Mitigation of Active Corrosion Fatigue and Corrosion Pit Initiated Fatigue in AA7075-T6 with Low Plasticity Burnishing

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ABSTRACT

Corrosion related fatigue failures of aluminum structural alloys adversely impact the structural integrity of aging aircraft. A chemically active environment, susceptible material and alternating tensile stresses are all required for failure. Conventional mitigation strategies isolate the corrosive environment with coatings, change the alloy or heat treatment, or reduce the applied stress by redesign, all expensive solutions. This paper describes an alternate approach, employing surface enhancement by low plasticity burnishing (LPB) to introduce a deep, stable layer of compressive residual stress to eliminate the tensile stresses necessary for failure without altering environment, material or design.

Either 100 hr salt fog pitting or active corrosion in 3.5% NaCl during fatigue reduced the endurance limit of the baseline machined 7075-T6 surface from 205 MPa (30 ksi) to 103 MPa (15 ksi). LPB prior to corrosive exposure increased the endurance limit for 100 hr pitted samples to 310 MPa (45 ksi), and for active corrosion fatigue to 275 MPa (40ksi). The results support the use of LPB processing of fatigue critical aircraft structural components as a cost effective alternative to alloy substitution or component redesign.

INTRODUCTION

The pronounced fatigue strength reduction caused by salt corrosion pitting or corrosion fatigue in a marine environment is well established for aluminum alloys.[1] Fatigue cracks commonly initiate from corrosion pits in the aluminum alloy 7075-T6 used for aircraft structural components. Pitting arises from intergranular corrosion to a depth dependent upon the service environment and the time of exposure, i.e., the age of the aircraft.

Annual costs for corrosion inspection and repair of Naval aircraft alone are estimated to exceed one billion dollars. By the year 2015 over 90% of military aircraft are expected to exceed 20 years of age.[2] A means of mitigating corrosion and fretting related fatigue damage is needed.

Low plasticity burnishing (LPB) can provide a layer of compressive residual stress of sufficient depth to effectively eliminate the fatigue debit from prior salt pit corrosion.[1,3] The LPB process can be performed on conventional CNC machine tools in a shop environment at speeds comparable to machining operations. The residual stress distributions developed by LPB in nickel[3], titanium[4], and aluminum alloys and steels exceed 1 mm (0.04 in.) in depth, well beyond the depth of typical corrosion pits, which serve as the initiation sites for fatigue cracks.

The effect of LPB applied after corrosion pitting of AA7075-T6, simulating an overhaul operation, has previously been shown to fully restore the corrosion fatigue debit.[5] The current investigation addresses the effect of LPB processing, prior to corrosion pitting or exposure to active corrosion fatigue in the absence of deep pitting, on the fatigue performance of AA7075-T6.

EXPERIMENTAL TECHNIQUE

Material
Aluminum alloy 7075-T6 was acquired in the form of 13 mm (½ in.) plate to AMS 4045. In the -T6 heat-treated condition, the material was found to have a hardness of 89 HRB and electrical conductivity of 33.0% IACS. Chemistry was verified to be within

limits of the AMS 4045 specification. Tensile properties were verified as UTS=601 MPa (87.3 ksi), 0.2% yield strength of 542 MPa (78.7 ksi) with an elongation of 11%.

Low Plasticity Burnishing

LPB produces a layer of compressive residual stress of high magnitude and depth with minimal cold work.[6] The process has been described in detail previously,[7] as characterized by a single pass of a smooth free rolling ball under a normal force sufficient to plastically deform the surface of the material. Hertzian loading creates a layer of compressive residual stress to a depth as deep as 4 mm (0.16 in.). 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 solid 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. The LPB processing of fatigue specimens used in this investigation is depicted in Figure 1.
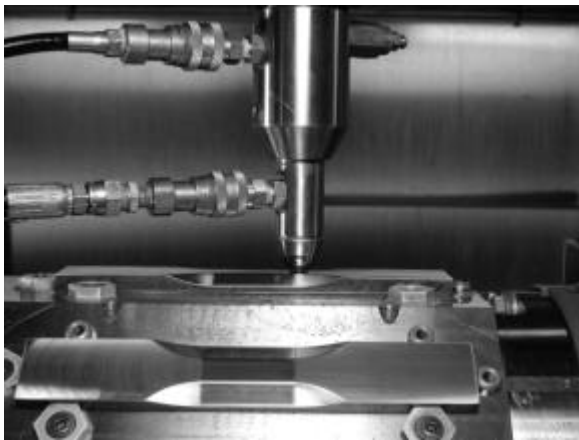

Figure 1 – LPB processing of fatigue samples with at single point contact LPB tool in a 4-axis CNC mill.

