THE EFFECT OF ANODIZING TIME ON THE TRIBOLOGICAL PROPERTIES OF 6061-T6 ALUMINUM ALLOY

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Abstract

Wear resistance is vital for parts that require sliding contact. Different surface treatments have existed in industry and anodizing is the one of techniques for forming a protective oxide coating to improve hardness and abrasion resistance. Due to its good mechanical properties after precipitation hardening, the 6061-T6 aluminum alloy is extensively chosen in the aircraft industry. Its major alloying elements are magnesium and silicon. Thus, anodic coatings of good quality can be easily applied to this alloy. In this study, the effect of anodizing time on the tribological properties of 6061-T6 aluminum samples was evaluated. The aluminum samples were anodized in two different electrolytes of sulphuric and chromic acid to specify the effects of anodizing solution type on the tribological properties of the anodic coatings. The anodized specimens were tested using a ball-on-disc tribometer and tribological properties such as friction coefficient and specific wear rate were characterized. At the end of the work, optimum anodizing time was identified for best wear properties.

Keywords: Anodization, aluminum alloys, 6061 alloy, wear, tribology

1. INTRODUCTION

Aluminum (Al) and its alloys extensively used in specific industries such as automotive, marine and aerospace which requires excellent mechanical properties, high corrosion resistance and especially their light weight properties. In this regard, 6061-T6 aluminum alloy is the best suitable material. The disadvantage of Al alloy is having poor tribological properties. In order to overcome this problem, the best method is anodizing of Al alloy to form a protective oxide coating. After anodization process, the alloy has higher hardness values and abrasion resistance properties [1].

Generally, this protective layer is thin but it can increase not only abrasion resistance but also the corrosion properties. Anodizing of Al alloy has applied over 100 years and commercialized for long years. During the process sulphuric, chromic, phosphoric, oxalic, or other types of acids can be used. There are lots of parameters can affect the morphology of this coating such as type and concentration of the electrolyte, alloy substrate, temperature, and time of the anodization process [2]. Sulphuric acid anodizing (SAA) is seen as an alternative to chromic acid anodizing (CAA), because of it is safer, produces more durable anodized layer, more cost effective and can be used wider range of materials. Kwolek et al. [2] has conducted research by anodizing onto 6061-T6 Al Alloy using sulphuric acid in order to investigate the effect of anodization time on the tribological properties. At the end of the study, they proposed a new method for hardness measurement. Hardness of coating was estimated by the basis of the scratch test method. They also concluded that the abrasion resistance of the coating increased by increasing with its thickness [3]. Wragg et al. has investigated the effect of different electrolyte i.e. chromic and sulphuric acid on the fatigue life of 7050 T7451 Al alloy. They have suggested that sulphuric acid anodizing could be replaced to chromic acid anodizing in terms of the fatigue properties [4].

In the literature, there is little published work investigating the effect of anodization time and different type of electrolyte on the tribological properties of 6061-T6 aluminum alloy. The aim of this study was to specify the effect of electrolyte type i.e. sulphuric acid anodizing and chromic acid anodizing and also optimum anodization time in terms of the friction coefficient and specific wear rate of 6061-T6 aluminum alloy.

2. EXPERIMENTAL DETAILS

In this study, 30 x 50 x 4 mm^3 specimen was prepared from the sheet metal. The chemical composition of 6061-T6 alloy is given in **Table 1**. The prepared specimen was pre-anodized by following steps for sulphuric and chromic acid electrolytes: degrease, alkali clean, rinse, pickle and rinse. The process parameters of anodizing for both electrolytes were 10, 20 and 30 minutes. For sulphuric (H_2SO_4) acid anodizing, process temperature was 20 °C, current density was 150 A/m^2 and voltage was 15 V, while for chromic (H_2CrO_4) acid anodizing process temperature was 42 °C, current density was 30 A/m^2 and voltage was 20 V. Finally, post anodizing procedures were applied to specimens by rinsing and sealing. After completion of the anodizing process, coating thickness was measured by EBAN5000 Coating Thickness Meter device.

