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Research Article

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Posted Date: September 4th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10754824/v1>

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Additional Declarations: No competing interests reported.

Geometry-controlled effects of circular and semi-circular laser textures on the tribological behavior of G13Cr14Co12Mo5Ni2 bearing steel

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Abstract: This study investigates the influence of texture geometry on the tribological performance of G13Cr14Co12Mo5Ni2 bearing steel by comparing circular and semi-circular laser textures with nearly identical projected areas and depths. The textures were fabricated using ultraviolet femtosecond laser processing, and their tribological behaviors were evaluated through ball-on-disk tests under dry sliding and PAO6 lubrication conditions. Surface morphology, wear characteristics and elemental distributions were analyzed by three-dimensional profilometry and SEM–EDS, while a thin-film lubrication model was developed to clarify the geometric effect on local pressure generation. Under PAO6 lubrication at 30 N, the semi-circular texture achieved the lowest friction coefficient 0.11–0.13 and specific mass wear rate $2.98 \times 10^{-7} \text{ g} \cdot \text{N}^{-1} \cdot \text{m}^{-1}$. Compared with the circular texture, the semi-circular geometry exhibited improved debris accommodation, reduced ploughing damage and enhanced texture-edge integrity. Numerical analysis revealed that the asymmetric geometry generated stronger local positive-pressure responses, promoting lubricant redistribution and load support. These findings demonstrate that texture asymmetry provides an effective strategy for improving lubricated tribological performance by integrating lubricant retention, debris management and pressure regulation.

Keywords: surface texture; bearing steel; semi-circular texture; PAO6 lubrication; friction and wear

1. Introduction

Friction and wear are major causes of energy loss and surface failure in bearings, gears and other sliding components. Surface texturing has been extensively investigated as an effective approach for improving interfacial lubrication and tribological performance by introducing engineered microstructures into contacting surfaces [1–4]. Micro-pits and grooves can act as lubricant reservoirs and debris traps, interrupt continuous asperity contact and modify local lubricant flow, thereby reducing friction and wear under appropriate operating conditions [1–3]. However, the effectiveness of surface texturing strongly depends on texture geometry, depth, density, orientation, lubrication regime and operating conditions [1,4,5]. Therefore, understanding the relationship between texture geometry and lubrication behavior is essential for the rational design of textured surfaces[6,7].

Circular dimples are among the most widely investigated surface textures because of their simple geometry, ease of fabrication and good parameter controllability. They can retain lubricant and accommodate wear debris and, under suitable film thickness and sliding conditions, induce local hydrodynamic pressure through variations in lubricant-film thickness [8–10]. Nevertheless, their centrosymmetric geometry provides limited directional regulation of lubricant flow, and the pressure-generating capability may remain weak when an effective converging gap cannot be established along the sliding direction [6,11]. Consequently, texture shape and orientation have increasingly become important design variables for improving hydrodynamic lubrication performance[12,13].

Directional and asymmetric textures provide an alternative approach to regulating lubricant flow. Previous studies have demonstrated that asymmetric structures, including chevron-, wedge- and groove-type textures, can modify lubricant flow paths and pressure distributions by introducing geometric convergence along the sliding direction [14–16]. Numerical investigations have shown that texture geometry and orientation significantly influence hydrodynamic pressure generation and load-carrying capacity [17–20]. In particular, directional textures can promote local pressure accumulation near the inlet region and provide stronger pressure regulation compared with conventional symmetric textures [21,22]. These findings indicate that

geometric asymmetry may provide an additional mechanism for improving lubrication performance beyond the conventional lubricant-storage and debris-trapping effects of surface textures[23].

The tribological performance of textured surfaces is also strongly influenced by lubrication conditions. Laser surface texturing has been reported to improve tribological functionality by modifying the contact interface and lubricant distribution [24,25]. Experimental studies under oil-lubricated and starved lubrication conditions further demonstrated that texture geometry interacts with lubricant supply and contact conditions, resulting in different friction and wear responses [26]. Therefore, the advantages of surface textures should be evaluated by considering both geometric characteristics and lubrication environments.

Despite these advances, isolating the intrinsic effect of texture geometry remains difficult because texture shape is frequently varied simultaneously with depth, area ratio, density or arrangement [1,4,5]. As a result, the individual contribution of morphology to lubrication pressure generation and friction behavior remains insufficiently understood. Direct experimental–numerical comparisons between symmetric and asymmetric textures under approximately identical geometric conditions are still limited[27,28].

In the present study, circular and semi-circular laser textures with nearly identical projected areas and identical depths were fabricated on G13Cr14Co12Mo5Ni2 bearing steel to isolate the effect of texture geometry. The projected areas of the circular and semi-circular textures were 0.754 and 0.748 mm², respectively, with an area difference of less than 1%, while both textures had a depth of 25 μm. Ball-on-disk tribological tests under dry sliding and PAO6 lubrication were combined with three-dimensional surface characterization, SEM–EDS analysis and thin-film lubrication simulation. The friction and wear behavior, worn-surface characteristics and local positive-pressure responses were systematically compared. The objective was to determine whether the asymmetric semi-circular geometry could retain the lubricant-storage and debris-accommodation functions of conventional textures while promoting local pressure redistribution, thereby providing a basis for

geometry-oriented optimization of laser-textured bearing surfaces.

2. Methodology

2.1. Sample material and texture preparation

The material for the test disk is G13Cr14Co12Mo5Ni2 bearing steel, which belongs to the C–Cr–Co–Mo–Ni series of high-temperature stainless bearing steel. Its chemical composition is shown in Table 1. To facilitate the operation of the friction and wear testing machine, cut a disc with a diameter of 50.8 mm and a thickness of 3.18 mm.

Table 1

Chemical composition of G13Cr14Co12Mo5Ni2 bearing steel (wt.%).

Element	C	Cr	Co	Mo	Ni	Fe
Content/wt.%	0.13	14.0	12.0	4.5	2.0	balance

Before laser texturing, the specimens were ground and polished to minimize the influence of initial surface topography. Circular and semi-circular textures were designed with nearly identical projected areas and the same depth to isolate the effect of texture geometry. The circular and semi-circular textures had radii of 0.49 and 0.69 mm and projected areas of 0.754 and 0.748 mm², respectively, with an area difference of less than 1%; both had a depth of 25 µm. This design enabled a geometry-focused comparison of tribological behavior and local hydrodynamic pressure response under approximately equal-area and equal-depth conditions.

2.2. Preparation of surface textures

Both circular and semi-circular textures were fabricated using ultraviolet femtosecond laser processing [29], and the laser texturing process is schematically illustrated in Fig. 1(a). During the processing, the laser parameters were set as shown in Table 2. The design depth of both textures was 25 µm.

To ensure a reasonable comparison, the geometric design and arrangement of the circular and semi-circular textures are illustrated in Fig. 1(b). Both textures were

arranged in regular arrays. The straight edges of the semi-circular texture were oriented towards the upstream direction, and the curved edges were located on the downstream side, to enhance the geometric asymmetry in the sliding direction [31,32].

Table 2

Laser surface texture processing parameters.

Parameter	Symbol	Numerical value	Unit
Laser output power	P	10	W
Repetition frequency	f	2000	Hz
Scanning speed	v	200	mm/s
Number of pulses	N	1000	—
Texture depth	d	25	μm
Spot diameter	D	13	μm
Scan pitch	h	0.005	μm
Circular texture radius	r _c	0.49	mm
Semi-circular texture radius	r _s	0.69	mm

After the laser texturing process was completed, Brinell hardness tests were conducted on the samples to characterize their actual hardness state before the friction test. The Brinell hardness tests were performed according to GB/T 231.1-2018, and the testing machine was verified and calibrated according to GB/T 231.2-2022. The measured hardness values are summarized in Table 3.

Table 3

Brinell hardness test results of samples after laser processing.

Sample Number	Test 1	Test 2	Test 3	average
CSCL2604001	252.0HB5/750	246.9HB5/750	261.0HB5/750	253.3HB5/750

As shown in Table 3, the measured hardness values were 252.0, 246.9 and 261.0 HB5/750, with an average hardness of 253.3 HB5/750. This result indicates that the samples maintained a relatively stable hardness level after laser processing, providing a consistent material hardness basis for the subsequent ball-on-disk friction tests.

2.3. Tribological tests

After laser processing, the samples were ultrasonically cleaned with anhydrous ethanol to remove residual particles and surface contaminants, and then dried with hot air. Before the friction test, the disk surfaces and Si₃N₄ balls were wiped again with anhydrous ethanol to reduce the influence of surface contamination on the friction

results.

