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LASER SURFACE TEXTURING TO IMPROVE THE TRIBOLOGICAL PROPERTIES OF Ti ALLOYS

LASERSKO TEKSTURIRANJE TITANOVIH ZLITIN ZA IZBOLJŠANJE TRIBOLOŠKIH LASTNOSTI

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Friction and wear requirements in the aerospace/space industry or in biomedical applications are governed by life-limiting challenges: the wide range of contact stresses and sliding speeds in movable parts and operating conditions such as extreme temperature changes, humidity and abrasive wear caused by electrostatically attracted dust. Surface modification by laser texturing has been introduced to adjust the surface characteristics of the base material to overcome its tribological limitations of use via different surface topographies, allowing for the ability of lubricant retention. Laser surface texturing is therefore effective in enhancing the tribological performance of materials via controllable surface topographies acting as traps for wear debris and lubricant reservoirs, leading to reduced abrasion. This paper reviews the tribological behaviour of a laser-textured Ti6Al4V alloy with different textures: lines, crosshatch and dimples. The fiction and wear characteristics for dry sliding are discussed and compared.

Keywords: Ti6Al4V alloy, surface texturing, tribology, friction/wear

Zahteve glede trenja in obrabe v letalski/vesoljski industriji ali biomedicinskih aplikacijah so pogojene z izzivi, ki omejujejo življenjsko dobo komponent: širok razpon kontaktnih napetosti in drsnih hitrosti v premičnih delih ter pogoji delovanja, kot so ekstremne temperaturne spremembe, vlaga in abrazivna obraba, ki jo povzroča elektrostatično privlačen prah . Modifikacija površine z laserskim teksturiranjem je bila uvedena za prilagoditev površinskih značilnosti osnovnega materiala za uspešno premagovanje njegovih triboloških omejitev uporabe prek različnih površinskih topografij, ki omogočajo sposobnost zadrževanja maziva. Lasersko površinsko teksturiranje je torej učinkovito pri izboljšanju tribološke učinkovitosti materialov prek nadzorovanih površinskih topografij, ki delujejo kot pasti za ostanke obrabe in rezervoarje maziva, kar vodi do zmanjšane abrazije. Ta članek obravnava tribološko obnašanje lasersko teksturirane zlitine Ti6Al4V z različnimi teksturami: črte, šrafura in jamice. Obravnavane in primerjane so značilnosti trenja in obrabe pri suhem drsenju.

Ključne besede: Ti6Al4V zlitina, površinsko teksturiranje, tribologja, trenje/obraba

1 INTRODUCTION

Laser surface texturing (LST) is an effective technique employed to create a specific pattern or texture on a surface, leading to modified surface properties, enhancing the tribological characteristics of materials such as load capacity, friction and wear resistance.[1]

The study of the influence of different surface textures has been conducted for tribological applications, utilizing various texturing techniques such as machining processes, ion-beam texturing, surface etching, and laser texturing.[2] In the last decade, however, scientific discussions highlight LST as a highly promising technology, due to short processing times, precise control, and environmental friendliness.[3,4] The enhanced performance of such modified surfaces is attributed to their ability to facilitate continuous lubrication by storing lubricant on the textured surface, generating micro-hydrodynamic effects, reducing abrasive wear through wear-debris entrapment, and minimizing the contact area.[5]

The sliding conditions in the contact area can be additionally improved by using appropriate lubricants.[6–9] This leads to a reduction of wear and the volume of wear debris. The most common is liquid lubrication, which has been successfully used in different applications for several years.[10,11] The leading role in this field belongs to oil-based lubrication with the emphasis on low-viscosity oils.[12] Another promising and rapidly developing area is water-based lubrication, which is within the concept of green tribology, focusing on the reduction of waste and the elimination of hazardous substances.[13]

