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ORIGINAL ARTICLE

Effect of Laser-Textured Surface of Ti6Al4V on Frictional Wear Behavior

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ABSTRACT – The need for titanium and its alloys has led to a significant increase in commercial manufacturing, although this material's poor tribological qualities have been a drawback. The present study was to determine the effect of laser-textured surfaces to enhance Ti6Al4V surface wear performance. The sample underwent laser texturing based on pre-set parameter values at 15 W power at a laser scanning speed of 200 mm/s with a frequency of 50 kHz. The surface morphological and topological profile of laser-textured Ti6Al4V was characterized with also the surface microhardness. A comparative appraisal of wear rate (WR) and coefficient of friction (COF) for related samples of as-received Ti6Al4V and laser-textured Ti6Al4V was performed under dry and oil sliding conditions. The results revealed that the formation of oxidation due to the frictional force and plastic displacement plays a role of abrasive to the laser-textured surface and may result in increasing the COF. The wear rate of the laser-textured surface of Ti6Al4V exhibited 88.31% improvement compared to the as-received Ti6Al4V in the dry sliding wear test. It was proved that Ti6Al4V could benefit from LST to gain effectively enhanced wear performance.

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INTRODUCTION

The first commercially successful products were created by The Titanium Metals Company of America (TMCA) in 1950. Over the past 50 years, titanium alloy grade 5 (known as Ti6Al4V) production has increased at an average yearly rate of roughly 8% since that time because of its biocompatibility, corrosion resistance, high specific strength, strength-to-weight ratio, and other properties that make it suitable for use in the petrochemical, aerospace, and automotive industries. [1]–[3]. The engineering parts in these industries typically function under a tough environment where heat, friction and dynamic motion interact. As a result, the materials will deteriorate quickly, and the component life will be reduced [4]. Additionally, grade 5 titanium alloys have poor tribological characteristics, less hardness, and a high coefficient of friction [5]. Therefore, it is essential to boost these characteristics to improve engineering component performance and extend their service life without experiencing any unexpected failure.

There are now ongoing efforts to enhance the tribological characteristics of titanium using surface engineering techniques and a better comprehension of wear mechanisms in connection to the assessment of the surface condition. The condition of the material's surface affects several characteristics, including corrosion resistance, resistance to abrasive wear, and wear resistance [6]. When it comes to materials like piston rings, thrust bearings, and face seals, wear resistance is crucial. There are four primary strategies that can be used to enhance the characteristics as suggested by Zhecheva et al. [2] as follows: to enhance hardness; to decrease frictional coefficient; to raise compressive residual stress, and to increase surface roughness.

These mechanisms, which are obtained through sandblasting, acid etching, media blasting, modulation-assisted machining, electron-beam, and ion-beam laser texturing, are discussed in the surface modification. Each technique has benefits and disadvantages, but laser surface texturing (LST) is the most popular due to its advantages over other techniques, including high accuracy, good consistency, and speed. Additionally, laser texturing can be viewed as an eco-friendly technique because no waste is produced throughout the process [7]. LST is contactless material processing technology, so it also can lower the machining temperature, while dry machining of titanium alloys may produce a high temperature that increases the residual stress [8].

Gaikwad et al. [7] discovered that the dimple textured surfaces on Ti6Al4V may reduce the coefficient of friction by 67% with respect to the untextured surface. Similarly, the laser textured Ti6Al4V by dimple pattern with a density of 5%, with a combination of laser synthesized, revealed the lowest mass loss values, and the wear rate decreased by 20% to 26.6% compared to the untextured surfaces [9]. The study from Vignesh and Barik [10] on AISI H-13 steels was also resulting an improvement of COF and WR by 45% and 51%, respectively. Sadeghi et al. [11] revealed that the lower friction coefficient is due to the contact surface that led to enhanced destruction and wore on the surface of the Ti6Al4V surface. As shown above, most studies that examined the dimple pattern effect succeeded in improving the frictional wear properties of Ti6Al4V; however, other textured, such as grid arrays, are still lacking studies.

The main aim of this study is to improve the tribological properties of titanium grade 5 (Ti6Al4V) by the LST with a grid array pattern. The substrate alloy underwent laser machining with predetermined laser parameters. Next, the surface

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morphology is characterized by surface elemental composition analysis and surface roughness. In addition, the Vickers hardness test was also carried out on the surface of the material. The effect of wear variables such as the wear rate (WR) and coefficient of friction (COF) of the laser-textured Ti6Al4V under dry and oil-lubricated sliding conditions was discussed. Furthermore, the optimum setting of wear variables for the wear resistance was determined.

