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Effect of anodized coatings on fatigue strength in aluminum alloy

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Abstract

In order to investigate the effect of anodized film on fatigue strength of aluminum alloy, A2014-T6, repeated tensile fatigue test was conducted in laboratory air under the stress ratio, R, of 0.01 using smooth specimen with anodized film thickness of 3 μ m. Fatigue strength of anodized specimen tested under R=0.01 decreased by 18-20 % as compared with that of the untreated one, even though the anodized film did not affect the fatigue behavior under the rotating-bending fatigue test of R = -1. The anodized film is fractured at an early stage of repeated tensile fatigue process, because it is too brittle to accommodate the substrate metal. Many cracks are induced to initiate at the substrate by flaws of the anodized film. It was pointed out through the study that the fatigue strength of anodized aluminum alloy is controlled by the crack initiation behavior in the substrate induced by the rupture of the anodized film, which is related to deformation of the substrate metal during fatigue process.

1 Introduction

Anodizing is a well-established electrolytic process employed to produce anodic oxide films on the surface of an aluminum alloy. Anodized coatings are commonly applied to aluminum alloys to provide corrosion and wear resistant surfaces. Despite the benefits of anodized coatings, it is pointed out that they have been shown to adversely affect the fatigue performance of the underlying aluminum alloys [1-3]. However, there are a little information about the influence of anodized film on fatigue process as crack initiation and propagation.

The purpose of the present study is to investigate the effect of anodized film on fatigue strength in aluminum alloy, A2014-T6. Repeated tensile fatigue test was

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conducted in laboratory air using smooth plate specimen with anodized film thickness of 3 μ m. Based on the experimental results, and observation of fracture surface and failure of anodized film during fatigue process, fatigue fracture mechanisms of anodized aluminum alloy was discussed.

2 Experimental procedures

2.1 Testing material and specimen

The material used in this study was wrought aluminum-cupper alloy, A2014. The chemical composition (mass %) of this alloy is 0.39 Fe, 4.82 Cu, 1.05 Si, 0.93 Mn, 0.64 Mg and bal. Al. The material was hot-forged followed by extrusion to a rod with 25 mm diameter and given a solution heat treatment at 778 K for 9 ks, was water-quenched, and then artificially aged for 28.8 ks at 443 K. The mechanical properties of the material after the T6 heat treatment are as follows; 0.2 % proof stress $\sigma_{0.2}$ =418 MPa, tensile strength σ_B =486 MPa, elongation δ =20.8 %, Vickers hardness HV=167, and grain size d=58 μ m.

The specimen for axial fatigue testing was machined into smooth-plate geometry of dimensions as 12 mm long by 6 mm constant width and 3 mm thickness gauge section. And also, hourglass shaped specimen for cantilever-type rotating-bending fatigue testing was machined with a 8 mm minimum gauge diameter. Surface of the specimen was mechanically polished with emery paper and subsequently rapped with of 3 μ m diamond-paste prior to anodizing. The sulfuric acid anodizing process was employed and anodic oxide film with thickness of 3 μ m was coated on the specimen surface. Vickers hardness of the anodized layer was 450 and essentially hard as compared with that of substrate material. Residual stresses in the anodized specimen was measured by the X-ray method in which the diffraction plane is Al(310) by Cr-Kα. The compressive residual stress of about 5.5 MPa was measured on the rapped specimen surface. On the other hand, the tensile residual stress of about 1.5 MPa was on the substrate aluminum alloy bellow the anodized film.

2.2 Testing Method

Fatigue tests were performed in air and laboratory atmosphere. Axial fatigue tests for plate specimens were conducted using sinusoidal waveform at the frequency of 20 Hz. The stress ratio (minimum stress to maximum stress) R was 0.01. Rotary bending fatigue tests for the hourglass shaped specimens were performed using cantilever-type rotating bending fatigue machine operating at 1780 rpm (f =29.7 Hz). By the nature of the rotary bending test, R was -1.

