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The Fretting Fatigue of Commercial Hard Anodized Aluminum Alloy

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An investigation has been carried out in order to study the fretting fatigue behavior of a 2014-T6 aluminum alloy, which has been coated with a commercial hard anodizing of approximately 20-25 μm in thickness. The hardness (HV) was significantly improved up to about 380 after hard anodizing coating while the hardness value of original 2014-T6 was 175. Fretting reduced drastically the fatigue life of samples in both conditions, substrate and coated conditions. The application of such a coating to the substrate may increase the fretting fatigue life in comparison with the uncoated samples in low-stress region for rotating bending fatigue loading while at higher stresses the effect of anodizing is reversed. This may be result from early initiation of cracking of hard anodizing film due to high-stress concentration resulting from bulk stresses. On the other hand, the increase in fretting fatigue life in low-stress region may be probably attributed to low coefficient of friction that prevents metal-to-metal contact, which may result in higher fretting fatigue life because of retardation of crack initiation resulting from lower stress concentration compared to the substrate.

Keywords commercial hard anodizing, fretting fatigue properties, 2014-T6 aluminum alloy

1. Introduction

Fretting phenomenon is defined as small oscillating movements in the contact between two surfaces, where at least one of them is subjected to vibration or cyclic stress. This type of fretting configuration is called fretting fatigue if one of the contacting parts is also subjected to constant or cyclic bulk stress.

Fretting increases tensile and shear stresses at the contact surface and generate flaws which lead to premature crack nucleation, and finally it results in failure due to the reduction of fatigue resistance of materials. Fretting fatigue leads to failure due to the reduced part lives. In order to increase the lives of parts, several researchers have worked on the fretting fatigue problem.

Aluminum alloy, which has superior mechanical properties, low cost, light weight, and reliability, has been widely used for automobile parts, aircraft parts, air and oil compressors and other components. However, aluminum alloy has problems of surface damage due to its softness and corrosion. Therefore, improvements of surface properties are required in practical applications. Hard anodizing film is widely used for this purpose. Once these engineering and structural applications suffer a load, fretting fatigue can be a potential failure mode. Although some research works on fatigue of aluminum alloys with anodic and hard anodizing coatings have been reported (Ref 1-6), those on fretting fatigue under rotating bending fatigue have rarely been done.

The present study deals with the influence of commercial hard anodizing on fretting fatigue behavior of a 2014-T6 Al alloy under rotating bending fatigue loading. Furthermore, Scanning electron microscope (SEM) observations results on surface and fracture surface morphology are also reported.

2. Experimental Details

The material of this study was a 2014 aluminum alloy (AA 2014) having the chemical compositions presented in Table 1.

Figure 1 shows a schematic diagram of the T6 heat treatment carried out substrate. The specimens were solution treated at 520 °C for 2 h and water quenched to room temperature. Subsequently they were aged at 170 °C for 10 h (referred to as T6 condition).

The gage portions of all samples were polished with SiC papers grit 800-1200, and cleaned with acetone. Such a procedure allowed the elimination of the remaining circumferential notches that could act as stress concentrators during pure and fretting fatigue tests. The residual polishing marks were oriented along the length of the specimens.

Figure 2 shows the fretting specimens and the fretting pads drawings. All the dimensions shown are given in mm. Fretting fatigue pads were manufactured from AISI 4140 steel plate. It has a hardness value of 339 HV. The pads were harder than substrate material (175 HV), but was softer than those of coated specimens (380 HV). The gage parts of the fretting pads were polished with silicon carbide papers grit 800-1200 and subsequently polished with alumina. They were then degreased with acetone. The plain fatigue life data were obtained with

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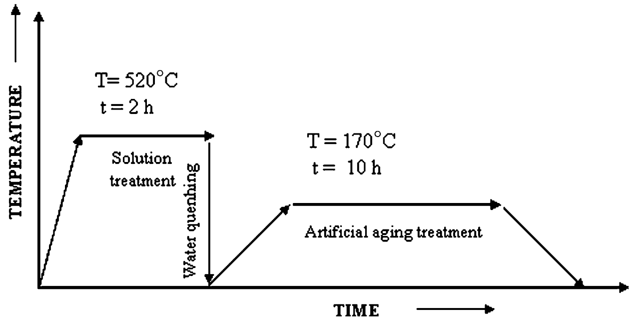