Table 1 Chemical composition of 6061-T6 alloy (wt%)

Al	Mg	Si	Fe	Cu	Zn	Ti	Mn	Cr	Other
96	1.11	0.64	0.54	0.22	0.24	0.10	0.08	0.09	0.08

The tribological properties were characterized by using CSM wear tester as shown in **Figure 1**. Ball-on-disc method was chosen and AISI 52100 steel ball with diameter of 3 mm was used. Test parameters were as follows: 8 mm slides, 2 N constant load, total distance 15 meters and linear speed 2.5 cm/s. All tests were performed under dry conditions. Wear resistance of all specimens was evaluated by the specific wear rate k (mm^3/Nm) considering the Archard equation $k=V/(XL)$ where V is the wear volume (mm^3), X is sliding distance (m) and L is the normal load (N). After completion of wear tests, the wear area and volume were calculated by measuring wear scar with Mitutoyo SJ-400 profilometer. The wear data in x – y directions was imported to Origin Lab software. First, the wear area was calculated by integrating the wear scar and then total wear volume was specified.

Figure 1 CSM wear tester

Nanoindentation measurements were done by atomic force microscopy for the lowest and highest abrasion resistance anodized specimens considering Oliver-Pharr method.

3. RESULTS AND DISCUSSION

After completion of anodization, coating thickness measurements were performed by EBAN5000 Coating Thickness Meter device. All values are given in **Table 2**. For the same anodization time, the coating thickness of specimens which anodized in sulphuric acid thicker than chromic acid ones.

Table 2 Coating thickness after anodization process

	Coating thickness (μm)
10 minutes Chromic (H_2CrO_4) acid	1
20 minutes Chromic (H_2CrO_4) acid	2
30 minutes Chromic (H_2CrO_4) acid	3
10 minutes Sulphuric (H_2SO_4) acid	2
20 minutes Sulphuric (H_2SO_4) acid	7
30 minutes Sulphuric (H_2SO_4) acid	10

The coefficient of friction (μ) and specific wear rate k (mm^3/Nm) of the base specimen and anodized specimens were obtained by using ball-on-disc wear tester CSM. The friction coefficient as a function of distance for the specimens anodized in sulphuric acid and chromic acid and base specimens are shown in **Figure 2**. The mean coefficient of friction (μ) values is written on each plot. The friction curve for the base specimen has shown typical friction characteristics; running-in and steady-state behavior. After 0.8 m, it has a stable friction coefficient which is 0.65 mean value. During the wear test, there are some fluctuations existed. The reason for this case is the formation and breaking of the oxide film repeatedly. Specimens which anodized in chromic acid have different characteristics in comparison to base specimens. For specimen 10 minutes anodized in chromic acid, initially it showed a very low and stable coefficient of friction. After 10 meters of distance, it suddenly increased to a value of 0.66 mean coefficient of friction. The same behavior was also observed for specimen 20 minutes anodized in chromic acid. But a sudden increase was observed almost after 6 meters of distance. For specimen, 30 minutes anodized in chromic acid, has almost the same characteristics as the base specimen. After running in period, some fluctuations were observed during the wear test, and it ended with a value of 0.66 mean coefficient of friction. It can be said that the specimens which anodized in chromic acid have lubricant coating properties on the surface of aluminum alloy. But this thin coating easily has broken for a specimen 30 minutes anodized while it has long-lasting for specimens 10- and 20-minute ones. After breaking of the coating, all wear tests were completed with values of 0.66 – 0.67 mean coefficient of friction which was almost the same values as the base specimen had. Fluctuations were observed until the end of the wear tests due to the repeated formation and breakage of the oxide film. For specimens anodized in sulphuric acid, they have exhibited higher but stable friction characteristics than base specimen one. Regardless of the anodizing time, all specimens anodized in sulphuric acid have reached steady state behavior after almost 2 meters of distance. It can be said that the specimen which anodized in sulphuric acid has more durable thin coatings than the chromic acid one. For specimens 10, 20 and, 30 minutes anodized in sulphuric acid has mean coefficient of friction (μ) values 0.81, 0.79, and 0.78, respectively. Dervishi et al. has investigated the effects of anodization time on the tribological properties of aluminum alloy [5]. They concluded that thicker and harder anodic coatings were obtained in sulphuric acid in comparison to phosphoric acid. They got almost same coefficient of friction (μ) values as in this study. But they also mentioned that there is a challenge uncertainty of tribological tests because of the effects of different parameters. The coating porosity which serves as lubricant reservoir can affect the coefficient of friction. Novak et al. mentioned that tribological data can differ due to different operators, limited number of samples and misalignment of the force transducer [6].