MATERIAL AND EXPERIMENTAL WORK

Material Preparation

The materials used in this study is the Ti-6Al-4V (manufacturer Japan Nippon Mill) with a thickness of 1.2 mm, which was cut to 65×15 mm. The chemical composition (testing resulted from Dickson Testing Company, Inc) of titanium alloys used in this study is specified in Table 1. All the samples were cleaned for 10 minutes in an ultrasonic bath with acetone and distilled water before being dried in room air.

Table 1. Chemical composition of the material studied

Ti	Al	V	Fe	C
Bal.	6.36	4.15	0.17	0.02

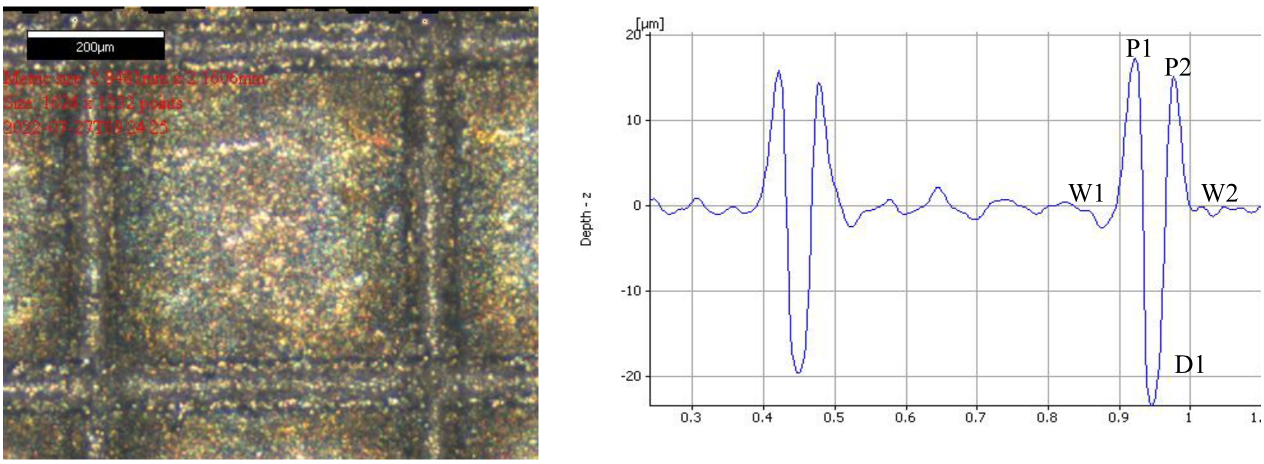
Laser Surface Texturing

The laser surface texturing process was applied using a nanosecond pulse fibre laser at a wavelength of 1064 nm, generating a max power of 30 W to achieve micro-grid array patterns. The input information of the laser system is presented in Table 2. The laser-textured surface of Ti6Al4V will then be taken for characterization using optical 3D surface metrology (Alicona IFM) with a magnification of 20×.

Table 2. Laser surface texturing parameter

Laser parameters	Unit	Value
Output wavelength	nm	1064
Average laser beam power	W	30
Output laser power	W	15
Laser frequency	kHz	50
Laser scanning speed	mm/s	200
Laser scan run		1
Hatching line distance	mm	0.5

The LST on the Ti6Al4V surface can be seen in Figure 1(a) and the profile of the crater after texturing is displayed in Figure 1(b). The width of the crater (W1-W2) is 90 µm, while the depth of the crater (P1-D1) is 230.49 µm, and the measurement profile from peak to peak (P1-P2) is 50 µm. The laser textured area density (TAD) is the ratio of the textured area from the whole area of a grid [10]. From the laser parameter that had been used in this work, the TAD is 50%.



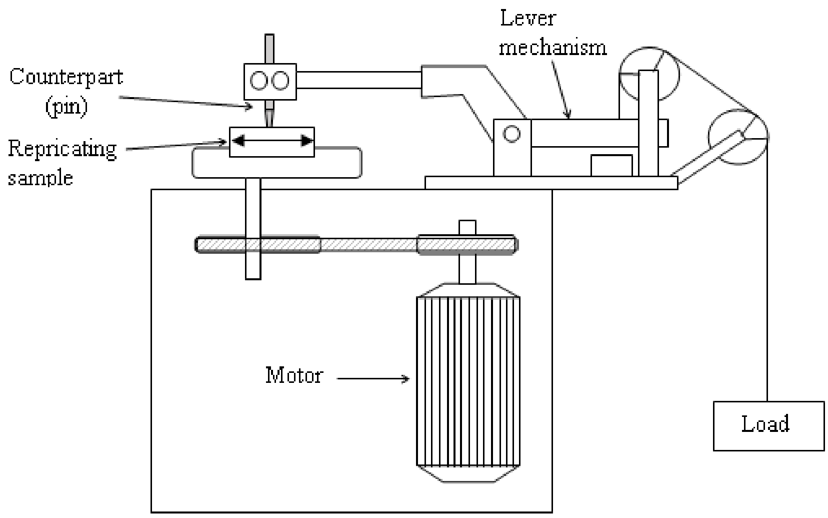
(a) (b)