The friction tests were conducted using a ball-on-disk contact configuration according to the general principle of laboratory sliding wear tests. The Rtec tribometer system and the corresponding ball-on-disk friction and wear configuration are shown in Fig. 1(c,d). In the experiment, a Si_3N_4 ball with a diameter of 6 mm was used as the upper counterbody, and a G13Cr14Co12Mo5Ni2 bearing steel disk served as the lower specimen. The disk specimen had a diameter of 50.80 mm, a thickness of 3.18 mm, and a wear track radius of 8 mm. During the lubricated tests, PAO6 oil was uniformly applied to the disk surface. The disk was rotated at 200 r/min, and the test duration was 1800 s, with normal loads of 15 N and 30 N, respectively.

To distinguish the effects of surface texture and lubrication condition, tribological tests were conducted under dry sliding at 15 N and 30 N, and under PAO6 lubrication at 30 N. The comparison among the smooth, circular-textured and semi-circular-textured surfaces under PAO6 lubrication at 30 N was used to evaluate the additional effect of texture geometry on the basis of oil lubrication [33]. The friction coefficient curves shown in this study are representative curves obtained under the corresponding test conditions. Repeated tests should be further conducted in future work to evaluate the statistical reproducibility of the friction results.

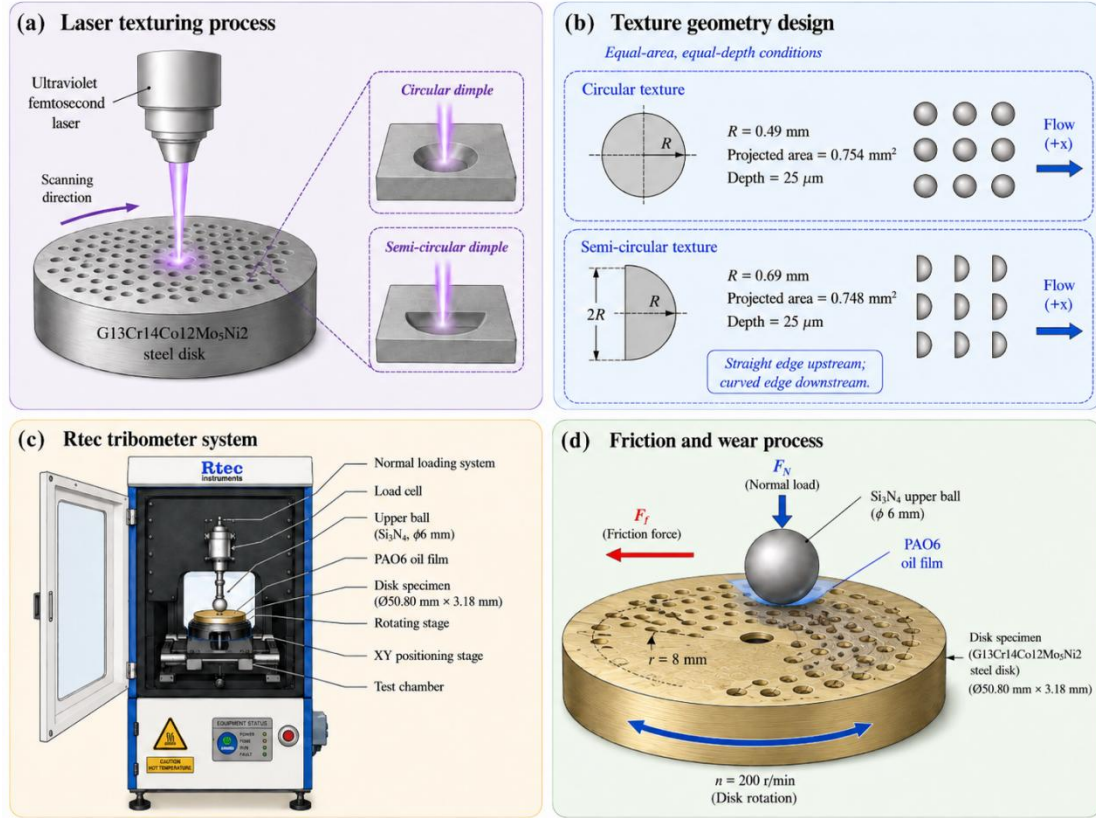


Fig. 1. Schematic illustration of laser texture fabrication, texture geometry design, experimental setup and ball-on-disk friction and wear process: (a) laser texturing process; (b) texture geometry design; (c) Rtec ball-on-disk tribometer system; and (d) ball-on-disk friction and wear process

2.4. Surface characterization and wear quantification

After the tribological tests, the worn surfaces were characterized by scanning electron microscopy SEM, energy-dispersive X-ray spectroscopy EDS, and three-dimensional surface profilometry. SEM was used to examine characteristic wear features, while EDS was employed to analyze the elemental distributions in representative worn regions. Fe, Cr, Co, Mo, and Ni were used to characterize the exposed steel matrix, whereas O and Si were examined as indicators of possible oxidation and material transfer from the Si_3N_4 counter ball, respectively. The C signal was considered only as a reference because of possible contributions from lubricant residues, contamination, or wear debris.

Three-dimensional surface profilometry was used to characterize the wear-scar topography and obtain two-dimensional cross-sectional profiles [15,34]. Wear width,

maximum depth, and surface fluctuations were evaluated, and the wear volume was estimated as:

$$V = \iint_A \max[z_{\text{ref}} - z(x, y), 0] dA \quad (1)$$

where V is the wear volume, z_{ref} is the reference height of the unworn surface, $z(x, y)$ is the measured surface height, and A is the integration area. Because the original texture cavities may affect the calculated volume loss, profilometry was mainly used for morphological comparison, whereas mass loss was used for quantitative wear evaluation.

The specimens were cleaned, dried, and weighed before and after the tribological tests [18]. The specific mass wear rate k_m was calculated as :

$$k_m = \frac{\Delta m}{F_N s} \quad (2)$$

where Δm is the mass loss g, F_N is the normal load N, and s is the sliding distance m. For a wear-track radius of 8 mm, rotation speed of 200 r/min, and test duration of 1800 s, the sliding distance was:

$$s = 2\pi r N = 2\pi \times 0.008 \times 6000 \approx 301.59m \quad (3)$$

where r is the wear track radius and N is the total number of revolutions.

2.5. Numerical simulation

To investigate the effect of texture geometry on local lubrication pressure, a two-dimensional thin-film lubrication model was established in COMSOL Multiphysics. A $2.17\text{mm} \times 2.17\text{mm}$ texture unit was used as the computational domain, including smooth, circular-textured and semi-circular-textured surfaces. The upper surface was represented by the equivalent spherical gap of a Si_3N_4 ball with radius $R=3$ mm. The local film thickness was defined as

$$h(x, y) = h_{\min} + \frac{x^2 + y^2}{2R} + h_{\text{tex}}(x, y) \quad (4)$$

where $h_{\min}$ is the minimum film thickness and $h_{\text{tex}}(x, y)$ represents the additional film thickness introduced by the texture cavity. The values of $h_{\min}$ were 0.5, 1 and 2 μm . The circular and semi-circular texture radii were 0.49 and 0.69 mm, respectively, with an identical depth of 25 μm . A smooth-step transition with a width

of 10 μm was applied at the texture boundaries to improve numerical stability. For the semi-circular texture, the straight edge faced upstream and the curved edge downstream.

The surrounding boundaries were assigned ambient pressure $p=0$ Pa, while relative sliding was imposed along the $+x$ direction. PAO6 oil was modeled as an incompressible Newtonian fluid with a density of 828 kg/m^3 and a dynamic viscosity of $0.0253 \text{ Pa}\cdot\text{s}$, and viscosity variation due to frictional heating was neglected. Because cavitation was not explicitly modeled, only the positive-pressure component was used for quantitative comparison:

$$p^+ = \max(p, 0) \quad (5)$$

The integrated positive-pressure load and pressure centroid were calculated as

$$W = \int_A p^+ dA \quad (6)$$

$$x_c = \frac{\int_A x p^+ dA}{\int_A p^+ dA} \quad (7)$$

$$y_c = \frac{\int_A y p^+ dA}{\int_A p^+ dA} \quad (8)$$

Where A is the computational domain, W represents the integrated positive-pressure contribution, and x_c and y_c are the coordinates of the pressure centroid.

The domain was discretized using a free triangular mesh with local refinement near texture edges and high-pressure-gradient regions. Based on the grid-independence study, the fine mesh was adopted, with maximum and minimum element sizes of 10 and $1.5 \mu\text{m}$, respectively, a maximum element growth rate of 1.2 and a curvature factor of 0.2. Steady-state solutions were obtained for $h_{\min} = 0.5, 1$ and $2 \mu\text{m}$. The model was intended to compare the relative pressure-generation and load-supporting tendencies of different texture geometries rather than reproduce the full elastic to hydrodynamic contact under the experimental load. Accordingly, W represents only the local positive-pressure contribution within the selected computational domain and should not be directly compared with the externally

applied load.

