IMPROVING THE FATIGUE RESPONSE OF AEROSPACE STRUCTURAL JOINTS

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Abstract. The effect of various surface treatments on the fretting fatigue and joint fatigue performance of a 7xxx series aluminum alloy was investigated with the objective to reduce the nucleation and growth of fretting cracks and enhance the fatigue life of aerospace joints. The results indicate that anodizing does not influence the fretting fatigue performance and the type of anodizing does not affect the joint fatigue life. UltraCem coating inhibited fretting crack nucleation in the fretting specimen, increasing the fatigue life. Shot peening increased the fretting fatigue life significantly due to the compressive residual stresses it imparts; however, the stresses were not deep enough to influence the fretting cracks which nucleated in the hole bore of the joint specimens. Laser peening and low plasticity burnishing induce deeper compressive residual stresses than shot peening, which appear to inhibit the growth of fretting cracks in both the fretting and joint specimens, resulting in a significant fatigue life improvement.

INTRODUCTION

Fatigue performance is an important selection criterion for aerospace materials due to the cyclic stresses an aircraft experiences. In recent years, advanced aluminum alloys have been developed which offer improvements in intrinsic fatigue crack nucleation and growth resistance as well as increased strength and toughness compared to incumbent alloys. However, when these materials are tested in a more structurally realistic way, such as in a joint test, the improvement in fatigue life is not as large[1]. The reason for this smaller increase in fatigue performance is believed to be primarily due to a change in the crack nucleation mechanism. Basic stress-cycle (S-N) fatigue tests use a simple one-piece specimen to determine the fatigue life of the alloy. In this situation, the crack usually nucleates at one of the larger microstructural inhomogeneities such as a constituent particle or micropore. However, when the same alloy is tested in a joint configuration, the situation is much more complex with additional factors contributing to the 'quality' of the specimen. In an aerospace joint, the overall condition of the specimen depends on the quality of such things as:

- machining, including fastener hole production and hole bore surface finish
- faying surface quality and treatment, including anodizing and priming
- specimen assembly, including alignment, fastener type, fastener fit and joint preload or clamping force
- amount of fretting occurring between the faying surfaces of the plates and between the fasteners and the plate.

Mechanically fastened joints are a common design feature used by airframers and are often considered a fatigue critical detail in metallic aerospace structures. To enable weight reduction while allowing aluminum structures to operate at increased stress levels, improvements in joint fatigue must be realized[2]. All of the above factors can contribute to a decrease in the joint fatigue life and while cracks in joints may nucleate due to poor machining quality, crack nucleation can also be caused by fretting during service.

Fretting fatigue can occur when two materials, which are nominally joined, undergo small relative cyclic displacements. The normal and tangential stresses induced in the material's surface during fretting can nucleate cracks after a low number of cycles, which then propagate under the fatigue stress to cause fracture. As airframers use more corrosion resistant alloys and take advantage of the use of interference fit fasteners and hole cold working processes to reduce the stress concentrations associated with fastener holes, fretting initiated fatigue failures may be more commonly observed[3]. This is especially true for low load transfer (LLT) joints due to the reduced potential for failures nucleating from stress concentration associated with fastener hole.

Research has shown that certain surface treatments may improve fretting resistance and joint fatigue life through a number of different mechanisms[4]:

- Introducing compressive residual stress at the surface and/or in the hole bore which may slow or stop fretting nucleated cracks from propagating.
- Decreasing the coefficient of friction to prevent the stick-slip condition required to nucleate fretting cracks.
- Increasing the surface hardness to prevent wear.
- Altering the surface chemistry.
- Increasing the surface roughness to limit the surface-to-surface contact which is required to nucleate fretting cracks.

This research examined a number of coatings and surface treatments as possible methods to reduce fretting and delay initial crack growth, thus enhancing the overall fatigue life of the material. Basic fretting fatigue tests and low load transfer (LLT) joint fatigue tests were used to characterize the results. Focus was given to treatments that are relevant to aerospace structures and are ready or near-ready for commercial applications.

BACKGROUND

The following section provides a brief description of each of the methods examined in this work including the benefits and disadvantages to fretting and joints, comments on their practicality and stage of development.

Anodizing[5,6]

Anodization is a mature, relatively low cost technology that is already used by aircraft original equipment manufacturers (OEMs) on large parts to prevent corrosion. The aluminum part is placed in an acidic bath for a given time under an applied current which anodizes the aluminum to produce a protective layer of Al_2O_3.

