OVERVIEW OF LOW PLASTICITY BURNISHING FOR MITIGATION OF FATIGUE DAMAGE MECHANISMS

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ABSTRACT

Surface enhancement technologies such as shot peening (SP), laser shock peening (LSP), and low plasticity burnishing (LPB) can provide substantial fatigue life improvement. However, to be effective, the compressive residual stresses that increase fatigue strength must be retained in service. LPB provides thermally stable compression and can be performed in conventional machine shop environments on CNC machine tools. LPB enables the extension of component service lives fatigue limited by various damage mechanisms including foreign object damage (FOD), corrosion fatigue, pitting, and fretting. The thermal and mechanical stability of the compressive layer are briefly reviewed. The LPB process, tooling, and control system are briefly described. Four representative applications are presented: thermal stability in IN718, improved damage tolerance in Ti-6-4 fan blades, mitigation of fretting fatigue damage in Ti-6-4, and improved corrosion fatigue in 17-4PH stainless steel.

INTRODUCTION

LPB[1,2,3,4] provides deep, stable compressive residual stresses with lower cold work than conventional deep rolling.[5,6] Reduced cold work and dislocation density as well as dislocation arrangement improve retention of beneficial compression at elevated temperatures.[6,7,8] LPB surface treatment is applied using conventional multi-axis CNC machine tools to position the tool and a novel LPB dual hydraulic control that floats the burnishing ball with constant volume delivery of fluid while separately controlling the variable burnishing force synchronized with the tool positioning. LPB has been shown to improve high cycle fatigue (HCF) performance,[9,10] damage tolerance,[11] corrosion fatigue,[12] stress corrosion cracking (SCC),[13] and fretting fatigue damage[14] in turbine engine components, aging aircraft structures, nuclear waste-material containers, biomedical implants, and welded joints. This paper presents a brief overview of the improved damage tolerance achievable with LPB for various materials and damage mechanisms.

THE LOW PLASTICITY BURNISHING (LPB) PROCESS

LPB is a method of CNC controlled burnishing designed to produce a deep layer of highly compressive residual stress with a minimum amount of cold work. The basic LPB tool is comprised of a ball supported by a constant volume flow of fluid in a spherical hydrostatic bearing as shown in Figure 1, and can be held in any CNC machine or robotic positioning apparatus. The patented constant volume support prevents the ball from contacting the bearing surface. The ball rolls across the surface of a component in a pattern defined by the CNC code. The tool path and normal pressure applied are designed to create a chosen distribution of compressive residual stress. Design

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methodologies have been developed[15] to determine the residual stress distribution required for optimum performance. As the ball rolls over the component, a surface layer with a depth dependent upon the ball size and normal force is plastically deformed. Constraint from the surrounding material produces a layer of compression after the ball passes. No material is removed during the process. LPB smoothes surface asperities leaving an improved surface finish that can be better than 5 µin., RA. The patented constant volume hydrostatic bearing design allows dual balls to be supported simultaneously in a caliper tool shown Figure 2 processing the leading edge of a 17-4PH compressor blade. Processing of the dovetail of a Ti-6Al-4V blade with a single point tool is shown in Figure 3.

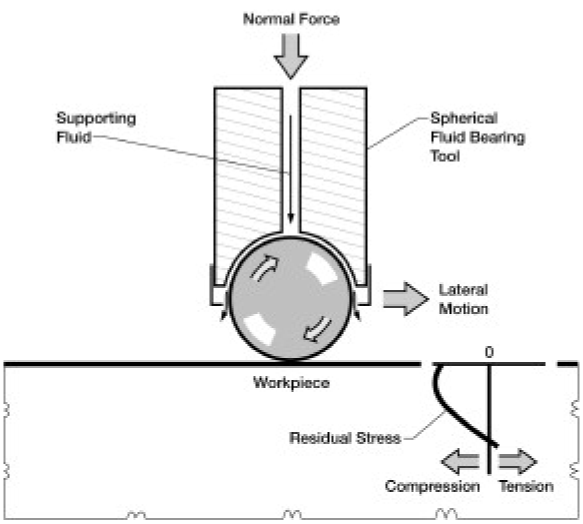

Figure 1- LPB Schematic showing constant volume ball support and separately controlled normal force.

