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STUDIES ON THE EFFECTIVENESS OF LOW PLASTICITY BURNISHING WITH 4-AXIS CNC VERTICAL MILL FOR COMPRESSIVE RESIDUAL STRESS LAYER IN AUSTENIZED STEEL

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ABSTRACT: The present work focuses to study the effectiveness of low plasticity burning process. Compressive residual stresses equivalent to material yield strength in quenched and tempered 40 HRC austenized steel were achieved on as-corroded surfaces and sub-surface layers. The total depth of compression was about 1.25 mm. Corrosion damage from 100 and 500 hour salt fog exposures reduced the fatigue strength respectively by about 25 and 50 percent relative to the as machined uncorroded fatigue strength. Fractography revealed that fatigue failures of salt fog-exposed specimens initiated at corrosion pits. Fatigue failures in LPB treated corroded specimens also initiated at corrosion pits.

Keywords: *Plasticity burning process, residual stress, yield strength, austenized steel*

1. INTRODUCTION

Pitting corrosion is known to significantly reduce fatigue strength and life, especially in the high cycle fatigue regime. Typically, fatigue endurance limits are reduced by pitting to nominally half or less those of uncorroded strength levels [1,2]. The effects of corrosion and corrosion-induced fatigue reduce useful component life and increase aircraft maintenance costs. The corrosion rework practice in aircraft components is to mechanically remove corroded layers either by hand or by machining followed by a mechanical surface enhancement treatment. The most commonly used treatment is shot peening, which introduces compressive residual stresses into component surface and subsurface layers. This at least partly compensates for loss of component strength that has resulted from reduction of section size by removal of corrosion-damaged layers.

New surface enhancement technologies have recently been developed which are superior to shot peening as regards compressive residual stress magnitudes and depths to which compression can be achieved. Laser shock peening (LSP) has produced marked fatigue life increases in titanium alloy specimens containing deep foreign object damage (FOD)[3,4]. LSP is quite expensive to perform and, for reasons of safety and delicacy of apparatus, is not readily or easily adaptable to aircraft manufacturing and overhaul shop environments. More recently, low plasticity burnishing (LPB) has been demonstrated to provide depths and magnitudes of compressive residual stress comparable to those from LSP yet at far lower cost. LPB can be performed on conventional and CNC machine tools at costs and speeds comparable to those in conventional machining operations. Recent modeling of fatigue crack growth from corrosion pits in 7075-T6 aluminum alloy specimens indicated that the pits can be considered as semi-elliptical surface cracks of depth on the order of average pit depth for the purpose of predicting fatigue strength degradation8. Therefore, if one could induce a layer of compressive stress of sufficient magnitude and depth into a pitted material, one might prevent the formation of fatigue cracking or at least significantly inhibit growth. Residual stress distributions developed via LPB in Ti- 6Al-4V and Inconel 718 have exceeded 1 mm depth, well beyond the depth of typical corrosion pitting {5,6].

The present work was to investigate the effectiveness of LPB in creating a compressive residual stress layer in 4340 steel to improve the fatigue strength of salt fog-pitted specimens relative to the uncorroded level.

2. EXPERIMENTAL PROCEDURE

A steel plate of 12.5 mm thick with the chemical composition as given in Table-1 was machined into blanks, 200 X 30 X 10 mm. The blanks were heat-treated by austenitizing, quenching and tempering. The tensile, 0.2% offset yield strengths and hardness of the steel plates are 1160 MPa, 1090 MPa and 40 HRC respectively.

Table-1 Chemical composition of plate

ELEMENT	C	Mn	S	P	Si	Cr	Ni	Mo	Fe
%wt	0.40	0.65	0.02	0.02	0.21	0.74	1.60	0.20	REMAINDER

2.1 LOW PLASTICITY BURNISHING

The low plasticity burnishing (LPB) involves a single pass of a smooth free rolling spherical ball under a normal force sufficient to plastically deform the surface of the material, thereby creating a compressive layer of residual stress. The process is shown schematically in Fig-1. The ball is supported in a fluid bearing with sufficient pressure to lift the ball off the surface of the retaining spherical socket. The ball is in mechanical contact only with the surface to be burnished and is free to roll on the surface of the work piece. 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.