LST has been successfully applied to various engineering materials such as ceramics,[14] metals,[15] and polymers,[16] finding utility in the biomedical, tribological, and coating domains. Different patterns and textures, including dimples and microgrooves of varying shapes and sizes, have been generated by LST to improve the material's tribological behavior through enhancing the coefficient of friction (CoF) and the wear resistance.[17,18] The dimensions and density of laser-textured patterns play a critical role in determining wear and the coefficient of friction. Numerous researchers have investigated the impact of dimple size, depth, and density on the tribolo-

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gical performance of titanium alloys.[19–21] Their findings highlight the role of dimple density in reducing the abrasive wear by facilitating the storage of wear particles within the dimples. Moreover, studies have demonstrated that the CoF and wear volume on surfaces featuring crosshatching patterns and dimple textures are lower in seawater compared to the untreated Ti6Al4V surface.[5]

The Ti6Al4V alloy is the most popular among Ti alloys, being suitable in various applications from aerospace to biomedicine. Its main beneficial characteristics are high strength, low density, high fracture toughness, good corrosion resistance and biocompatibility.[5,22–24] However, a low surface hardness, a high CoF and wear resistance limit its use in tribologically demanding environments, which is even extrapolated in physiological conditions present in biomedical applications. Here, laser-surface texturing is presented as a surface-modification tool that changes the Ti6Al4V morphology through different textures: lines, crosshatch and dimples. The tribological response of laser-surface-modified Ti6Al4V in air is discussed.

2 LASER SURFACE TEXTURING

When a surface is subjected to laser irradiation, it heats up and causes the material to be removed through melting and vaporization in the irradiated area. This process selectively removes material and alters the surface topography.[16] Laser ablation enables the precise removal of material at the micron level and is a rapid method, making it effective for creating textures.[25,26] Over the past decade, LST has already been successfully employed to modify the surface morphology aiming to improve tribological properties and/or biocompatibility.[3,4] The added value of such modified surfaces lies in their capability for continuous lubrication, facilitated by lubricant retention on the textured surface, the generation of micro-hydrodynamic effects, a reduction of abrasive wear through wear debris entrapment, and minimization of the contact area.[5] LST is therefore addressed as a highly promising technology, characterized by rapid processing, precise control, and environmental friendliness.

A LPKF nanosecond Nd-YAG laser with 1064-nm wavelength and an output power of 10 W was used for the laser texturing. We performed three different types of textures: lines, crosshatch and dimples. The surface morphology depends on the basic laser parameters such as power, frequency, speed, number of repetitions as well as on the scan-line separation for the lines and crosshatching patterns, or the circle size and the inter-circle distance for the dimple pattern. Here, the processing speed was 100 mm/s (dimples) and 300 mm/s (lines) and the laser-pulse frequency was 30 kHz. The system is equipped with a Scanlab SCANgine 14 processing head, which has an F theta-Ronar lens with a focal length of 360 mm and a double galvano configuration, while the marking field is (250 × 250) mm^2. The marking shapes were programmed using SAMLight SCAPS v3.5.5 software. The complete set of processing parameters is summarized in **Table 1**. The scan-line separation for producing the lines and crosshatching patterns was set to Δx = 100 μm, 180 μm and 280 μm, and the laser texturing was repeated five times on each laser trace. In the crosshatching patterns Δy was kept constant at 280 μm. The pattern of dimples (50 μm and 100 μm in diameter) was processed at a 100 μm (50–100), 200 μm (100–200) and 400 μm (100–400) center-to-center distance and with five repetitions. Laser-texturing was conducted under ambient conditions.

