Technical Article

Effects of Alloy Types On the Gloss of Anodized Aluminum

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The effects of alloying elements, microstructures and coating thickness on the surface gloss of anodized aluminum panels were investigated. Three automotive aluminum alloys (AA5083, AA5657 and AA6111) were tested. The oxide film growth rates for the three alloys are all in the 0.46 to 0.49 μ m/min (18.1 to 19.3 μ -in./min) range. The gloss of anodized AA5657 was the highest, followed by AA6111 and AA5083. For AA5657 and AA6111 alloys, the magnesium contents are about the same, but AA6111 alloy has much higher manganese, silicon and copper content, which contributed to the higher roughness and lower gloss. For AA5083 alloy, the grain size changes during forming did not effect the gloss changes during anodizing.

Anodizing is an electrochemical process in which the aluminum part is made the positive electrode (anode) in



Fig. 1—Schematic illustration of anodic oxide structure; typical oxide thickness, 10 to 30 mm (~0.4 to 1.2 in.); pore diameter, 20 nm (~0.8 µ-in.).

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Allov Composition (wt%)							
Mg	Mn	Si	Cu	Fe	Zn	Cr	Ti
4.60	0.79	0.10	0.02	0.18	0.01	0.11	0.01

5083	4.60	0.79	0.10	0.02	0.18	0.01	0.11	0.01	Bal.
5657	0.59	< 0.01	< 0.1	0.03	0.03	< 0.01	< 0.01	0.02	Bal.
6111	0.66	0.20	0.60	0.85	0.23	0.01	0.01	0.03	Bal.

Nuts & Bolts: What This Paper Means to You

Anodized aluminum finishes are used in many decorative applications. In the automotive industry, gloss is critical to customer acceptance, but little has been studied in this area to date. Here, three automotive aluminum alloys were studied to determine how the alloying elements, microstructures and coating thickness affects the surface gloss of the anodized finish. a suitable electrolyte (e.g., sulfuric acid). Sufficiently high voltage is applied to establish the desired polarization to deposit oxygen at the surface. The aluminum surface reacts with the oxygen to produce adherent, oxide coatings:

$$2AI + 3H_2O \rightarrow Al_2O_3 + 3H_2\uparrow$$

In the sulfuric acid anodizing process, the oxide formed is slowly dissolved by the electrolyte. Thus, a porous oxide coating is produced (Fig. 1). The net coating growth rate and its porosity depend on the equilibrium set up between the film growth and dissolution.

Anodizing technology for aluminum goes back to 1940's, and is extensively used in architectural applications, especially in Europe.¹ For automotive applications, the gloss requirements are more demanding than for architectural applications, and it is important to determine the surface gloss of the finished part and how the final gloss is affected by different factors. In this investigation, we studied the effects of alloying elements, microstructures and coating thickness on the gloss of anodized aluminum for three automotive alloys (AA5657, AA5083, and AA6111).

Experimental *Materials*

Al

Three types of alloys were studied in this work. The chemical composition of these alloys is given in Table 1.² The AA5657 is an automotive trim alloy. The AA6111 is an alloy commonly used for exterior aluminum body parts.³ The AA5083 is from the family of alloys used in unexposed (exterior) automotive applications.

The AA5083 alloy was tested as received and in the fully annealed condition. The AA5657 alloy was tested in the as-received condition (one-side bright-rolled). The alloy AA6111, which is a heat-treatable alloy, was tested as received and after heat treatment at 177°C (351°F) for 30 min.

The metal surfaces for alloys 6111 and 5083 were manually polished with a polishing wheel prior to anodizing. Alloy 5657 was received in the bright-rolled condition. Polishing was done using a random-orbital sander.^{**} Initial

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Alloy

^{**} DeWalt random-orbital sander (Model# DW421), DeWalt Industrial Tool Co., Baltimore, MD.





sanding was done using sanding pads^{***} at 400 grit followed by finishing films^{****} at 600, 800 and 1500 grit. The amount of sanding varied with the initial condition of the aluminum samples.

Anodizing Process

The anodizing process diagram is shown in Fig. 2. The aluminum surface was first cleaned in an alkaline cleaning tank, followed by dipping in the de-smut tank to remove any black surface film (smut). It was then anodized for varying lengths of time (depending on the coating thickness desired) to grow a porous oxide layer. The film was then sealed in a two-step sealing process that basically hydrated the oxide, causing it to expand and fill up the pore spaces. Rinsing operations were incorporated between process steps to minimize the cross-contamination of the process solutions.