Figure 1. The LST of (a) grid-array pattern resulted on Ti6Al4V, and (b) surface profile of crater from laser textured

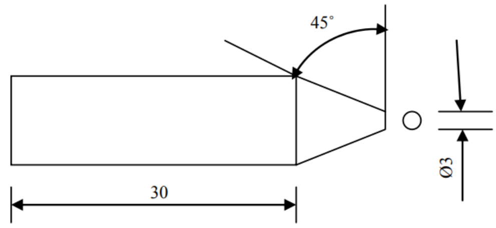
Frictional Wear Test

Friction and wear tests have been carried out at in-room temperature with pin-on-flat DUCOM TR20, as shown in Figure 2(a). The pins of similar material (as counterparts) were cut according to the standard dimensions as depicted in Figure 2(b) to assess wear behaviour. After the laser texturing was complete, each specimen was given a thorough cleaning with acetone, followed by cleaning in the ultrasonic bath for ten minutes, and then it was allowed to dry naturally.

During the process of the testing, the friction coefficient, more specifically the dynamic friction coefficient, was automatically recorded using Winducom 2020 data acquisition software. Test conditions are shown in Table 3.



(a)



(b)

Figure 21. The schematic diagram of (a) pin-on-flat for frictional wear test and (b) standard dimension of pin for the test (all dimensions in mm)

Table 3. Frictional wear test condition

Wear variables	Unit	Value
Applied load, F	kg	2, 4, 6
	N	20, 40, 60
Sliding speed, *v*	RPM	25, 50, 75
	m/s	0.002, 0.003, 0.005
Sliding time, *t*	minutes	5, 10, 15
Lubrication		Dry, Oil
Wear track (reciprocating)	mm	60
Temperature, T	°C	25

In order to analyze the dry sliding wear behavior of titanium materials, one of the most frequent approaches is to calculate the wear rate using a pin and reciprocating pin-on-flat wear machine in conjunction with the weight loss method [12]. The wear rate was calculated in compliance with ASTM G133 using Eq. (1).

$$\mathrm{WR} = \frac{V}{F.L} \tag{1}$$

where V is the wear volume in mm^3, F is the loading force in N, and L is the length of the stroke (sliding distance) in m, which result in the WR, wear rate in $\frac{mm^3}{m.N}$.

The surface morphology of the laser-textured surface and wear tracks were observed by SEM. Surface roughness parameter such as Ra, Rq, and Rsm was also measured by the 3D optical microscope used for surface topological profile measurement. The work hardening of the surfaces due to the friction shear was identified and determined by using the Wilson Tukon VH1202 microhardness indentation test at a constant load of 0.5 kg.

RESULTS AND DISCUSSION

Surface Characterization

In order to characterize the elemental on the laser-textured Ti6Al4V surface, the SEM Hitachi S-3400N was used. Figure 3 shows the result of the elemental weight percentage from two different spots after LST. At a blue spot, the element found is 100% titanium, while the spot area marked with red shows that there are several main elements which are titanium and aluminum from Ti6Al4V accumulated after laser texturing. Oxidation and minor carbonization are also formed in this bulged area. While the visible Na is suspected to be from contamination after ultrasonic cleaning in a water bath.