Fig. 1 Schematic diagram of T6 heat treatment process carried out substrate

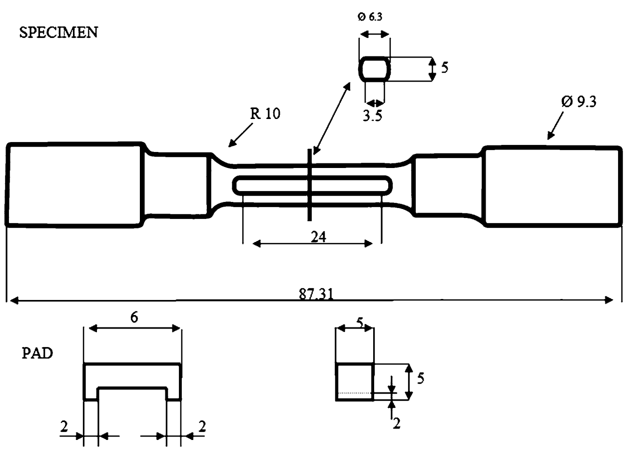

Fig. 2 Sketches of the fretting fatigue specimens and the pad employed in this study. All the dimensions are in mm

Table 1 Chemical composition of 2014 aluminum alloy (wt.%)

	Cu	Mg	Mn	Si	Fe	Cr	Zn	Al
(% Wt)	4.51	0.39	0.60	0.68	0.33	0.05	0.090	Balance

round bar fatigue specimens whose diameter and length of the gage section were 5 and 24 mm, respectively. The pads were seat on the specimens with a special holder that was produced by us.

Hard anodizing coating was carried out industrially. A proprietary electrolyte bath was used for the deposition of the hard anodizing coatings. Detailed experimental conditions concerning hard anodizing processes are given in Table 2. The coating thickness was measured by Scanning electron microscope (SEM) and found to be 20-25 μm.

However, both the thickness and state of the fracture surfaces in addition to fretting scars were also evaluated by means of SEM technique. As hard anodized layer is amorphous, no crystalline peaks were observed in x-ray diffraction patterns. Thus, Fig. 3 reveals only x-ray diffraction result in substrate.

The microhardness on the cross section of samples with T6 condition, T6 + Hard anodizing coating and pad material was measured with Vickers hardness, using a PC controlled

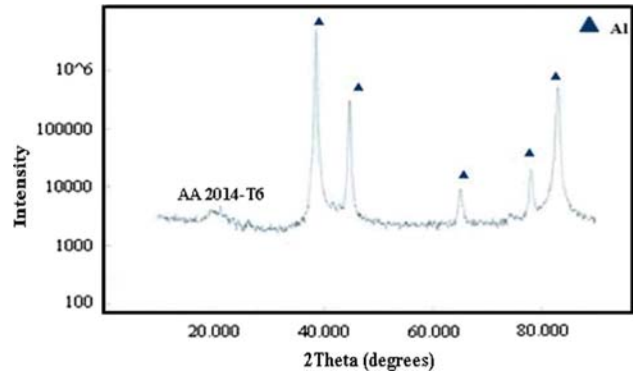

Fig. 3 X-ray diffraction result showing Al in substrate

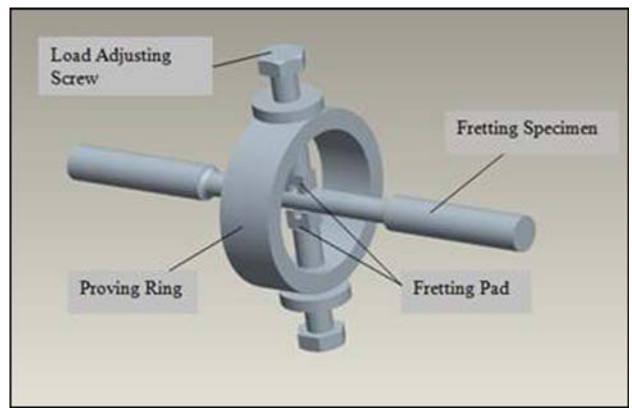

Fig. 4 Schematic representation of fretting fatigue test setup

Table 2 HA process parameters employed in the present work

Electrolyte bath	Temperature, °C	Power	Current, A/dm^2	Time, h
Sulfuric acid 50 vol.%	0-5	DC	2	1

Buehler-Omnimet tester. Vickers hardness numbers were obtained by averaging eight measurements on each specimen.

An experimental facility, with a ring type load cell and bridge-type fretting pads, which can simulate fretting fatigue conditions, was designed and fabricated. Figure 4 shows a schematic view of fretting fatigue test setup employed in the present study. The specimens were gripped and loaded cyclically in a rotating bending testing machine.