Different anodizing methods provide variations in the hardness, thickness, and porosity of the anodized layer as well as offering alternative levels of corrosion performance and environmental impact. However, it is commonly recognized that anodizing can significantly reduce the fatigue life due to the presence of pores and microcracks in the anodized layer. Much research has been conducted to develop improved anodizing techniques to increase fatigue life, reduce the time and cost of the procedure, and minimize environmental impacts. Four different anodizing techniques were chosen for evaluation in this work:

1. Chromic acid anodizing (CAA) produces a thick, hard and porous layer which provides good chemical and mechanical adhesion to the primer. Currently used by OEMs.

2. Phosphoric acid anodizing (PAA) provides a layer of medium thickness that has good adhesion and good corrosion performance. It is more environmentally 'friendly' compared to the methods that use chromium. It is currently used by OEMs.
3. Alodine 1200 is a chromium based conversion coating which provides a thinner, softer, gelatinous coating that only offers chemical adhesion to the primer. The processing parameters for this version of Alodine were developed by Alcoa Inc.
4. Sulfuric/boric acid anodizing is a combination of 1% boric and 5% sulfuric acid which provides a softer layer than chromic or phosphoric acid but better adhesion than Alodine. This process does not contain chromium so is also environmentally friendly.

While previous data shows that anodizing is detrimental to standard fatigue behavior, effects on fretting fatigue are generally not known but are thought to be minimal[2]. As anodizing is a currently used corrosion treatment for aircraft, any improvements to fatigue life that originate from this technique could be easily adopted to practical applications.

UltraCem[7]

UltraCem is a hard electroless nickel-boron layer applied to the surface of a material to improve wear resistance and reduce friction. It also provides corrosion resistance. This newly developed process is more applicable to smaller parts and to material exposed to high wear situations. While it may not be suitable for the structural components of an aircraft wing, it has been included in this test program to examine the fretting benefits of this coating.

Shot Peening[4, 8-11]

Shot peening is a low cost, mature technology which is currently used by OEMs on wing skins to correct distorted parts, form complex curvatures, inhibit fatigue and SCC and relieve residual stresses due to machining. Small steel or glass shots are impacted on the surface which produce a superficial compressive residual stress in the surface. The compressive residual stress has been reported to be as high as 60% of the material's ultimate strength[11]. This compressive stress induces crack closure and the strain hardening reduces the amount of crack tip plasticity which acts to improve fatigue life by retarding growth of small cracks ($\Delta K < 11$ MPa-m)[11]. However, shot peening can also cause subsurface cracks, stress concentrations, a high level of cold working and surface roughening[8].

Laser Peening[11 -16]

Laser peening is a developing technology which induces a deep compressive residual stress in the material by forming an expanding plasma shock wave near the surface from a high energy laser beam. This process produces a higher magnitude and deeper compressive residual stress compared with shot peening. Laser peening causes little strain hardening or surface roughening but may cause in-plane stress concentrations which act as crack initiation sites[12]. Laser peening can result in specimen bending if only one side is treated.

Low Plasticity Burnishing[17-19]

Low plasticity burnishing (LPB) is a new method of surface enhancement which induces deep compressive residual stress by the forced application of a smooth rolling ball across the surface of the metal. LPB produces a smooth, mirror-like surface and minimal cold working, and has been shown to improve fatigue, fretting fatigue and stress corrosion performance. However, LPB can also result in specimen bending if only one side is treated and may move crack nucleation to a subsurface site below the compressive layer[18]. LPB is more suited for treating spot locations and can be used with CNC machine tools at near machining speeds.

EXPERIMENTAL METHOD

To focus on the effects of the surface treatments, only one alloy was used to produce all the fretting and joint specimens. 7085-T7651, an aerospace aluminum alloy, was chosen as it is known that 7XXX series alloys have lower fatigue properties at higher Kt values or in joints compared to 2XXX series alloys, thus producing the 'worse case' scenario (TYS(L)=538MPa, UTS(L)=569MPa, E=70GPa). The production quality 7085-T7651 plate was originally 38.1mm (1.5in) thick and specimens were extracted from the t/2 plane, which is the standard sampling location for determination of plate properties. All fretting and joint specimens were oriented parallel to the longitudinal (rolling) direction of the plate. Figure 1 shows dimensional diagrams of the fretting and joint specimens. The LLT joint fatigue specimen is a reversed double dog-bone, designed to have approximately 5% load transfer per fastener and a secondary bending ratio of approximately 0.10 to 0.25. This specimen is representative of a joint between the wing skin and stiffener.

The anodizing treatments were applied to the machined surfaces of the specimens at the Alcoa Technical Center, while the residual stress inducing processes and UltraCem were applied by external resources. For the LLT joints, all processes were applied prior to hole fabrication in the specimen. The chromic, phosphoric and sulfuric-boric anodizing parameters followed standards used by OEMs, while the Alodine 1200 technique followed a new practice developed by Alcoa. The anodizing parameters are provided in Table 1.

