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Effect of hard anodize thickness on the fatigue of AA6061 and C355 aluminium

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Anodizing is a process by which a controlled columnar growth of amorphous aluminium oxide is developed on the surface of an aluminium alloy. Anodic coatings are commonly applied to aluminium alloys to provide corrosion and wear resistance [1, 2]. Coatings for corrosion resistance are typically thin, ranging from 2 to 25 μm [3]. For wear resistant applications, thicker hard anodize or type III coatings are employed, with thicknesses ranging from 13 to 114 μm [3]. Hard anodize coatings are typically cracked, due to residual stress accommodation, leading to diminished corrosion and fatigue resistance.

The fatigue debit was noted in the initial report on the development of hard anodize coatings [4]. The alloy 75S-T6 (AA7075) with 50 μm coating retained 55% of its fatigue strength at 120 000 cycles. Others [2] have shown retained fatigue strenghts at 10^6 cycles of 41% for AA7075. For AA6061, a fatigue debit of 60% was observed relative to unanodized specimens after 10^6 cycles. However, for the cast aluminium alloy, A356, no fatigue debit was observed.

The objective of the present investigation was to generate stress–life (S–N) curves for AA6061 and AA C355 aluminium with varying thicknesses of modern hard anodize coatings. These aluminium–silicon–magnesium alloys provide an effective means of comparing the effects of anodizing on the fatigue behaviour of wrought and cast materials without significant complication from compositional differences.

Hour-glass shaped specimens for rotary bend fatigue testing were machined with a 7.9 mm minimum gauge diameter prior to coating. Gauge section surface roughness was 0.8 μm R_a maximum prior to anodizing. Axial fatigue specimens were machined into round bar geometry of dimensions 19 mm long by 5 mm constant diameter gauge section. Gauge section surface roughness was 0.4 μm R_a maximum prior to anodizing. Specimens of AA6061-T6 and AA6061-T651, both certified to AMS 4117, were machined from the 16 mm and 19 mm diameter bars, respectively. Specimens of AA C355-T6, certified to AMS 4215, were machined from separately cast bars nominally 19 mm in diameter.

Specimens were hard anodized in accordance with MIL-A-8625 type III [3] requirements. Table I gives the resulting coating thicknesses. Fig. 1 illustrates typical coating cross-sections. Note the cracking of the coatings. The post-anodizing surface roughnesses for the AA6061 and AA C355 specimens were about 1.6 and 4.5 μm R_a, respectively. Note that pitting and cracking of the hard anodized surface lead to inaccuracies in roughness measurements by stylus profilometry.

Axial fatigue tests were performed using a sinusoidal wave form at 60 Hz. The stress ratio (minimum stress to maximum stress) R was 0.1 Rotary bending fatigue tests were performed using Krouse testing machines operating at 8000 rpm. By the nature of the rotary bend test, R was -1.

The results of axial fatigue testing are shown in Fig. 2. As shown, the data for the uncoated AA6061-T651 compared favourably to the interpolated equivalent stress model for AA6061-T6 given in MIL-HDBK-5F [5]. Both the HC3 and HC5 coatings decreased the fatigue strength at all lifetimes. The thicker HC3 coating showed slightly greater life reduction compared to the HC5 at all stress levels. However, for design, this was not statistically significant.

The results for rotary bend fatigue testing of AA6061-T6 in the various states of anodization are shown in Fig. 3. Again, both the HC3 and HC5

TABLE I Anodize coating thickness

	AA6061-T651 Axial		AA6061-T6 Rotary Bend		AA C355-T6 Bending HC5
	HC3	HC5	HC3	HC5	
Thickness (μm)	56	30	61	41	51

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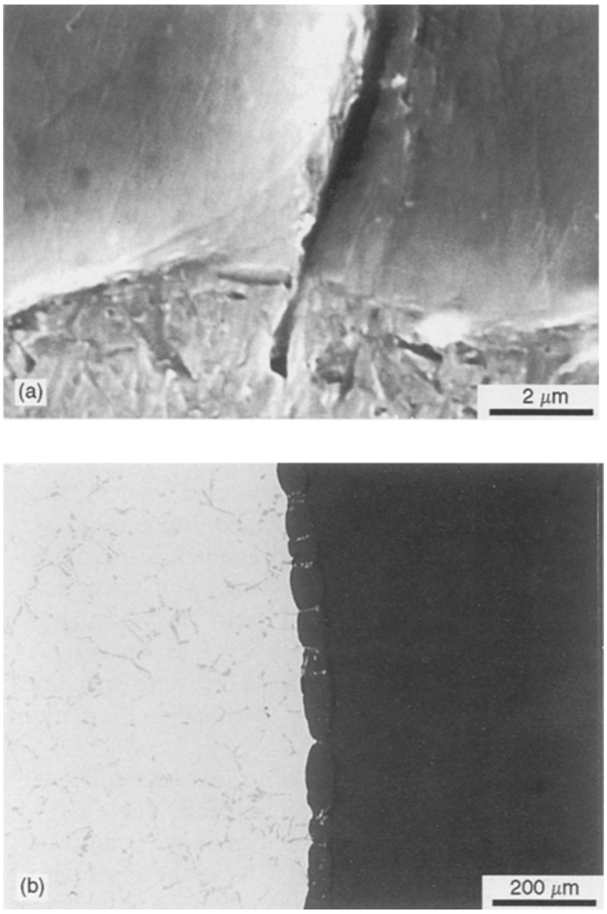