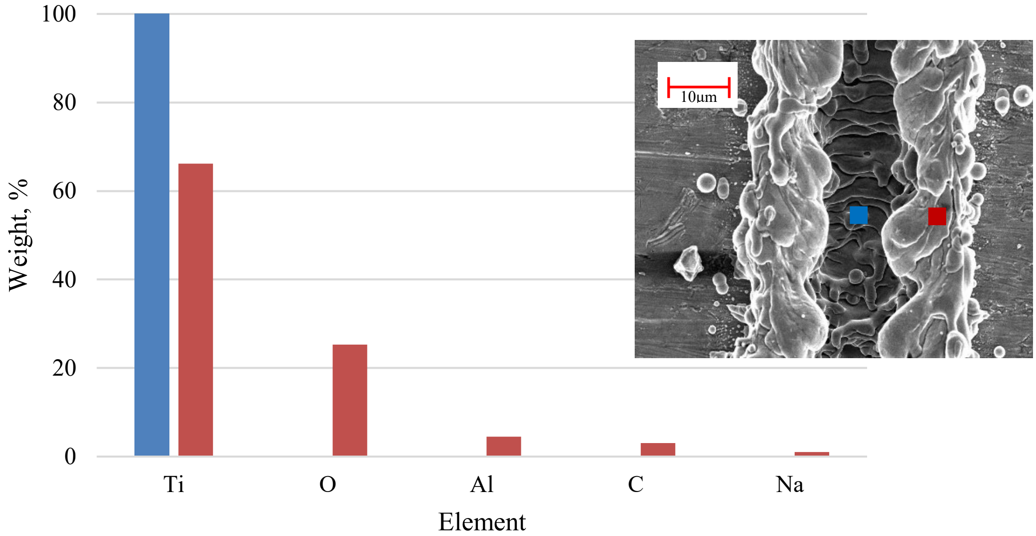


Figure 32. The result of SEM-EDX of laser textured Ti6Al4V on two different laser spots before the wear sliding test

Figure 4 shows the presence of O from the untextured surface after the sliding wear test. When compared to the laser-textured surface, the oxidation occurred at the peak of the crater, as displayed in Figure 2.

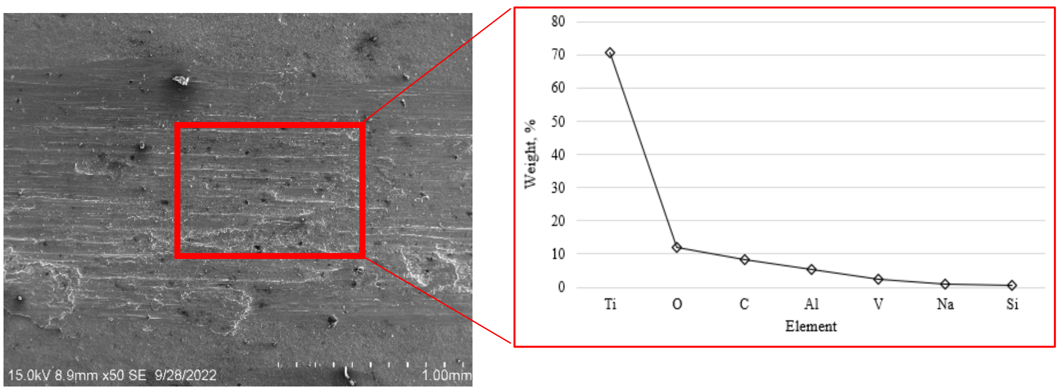


Figure 43. The result of SEM-EDX of untextured Ti6Al4V after sliding wear test indicates the formation of oxidation

Surface roughness for both surfaces in Table 4 was obtained from topology analysis through a 3D Laser Microscope. The most used single-value parameters for characterizing and assessing the surface texture and quality of machined components are the average roughness (Ra) and the root-mean-square roughness (Rq) [13]. According to ISO 4287, Ra describes the arithmetical average deviation of surface height from the mean line within the sampling length L. It is widely used in the automotive and metalworking industries to specify the surface roughness of various. Rq evaluates the root-mean-square value of surface height within a sampling length. It is generally more sensitive to peaks and valleys than Ra and is commonly specified for surfaces of optical components. In addition to these two profile parameters, Rsm also significantly can be characterized by the surface. Rsm is measured from the mean spacing of profile elements.

Table 4. The surface roughness parameter for both surfaces

Surface	Ra	Rq	Rsm
Untextured	0.573±0.017	0.722±0.021	7.635±0.988
Laser surface textured	3.525±0.047	5.102±0.165	100.265±24.544

The result from hardness testing is given in Figure 5. The surface of as received Ti6Al4V has a hardness value less than 250 HV, as deep as 0.0839 mm to 0.1513 mm, then the hardness value remains at 311.8±0.1 HV as displayed in Figure 5(a). The laser-textured surface produces a layer of hardness further inwards up to 0.3357 mm at 316 HV, but at 0.2099 mm, the hardness value is high, which is an average of 335 HV as shown in Figure 5(b). In general, surface modification by giving a texture to the surface via laser can increase the hardness of the material. The hardness result of laser-textured Ti6Al4V is expected to have a positive effect on the frictional wear behavior.

