Experimental characterization of friction and wear behavior of textured Titanium alloy (Ti-6Al-4V) for enhanced tribological performance

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Abstract
Laser surface texturing (LST) is an effective surface engineering technique that can improve the efficiency and reliability of a tribosystem. In this study, surface textures with combined dimple patterns were prepared on a Ti-6Al-4V alloy surface using a Nd:YAG pulsed laser. Sliding dry and MoS₂ solid-lubricated experiments were performed to assess the tribological characteristics of these specimens using a ball-on-disk mode. An L₉(3⁴) orthogonal array table was used to prepare an experimental plan, which contained three parameters: the sliding speed, applied load, and the area density of dimple on the friction properties. The results show that the MoS₂-added textured surface effectively decreased the coefficient of friction and reduced adhesion wear compared to an untextured surface. Analysis of variance (ANOVA) suggested that the texture area density has a major effect on the friction coefficient at a confidence level of 99%, followed by the applied load and sliding speed. Scanning electron microscopy (SEM) revealed that the wear mechanisms were adhesive and abrasive wear, and a transfer layer from the Ti-6Al-4V alloy was obtained on the counterpart ceramic ball. In conclusion, a higher texture area density is advantageous to increase the friction and wear performance of the Ti-6Al-4V alloy surface.

1. Introduction

Titanium alloys are extensively used within various engineering sectors such as aerospace, medical science, transportation, and chemical and marine industries [1–3]. The global popularity of these alloys arises from their availability, biocompatibility, good corrosion resistance, high strength-to-density ratio, and excellent creep resistance [1–3]. Among the different types of titanium alloys, the Ti-6Al-4V alloy is used for extensive technological applications. Though, the Ti-6Al-4V alloy shows poor response to tribological properties, limiting its sliding and fretting applications due to low wear resistance [1–3].

Recently, numerous methods for modifying the surface of titanium alloys have been developed to improve their wear properties [4, 5]. These techniques include ion implantation, coating, anodizing, thermal oxidation, and laser alloying. Among these techniques, laser surface texturing (LST), which generates an artificial topography of microdimples, microgrooves, or microchannels on the contact surface, has proven to be the best alternative method applicable to a variety of engineering applications. Contribution to lubricant feeding and retention of the lubricant to contact surfaces, trapping wear particles to reduce contact surface wear, and improving the load-carrying capacity of the textured surface to create hydrodynamic action are probably the most widely understood textured surface mechanisms [4–6]. Various researchers have studied the improvement in the tribological performance of textured titanium alloy surfaces in relation to various shapes, forms, and experimental parameters, and reported outstanding performances. Hu et al [7, 8] investigated the influence of dimple density of the texture on the tribological behavior of titanium alloys, and found that under dry, oil-lubricated, and MoS₂ solid-lubricated conditions, a higher dimple density resulted in excellent friction and wear.
performance. Sun et al.\textsuperscript{[9]} also investigated the tribological characteristics of untextured and textured titanium alloy surfaces under high-temperature environmental conditions and found that the anti-wear capability of the titanium alloy was improved by the presence of tribo-oxides on the textured titanium alloy surface.

The Taguchi method is one of the most frequently used methods that allows enhancement with a smallest number of experiments. It also reduces cost and time while optimizing performance and quality.\textsuperscript{[10, 11]} Furthermore, various factors can be consecutively enhanced, and more quantitative information can be collected from small experimental trials.\textsuperscript{[10–13]} This method uses orthogonal arrays to describe the experimental plans, and the treatment of experimental results is according to the analysis of variance (ANOVA). The Taguchi technique has been extensively used in experimental studies on the tribological behaviors of numerous materials under different test conditions. For instance, using the L\textsubscript{4} Taguchi experimental design, Wu et al.\textsuperscript{[12]} testified the influence of three surface texture parameters, the dimple distance, dimple depth, and applied load, on the tribological behaviors of microtextured Ti-6Al-4V alloy surfaces. They confirmed that the dimple space had the highest influence on the wear rate and friction coefficient. Segu et al.\textsuperscript{[13]} also used an L\textsubscript{3} orthogonal array to further examine the impact of three factors, sliding speed, dimple density, and applied load, on the tribological performances of multidimple patterns on steel surface under dry and MoS\textsubscript{2}-lubricated sliding conditions. They showed that the dimple density was the most important factor influencing the coefficient of friction and wear life, followed by the applied load and sliding speed. Based on the aforementioned discussion, LST is a simple and effective technique for increasing the tribological properties of friction pairs. Additionally, Taguchi methods are highly effective for determining the influential parameters of textured surfaces. However, data on the synergistic effect of merged textured patterns and MoS\textsubscript{2} solid lubricant on Ti-6Al-4V alloys under various contact conditions, as well as investigations of friction performance using the Taguchi technique, are very limited. In the present study, we designed and fabricated microtextured patterns on a Ti-6Al-4V alloy surface using a commercial Nd:YAG laser ablation process, combining ellipses and circular dimples to increase wear resistance. Subsequently, the tribological performance of dry and MoS\textsubscript{2} solid lubricants was evaluated under a variety of sliding conditions. Additionally, L\textsubscript{4} (3\textsuperscript{4}) orthogonal array experiments, which included three factors: texture area density, applied load, and sliding speed, were further used to investigate the friction performance. This work paves the way for future research on the Ti-6Al-4V alloy using combining ellipses and circular dimples with dry and solid lubrication conditions.