Shot peening and laser peening were performed by the Metal Improvement Company (MIC)[20]. Shot peening was only applied to the fretting contact area of the fretting fatigue specimens and the reduced width area of the LLT specimens following a standard process established for aircraft OEMs. The parameters were 100% coverage, 230-280 cast shot and 0.005A nominal intensity. As the laser peening process is a new and developing technology, collaborative work was undertaken with MIC and the University of California, Davis, to find a set of processing parameters which would be beneficial for the fretting and joint specimens. The set of parameters chosen were a laser strength of 4GW/cm^2, 18 nanosecond duration of pulse and 3 passes over the area (4-18-3). The fretting specimens were treated between the grip ends on both sides with a 2.5mm square spot size while the LLT joint specimens were treated on both sides in the reduced gauge with a 4.7mm square spot size believed to be more suitable for treatment around fastener holes. The low plasticity burnishing (LPB) was applied to the fretting and joint specimens by Lambda Technologies[21] in the fretting pad contact region and in a rectangular region which encompassed the location of the fastener holes in the joints, as shown in Figure 2. The UltraCem coating was applied by UCT Coatings Inc.[7] The surface of the fretting specimens was pretreated with nickel phosphorus and then a layer of UltraCem was applied to the entire specimen. For this evaluation, UltraCem was not applied to LLT joint specimens since this treatment would not be as applicable to large aircraft structural components. Metal coupons having the same thickness as the fretting and joint specimens were also treated by each technique. These specimens were used to measure the residual stress in the metal, the surface roughness, and to obtain images of the microstructure.

To replicate commercial applications as closely as possible in the joint specimens, the surface treatments that impose a compressive stress but no corrosion prevention layer, were also anodized using the standard chromic acid anodizing practice and primed using Sterling U-1201 yellow, strontium chromate epoxy primer, which meets Mil Spec No. Mil-P23377D. To assemble the specimens, the sideplates were stacked as shown in Figure 1, and fastener holes were match drilled and reamed to a final diameter of 6.26 mm. The holes were then countersunk 100° using a tool with an integral radius which removes the sharp corner transition from the countersink to hole bore. The holes were deburred and PR1422 Class B Fuel Tank Sealant was applied to the reduced section of one sideplate, while an adhesive, Thermoset 600 resin was applied to the grip area of the opposing sideplate. The sideplates were fixtured to ensure hole alignment and Aero-Lite AL755-AP-8-9 fasteners were installed using KFN587-4 collars torque tightened to 7.9 N-m. The measured interference between the fastener and hole diameter was 0.076 mm.

Multiple fretting and joint tests were conducted where possible for each treatment. The LLT joints were tested in high humidity air (>90%) under constant amplitude loading. Specimens were tested using a mean stress level of 46.5 MPa ± 98.3 MPa and ±118.2 MPa, using a test frequency of 10 Hz. The 98.3 alternating stress level was selected since it would produce a stress which is 25% higher than the maximum expected ground-air-ground (GAG) cycle for a twin aisle aircraft with under wing engines. Additional tests were conducted at the alternating stress of 118.2 MPa, which would represent a 20% coupon to structure factor. Use of a negative stress ratio was selected in order to be more representative of the negative GAG cycle an aircraft will experience.

The fretting pads were made from 7085-T7651 and used in the as-polished condition to minimize complications which may arise from the application and use of the surface treatments on the pads. Additionally, this meant that all specimens experienced the same fretting pad contact conditions. The fretting fatigue tests were conducted under only one set of test conditions to be able to directly compare the effects of the surface treatments. The test parameters used were a maximum fatigue stress of 221MPa, R ratio of 0.1 at a frequency of 25Hz in room temperature and approximately 55% relative humidity. The maximum normal force applied by the fretting pad was approximately 77MPa which was matched by an equal force on the opposite side of the specimen to prevent bending. The tests were conducted until failure with a run-out of 5 million cycles.

Electrolyte	Time	Temp	Volts	Thickness
50g/l Chromic acid	40 min	40°C	0-50 Ramp	>2153 mg/sq m
Phosphoric acid	25 min	29.4°C	15	Visual color determination
5%Sulfuric / 1%Boric	15 min	23.9°C	5-15 Ramp	2153-6458 mg/sq m (1-3micron)
15% Alodine 1200	45 sec	21.1°C	NA	764-1598 mg/sq m

Table 1: Parameters used for anodizing the specimens.