X-ray Diffraction Surface 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 previously.[8] 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.[9] 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.[10,11,12]

High Cycle Fatigue Testing

Four-point bending was the HCF testing mode selected to provide maximum sensitivity to the surface condition.[13] Fatigue testing was conducted at room temperature under constant sinusoidal load amplitude at 30 Hz, R=0.1. Fatigue data were developed as S/N curves of nominally eight samples each.

The 7075-T6 HCF samples were finish 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. S/N curves for 7075-T6 were prepared for the following combinations of surface condition, corrosion damage, or corrosive environment:

1. Machined baseline
2. Machined + LPB + 100hr salt fog
3. Machined + LPB + active corrosion fatigue

Corrosion and Fretting Exposure

The 7075-T6 salt fog corrosion samples were exposed at 35° C per ASTM B117 for a period of 100 hours. The pH of the solution was maintained between 6.5 and 7.2. Following exposure to the salt fog, any residual salt was removed by soaking and then rinsing the samples in tap water, followed with a distilled water rinse. Patches of gray and white corrosion product evident on the surface of the samples were identified by x-ray diffraction as α-Al_2O_3. The corrosion product was not removed prior to fatigue testing.

The 7075-T6 active corrosion fatigue tests were

conducted with the sample gage section wrapped in a chemical-free laboratory tissue saturated with 3.5-wt% NaCl solution and sealed with polyethylene film and vinyl to avoid evaporation. The saturated tissue served as a wick to maintain the salt solution in contact with the sample surface.

RESULTS AND DISCUSSION

Residual Stress Distributions

The residual stress distributions developed by machining and LPB processing of 7075-T6 are shown in Figure 2. Machining of 7075-T6 produced low tension on the surface and compression of less than –68 MPa (–10 ksi) below the surface. In contrast, LPB produced maximum compression on the order of –480 MPa (–70 ksi) between the surface and a depth of nominally 0.2 mm (0.008 in.). Maximum cold work occurs from the surface through the region of maximum compression, and then diminishes with depth. X-ray diffraction measurement could not be made reliably below a depth of 0.5 mm (0.02 in.) in the 7075-T6 because of the coarse grain size encountered at depths beneath the deformed surface layer.

No attempt was made to optimize the LPB parameters to achieve a specific level of residual stress or cold work that would provide the best fatigue performance. The parameters were simply chosen, based upon prior experience, to produce a deep layer of compression with available tooling. Optimizing the combination of LPB parameters (including normal force, ball size, ball modulus, and feed) allows the residual stress and cold work distributions to be tailored to the application.

Corrosion and Fretting Damage

Corrosion of the 7075-T6 only during fatigue testing was termed "active corrosion" for the purposes of this study, to indicate that the corrosion process was active only during cyclic loading, resulting in "corrosion fatigue". In contrast, salt fog exposure prior to fatigue testing produced pitting damage, but the corrosion process was not active during fatigue loading. Fatigue testing then measures the effect of the prior damage, and the fatigue cracking process is not assisted by corrosion.