2. Experimental methods

2.1. Test material preparation and LST

The titanium material used in this investigation was a Ti-6Al-4V rod, which was supplied by XTM Company, South Korea. The selected Ti-6Al-4V alloy rod was cut into discs 10 mm in thickness and 30 mm in diameter. Prior to Nd:YAG laser texturing, the disc samples were wet-ground with progressive grades of silicon carbide (SiC) paper and polished smoothly with diamond polishing paste to a surface roughness of $Ra < 0.10 \mu m$ (Mitutuyo SJ-410), and cleaned using acetone in an ultrasonic washer for 15 min. The tribological test used untextured and textured disc specimens. The untextured specimens were also finished by smoothly polishing to a surface roughness (Ra) of about 0.10 $\mu m$ for comparison.

LST was performed on the polished titanium alloy disc surfaces using a commercial Q switch Nd:YAG laser system. The laser was operated at 10 Hz with a wavelength of 1064 nm, repetition rate of 2 kHz, and pulse duration of approximately 20 ns. Combined textured patterns with some formulated arrays were prepared by merging ellipses and circular dimples. The dimples on the titanium alloy surface were arranged in a hexagonal array. The radius of the circular dimple was approximately 50 $\mu m$, and the axis length of the elliptical dimple was approximately 130/65 $\mu m$. The textured dimple depth was approximately 29 $\mu m$ for the storage of the solid lubricant and debris. In this friction test, three kinds of textured surfaces with dimple distances of 200, 250, and 350 $\mu m$ were prepared and named as CT-200, CT-250, and CT-350, respectively. As a result, three texture area densities of 7.40%, 14.51%, and 22.67% were attained.

2.2. Friction and wear test

Friction and wear tests of the untextured and textured surfaces were investigated using a unidirectional friction machine (MPW110, NEOPLUS, South Korea) with the ball–on-disk configuration. The sliding system consisted of a stationary lower titanium alloy disc specimen and a rotatory upper Si\textsubscript{3}N\textsubscript{4} ball specimen, as illustrated in figure 1. The textured and untextured disc specimens were tightly secured to the lower specimen holder. A Si\textsubscript{3}N\textsubscript{4} ceramic ball with a diameter of 12.7 mm was used in all tests for friction partner materials. Before the sliding friction test, the untextured and textured disc specimens were polished using commercial MoS\textsubscript{2} solid lubricant.

In this study, two kinds of tribological tests were conducted. First, single-factor friction tests were performed with sliding speeds ranging from 0.08 to 0.42 m s\textsuperscript{–1}, and the normal load was 15 N using CT-250 specimens.
Table 1 shows the ball-on-disk test conditions. The textured test specimens used in the single-factor tests with and without the MoS$_2$ solid lubricant were named CT-250-W and CT-250, respectively. In addition, the untextured disc specimens with (UT) and without (UT-W) the MoS$_2$ solid lubricant were assessed for comparison under the same test conditions. Moreover, the Taguchi analysis was applied to examine the influence of the texture area density, sliding speed, and applied load on the friction and wear performance. The area density of the dimple, sliding speed, and applied load varied from 7.40% to 22.67% $\mu$m, 100 to 350 rpm (0.15 to 0.55 m s$^{-1}$), and 10 to 25 N, respectively. The coefficient of friction was determined by averaging all obtained values after a sliding time of 300 s at room temperature. Under the given test conditions, each test was repeated three times for statistical analysis, and the average value was presented. The surface topographies of the worn areas of the Ti-6Al-4V alloy disc and the Si$_3$N$_4$ ball were examined by field emission scanning electron microscopy (FE-SEM) (S-4100, Japan, Hitachi). Analysis of variance was also carried out on factors influencing the friction coefficient obtained via the Taguchi method. The optimal values of each parameter were suggested.