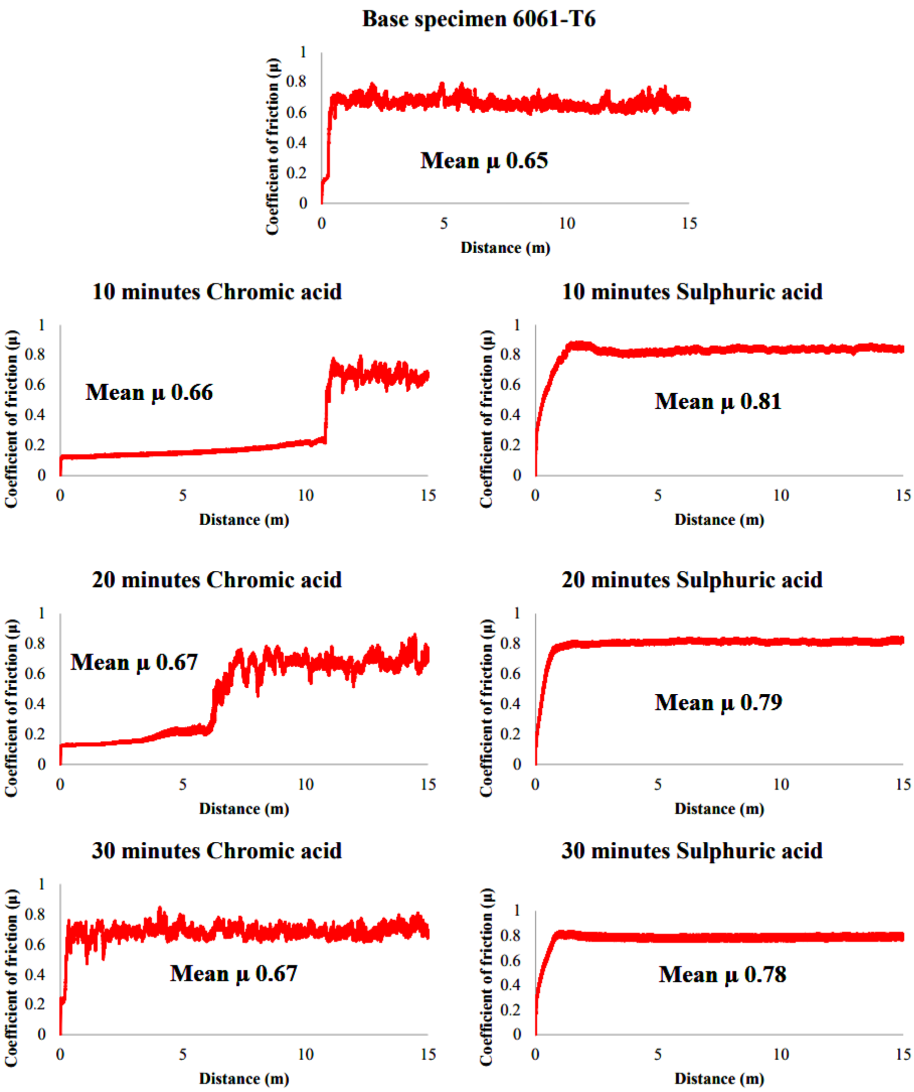

Figure 2 Distance vs. coefficient of friction plot for all specimen

Wear profiles in x – y direction for anodized and base specimens were imported to Origin Lab software and wear area was calculated for each specimen as shown in **Figure 3**. After calculation of wear area, the specific wear rate was specified. By taking into consideration specific wear rate, the result of wear test is more reliable because the effect of test parameters load, and distance are removed. The specific wear rate of anodized specimens and base specimen was calculated according to the Archard equation and is given in **Figure 4**. The most remarkable result is the specimens which anodized in sulphuric acid have the lowest specific wear rates in comparison to the base specimen and the specimens which anodized in chromic acid. The lowest specific wear rate value belongs to the specimen which anodized for 10 minutes in sulphuric acid. Nanoindentation measurements were performed for only two specimens as tabulated in **Table 3**: 10 minutes sulphuric acid anodized, and 20 minutes chromic acid anodized. The reason of choosing these two different specimens was the lowest and highest wear resistant properties according to calculated wear area. It is too hard to correlate the tribological properties and mechanical properties due to the complex and/or competing wear mechanisms. But it can be said that higher hardness values give more wear resistance to the surface. According to **Table 3** for every nanoindentation depth, the specimen which anodized in sulphuric acid for 10 minutes gives higher values than specimen chromic acid for 20 minutes. In the literature, a negative and a positive correlation observed between hardness and coefficient of friction. The reason of these differences can be attributed to complex process-structure relationships with influential parameters such as pore size, hardness, porosity, and chemical composition. The assessment of the wear type (adhesive, abrasive and oxidative) is beyond the scope of this study. There are some advantages of sulphuric acid anodizing in the literature [7]: it produces thicker and more durable anodized layer for the same anodization time than chromic acid anodizing. This property makes it better to use sulphuric acid anodizing specimens in harsh conditions such as abrasion and corrosion. A more uniform and consistent finish can be obtained for sulphuric acid anodizing process.