By adjusting the loading screw on a proving ring with a torque driver, the normal contact load between the contact pads and specimen was controlled. The fretting fatigue tests were carried out a constant average contact pressure of 100 MPa. The average contact pressure was calculated by dividing the contact (normal) load per one foot of the fretting pad by the apparent contact area (=pad food size x specimen thickness = $2 \times 3.5 = 7.0$ mm^2). When a fatigue specimen is subjected to cyclic stresses, fretting between the contact pads and the specimen is generated. Uncoated fretting pads were used for testing against coated as well as uncoated test specimens. Plane and fretting fatigue testing were carried out at room temperature in a four-point loading rotating bending machine (R = −1) under constant stress amplitude at a rotational speed of 5000 rpm. The each data point on *S-N* curve represents the average of two specimens tested under identical conditions.

Rotating bending fatigue tests is a simple method of determining fatigue properties at zero mean loads by applying known bending moments to rotating round specimens. The specimen has a continuous radius such that the maximum bending stresses are constant at all cross sections. The stress at a point on the surface of rotating bending specimens varies sinusoidally between numerically equal maximum tensile and compressive stress values in every cycle. In this test, the maximum number of cycles to failure is obtained at a given stress level. The stress S is continually reduced, and the number of cycles to failure N_f increases. Finally, the limiting value of stress (endurance/fatigue limit) is reached where fatigue failure will not occur (Ref 7, 8). However, for aluminum alloys as most nonferrous, the S-N_f curve does not approach an asymptote. In general; a fatigue limit is often arbitrarily defined as the fatigue strength at 10^7 cycles and should be experimentally determined (Ref 9).

The relationship between the stress amplitude and the number of cycles to failure for the all the condition analyzed is defined by the expression (Ref 10);

$$S = AN_f^b \qquad \text{(Eq 1)}$$

where, S = Stress amplitude; A = Fatigue strength coefficient; b = fatigue strength exponent; N_f = Number of cycles to failure; S-N_f curve was obtained by least square fitting the relationship in Eq 1.

3. Results and Discussion

Figure 5 shows the cross section view of hard anodizing-coated specimen. The coating thickness was measured and found to be approximately 20-25 µm. Observations on surface of coatings indicated little presence of relatively a little number of cracks in hard anodizing coating.

The steel pads have a hardness value of 339 HV. The hardness measurements show that the pads were harder than substrate material (175 HV), but was softer than those of coated specimens (380 HV). The corresponding fretting fatigue *S-N* curves at a contact pressure of 100 MPa is displayed in Fig. 6 and associated fretting fatigue strengths are also given on Table 3 for a life of 10^7 cycles since that is the case (Ref 9).

It is apparent that fretting has a deleterious effect on the fretting fatigue life of samples in conditions, substrate and coated conditions, at all values of the applied bending stress. A first comparison with plain fatigue strength clearly shows that the fatigue strength reduction is more dramatic for the untreated substrate. However, the reductions at fatigue strength for hard anodizing coated specimens are less than untreated substrate though hard anodizing treatment fully protects against fretting loading. On the other hand, an interesting result of this work is that the trend of the effect of hard anodizing coating depends on the value of stress. Hard anodizing coating has increasing effect on fatigue life of the specimens in low-stress region at approximately 220 MPa. However, for higher stress the coating has no nearly effect in the fatigue life. It is obvious that the influence of hard anodizing coating is more profound at lower stresses. The no effect of hard anodizing coating at the higher

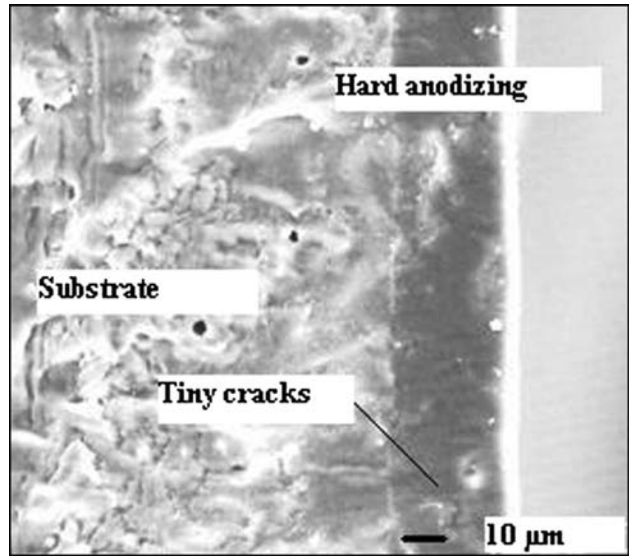

Fig. 5 SEM micrographs showing the cross section of hard anodizing coated specimen