3. Results and discussion

3.1. Morphology of textured and untextured Ti-6Al-4V alloy surfaces

The SEM pictures in figure 2 show the typical microstructure of the untextured and textured surfaces of the Ti-6Al-4V alloy with different dimple spacing and densities, a low texture area density of 7.40% (figure 2(a)), and a high texture area density of 22.67% (figure 2(b)). It can be seen that regular combined dimple textures were produced through laser micromachining, and the combined dimples were arranged in the form of a hexagonal array. The close-up view of a single circular dimple region clearly reveals the geometry of the dimple, including the heat-affected area created around the dimple due to the laser-metal interaction, leading to the melting and vaporization of the Ti-6Al-4V alloy surface, as shown in figure 2(c). Additionally, the cladding layer and the heat-affected zone adjacent to the dimple base material were elongated to mimic a typical dendritic structure. Similar morphological attributes have been reported by earlier researchers [14, 15]. Some of the untextured and textured specimens were also polished with a MoS$_2$ solid lubricant. This shows that a thin MoS$_2$ film was uniformly adsorbed on the Ti-6Al-4V alloy surface, and the dimples were also filled by the MoS$_2$ solid lubricant, as shown in figures 3(a) and (b). Furthermore, the XRD analysis revealed that the untextured and textured samples predominantly contained Ti as hexagonal packed (hcp) structures in $\alpha$-Ti as well as in the form of body-center cubic (bcc) phases in $\beta$-Ti (figure 4). With a limited amount of the $\beta$ phase, the diffraction peaks from the $\alpha$ phase were clearly visible in the pattern. Additionally, the textured pattern revealed that the tiny peak near the $2\theta$
value of $80^\circ$ was caused by the laser heat altering the oxide crystallinity, converted it to crystalline rutile TiO$_2$ [16].

3.2. Friction and wear performance of untextured and textured Ti-6Al-4V alloy surfaces under dry and MoS$_2$ solid lubricants

The fundamental mechanisms of tribological phenomena are highly complicated, and the friction material needs to provide stable and repeatable friction with a low wear rate for good durability. In addition, it must show...
kindness to the mating surface of the friction pair. Figure 4 presents the curves for the friction coefficient performances of four types of surfaces: UT, UT-W, CT-250, and CT-250-W at sliding speeds of 0.08 m s$^{-1}$ and 0.42 m s$^{-1}$. As presented in figure 5(a), in most of the cases, similar friction performance can be perceived for both the textured and untextured surfaces without solid lubricants; that is, the coefficient of friction increased rapidly during the initial sliding phase and had constant values with relatively high fluctuations. Two discrete coefficient of friction areas are commonly presented in other tribological investigations on textured and untextured surfaces: running-in and steady-state areas [12, 13]. Under the same test conditions, the friction coefficient for the UT, UT-W, and CT-250 samples increased abruptly from an initial value of approximately 0.08 to a stable value of approximately 0.35–0.45, which relate to high fluctuation. In comparison, the friction coefficient of CT-250-W sustained a lower and more stable value below 0.05 with almost no fluctuation for approximately 25–50 s at the early stage, and then increased to a steady value of approximately 0.26. It was also shown that the fluctuation of the friction coefficient in the stable period for the CT-250-W specimen is relatively milder than for the other three kinds of samples (figure 5(a)). When the sliding speed was raised to 0.42 m s$^{-1}$ (figure 5(b)), the values of friction coefficient were slightly lower than those for the corresponding samples at a sliding speed of 0.08 m s$^{-1}$. Furthermore, the variations in friction coefficients were comparable to those at low sliding speeds (figure 5(a)).

