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Fabrication and tribological characterization of aluminium alloy by using photochemical machining

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KEYWORDS

Textured surface
Dimple density
Dimple depth
Dry condition
Worn surface

ABSTRACT

Photochemical texturing (PCT) is a widely used method to modify physical topography of the surface nearly all type of materials. However, the usage of this method is the most commonly used in microelectronic mechanical systems (MEMS) industries. While there have been few reported studies on the use of PCT technique for metal surfaces and there has been very limited work on the tribological characteristics from such surfaces. Therefore, the objective of the present work was to gain a better understanding on the wear and friction behaviour of textured aluminium alloy, AA2017-T4 by considering their geometrical texture characteristics. In this study, AA2017-T4 disks have been texturized into circular dimples with different area density (0 to 20%) and depth (5 to 15µm). Ball on disc tests were performed under dry condition. The worn surface of AA2017-T4 disks was analyzed to understand the wear mechanism and durability of the textured surface during testing. The results indicate that a higher density of circular dimples (20%) had less wear and a lower coefficient of friction compared to non-textured disk. The results suggest that the tribology performance is only dependent on the surface area density but does not influence by depth characteristics.

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1.0 INTRODUCTION

Surface texturing is a surface modification technique for improving energy efficiency with artificial topography in the manufacturing and automotive industries (Ahmad et al., 2020). Experimental work by (Etsion and Sher, 2009; Wu et al., 2016) indicated that surface texturing could help achieve this energy conservation optimization by reducing the friction coefficient and improving wear properties of the materials. This is because textured surfaces enhance the lubrication and friction properties of the surfaces in contact. As a result, the power output, fuel consumption, emissions, and part service life are improved (Nakada, 1994). Surface texturing have advantages such as ability act as lubricant reservoirs, alter hydrodynamic pressure and trap debris (Lu and Wood, 2020). Laser surface texturing is one of the surface texturing methods where the surface feature can be produced, especially on metal surfaces (Zhang et al., 2018). However, this method has been created heat-affected zones near-surface regions of the pore, that will detrimentally affect in surface functionalities, and therefore limiting the applications of the method (Roduan et al., 2020). Surface textures generated in computer numerical control (CNC) micromachining may result in irregularity on the surface such as ridge or burr formation. These features are problematic and raise many issues such as an increase of stress concentration at hole edges and affect the fatigue strength.

Alternatively, the coupling of photolithography with chemical etching which is often known as photochemical texturing (PCT) technique could be used, suited for fast surface texturing on a wide variety of materials and surface geometries. This technique is being able to generate texture surfaces of high precision on the nanoscale and the cost of the process low. Recently, the PCT technique has been demonstrated as an excellent tool to alter surface topography/roughness and surface finish on various types of materials. However, the usage of this method is the most widely used and perhaps most important technology in microelectronic mechanical systems (MEMS) industries (Nurhaziqah et al., 2018).

While there have been few reported studies on the use of PCT technique for metal surfaces including PCT on steel (Hao et al., 2014; Xu et al., 2018; Sanchez et al., 2020) and copper disk (Otero et al., 2017) and there has been very limited work on the tribological characteristics from such surfaces. Their results indicated that dimples were effective alternative for reducing the friction coefficient in lubricated condition. Besides steel and copper, aluminum (Al) alloy is becoming an increasingly important material in automotive and machinery application. Effects of surface texturing on friction and wear of Al alloy are still not clarified and need to be investigated. The important fabrication parameters such as type of etchant and etching rate must be considered as a valid input while designing a dimple on Al alloy. This feasibility of using the PCT technique for the surface modification of Al alloy is evaluated on this paper. However, the effect of surface texturing on improving the tribological properties depends on the dimples shape, dimples area density, dimples depth and pattern of dimples. Conventionally, to achieve maximum tribological performance from surface texturing, optimization is required based on geometrical characteristics especially size and density of the micro dimples (Wakuda et al., 2003). According to Wakuda et al., (2003), dimples area density is one of the main parameters for surface texturing and the area density in the range 5 to 20% is preferable for friction reduction.

This paper aims to offer some aid in PCT process on the surface of the Al alloy 2000 series specifically. It provides information about the effectiveness of fabricated dimples (different area density and depth) by undergoes the tribological test under dry condition. A series of experiments will be carried out in the two phases. In the first stage, we designed a circular dimple texture pattern at different area density (5%, 10% and 20%). We investigated the tribological behaviour of textured surface by the ball on disc wear tester under dry condition. The tribological characteristics will be evaluated in terms of the friction coefficient, wear rate, microphotography of the worn surface. The second phase, the durability of the dimple textured surface was considered at different dimple depth under dry condition. The different of dimple depth was achieved by etching time during the photochemical procedure. The etching time was varied at 30, 40, 50, and 60 min.