3 Experimental results and discussions

3.1 *S-N* curves of anodized specimens

Figure 1 shows the *S-N* curves obtained from the axial repeated tensile fatigue tests, R=0.01. It can be seen from this figure that the anodized coating decreased

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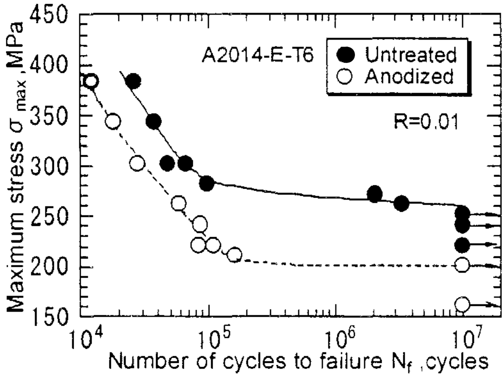

Figure 1: *S-N* curves obtained under repeated tensile fatigue test, *R*=0.01.

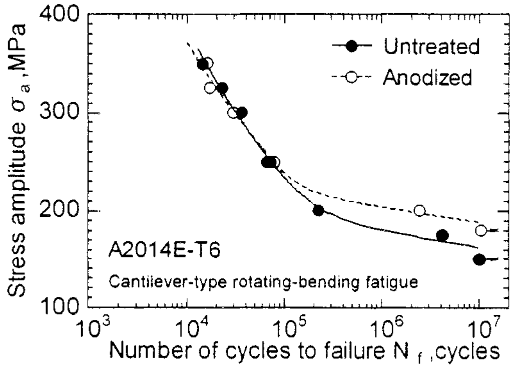

Figure 2: *S-N* curves obtained under rotating-bending fatigue test, *R*=-1.

the fatigue strength at all lifetime. Life reduction at low stress level is slightly greater than that at high stress level. The fatigue strength of untreated specimen at 10^7 cycles was σ_{max} =250 MPa and that of anodized specimen was σ_{max} =200 MPa. Therefore, decrease in fatigue strength due to anodizing was 20 % for A2014-T6.

The results for cantilever-type rotating-bending fatigue testing (*R*=-1) of anodized and untreated specimens are shown in Fig. 2. No difference is found in fatigue strength between both specimens at high stress amplitude level and short life region. But the anodized coating specimen shows slightly greater fatigue strength compared to the untreated one at low stress amplitude level. Possible threshold behavior was observed around 180 MPa, leading to run-out in the case of the anodized specimen and increase in fatigue strength of 20 % showed as compared with untreated specimen. A mechanism for the increase in fatigue strength of coating specimen is expected that the hard surface layer can act as barriers to the egress of dislocations, causing dislocation pile-ups and formation of crack nuclei beneath the coating film. This behavior has been reported by one of the authors through the studies about the fatigue tests of TiN coated carbon steel [4-7]. It is of interesting that the fatigue strength of anodized coating specimen shows the dependency on the applied stress ratios.

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3.2 Fractography

To clarify the decrease in fatigue strength of anodized coating specimen under the R=0.01, fracture surface was observed by a SEM. Figure 3 shows a typical example of the crack initiation site on fracture surface of untreated specimen. A facet was observed at crack initiation site, at which a crack caused with the crystal slip beneath the specimen surface. An example of fracture surface on anodized specimen was shown in Fig. 4. Ratchet marks on the fracture surface can be found in Fig. 4(a), which are the result of multiple fatigue crack origins. From the observation of higher magnification as shown in Fig. 4(b), a crack is formed due to the crystal slip as same as Fig. 3. Figure 4(c) shows the results observed both of fracture surface and specimen surface, that is, the observation was made from the 30°inclined direction. Initiated cracks at the multiple crack initiation sites propagated independently and coalesce the cracks in neighborhoods. Then crack propagation path on the surface of coating specimen presents a zigzag pattern.

Figure 5 shows the experimental relationship between applied maximum stress and number of cracks on the fracture surface. The number of cracks formed on the fracture surface of anodized specimens is larger than that of the untreated

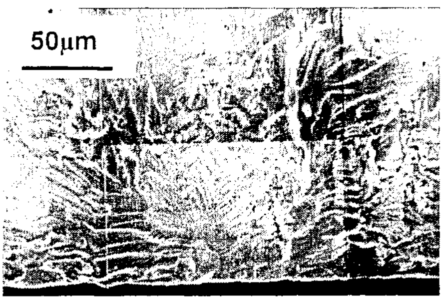

Figure 3: A typical SEM observation of crack initiation site on the untreated specimen.

