THE EFFECT OF DIMPLE DEPTH TO THE FRICTION AND WEAR IN LINEAR MOTION

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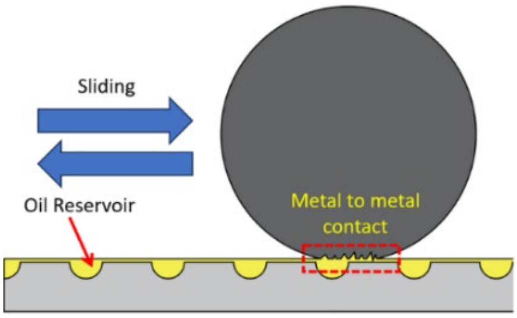
GRAPHICAL ABSTRACT



ABSTRACT

Friction and wear remain major contributors to energy loss in mechanical systems, underscoring the need for effective surface-engineering strategies. This study evaluates the influence of dimple depth on the tribological performance of aluminium alloy surfaces textured using Laser Surface Texturing (LST). Elliptical dimples with depths of 100 µm, 150µm, and 200µm were tested under lubricated linear reciprocating motion. The 150µm dimples achieved the lowest coefficient of friction (COF), reducing friction by 20.5%, 26.2%, and 5.0% compared to the untextured surface at 40N, 50N, and 60N, respectively. Wear analysis showed that the 150 µm depth reduced scar length by 21–28% relative to the deeper 200µm texture, while surface roughness measurements (Ra≈ 0.095µm) confirmed effective lubrication retention. Overall, the 150µm dimples consistently outperformed both shallower (100µm) and deeper (200µm) textures, demonstrating that an intermediate depth enhances lubrication stability, reduces asperity contact, and improves component durability.

KEYWORDS

Surface texturing, Dimple ratio, Laser surface texturing (LST), Friction, wear.

INTRODUCTION

Friction and wear are critical factors influencing the performance, reliability, and service life of components operating under sliding or reciprocating motion. In mechanical systems such as journal bearings, piston rings, and linear motion assemblies, excessive friction leads to high energy loss, while wear causes material degradation and premature component failure. Studies estimate that nearly 20% of the world's total energy consumption is lost to friction and wear in engineering systems, underscoring the need for tribological optimization strategies [1]. The field of tribology, which encompasses the study of friction, wear, and lubrication, provides insights into how these phenomena can be minimized through surface engineering and material modification [2,3]. Improving surface characteristics at the micro-scale has emerged as a sustainable approach to enhancing the tribological efficiency of modern mechanical devices [4].

One of the most promising surface engineering methods is Laser Surface Texturing (LST), which enables the precise fabrication of micro-dimples on metallic surfaces to alter lubrication behavior.

Micro-dimples act as localized reservoirs that store and release lubricant during motion, maintain film stability, and trap wear debris, thereby reducing asperity contact and frictional losses [5]. These textured features create micro-hydrodynamic effects that increase the load-carrying capacity and improve lubricant flow in boundary and mixed lubrication regimes [6-8]. Over the past two decades, researchers have reported significant friction reductions ranging from 20% to 60% on laser-textured surfaces under various loads and speeds, highlighting the potential of controlled micro-texturing for tribological enhancement [9].

Although numerous studies have explored surface texturing, the dimple aspect ratio, defined as the ratio of dimple depth to diameter, remains a key geometric parameter governing texture performance. Previous work has shown that excessively shallow dimples may fail to retain sufficient lubricant, while overly deep textures may trap air and promote cavitation, leading to lubricant starvation and instability [10]. Determining the optimal dimple aspect ratio is therefore crucial for achieving a balance between hydrodynamic pressure buildup and lubricant retention capability. The ideal geometry also depends on operating parameters such as load, frequency, and lubricant viscosity, which vary widely across tribological systems [11]. For aluminum alloys, which are lightweight yet prone to adhesive wear, optimizing dimple geometry offers a particularly effective means of improving wear resistance and frictional performance in sliding interfaces [12].