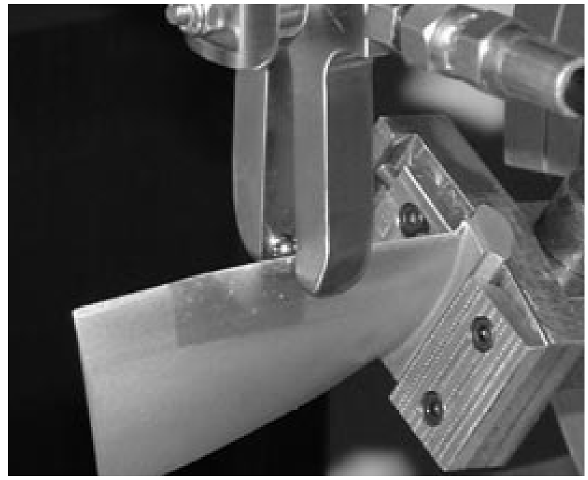

Figure 2 LPB treatment of LE of 17-4PH compressor blade with caliper tool.

Figure 3 Single point tool LPB processing of the dovetail of Ti-6-4 compressor blade.

THERMAL STABILITY OF LPB RESIDUAL STRESS DISTRIBUTIONS

The high degree of cold work produced by SP is known to lead to both thermal and mechanical relaxation.[6,9] LPB processing parameters are controlled to develop a deep layer of high compression while introducing less than nominally 5% cold work. Residual stress and percent cold work depth profiles for cut wire shot peened (CW14, 8A, 400%) and LPB processes IN718 are shown in Figure 4 before and after exposure to 525°C and 600°C for 100 hr. The residual stresses from shot peening relax nearly completely near the surface where the material is highly cold worked. Both the LPB layer and the deeper, less cold worked, portion of the shot peened layer retain compression after exposure. Thermal stability is attributed to a reduced dislocation density and correspondingly limited dislocation annihilation at elevated temperatures, thus eliminating a mechanism for relaxation.

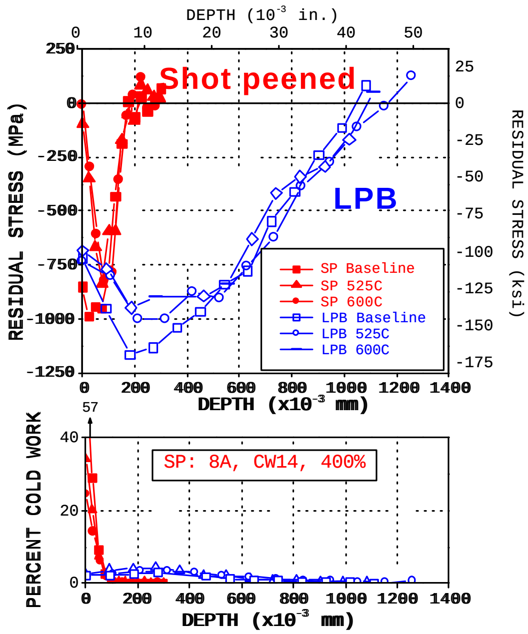

Figure 4 – Thermal relaxation of surface treated IN718 showing relaxation in highly cold worked layers.