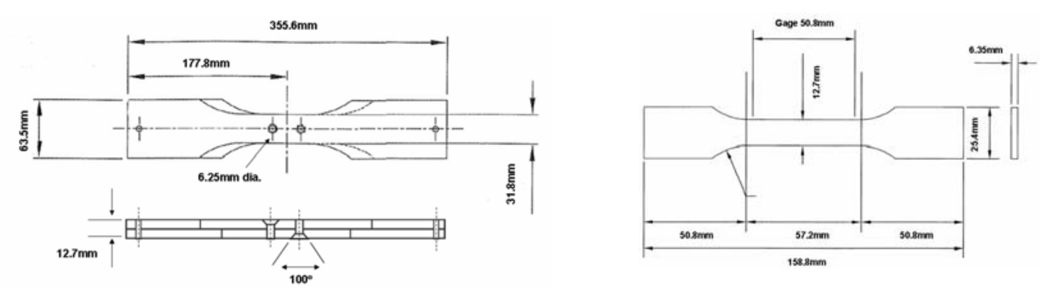


Figure 1: Dimensional diagrams of the low load transfer joint (left) and fretting fatigue (right) specimens.

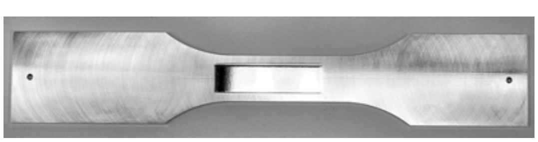


Figure 2: LLT joint fatigue sideplate after application of the low plasticity burnishing.

RESULTS

Characterization of the surface techniques

The surface treatments, and their effect on the metal, were characterized by obtaining optical images of the surface and grain structure, and by measuring the surface roughness using a MicroXAM Interferometer Surface Profiler. Table 2 provides a visual summary of the results. In the as-machined condition, the 7085 has some uniform machining marks which produce an average surface roughness (Ra) of 0.65μm. The specimens treated with the various anodizing techniques still show the machining marks although they have a slightly rougher surface possibly due to the growth of the anodized layer. The anodized layer is too small to be seen using an optical microscope and no significant effect on the grain structure was observed. The UltraCem coating was approximately 8-10μm thick which can be clearly seen under an optical microscope. The surface of the coating is uniformly rough with an average roughness higher than the as-machined specimen. Shot peening produced the highest surface roughness with an average value of 2.52μm. The deformation of the grains in the subsurface layer can be seen in the cross-sectional image. Laser peening also produces a rougher surface than the as-machined condition, however, the underlying machine marks are still evident. The surface of the low plasticity burnishing specimen has the lowest surface roughness and the machining marks have been removed. The rolling undulations from the repeated application of the ball can be seen in the surface profile while the appearance to the naked eye is shiny and very smooth. No effect on the sub-surface grains can be seen.

The residual stress induced in the metal after the application of the surface treatments was measured using a hole drilling technique (ASTM E837) for the as-machined, anodized, UltraCem and shot-peening treatments. As the laser peening and LPB had higher stresses, an EDM slitting process[15] and an X-ray diffraction technique[19] were used, respectively, to measure the residual stresses. The average residual stress as a function of the depth can be seen in Figure 3 and while the values may be approximate, the trends in residual stress between treatments should be reliable. The as-machined and all of the anodized specimens appear to have a slight compressive residual stress (max. ~30MPa) just below the surface, which may be due to the stresses induced during machining as anodizing is not expected to have a significant stress effect. The residual stress goes to zero in all of these specimens by a depth of ~150μm. The application of the UltraCem layer appears to produce a relatively low compressive residual stress (max. 100MPa) which decreases and crosses zero stress at a depth of ~130μm below the surface. Shot peening, laser peening and LPB techniques induce higher compressive residual stresses (max. ~250 to 530MPa). The residual stress induced by shot peening decreases to zero more quickly (~150μm) than from laser peening (~1400μm) and LPB (~750μm) which maintain a significant level of compressive stress further below the surface. The approximate depth of a fretting crack as seen in prior work is also indicated on the graph[22]. The UltraCem, LPB, shot peening and laser peening all have significant compressive residual stress at the depths seen by the fretting crack and therefore it may be hypothesized that if a fretting crack nucleated in these specimens, its growth would be restricted and thus the fretting life would be increased.