Table 1: Laser texturing parameters. The laser power output was 10 W at the pulse frequency of 30 kHz

Sample	Pattern type	Number of repetitions	Distance between lines/circle centres (μm)	Size of circles (μm)	Processing speed (mm/s)
(a)	lines	5	100		300
(b)	lines	5	180		300
(c)	lines	5	280		300
(d)	crosshatching	5	100		300
(e)	crosshatching	5	180		300
(f)	crosshatching	5	280		300
(g)	dimples	5	100	50	100
(h)	dimples	5	200	100	100
(i)	dimples	5	400	100	100

It's important to emphasize that following the laser texturing, distinct bulges were observed around the textures. These bulges were subsequently removed before tribological testing to prevent any interference with friction and wear. As reported in [27], the material within these bulges is notably harder compared to the base material. Consequently, all laser-textured samples underwent grinding with paper down to 2400 grit. Despite the removal of hard bulges, the hardness of the surface material surrounding the textures (> 300 HV0.01) still exceeds that of the base material (240 HV0.01).[28]

The morphology of the lines, crosshatching patterns and dimples are presented in **Figure 1**. We can see that the separation of scan lines determines the density of texture for both: line patterns and crosshatching textures. Texture density was gauged experimentally by measuring surface areas using SEM, calculated as the ratio of laser-textured surface (featuring cavities with bulges) to the total surface area. For line patterns, the texture density declines from around 40 % to 20 % as the scan-line separation increases from 100 μm to 280 μm. Similarly, for crosshatching textures, the density, slightly higher than that of lines, decreases from approximately 45 % to 25 % with increasing scan-line separation. For dimples we can see that the surface 50–100 has the highest texture density around 40 %, while the surface 100–400 has the lowest texture density around 10 %.

The insets in **Figure 1** illustrate the corresponding height profiles that determine the dimensions and depths

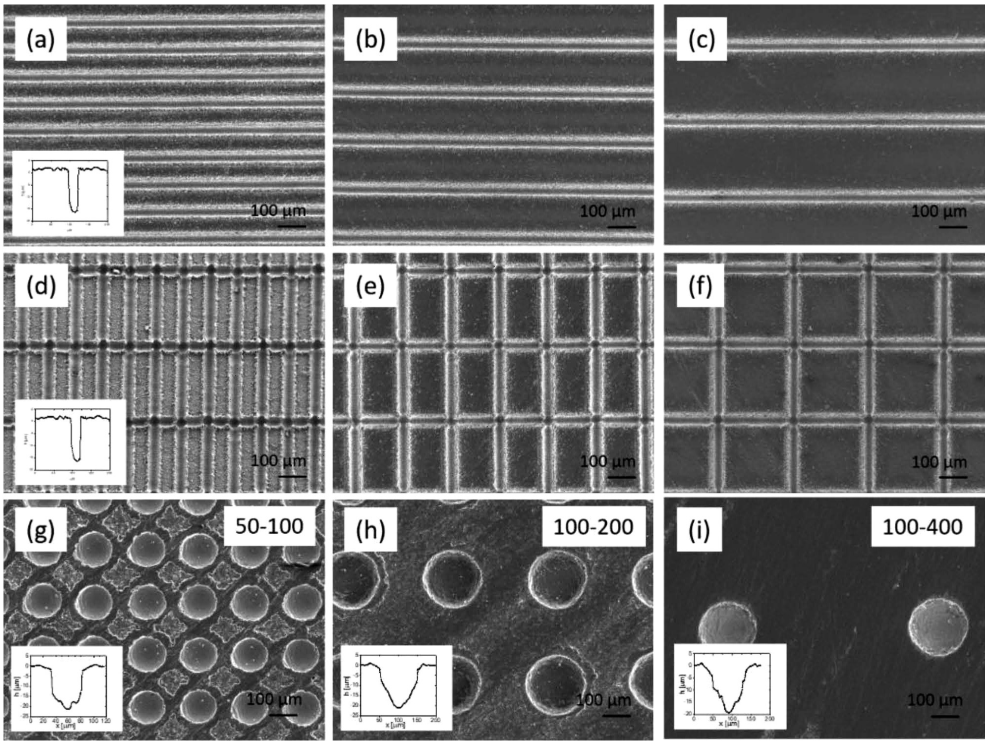

Figure 1: Morphological details of different laser-textured surfaces: lines (Δy = 100, 180 and 280 µm, a-c), crosshatch (Δx = 100, 180 and 280 µm, d-f) and dimples (50-100, 100-200, 100-400, g-i). The insets in images (a), (d), (g), (h) and (i) present the profiles measurements revealing the width and the depth of the laser textures

of the lines and dimples. The channels' width in both line patterns and crosshatching textures measures approximately 30 µm, with a depth of around 20 µm (**Figures 1a** to **1f**). The dimples are approximately 20 µm deep, but their diameter is 50 µm or 100 µm as planned (**Figures 1g** to **1i**).