Figure 1 Cracks in hard anodize extend through the coating to the interface: (a) electron micrograph of cross-sectioned HC5 hard anodize (top) on AA6061 (bottom) and (b) photomicrograph of cross-section through HC5 hard anodize (centre) on C355 (left).

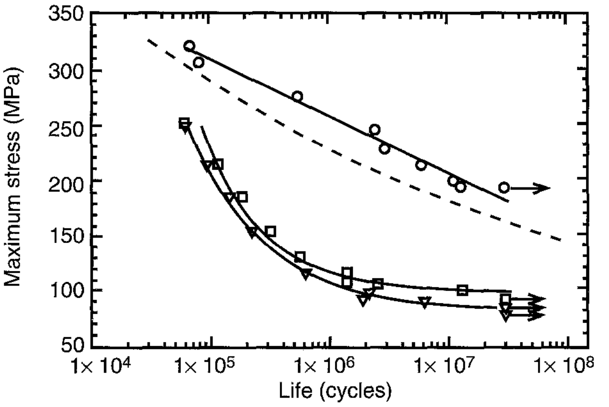

Figure 2 Room temperature ($R = 0.1$) axial fatigue results for AA6061-T651 in the unanodized and hard anodized conditions and standard data for AA6061-T6. (○), Uncoated; (□), HC5; (▽), HC3; (— — —), [5].

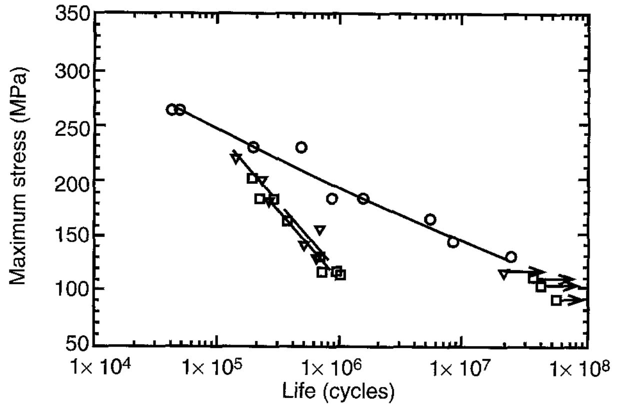

Figure 3 Room temperature rotary bend ($R = -1$) fatigue results for AA6061-T6 in the unanodized and hard anodized conditions. (○), Uncoated; (□), HC5; (▽), HC3.

coatings decreased the fatigue strength at all lifetimes. However, possible threshold behaviour was observed around 120 MPa, leading to runouts in the case of the HC5 material. The decreasing fatigue debit at high cycles was consistent with the axial data.

The data points were curve fit to the model:

$$\log(N) = A + B\log(S - C) \qquad (1)$$

where N is life, S is stress, and A, B and C are adjustable parameters as given in Table II. Runout tests, indicated by arrows in Figs 2 and 3, required special attention. For the axial tests, runouts were included in the curve fit as if they were actual failures. If the curve fit residual at the runout was negative, the lowest stress runout was censored. This was repeated for all runouts until their residuals were above the fit line [6]. This ensures a more conservative curve fit at long lifetimes. For the rotary bend tests, it was not possible to include the runout tests due to the sharp transition after about 10^6 cycles.

Fig. 4 shows the fatigue debit for AA6061 expressed as a percentage of retained strength as a function of life based on the fit curves. The maximum fatigue debit for the axial tests was between about 1.5×10^6 and 2.5×10^6 cycles. Given the threshold shown in Fig. 3, the same observation can be made for the rotary bend data. Under stresses of less than about 100 MPa, the axial fatigue data shown increased retained strength for the hard anodized material. Thus, high design life parts experience a diminishing effect of hard anodize on the fatigue strength. In the worst case (HC3), the