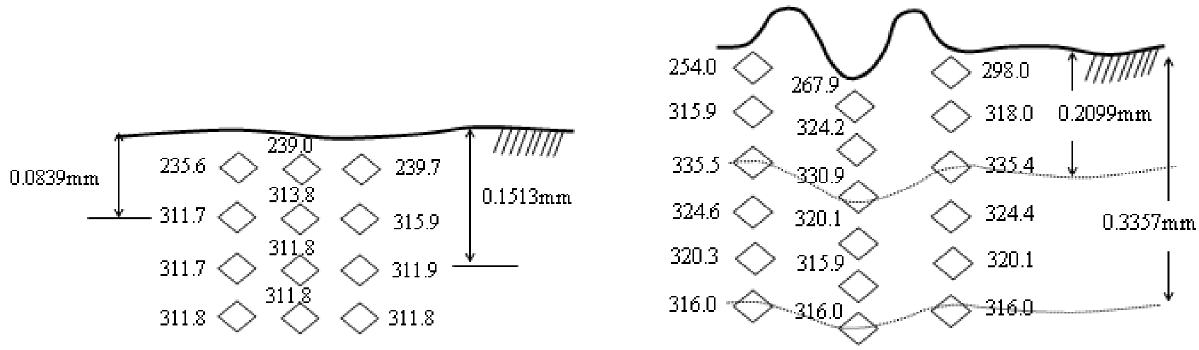


Figure 54. The microhardness value from Vickers hardness tester machine of (a) as received surface, and (b) laser textured surface

Frictional Wear Behavior of Untextured Surface under Dry Sliding Conditions

Figure 6 demonstrates that the higher sliding speed will decrease the wear rate (WR). Al-Samarai et al. [14] reported similar observations in their experiments. They studied the effect of different surface roughness values of Ra with varying rotational speeds. The higher value of friction is attributed to the higher value of (Ra). The smoothness of the surface as well as sliding distance reduces the volumetric wear rate due to lacking wear resistance of the material's thin film. This result was also reported by Molinari et al. [15], that the effect of the oxide layer formed by the laser spot suspected would give sufficient protection layer to the surface [16] noticed from the initial high WR value at the lowest speed. The presence of oxide is proven in Figure 4, where the untextured surface does not show any presence of O, as shown in Table 1 (as issued by the manufacturer).

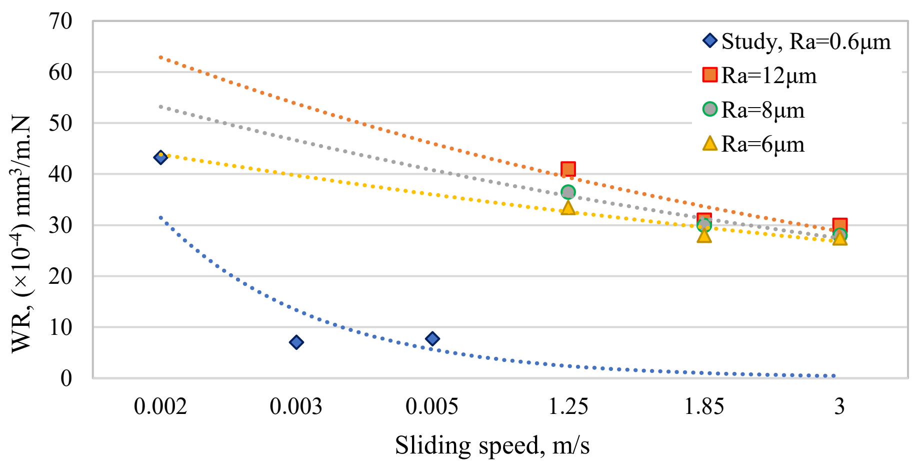


Figure 65. Effect of sliding speed on frictional wear behavior of the untextured surface compared to the study by Al-Samarai et al. [14] of three Ra values; Ra=12 µm, Ra=8 µm, and Ra=6 µm

From Figure 7 when the load was 20 N, the COF was the highest and linearly decreased by 12% until the load was 60 N. However, the WR was the lowest at 20N, then increased rapidly before slightly decreasing at 60 N. According to Archard's law, the volumetric loss of the material is inversely proportional to the hardness value of the material. This implies that the higher the hardness of the material, the smaller the volume loss [1]. The as-received surface exhibit a significant difference in hardness values, so the experimental sliding wear data correlate well with Archard's law.

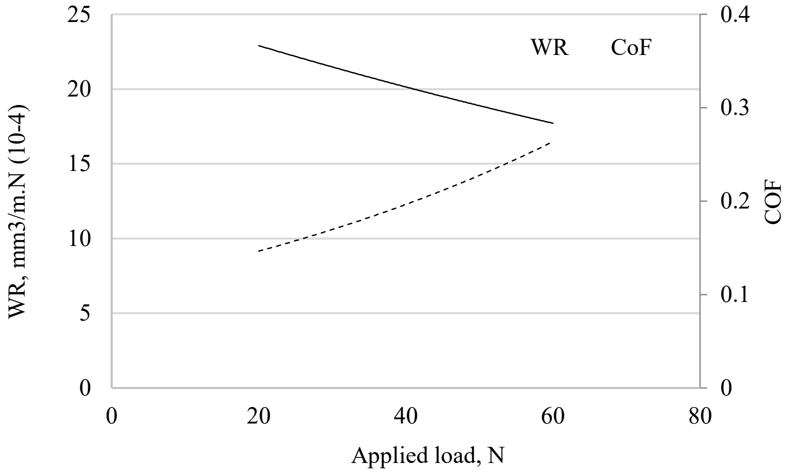


Figure 76. Effect of applied load on frictional wear behavior of the untextured Ti6Al4V surface