The average value of friction coefficients of the UT, UT-W, CT-250, and CT-250-W surfaces as a function of increasing sliding speeds are summarized in figure 6. There is a point for each deviation of friction coefficients, and each data point indicates an average of three repeated experiments. As shown in the same figure, the friction coefficients display a slow downtrend with increasing sliding speeds for all the tested specimens. However, the value for the textured surfaces is slightly lower than that for the untextured sample. The average value of friction coefficients were quite high at sliding speeds of 0.08 m s$^{-1}$ and 0.42 m s$^{-1}$. However, the sliding speed ranging from 0.17 to 0.33 m s$^{-1}$ seems to be a good range in average friction coefficients could be reduced and maintained constant. The value of the average coefficients of friction for the CT-250 sample are slightly lower than those for the UT and UT-W samples, while that for the CT-250-W sample is relatively lower. Overall, the average friction coefficients for UT, UT-W, CT-250, and CT-250-W were in the ranges of 0.36 to 0.46, 0.27 to 0.44, 0.21 to 0.35, and 0.17 to 0.28, respectively. In addition, the solid lubricants affected the friction performance directly. Under the current sliding test conditions, the textured surface filled with the MoS$_2$ solid lubricant can decrease the average friction coefficients by 10%–20% compared with that of an untextured surface. Therefore, the average friction coefficient was highest for UT, low for UT-W, lower for CT-250, and lowest for CT-250-W, i.e., in the following order: CT-250-W < CT-250 < UT-W < UT.

3.3. Wear mechanism analysis of untextured and textured Ti-6Al-4V alloy surfaces

The representative photographs of the worn surface of textured and untextured specimens acquired by SEM after 300 s of sliding time are presented in figure 7. Distinct differences in the features between the two surfaces were expected. Wear scars are obviously detected along the sliding direction for all test specimens. The untextured UT and UT-W surfaces show severe grooves, plow furrows, adhesive wear, plastic deformation, and a spread of abrasive debris that mainly accumulated around the sliding direction (see figures 7(a)–(c)). It was also

![Figure 4. XRD diffractogram for the untextured and textured specimens.](image)
found that the solid lubricant film rapidly became defective on the UT-W surfaces (figure 7(c)) and was exposed to severe plow and abrasion wear.

For the CT-250 surfaces, as presented in figures 7(d) and (e), in addition to a slightly narrower wear scar, no apparent difference can be identified in comparison to the untextured surface, which exhibits low wear resistance. Without the solid lubricant, most of the textured dimples are severely worn out, which can be primarily attributed to the visible distinction in hardness between the Ti-6Al-4V alloy specimens and the mated ceramic ball. The hardness of the Si3N4 ceramic ball is approximately 16 GPa, while the equivalent value for titanium alloy is approximately 36 HRC. However, as seen in some dimples, incomplete wear occurs at the edge of the wear scar for the CT-250 surface. As shown in the magnified image of figure 7(f) for incomplete wear, the wear debris was effectively captured by the dimples. This demonstrates that the friction coefficients for the textured CT-250 surfaces are slightly lower than those for the smooth ones (figure 6). This may be more attributed to the debris-trapping and capturing effective role of dimples in the sliding friction process, which is effective in reducing abrasive wear [17, 18]. Even though most of the dimples are worn out, the wear scar is narrower for the textured CT-250 surface than the untextured wear scar, and the dimples remain intact when debris enters. As can be seen the plastic deformation and mild adhesive wear were the major wear forms of the Ti-6Al-4V alloy surface which results from the influence of surface texture on storing some debris, increasing the contact stress, and the adhesion wear [1, 2].

Figure 5. Changing trend of friction coefficient for the four types of samples with increasing sliding time at two different sliding speeds: (a) 5 m s\(^{-1}\) and (b) 25 m s\(^{-1}\).
It can be shown from figures 8(a) and (b) that the wear scar is narrower and relatively milder for CT-250-W surfaces with slight sliding marks, scratches, and plowings, but they are not as severely worn in size and distribution in contrast to the other three kinds of samples. This results from the relatively low hardness of Ti-6Al-4V alloy surface compared to the hard ceramic grinding ball. Moreover, with the increase in sliding speed \( > 0.25 \text{ m s}^{-1} \), there are plowing and grooved surfaces with abrasive debris, and some of the dimples are almost worn out owing to breakage of the solid lubricant layer, the positive of texture surface was limited, thereby there no significantly decrease in the plowing of the wear track. This indicates that the wear scar is severe with a typical abrasive wear mechanism occurring during the sliding test (figure 8(c)). As a result, the friction coefficient increases slightly (figure 6). Therefore, the textured surface polished with the MoS2 solid lubricant exhibited lower friction and wear. This results from the synergy effect of textures and solid lubricants is that surface dimples act as reservoirs of lubricant that provide lubricants material to the sliding contact [6]. It has also attributable the fact that higher texture densities release more lubricating materials, but there is a limit to this advantage as the contact surface approaches a flat surface from which the solid lubricant is easily removed during sliding [6].