Fretting Fatigue Results

Three to five specimens were tested under fretting fatigue conditions for each surface treatment and the results can be seen in Table 3. For the as-machined, all the anodized and some of the laser peened specimens, failure occurred at the fretting pad and is therefore attributed to fretting crack nucleation and growth (indicated by italics in Table 3). In the

UltraCem specimens, failure occurred in the grip region or at a corner. For the shot peened specimens, failure was also in the grip region or the test was a run out. For the laser peened and LPB specimens, failure sometimes occurred at the edge of the treated area where the change in residual stress in the specimen makes it more favorable for a crack to nucleate at this location. Moving the nucleation site from the fretting region to an alternative location, such as the edge of the treated region or below the surface where the residual stress ends, has been noted as a side effect of some surface treatments[8]. Thus these treatments only remain valuable if the nucleation at these alternative sites is delayed enough to prolong the overall life. Figure 4 shows the mean fretting fatigue life for each surface treatment with the error bars representing the maximum and minimum lives obtained. The failures which were not caused by fretting were still included as a change in the nucleation mechanism from fretting to another source was still considered a viable method of life extension.

The anodizing techniques showed no fretting life improvement over the as-machined specimens but neither did they show a reduction in the fretting life. This has also been noted by others[2, 10]. As these surface techniques do not induce a residual stress nor significantly change the surface topography, they appear not to be able to positively influence the fretting characteristics. Alternatively, while anodized surfaces are known to decrease the fatigue life of aluminum due to the presence of pores and microcracks, these results indicate the fretting stresses and damage are greater than that from the anodized surface. Thus anodizing appears to have no negative effects on the fatigue life if fretting is also present.

The surface treatments which induce compressive residual stress in the aluminum all resulted in a significant increase in the fretting fatigue life. Laser peening and LPB both showed approximately five times improvement in the fretting fatigue life. Both of these techniques induce high compressive residual stresses to significant depths. Most of the laser peened specimens failed due to fretting but the results indicate that the compressive residual stresses delayed fretting crack growth, and/or the rougher surface delayed fretting crack nucleation to the extent that the overall life was improved. The LPB specimens did not fail due to fretting but instead tended to fail at the edge of the burnished region. These results indicate that LPB can inhibit fretting crack nucleation or growth to a large enough extent so that the next nucleation feature causes the failure. Longer fretting fatigue life may be achieved if the transition from the burnished to the untreated region is improved. As laser peening and LPB are still developing, it is possible that a more optimized set of treatment parameters could be found to further improve the fretting fatigue performance.

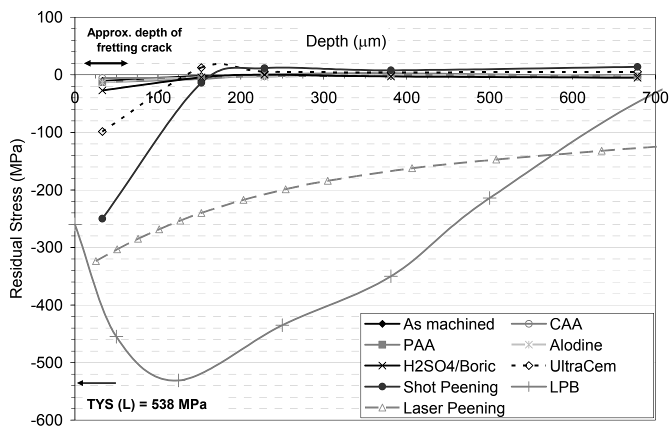


Figure 3: Residual stress profiles in the near-surface region of the 7085 after surface treatment.