This study investigates the effect of varying dimple depth on the friction and wear behavior of laser-textured aluminum alloy surfaces under lubricated linear reciprocating motion. Using a Laser Surface Texturing system, elliptical dimples of fixed diameter but different depths (100 µm, 150 µm, and 200 µm) were fabricated to evaluate the relationship between aspect ratio and tribological response. A commercial mineral-based industrial lubricant was employed as the test medium. This lubricant was selected for its viscosity characteristics, with a viscosity index representative of oils typically used in boundary and mixed lubrication regimes for aluminium-based sliding components. The tests were conducted on a linear reciprocating tribometer in accordance with ASTM G133, under controlled loads and frequencies. The experimental results, supported by surface-morphological analysis, aim to identify the optimal aspect ratio that minimizes the coefficient of friction and the wear scar diameter. The findings are intended to contribute to the growing body of tribology research by offering practical insights into how micro-texture geometry can be tuned to enhance surface performance in boundary and mixed lubrication regimes.

METHODOLOGY

Sample lubricant preparation

The lubricant used in this study was a commercial mineral-based industrial oil, selected as the benchmark lubricant for its stable viscosity, thermal resistance, and compatibility with aluminium surfaces under boundary lubrication conditions. Before testing, the lubricant's properties were characterized according to ASTM D445, revealing a kinematic viscosity of 108.2 mm^2/s at 40 °C, 14.1 mm^2/s at 100 °C, a viscosity index of 132, and a flash point of 227 °C, confirming its suitability for high-friction applications. Before each experiment, the lubricant was filtered to remove impurities and preheated to room temperature to ensure consistent flow behavior. During tribological testing, approximately 15 mL of lubricant was uniformly applied to the contact surface between the aluminium plate and the test ball to maintain boundary lubrication throughout the reciprocating motion. This controlled application ensured consistent film formation, minimized the influence of debris, and allowed accurate evaluation of the effect of dimple aspect ratio on friction and wear performance under lubricated conditions.

Table 1. Experimental parameters and conditions

Parameter	Specification / Description
Test Machine	Linear Reciprocating Tribometer (ASTM G133 standard)
Normal Load (N)	40, 50, and 60
Sliding Frequency (Hz)	6
Test Duration	30 minutes per sample
Lubrication Type	Mineral-based industrial oil (benchmark lubricant)
Lubricant Volume	15 mL applied uniformly on the contact surface
Test Environment	Ambient temperature (≈ 25 °C)
Measured Parameters	Coefficient of Friction (COF), Wear Scar Diameter (WSD), Physical Wear Appearance
Post-Test Analysis	Microscopic surface examination using a high-resolution optical microscope

Sample material and experiment setup

The test material used in this study was an aluminum alloy, selected for its widespread industrial application, low density, and suitability for micro-texturing processes. The samples were prepared in square plates measuring 20 mm × 20 mm, with surfaces polished to a uniform finish before texturing to minimize surface roughness variations. Surface dimples were fabricated using Laser Surface Texturing (LST), which provides high-precision and repeatability in controlling geometric parameters. Each sample was textured with elliptical dimples having a major axis of 500 µm, a minor axis of 80 µm, and depths of 100 µm, 150 µm, and 200 µm, respectively, to investigate the influence of aspect ratio on friction and wear performance. The consistent dimple spacing and geometry ensured accurate comparison between samples. After texturing, the specimens were ultrasonically cleaned in acetone to remove debris and oxide residues, then dried and stored in a desiccator before testing to prevent surface contamination. Figure 1 and Table 1 show the sample material, the experimental setup, and the parameters.

