The Impact of Surface Roughness on the Performance of Anodized Coatings on 6061 Aluminum

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Abstract: This study aims to evaluate how anodization type and surface roughness affect the performance of anodized Al 6061 samples. The samples tested included a Bare Al 6061 sample, multiple Type III Hard Anodized Al 6061 samples, and multiple Plasma Electrolytic Oxidation (PEO) coated Al 6061 samples. The tests conducted were profilometry, sectioning the sample and performing SEM/EDX, corrosion testing, and hardness testing. The results reveal key relationships between surface roughness, anodization type, and the quality of the performance of those properties, helping determine an optimal surface roughness value. This provides Applied Materials actionable data to optimize coating processes and enhance the durability of anodized Al 6061 in critical applications.

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Project Background

Achieving optimal surface roughness for enhanced mechanical performance requires an understanding of how anodization techniques influence the relationship between surface texture and coating behavior. Type III HA and PEO are commonly used to enhance the durability of aluminum, offering distinct properties valuable to the semiconductor industry. These coatings are applied to aluminum components within semiconductor OEM chambers, where they help extend equipment lifespan and reliability under harsh operating conditions.

Table 1. Given Surface Finish (Ra) ranges of the substrate.

Substrate	Low (µin)	Mid (µin)	High (µin)
Al 6061	5.4 ± 0.8	19.0 ± 3.4	47.1 ± 4.5

Type III Hard Anodization

Type III HA forms a dense, thick oxide layer by immersing the aluminum in a chilled sulfuric acid electrolyte while applying high voltages (up to 100V) at high current densities (24-36 amps per square foot). This process can achieve thicknesses above 50µm, suitable for wear-intensive applications. The oxide film formation occurs as Al^{3+} ions migrate away from the substrate towards the electrolyte, while O^{2-} ions move in the opposite, leading to a thick, uniform, and abrasion-resistant oxide layer [1]. More visual can be seen in Figure 1.

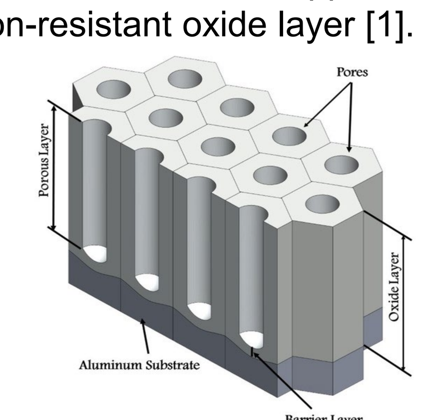

Figure 1. Schematic of hexagonal array of nano structure of hard anodized coating on aluminum.

Plasma Electrolytic Oxidation

PEO is a high-energy electrochemical process that forms a ceramic-like oxide layer through controlled micro-arc discharges on the aluminum surface. It results in a coating with a dual-layer structure: a dense inner layer and a porous outer layer that provides excellent wear resistance [3]. This differs than Figure 1. PEO coatings typically range from 10-30µm, as thicker PEO layers can lead to increased brittleness and defect formation.

Experimental Methods

Profilometry:

- 5 points on each sample were measured using the Zygo ZeScope Optical Profilometer, recording the Ra and Sa values. Values were recorded to report the average values and standard deviation, allowing comparison between Bare Al, HA, and PEO.
- The Ra value describes the average absolute deviation from the mean height across a line by using a single line profile.
- The Sa value is a 3D measurement calculated over a surface area and is the average deviation from the mean plane of the surface, across a defined scan area.

Corrosion Testing:

- Tested 6 samples (HA and PEO) from each varying surface roughness in 5wt% HCl solution.
- Grouped samples by roughness and tested at room temperature (~25°C). Immersed samples for 3 hours and monitored corrosion visually every 30 minutes, noting bubble formation and surface changes.

Hardness Testing:

- Indented and obtained indent dimensions for each sample (Bare, PEO, and HA) at 5 random points using a Wilson Vickers Hardness Tester
- PEO samples were Indented and marked to find indents with optical microscopy using an Olympus BX41M
- All indents were loaded using a 1 kg load and a 10 s load time

SEM:

- One of each sample type was ground to expose the cross section using a belt grinder then mounted in Bakelite.
- Each mounted sample was polished for 2.5 hours using a Pace GIGA-S Vibratory Polisher and colloidal silica.
- Each polished sample was sputter coated with gold to improve SEM image resolution.
- The cross section of each sample's coating was analyzed with SEM and EDX using a NanoScience Phenom SEM.