Facts like these show that the mark left by the pin on the titanium sample is caused not only by the loss of material but also by the plastic displacement of material out of the toroidal finger [16], as illustrated in Figure 8. Figure 8(a) is in the original position, while the beginning of friction is in Figure 8(b), as the pin and the resulting debris are on track. However, in Figure 8(c), the debris begins to accumulate. At an increased distance, the pin is bumped from the surface in Figure 8(d) because the contact surface [11] and scarred the hardness layer, as explained in Figure 5(b). Finally, the debris separates the pin on the track, leaving the accumulated debris behind. In conclusion, this study has shown the effect of the hardness layer give the impact of applied load on the WR and COF.

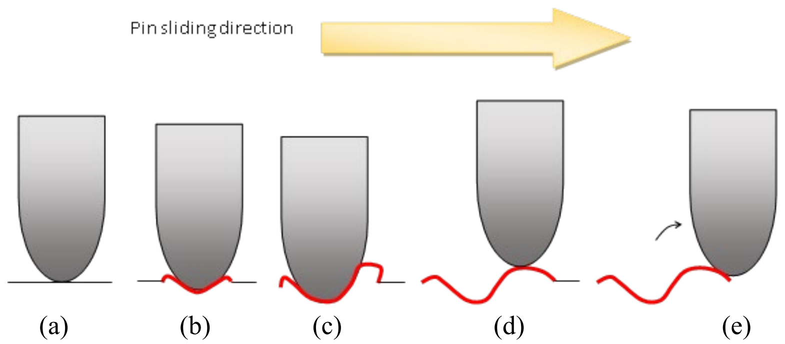


Figure 87. The volume displaced occurs, and the mark left on the pin is out from the wear track when the sliding speed increases

Oxidation can be considered the main factor for decreasing COF based on the explanation of the previous results. Figure 9 demonstrates the longer sliding distance will decrease the COF. However, WR has the opposite effect because the greater the friction distance, it provides relief to the surface to slide. This result was also obtained in another study that the WR strictly raised until it reached 1700 m [17]. The authors found that thermo-mechanical effects determine how Ti6Al4V wears, and they pointed out that a tribo-oxide layer made of titanium and vanadium oxides forms on the surface of the sample.

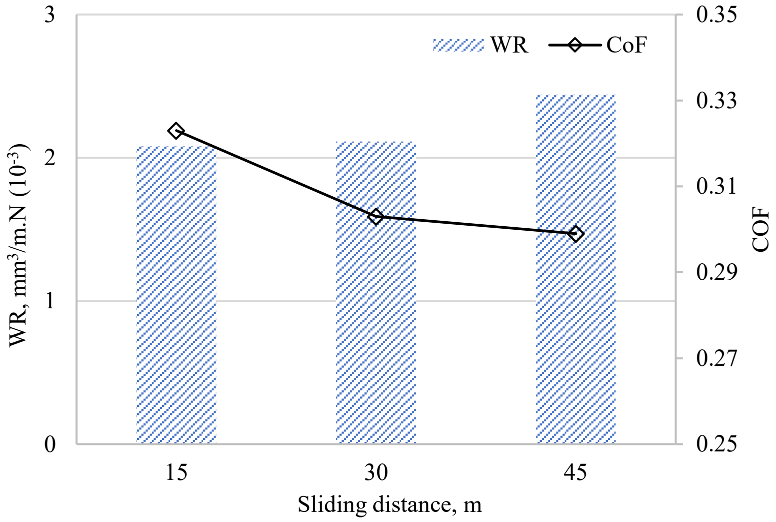


Figure 98. Effect of sliding distance on frictional wear behavior of the untextured Ti6Al4V

The Effect of Laser-Textured Surface and Lubrication Conditions

The analysis of these results distinguishes several periods (phases) on successive regimes of friction and wear behavior [1]. From Figure 10, (1) the first period is the accommodation (or pre-wear period) in the first 10 seconds when the coefficient of friction goes up instantly because the surface of both surfaces is the most flexible [18]. Plastic deformation smooths out the surface and makes it less rough. (2) In the second period, the friction coefficient of the laser-textured surface goes down a little bit. Probably, friction wear creates a smooth surface on the track that acts like a solid lubricant. (3) The third period was marked by a sharp increase in the friction coefficient, as indicated in Figure 10 for laser-textured surfaces. The surface is fragmented and oxidized and probably plays an abrasive role.