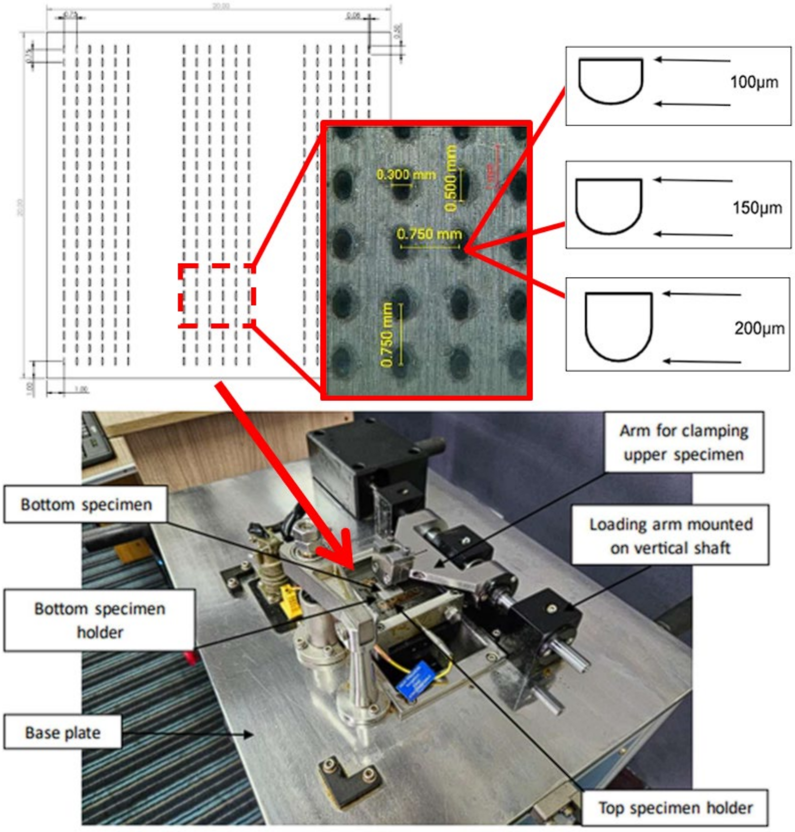


Figure 1. Sample material and experimental setup

RESULTS AND DISCUSSION

Analysis of the coefficient of friction

Based on the COF results shown in Figure 2, the 150 µm dimple depth consistently achieved the lowest friction across all applied loads, confirming its role as the optimal geometry. At 40 N, the 150 µm surface recorded a COF of about 0.097, compared to the smooth surface at 0.122, which corresponds to a 20.5% reduction. At 50 N, the 150 µm texture (≈0.096) performed even better against the smooth surface (0.130), achieving a 26.2% reduction. At 60 N, the COF for the 150 µm dimples (0.095) was lower than that of the smooth surface (0.100), resulting in a 5.0% reduction. These results demonstrate that the advantage of optimized dimples is most pronounced at medium load, while still providing benefit under light and heavy loads.

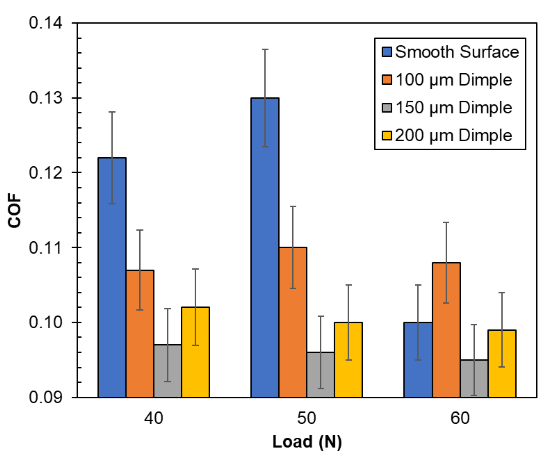


Figure 2. Coefficient of Friction for all samples at 6Hz

The superior behavior of the 150 µm dimples can be attributed to their balanced aspect ratio, which provides both lubricant retention and stable load distribution. Shallow textures at 100 µm recorded COF values around 0.107–0.110, meaning they reduced friction by only 10–15% compared to the smooth surface, but were consistently less effective than 150 µm. The deeper 200 µm dimples showed values around 0.100–0.102, giving reductions of only 8–10%. This indicates that too shallow dimples cannot retain enough lubricant, while overly deep dimples may trap oil excessively, leading to unstable lubrication. In contrast, the optimized 150 µm geometry acted as effective micro-reservoirs, releasing lubricant under pressure to maintain a thin, continuous film and minimize direct asperity contact.