Macroscopic and fractographic examination of the exposed surfaces revealed that 100 hr salt fog exposure of the machined surface resulted in uniform corrosion of the test surfaces. Pit depths averaged

100µm to 120µm (0.004 to 0.005 in.). After penetration of the surface, the corrosion crevices often were observed to progress laterally, thereby delaminating layers of material, apparently following the elongated grain boundaries produced by rolling of the plate.
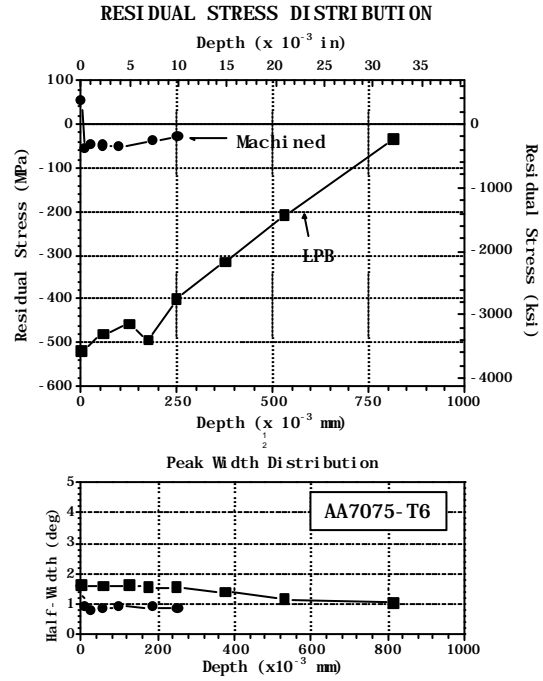

Figure 2 - Residual stress and half width distribution in machined and LPB processed AA7075-T6.

Shallower pitting was observed on the surfaces that received LPB after machining (and prior to salt fog exposure) than those machined surfaces directly exposed. Pits formed on the LPB surfaces after 100 hr salt fog exposure had irregular, near circular shapes with a 34µm (0.0013 in.) average depth and a nominal 44µm (0.0017 in.) diameter. This is nominally one-third the depth of pitting observed for the machined samples.

Active corrosion during cyclic loading at ambient temperature produced much shallower pits than 100 hr salt fog exposure at 35C. This was true even for active corrosion fatigue samples achieving the maximum exposure time for 10^7 cycles to run-out, or 108 hours of testing, in 3.5 wt% NaCl solution. For both the machined and LPB surfaces, the pits were nominally 9µm (0.0003 in) deep, and were numerous across the entire exposed surface. Pits on the machined surface tended to be circular with nominal

diameter of 5μm (0.0002 in.). Pits on the LPB surface tended to be irregular and interconnecting to extend up to 20μm (0.0079 in).

HCF Performance

The S/N curves generated for 7075-T6 in both the baseline (as-machined) and LPB conditions, after 100 hr salt fog exposure or active corrosion fatigue, are presented in Figure 3. Fatigue tests were continued for a minimum of 2.5 x 10^6 cycles with a maximum run-out at 1.2 x 10^7 cycles. The fatigue data are presented as semi-logarithmic S/N curves in terms of the maximum stress.
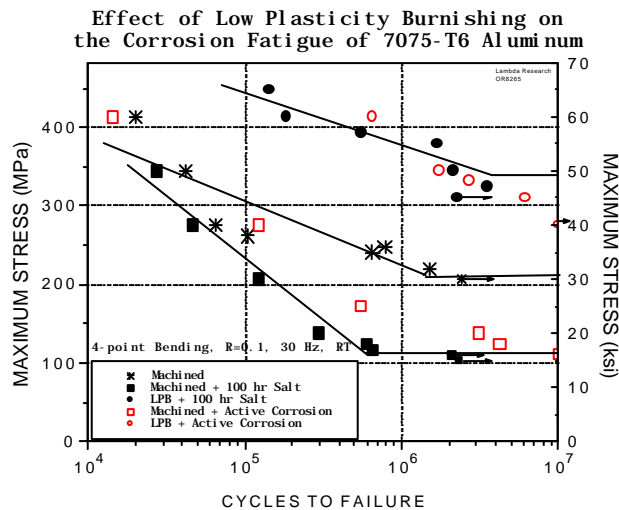

Figure 3 - High cycle fatigue results for salt fog pitted and active corrosion fatigue of machined 7075-T6 with and without LPB processing prior to exposure to corrosion.