3 TRIBOLOGICAL EVALUATION

Tribological evaluation conducted utilizing a ball-on-flat contact arrangement (TRIBOtechnic friction testing tribometer) and employing a reciprocating sliding motion provides general information about surface friction and wear characteristics. Typical parameters defining the experimental conditions were chosen as follows: normal load of 5 N, corresponding to a nominal contact pressure of 1.0 GPa, an average sliding speed of 5 mm/s and a total sliding distance of 1000 mm. The stationary counter body was a 100Cr6 bearing steel ball with a diameter of 5 mm for lines and crosshatch, and with a diameter 10 mm for dimples. The coefficient of friction (COF) was measured continuously during the tests, with the steady-state COF calculated as the average value of the last 100 seconds. The wear tracks were further analysed with SEM and with an optical 3D measurement system Alicona InfiniteFocus G4 for the final calculation of the wear volumes.

Below, the dry-sliding tribological response of the lines, crosshatch textures and dimples in comparison to non-textured (NT) Ti6Al4V surface is discussed.

3.1 Lines and Crosshatch

For the lines and crosshatch tribological evaluation a relatively small ball diameter of 5 mm was chosen to simulate the most critical contact situations with very small contact areas and high-pressure spikes as well as to study the influence of the texturing type, spacing and orientation on the friction and wear. With the aim of investigating the effect of the texturing-orientation, line patterns (**Figures 2a** to **2c**) were slid in three directions: parallel (0°), perpendicular (90°) and at an angle of 45° to the texturing direction and crosshatching patterns (**Figures 2d** and **2e**) in two directions: perpendicular (90°) and at an angle 45° Examples of line texturing of Δx = 180 µm and crosshatching patterning of Δx = 280 µm are presented.

To understand frictional response of laser textured surfaces we extracted the steady-state coefficient of friction (COF). We can see in **Figure 3** that in case of lines, a similar steady-state COF of about 0.42 is measured for all three line-textured surfaces with distances between the lines of 100 µm (a), 180 µm (b) and 280 µm (c), regardless of the lines' density and the sliding direction of 0°, 90° and 45°. This is also in a good agreement with the friction behaviour of the non-textured (NT) Ti6Al4V material with a COF around 0.4, as shown in **Figure 3**. This is typically reported for Ti6Al4V, both for very short sliding distances of just few millimetres, up to extended sliding of a few hundred metres.[29,30]