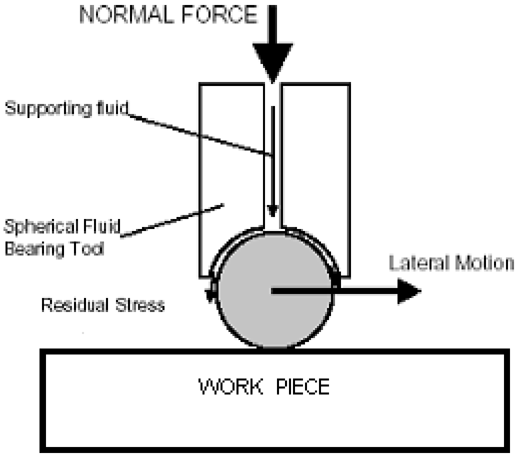

Fig- 1 **-** Low Plasticity Burnishing

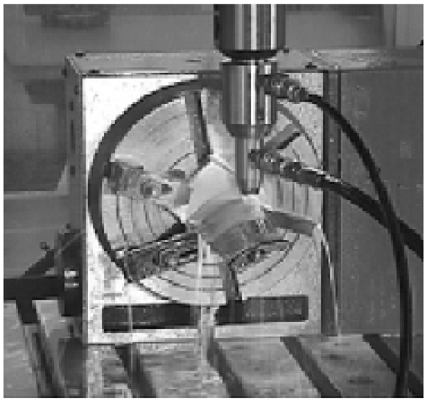

Fig- 2 LPB tool being used in four-axis mode while performing LPB on a compressor blade in a 20 HP vertical CNC mill.

The burnishing ball develops subsurface contact stresses in the work piece. These stresses act parallel to the plane of the surface and 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, thereby producing deep subsurface compression. The normal force required and the depth at which yielding first occurs depend upon the ball diameter. The speed of burnishing up to 2.5 m/sec has been found to have no effect upon the residual stress distribution produced. This allows 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 plastic deformation of the surface is necessary to achieve surface compression. 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 [7,8]

The LPB tool was designed to fit a CAT-40 tool holder in a 20 HP vertical CNC mill for four-axis operations as shown in Fig-2. The quill of the machine is not rotated. 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. 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 burnishing force and tool feed can be varied in order to feather the residual stress field, thereby 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, readily available from ball bearing applications, have been used successfully in the current apparatus. The surface finish achievable depends upon the finish of the ball. Bearing balls are commonly available with finishes of grade 25.

2.2 X-ray Diffraction Characterization

Diffraction peak broadening, measured along with the residual stress, allows the amount of damage developed by surface enhancement 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 [9]. 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 cumulative and is independent of the mode of deformation. Thus, the subsurface yield strength distribution can then be estimated from true stress-strain curves 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.

2.3 High Cycle Fatigue Testing

Four-point bending was selected to provide maximum sensitivity to the surface condition. Fatigue testing was conducted at room temperature on a 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 the testing of highly compressive surface conditions created by surface enhancement methods. The test specimen provides a nominally 0.5 in. wide by 1-in. long region under uniform applied stress to minimize scatter in fatigue testing.

The original gage section thickness of nominally 15 mm was chosen to be adequate to support the tensile stresses induced in the back surface of the specimen when a deep highly compressive layer was formed on the test surface. The gage section thickness was then reduced to 0.25 in by milling the backside to insure failure out of the highly compressive surface in four-point bending. The samples were finished machined by milling using conventional end milling to simulate the surface conditions including residual stress and cold work that would be present on a machined structural aircraft component manufactured from the steel. Base line S/N curves were developed for the as-machined condition and the machined condition plus LPB processing. S/N curves were then developed for specimens that had been machined and then exposed to either 100 or 500 hours in the salt fog environment. Half of the specimens given the 100 and 500-hour exposures were then LPB processed. S/N curves were then generated for the as-corroded and corroded plus LPB specimen groups.