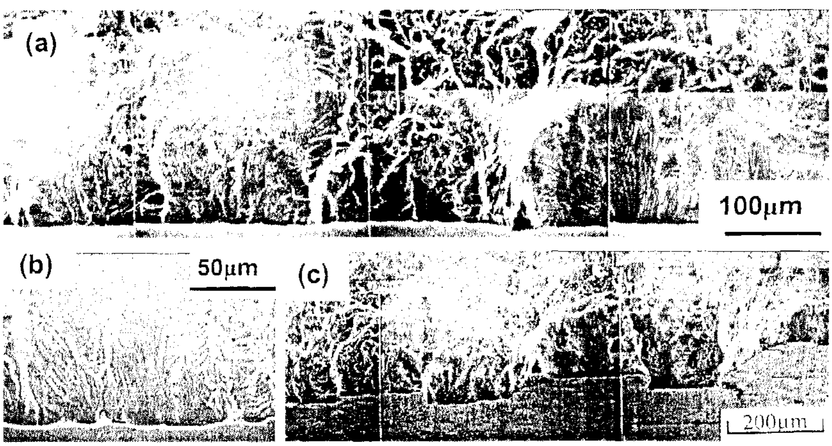

Figure 4: Typical example of fracture surface on anodized coating specimen.

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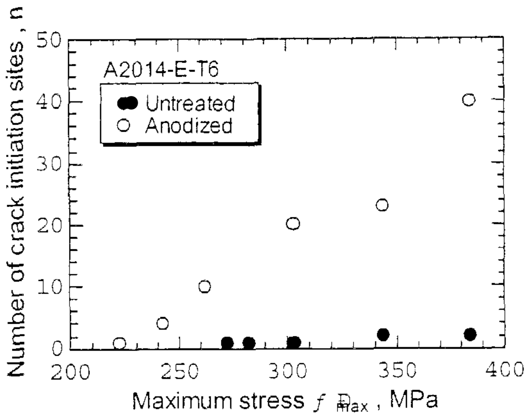

Figure 5: Experimental relationship between number of crack initiation site on fracture surface and applied maximum stress.

specimens, in which only one or two cracks exist. And also, it is recognized from this figure that the number of crack initiation sites depends on applied stress and increases as increasing applied stress. From the observation of fracture surface tested under the rotating-bending fatigue, no difference was observed in the number of crack initiation sites between anodized and untreated specimens. Therefore, It is suggested that the decrease in fatigue strength of anodized coating specimen is caused by the increase in crack initiation sites and crack propagation rate due to coalescence to cracks.

The surface of fatigue-ruptured specimen was observed. Figure 6 shows the results observed by a SEM on anodized coating specimen tested under R=0.01. A lot of flaws of coating film perpendicular to the stress axis were observed. On the other hand, any flaws could not be found on the coated specimen surface ruptured under the fatigue test of R=-1 and leaded to run-out under the R=0.01. Figure 7 shows an example of cracks initiated on substrate metal accompanying a flaw of anodized coating film. From this figure, it is understood that flaws developed in the film during fatigue process act as stress raisers, and can thus contribute to initiation sites for fatigue crack and fatigue failure.

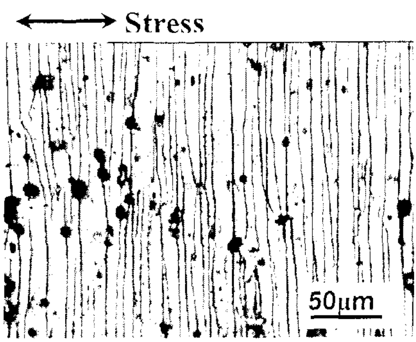

Figure 6: SEM observation of fracture on anodized coating film after fatigue test.