Results & Discussion

Profilometry

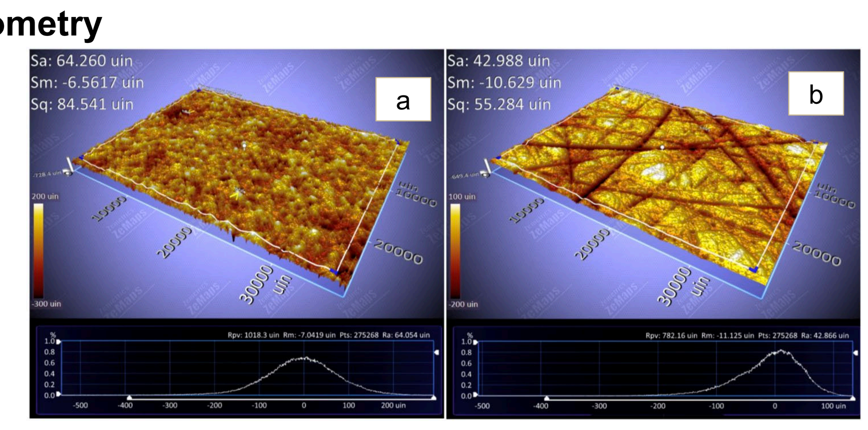

Figure 2. Optical profilometer images of Mid Ra range, a) PEO sample, b) HA sample

- Figure 2a: PEO samples have a consistent nonuniform surface with many small/short peaks and valleys on the surface, creating a more uniform look (shown by color scale)
- Figure 2b: HA samples have more machining marks and a visually uneven surface with little uniformity and greater difference between the peaks/valleys (shown by color scale)
- This means that the average Ra for PEO will be greater than that of the HA samples which are represented in our data in the table below.

Table 2. Overall averages for Mid Ra HA and PEO samples.

Anodization Type	Measured Ra Average (µin)	Ra Values Standard Deviation (µin)
PEO	60.724	3.525
HA	45.528	7.766

The standard deviation of the Ra values in the table above is larger for HA, correlating to the bar charts in Figure X. This explains how there are greater differences between the five measurements on the Mid Ra HA samples than the PEO.

Corrosion Test

Table 3. Time measured for the formation of bubbles on the surface of the samples immersed in 5wt% HCl solution.

Anodization Type	Substrate Ra	Time (min)
PEO	Low	27.6
	Mid	29.3
	High	30.2
HA	Low	42.4
	Mid	42.4
	High	46.7

Vickers Hardness Test

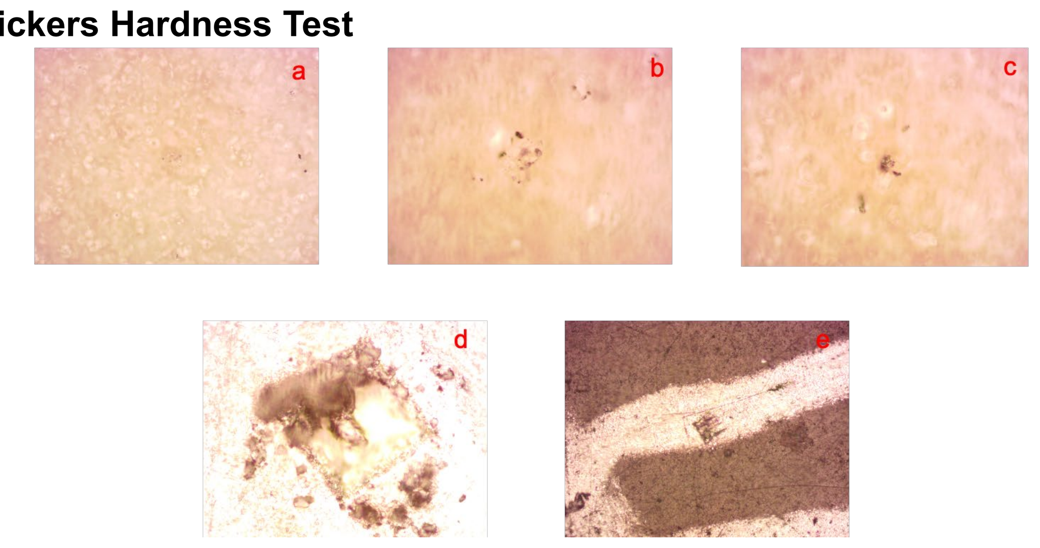

Figure 4. PEO (a, b, c), bare aluminum (d), and HA (e) sample indentations

- Figures 4 (a, b, and c): PEO sample indentations show very uncharacteristic and poorly defined indents compared to those found in literature suggesting another method to determine coating hardness may be required
- Figures 4 (d and e): bare aluminum and HA indents appear well defined and consistent to those found in literature