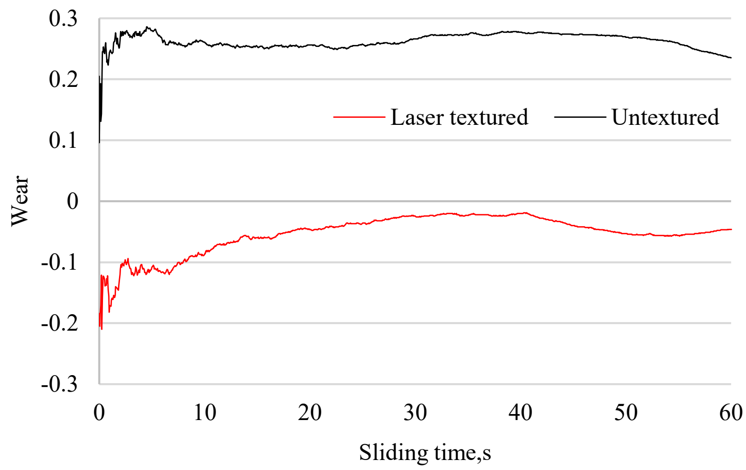


Figure 109. Wear behavior of untextured and laser-textured Ti6Al4V under dry sliding conditions

Figure 11 clearly shows the significance of friction reduction when using a laser-textured surface. From this figure, the laser-textured surface did not exhibit the break-in period at the start of the tests, which is generally related to the early removal of asperities. It has been noted before that this initial phase of significant friction during the test does not occur, as reported by Gaikwad et al. [7] for other textured surfaces. In these conditions, the textured effect keeps friction values constant while remaining low. After an initial period of low friction values, all samples experienced a sharp increase in friction. Friction coefficients were initially low because oil was still retained in the textured surfaces, as seen by the solid crater bulges visible at the start of the test [19]. During the duration of the test, the crater wore away because asperity interactions occurred, and the laser-textured surface was not enough to keep a lubricant layer between the contacting surfaces. As a result, the textured surfaces started to act as receiving surfaces, obtaining decreased friction values.

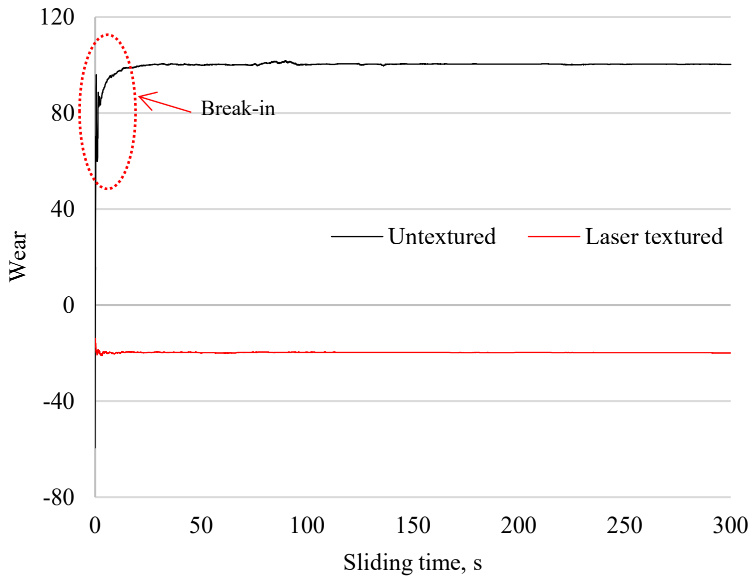


Figure 1110. The wear of untextured and laser-textured Ti6Al4V under oil lubricant conditions

Figure 12 shows the WR and COF for untextured and laser textured surface of Ti6Al4V for both conditions under dry and oil lubrication. The COF of the laser-textured surface is higher than that untextured during dry wear sliding. However, the untextured surface will directly show the stable phase compared to the laser-textured surface. This indicates the WR is improved by 86.96% compared to untextured because of surface oxidation, as reported by Molinari et al. [15]. The final period corresponds to the stabilization of the friction coefficient [18], and there was no more pre-wear period. As shown in Figure 12, the improvement of wear rate is 37% for laser textured surfaces compared to untextured surfaces, and the COF significantly drops by 8.2%. This also claimed that laser texturing has a huge impact on the surface wear resistance by changing the minor decrease of COF. The previous research from [18] applied surface modification of Ti6Al4V by shot peening led to an increase in wear up to 25% and a decrease in COF maximum of 12%, like the current study, but the COF is still higher than laser textured surface. Both tests point to the conclusion that surface modification of Ti6Al4V resulted in an improvement in wear rate, but the LST exhibits excellent wear performance compared to shot peening.