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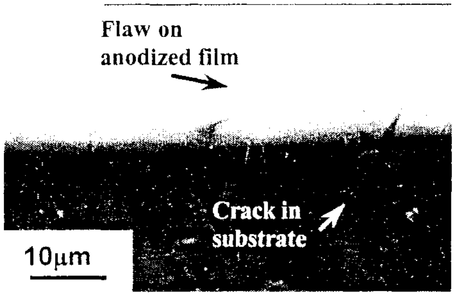

Figure 7: An example of crack initiation on substrate accompanying at flaw of anodized film.

3.3 Rupture behavior of anodized film

3.3.1 Static tensile test

Because that anodized coating films are hard and brittle, the films will readily rupture when deformed. Static tensile test of anodized coating specimen was performed and rupture behavior of coating film was discussed. Figure 8 shows the experimental relation between flaw density on the coating film and applied static stress, or total tensile strain of the specimen, where flaw density was defined as the number of flaws per millimeter along the axial direction. It was found that flaws on coating film occurred at the applied tensile stress of 360-390 MPa and the total tensile strain of 0.5-0.55 %, and that they increased with the stress or strain.

From the comparison between the tensile stress occurring the flaw of coating film and *S-N* curve in Fig. 2, all applied stress amplitudes in rotating-bending fatigue test are bellow the rupture stress of coating film. Therefore, coating film does not rupture during fatigue process tested under R=-1 and no fatigue debit to anodized

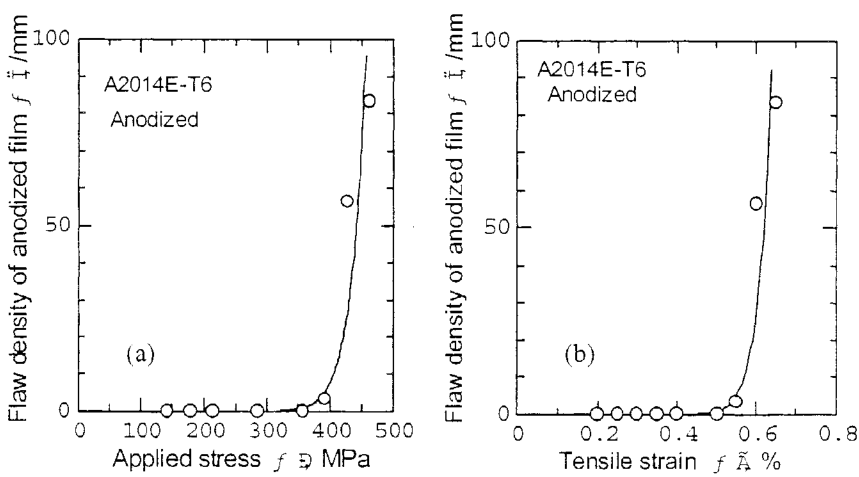

Figure 8: Change in flaw density of anodized coating film during static tensile test.

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anodized specimen is observed. On the other hand, same discussion can not applied to the results obtained from the repeated tensile fatigue tested under R=0.01 (see Fig. 1), because that decrease in fatigue strength occurred at the applied maximum stresses bellow the critical stress formed flaws of film.

3.3.2 Repeated tensile fatigue test

To discuss the rupture behavior of anodized coating film during fatigue process, the surface of coating specimen interrupted fatigue test was observed by a SEM. Figure 9 shows the experimental relationship between flaw density on the coating film and fatigue life fraction, N/N_f, obtained from the fatigue test under R=0.01. Flaws on the film were observed at N/N_f of 0.15-0.25 and flaw density increased with stress cycling. It should note in this figure that applied stresses in experiments are bellow the static tensile stress formed the flaws of film and flaw initiation life depends on applied stress. Crack length of about 50 μm was observed on untreated specimen surface at N/N_f of 0.31. From the experimental results, it is considered that fatigue crack initiation of coated specimen induced by the flaw of film will occur at an early stage of fatigue compared with untreated specimen. This fact was only seen in the case of repeated tensile fatigue of R=0.01 but not for rotating-bending fatigue of R=-1. Rupture of coating film will be related to the deformation of substitute metal during fatigue process.

