Diffraction Notes

LAMBDA RESEARCH 5521 FAIR LANE CINCINNATI, OH 45227 (513) 561-0883 NO. 26 Spring 2000

Effect of Low Plasticity Burnishing (LPB) on the HCF Life of IN718

High cycle fatigue (HCF) ultimately limits the performance of aircraft and automotive components, increases maintenance costs and reduces the service life. The HCF life of automotive and aerospace components can be 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.

All methods of surface enhancement 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 alloys. 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.). Because each shot impacts the surface at a random location, peening for sufficient time to achieve uniform surface coverage results in many multiple impacts, producing a highly cold worked surface layer **[1]**. Conventional shot peening produces from 10% to 50% cold work, more than grinding, machining, or other common surface finishing processes **[2]**.

Laser shock peening (LSP) **[3]** has been successfully applied for surface enhancement of titanium alloy fan blades, and demonstrated on nickel superalloys and steels **[4]**. 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 to 7% cold work **[5]**.

ANNOUNCEMENTS

Welcome New Employee

Please join us in welcoming a new employee to Lambda Research: Terry Jacobs is our new manufacturing engineering supervisor.

11th AeroMat Conference & Exposition

Paul Prevéy will be presenting a paper entitled "Surface Enhancement of Ti-6Al-4V using Low Plasticity Burnishing" at the 11th AeroMat Conference in Bellevue, Washington, June 26-29, 2000.

Accreditations

Lambda Research has again been audited and certified to meet the rigorous GE S400 specification required for materials testing laboratories. Lambda Research is proud to have been again selected as the source for x-ray diffraction testing services related to critical turbine engine performance.

The Food and Drug Administration (FDA) recently audited Lambda Research for the performance of qualitative phase analysis of pharmaceuticals. We are pleased to announce that Lambda Research has been granted approval under the FDA's good laboratory practices for the performance for x-ray diffraction analyses of pharmaceutical components.

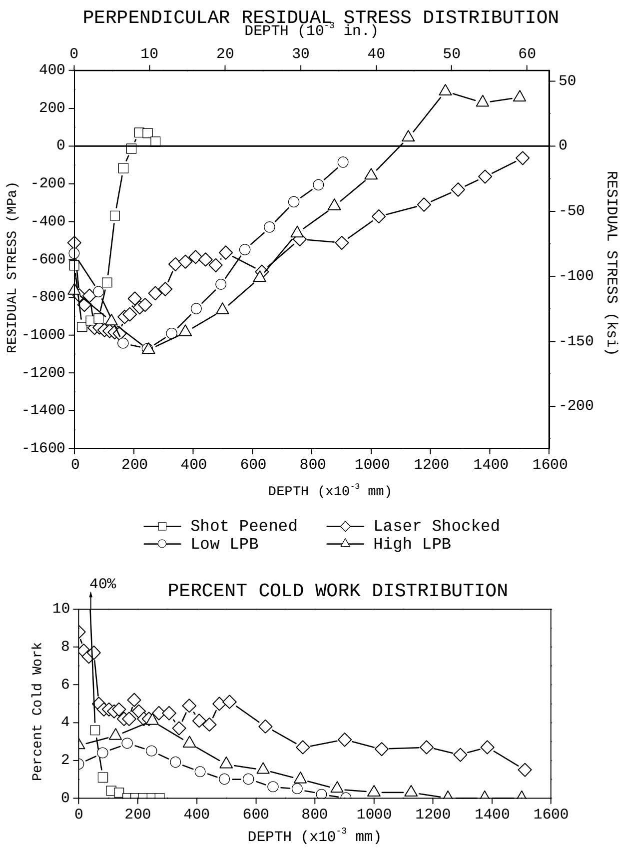

Figure 1 - Subsurface residual stress and cold work distributions produced by shot peeing (8A), LSP (3X) and two levels of LPB in IN718.