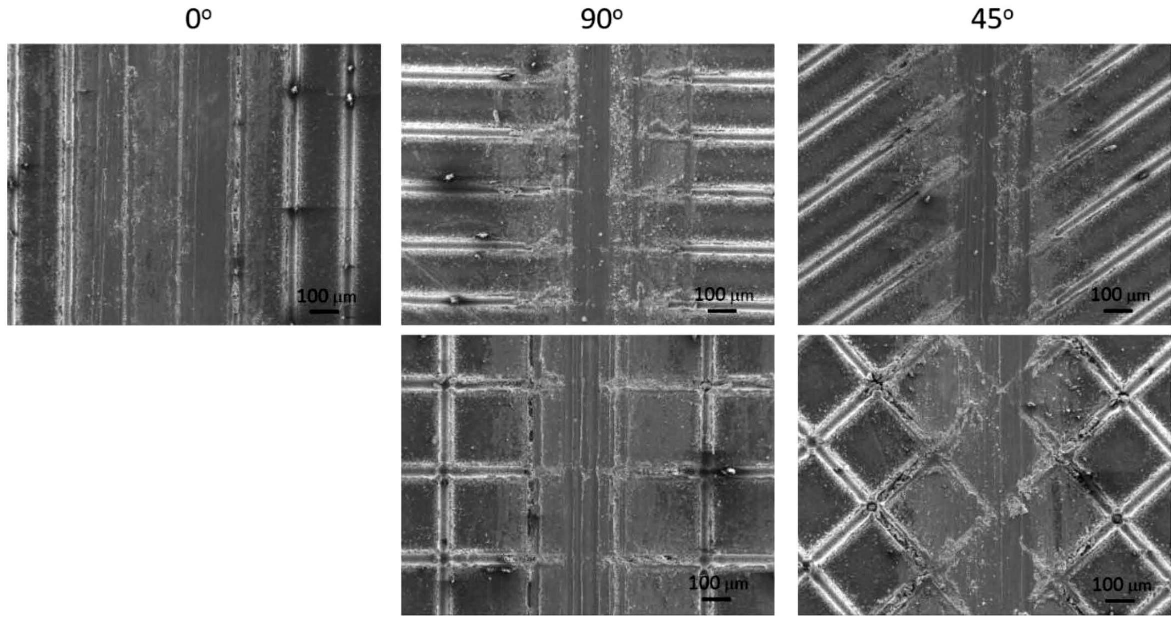

Figure 2: Typical wear tracks for lines (a, b, c) and crosshatching patterns (d, e) when sliding in air in various directions: parallel (0°), perpendicular (90°) and at an angle 45°

A similar trend is observed for the crosshatching patterns (**Figures 3d** to **3f**); however, the steady-state COF values are slightly higher (≈0.45) than for the lines and the NT surface, especially when using the densest crosshatching patterns (Δx = 100 μm and Δy = 280 μm), caused by nearby lines and surface irregularities being present in different directions.

In terms of wear, a combination of abrasive and adhesive wear mechanisms for all the Ti6Al4V surfaces was observed (**Figure 4**). For the NT surface, the wear volume was measured in the range of 0.004 mm^3. In the case of the line-textured surface the wear volume almost doubled, increasing to 0.0065 mm^3 and even up to 0.0096 mm^3 when the sliding was perpendicular (90°) or at 45° to the lines' direction, and around 0.007 mm^3 for parallel sliding (0°) and the dense pattern (a) (**Figure 4**). Reducing the lines' density (b & c) resulted in reduced wear, and reaching even lower values than the NT surface for the lines' directions 0° (parallel) and 45° for the lines' distance 280 μm (**Figure 4**).

For the crosshatching patterns the situation is the opposite. Sliding directions 90° and at 45° show similar results. For the highest crosshatching pattern density (d45 – 100 μm and 45°) the wear volume under dry sliding is in the same range, 0.0062 mm^3, as for the line pattern (a45 – 100 μm and 45°) which is 0.0065 mm^3, but it increases to over 0.0075 mm^3 as the pattern density is reduced (f – 280 μm and 90°) (**Figure 4**).

