of the LPB zone on the E946 sample was in tension due to insufficient burnishing pressure promoting crack growth along the surface. The lateral crack growth arrest at the boundary of the burnished zone is attributed to high surface compression from prior grinding. Surface residual stress measurements made after fracture revealed relatively high axial compression of -661 MPa (-95.9 ksi) and -472 MPa (-68.5 ksi) due to prior grinding of the E946 and E960 Kb bars, respectively.

Two Inconel 718 Kb bars were processed under high pressure to insure surface compression. The nominally 0.6 mm (0.025 in.) deep compressive layer arrested the 0.56 mm (0.022 in.) deep monitored crack. Failure in both samples occurred at a location remote from the crack at the edge of the LPB zone as shown in Figure15.

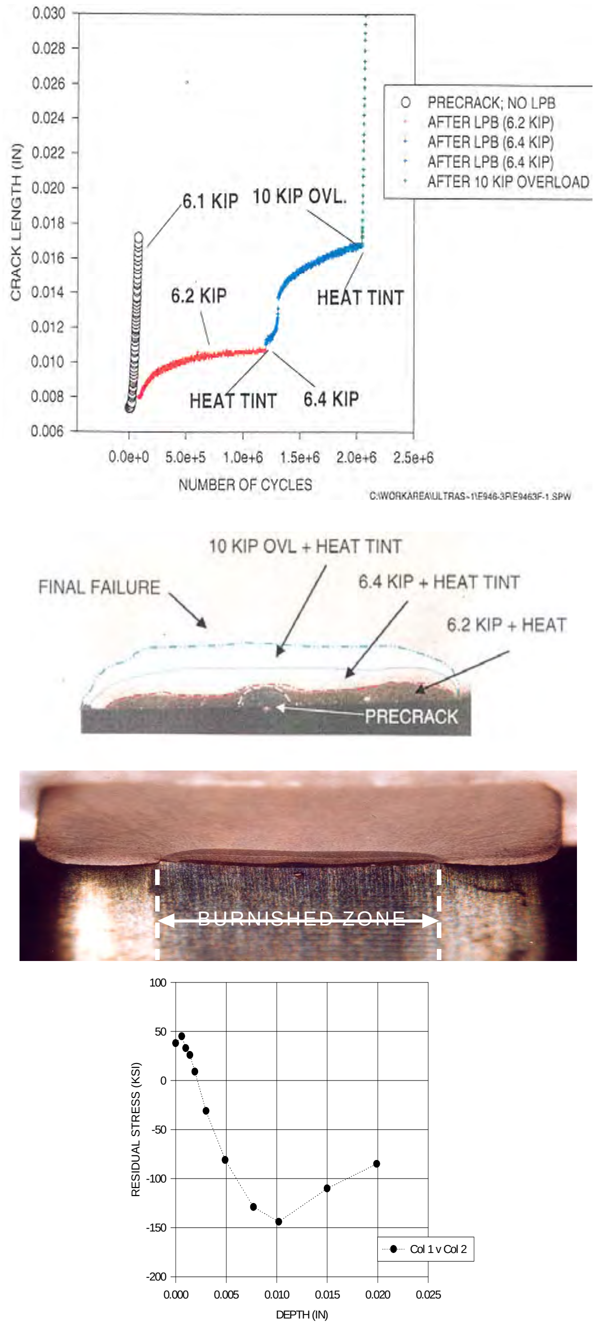

Figure 14 - Effect of LPB on crack growth in E946 EDM notched removed (0.008 in.)