2.6. Grid-independence verification

To evaluate the dependence of the numerical results on mesh density, grid-independence verification was conducted for the smooth surface, circular-textured surface and semi-circular-textured surface, with $h_{\min}=0.5 \mu\text{m}$ selected as the representative condition. The sensitivity of the numerical results to mesh density was evaluated by comparing the maximum positive pressure $P_{\max}$ and the integrated load-carrying capacity W under different mesh levels. The change rates for smooth surfaces and circular textures are calculated based on the fine grid results; due to the large local pressure gradient of semi-circular textures, ultra-fine grid calculations are further supplemented, and the change rates are calculated based on the ultra-fine grid results.

The relative change rates of the maximum positive pressure and integrated load-carrying capacity were calculated according to Eqs. (1) and (2), respectively:

$$\delta_p = \frac{|P_{\max,i} - P_{\max,\text{ref}}|}{P_{\max,\text{ref}}} \times 100\% \quad (9)$$

$$\delta_w = \frac{|W_i - W_{\text{ref}}|}{W_{\text{ref}}} \times 100\% \quad (10)$$

where $P_{\max,i}$ and W_i are the maximum positive pressure and integrated load-carrying capacity obtained using the current mesh, respectively, while $P_{\max,\text{ref}}$ and W_{ref} are the corresponding values obtained using the reference mesh.

Table 4

Grid-independence verification results at $h_{\min}=0.5\mu\text{m}$.

Model	Mesh level	Maximum element size/ μm	Minimum element size/ μm	Degrees of freedom	P_{max}/Pa	W/N	$\delta_P/\%$	$\delta_W/\%$
Smooth surface	Coarse	30	5	26773	2.6907E5	0.003606	1.04	0.09
Smooth surface	Medium	20	3	59425	2.7228E5	0.0036083	0.14	0.03
Smooth surface	Fine	10	1.5	234713	2.7190E5	0.0036094	0	0
Circular texture	Coarse	30	5	26773	719.25	2.9854E-4	0.09	0.07
Circular texture	Medium	20	3	59425	718.87	2.9841E-4	0.04	0.02
Circular texture	Fine	10	1.5	234713	718.6	2.9834E-4	0	0
Semi-circular texture	Coarse	30	5	26773	2.1607E5	0.0029775	8.62	5.63
Semi-circular texture	Medium	20	3	59425	2.2165E5	0.0030631	6.26	2.91
Semi-circular texture	Fine	10	1.5	234713	2.3539E5	0.0031414	0.45	0.43
Semi-circular texture	Extra-fine	7	1	507969	2.3645E5	0.003155	0	0

As shown in Table 4 and Fig. 2, the smooth surface and circular-textured models were insensitive to mesh density. When the grid is refined from medium to fine, the change rates of $P_{\max}$ and W for both are less than 0.2%, indicating that a medium or finer grid can already obtain stable calculation results. In contrast, the semi-circular texture model, due to the presence of straight and curved boundaries, has a larger local pressure gradient and is more sensitive to the grid. To further verify the convergence of the semi-circular model, an ultra-fine grid was added for calculation in This study. The results show that when the grid is further refined from fine to ultra-fine, the change rates of $P_{\max}$ and W for the semi-circular texture model are only 0.45% and 0.43% respectively, indicating that the fine-mesh results had essentially converged. Considering both computational accuracy and efficiency, the fine mesh was adopted for subsequent simulations.

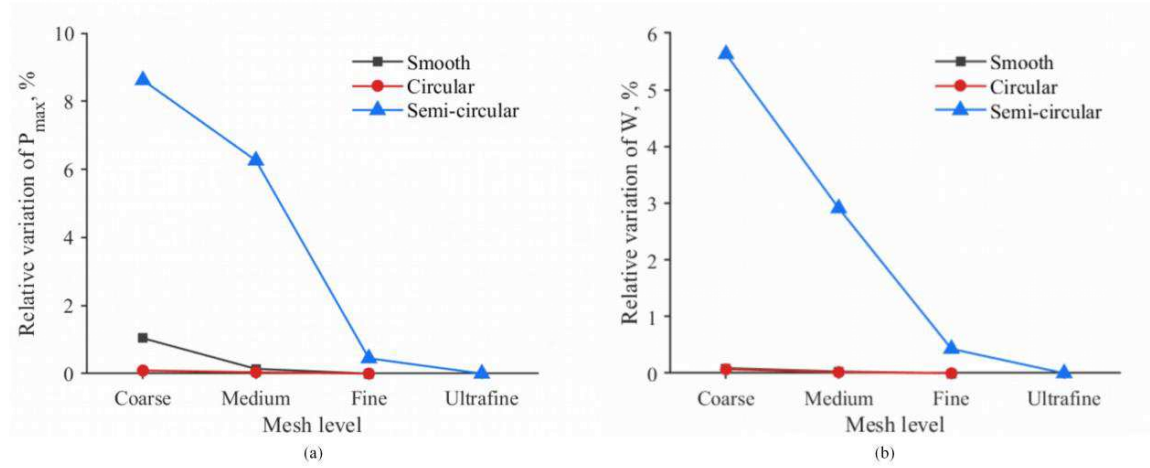


Fig. 2. Variations in $P_{\max}$ and W for the three surface models under different mesh levels: (a) $P_{\max}$ and (b) W

3. Results and discussion

3.1 Friction coefficient evolution

As shown in Fig. 3, under dry sliding at 15 N, the smooth surface rapidly reached a high-friction steady state of approximately 0.76-0.78, whereas the circular and semi-circular-textured surfaces stabilized at lower values of about 0.63-0.67 and 0.65-0.70, respectively. When the load increased to 30 N, the smooth surface still

exhibited the highest friction coefficient 0.66-0.69, while the circular and semi-circular textures decreased to approximately 0.60-0.63 and 0.58-0.61. These results indicate that surface texturing can reduce friction under dry sliding by interrupting continuous asperity contact and accommodating wear debris, although the absence of lubricant limits the overall friction-reduction effect [35,36].

PAO6 lubrication markedly reduced the friction coefficients of all surfaces. At 30 N, the smooth, circular-textured and semi-circular-textured surfaces exhibited friction coefficients of approximately 0.13-0.15, 0.12-0.14 and 0.11-0.13, respectively. The semi-circular texture showed the lowest and most stable friction response, suggesting that the asymmetric geometry was more favorable for lubricant retention, directional redistribution and local pressure regulation within the contact interface [37,38].

Overall, the friction behavior was primarily governed by lubrication condition, while texture morphology further influenced the magnitude and stability of friction [39,40]. Under dry sliding, the main contribution of the textures was debris accommodation and interruption of continuous solid contact; under PAO6 lubrication, the textures additionally functioned as lubricant reservoirs and local flow-regulating units. The superior performance of the semi-circular texture therefore reflects the combined effect of lubricant retention and geometry-induced interfacial flow regulation .

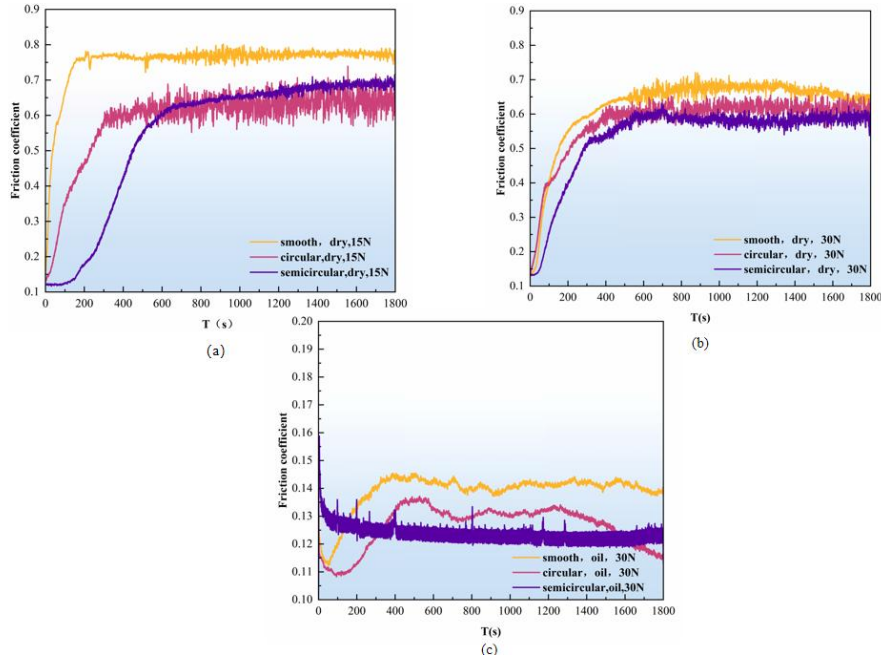


Fig. 3. Friction coefficient curve (a) 15N dry sliding coefficient curve; (b) 30N dry sliding coefficient curve; (c) 30N oil friction coefficient curve.