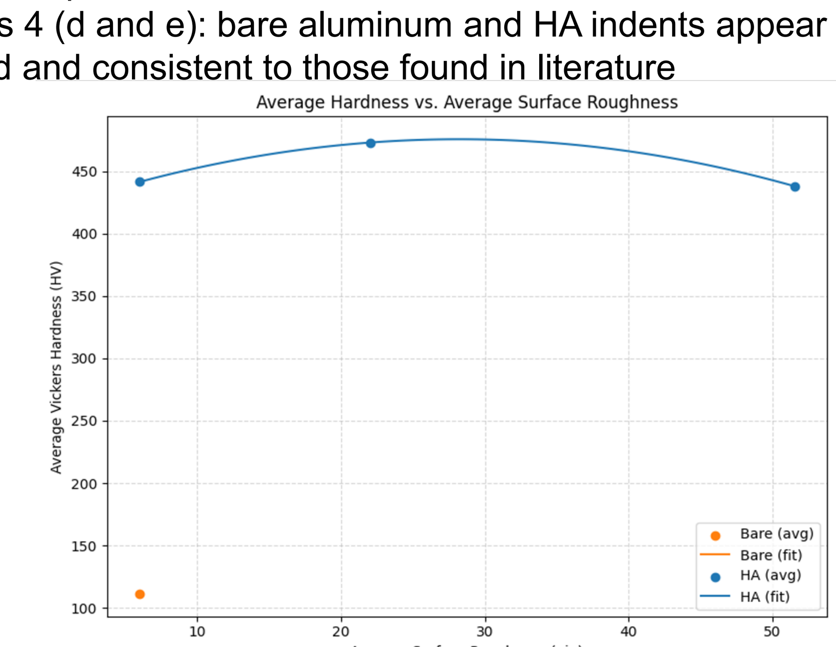

Figure 5. HA avg. Vicker's hardness vs avg. surface roughness and relationship between hardness and surface roughness

Table 4. Average hardness for samples of each anodization type and surface roughness

Anodization Type	Substrate Ra	Mean hardness (HV)	Standard deviation
HA	Low	441.52	18.26
	Mid	473.02	32.00
	High	438.10	28.15
Bare Al	Low	111.40	2.44

Results & Discussion Cont.