The SEM images in figures 9(a)–(c) show the worn surface on the sliding counterface of the Si3N4 ceramic ball after a friction time of 300 s. Generally, material transfer is pronounced on the ball surfaces of all test disc surfaces. It can be clearly seen from the SEM images that the wear scar area predominantly consists of adhered Ti-6Al-4V alloy layers that are transferred from Ti-6Al-4V alloy disc surfaces. It is expected that the worn scar area of the ball sliding against the CT-250-W surface is less than that sliding with untextured surfaces (figure 9(c)). However, when sliding against an untextured surface, severe titanium alloy adhesion can be observed on the worn surface of the counter ball, which may be the reason for the high and severely fluctuating friction coefficient (figure 9(a)). The corresponding energy dispersive X-ray spectroscopy (EDS) analysis was applied to examine the adhesive layer formed on the ball wear scars that slid against the CT-250-W discs. As shown in figure 9(d), EDS confirmed that the ball wear scars were composed of elements Ti, Si, Al, S, Mo, and V. This indicates that the transfer and adhesion of Ti-6Al-4V alloy materials to the ceramic ball occurred during the friction process. This is because lower soft disc materials can migrate and adhere to the surface of a hard ceramic ball. The counter ceramic ball completely covered by the wear debris that mainly generated from the titanium alloy. The EDS analysis also indicated that a few solid lubricants also migrated and compacted on the ball wear scar region and thus stable friction coefficient can be obtained on the sliding surface. A comparable outcome has also been confirmed by Qin et al [18].

The anti-wear ability of the untextured and the textured Ti-6Al-4V alloys were further examined in detail. Figure 10 depicts the wear rate of Ti-6Al-4V alloy at various sliding speeds. As evident, the trend of wear rates remained consistent with increasing sliding speeds. Furthermore, the wear rate of the untextured surfaces decreased to a low extent, following which it stabilized as the sliding speeds increased. Conversely, the wear rate of the textured surfaces showed decreased and remained stable as the sliding speeds increased, indicating that the surface textures affect the lowering of wear rates. In general, the CT-250 surface had a slightly lower wear rate than the untextured UT and UT-W surfaces, while the CT-250-W surface had a significantly lower wear rates.

![Figure 6. The average coefficients of friction at different sliding speeds for UT, UT-W, CT-250, and CT-250-W specimens.](image-url)
than the other three types of surfaces. Additionally, the textured surface filled with the solid was found to contribute significantly to the anti-wear ability.

3.4. Taguchi experiments: design and analysis
Based on the above tribological experimental results, the dimple surface mixed with solid lubricants had a significant influence on the coefficient of friction and anti-wear properties. The purpose of the experimental design was to further examine the friction properties of the textured CT-250-W samples. The experimental investigation plan was formulated considering 3 parameters and 3 levels based on the Taguchi method: dimple area density (D), sliding speed (S), and applied load (L). The parameters and their levels chosen for experimentation are listed in table 2. The standard L₉(3⁴) orthogonal array was designed and used as an experimental plan on three relevant input dimple parameters, including D, L, and S, to investigate the friction properties. Table 3 presents the general layout of the L₉ orthogonal array designed using the Taguchi method.
Figure 8. SEM micrographs of the textured CT-250-W specimens at 14.51%, following wearing after 300 s sliding time and 15N applied load.

Table 2. Parameters and their levels of textured surface used in the experiment.

| Design factors | Levels | 1  | 2  | 3  |
|----------------|--------|----|----|----|
| A Normal load, N | 10 | 17 | 25 |
| B Sliding speed, m/s | 0.15 | 0.39 | 0.55 |
| C Texture area density, % | 7.40 | 14.51 | 22.67 |

Table 3. Experimental L₉ orthogonal array with design factors and interactions assigned.

| Experimental No | Column 1 | Column 2 | Column 3 |
|-----------------|----------|----------|----------|
| 1               | 1        | 1        | 1        |
| 2               | 1        | 2        | 2        |
| 3               | 1        | 3        | 3        |
| 4               | 2        | 1        | 2        |
| 5               | 2        | 2        | 3        |
| 6               | 2        | 3        | 1        |
| 7               | 3        | 1        | 3        |
| 8               | 3        | 2        | 1        |
| 9               | 3        | 3        | 2        |
The standard $L_9$ orthogonal array consists of 3 columns and 9 rows, comprising 9 experimental runs concerning 3 control parameters. The experiments were performed based on the orthogonal array with the level of parameters given in each array row. The friction test results were subjected to ANOVA. The test was conducted with the purpose of determining the effects of $S$, $D$, and $L$ on the sliding friction. Table 4 presents the average friction coefficients from the $L_9$ orthogonal array of the parameters in table 3.