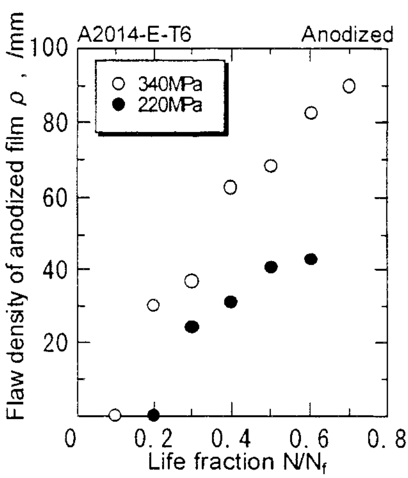

Figure 9: Change in flaw density of anodized film formed during fatigue process.

3.4 Cyclic deformation behavior

In order to discuss the effect of cyclic deformation on rupture of coating film, deformation behavior of the specimen during fatigue process was measured by strain-gage method. Figure 10 shows the variation in total strain of the specimen during fatigue, which includes a cyclic and ratchet strain, obtained from the repeated tensile fatigue testing. It can be seen from this figure that the total strain

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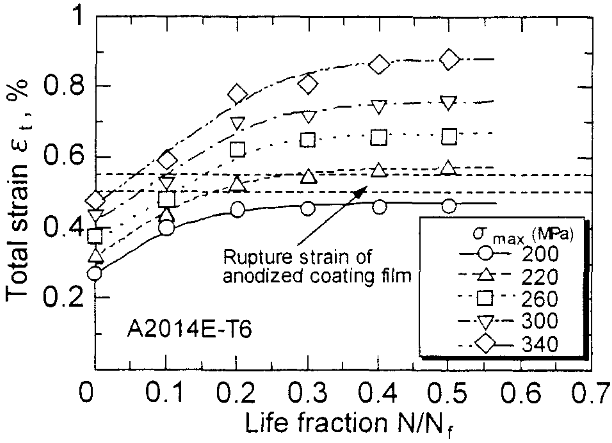

Figure 10: Change in total strain during repeated tensile fatigue process.

increases with stress cycling and reaches to steady state condition in 30-40 % of life to failure. In this figure, rupture strain of anodized coating film, 0.5-0.55 %, obtained from static tensile test mentioned above, is shown with dotted lines. The total strain of the specimen increases with cycling and comes up to the rupture strain of coating film in 5-20 % of life to failure, depending on applied stresses. An exception is in the case of applied stress of 200 MPa, because that this specimen leaded to run-out and no flaws of coating film observed on the specimen surface after testing.

Figure 11 shows the cyclic stress-strain curve obtained from Fig.10. The strains in this figure were obtained at 20 % of life to failure, because the rupture of coating film occurred in an early stage of the fatigue process. It can be seen from this figure that the strain formed during fatigue is larger than that occurred during static tension at the same applied stress.

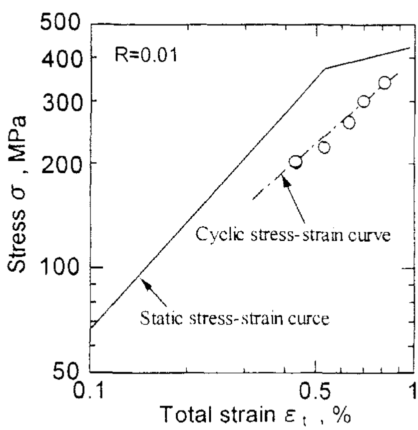

Figure 11: Cyclic stress vs. strain curve obtained at N/N_f=0.2 under repeated tensile fatigue test.