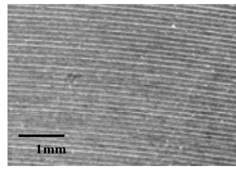
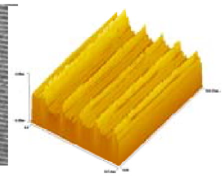
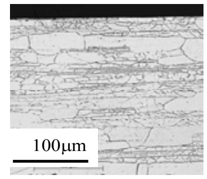
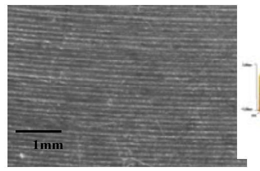
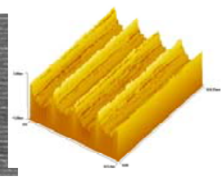
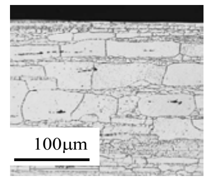
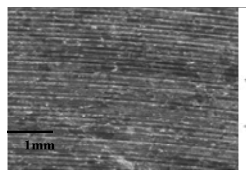
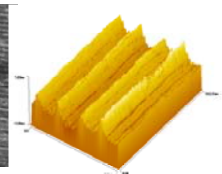
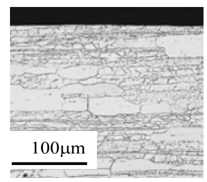
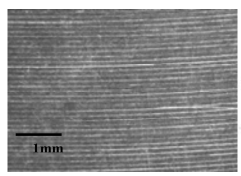
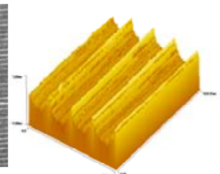
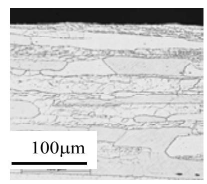
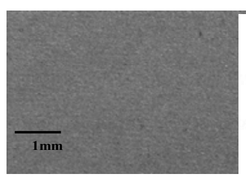
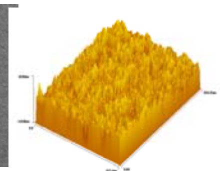
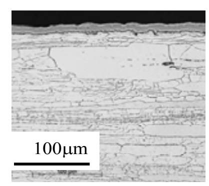
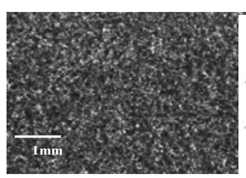
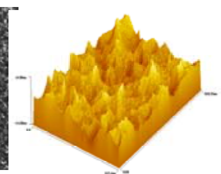
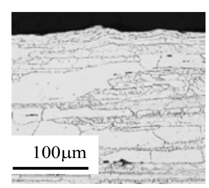
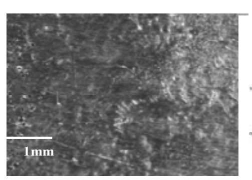
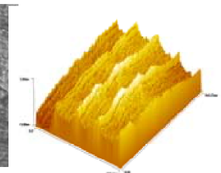
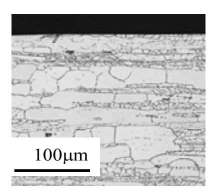
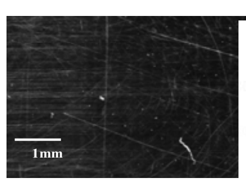
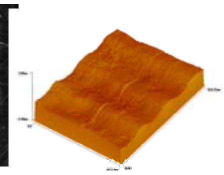
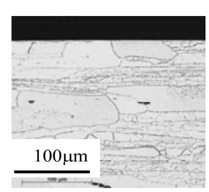
Surface Treatment	Topographical Surface	Surface Roughness (Ra)	Cross-section
As machined $Ra_{(avg)} = 0.65$			
Chromic acid anodizing (CAA) $Ra_{(avg)} = 0.89$			
Phosphoric acid anodizing (PAA) $Ra_{(avg)} = 0.88$			
Alodine 1200 $Ra_{(avg)} = 0.88$			
UltraCem $Ra_{(avg)} = 1.32$			
Shot peening $Ra_{(avg)} = 2.52$			
Laser peening $Ra_{(avg)} = 1.13$			
Low plasticity burnishing $Ra_{(avg)} = 0.14$			

Table 2: Topographical characteristics of the surface techniques and the effect on grain structure.

The specimens tested with the UltraCem coating showed greater than ten times improvement in fretting fatigue over the baseline. These specimens also did not fail due to fretting, and experimental observation indicates that the hard, low friction UltraCem coating inhibits fretting crack nucleation. While this coating showed good fretting and wear resistance, it may be difficult to use this technique on large aerospace parts. It would be better suited for smaller components which undergo high fretting or wear conditions.

The shot peened specimens achieved a greater than twenty times life improvement over the baseline and no failures occurred due to fretting. The specimens failed in the grip section or test run outs occurred. This technique, which induced high compressive stresses and a very rough surface, appears to inhibit fretting cracks from nucleation and/or propagating. Some shot peened specimens were also chromic acid anodized to determine if the anodizing affected the benefits of shot peening under fretting conditions. While the mean life of these specimens was slightly higher than that of the shot peened specimens, the results still lie within the experimental uncertainty and thus it is believed that this higher result is probably caused by the statistical variation in fatigue tests. These specimens also did not fail due to fretting and were either run outs or failed at the grip. Thus under fretting fatigue conditions anodizing does not appear to negatively effect the benefits of shot peening.