2.0 MATERIALS AND METHODS

Al alloy AA2017-T4 disk purchased from Misumi Malaysia Sdn. Bhd with diameter 25 mm and hole (diameter 4 mm) was used as the substrate. The typical alloying element for this alloy is copper, as shown in Table 1. AA2017-T4 disks were cleaned ultrasonically before texturing by distilled water, ethanol and acetone each for 40, 20 and 20 min, respectively. Fabrication of circular dimples was divided into two parts; (1) dimple area density and (2) dimple depth. Dimple area density and depth are chosen to be varied to study their role in improving wear resistance and friction. For the first part, the AA2017-T4 disks were textured into three different dimple area density each varied from 5%, 10% and 20%. Dimple distribution with different area density is calculated using the equation (1 – 3) as referred to Lazim et al., 2016. The schematic diagram of the texture on the UHMWPE surface is, as shown in Figure 1. The area of dimple density from the total surface area was calculated using equation (1). The equation (2) was used to find the grid size on the imaginary square of the sample surface. The length of the imaginary square was referred to as L. The distance l between the micro dimples can be determined by using equation (3). The parameter used for the dimple textured for different density was calculated and recorded in Table 2. The designed pattern was printed onto an overhead projection (OHP) plastic sheet as the photomask for the fabrication. For the second part, different etching time was done for each sample (30 min, 40 min, 50 min and 60 min) to obtain the different depth of fabricated dimple.

$$Percentage\ area = \frac{\text{density}}{100} \times L^2 \tag{1}$$

$$Grid\ size = \sqrt{\frac{\text{Percentage area}}{\text{Area of dimple}}} \tag{2}$$

$$l = \frac{\text{L}}{\text{Grid}} \tag{3}$$

Table 1: The chemical composition of Al alloy A2017.

Chemical compositions	**Al**	**O**	**Cu**
Weight percentage (%)	91.79	3.02	5.19

The dimple structure fabrication process starting with the photoresist coating, hard bake, UV exposure, pattern development, wet chemical etching and ends with the photoresist removal. In this research, AZ4533 was used as photoresist, which usually used for negative photoresist. The photoresist was coated on the surface of the AA2017-T4 disk by using a spin coater machine. The disk was rotated at a certain speed to obtain a uniform photoresist coating. The process included two stages; as the first stage starts by rotating the disk at 450 rpm for 10 s continuously after the photoresist is poured. The second stage of coating started when the disk was rotated with 4000 rpm for 60 s. In this research, the estimated thickness of the photoresist is 3.30 μm. The fabrication process continued with the soft baking. In this process, the disk was baked in a hot oven for 10 minutes at 110°C. The disk was then left for 12 to 24 hours at room temperature to ensure that the photoresist adheres well on the surface of the disk. After the soft baking process, the coated disk was exposed to an ultraviolet light (UV light). The model of the UV light source machine used in this research was UV-CL290KR. Before exposure, the OHP transparency plastic sheet photomask with 5, 10 and 20% area density were placed above the sample stage. The desired shape of pattern can be achieved using UV light to transfer images from a photomask to a coated AA2017-T4 disk. When the photoresist was exposed to UV light, polymerization had occurred, and the chemical bonds on the exposed area had broken.

Table 2: Parameter of the dimple texture for photochemical machining.

Dimple Diameter (μm)	**Dimple Area Density (%)**	**Percentage Area (m^2)**	**Grid size, *n* × *n***	**Distance between adjacent dimple, *l* (m)**
300	0 (Flat surface)	0	-	-
	5	3.13×10^{-5}	63 × 63	3.97×10^{-4}
	10	6.25×10^{-5}	89 × 89	2.81×10^{-4}
	20	12.50×10^{-5}	126 × 126	1.98×10^{-4}

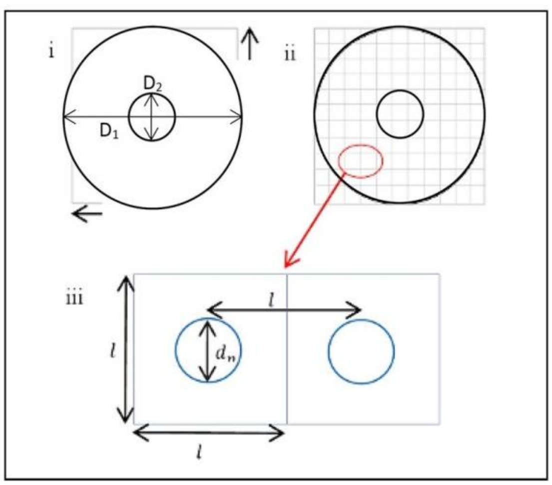

Figure 1: Schematic diagram of the texture on the UHMWPE surface.