Gloss Measurement

The gloss of the sample surface was measured using a portable gloss meter^{\dagger}. The unit was placed directly on the sample and the gloss measurement was taken at both 60° and 85° illumination angles. The illumination angle is the angle between the axis perpendicular to the sample surface and directed light. The directed light reflected from the surface was measured photoelectrically and is described by the reflectometer value R. This is a relative measurement based on the gloss value of 100 for a highly polished black glass plate with a refractive index of 1.567.

Coating Thickness Measurement

The oxide coating thickness was measured by an eddy current device.^{††} When a conductive material (aluminum) is subjected to an AC magnetic field from the probe, eddy currents are induced in the material in proportion to the frequency and resistivity. The induced eddy currents generate an opposing magnetic field, which alters the circuit reactance and the output voltage of the probe. Non-conductive coatings, such as an anodized coating, introduces a gap (lift-off) between the probe and aluminum. This gap produces a loss in eddy current penetration, which is compared to a measurement directly on the basis material to determine coating thickness.

**** 3M Hookit[™] finishing films, 3M Corp., Maplewood, MN.

Table 2Etchants & Etching Conditions for Various Alloys

Alloy	Etchant (vol%)	Temperature	Time (min)
5083	0.5 HF	Room	2
5657	10 H ₃ PO ₄	50°C (122°F)	4
6111	0.5 HF	Room	2

Surface Roughness Measurement

Three-dimensional surface roughness was measured on the oxide/air and the metal/oxide interfaces by a non-contact optical profiler .^{†††} Due to the transparent nature of the aluminum oxide, double interference fringes occur at both the oxide/air surface and the metal/oxide interfaces, causing measurement problems. For an accurate oxide surface roughness measurement, we vacuum-deposited a thin Au-Pd layer onto the oxide/air surface to eliminate the interference fringe from the metal/oxide interface. To measure the metal surface roughness after anodizing, the oxide film was stripped off in a phosphoric/chromic stripping solution. An R_a value, which is a measure of the surface profile arithmetic average deviation from the centerline, was used to quantify the surface roughness.



Fig. 4–Optical micrograph of AA5083 in the cold-worked state.



Fig. 5–Optical micrograph of AA5083 after superplastic forming.

^{*** 3}M HookitTM Gold sanding pads, 3M Corp., Maplewood, MN.

[†] Micro-TRI Gloss meter, BYK-Gardner USA, Columbia, MD.
[†] Fischerscope Multi Measurement System (MMS), Fischer Technology, Inc.,

Fischerscope Multi Measurement System (MMS), Fischer Technology, Inc., Windsor, CT.

^{†††} Wyko Optical Profiler, Veeco Corporation, Woodbury, NY.

Table 3 Coating Growth as a Function of Alloy Type & Heat Treatment

Alloy	Treatment	Growth rate (µm/min)	Growth rate (A-min/dm²/µm)
5083	Cold-worked	0.464	3.48
5083	Annealed	0.489	3.30
5657	As-received	0.483	3.35
6111	As-received	0.455	3.55
6111	After heat-treatment	0.483	3.35



Fig. 6-Optical micrograph of AA5657.



Fig. 7-Optical micrograph of AA6111, as-received.



Fig. 8–Optical micrograph of heat-treated AA6111.

Metallography

All alloys were examined metallographically to determine the grain structure. For AA5083, the samples were first aged at 150°C (302°F) for 24 hr to precipitate Al_3Mg_2 at the grain boundaries. This promotes preferential attack at the grain boundaries during the etching process to reveal grains.⁴ For other alloys, no aging steps were required to reveal grain structures. Alloy samples were mounted on their edges and examined by optical microscopy. The etchants and the etching conditions for various alloys are listed in Table 2.