![Figure 9. SEM micrographs of the ceramic ball surfaces: (a) sliding with UT, (b) sliding with CT-250, (c) sliding with CT-250-W and (d) EDS results.](image)

![Figure 10. Average wear rates of untextured and textured surfaces at various sliding speeds, with a sliding time of 30 s and a normal load of 15 N.](image)
Table 5 shows the ANOVA analysis results for the value of average friction coefficients; the results for the three factors varied at three levels and variable. The F values for L, S, and D attained in ANOVA for the average coefficients of friction were 0.044, 0.059, and 0.099, respectively, while the critical values of the F test for 90%, 95%, and 99% confidence levels were in sequences of 9, 9, and 19, respectively [19, 20]. Column 5 of the ANOVA results in Table 5 indicates the percentage contributions (P) of L, S, and D to the total variation in the friction coefficients were 20.22%, 29.58%, and 50.20%, respectively. Equally, from the ANOVA results presented in Table 5, we can see that the D parameter is the most significant parameter effecting the friction coefficients; therefore, particular attention should be paid to this factor. In addition, parameter L has a certain influence on the average coefficient of friction, followed by S with confidence level percentages of 20.22% and 29.58%, respectively. According to ANOVA outcomes, D statistically and physically affects the coefficient of friction; thus, a higher texture area density integrated with a solid lubricant is helpful for enhancing the friction and wear performance of Ti-6Al-4V alloy surfaces by storing and supplying adequate MoS2 solid lubricant to the sliding interface and trapping wear debris.

The ANOVA results confirm that the effects of D on the friction coefficient are reliable with the tribotest experimental results. Additionally, the friction life and wear resistance of the textured surface was also confirmed to be dependent on D0. In general, the longevity of solid lubricants on contact surfaces is also determined by the reserved solid lubricant in the dimples, as well as the efficiency with which the dimples provide the solid lubricant to the contact surface. In the case of the textured surfaces with a low D value, the dimples may retain lower volumes of the solid lubricant, resulting in severe wear and increased friction due to an insufficient solid film form. Thus, textured surfaces with higher area densities of the dimple pattern are advantageous for increasing the preservation of the solid lubricant, as the lubricants can be effectively fed to the sliding surface via the dimples, thereby extending the effective life of the sliding surface [13, 18].

4. Conclusions

Under all sliding test conditions, the textured surface with and without molybdenum disulfide solid lubricant demonstrated excellent friction-reducing and anti-wear properties. This could be attributed to the effective

| Source of variance | Sum of squares (x10^-5) | Variance (x10^-5) | Test F | F | Pb (%) |
|--------------------|------------------------|-----------------|--------|-----|--------|
| L                  | 0.2488                 | 0.1244          | 0.044  | 9c  | 20.22  |
| S                  | 0.5088                 | 0.2544          | 0.059  | 19d | 29.58  |
| D                  | 1.4708                 | 2.3544          | 0.099  | 99e | 50.20  |
| Error              | 0.2562                 | 0.2628          | 0.25   |     |        |
| Total              | 2.4846                 |                 | 100    |     |        |

* Degree of freedom.
* Percentage of contribution.
* Confidence level 90%.
* Confidence level 95%.
* Confidence level 99%.
trapping of wear particles and the transfer of the reserve solid lubricant into the sliding contact surface, thereby enabling the continuous maintenance of a solid lubricant film. Among the samples, the textured CT-250-W surfaces had the lowest friction coefficient. Additionally, the friction coefficient was reduced by approximately 10%–15% when compared to the untextured surface, which significantly demonstrates the effect of combined surface texturing. The untextured Ti-6Al-4V alloy surface was primarily worn by adhesive wear, plastic deformation, and mild abrasive wear. However, wear loss, abrasion, and adhesion were reduced on the textured Ti-6Al-4V alloy surface filled with the solid lubricant. Additionally, by creating a thin lubricating film at the friction interface, the adhesion of titanium alloys to their counterpart steel balls was reduced. The use of the Taguchi method in the experimental design enabled successful analysis of the friction performance. The most significant variables affecting the friction coefficient of the Ti-6Al-4V alloy were confirmed to be the texture area density (50.20%), followed by sliding speed (29.58%), and applied load (20.22%), as confirmed from the analysis of variance. Thus, the contributions of the textured alloy surface were confirmed to be of the following order: dimple density > sliding distance > load.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Competing interests

The authors declare that they have no competing interests.

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