SEM

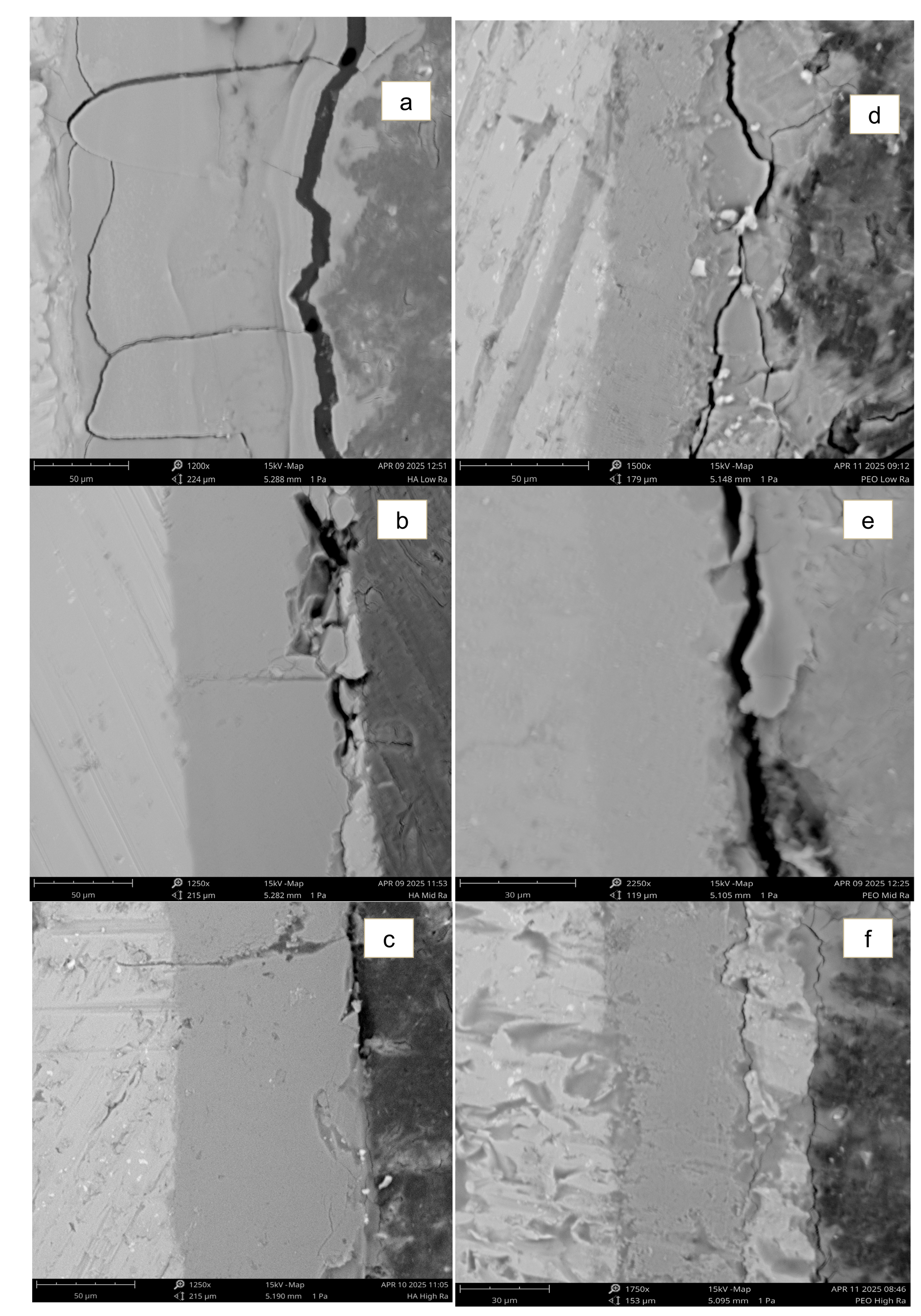

Figure 6. SEM images of each sample type. a) HA Low Ra, b) HA Mid Ra, c) HA High Ra, d) PEO Low Ra, e) PEO Mid Ra, f) PEO High Ra

Table 5. SEM Results showing Coating Thickness

Anodization Type	Substrate Ra	Coating Thickness (µm)
PEO	Low	~60
	Mid	~40
	High	~60
HA	Low	~130
	Mid	~140
	High	~100

Conclusions & Future Work

Profilometry accurately showed the multiple roughness measurements across each sample proving that HA high Ra samples have an overall higher average Ra, and the same trend for the PEO. Also, there is a greater difference between the 5 measurements on the HA samples than on PEO samples, meaning there is a more consistent nonuniform surface for PEO as shown by the standard deviation in Figure 7 below.

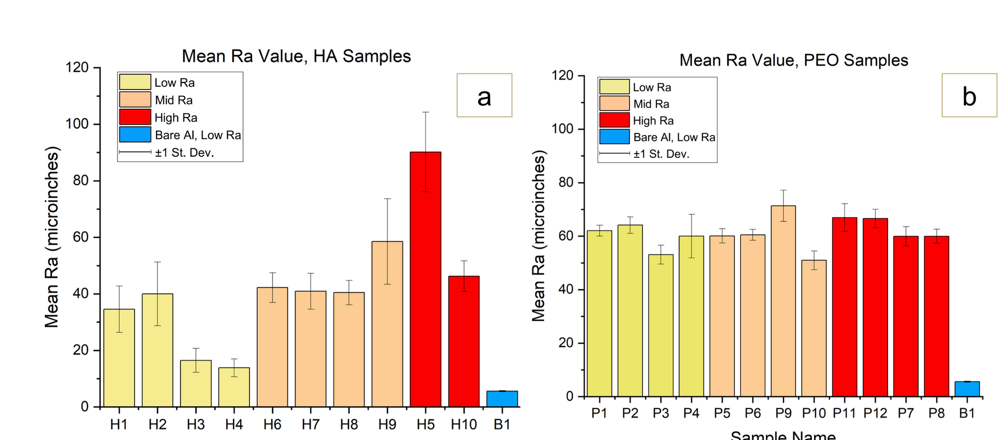

Figure 7. Average Ra Values across HA (a) samples and PEO (b) samples.

- To better understand the effect of harsh environments on the two types of anodized coatings, further corrosion testing should be performed over extended periods of time, at more extreme temperatures, and with higher concentration acids. The minimum recommended time for corrosion testing on anodized aluminum is around 8 hours [2], therefore more testing would be needed to ensure adequate results.
- Vicker's hardness testing showed high agreement with literature as well as little to no correlation between surface roughness and hardness for HA and Bare aluminum samples [3][4]. PEO examples however, showed poorly defined indentation signifying a higher hardness the prior tests and as a result would require more testing in the future.

References:

[1] *Anodizing of aluminum and its alloys -Determination of breakdown voltage and withstand voltage*. (2019). International Organization for Standardization. https://cdn.standards.iteh.ai/samples/72172/e0a8cb1011c2477d877068c75ef1030f/ISO-2376-2019.pdf
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[3] "Aluminum 6061-T6; 6061-T651." MatWeb, ASM, www.asm.matweb.com/search/specificmaterial.asp?bassnum=ma6061t6. Accessed 14 Apr. 2025.
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