During the exposure process, the parameters that should be considered is the exposure time as it will affect the next development process. In this research, the exposure time was 120 seconds. During the development process, the exposed part is removed by using diluted potassium hydroxide (KOH) with distilled water [the ratio was 1: 3]. KOH acted as a developing solution and also known as AZ400K. The disk was then soaked in the developer solution for 90 s in order to create the desired pattern. As the development process complete, disks were rinsed with distilled water and blew with nitrogen gas. The next process was wet chemical etching.

The etching is a process where the chemical etchant removed the uppermost layer of a disk surface that is not protected by the photoresist. Etching has been used to create a cavity in a material; the depth of the hole may differently depend on the function of etching time. The etchant use is the mixture of nitric acid (HNO_3) and phosphoric acid (H_3PO_4) [12.5%: 87.5%] ratio by volume. The etchant and the disk were immersed in a water bath at 35°C. Different etching time is done for each sample (30 min, 40 min, 50 min and 60 min). The last photochemical step is the removal of the unexposed photoresist film from the disk which was done by soaked the disk in an amine-solvent mixture (AZ 100 remover). The cleaned disk was rinsed with distilled water and blew with nitrogen gas.

The surface was characterized by using 3D optical profiler ZeGage™ to obtain 3D topography images and to examine the dimension of dimple fabricated on AA2017-T4 disk. Tribological characterization of the textured disks was evaluated by using ball-on-disk sliding tester. In the present research, the tests were done in two conditions, as described in Table 3. The test condition one was applied to different area density of the textured surface. This test investigated the influence of geometrical characteristics specifically; area density on the friction and wear behaviour of textured surfaces. The second condition aimed to determine the durability of the textured surface by manipulated the depth of dimple. All tests were done in dry conditions. The wear rate (W) was calculated based on the Archard equation, as shown in Eq. (4). V is total wear volume, F is the normal load used, and T is the total sliding distance. The total wear volume can be obtained by multiply cross-sectional area, A with sliding diameter, D. The A was evaluated by using the 3D optical profiler. The worn surface morphologies were analyzed using scanning electron microscopy (SEM).

$$k = \frac{V}{FT} \tag{4}$$

Table 3: Tribological test conditions.

	Test condition 1	Test condition 2
Material counterpart	Silicon nitride (Si_3N_4) ball (Diameter 8 mm)	
Area density (%)	0, 5,10,20	0, 20
Sliding speed (rpm)	30	60
Load (N)	1	1
Sliding rotations	1000	2000

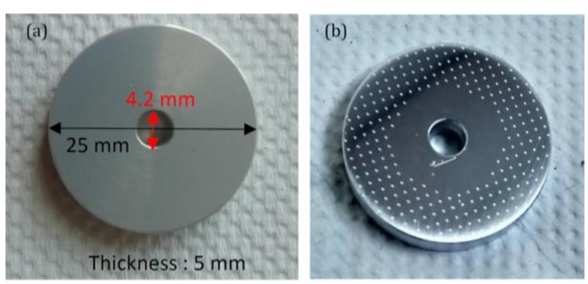

Figure 2: Dimple texture on the AA2017-T4 disk after the photochemical fabrication.

3.0 RESULTS AND DISCUSSION

3.1 Surface Characterization of Textured Surface

Figure 2 shows the example of dimple texture on the AA2017-T4 disk after the photochemical fabrication. For the tribological test condition 1, the texture surfaces were fabricated at 5, 10 and 20 % of area density with fixed depth (approximately at 11 μm) as shown in Figure 3 and 4, respectively. The depth formed was corresponding with 50 minutes of the etching duration. By referring to Figure 4, it can be observed that the dimple feature was completely smooth with no ridge or burr on the edge of micro-pit. Besides, in this study, the dimple shape with smooth bottom with an average roughness of less than 2 μm was achieved by wet chemical etching after the photolithography process. As compared with the dimples fabricated using micro CNC machining, studied by Roy et al., 2014 and Zaki et al., 2019, we have proved that PCT technique can provide a smooth surface finish of textured Al alloy surfaces. Thus, this could have resulted in smooth stress distribution under the contact sliding (Tong et al., 2019). On the others hand, all the dimples in this research were circular with smooth bottom could be reasons for enhancing the lubrication effects which help to squeeze the lubricant out of dimples due to the hydrodynamic load lifting effect (Ji et al., 2018)