2.4 Salt Fog Corrosion Exposure

Salt fog corrosion exposures were performed at 35° C per ASTM B117, Standard Practice for Operating Salt Spray (Fog) Apparatus. The fog produced was such that 1.0-2.0 ml/hr of 5 ± 1 mass percent NaCl aqueous solution collected on each $80cm^2$ horizontal surface. The pH of the solution was maintained between 6.5 and 7.2. The specimens with the test surface inclined at about 30^0 from horizontal were exposed in two groups for 100 and 500 hours respectively. Only the specimen gage section areas as machined by end milling-end cutting were exposed. The remaining area of each specimen was protected from exposure using an organic polymer stop off coating. Following salt fog exposures, the coating was removed. The specimens were then soaked and rinsed in tap water followed by a distilled water rinse to remove any salt solution remaining, and then were dried. Specimens exposed for 100 hours received no further cleaning prior to LPB treatment and fatigue testing. Specimens exposed for 500 hours were heavily encrusted with red rust. The rust was removed from these by motorized, light wire brushing prior to LPB treatment and fatigue testing. Wire brushing was performed at 3450 RPM using a 200 mm diameter wire wheel having 0.3 mm diameter carbon steel wires.

3. RESULTS AND DISCUSSION

Fig- 3 shows typical residual stress-depth distributions developed by LPB of the alloy steel, 40 HRC. LPB parameters were developed using Taguchi analysis in a designed experiment to optimize compressive residual stresses and total depth of compression. Residual stress-depth results in Fig-3 show differences based on orientation to the direction of ball travel. At greater depths the relative compression magnitudes were opposite while the depth of compression was greater parallel to the ball path. These effects occur as a result of the directionality of plastic deformation created in the LPB process. Overall the depth of compression in both directions, 1.2 - 1.4 mm, was at least three times greater than can normally be achieved via shot peening a material of this hardness at 0.25-0.38 mm. The ball travel direction was always perpendicular to the specimen longitudinal plane of symmetry. Thus, the component of greater compressive residual stress magnitude was oriented in the same direction as the principal applied stress during bending fatigue testing. The cold work-depth distribution resulting from LPB can also be seen in Fig-3. The amount of cold work was generally small (< 3%) as is desirable in LPB. The maximum cold work at the surface was only very slighter greater than at any subsurface.

