Effects of groove-textured surfaces filled with Sn–Ag–Cu and MXene–Ti₃C₂ composite lubricants on tribological properties of CSS-42L bearing steel

Yawen XUE^{1,2}, Chaohua WU^{1,2,*}, Xiaoliang SHI^{1,2,*}, Qipeng HUANG^{1,2}, Ahmed Mohamed Mahmoud IBRAHIM³

¹ School of Mechanical and Electronic Engineering, Wuhan University of Technology, Wuhan 430070, China

² Shenzhen Research Institute of Wuhan University of Technology, Shenzhen 518000, China

³ Department of Production Engineering and Mechanical Design, Faculty of Engineering, Minia University, El-Minya 61519, Egypt

Received: 01 March 2021 / Revised: 30 April 2021 / Accepted: 04 August 2021

© The author(s) 2021.

Abstract: To improve the tribological performance of CSS-42L bearing steel, smooth surfaces (SSs), groove-textured surfaces (GSs), GSs with Sn–Ag–Cu (GSs–SAC), and GSs with Sn–Ag–Cu–Ti₃C₂ (GSs–SACT) were prepared on CSS-42L. In addition, experimental studies were conducted on tribological properties. The obtained results indicated that GSs–SACT exhibited the best anti-friction and noise reduction performances. These remarkable tribological performances were attributed to the synergistic effects of grooves, Sn–Ag–Cu, and MXene–Ti₃C₂. The inconsistent rules of frictional forces were improved by the grooves and SACT, which inhibit the friction-induced noise. The micro-nano size-effects of MXene–Ti₃C₂ enhanced the repairing effect and anti-friction property of composite lubricants, which improved the profile characteristics of GSs–SACT.

Keywords: CSS-42L; MXene; Sn–Ag–Cu–Ti₃C₂ (SACT); grooves; tribological properties; friction-induced noise

1 Introduction

As the core component of equipment, bearings determine reliability and the performances of bearing steels are the key factors that ensure the durability of bearings. Owing to the rapid development of high-end equipment, bearing steels are required to operate reliably for longer life-spans under higher speed, larger load conditions, and harsher environments. Presently, CSS-42L, a representative third generation aerospace bearing steel, is the most promising bearing material. Hence, investigations on the tribological properties of CSS-42L are of great engineering significance and crucial for improving the working performance of high-end equipment bearings [1–3].

With low shear strength, high bearing capacity, and large surface area ratio characteristics, two dimensional (2D) MXene exerts unique enhancement effects on nano-micro scale friction systems, which have been

widely investigated in the tribology field [4–9]. The structural features and tribological properties of MXene/UHMWPE nanocomposites were studied by Zhang et al. [10]. The results obtained from this study demonstrated that MXene–Ti₃C₂ suppressed the adhesion wear at the interface and improved the tribological properties, and creep resistance of composites. However, Lian et al. [11] evaluated the tribological properties of Ti₃C₂ coatings on copper plate surfaces. The obtained results showed that during the sliding process, the graphitized Ti₃C₂ coatings reduced the direct contact between the sliding surfaces, thereby inhibiting the production and adhesion of wear debris on the worn surfaces. Rosenkranz et al. [12] prepared MXene coatings on stainless steel (AISI 304) and performed the ball–disc friction experiments. The experimental results indicated that MXene coatings exhibited excellent tribological properties. The friction coefficient was reduced by approximately

* Corresponding authors: Chaohua WU, E-mail: wuchaohua@whut.edu.cn; Xiaoliang SHI, E-mail: sx1071932@126.com

300%, and the adhesive wear on the surface was effectively prevented. In another study, polymeric-based composites reinforced with MXene and nano- Al_2O_3 were prepared by Guo et al. [13]. They verified that hybrid lubrication films with ultra-low friction coefficients were formed at the interface, which could achieve super-lubricity on the surface.

The Sn–Ag–Cu alloy with a weak shear strength is a solid lubricant with outstanding lubrication abilities [14–16]. Liu et al. [17] filled Sn–Ag–Cu into micro-holes on M50 surfaces, and then studied the self-repairing function of self-lubricating composites. It was observed that owing to the high fluidity of Sn–Ag–Cu, this alloy can form glaze/lubrication films, which exhibit a self-healing effect by covering the cracks and filling the pits on the worn surfaces. To improve the tribological properties of materials, lubricants, nano-reinforcers, surface textures, and synergistic lubrication technologies have been investigated by several researchers [18–21]. Zhou et al. [22] studied the possible lubrication and self-healing effect of Sn–Ag–Cu and TiC by filling the micro-holes on a TC4 surface with the lubricant composites. A newly formed uniform lubrication/protective layer was observed on the surfaces, which improved the tribological properties of TC4. Hua et al. [23] prepared Gr (graphite)– MoS_2 –PI (polyimide)–CNTs (carbon nanotubes) composite lubricants, filling into the surface textures of GCr15 bearing steel. It was reported that the synergistic effects of hybrid lubricants improved the wear resistance and service life of materials.