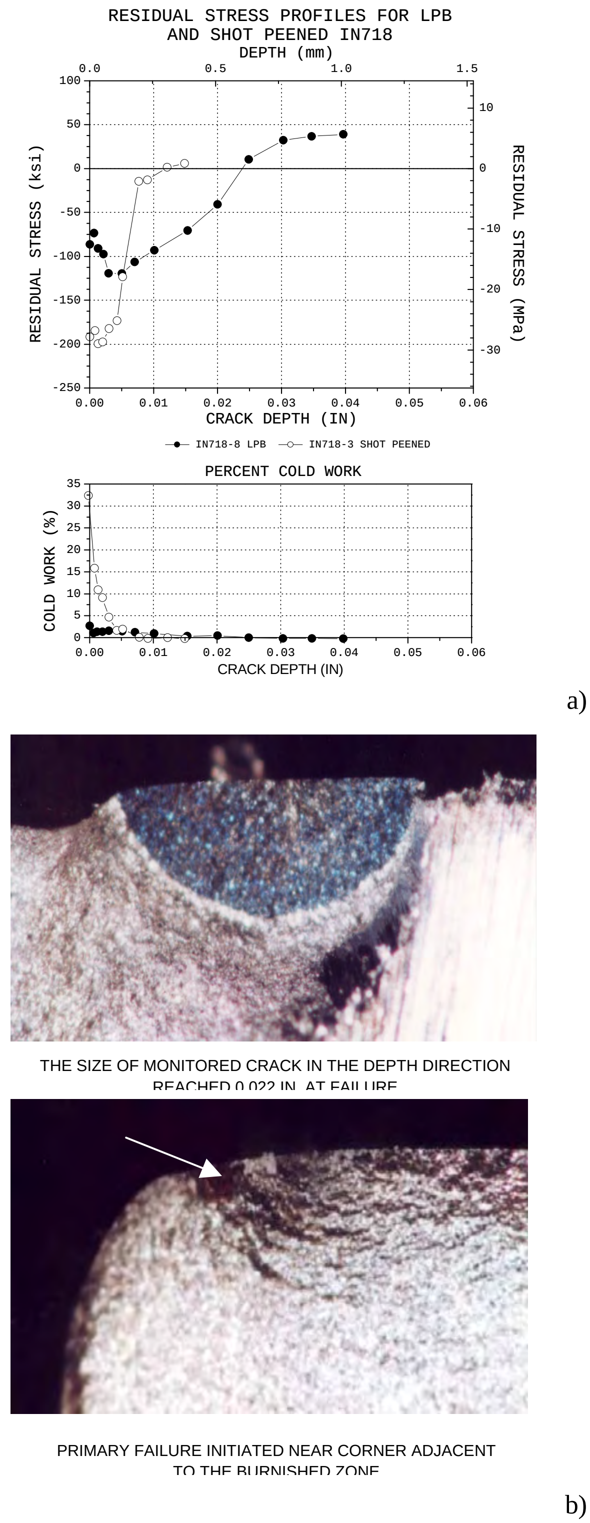

Figure 15 - a) Residual stress and cold work distributions in LPB processed IN718. b) Primary failure and monitored crack faces.

CONCLUSIONS

Low plasticity burnishing produces a deep high magnitude compressive layer with minimal cold working of the surface and no detectable surface damage in IN718.

Compression reaches a maximum below the surface on the order of the material yield strength. The depth of compression can be 5X to 8X greater than shot peening. Surface compression is achievable with empirically determined processing parameters. The low cold worked surface is more stable at 600C (1110F) than a shot peened surface.

Sharp FOD resistance tests simulated using 0.12 mm (0.005 in.) and 0.25 mm (0.010 in.) deep notches showed no loss of HCF life for all levels of LPB tested. The shot peened specimens all failed from the FOD scratch at reduced lives.

LPB processing at the highest level caused complete arrest of existing fatigue cracks in NASA superalloys E960 and E946. A 30% increase in cyclic load bearing strength has been demonstrated for cracked nickel base superalloys. LPB processing has been demonstrated to be an effective means of suppressing small crack growth in nickel base superalloys.

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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] P. Foget, et al. (1990), Materials and Manufacturing Processes, **5**, No. 4, 501-528.

[6] 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.

[7] 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, (2000) this volume.

[8] P. Prevey, et al., (1997), Proc. ASM/TMS Materials Week, Indianapolis, IN, Sept 15-18, 1997, pp. 3-12.

[9] B. Eigenmann, V. Schulze, and O. Vöringer, (1994), Proceeding ICRS IV, pp. 598-607.

[10] H. Hanagarth, O. Vöringer, and E. Macherauch, "Relaxation of Shot Peening Residual Stresses of the Steel 42 CrMo 4 by Tensile or Compressive Deformation," Shot Peening, Editor K. Iida, The Japenese Society of Precision Engineering, Todyo, Japan, 1993, pp. 337-345.

[11] U.S. Patent 5,826,453 (Oct. 1998), other patents pending.

[12] 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.

[13] 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.

[14] 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.

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

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

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

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

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

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

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

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

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

[24] V.T. Stepurenko, et al., (1976), Protection of Metals, **12**,

No. 4, pp. 386-389.
[25] D.D. Papshev, Yu G. Golubev, (1972), Russian Engineering Journal, **52**, No. 4, pp. 48-51.
[26] M. Kh. Freid, et al., (1994), Protection of Metals, **20**, No. 2, pp. 263-265.
[27] L.M. Belkin, et al, (1984), Soviet Engineering Research, **4**, No. 9, pp. 30-32.
[28] L.M. Belkin, (1983), Soviet Materials Science, **19**, No. 3, pp. 225-228.
[29] M. Fattouh, et al., (1988), Wear, **127**, pp. 123-137.
[30] N.H. Loh, et al., (1989), Wear **129**, No. 2, pp. 235-243.
[31] N.H. Loh, et al., (1993), Precision Engineering, **15**, No. 2, pp. 100-105.
[32] B. Kotiveerachari, R.L. Murty, (1985), International Journal of Production Research, **23**, No. 3, pp. 499-521.
[33] D.A. Hills, et al., (1979), Proc. Int'l Conference Wear of Materials, ASME, New York, NY, pp. 396-402.
[34] S. Braham, J. Frelat, (1993),Proc. Computer Methods and Exp. Meas. for Surface Treatment Effects, Computational Mechanics Publications, Southampton, U.K., pp. 255-264.
[35] P.S. Prevey, (1986), Metals Handbook, Vol 10, ASM, Metals Park, OH, 380-392.
[36] M.E. Hilley, ed. (1971) Residual Stress Measurement by XRD, SAE J784a, SAE, Warrendale, PA.
[37] Noyan & Cohen (1987) Residual Stress Measurement by Diffraction & Interpretation, Springer-Verlag, NY.
[38] P.Prevey, W.P. Koster, (1972) "Effect of Surface Integrity on Fatigue of Standard Alloys at Elevated Temperatures," Fatigue at Elevated Temperatures, ASTM STP561, ASTM, Phil., PA., pp. 522-531.