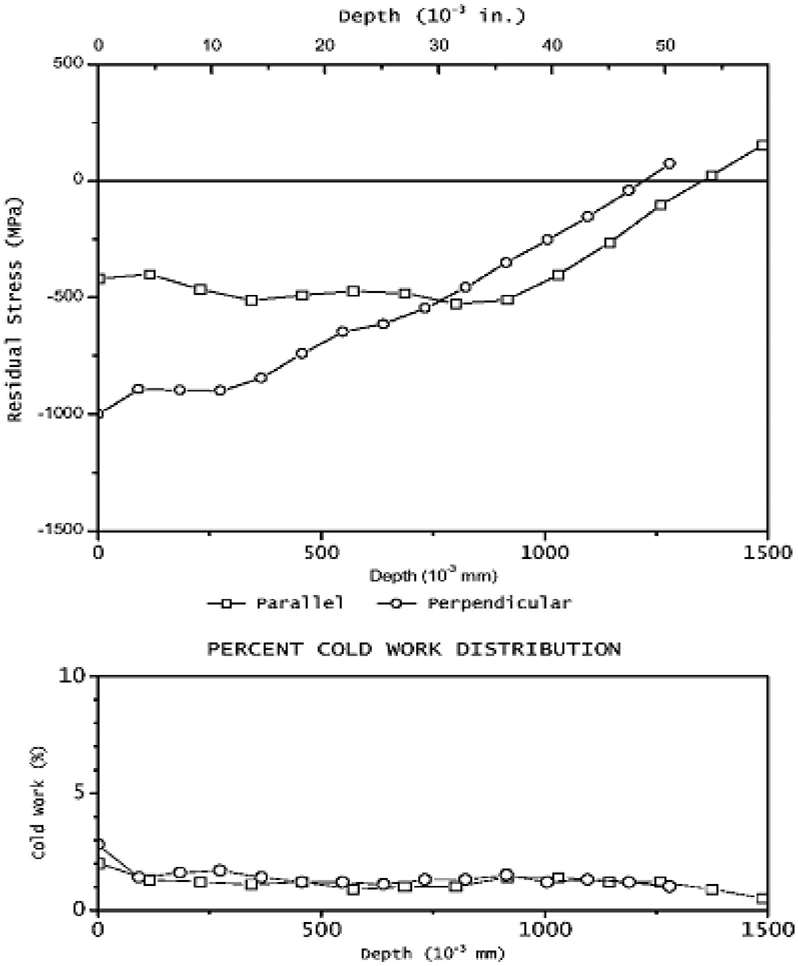

Fig-3 Residual stress-depth and percent cold work depth distributions

Optical examination of salt fog corroded surfaces revealed generally that only slight general corrosion and pitting, typically 0.05-0.10 mm deep, had occurred after 100hour exposure. After 500hour exposure, severe general corrosion and pitting, typically 0.12-0.25 mm deep had occurred. Fig-4 shows macro photographs of typical surfaces after 100 and 500hour salt fog exposures. Surface roughness data presented in Table-2 give indications of the surface degradation from salt fog exposure as well as the improvement thereof from LPB. The corrosion seriously degraded the machined surfaces with roughness increasing with exposure time. LPB of 100 hour exposed surfaces improved overall roughness to a level superior to the starting as-machined surfaces. LPB improved 500 hour exposed surfaces; however, these surfaces remained much rougher than in the as machined condition.

Fig-5 shows fatigue S-N curves generated from specimens having six different surface conditions. These were:

- As machined
- Machined + LPB
- Machined + 100hr salt fog exposure
- Machined + 100hr salt fog exposure + LPB
- Machined + 500hr salt fog exposure
- Machined + 500hr salt fog exposure +LPB

For convenience in visualizing fatigue strength differences, maximum stress values at 10^7 cycles for each surface condition are presented in bar chart form in Fig-6. As seen in Fig- 4 and 5, LPB treatment increased long-life fatigue strength approximately 30 percent relative to the as machined condition at all cyclic lives. This increase is attributed to delay in crack initiation and retardation of fatigue crack growth by the residual compressive stresses induced in surface and subsurface layers by LPB. As would be expected, corrosion on machined surfaces reduced fatigue resistance. As revealed in Fig-5, salt fog corrosion exposures greatly reduced fatigue strength relative to the machined condition at all cyclic lives. Fatigue strength reductions relative to the as machined condition of 30-35 percent and 45-55% were observed in specimens exposed for 100 and 500hrs respectively.