The residual stress and cold work distributions developed by conventional shot peening (8A intensity, 200%), LSP and LPB in aged 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 **[6, 7]**. Surface compression can relax to less than 50% of the initial value in only minutes at even low service 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 **[8]**. Surface compression created with minimal cold work is expected to be more stable both at high temperatures and with subsequent plastic deformation.

LOW PLASTICITY BURNISHING (LPB) PROCESS

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 **[9]**. 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.

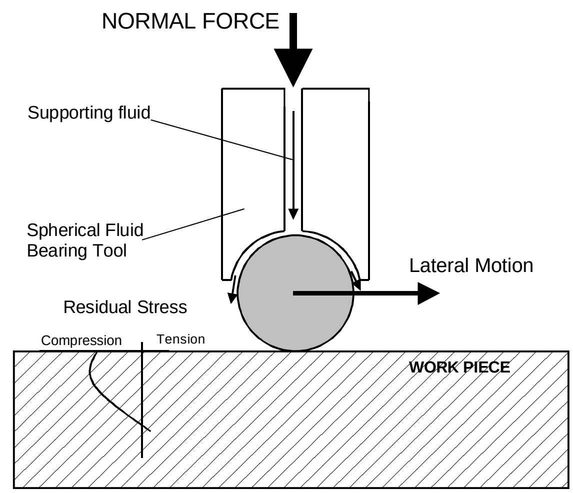

Figure 2 - Low Plasticity Burnishing schematic.

Although the tool designs and hydraulic systems differ, the LPB tooling is similar to "deep rolling" tools using a hydrostatically supported burnishing ball **[10-12].** The processes differ in the method of use and the level of cold work generated in developing the compressive layer. Line broadening and micro-hardness distributions generated by deep rolling show even higher cold working than shot peening **[10, 12]**. In contrast, LPB produces cold working an order of magnitude lower than shot peening.

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. 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 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.

HIGH CYCLE FATIGUE PERFORMANCE

IN718 was acquired as bar stock in the mill annealed condition, solution treated at 1800F and aged at 1350F/8h + 1125F/8h, producing a hardness of 43 ± 2 HRC. Room temperature UTS was1,364 MPa (198 ksi), and the 0.2% YS was 1,109 MPa (161 ksi) in the aged condition.

After heat treatment, 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.

Four-point bending was chosen as the loading mode for HCF testing to provide maximum sensitivity to the surface condition **[13]**. A trapezoidal HCF specimen cross-section was used to drive the highly compressive gage section surface into tension while providing a large surface area (14.5 x 35 mm) under constant stress to minimize scatter in the fatigue data. The 9.5 mm (0.375 in.) sample thickness accommodated a deep compressive layer without high internal tension. Fatigue testing was conducted at room temperature using constant stress sinusoidal loading at 30 Hz, R=0.1

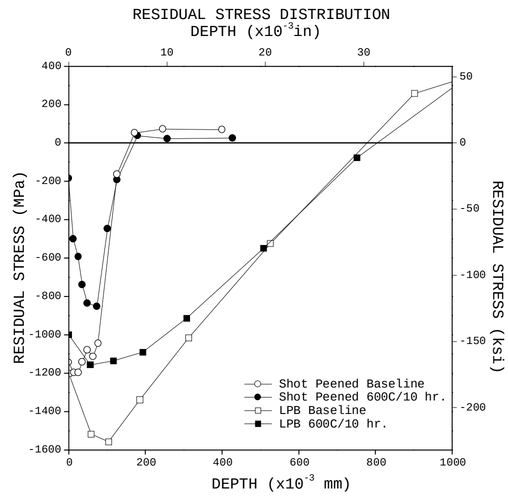

Fig. 3 - IN718 shot peened coupons. Baseline vs. thermal exposure at 600C/10 hr.

As previously reported **[6]**, thermal exposure nearly eliminates the protective compressive layer at the surface of the 40% cold worked shot peened sample, as shown in Figure 3. The 3% cold worked LPB samples relaxed only as much as the reduction in yield strength at 600C.