HCF PERFORMANCE AND DAMAGE TOLERANCE

The HCF results for IN718 presented in Figure 5 show substantially improved performance for LPB over SP after exposure to either 525°C or 600°C. The reduced fatigue strength for SP after either 525°C or 600°C exposure is attributed to the loss of surface compression seen in Figure 4. Similar fatigue benefits from LPB are documented for Ti-6-4.[16] LPB has been applied using caliper tools to induce through-thickness compression in the edges of Ti-6-4 fan and compressor blades to improve damage tolerance.[17,18] The fatigue performace of actual fan blades with leading edge FOD tested at R=0.1 to simulate the centrifugal mean stress in a rotating engine is shown in Figure 6. In the absence of FOD, LPB processing increased fatigue strength by nominally 207 MPa (30 ksi) over non-processed blades, approaching the material yield strength. In all but one instance, LPB processed blades tested without FOD at such high stress levels failed outside the most highly stressed LPB-processed area, usually in the dovetail region. Introduction of 0.5 mm (0.02 in.) deep simulated FOD in non-LPB blades reduced the fatigue strength 65% from 689 to 241 MPa (100 to 35 ksi). The fatigue strength of LPB blades with 0.5 mm FOD was equal to that of non-LPB processed blades without FOD. Deeper 1.3 mm (0.05 in.) FOD reduced the fatigue strength after LPB to only 10% less than the strength of undamaged, unprocessed blades. Similar benefits have been achieved Ti-6-2-4-2[19] and 17-4PH[20] stainless steel blades.

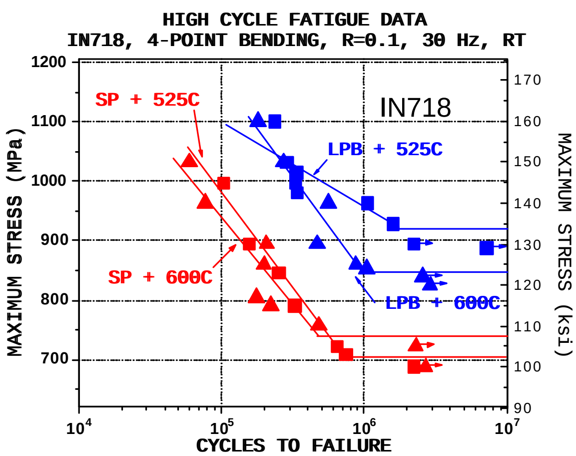

Figure 5 - High cycle fatigue performance of surface treated IN718.

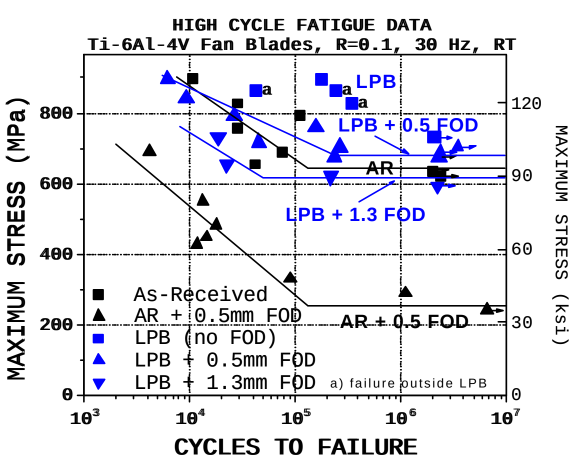

Figure 6 - Effect of LPB in mitigating HCF and FOD damage in Ti-6-4 fan blades.

MITIGATION OF FOD AND CORROSION FATIGUE DAMAGE IN 17-4 PH STAINLESS STEEL

The corrosion fatigue performance of thick section 17-4 PH stainless steel specimens tested in 4-point bending is shown in Figure 7. Active corrosion in a 3.5% NaCl neutral salt solution and 0.25 mm (0.010 in.) deep FOD are included, comparing the performance of low-stress ground base-line surface with shot peening and LPB. The base-line and shot peened fatigue strengths are similar, 1033 MPa (150 ksi) and 1000 MPa (145 ksi), respectively. In contrast, LPB produced a 10^7 cycle bending fatigue

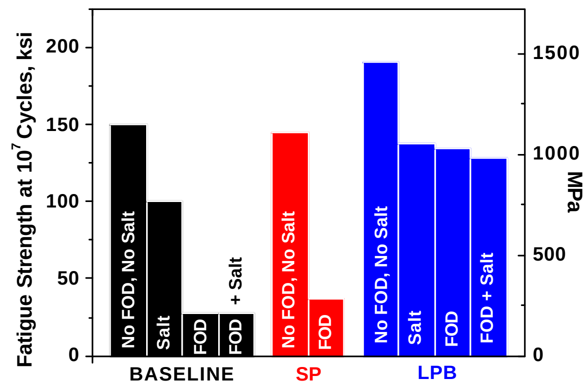

Figure 7 HCF and corrosion fatigue of 17-4 PH stainless steel.