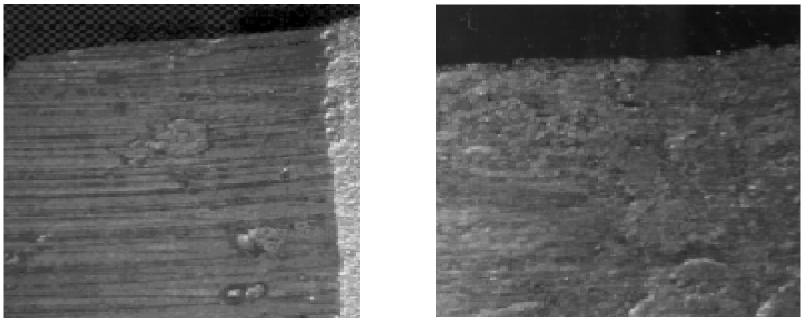

Fig-4 Typical surface appearance after salt fog exposure

LPB treatment after corrosion exposure greatly improved the fatigue strength of corroded surfaces. For the 100-hr. exposed condition, the improvement was nearly 50 percent, giving fatigue strength at 10^7 cycles more than 10 percent greater than for the original machined condition. The 60 percent fatigue strength improvement by LPB for the 500hr exposed condition was also quite marked; however, the strength level after LPB remained 25 percent less than for the original as machined condition. Apparently, compressive stresses from LPB tend to delay and retard crack initiation and progression in corrosion damaged; however, not to the full extent exhibited by LPB treatment on a relatively undamaged, machined surface.

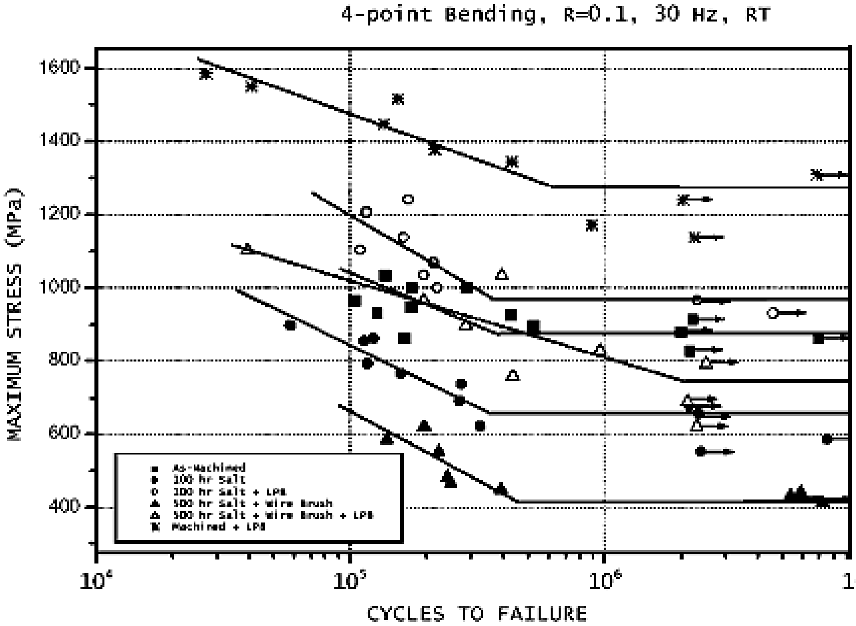

Fig-5 High cycle fatigue S/N Data

Fatigue fractures in all specimens were examined optically at magnifications to 40x to ascertain fatigue origin locations relative to processed surface areas and to determine if any extraneous features had influenced failure. In general, all fatigue failures occurred within specimen gage sections and within representatively processed surface areas. All fatigue origins occurred at specimen surfaces as could be observed optically. This is not surprising because the applied stress bias of the four-point bending, R = 0.1 testing mode would inherently favor surface fatigue origins. All machined and LPB treated machined specimens exhibited single fatigue crack origins. Multiple fatigue initiation sites were observed generally in salt fog corroded specimens and LPB treated corroded specimens. These sites were at corrosion pits even in the case of the LPB treated specimens despite their significantly greater fatigue strengths relative to as corroded-untreated specimens. This was in contrast to observations made in a previous similar investigation on 7075-T6 aluminum alloy [10] wherein fatigue origins in LPB treated specimens occurred subsurface remote from corrosion pits having the same order of depths as those observed in the current investigation. In that previous work, full rather than partial restoration of fatigue strength from LPB after both 100 and 500 hr exposures was achieved. From this, it is apparent that not all degrees of corrosion damage in steel can be fully mitigated by LPB notwithstanding that pits were only 20 percent or less than the LPB depth of compression.