TABLE II Curve fit parameters for fatigue of AA6061-T6

Test orientation	Material/coating	A	B	C	R^2	Runouts censored
Rotary bend	AA6061-T6	72.40	−24.27	−348.17	0.967	0 of 0
Rotary bend	AA6061-T6/HC3	0.85	−34.95	−1774.4	0.852	1 of 1
Rotary bend	AA6061-T6/HC5	54.42	−16.51	−743.87	0.973	3 of 3
Axial	AA6061-T651	161.36	−50.79	−889.29	0.980	0 of 1
Axial	AA6061-T651/HC3	8.10	−1.47	80.11	0.984	1 of 2
Axial	AA6061-T651/HC5	7.51	−1.19	97.07	0.985	1 of 1

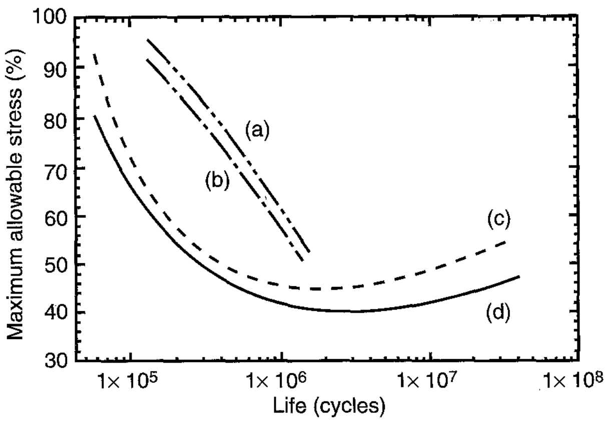

Figure 4 Percentage of fatigue strength retained following anodization of AA6061-T6 and AA6061-T651. (a) Rotary HC3, (b) rotary HC5, (c) axial HC5 and (d) axial HC3.

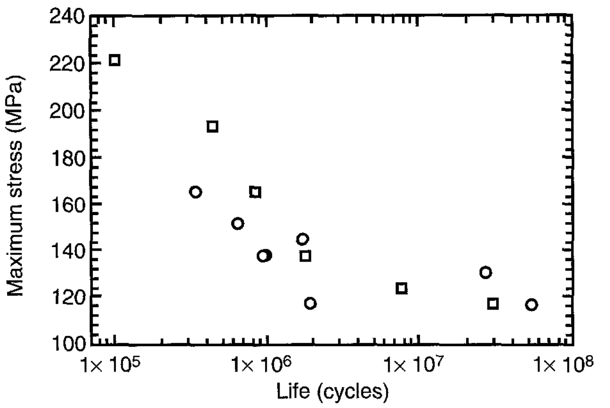

Figure 5 Room temperature rotary bend ($R = 0.1$) fatigue results for AA C355-T6 in the (○) hard anodized (HC5) and (□) unanodized states.

minimum retained strength was 40% corresponding to a fatigue debit of 60%, which was consistent with data in the literature [2]. However, the increase in retained strength at long lives was not consistent with Gilig's [7] stress–life curve for hard anodized AA7075.

The results from a smaller set of experiments performed on AA C355-T6 in rotary bending are presented in Fig. 5. The HC5 coating did not have a significant effect on the fatigue of this material. This was consistent with observations on AA 356 [2]. As a cast alloy, the intrinsic flaw size was greater than in the wrought AA6061. Fig. 1b shows that the crack lengths through the anodize coating are of the same size as the silicides in the basis metal. Thus, it is plausible that the flaws introduced by the hard anodize coating were not of sufficient size to appreciably affect the fatigue behaviour of the C355-T6.

In summary, hard anodization of wrought AA6061-T6 and AA6061-T651 gives rise to an appreciable reduction in the fatigue strength. In the worst case, the retained fatigue strength was only 40% of the uncoated material fatigue strength, corresponding to a fatigue debit of 60%. However, under stresses less than about 100 MPa, the retained strength begins to increase, approaching that of the uncoated material. Retained strength possibly shows a minor direct variation with coating thickness. However, insufficient data were available for confirmation. Finally, in the case of cast C355-T6, hard anodization does not have an appreciable effect on the fatigue behaviour.

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References

1. S. WERNICK, R. PINNER and P. G. SHEASBY, "The surface treatment and finishing of aluminum and its alloys", 5th edn (American Society for Metals International, Metals Park, Ohio, 1987).
2. J. S. ABBOTT, *Adv. Mater. Proc.* **September** (1994) 29.
3. "Military specification, anodic coatings, for aluminum and aluminum alloys", MIL-A-8625E, United States Department of Defence, Washington D.C., (1988).
4. *Mater. Meth.* **32** (1950) 62.
5. "Military handbook, metallic materials and elements for aerospace vehicle structures", MIL-HDBK-5F, United States Department of Defence, Washington D.C., (1992).
6. J. B. CONWAY and L. H. SJODAHL, "Analysis and representation of fatigue data" (American Society for Metals International, Metals Park, Ohio, 1991) p. 201.
7. F. G. GILLIG, "Study of hard coatings for aluminum alloys", WADC technical report 53-151, May (1953).

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