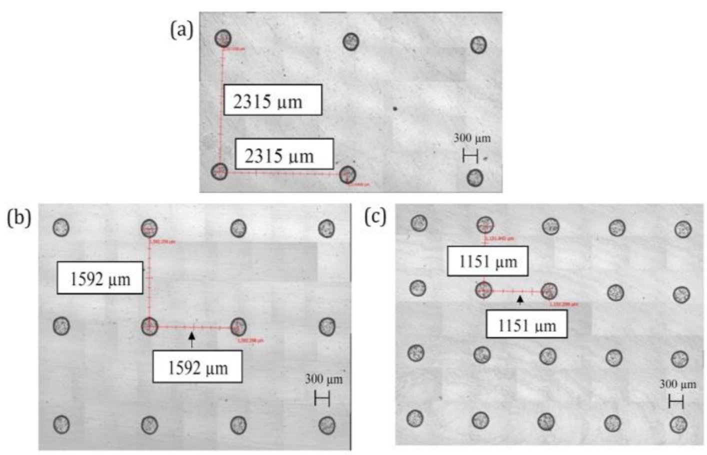

Figure 3: Texture surfaces at 5, 10 and 20 % of area density with fixed depth.

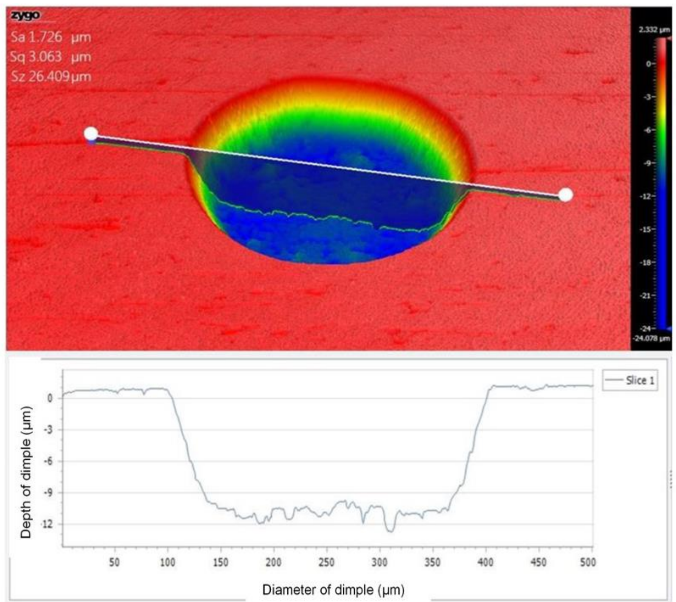

Figure 4: Dimple texture surface.

For the tribological test condition 2, the textured surfaces were fabricated at different dimple depth. Depth of dimple increases with an increase in etch time, as shown in Figure 5. The dimple depth formed was 6 µm with 30 minutes etching time, 8 µm with 40 minutes etching time, 13 µm with 50 minutes etching time and 15 µm with 60 minutes etching time. The etching rate for each samples starting from sample etched for 30 minutes until 60 minutes were 0.17 µm/min, 0.2 µm/min, 0.26 µm/min and 0.3 µm/min. From 3D optical profiler observation of the etch-pit, it was clarified that the pits are shallow at short of etching time. The depth of the dimple pit was controlled approximately using the etch time through oxidation reaction, which caused the dissolution of Al alloy surface (Nurhaziqah et al., 2018).

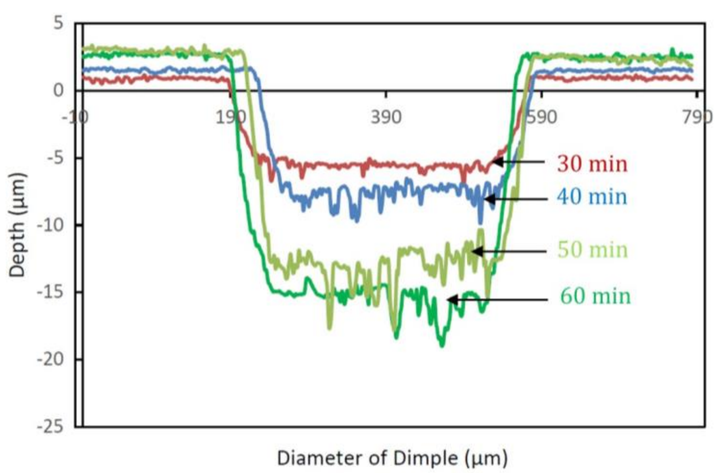

Figure 5: Depth of dimple.