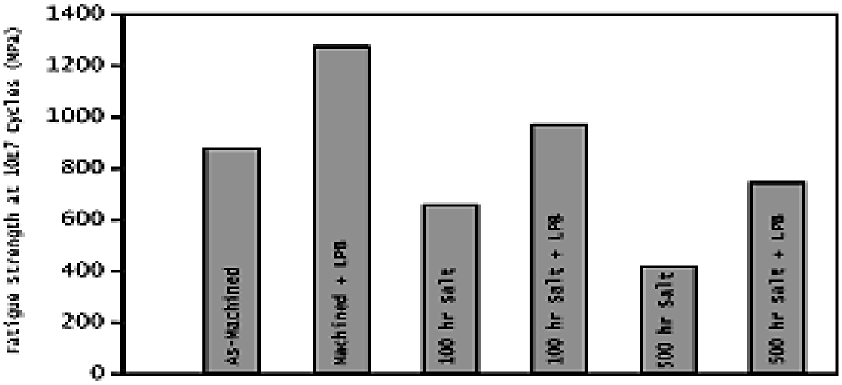

Fig-6 Long life fatigue strength

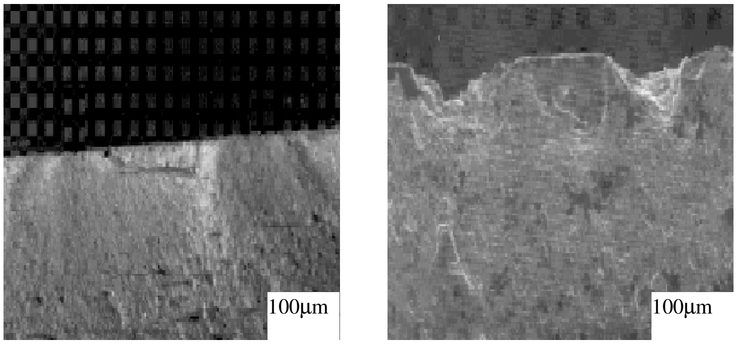

Fig-7 Fatigue origins in two LPB treated, 100 hr salt fog exposed specimens

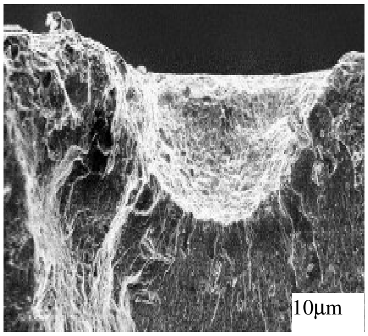

Fig-8 Microscopic fatigue origins from corrosion pit in LPB treated, 500 hr. salt fog exposed specimen.

A few specimens were selected for higher magnification fractographic observation via scanning electron microscopy (SEM). As machined and LPB treated machined specimens exhibited single fatigue origins at specimen surfaces, confirming optical observations. Also confirming optical observations, fatigue origins in as-corroded and LPB treated corroded specimens were from corrosion pits. Fig-7 is an exemplary micrograph of fatigue origins in an LPB treated, 100 hour exposed specimen. Corrosion pits were observed to be approximately hemispherical in shape. Fig-8 is an exemplary micrograph showing multiple fatigue initiation sites at the boundary of a pit in an LPB treated, 500hr exposed specimen.

4. CONCLUSIONS

Low plasticity burnishing was successfully applied to produce significant compressive residual stresses in 4340 steel, 38 HRC from the surface to about 1.25 mm deep. The magnitude of compression exceeds that which can be achieved via conventional shot peening while the LPB depth of compression is two to three times greater. Salt fog exposures produced general corrosion and pitting to depths up to 0.25 mm. This resulted in fatigue strength degradation upto 60 percent relative to the as machined, uncorroded surface condition. LPB treatment on 100-hr salt fog corroded surfaces, without removal of pitted material or corrosion products restored the fatigue strength to greater than that from the as machined uncorroded condition. LPB treatment on 500-hr.salt fog corroded surfaces, after removal of only the loose corrosion product, restored fatigue strength to within 75 percent of the as-machined uncorroded strength.

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