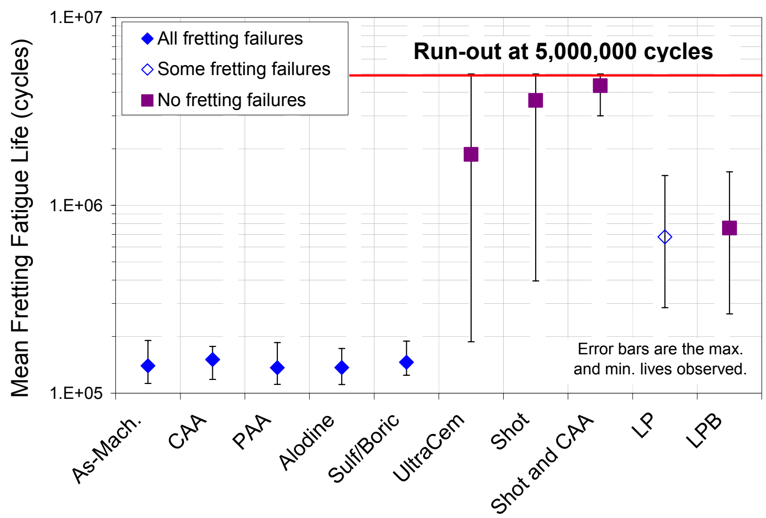


Figure 4: Mean fretting fatigue life for the various surface treatments. Error bars indicate the minimum and maximum test result.

Test No.	Bare	CAA	PAA	Alodine	Sulf/Boric	UltraCem	Laser peening	Shot peening	Shot peening and CAA	Low plasticity burnishing
1	*112,559*	*160,982*	*115,794*	*172,930*	*124,555*	4,569,163	1,442,232	5,000,000	2,998,582	264,035
2	*190,547*	*134,432*	*127,529*	*111,068*	*139,438*	546,831	*371,375*	5,000,000	5,000,000	1,504,906
3	*135,147*	*163,549*	*141,688*	*149,133*	*189,230*	2,169,565	*614,980*	4,065,328	5,000,000	688,422
4	*113,105*	*118,231*	*111,501*	*123,681*	*131,034*	187,520	*284,759*	395,467		591,135
5	*147,344*	*177,415*	*185,737*	*127,173*		5,000,000				
Mean fretting fatigue life	139,740	150,922	136,450	136,797	146,064	1,868,270	678,337	3,615,199	4,332,861	762,125
Std. Dev.	32,049	23,996	29,939	24,415	29,415	1,996,390	528,103	2,191,243	1,155,519	527,411

Table 3: Fretting fatigue cycles to failure for each specimen tested (run-out 5 million cycles). Specimen results in *italics* failed due to fretting with the fretting pad.

Low Load Transfer Joint Fatigue Results

Low load transfer joint fatigue tests were conducted on specimens having different anodizing and residual stress treatments. A summary of the cyclic lives is provided in Table 4. When comparing the various anodizing treatments, no difference in cyclic lives was observed (Figure 5). At an alternating stress of 98.3 MPa, the log mean cyclic lives ranged from 472,362 to 554,048 cycles, while at an alternating stress of 118.2 MPa the log mean cyclic lives ranged from 190,786 cycles to 276,219 cycles. Failures in most instances initiated in the countersunk region of the hole bore at the contact point of the fastener head (Figure 6A) and it is hypothesized that the nucleation for these cases was due to fretting between the fastener head and the untreated aluminum in this region. Thus, as the crack nucleation was away from the treated surface, the crack was probably not affected by the surface treatment and thus it may be reasonable to expect there would be no difference in the joint fatigue life.

Testing was also conducted on specimens that were shot peened, laser peened and low plasticity burnished prior to chromic acid anodizing. The evaluated shot peening process provided no additional benefit in LLT joint fatigue life. At both stress levels the observed cyclic lives were similar to the baseline chromic acid anodized specimens. Inspection of the failed specimens revealed that failure also initiated in the countersink location of the hole near the corner of the fastener head (Figure 6B). This location was approximately 300 μm below the surface of the plate which is below the compressive residual stress layer imparted by shot peening. However, laser peening and LPB imparted a much deeper compressive residual stress and, as a result, the propagation of cracks at the countersink was inhibited. This is shown in Figure 7, in which a small fatigue crack was observed to initiate in the countersunk region of the LPB specimen but had not propagated sufficiently to cause failure after 2,436,841 cycles. As a result, at the 98.3 MPa alternating stress level, both processes showed potential to improve cyclic fatigue life by 2 to 4 times. When tested at the higher alternating stress level, both the laser peened and LPB specimens had failures initiate from the corners of the specimen, an area which was not treated, and as a result no improvement in fatigue life was obtained. This was clearly a specimen effect and not an indicator of the effectiveness of the processes. Although no improvement was observed in the fatigue life of specimens tested at the higher stress level, the processes clearly demonstrated the ability to inhibit failure initiation due to fretting between the fastener head and countersink, which was a common initiation source for the anodized specimens.