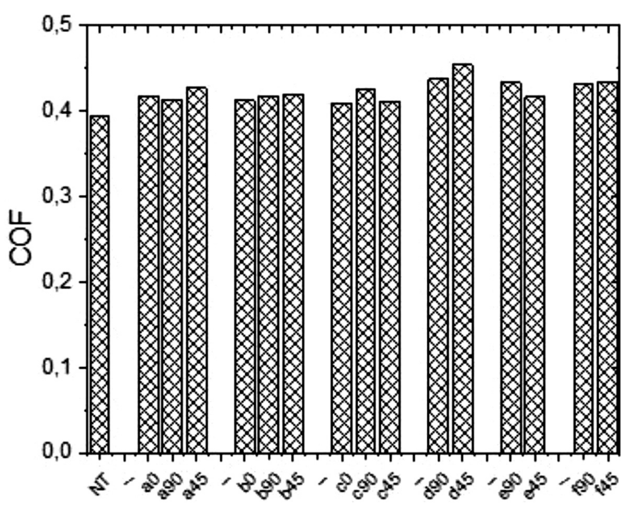

Figure 3: Dry-sliding COF for NT Ti6Al4V sample and samples with lines (a – 100 μm, b – 180 μm and c – 280 μm), and crosshatch (d – 100 μm, e – 180 μm and f – 280 μm) surface-texturing patterns and for different sliding directions (0°, 90°, 45° for a-c and 90°, 45° for d-f)

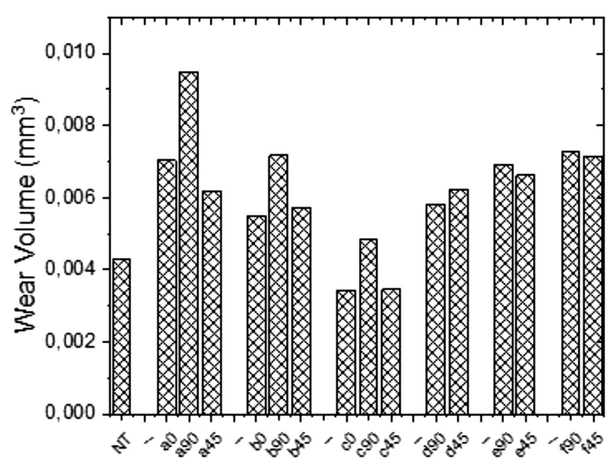

Figure 4: Dry-sliding wear volumes for NT sample and samples with lines (a – 100 μm, b – 180 μm and c – 280 μm), and crosshatch (d – 100 μm, e – 180 μm and f – 280 μm) surface-texturing patterns and for different sliding directions (0°, 90°, 45° for a-c and 90°, 45° for d-f)

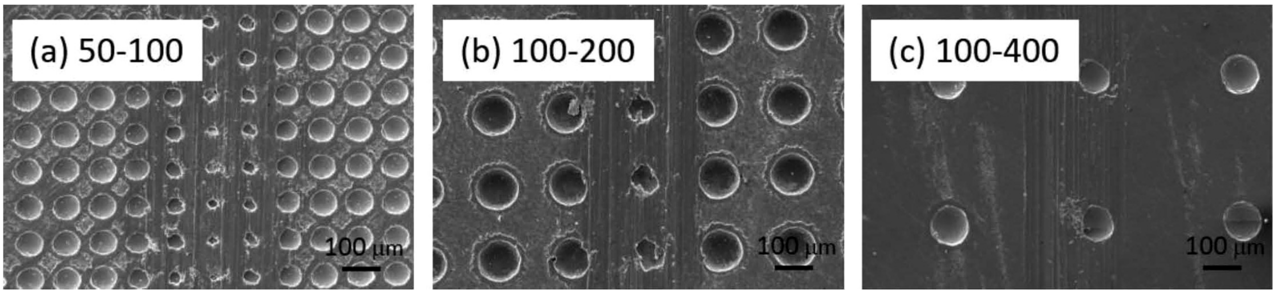

Figure 6: Typical wear tracks for dimple textured surface when sliding in air: a) 50–100, b) 100–200 and c) 100–400

3.2 Dimples

On dimple textured surface the sliding was performed along the dimple texturing pattern. Typical wear tracks are shown in **Figure 6**. The best results with the lowest steady state COF are observed for the 50–100 and 100–200 surfaces with the high surface texture-density (TD), with measured steady-state COFs around 0.36 and 0.37, respectively (**Figure 7**). A slightly higher COF, however still significantly lower in comparison to NT surface (which is around 0.42), 0.38 is measured for the 100–400 surface with the lowest TD (**Figure 7**). A slight increase in COF with reduced TD, which is correlated to the size of the dimples and their center-to-center distance can be understood with the variation in micro-hydrodynamic effects of the dimples, leading to increased friction.[24,31]