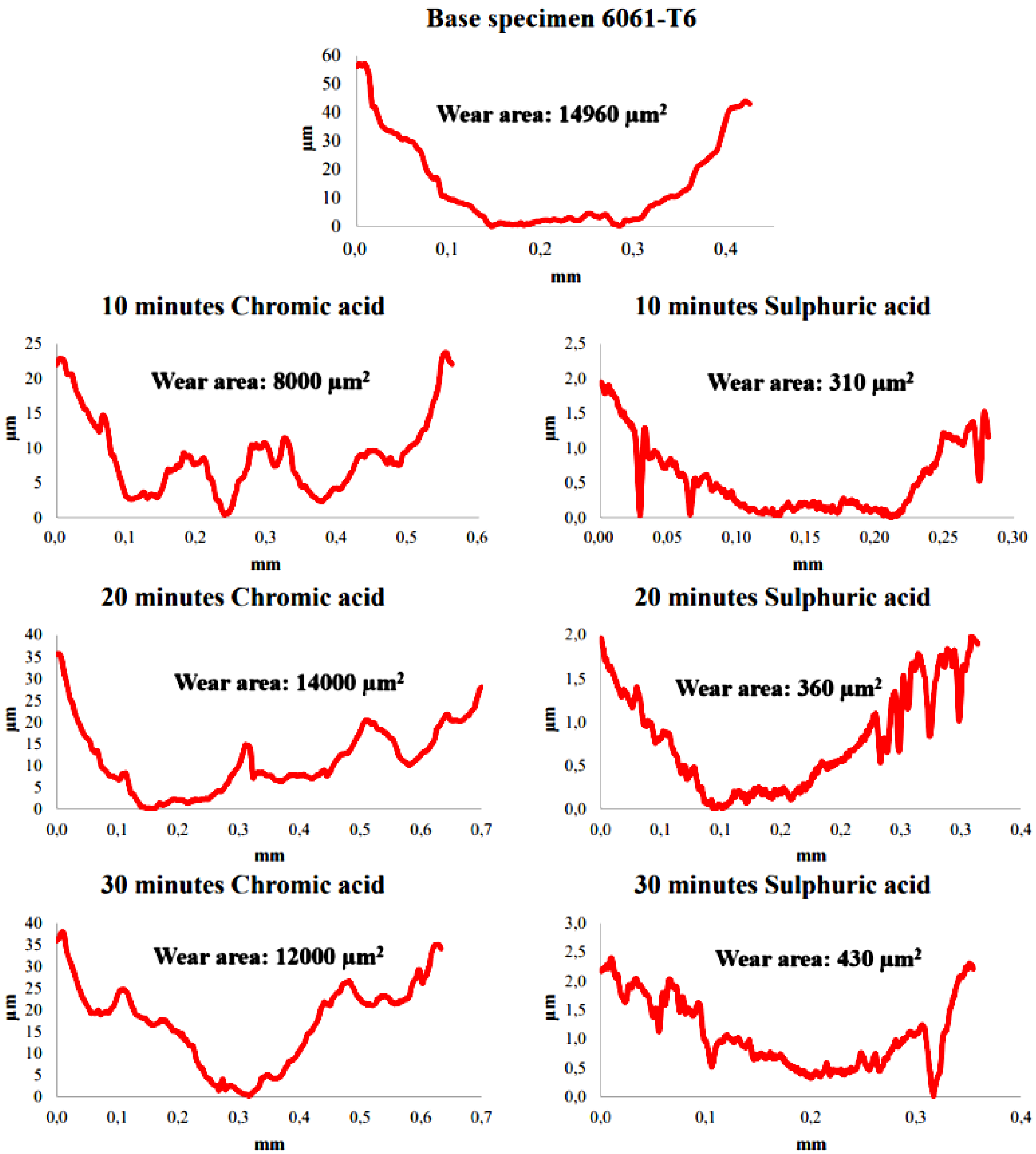

Figure 3 Wear profiles in x – y direction for anodized and base specimens

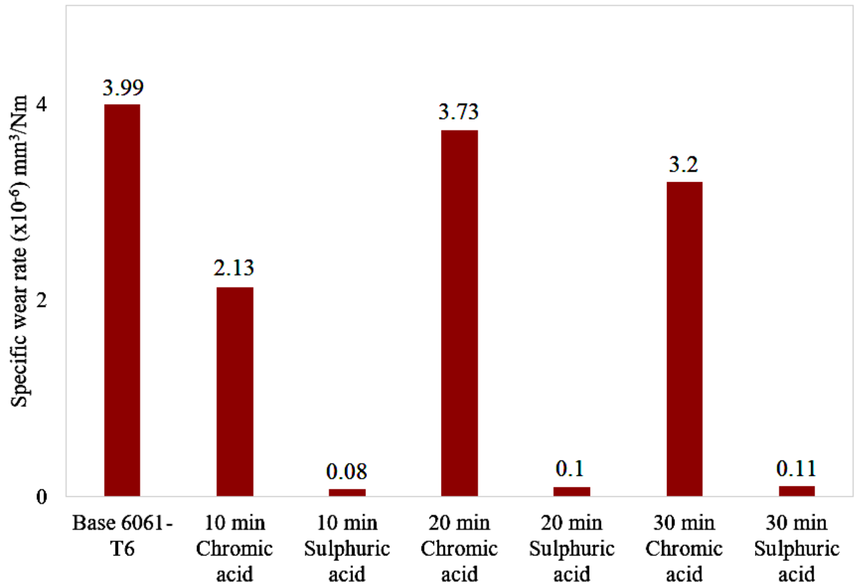

Figure 4 Specific wear rate for all specimen

The morphological properties of oxide coatings are also important. For future works, surface and cross-section of the anodized specimens can be investigated by SEM and EDS analysis. As the porosity and average pore size have influenced the tribological properties of specimens, SEM analysis will give more detailed information. Finally, exact wear mechanisms can be understood after completion of wear tests.

Table 3 Nanoindentation measurements

Depth (nm)	***H*** (GPa)	
	10 minutes sulphuric acid anodized	20 minutes chromic acid anodized
10	41	25.6
20	10	6.48
30	4.6	2.92
1000	$12x10^{-3}$	$2.73x10^{-3}$
1250	$13x10^{-3}$	$5.88x10^{-3}$
1500	$4.6x10^{-3}$	$5.66x10^{-3}$
2000	$7.9x10^{-3}$	$7.09x10^{-3}$

4. CONCLUSION

6061-T6 aluminum alloy specimens were anodized in two different electrolytes (sulphuric and chromic acid) for 10, 20, and 30 minutes. The coating thickness was strongly dependent on the anodizing time and for the same anodization time, sulphuric acid gives a thicker coating than chromic acid. It is clear that 10 minutes of sulphuric acid anodization has given the best wear resistance to 6061-T6 aluminum alloy. As the coatings produced by chromic acid anodization were easily broken, the coefficient of friction values was almost the same with the base specimen. For specimens which anodized in sulphuric acid have given higher coefficient of friction than base specimens. The highest nanoindentation measurement was obtained for the specimen which anodized in sulphuric acid for 10 minutes.

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