3.2 Wear mass loss and specific mass wear rate

Fig. 4 summarizes the mass loss and specific mass wear rate of smooth, circular-textured and semi-circular-textured surfaces under dry sliding and PAO6 lubrication conditions. Under dry sliding at 15 N, the smooth surface exhibited the lowest specific mass wear rate of $2.87 \times 10^{-7} \text{ g} \cdot \text{N}^{-1} \cdot \text{m}^{-1}$, whereas the circular and semi-circular textured surfaces showed slightly higher values of 4.75×10^{-7} and $4.35 \times 10^{-7} \text{ g} \cdot \text{N}^{-1} \cdot \text{m}^{-1}$, respectively. This indicates that although surface textures can reduce friction by interrupting direct asperity contact, their cavities and edges may introduce additional stress concentration and local instability under low-load dry sliding conditions.

When the normal load increased to 30 N, the wear rates of all specimens increased due to intensified contact stress and material removal. However, both textured surfaces exhibited lower wear rates than the smooth surface, with reductions of approximately 15% and 17% for circular and semi-circular textures, respectively. The improved wear resistance can be attributed to the ability of texture cavities to accommodate wear debris and alleviate repeated abrasive interaction during sliding.

Under PAO6 lubrication at 30 N, all surfaces exhibited significantly reduced wear rates compared with dry sliding conditions. The semi-circular-textured surface achieved the lowest specific mass wear rate of $2.98 \times 10^{-7} \text{ g} \cdot \text{N}^{-1} \cdot \text{m}^{-1}$, followed by the circular texture and smooth surface. The superior wear performance of the semi-circular texture is mainly associated with its asymmetric geometry, which promotes lubricant retention, debris accommodation and local lubricant redistribution. These results demonstrate that texture geometry plays an important role in determining wear behaviour, particularly under lubricated conditions.

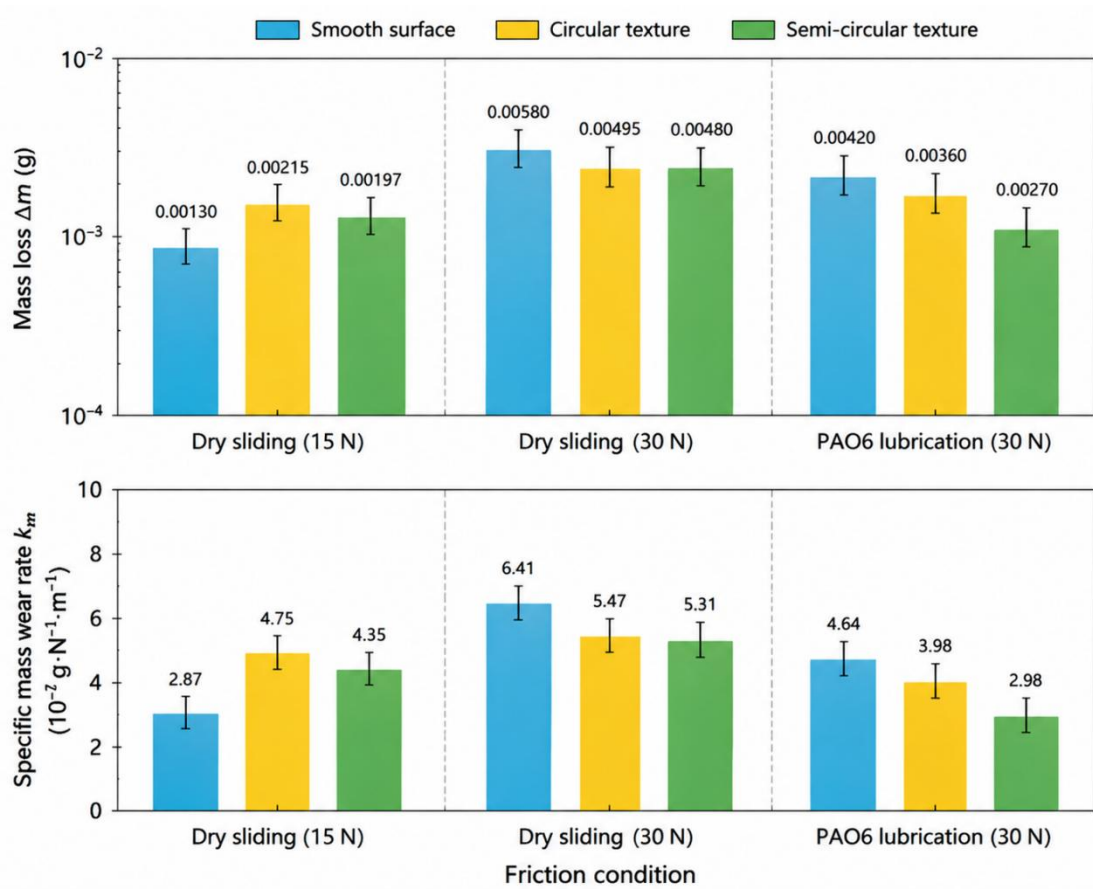


Fig. 4. Comparison of mass loss and specific mass wear rate of smooth, circular-textured and semi-circular-textured surfaces under dry sliding and PAO6 lubrication conditions.

3.3 Wear scar morphology and profile analysis under different friction conditions

The three-dimensional wear morphologies and corresponding cross-sectional profiles of the circular-textured, semi-circular-textured and smooth surfaces under

different tribological conditions are presented in Figs. 5-7, respectively. Under PAO6 lubrication at 30 N, the wear scars were generally less severe than those obtained under dry sliding. The smooth surface exhibited a continuous wear track with visible ploughing, indicating that local asperity contact persisted despite the presence of the lubricant. In contrast, characteristic cavities remained within the wear tracks of both textured surfaces, suggesting that the textures provided additional spaces for lubricant retention and wear-debris accommodation[41]. Notably, the semi-circular-textured surface exhibited relatively moderate surface fluctuations and retained texture features, indicating a more favorable lubricated contact state. These observations are consistent with its lower friction coefficient and specific mass wear rate under PAO6 lubrication.

Under dry sliding at 30 N, pronounced grooves, surface undulations and localized material removal were observed for all three surfaces, indicating intensified abrasive and adhesive wear in the absence of an oil film. The corresponding cross-sectional profiles also exhibited greater height fluctuations than those under PAO6 lubrication. Although the circular and semi-circular cavities could still accommodate part of the wear debris and interrupt continuous solid-to-solid contact, their protective effect was limited without lubricant replenishment. Local geometric discontinuities at the texture boundaries may additionally increase contact fluctuations and contribute to localized damage. Nevertheless, the textured surfaces retained characteristic cavity features within the wear tracks, supporting their role in modifying the local contact and debris distribution during sliding.

At 15 N under dry sliding, the wear damage was generally reduced compared with that at 30 N, demonstrating the influence of normal load on surface material removal. The three-dimensional morphologies and cross-sectional profiles show that increasing the load intensified surface deformation and profile fluctuations, whereas PAO6 lubrication produced a more pronounced reduction in wear damage than simply decreasing the normal load. Overall, the results in Figs. 5-7 demonstrate that the wear behavior of G13Cr14Co12Mo5Ni2 bearing steel is governed by the coupled effects of

lubrication condition, normal load and texture geometry. Surface texturing provides debris-accommodation and contact-interruption functions under dry sliding, while under PAO6 lubrication it additionally facilitates lubricant retention and local interfacial regulation. The comparatively mild wear characteristics of the semi-circular texture further indicate the potential advantage of asymmetric texture geometry under lubricated sliding.