3.2 Effect of Dimple Area Density on Tribological Behavior

Figure 6 presents the typical coefficient of friction for sliding rotations of different dimple area fraction samples (0%, 5%, 10% and 20%) tested using tribological test's condition 1 (Table 3). The average coefficient of friction of 0%, 5%, 10% and 20% dimple area were 0.60, 0.48, 0.48 and 0.45, respectively. The results show that all textured AA2017-T4 alloys have a lower coefficient of friction than the non-textured sample. At load 1 N, the performance of dimple surface was very significant; the 20% dimple area fraction sample stabilizes at the lowest friction coefficient value, this reduction is approximately 25% compared to non-textured surface. Thus, this indicates that the surface texturing substantially showed good friction reduction and the 20% dimple area fraction tends to serve the minimum friction force. This may be attributed to the textures reduced real contact area and thus decrease interface friction (Kumar et al., 2020).

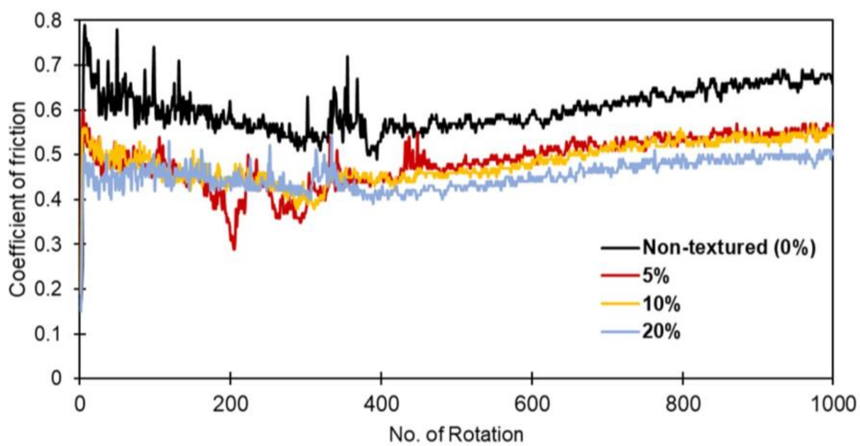

Figure 6: Coefficient of friction for sliding rotations of different dimple area fraction samples (0%, 5%, 10% and 20%) tested using tribological test's condition 1.

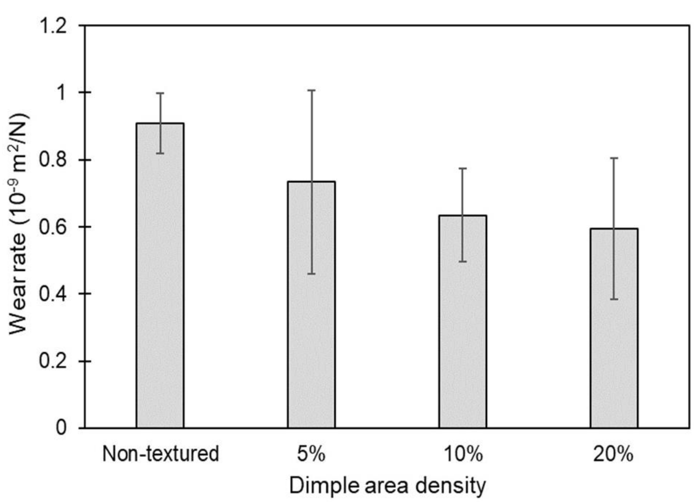

Figure 7: Wear rate of the non-textured and textured AA2017-T4 samples.

Figure 7 presents the wear rate of the non-textured and textured AA2017-T4 samples. It can be seen that the wear rate of high texture area density (10% and 20%) lower compared to those of the non-textured AA2017-T4 sample. Under dry sliding conditions, wear consumes energy by frictional heating during friction processes including for plastic deformation and wear particles generation. The textured AA2017-T4 sample with high texture area density exhibited a low wear rate due to heat dissipation is more easily to take place at the contact interface resulting in a lower temperature rise observed in the textured samples (Wu et al., 2015). Under low-temperature contact, the decrement of wear particles generation from wear track can be expected.