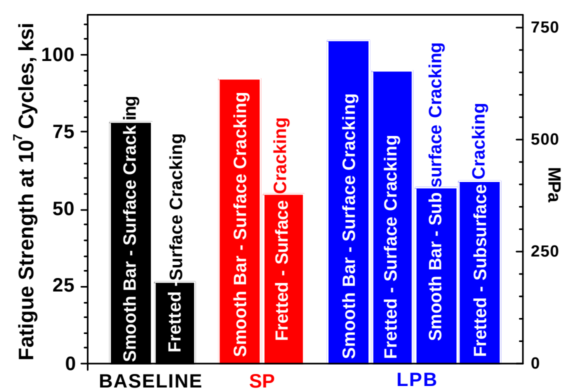

Figure 8 - Ti-6Al-4V fretting fatigue data for shot peened and LPB surface treatments.

strength of 1310 MPa (190 ksi), exceeding the material's 1033 MPa tensile yield strength due to the introduction of residual compression on the order of the yield strength. Active corrosion decreases the base-line fatigue strength to nominally 690 MPa (98 ksi), while the corrosion fatigue strength with LPB is nominally unaffected. FOD, simulated by a 0.25 mm deep by 0.76 mm long electrical discharge machined (EDM) notch, penetrated the SP compressive layer, dramatically reducing both the baseline and SP fatigue strengths. The fatigue strength with prior LPB and FOD was nominally 1033 MPa (150 ksi), comparable to the strength of the base-line material without FOD. The combined effect of FOD and active corrosion is almost identical to that of FOD alone, indicating no compound effect.

MITIGATION OF FRETTING FATIGUE DAMAGE IN TI-6AL-4V

Fretting occurs when component surfaces are pressed into physical contact under loading conditions that produce small relative movement. Shallow shear fatigue cracks initiated at the edges of the fretting scars can grow in mode I fatigue to failure. Fretting fatigue tests were conducted on Ti-6-4 to study the effects of LPB and SP surface treatments.[14] Fretting damage was produced during fatigue cycling by pressing two 6.3 mm (0.25 in.) diameter Ti-6-4 alloy cylindrical rods onto the specimen gage section using a bridge device[21] with a constant normal force of 33.7N (150 lbs) (i.e., 16.8 N per rod). The nominal contact stress was 462 MPa (67 ksi). The R=0.1 fatigue results are shown in Figure 8. The 10^7 cycle fatigue strength for electropolished base-line Ti-6-4 is nominally 538 MPa (78 ksi), which decreased drastically to 172 MPa (25 ksi) with fretting. Compression from shot peening provides significant benefit, restoring the fatigue strength to 380 MPa (55 ksi). In contrast, LPB provided nearly complete mitigation. All but two LPB specimens tested at high stress levels (758 and 827 MPa (110 and 120 ksi) failed outside of the LPB zone or sub-surface, with cracks initiating below the compression layer, and not from the fretting scars.

SUMMARY

The deep compression produced with low cold working by LPB has been shown to resist thermal relaxation at turbine operating temperatures far better than conventional shot peening. The deep layer of compression has been shown to completely mitigate FOD up to 0.25 mm (0.01 in.) deep in Ti-6-4, IN718 and 17-4PH. Damage 1.27 mm (0.05 in.) deep can be tolerated in Ti-6-4 blade edges. The corrosion fatigue strength of 17-4 PH and fretting fatigue performance of Ti-6-4 can be substantially improved. Performance studies of other alloys are in process with comparable initial results. LPB can be performed on conventional CNC machine tools in a machine shop environment either during original manufacturing or overhaul and repair, supporting a wide range of potential applications.

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