These findings are consistent with previous studies. Wang et al. [5] reported that moderate dimple depths stabilize the lubricant film, resulting in significant friction reduction, whereas excessive dimple depth leads to oil starvation. Similarly,

Olofinjana et al. [13] and Cai et al. [7] emphasized that proper aspect ratios enhance hydrodynamic lift. Still, over-texturing can increase turbulence and shear, with a supporting hypothesis that an optimum dimple aspect ratio maximizes the balance between lubricant retention and hydrodynamic pressure, thereby minimizing COF under boundary or mixed lubrication conditions. The present results strongly support this hypothesis, with the 150 µm dimples providing up to 26% lower COF than smooth surfaces, making them the most effective configuration tested.

Analysis of a Wear Scar

Figure 3 shows the scar length for all samples; at 40 N, the smooth surface exhibited the shortest scar length of approximately 0.60 mm, while the 100 µm and 200 µm dimple textures recorded much longer scar lengths, around 3.20 mm and 3.35 mm, respectively. The 150 µm dimples achieved an intermediate scar length of roughly 2.40 mm. This means that the 150 µm texture reduced scar length by about 25% compared to 100 µm and 28% compared to 200 µm, indicating superior wear resistance among the textured surfaces. Although the smooth surface exhibited the lowest scar length (≈0.60 mm), this does not necessarily indicate superior wear behavior. Under the present 30-minute test, the untextured aluminum provides a continuous, flat contact, which confines the interaction to a narrow track with limited growth in the sliding direction. This produces a short-measured scar length but at the expense of higher local contact pressure and interfacial shear, reflected in the higher COF. The wear mechanism is dominated by adhesive junction formation and localized micro-ploughing within a small contact zone.

In contrast, the dimpled specimens redistribute the load around the dimple rims and locally perturb the contact geometry. This promotes partial micro-hydrodynamic support and encourages the wear track to extend over a longer distance with a more distributed stress field. As a result, the textured surfaces exhibit a longer, less severe wear track, accompanied by reduced friction. In contrast, the smooth surface presents a short, highly stressed track associated with a higher COF.

At 50 N, the 150 µm dimple depth again demonstrated competitive performance, with a scar length of about 2.58 mm, slightly higher than the 100 µm case (~2.45 mm) but significantly lower than the 200 µm case (~3.27 mm). Compared to the deepest dimples, the 150 µm depth reduced wear by approximately 21%, confirming that an optimal dimple depth helps balance lubricant retention and surface load distribution. The smooth surface showed a scar length of about 0.71 mm, which was over 70% lower than that of the textured surfaces. However, this reduction may be misleading, as smooth surfaces under high load tend to experience unstable lubrication regimes, leading to higher COF and possible seizure during prolonged operation.