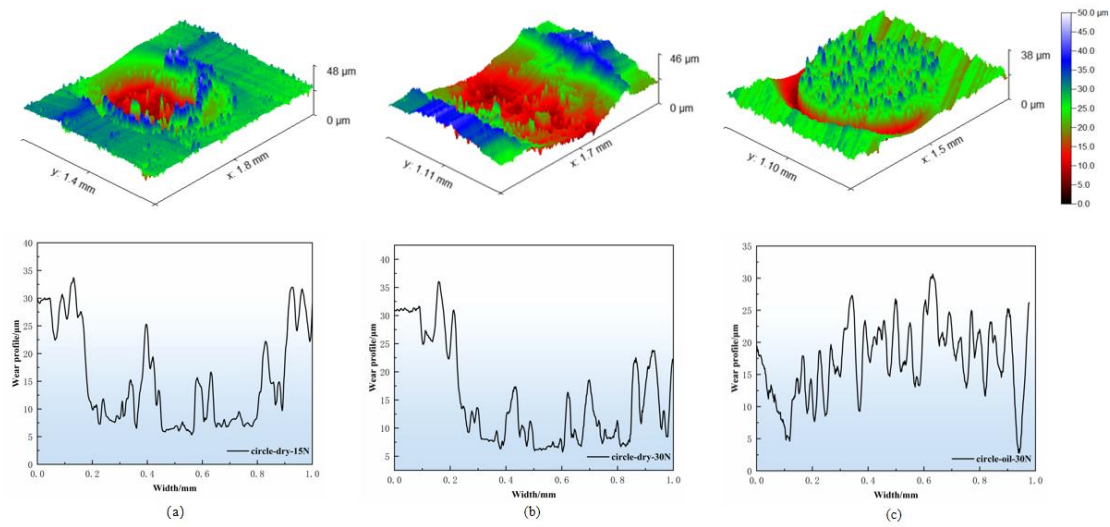


Fig. 5. Three-dimensional wear morphologies and corresponding cross-sectional profiles of the circular-textured surface under different tribological conditions: (a) dry sliding at 15 N; (b) dry sliding at 30 N; and (c) PAO6-lubricated sliding at 30 N.

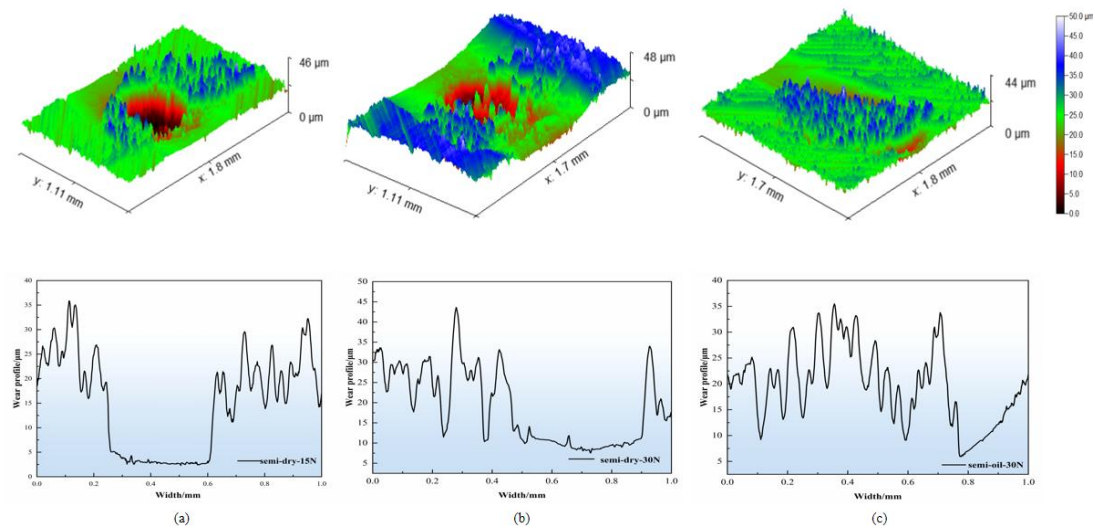


Fig. 6. Three-dimensional wear morphologies and corresponding cross-sectional profiles of the

semi-circular-textured surface under different tribological conditions: (a) dry sliding at 15 N; (b) dry sliding at 30 N; and (c) PAO6-lubricated sliding at 30 N.

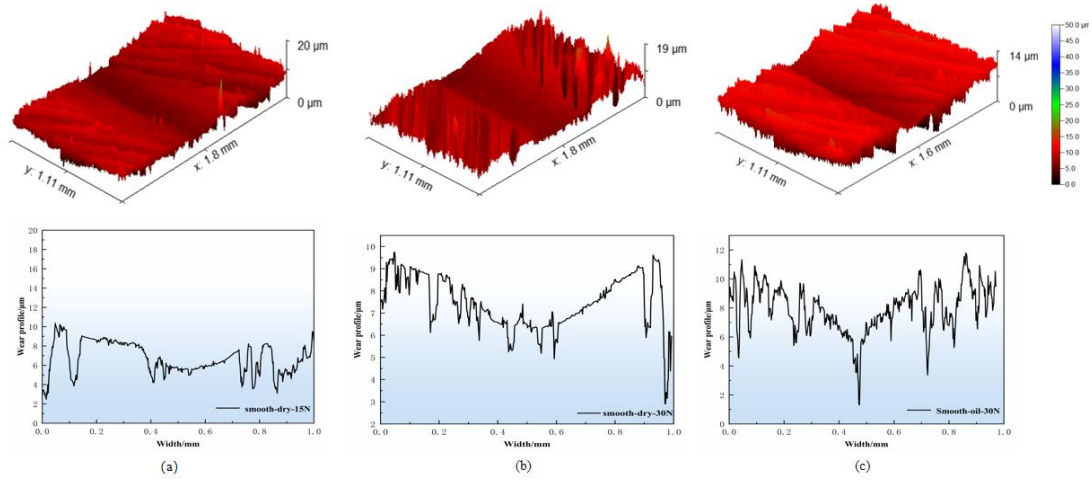


Fig. 7. Three-dimensional wear morphologies and corresponding cross-sectional profiles of the smooth surface under different tribological conditions: (a) dry sliding at 15 N; (b) dry sliding at 30 N; and (c) PAO6-lubricated sliding at 30 N.

3.4 SEM–EDS analysis of worn surfaces

Fig 8 shows the SEM-EDS results of the three surfaces after PAO6-lubricated sliding at 30 N. The smooth surface exhibited continuous ploughing grooves and local spalling, indicating residual asperity contact and abrasive wear. The circular-textured surface showed granular debris, local scratches and edge damage around the cavities, whereas the semi-circular-textured surface exhibited milder ploughing, better edge integrity and less material tearing, with debris preferentially retained within the cavities. These observations indicate that the semi-circular texture provided more effective debris accommodation and lubricant retention under PAO6 lubrication. EDS mappings showed that Fe, Cr, Co, Mo and Ni remained dominant in the worn regions, while localized O enrichment suggested slight oxidation or oxidized wear debris. The weak Si signal indicated limited material transfer from the Si_3N_4 counter ball. The C signal may originate from lubricant residues, contamination or carbonaceous debris; therefore, the chemical states of possible oxides or tribofilms cannot be determined from EDS alone .

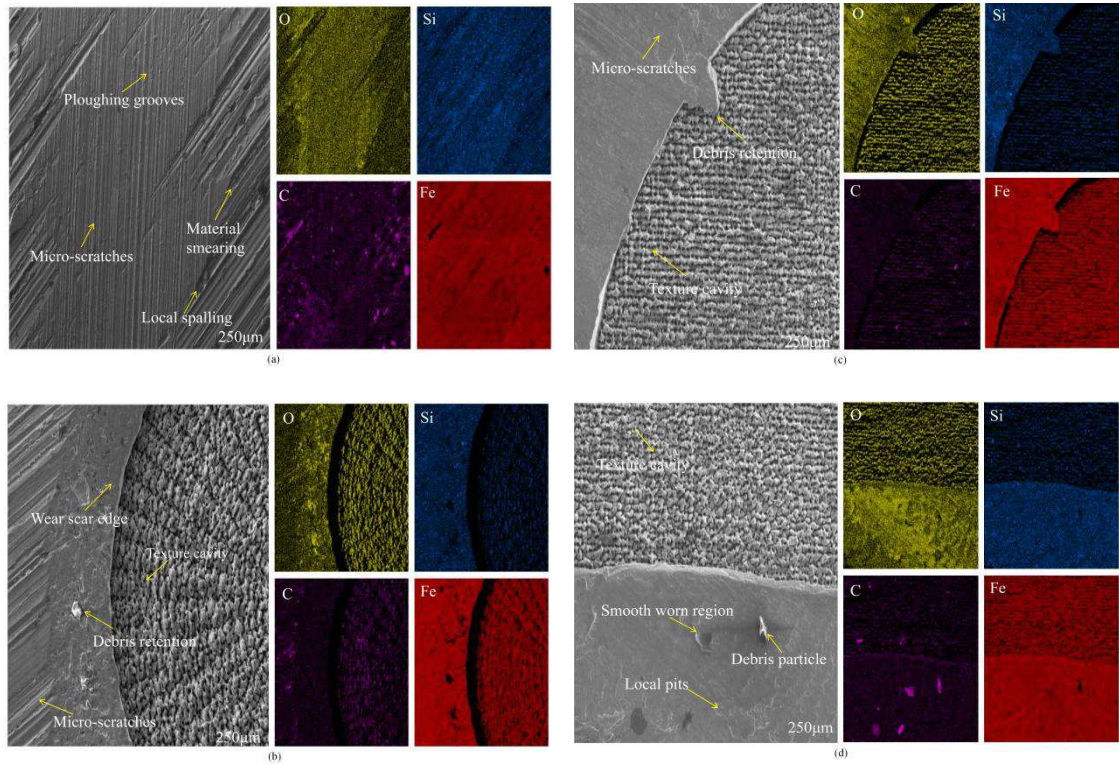


Fig. 8. SEM – EDS analysis of smooth, circular-textured and semi-circular-textured surfaces after PAO6-lubricated sliding at 30 N: (a) smooth surface, (b) circular-textured surface, (c) arc-edge region of the semi-circular texture, and (d) straight-edge region of the semi-circular texture.