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3.5 Strain-based S-N curve

Figure 12 shows the relationship between total strain and number of cycles to failure of anodized coating specimens for the repeated tensile fatigue testing. The total strain was calculated from the cyclic stress-strain curve obtained from the experimental results mentioned before section. It can be clearly understood that the cyclic strain of anodized coating specimens with finite fatigue life is above the rupture strain of coating film and infinite fatigue life of the coating specimen is defined as the upper limit of stress at which rupture of coating film does not occur. From the experimental results and discussion, anodized coating film is fractured at an early stage of the fatigue process because it is too brittle to accommodate the substrate metal under testing conditions where large deformation occurs or accumulates during fatigue. Thus, many cracks may be induced to initiate at the substrate by flaws of coating film and fatigue strength decreases as the results. On the other hand, under testing conditions without large cyclic deformation of the specimen, crack initiation is delayed by hard coating film on the specimen surface.

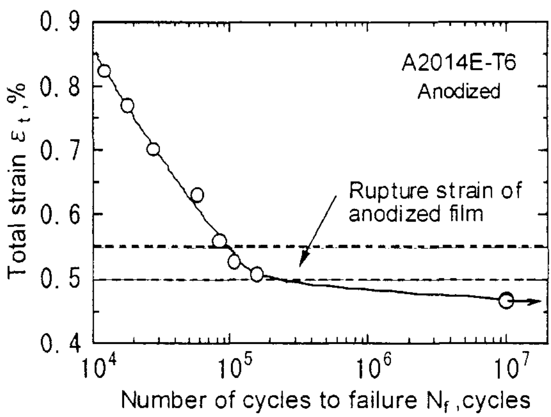

Figure 12: Relationship between total strain and number of cycles to failure of anodized coating specimen.

4 Conclusions

The following conclusions were obtained from the fatigue tests of anodized coating wrought A2014-T6 aluminum alloy.

(1) Anodization of the specimen gives reduction of about 20 % in fatigue strength under the testing condition of R=0.01, that is, repeated tensile fatigue.

(2) However, the effect of anodized coating on fatigue strength does not find at high stress amplitude range and fatigue strength of anodized coating specimen at 10^7 cycles increases about 20 % compared with uncoated specimen for the cantilever-type rotating-bending fatigue test, R=-1. Fatigue strength of anodized coating specimen shows the dependency on applied stress ratio.

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(3) Anodized coating film is ruptured at total tensile strain of 0.5-0.55 % under the static tensile test.
(4) Decrease in fatigue strength of anodized coating specimen is caused by formation of many cracks at an early stage of fatigue process induced by the flaws in the film, which act as stress raisers.
(5) The fatigue strength of anodized coating specimen can be explained by the deformation behavior during fatigue process. Accumulated strain of the substrate during cycling controls the fracture of coating film and flaws developed in the film contribute to crack initiation for fatigue failure.

References

[1] Cree, A.M. and Weidmann, G.W., Effect of anodized coatings on fatigue crack growth rates in aluminium alloy, *Surface Engng*, **13**-1, pp.51-55, 1997.
[2] Rateick, Jr R.G., Binkowski, T.C. and Boray, B.C., Effect of hard anodized thickness on the fatigue of AA6061 and C355 aluminium, *Jour. Mater. Sci. Letter*, **15**, pp.1321-1323, 1996.
[3] Cree, A.M., Weidmann, G.W. and Hermann, R., Film-assisted fatigue crack propagation in anodized aluminium alloys, *Jour. Mater. Sci. Letter*, **14**, pp.1505-1507, 1995.
[4] Shiozawa, K., Nishino, S. and Handa, K., The effect of applied stress ratio on fatigue strength of TiN-coated carbon steel, *JSME Inter. Jour.*, Series I, **35**-3, pp.347-353, 1992.
[5] Shiozawa, K., Tomosaka, T., Han, L. And Motobayashi, K., Effect of flaws in coating film on fatigue strength of steel coated with titanium nitride, *JSME Inter. Jour.*, Series I, **39**-1, pp.142-150, 1996.
[6] Shiozawa, K., Some affecting factors for fatigue strength of ceramics coating steel, *Surface Treatment*, ed. M.H. Aliabadi and C.A. Breddia, Computational Mech. Pub., pp. 227-236, 1997.
[7] Shiozawa, K., Effect of coating thin film on fatigue strength of materials, *Fatigue '99*, ed. X.R. Wu and Z.G. Wang, Higher Edu. Press, **3**, pp.1913-1920, 1999.