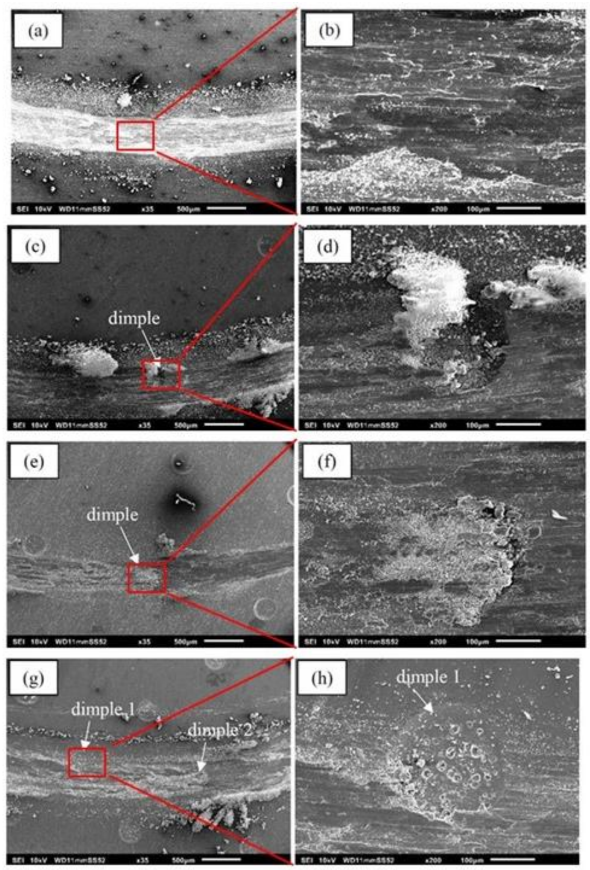

Figure 8: morphologies of non-textured and textured AA2017-T4 samples as observed under SEM.

Figure 8 (a–h) displays the morphologies of non-textured and textured AA2017-T4 samples as observed under SEM. The worn surface of the non-textured sample shows a typically worn morphology of Al alloy with the clear presence of shallow ploughing strips along sliding direction and plastic deformation as a sign of adhesion was observed in the areas of wear scars (Kumar et al., 2009). The worn surfaces of textured samples show the dimples orientation along with wear tracks running parallel to the sliding direction. The dimples appear to be filled with wear debris, as seen from Figure 8 (d, f, and h). All the dimple textured samples did not show significant wear or appreciable change in surface morphology. In overall, the dimples with the higher area density on the AA2017-T4 surface led to decrease in friction and wear due to the benefit of the dimple in the reduced real contact area and heat dissipation at the contact interface as well as the serve as traps for the wear debris. This finding consistent with the previous observation by Kumar *et al.,* 2020.

3.3 Effect of Dimple Depth on Tribological Behavior

In this section, the durability of the textured surface was investigated at higher sliding rotation, 60 rpm compared to the test in Section 3.2. The textured area densities were fixed to 20%, and the depth of dimple was varied; 5 µm, 8 µm, 13 µm and 15 µm. Figure 9 shows the friction coefficient of the non-textured and textured AA2017-T4 samples, which was obtained from Condition two of the tribological test (Table 3). The graph is indicating that all samples regardless of the different dimple depths, have shown a similar friction coefficient trend at the run-in period. As compare with Figure 6, the presence of dimples on the surface is not beneficial in terms of reducing friction at high speed of sliding rotation (60 rpm). These results indicate at higher sliding speeds did not cause any change in friction level when high area density textured samples were used. However, this study revealed that 15 µm of dimple depth exhibits a low friction coefficient (approximately 0.2) at the initial period of sliding roughly until 100 of disk sliding rotation. This can be explained by using the relation of friction coefficient and spatiotemporal mapping analysis. In Figure 10, the spatiotemporal map shows the distribution of friction force on the sliding track of the non-textured and 15 µm dimple depth of textured disk. The obtained friction coefficient from the ball on disk tests is in good conformity with the spatiotemporal map of friction force obtained from "TriboMaster" software. This software developed originally in our laboratory by Fukuda, which can explain complex wear mechanisms even at the initial period of sliding (Fukuda, 2017; Fukuda and Morita, 2017). As seen in Figure 10b, the low friction at the initial period of sliding implies that the force required for sliding to occur less at the contact of Si3N4 ball and AA2017-T4 sample. This behaviour is more influenced by the presence of dimple texture which can reduce real contact area and thus decrease interface friction (Kumar et al., 2020). During the run-in period, due to the temperature increases at the contact surface, plastic deformation occurs at the vicinity of the surface asperities and consequently leading to material transfer approximately at 500 rotations. This results in unstable friction curves for 15 µm dimple depth of the textured sample.