Fig 9 presents the SEM-EDS results of the three surfaces after dry sliding at 30 N. Compared with PAO6 lubrication, all surfaces exhibited more severe ploughing, material smearing, debris accumulation and local spalling, indicating intensified abrasive and adhesive wear. The smooth surface showed continuous grooves and material removal, while the circular texture exhibited pronounced debris accumulation and edge damage. Although the semi-circular cavities retained wear debris, the absence of lubricant replenishment and oil-film separation limited their ability to suppress direct asperity contact and surface damage. Overall, surface textures primarily provided debris accommodation and interruption of continuous solid contact under dry sliding, whereas under PAO6 lubrication they additionally promoted lubricant retention and interfacial flow regulation. The milder damage and better edge integrity of the semi-circular texture under PAO6 lubrication can therefore be attributed to the combined effects of lubricant retention, debris trapping and

asymmetric geometry-induced flow regulation. Numerical simulations were subsequently performed to clarify the influence of texture geometry on local positive-pressure generation.

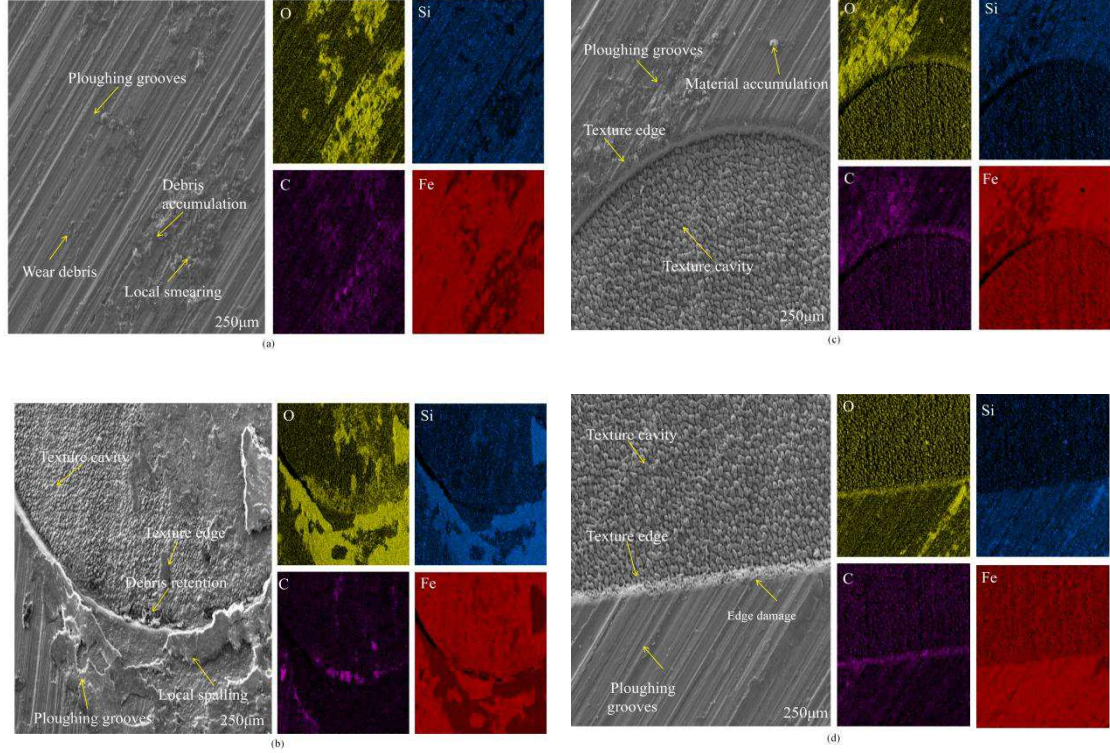


Fig. 9. SEM – EDS analysis of smooth, circular-textured and semi-circular-textured surfaces after dry sliding at 30 N: (a) smooth surface, (b) circular-textured surface, (c) arc-edge region of the semi-circular texture, and (d) straight-edge region of the semi-circular texture.

3.5 Numerical analysis of positive pressure characteristics

3.5.1 Positive pressure distribution under different oil film thicknesses

The positive-pressure distributions of the smooth, circular-textured and semi-circular-textured surfaces at different minimum oil-film thicknesses are shown in Fig. 10. Only the positive-pressure component was considered to identify the effective load-supporting regions. For the smooth surface, a pronounced pressure concentration appeared near the contact center at $h_{\min}=0.5\mu\text{m}$, and its magnitude decreased progressively as $h_{\min}$ increased to $2\mu\text{m}$, indicating a weakened hydrodynamic pressure response with increasing film thickness.

The circular-textured surface exhibited a consistently weak positive-pressure

field over the investigated film-thickness range, suggesting that the present axisymmetric cavity did not form an effective local converging wedge. In contrast, the semi-circular texture generated a distinct pressure concentration near its straight boundary. Although the pressure intensity decreased with increasing h_{min} , its response remained substantially stronger than that of the circular texture. This confirms that the asymmetric semi-circular geometry promoted local lubricant redistribution and positive-pressure generation.

Overall, both oil-film thickness and texture geometry strongly affected the local pressure field. A thinner film enhanced the pressure response, while the semi-circular texture exhibited the most favorable pressure-generation tendency among the textured surfaces. However, hydrodynamic pressure alone does not fully determine tribological performance, because lubricant retention, debris accommodation and surface damage evolution also contribute to friction and wear behavior.

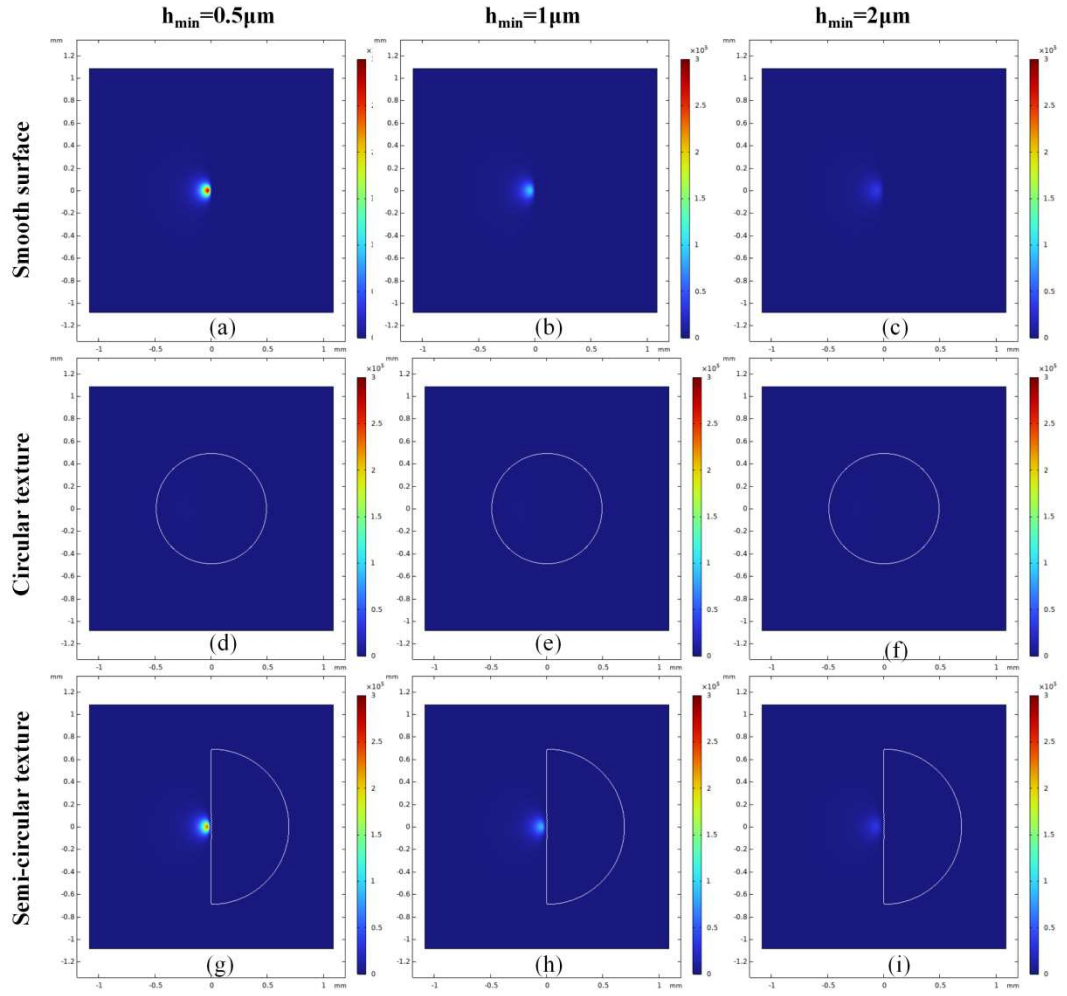


Fig. 10. Positive pressure distributions of different surface models under various minimum oil film thicknesses: (a–c) smooth surface, (d–f) circular-textured surface, (g–i) semi-circular-textured surface. The minimum oil film thicknesses are 0.5 μm , 1 μm and 2 μm from left to right, respectively.