Test No.	Alt. stress (MPa)	CAA (1)	PAA (1)	Alodine (1)	Sulf/Boric (1)	Laser peening	Shot peening (1)	Low plasticity burnishing
1	98.3	449,744 (2)	578,894	566,401	259,664	2,436,841 (3)	613,388	2,301,866 (4)
2	98.3	592,092	530,269	529,628	485,411	687,283 (4)	443,711	
3	98.3					829,195+		
Log Mean		**516,033**	**554,048**	**547,706**	**472,362**	**1,115,680**	**521,696**	
1	118.2	269,264	271,288	332,597	340,302	173,267 (3)	368,135	157,183 (3)
2	118.2	135,180	230,936	300,277	179,227		277,380	
3	118.2		200,795	211,053	220,871		155,131 (2)	
Log Mean		**190,786**	**232,573**	**276,219**	**237,941**		**227,383**	

1) Failure initiated at countersink of hole unless footnoted otherwise
2) Failure initiated at faying surface
3) Failure initiated at edge of specimen adjacent to hole
4) Failure initiated in reduced width area of specimen away from hole and from treated region.

Table 4: Low load transfer (LLT) joint fatigue cyclic lives (mean stress = 46.5 MPa)

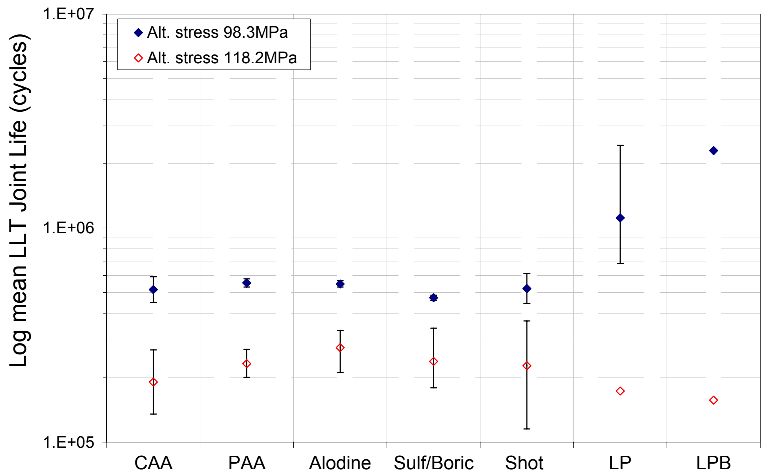


Figure 5: Log mean LLT joint fatigue life for the various surface treatments. Error bars indicate the minimum and maximum test result.

A B

Figure 6: Fracture surface of failed LLT joint fatigue specimens both showing fatigue cracks initiating from countersink, potentially fretting related. A) Chromic acid anodized specimen (life = 592,092 cycles) and B) shot peened specimen (613,388 cycles)

Figure 7: Small fatigue crack which initiated in the countersunk region of the low plasticity burnished specimen but did not propagate to failure (cyclic life of 2,301,866).

SUMMARY AND CONCLUSIONS

The effect of different surface treatments on fretting were evaluated in fretting fatigue and joint fatigue tests. Fretting fatigue and joint fatigue tests both demonstrated the various anodizing conditions did not change the fatigue life, however for differing reasons. For fretting, no difference between anodizing techniques was observed because all of the anodizing conditions provided similar surface roughness and no compressive residual stress, and therefore had little effect on the fretting crack nucleation or growth. For the LLT joint fatigue tests, the fatigue failures consistently initiated in the countersunk region of the hole, a non-anodized area since holes were drilled and reamed after anodizing. The failures appear to have initiated due to fretting between the countersunk bare aluminum surface and the fastener head. Overall, the type of anodizing treatment appears to not be an important factor in fretting or joint fatigue life especially when joints are assembled according to standard aerospace procedures. This suggests that more emphasis in the selection of an anodizing process can be placed on environmental and processing factors.

Shot peening improved fretting fatigue through a rougher surface and compressive residual stresses, however it did not influence joint fatigue since the residual stress imparted was not deep enough to influence the propagation of small fretting fatigue cracks in the countersink. UltraCem also improved life in the fretting fatigue specimens by inhibiting the nucleation of fretting cracks. It was not evaluated in the joint tests. Laser peening and low plasticity burnishing improved both fretting fatigue and joint fatigue. The compressive residual stresses imparted by laser peening and LPB were of sufficient magnitude and depth to inhibit the growth of fretting nucleated cracks between the fastener head and countersunk hole in the joints, and delay the nucleation and/or growth of fretting cracks in the fretting fatigue specimens. Laser peening and low plasticity burnishing appear to be promising technologies for the improvement of joint fatigue life when there is a concern of fretting initiated cracks due to the relatively deep compressive residual stresses which they impart.

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