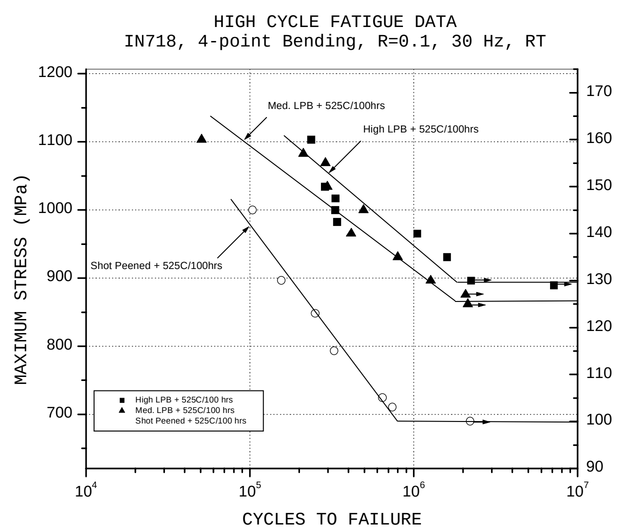

Fig. 4 - Shot Peen, Medium and High LPB 525C/100 hrs.

The high cycle fatigue performance after exposure at 525C (975F) and 600C (1110F) for 100 hrs. are shown in Figures 4 and 5. A conventional 8A shot peened surface is compared to that of a "medium" and "high" LPB condition producing depths of compression of nominally 0.8 and 1 mm, respectively. At the lower temperature the nominally 30% increase in the 10^7 fatigue life achieved relative to conventional shot peening appears to be associated with retention of the higher surface compressive stress. The improved fatigue performance in the finite life range, between 10^5 and 10^6 cycles, is attributed to the effectiveness of the deep subsurface compression in retarding crack growth. Similar performance with reduced benefit primarily in the improved endurance limit is seen at the higher temperature.

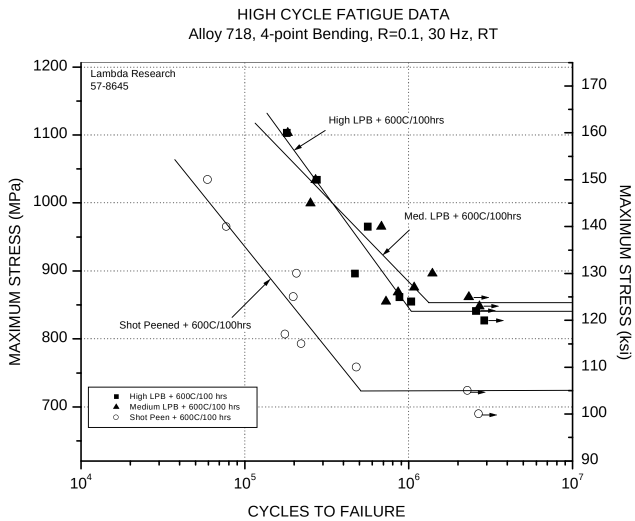

Fig. 5 - Shot Peen, Medium, and High LPB 600C/100 hrs.

CONCLUSIONS

Low plasticity burnishing produces a deep, high magnitude compressive layer with minimal cold working in IN718. Compression reaches a maximum below the surface on the order of the material yield strength. The depth of compression can be five times greater than shot peening and more stable at elevated temperatures.

High cycle fatigue performance of low plasticity burnished IN718 is consistently superior to 8A shot peening, both in terms of endurance limit and finite life performance.

ACKNOWLEDGMENTS

The present work was supported by NASA SBIR contracts NAS3-98034 and NAS3-99116.

REFERENCES

[1] 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.

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

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

[4] 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.

[5] 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).

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

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

[8] 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, Tokyo, Japan, 1993, pp. 337-345.

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

[10] 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.

[11] 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.

[12] 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.

[13] P.Prevéy and 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.