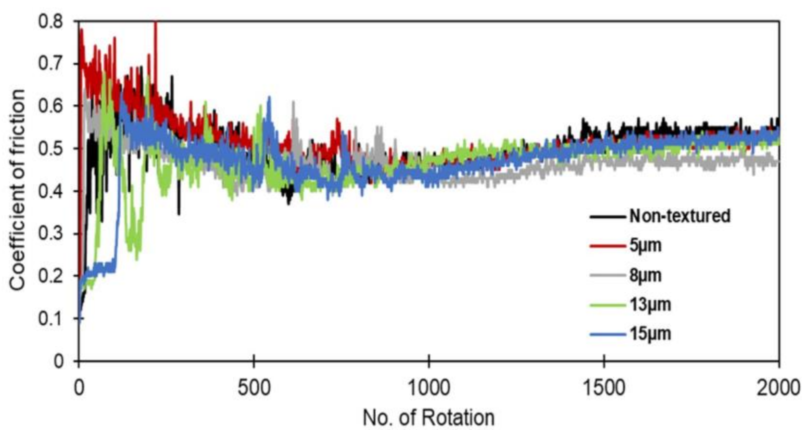

Figure 9: Friction coefficient of the non-textured and textured AA2017-T4 samples.

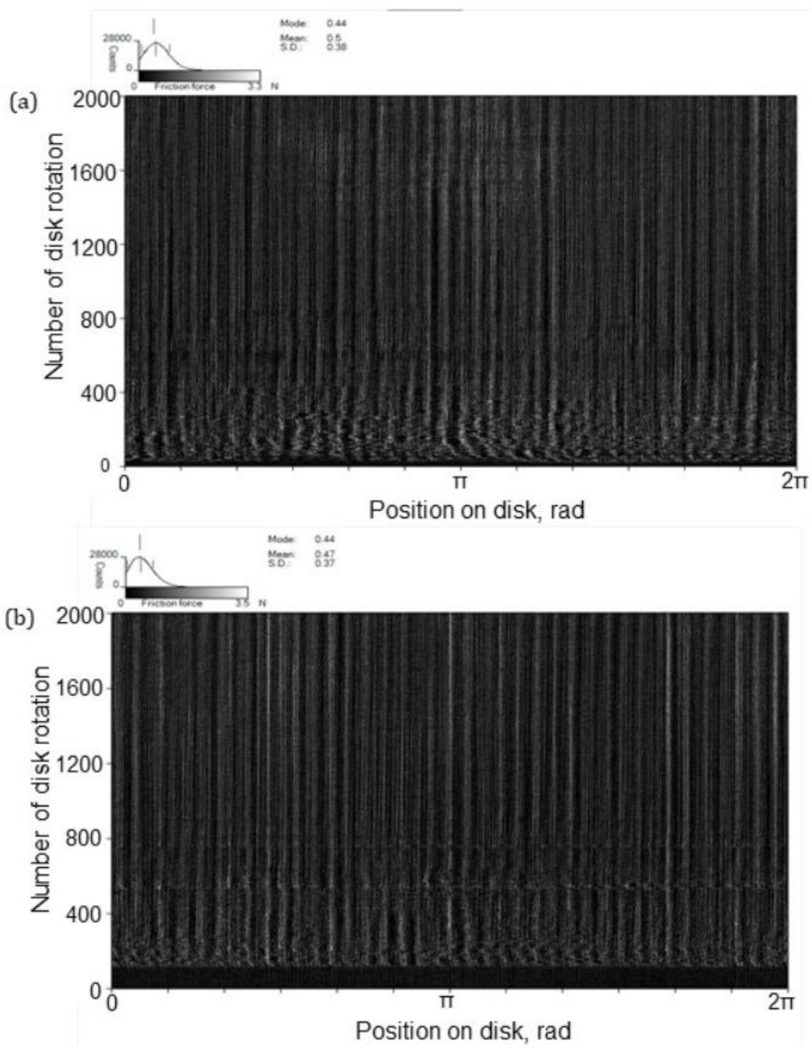

Figure 10: Distribution of friction force on the sliding track of the non-textured and 15 μm dimple depth of textured disk.