3.5.2 Quantitative analysis of positive pressure parameters

The characteristic positive-pressure parameters are summarized in Table 5. For the smooth surface, increasing $h_{\min}$ from 0.5 to 2 μm reduced $P_{\max}$ from 2.72×10^5 Pa to 3.40×10^4 Pa and W from 3.61×10^{-3} N to 1.64×10^{-3} N, confirming the weakening of the local pressure-supporting response with increasing film thickness .

The circular-textured surface showed much lower $P_{\max}$, P_{avg} and W values than the other two surfaces. At $h_{\min}=0.5\mu\text{m}$, W was only 2.98×10^{-4} N, approximately one

order of magnitude lower than that of the smooth surface. By contrast, the semi-circular texture reached $P_{\max} = 2.35 \times 10^5$ Pa and $W = 3.14 \times 10^{-3}$ N at the same film thickness, demonstrating a substantially stronger local pressure-supporting capability.

The pressure centroids were approximately symmetric in the y-direction for all models, whereas their x_c positions differed markedly. The circular texture showed a larger offset $x_c = -0.416$ mm, while the semi-circular texture remained closer to the smooth-surface response, indicating that texture geometry altered the spatial distribution of effective positive pressure. Overall, the semi-circular texture provided a more balanced lubrication response by combining strong local pressure generation with lubricant-storage and flow-regulation functions. It should be noted that W represents only the integrated local positive-pressure contribution within the computational domain and is therefore used for relative comparison rather than direct balance with the externally applied experimental load.

Table 5

Characteristic parameters of positive pressure under different surface morphologies and minimum oil film thicknesses.

Model	$h_{\min}/\mu\text{m}$	$P_{\max}/\text{Pa}$	P_{avg}/Pa	W/N	x_c/mm	y_c/mm
Smooth surface	0.5	2.72E+05	766.52	3.61E-03	-0.1355	≈ 0
Smooth surface	1	9.61E+04	521.26	2.45E-03	-0.1691	≈ 0
Smooth surface	2	3.40E+04	348.07	1.64E-03	-0.2087	≈ 0
Circular texture	0.5	718.6	63.36	2.98E-04	-0.4156	≈ 0
Circular texture	1	696.02	62.1	2.94E-04	-0.415	≈ 0
Circular texture	2	654	59.69	2.81E-04	-0.4198	≈ 0
Semi-circular texture	0.5	2.35E+05	667.11	3.14E-03	-0.1487	≈ 0
Semi-circular texture	1	8.63E+04	459	2.16E-03	-0.1831	≈ 0
Semi-circular texture	2	3.08E+04	305	1.44E-03	-0.2264	≈ 0

Note: $P_{\max}$, P_{avg} , W , x_c , and y_c were calculated based on the positive pressure

component $p^+ = \max(p, 0)$, $W = \int_A p^+ dA$, $x_c = \frac{\int_A x p^+ dA}{W}$, and $y_c = \frac{\int_A y p^+ dA}{W}$

4. Conclusion

In this study, circular and semi-circular laser textures with nearly identical projected areas and identical depths were fabricated on G13Cr14Co12Mo5Ni2 bearing steel to isolate the effect of texture geometry from texture size and depth. Ball-on-disk tests, surface characterization and thin-film lubrication simulations were combined to establish the relationship between texture geometry, interfacial pressure response and tribological performance. The main conclusions are as follows:

(1) Lubrication condition dominated the friction response, while texture geometry further influenced friction stability. Under PAO6 lubrication at 30 N, the semi-circular texture exhibited the lowest and most stable friction coefficient of approximately 0.11-0.13, compared with 0.12-0.14 for the circular texture and 0.13-0.15 for the smooth surface. Under dry sliding, both textures reduced friction to some extent through debris accommodation and interruption of continuous asperity contact, although their effectiveness was limited by the absence of lubricant.

(2) The semi-circular texture also exhibited the best wear resistance under PAO6 lubrication, with the lowest specific mass wear rate of $2.98 \times 10^{-7} \text{ g} \cdot \text{N}^{-1} \cdot \text{m}$. Three-dimensional morphology and SEM-EDS observations revealed milder ploughing, better texture-edge integrity and more effective debris accommodation than those of the circular texture, indicating improved lubricant retention and reduced local surface damage.

(3) Numerical simulation demonstrated a clear geometry-dependent positive-pressure response. The circular texture generated only a weak pressure field under the present conditions, whereas the semi-circular texture produced a localized high-pressure region near its straight boundary. At $h_{\min}=0.5\mu\text{m}$, the semi-circular texture reached $P_{\max} = 2.35 \times 10^5 \text{ Pa}$ and $W = 3.14 \times 10^{-3} \text{ N}$, showing a substantially stronger pressure-supporting tendency than the circular texture.

(4) The principal contribution of this study is the geometry-decoupled

comparison of symmetric and asymmetric textures under nearly equal-area and equal-depth conditions. The results show that the superior PAO6-lubricated performance of the semi-circular texture arises from a coupled pressure–storage mechanism, in which lubricant retention and debris trapping are complemented by asymmetric flow regulation and local positive-pressure generation. This finding provides a clearer basis for geometry-oriented optimization of laser-textured bearing surfaces under oil-lubricated sliding.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Author Contributions

X.W. conceptualized the study, designed the experimental methodology, fabricated the laser-textured samples, performed tribological experiments, conducted surface characterization and numerical analysis, and wrote the original manuscript. S.H. contributed to experimental validation, data interpretation, and manuscript editing. C.L. assisted with experimental analysis and discussion of the tribological mechanisms. P.K.L. supervised the research, provided scientific guidance, and critically revised the manuscript. All authors reviewed and approved the final manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

References

- [1] Gachot C, Rosenkranz A, Hsu SM, et al. A critical assessment of surface texturing for friction and wear improvement. *Wear* 372–373, 21–41 (2017). <https://doi.org/10.1016/j.wear.2016.11.020>
- [2] Rosenkranz A, Gachot C, Costa HL. Surface texturing in machine elements – A critical discussion for rolling and sliding contacts. *Adv Eng Mater* 21, 1900194 (2019). <https://doi.org/10.1002/adem.201900194>
- [3] Mao B, Siddaiah A, Liao Y. Laser surface texturing for improving tribological performance: A review. *J Manuf Process* 56, 153–168 (2020). <https://doi.org/10.1016/j.jmapro.2020.02.009>
- [4] Lu P, Wood RJK. Tribological performance of laser surface textured metallic surfaces: A review. *Surf Coat Technol* 405, 126532 (2020). <https://doi.org/10.1088/2051-672X/abb6d0>
- [5] Gropper D, Wang L, Harvey TJ. Hydrodynamic lubrication of textured surfaces: A review of modeling techniques and key findings. *Tribol Int* 94, 509 – 529 (2016). <https://doi.org/10.1016/j.triboint.2015.10.009>
- [6] Schille J, Schneider L, Mauersberger S, et al. High-rate laser surface texturing for tribological functionality. *Lubricants* 8, 33 (2020). <https://doi.org/10.3390/lubricants8030033>
- [7] Adjemout M, Brunetière N, Bouyer J (2015) Optimization of mesh density for numerical simulations of hydrodynamic lubrication considering textured surfaces. *Proc Inst Mech Eng J J Eng Tribol* 229(9):1132–1144. <https://doi.org/10.1177/1350650115574535>
- [8] Wang, Y., Jacobs, G., König, F., Zhang, S., von Goeldel, S.: Investigation of microflow effects in textures on hydrodynamic performance of journal bearings using CFD simulations. *Lubricants* 11(1), 20 (2023). <https://doi.org/10.3390/lubricants11010020>
- [9] Affatato, S., Valigi, M.C., Logozzo, S.: Knee wear assessment: 3D scanners used as a consolidated procedure. *Materials* 13(10), 2349 (2020). <https://doi.org/10.3390/ma13102349>