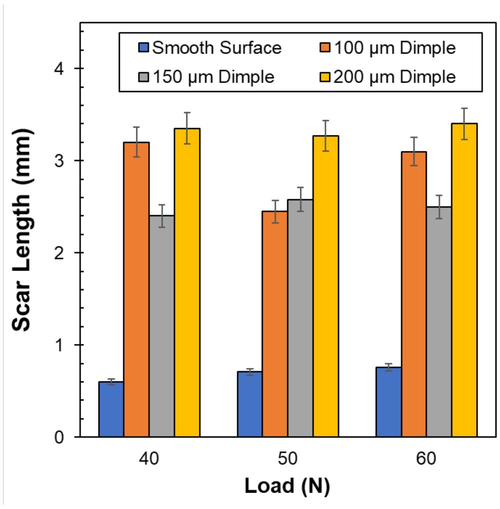


Figure 3. Scar length of all samples

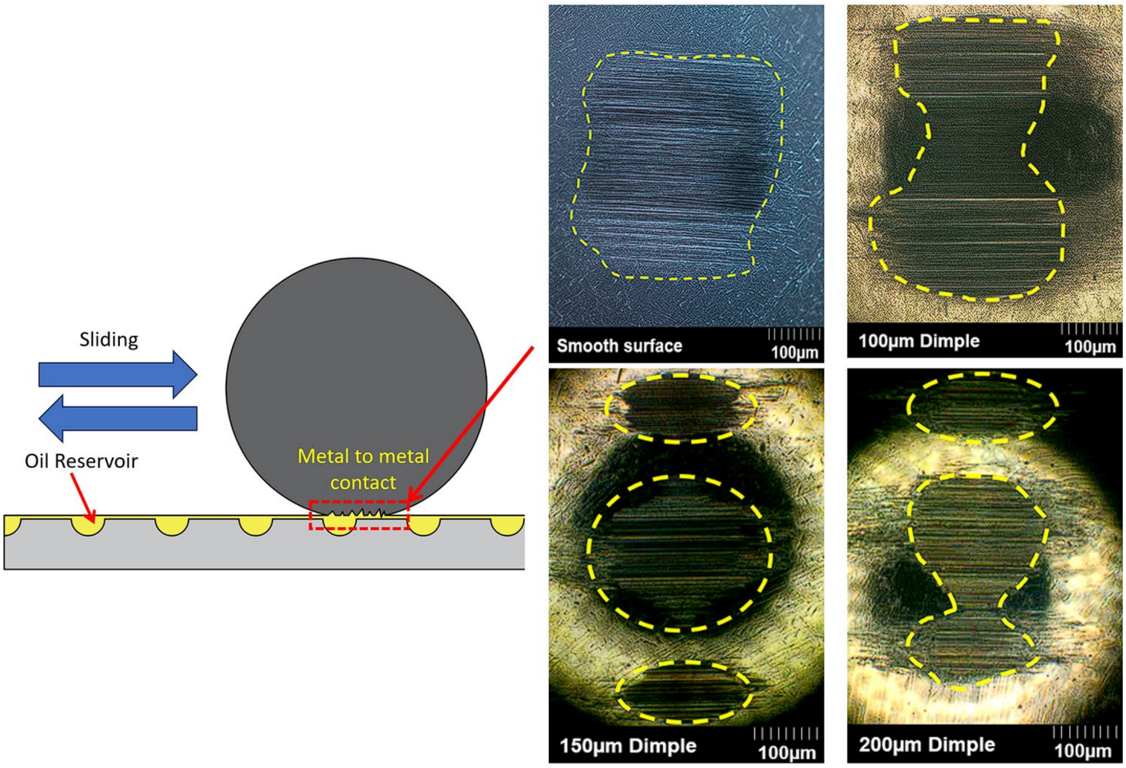


Figure 4. Analysis of the wear scar on the ball bearing

At 60 N, scar lengths increased slightly for most samples, with the 200 µm dimples performing the worst (~3.40 mm) and the 150 µm dimples maintaining a moderate value (~2.50 mm). Compared to the 200 µm case, the 150 µm depth reduced wear by around 26%, reinforcing the idea that excessive dimple depth accelerates wear by causing lubricant instability. Literature supports this observation: Pradhan et al. [10] reported that an-optimal dimple depth minimizes wear by improving lubricant entrapment and micro-hydrodynamic pressure, while overly deep textures increase localized stress concentrations.

The wear scars in Figure 4 reveal the strong influence of surface texturing depth on the tribological response of the aluminium alloy under lubricated reciprocating motion. The smooth surface exhibited a large, irregular scar dominated by continuous grooves, reflecting direct asperity contact due to insufficient lubricant entrainment. In comparison, the 100 µm dimpled specimen showed a more confined scar with a constricted, waist-like profile, suggesting that although some lubrication pockets formed, the shallow dimples could not retain adequate lubricant. This resulted in localized boundary lubrication, producing partial improvement over the smooth surface.