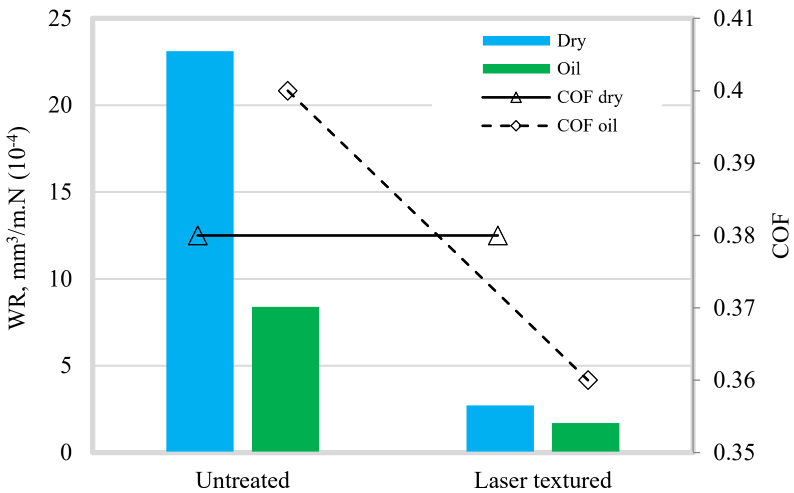


Figure 1211. The wear rate and COF of untextured and laser textured surface of Ti6Al4V under dry and oil lubrication test conditions for 20 N at 50 rpm with a sliding distance of 15 m

Generally, the active roles of surface laser textured in tribological performance lie in the main aspects, as explained in Figure 13. These have demonstrated better wear performance of laser textured surfaces under oil lubricant conditions, improved by 75% and as well as improved in reducing the COF. Clearly, the use of oil lubricant to enhance the frictional wear behavior also works best for untextured surfaces by improvement of up to 65.37%. However, when comparing the lubrication condition between laser-textured surfaces, the result shows a 25% WR improvement. This finding may lead to a better understanding of how the effect of microgrooves has a positive impact on increasing the surface lifetime [20]. Craters serve as reservoirs for lubricants, allowing them to be applied continuously during tests; this helps to reduce abrasive wear and maximize the elastohydrodynamic effect under liquid lubrication by collecting the debris [21]. A similar result, also reported by [22], explained thausing oil base lubrication significantly enhanced the lubrication performance and shortened the break-in period.

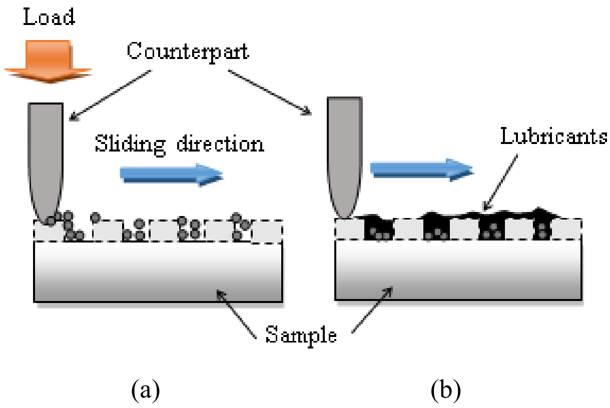


Figure 1312. A schematic diagram of active roles of surface texturing in frictional wear performance of (a) dry sliding condition, and (b) lubrication condition capturing friction debris

When compared to a titanium alloy that was put through a dry tribological test, the wear rates and coefficient of friction in the current study indicate much better with lower values. These similar results also essentially confirmed that the Ti6Al4V wear rate and friction coefficient can be lowered by changing the lubrication condition, which shortens the scuffling time. [4], [20]

CONCLUSIONS

This paper reports the effect of laser-textured Ti6Al4 compared to as received on frictional wear behavior. The effect of surface roughness parameters such as Ra and the microhardness values also had been examined to observe the nature of frictional wear behavior, before applying the surface modification method. The conclusion has been made as follows:

i. Three wear variables, applied load, sliding speed, and sliding distance, are essential to have an impact on the wear performance of the surface. The WR is affected by the oxidation surface layer and plastic deformation.

ii. The wear rate can be improved up to 88.31% by laser texturing of the Ti6Al4V surface compared to the untextured surface under dry sliding conditions. The hardness of the surface after LST gives effect the WR behaviour according to Archard's Law.

iii. The effect of oil lubrication conditions for laser textured surfaces increases the protection of worn by 75% compared to the untextured surface since the lubrication will act as the reservoir to smoothen the surface.

iv. The laser textured surface under the oil test condition improved 25% of frictional wear performance compared to the dry wear sliding test condition.

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