The S/N curves for samples with pitting from prior salt fog exposure appeared to exhibit an endurance limit, implying infinite life below some threshold stress level. As commonly observed in studies of corrosion fatigue, the S/N curves for samples exposed to active corrosion during fatigue testing do not appear to have an endurance limit.[14] In the discussion that follows, the results are considered and compared in terms of the fatigue life at nominally 2 x 10^6 cycles.

The machined (end milled) surface condition produced an apparent endurance limit on the order of 200 MPa (30 ksi). Salt fog exposure for 100 hrs reduced the endurance limit to nominally 100 MPa

(15 ksi), half that of the original machined surface before exposure to salt fog generated pitting corrosion. Loss of nominally half the extended life fatigue strength following salt fog corrosion pitting appears to be typical of the degradation reported in the literature[3]. The fractional loss of fatigue life at stress levels above the endurance limit increased rapidly as the maximum stress level reduced, reaching an order of magnitude at the 200MPa (30ksi) endurance limit

Active corrosion fatigue in 3.5% NaCl solution, with no prior corrosion damage, degraded the fatigue strength relative to the as-machined condition by an amount only slightly less than prior pitting corrosion up to a life of 10^7 cycles. Note the failure occurring in active corrosion fatigue at the 10^7 cycle endurance limit for a maximum stress of 110 MPa (16 ksi). The data appear to suggest further reduction in fatigue strength with increasing life and the absence of an endurance limit for active corrosion fatigue of the machined 7075-T6 surface.

LPB prior to salt fog pitting resulted in a 70% increase in the endurance limit, from nominally 200 MPa (30 ksi) to over 330 MPa (48 ksi). LPB prior to corrosion pitting increased the fatigue life at stress levels above the base line endurance limit by two orders of magnitude, a 100X life increase over the un-corroded original machined surface.

A comparable benefit in fatigue performance was observed for LPB prior to active corrosion fatigue in 3.5% NaCl solution. As noted above, a true endurance limit may not exist for the active corrosion fatigue mechanism; however, the fatigue strength at 10^7 cycles was at least 282MPa (41ksi), 32% higher than the un-corroded original machined surface. Fatigue lives were 100 times that of the baseline for stress levels above the baseline endurance limit of 220 MPa (32 ksi).

Fractographic analysis revealed that all the fatigue failures in specimens without prior LPB, whether exposed to salt fog pitting or active corrosion fatigue, initiated at the surface. A typical surface fatigue initiation site is shown in Figure 4. All of the salt fog pitted sample initiations were exclusively from corrosion pits, as observed previously[6]. Specimens tested at lower stresses generally exhibited origins from a single pit or surface location, while specimens tested at higher stress levels tended to have multiple nucleation sites.
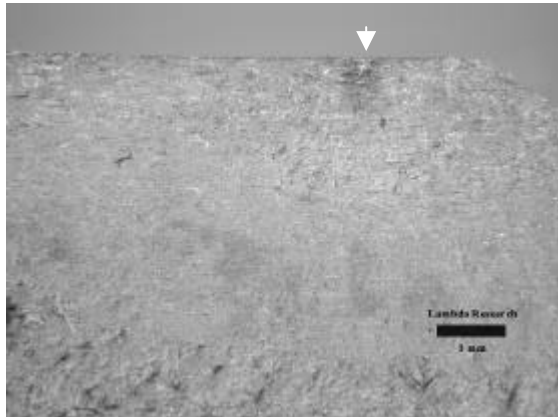
Figure 4 – Typical surface fatigue initiation site on machined 7075-T6 in active corrosion fatigue.

The effect of the layer of high residual compression produced by LPB was to drive fatigue origin below the surface by as much as 1mm (0.04 in.). All of the fatigue cracks in the LPB + salt fog pitted 7075-T6 samples originated not at the damaged surface, but subsurface. At the high stress levels required for failure of the LPB samples, the stress below the compressive layer simply exceeded the fatigue endurance limit, and the detrimental effects of surface pitting or active corrosion did not contribute to either the fatigue initiation or propagation process. As the fatigue failures did not originate in the LPB processed surface, the fatigue results can only be interpreted as indicating that the LPB surface has even higher fatigue strength than indicated.