The 150 µm dimpled surface displayed the smallest and most uniform wear scars, which directly correspond to its lowest coefficient of friction. The mechanism can be attributed to an optimal dimple aspect ratio that balances lubricant storage and hydrodynamic pressure generation. During sliding, the dimples act as micro-reservoirs, retaining lubricant and releasing it into the contact zone under load. This not only reduces the frequency of metal-to-metal contact but also promotes a stable mixed lubrication regime in which load is carried partly by the lubricant film and partly by the asperities. Additionally, the dimple geometry helps evenly redistribute stresses across the contact, reducing localized wear and preventing surface crack initiation.

In contrast, the 200 µm dimpled surface produced elongated, fragmented wear scars, indicating an unstable lubrication regime. The excessive depth of the dimples led to over-retention of lubricant and air entrapment, which can generate cavitation and flow turbulence during reciprocation [4]. This destabilizes the film, creating alternating regions of lubrication and starvation, thereby increasing surface stress concentration and irregular wear patterns [11]. Overall, the scar morphologies indicate that the 150 µm depth is the most effective geometry, as it minimizes COF and wear by sustaining a continuous, balanced lubrication film. In contrast, the smooth, shallow, and overly deep surfaces deviate from this optimum.

Analysis of Surface Roughness

The surface roughness profiles demonstrate that laser surface texturing significantly modifies the plateau regions of the aluminum alloy, as shown in Figure 5. The smooth specimen-

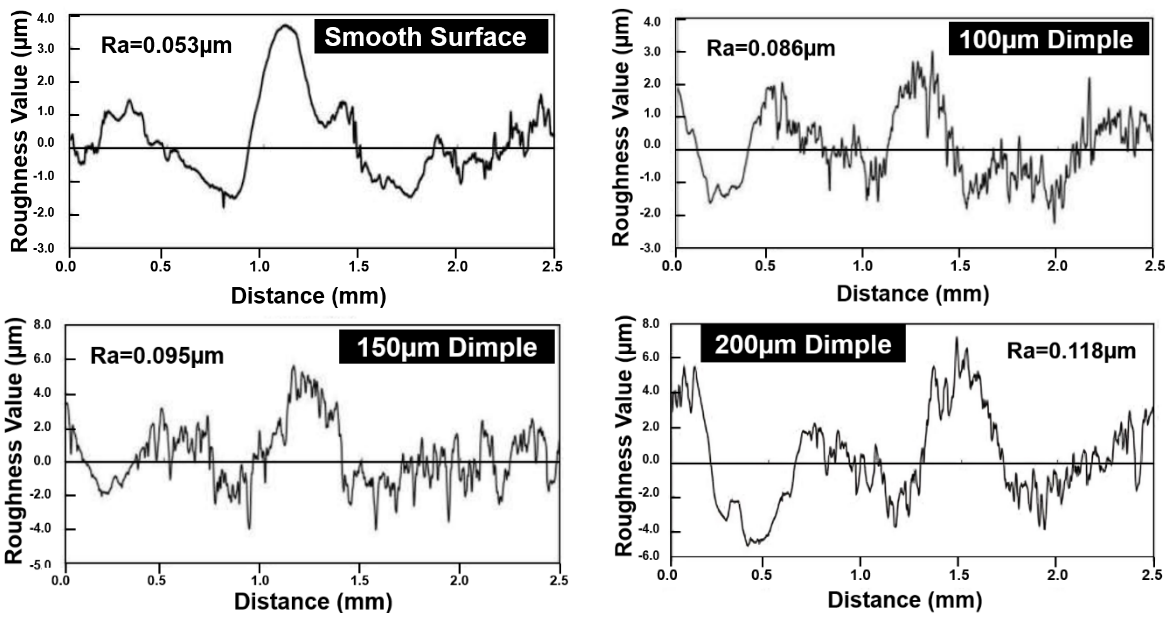


Figure 5. Analysis of surface roughness for all samples.