Results & Discussion

Oxide Film Growth

The effect of anodizing time on oxide film growth for the three alloys was examined in this study, and the results are shown in Fig. 3. The oxide film thickness increased linearly with anodizing time. Table 3 lists the oxide growth rates for the three alloys, as given by the slope of the fitted straight lines to the data of Fig. 3. The growth rates for the alloys tested were all in the range of 0.46 to 0.49 μ m/min (18.1 to 19.3 μ -in./min). For AA5083, annealing increased the growth rate by 6%, and for AA6111, heat treatment increased the growth rate by 4%. More samples need to be tested to verify the statistical significance of these results. The coating thickness was governed by the current density (1.6 A/dm²; 15 A/ft² in our study) and the time of anodizing. On an A-min basis, the growth rates were calculated to be in the range of 3.30 to 3.65 A-min/dm²/ μ m (0.78 to 0.84 A-min/ft²/ μ -in.).

Microstructures

Figure 4 shows the microstructure typical of the cold-worked AA5083 material. It consists of fine equiaxed grains with an average diameter of ~5 μ m (~200 μ -in.). After annealing, the average grain size was increased to ~10 μ m (~400 μ -in.) (Fig. 5). Figure 6 shows the microstructure of the AA5657 material. It consists of a cold-worked structure with elongated grains in the rolling direction. The microstructures of the AA6111 in the as-received and heat-treated conditions are shown in Figs. 7 and 8, respectively. Both exhibited the same average grain size of ~20 μ m (~800 μ -in.), and the heat treatment, because of its relatively low temperature and short duration (177°C; 351°F for 30 min),⁵ did not seem to affect the grain size.

Gloss of Anodized Alloys During Anodization

Alloy AA5083. The surface roughness (R_a) and 85°-gloss of AA5083 after annealing are shown in Fig. 9 as a function of coating thickness for both the metal/oxide interface and the oxide/air interface. The metal surface roughness started with an R_a value of 150 nm before anodizing. As the coating thickness increased from 0 to 5 μ m (0 to 197 μ -in.), the R_a value increased linearly to 380 nm. As the thickness increased from 5 to 15 μ m (197 to 591 μ -in.), the metal surface roughness values showed a more gradual increase from 380 to 490 nm. Beyond a thickness of 15 μ m (591 μ -in.), the metal surface roughness remained relatively constant at approximately 500 nm. The oxide/air surface roughness increased from 150 to 300 nm as the coating thickness greater than 5 μ m (197 μ -in.), the oxide roughness remained relatively constant at 280 nm.

As shown in Fig. 9, the variation in the surface roughness of the oxide surface with oxide thickness followed almost the same pattern as that for the metal surface, with most of the changes happening over the first 5 μ m (197 μ -in.) of film growth. The surface gloss decreased very sharply over the first 1 μ m (39 μ -in.) of film





growth, dropping from 135 (before anodizing) to about 100 (25% drop in gloss). From 1 to 25 μ m (39 to 984 μ -in.) of coating thickness, the gloss decreased more gradually from about 100 to 76.

The relationships between gloss and surface roughness are depicted in Figs. 10 and 11, for the metal surface and oxide surface, respectively. On the basis of the calculated regression coefficients, we deduced that the gloss during anodization correlated strongly with the metal surface roughness, and to a lesser degree with the oxide surface roughness. Since aluminum oxide is transparent, one would expect the metal/oxide interface to be the prevailing reflecting surface and its surface characteristics (roughness, texture, etc.) would have greater effect on the gloss of the anodized part.

Alloy AA6111. The surface roughness (metal/oxide interface, and oxide/air interface) and 85°-gloss of heat-treated AA6111 are shown in Fig. 12 as a function of coating thickness. The metal surface roughness started with an R_a value of 55 nm (before anodizing). As the coating thickness increased from 0 to 10 μ m (0 to 394 μ -in.), the R_o values increased linearly to 340 nm. From 10 to 27 μ m (394 to 1060 μ -in.) coating thickness, the metal surface roughness values remained relatively constant. The oxide roughness increased from 55 to 170 nm as the coating thickness grew from 0 to almost 5 μ m (197 μ -in.). For coating thicknesses greater than 5 μ m (197 μ -in.), the oxide roughness varied gradually from 170 to 250 nm.

As shown in Fig. 12, most of the gloss decrease occurred over the first 3 μ m (118 μ -in.) of film growth, dropping from 130 before anodizing to about 95 (25% drop in gloss). From 3 to 27 μ m (197 to 1060 μ -in.) coating thickness, the gloss remained more or less constant.