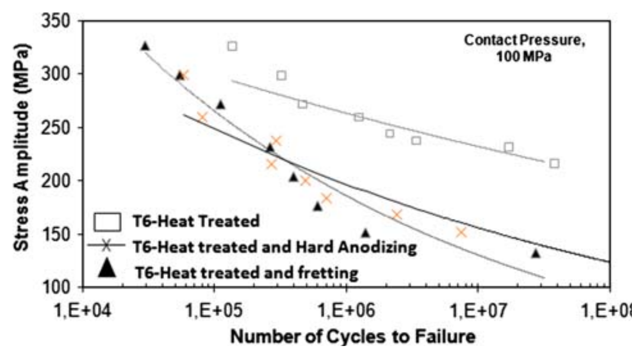

Fig. 6 *S-N* curves of fatigue and fretting fatigue for contact pressures of 100 MPa

Table 3 Plain and fretting fatigue limits for associated conditions

Surface treatments		Fatigue strength, MPa
T6 Heat treated	(Plain fatigue)	237
T6 Heat treated	(Fretting fatigue)	132
T6 + Hard anodized	(Fretting fatigue)	162

stresses in fretting fatigue life may be resulted from early initiation of cracking of hard anodizing film due to high-local stress concentration resulting from bulk stresses. The increase in fretting fatigue life in low-stress region for conditions considering (substrate hardness, pad materials, coating thickness and hardness and kind of loading) in this study may be probably attributed to low coefficient of friction that prevents metal-to-metal contact, which may result in higher fretting fatigue life because of retardation of crack initiation resulting from lower stress concentration compared to the substrate.

It is suggested that a fretting fatigue crack forms at the region where the frictional shear stress on contact surface

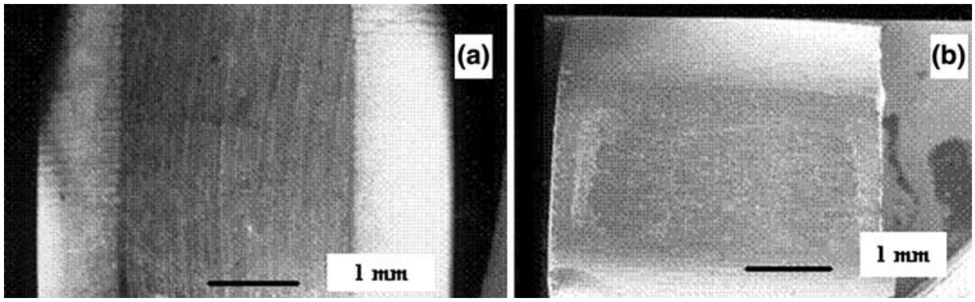

Fig. 7 Appearance of the fretting scars in specimens tested (a) Substrate and (b) Hard anodized

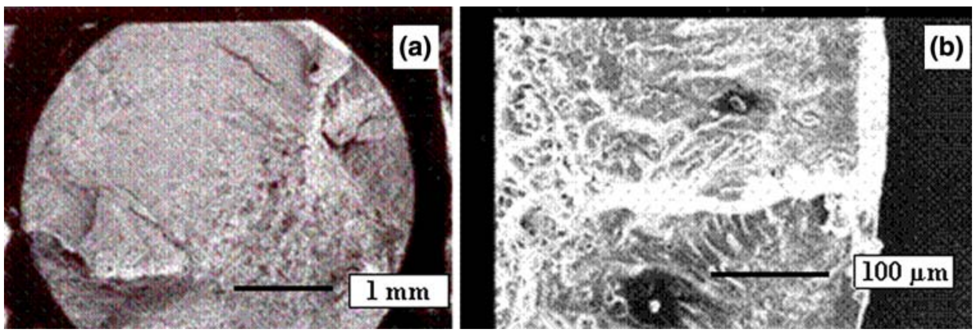

Fig. 8 Scanning electron microscope (SEM) micrographs showing the propagation of cracks on the specimen surface (a) plain fatigue (b) fretting fatigue

locally concentrates. Thus, the decrease in fatigue life by the fretting damage is considered to be due to the decrease in crack initiation life caused by the local stress concentration caused by fretting, and the acceleration of the initial crack propagation by fretting (Ref 11). As one of the main mechanisms of acceleration of initial crack by fretting, the wedge effect where the wear debris goes into the small initial fretting fatigue crack is considered (Ref 12). However, if the crack is fully filled with the wear debris, it is considered that the effect is decreased because the wear debris cannot go into the crack furthermore.