oi.org/10.3390/ma13102349

- [10] Bhaumik, S., Paleu, V., Chowdhury, D., Batham, A., Sehgal, U., Bhattacharya, B., Ghosh, C., Datta, S.: Tribological investigation of textured surfaces in starved lubrication conditions. *Materials* 15(23), 8445 (2022). <https://doi.org/10.3390/ma15238445>
- [11] Wang, W., He, Y., Zhao, J., Mao, J., Hu, Y., Luo, J.: Optimization of groove texture profile to improve hydrodynamic lubrication performance: Theory and experiments. *Friction* 8(1), 83 – 94 (2020).
- [12] Braun, D., Greiner, C., Schneider, J., Gumbsch, P.: Efficiency of laser surface texturing in the reduction of friction under mixed lubrication. *Tribol. Int.* 77, 142 – 147 (2014). <https://doi.org/10.1016/j.triboint.2014.04.012>
- [13] Wakuda, M., Yamauchi, Y., Kanzaki, S., Yasuda, Y.: Effect of surface texturing on friction reduction between ceramic and steel materials under lubricated sliding contact. *Wear* 254(3 – 4), 356 – 363 (2003). [https://doi.org/10.1016/S0043-1648\(03\)00004-8](https://doi.org/10.1016/S0043-1648(03)00004-8)
- [14] Conradi, M., Podgornik, B., Kocijan, A., Remškar, M., Klobčar, D.: Water versus oil lubrication of laser-textured Ti6Al4V alloy upon addition of MoS₂ nanotubes for green tribology. *Materials* 15(9), 2974 (2022). <https://doi.org/10.3390/ma15092974>
- [15] Valigi, M.C., Logozzo, S., Affatato, S.: New challenges in tribology: wear assessment using 3D optical scanners. *Materials* 10(5), 548 (2017). <https://doi.org/10.3390/ma10050548>
- [16] Ding, S., Wei, H., Yang, O., Deng, L., Mu, D.: Tribological behaviors of laser textured surface under different lubrication conditions for rotary compressor. *Sci. Rep.* 13, 5378 (2023).
- [17] Shen, Z., Wang, F., Chen, Z., Ruan, X., Zeng, H., Wang, J., An, Y., Fan, X.: Numerical simulation of lubrication performance on chevron textured surface under hydrodynamic lubrication. *Tribol. Int.* 154, 106704 (2021). <https://doi.org/10.1016/j.triboint.2021.106704>

[//doi.org/10.1016/j.triboint.2020.106704](https://doi.org/10.1016/j.triboint.2020.106704)

- [18] Di Puccio, F., Di Pietro, A., Mattei, L.: Pin-on-plate vs. pin-on-disk wear tests: theoretical and numerical observations on the initial transient phase. *Lubricants* 12(4), 134 (2024). <https://doi.org/10.3390/lubricants12040134>
- [19] Samanta, A., Huang, W., Lee, K., He, X., Kumara, C., Qu, J., Ding, H.: Effect of surface wetting on tribological behavior for laser textured steel using ionic liquid-based lubricants. *Manuf. Lett.* 35, 141 – 151 (2023). <https://doi.org/10.1016/j.mfglet.2023.07.009>
- [20] Gaudiuso, C., Volpe, A., Mezzapesa, F.P., Putignano, C., Ancona, A.: Tailoring the coefficient of friction by direct laser writing surface texturing. *Micromachines* 15(1), 7 (2024). <https://doi.org/10.3390/mi15010007>
- [21] Salguero, J., Sol, I.D., Dominguez, G., Batista, M., Vazquez-Martinez, J.M.: Tribological wear effects of laser texture design on AISI 630 stainless steel under lubricated conditions. *Metals* 12(4), 543 (2022). <https://doi.org/10.3390/met12040543>
- [22] Goldstein, J.I., Newbury, D.E., Michael, J.R., Ritchie, N.W., Scott, J.H.J., Joy, D.C.: *Scanning Electron Microscopy and X-ray Microanalysis*. Springer, New York (2017).
- [23] Qin, L., Huang, X., Sun, Z., Ma, Z., Mawignon, F.J., Lv, B., Shan, L., Dong, G.: Synergistic effect of sharkskin-inspired morphologies and surface chemistry on regulating stick-slip friction. *Tribol. Int.* 187, 108765 (2023). <https://doi.org/10.1016/j.triboint.2023.108765>
- [24] Grützmacher, P.G., Profito, F.J., Rosenkranz, A.: Multi-scale surface texturing in tribology—Current knowledge and future perspectives. *Lubricants* 7(11), 95 (2019). <https://doi.org/10.3390/lubricants7110095>
- [25] Lu, P., Wood, R.J., Gee, M.G., Wang, L., Pfleging, W.: A novel surface texture shape for directional friction control. *Tribol. Lett.* 66(1), 51 (2018).
- [26] Laki, G., Nagy, A.L., Rohde-Brandenburger, J., Hanula, B.: A review on fr

- iction reduction by laser textured surfaces in internal combustion engines. Tribol. Online 17(4), 318 – 334 (2022). <https://doi.org/10.2474/trol.17.318>
- [27] Li, K., Jing, D., Hu, J., Ding, X., Yao, Z.: Numerical investigation of the tribological performance of micro-dimple textured surfaces under hydrodynamic lubrication. Beilstein J. Nanotechnol. 8, 2324 – 2338 (2017). <https://doi.org/10.3762/bjnano.8.232>
- [28] Li, P., Zhang, F., Zhang, H., Wang, T., Wang, Q., Qiao, W.: Lubrication performance of kite-shaped microtexture under hydrodynamic lubrication. Tribol. Int. 179, 108144 (2023). <https://doi.org/10.1016/j.triboint.2022.108144>
- [29] Liu, S., Sai, Q., Wang, S., Williams, J.: Effects of laser surface texturing and lubrication on the vibrational and tribological performance of sliding contact. Lubricants 10(1), 10 (2022). <https://doi.org/10.3390/lubricants10010010>
- [30] Ryk, G., Kligerman, Y., Etsion, I.: Experimental investigation of laser surface texturing for friction reduction under lubricated sliding conditions. Tribol. Trans 59(1), 1 – 9. 1 (2016). <https://doi.org/10.3390/lubricants6030062>
- [31] Zhang, H., Geng, Y., Li, Z., Wang, X.: Effect of laser surface texturing on tribological behavior of stainless steel under lubrication conditions. Tribol. Int 131, 540 – 548 (2019). <https://doi.org/10.2139/ssrn.6146657>
- [32] Kovalchenko, A., Ajayi, O., Erdemir, A., Fenske, G., Etsion, I.: The effect of laser surface texturing on transitions in lubrication regimes during unidirectional sliding contact. Tribol. Int 135, 25 – 34 (2004). <https://doi.org/10.1016/j.triboint.2004.08.004>
- [33] Zhou, Q., Wang, X., Li, J., Chen, Y.: Influence of surface texture geometry on tribological properties under oil lubrication. Wear 450 – 451, 203258 (2016). <https://doi.org/10.1016/j.triboint.2016.03.015>
- [34] Zhang, J., Meng, Y.: Direct observation of wear debris trapping and lubrication mechanisms of textured surfaces. Wear 406 – 407, 111 – 120 (2018). <https://doi.org/10.1007/s11249-012-9935-6>

- [35] Wang, X., Kato, K., Adachi, K.: Experimental and numerical investigation of micro-dimple effects on lubrication performance. *Tribol. Int* 110, 1 – 10 (2017). <https://doi.org/10.1115/1.4032952>
- [36] Yu, H., Deng, H., Huang, W.: Optimization of surface texture parameters for improving tribological performance under lubrication. *Tribol. Int* 165, 107302 (2022). <https://doi.org/10.1108/ilt-10-2023-0333/v2/review1>
- [37] Kumar, A., Patel, V., Ramkumar, J.: Influence of laser surface texturing on tribological behavior of bearing steel under boundary lubrication. *Mater. Today Commun* 26, 102071 (2025). <https://doi.org/10.1016/j.apsusc.2025.165765>
- [38] Zhou, Y., Zhu, H., Tang, W.: Numerical analysis of hydrodynamic lubrication characteristics of textured surfaces. *Mech. Syst. Signal Process* 146, 107023 (2020). <https://doi.org/10.1299/jsmekanto.2020.17e18>
- [39] Liu, Y., Li, J., Zhang, C.: Laser surface texturing of bearing steel for improving tribological performance under oil lubrication. *Surf. Coat. Technol* 475, 130152 (2024). <https://doi.org/10.2139/ssrn.6146657>
- [40] Liu, J., Wang, L., Zhang, H.: Recent advances in laser surface texturing for tribological applications: Mechanisms and optimization strategies. *Surf. Interfaces* 56, 105623 (2025). <https://doi.org/10.3390/lubricants14060239>