CONCLUSIONS

The fatigue performance of the corrosion sensitive aluminum alloy 7075-T6 is greatly improved by low plasticity burnishing (LPB) performed prior to exposure to either salt fog pitting or active corrosion fatigue in 3.5% NaCl solution. Both corrosion mechanisms reduced the fatigue endurance limit of machined (end milled) 7075-T6 to half of the original fatigue strength. LPB prior to exposure to either corrosion mechanism increased the HCF strength to over three times the strength of a corroded machined surface and 150% of the strength of the non-corroded machined surface. The fatigue life of 7075-T6 exposed to either corrosion mechanism at stress levels above the endurance limit is at least 100 times greater with prior LPB processing.

The improvement in fatigue life and strength is attributed to the introduction of a layer of residual compression with a magnitude and depth sufficient to suppress fatigue crack initiation and propagation. The magnitude and depth of compression are sufficient to close shallower cracks emanating from corrosion pits and fretting scars, rendering them innocuous, and altering the mode of fatigue crack nucleation and growth.

LPB has been demonstrated to substantially improve the fatigue performance of the aluminum alloy 7075-T6 in corrosion fatigue. Applied locally to highly stressed fatigue prone locations in aging aircraft, LPB could extend the useful life of aging aircraft components limited by corrosion related fatigue.

REFERENCES

1   N.E. Dowling, Mechanical Behavior of Materials , Prentice Hall, NJ, 1993, p. 365.
2   V.S. Agarawala, "Corrosion and Aging: Aircraft Concerns," presentation at 11th Annual AeroMat Conference, Bellevue, WA, June 26-29, 2000.
3   P.S. Prevéy, J. Telesman, T. Gabb, P.Kantzos, "FOD Resistance and Fatigue Crack Arrest in Low Plasticity Burnished IN718," Proceedings of the 5th Nat. Turbine Eng. HCF Conference, 2000.
4   P.S. Prevéy, and M.J. Shepard, "Surface Enhancement of Ti-6Al-4V Using Low Plasticity Burnishing," Presentation at 11th AeroMat Conference, Bellevue, WA, June, 2000.
5   P. Prevéy, "Low Cost Corrosion Damage Mitigation and Improved Fatigue Performance of Low Plasticity Burnished 7075-T6," Proc. 4th International Aircraft Corrosion Workshop, Solomons, MD, Aug. 22-25, 2000.
6   U.S. Patent 5,826,453 (Oct. 1998) and 6,415,486 B1 (Jul. 2002), other patents pending.
7   P. Prevéy, "The Effect of Cold Work on the Thermal Stability of Residual Comp ression in Surface Enhanced IN718," Proc. 20th ASM Materials Solutions Conf. & Expo, St. Louis, MO, Oct. 10-12, 2000.
8   P. Prevéy, "The Measurement of Subsurface Residual Stress and Cold Work Distributions in Nickel Base Alloys," Residual Stress in Design, Process & Materials Selections, ed. W.B. Young, Metals Park, OH: Am. Soc. For Metals, 1987, p 11-19.
9   P. Prevéy, P. Mason, D. Hornbach, & J. Molkenthin, "Effect of Prior Machining Deformation Upon the Development of Tensile Residual Stresses in Weld Fabricated Nuclear Components," Journal of Materials Engineering and Performance, Vol. 5, 1,

February 1996, p. 51-56.

10 P.S. Prevéy, Metals Handbook, Vol 10, ASM, Metals
    Park, OH, (1986), p. 380-392.

11 M.E. Hilley, ed, Residual Stress Measurement by
    XRD, SAE J784a, SAE, Warrendale, PA (1971)

12 Noyan & Cohen, Residual Stress Measurement by
    Diffraction & Interpretation, Springer-Verlag, NY,
    (1987)

13 P. Prevéy, W.P Koster, "Effect of Surface Integrity on
    Fatigue of Standard Alloys at Elevated Temperatures,"
    Fatigue at Elevated Temperatures, ASTM STP561,
    ASTM, Phil., PA, (1972)pp. 522-531.

14 N.E.Frost, K.J.Marsh, and L.P. Pook, Metal Fatigue,
    Dover, NY, 1974, p 105-112