Alloy AA5657. The surface roughness (metal/oxide interface, and oxide/air interface) and 85°-gloss of AA5657 are shown in Fig. 13 as a function of coating thickness. The metal surface roughness started with an R_a value of 53 nm (before anodizing). As the



thickness for AA6111(HT).

coating thickness increased from 0 to 5 μ m (0 to 197 μ -in.), the R value increased slightly to 65 nm. From 5 to 10 μ m (197 to 394 μ in.) coating thickness, the metal surface roughness values actually decreased to 49 nm. The metal surface roughness showed a gradual increase from 49 to 80 nm as the coating thickness grew from 10 to 23 μ m (394 to 906 μ -in.). The oxide surface roughness reached a maximum at a coating thickness of almost 5 μ m (197 μ -in.). It then decreased with increasing coating thickness, remaining almost constant above about 15 μ m (591 μ -in.).

As shown in Fig. 13, most of the gloss decrease occurred over the first 10 μ m (394 μ -in.) of film growth, dropping from 150 (before anodizing) to about 116 (23% drop in gloss). From 10 to 23 μ m (394 to 906 μ -in.) coating thickness, the gloss remained more or less constant.

Effect of Alloy Grain Size

Aluminum alloys of fine grain size often give superior finishes in comparison with alloys of coarser crystal structure. The effect of grain size on gloss during anodization is shown in Fig. 14 for AA5083 cold-worked (AR) and after annealing (AN). The grain size of the AN material is two times larger than the CW material (see Figs. 4 and 5). However, Fig. 14 clearly indicates that the surface roughness or the gloss changes during anodization show little correlation with grain size. Finer grain size and wider size ranges will be investigated in future studies.

Effect of Alloying Elements

The effect of alloying elements on metal surface roughness during anodization is shown in Fig. 15. Among the alloys, AA5083 and AA5657 show the highest and lowest metal surface roughness,



Fig. 13–Variations of surface roughness and gloss with coating thickness for AA5657.



Fig. 15–Variations of metal surface roughness with coating thickness for different alloys.

respectively. At a given anodizing current density, aluminum alloys with a magnesium content greater than 1% tend to produce coatings of lower gloss values.6 The AA5083 has a high magnesium content (4.60%, see Table 1). During anodization, both aluminum and magnesium are oxidized at the metal/oxide interface.1 The differential oxidation rates of aluminum and magnesium will result in roughening of the metal surface. For a low magnesium content alloy (AA5657 at 0.59%, see Table 1), the surface roughness did not increase much. However, for a high magnesium content alloy (AA5083), the surface roughness increased substantially during anodization. For AA5657 and AA6111 alloys, the magnesium contents are about the same, but AA6111 alloy has higher manganese, silicon, and copper contents. These elements tend to remain on the metal surface during anodization. The interfacial enrichments of the alloy elements further promote differential oxidation of the metal surface, thus contribute to the increase in roughness.^{7,8}

Figure 16 shows the gloss versus coating thickness for the three alloys. AA5657 showed the highest gloss. AA6111 had a slightly higher gloss than AA5083 alloy. For AA5657, the gloss exhibited a linear decrease as the coating thickness increased from 0 to 10 μ m (0 to 394 μ -in.). With coating thicknesses greater than 10 μ m (394 μ -in.), no further gloss loss was observed. For AA6111 and AA5083 alloys, the critical coating thickness was around 1 to 3 μ m (39 to 118 μ -in.).

Conclusions

In this investigation, we selected three automotive aluminum alloys (AA5083, AA5657 and AA6111) to study the effects of alloying elements, microstructures and coating thickness on the gloss of anodized aluminum. Under similar anodizing conditions, the gloss of anodized AA5657 was the highest, followed by AA6111 and AA5083. For all the alloys, there was a decrease in







Fig. 16-Variations of gloss with coating thickness for different alloys.

gloss of the panels with increasing oxide thickness. The decrease in gloss correlated strongly with the increase in metal surface roughness during anodization, and to a lesser degree, with the increase in the oxide surface roughness.

For a low magnesium content alloy (AA5657), the surface roughness did not increase much with oxide growth. However, for a high magnesium content alloy (AA5083), the surface roughness increased substantially during anodization due to differential oxidation rates of aluminum and magnesium. For AA5657 and AA6111 alloys, the magnesium contents are about the same, but AA6111 alloy has much higher manganese, silicon and copper contents, contributing to the higher roughness and lower gloss. Of all the factors investigated, alloy composition and coating thickness were the two most important parameters affecting the gloss of finished parts.

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