In terms of wear, again, a combination of abrasive and adhesive wear mechanisms is observed for all the Ti6Al4V samples: NT and dimple-textured. Wear volumes are presented in Fig. 8. It can be observed that laser-texturing seemed to even intensify abrasive wear component in comparison to the NT surface with a wear volume of 0.0038 mm^3, mostly due to reduced contact area and increased contact stresses within the contact.[22] This is most pronounced for the highest TD (sample 50–100) where the wear volume is around 0.0185 mm^3 and then diminishes with reduced TD to 0.0062 mm^3 for the sample 100–200 and to 0.0071 mm^3 for the sample 100–400.

4 CONCLUSIONS

The surface modification of the Ti6Al4V alloy via laser texturing opens up a new aspect to the design of specific metallic parts for aerospace/space or biomedical applications. Laser surface texturing effectively modifies the surface morphology of the Ti6Al4V alloy, creating various textures such as lines, crosshatch, and dimples. These textures act as traps for wear debris and reservoirs for lubricants, enhancing the tribological performance by reducing abrasive wear and friction. The dimensions and density of laser-textured patterns play a critical role in determining tribological performance. Optimal parameters need to balance between reducing the friction and minimizing the wear, considering factors such as pattern size, depth, and spacing.

Further on, laser surface texturing shows promise for applications in aerospace, biomedical, and other high-performance industries where friction and wear resistance are critical. The ability to tailor the surface textures provides flexibility in optimizing the tribological properties for specific operational conditions. Further research could focus on optimizing the laser-texturing parameters to achieve superior tribological performance, exploring additional surface patterns, and investigating the impact of lubricants on textured surfaces. Moreover,

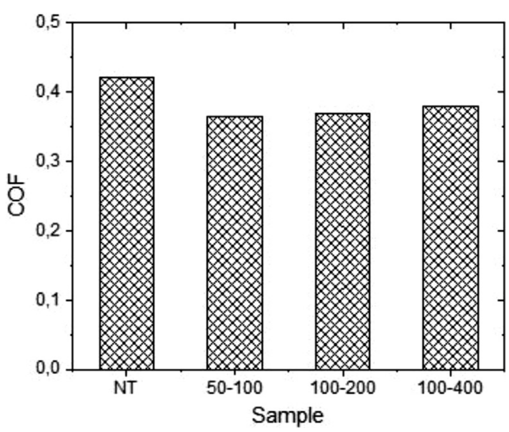

Figure 7: Dry-sliding coefficients of friction for Ti6Al4V non-textured sample (NT) and samples with dimples: 50–100, 100–200 and 100–400

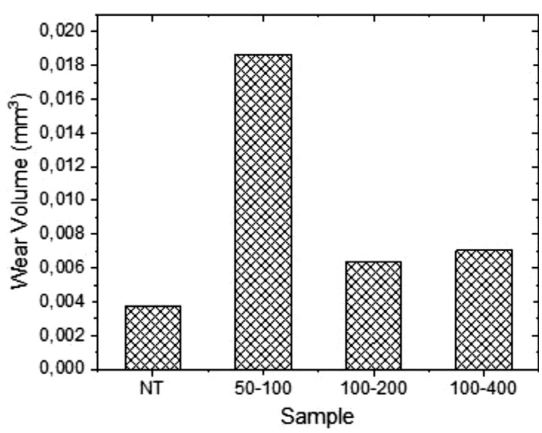

Figure 8: Dry-sliding wear volumes for Ti6Al4V non-textured sample (NT) and samples with dimples: 50–100, 100–200 and 100–400

understanding the long-term durability and reliability of laser-textured surfaces in real-world applications remains a crucial area for future study. Overall, laser surface texturing offers a viable solution to enhance the tribological properties of the Ti6Al4V alloy, addressing challenges in friction and wear under various operational conditions, thereby expanding its potential for diverse industrial applications.

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