The action of fretting causes considerable damage to the specimen surface. Figure 7 shows the appearance of the fretting scars on substrate and hard anodized specimens.

It can be observed that the extent of the fretting damage induced hard anodizing coating is less than that in the substrate. This effect may be due to increased hardness due to hard anodizing coating of the surface.

It is clear that during plain fatigue, cracks originate randomly at one or several points around the periphery of the specimen case while during fretting, cracks inevitably start from the same location at points adjacent the leading edge of the fretted areas where the bending stress and the induced shear stress highest. Crack propagation occurs from two sides resulting in the appearance of a final fracture area of the specimen as shown in Fig. 8.

4. Conclusions

This article investigates a hard anodizing coating applied to T6-Heat treated Al alloy against AISI 4140 steel under plain and fretting fatigue loading. This analysis leads to the following conclusions:

(a) The fretting reduces the fatigue life dramatically. The lowering of the fatigue life is due to the introduction of a shear stress on the surface through contact between the fretting pad and the substrate material.
(b) Hard anodizing coating increased the fretting fatigue life at low-stress levels. However, toward higher stress levels, the extent of increase in fatigue life decreased and at applied bending stress of approximately 220 MPa, it was observed that hard anodizing coating in fretting fatigue life nearly has no effect slightly.
(c) Hard anodizing coating can be used as one method to improve the fretting fatigue life at low service loads.

Acknowledgments

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References

1. M. Hirata, M. Maejima, K. Saruwatari, H. Shigeno, and M. Takaya, Rotational Bending Fatigue of Anodized Coating of Aluminium, *J. Surf. Finish. Soc. Jpn.*, 1996, **47**(4), p 376–377
2. A.M. Cree, G.W. Weidmann, and R. Hermann, Film-assisted Fatigue Crack Propagation in Anodised Aluminium Alloys, *J. Mater. Sci. Lett.*, 1995, **14**, p 1505–1507
3. P.R. Degat, Z.R. Zhou, and L. Vincent, Effect of Cromic Acid Anodizing Treatment of Fretting Behaviour During Fretting Tests on Pre-stressed Specimens, *Thin Solid Films*, 1997, **298**, p 170–176

4. I.R. McColl, S.J. Harris, Q. Hu, G.J. Spurr, and P.A. Wood, Influence of Surface and Heat Treatment on the Fretting Wear of an Aluminium Alloy Reinforced with SiC Particle, *Wear*, 1997, **203–204**, p 507–515
5. B. Rajasekaran, S.G.S. Raman, L.R. Krishna, and G. Sundararajan, Influence of Microarc Oxidation and Hard Anodizing on Plain Fatigue and Fretting Fatigue of Al-Mg-Si Alloy, *Surf. Coat. Technol.*, 2008, **202**, p 1462–1468
6. G.C. Tu, I.T. Chen, and R.Y. Hwang, Effect of Anodizing on the Corrosion Fatigue Behaviour of 2024-T3 Aluminium Alloy, *JSME Int. J., Ser. 1: Solid Mech. Strength Mater.*, 1990, **33**, p 527–534
7. S. Suresh, *Fatigue of Materials*, Cambridge University Press, Cambridge, 1991
8. B. Lonyuk, I. Apachitei, and J. Duszczyk, The Effect of Oxide Coatings on Fatigue Properties of 7475–T6 Aluminium Alloy, *Surf. Coat. Technol.*, 2001, **201**, p 8688–8694
9. S.K. Lin, Y.L. Lee, and M.W. Lu, Evaluation of the Staircase and the Accelerated Test Methods for Fatigue Limit Distributions, *Int. J. Fatigue*, 2001, **23**, p 75–83
10. L.O.H. Basquin, The Exponential Law of Endurance Tests, *Proc. ASTM*, 1910, **10**(2), p 625
11. H. Sumita, K. Nakazawa, R. Hamano, and N. Maruyama, Research on Improvement of Fretting Fatigue Characteristics of High-Strength Structural Material, *Rep. Nat. Res. Inst. Met.*, 1993, **14**, p 207–218
12. R.A. Antoniou and T.C. Radtke, Mechanisms of Fretting-Fatigue of Titanium Alloys, *Mater. Sci. Eng. A*, 1997, **A237**, p 229–240