exhibited the lowest Ra value of 0.053 µm, consistent with polished surfaces prepared for tribological testing, ensuring minimal asperity interference before sliding. In contrast, the 100 µm, 150 µm, and 200 µm dimpled surfaces showed progressively higher roughness values of 0.086 µm, 0.095 µm, and 0.118 µm, respectively. This increase reflects the formation of micro-rims, melt re-solidification, and heat-affected zones around the dimples, phenomena well-documented in LST processes. The trend indicates that deeper dimples lead to more pronounced surface disturbances, directly raising the measured Ra values.

The surface roughness profiles demonstrate that LST significantly modifies the plateau regions of the aluminium alloy. The smooth specimen exhibited the lowest Ra value of 0.053 µm, consistent with polished surfaces prepared for tribological testing, ensuring minimal asperity interference before sliding. In contrast, the 100 µm, 150 µm, and 200 µm dimpled surfaces showed progressively higher roughness values of 0.086 µm, 0.095 µm, and 0.118 µm, respectively. This increase reflects the formation of micro-rims, melt re-solidification, and heat-affected zones around the dimples, phenomena well-documented in LST processes. The trend indicates that deeper dimples lead to more pronounced surface disturbances, directly raising the measured Ra values.

These surface roughness findings are strongly correlated with the friction and wear behaviors observed earlier. The 150 µm dimple depth, with a measured surface roughness of Ra = 0.095 µm, produced the most uniform wear scars and achieved the lowest coefficient of friction, confirming that an intermediate roughness level provides the optimal balance between surface modification and lubrication stability. Shallow textures (100 µm) lacked the necessary oil storage capacity, while deeper textures (200 µm) introduced turbulence and asperity-induced stress. The findings support the idea put forward by Zhang et al. [14] and Lazov et al. [15] that there is a narrow window of aspect ratios that guarantees the greatest tribological benefits. So, the Ra values obtained not only show how much the surface changed due to LST, but also provide evidence that a 150 µm dimple depth is better for tribology, as it helps maintain a steady lubrication regime.

Conclusion

This study demonstrates that the aspect ratio of laser-textured dimples plays a decisive role in governing the tribological performance of aluminium alloy under lubricated linear reciprocating motion. Among the tested geometries, the 150 µm dimple depth consistently provided the best balance between lubricant retention and load support, resulting in superior performance across multiple metrics. Specifically, the 150 µm dimples reduced the coefficient of friction (COF) by 20.5% at 40 N, 26.2% at 50 N, and 5.0% at 60 N compared to smooth surfaces, highlighting their effectiveness in maintaining stable mixed lubrication. Similarly, wear resistance improved markedly: the 150 µm depth reduced wear scar length by 25–28% compared to shallow (100 µm) and deep (200 µm) dimples, and by 21–26% compared to the deepest geometry across all loads.

Surface roughness analysis confirmed that moderate texturing (Ra ≈ 0.095 µm) provides the optimal compromise between surface alteration and tribological benefit. In contrast, shallow textures (100 µm) lacked sufficient lubricant storage capacity, and whereas textures (200 µm) induced turbulence, cavitation, and stress concentration, leading to scar morphologies further validated these findings, showing that the 150 µm dimples generated the most uniform and confined wear tracks, while excessively deep textures produced gated and unstable wear tracks.

Overall, the findings substantiate the hypothesis that only a moderate dimple aspect ratio maximizes the synergy between lubricant retention and hydrodynamic pressure. By achieving up to 26% friction reduction and 28% wear improvement, the 150 µm configuration can be considered the optimal design for enhancing the efficiency and durability of aluminium sliding components.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Funding Declaration

There is no funding available

Data Availability

Data will be made available on request

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