Figure 11 further examines the effects of dimple depth on the wear resistance for the 20% of dimple area density. As can be seen in Figure 11, the wear rate did not differ significantly in all textured AA2017-T4 samples as compared to non-textured AA2017-T4 samples. In Figure 12, the 3D optical profiler image of the dimple structure on the wear track shows that the ability of textured dimples serves as micro-traps for wear debris. Micro-pores did not contribute to any apparent benefits in wear-resistant with the effect of dimple depth. A potential explanation of this observation is explained by Kumar *et al.,* (2020) as they found the size effect of the dimple depth is ineffective under dry sliding contact because it quickly loses its wear debris trapping ability after getting filled. In summary, the change of dimple depth does not cause a significant difference for the friction and wear resistance, especially under the dry condition and high sliding speed.

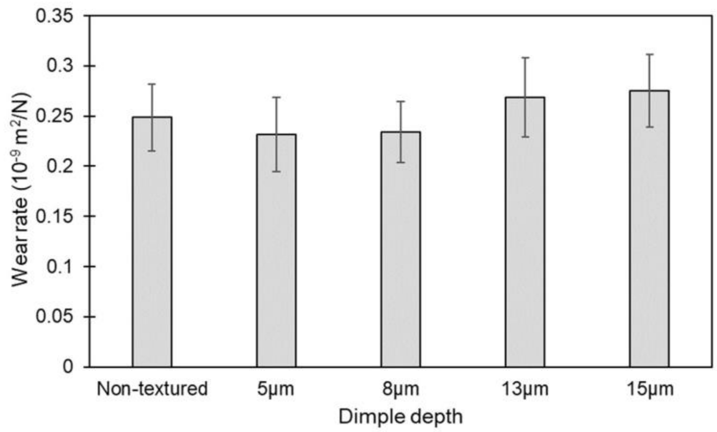

Figure 11: Wear resistance for the 20% of dimple area density.

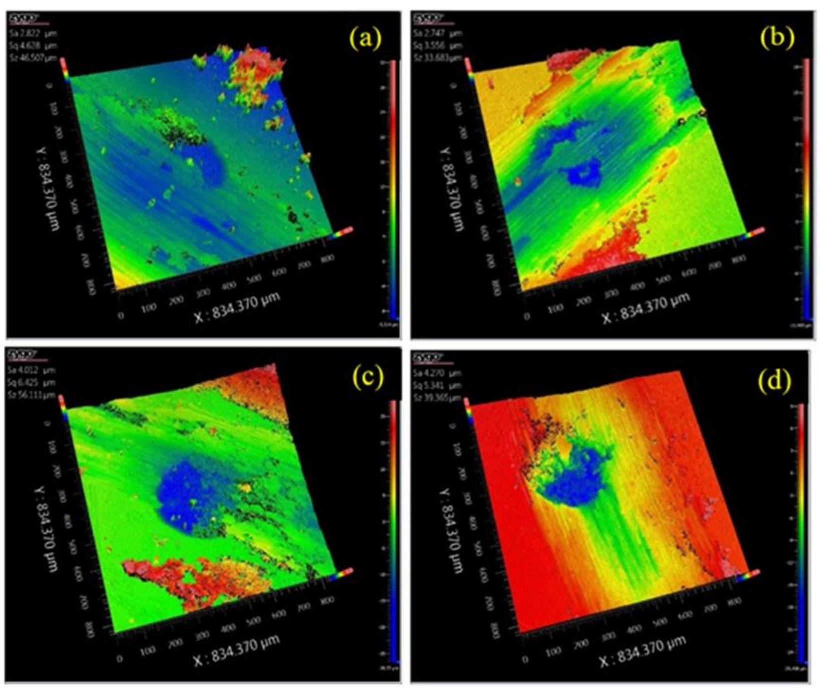

Figure 12: 3D optical profiler image of the dimple structure on the wear track.

4.0 CONCLUSIONS

In this paper, the authors have fabricated and investigated the possibility of dimple textured on the surface of AA2017-T4 alloys by photochemical machining could be improved the friction and wear resistance under dry sliding condition by manipulating their dimple area density and depth. The conclusions were stated as follows;

(a) The presence of dimple structure improved the friction and wear resistance of AA2017-T4 samples tested at 30 rpm of sliding rotation under dry condition. Results suggest that

20% of area density dimples have the highest friction reduction (25% of reduction) and low wear rate.

(b) As sliding speed was increased to 60 rpm, the friction reduction became less significant. The dimpled surfaces with different dimple depths are not beneficial in improving the tribology properties under dry condition due to it quickly loses its wear debris trapping ability after getting filled.

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