Friction-induced noise is a common problem in the solid lubrication field, which could reduce the friction system reliability and the durability of materials. Studies on the generation mechanisms and reduction technologies of friction-induced noise have been conducted by several scholars [24–27]. Friction-induced vibration and noise are the inherent properties of solid lubricated surfaces under dry friction. During the friction process, the tribological properties of materials induce friction-induced vibration at the friction interface, which is a self-excited vibration type. The vibration triggering the friction-induced noise could exacerbate the surface wear. The relationships between noise and friction could be established by analyzing the frictional force changes and surface

profiles. This noise is related to the friction behavior, which can be reduced by improving the antifriction performance on the surfaces [28]. The changes in the contact conditions from elastic to plastic effectively suppress the noise [29]. In addition, noise can be reduced by the surface modification technology [30]. The groove-textured surface with a damping element can suppress the self-excited vibration of friction system [31]. Mo et al. [32] studied the characteristics of friction-induced vibration and noise on groove surfaces. They verified that the noise was related to friction fluctuation. In addition, the grooves on the surface could reduce the friction fluctuation, thereby suppressing the self-excited vibration of the friction system. It was observed that the synergistic effects of grooves and the Sn–Ag–Cu alloy improved the tribological properties of GCr15 and reduced the adhesive wear on the surfaces, thus eliminating the high-frequency noise and low-frequency chattering [33].

The lubricant composite of MXene and Sn–Ag–Cu can improve the lubrication performances, thus extending the application field of Sn–Ag–Cu. The MXene with weak boundary multilayer structures exhibits a significant application potential in the tribology field. Nonetheless, the experimental studies and theoretical analyses on the tribological properties of MXene are negligible. In this study, smooth surfaces (SSs), groove-textured surfaces (GSs), GSs with Sn–Ag–Cu (GSs–SAC), and GSs with Sn–Ag–Cu– Ti_3C_2 (GSs–SACT) were prepared on CSS-42L. Furthermore, the anti-friction and wear resistance mechanisms of GSs–SACT were analyzed, and the synergistic effects of grooves and Sn–Ag–Cu– Ti_3C_2 on the friction-induced vibration and noise were investigated. This study could provide the experimental basis for the application of MXene in CSS-42L bearings to achieve excellent anti-friction, wear-resistance, and friction-induced noise reduction performances.

2 Materials and methods

2.1 Sample preparation

First, Ti_3C_2 nanosheets were obtained by etching Ti_3AlC_2 powders in hydrogen fluoride (HF) solution. Ti_3AlC_2 powders were added into 40% of the HF acid

solution and stirred at room temperature (20–25 °C) with an electromagnetic stirrer for 8 h. Subsequently, the suspensions were centrifuged for 30 min and washed with deionized water. Ti_3C_2 nanosheets were obtained by drying the sediments at 70 °C under vacuum conditions for 24 h. The microstructural morphology and elemental distributions of Ti_3C_2 are illustrated in Figs. 1(a)–1(d). Next, the raw Sn–Ag–Cu powders were prepared according to the compositions presented in Table 1, and the powders were milled by a vacuum ball mill for 12 h. Sn–Ag–Cu spherical powders were prepared via vacuum atomization at a temperature of approximately 500–600 °C, and the spherical powder sizes were approximately 20–50 μm . The Sn–Ag–Cu spherical powders are illustrated in Fig. 1(e). According to the mixing ratios of Ti_3C_2 (5 wt%) and Sn–Ag–Cu (95 wt%), the mixed powders

were stirred by the electric mixer at 1,000 rpm for 4 h. Finally, the lubricant composites of Sn–Ag–Cu and Ti_3C_2 were obtained.

The grooves were prepared on the surfaces of CSS-42L bearing steel (Table 2) using the electrical discharge machining technology. The texture density was designed to highlight the tribological enhancement effects of grooves in the range of wear tracks during the tests, and the groove sizes are presented in Table 3. The lubricant composites of MXene– Ti_3C_2 and Sn–Ag–Cu were melted at a temperature of 500–550 °C, into the grooves on CSS-42L surfaces, using the vacuum melting and infiltration technology for 50–60 min. After the infiltration, the temperature was reduced to 150–200 °C for 20–30 min. Subsequently, power was cut off, and the samples were cooled to room temperature (20–25 °C) inside a temperature-controlled furnace.

Fig. 1 (a) Ti_3C_2 microstructural morphology, (b–d) elemental distributions, (e) Sn–Ag–Cu spherical powders, and (f) groove-textured surfaces.

Table 1 Compositions and material properties of Sn–Ag–Cu.

Composition (wt%)			Melting point (°C)	Density (g/cm ³)	Particle size (μm)
Sn	Ag	Cu			
92	5	3	277	7.43	20–50

Table 2 Elemental compositions of CSS-42L.

Composition	C	Cr	Ni	Mo	V	Mn	Si	Nb	Co	Fe
Content (wt%)	0.15	13.80	2.11	4.50	0.60	0.21	0.25	0.025	13.00	Balance

Table 3 Geometrical parameters of samples.

Sample	Surface	Width, w (μm)	Pitch, p (μm)	Texture density	Depth, d (μm)
SSs	Smooth	No	No	No	No
GSs	Grooves	300	900	33.3%	500
GSs–SAC	Grooves + Sn–Ag–Cu	300	900	33.3%	500
GSs–SACT	Grooves + Sn–Ag–Cu– Ti_3C_2	300	900	33.3%	500

Furthermore, the samples were ground with 1500# sandpapers in the grinder for 20 min. The sample surfaces were polished by 4000# diamond grinding pastes in the grinder for 20 min. Finally, all samples were cleaned by the ultrasonic cleaner using alcohol, and the obtained samples are presented in Fig. 1(f).

2.2 Experimental

A test system for studying the tribological behavior and friction-induced noise was developed to synchronously collect friction coefficients, vibration acceleration, and noise in the test, as illustrated in Fig. 2. The 2D mechanical sensor with high tribometer sensitivity (MFT-5000 Rtec, USA) was used to collect the frictional force and load, and then the friction coefficients were automatically calculated. Moreover, the loading servo controller of the tribometer constantly modified the loading forces during the tests, which ensured that the test results were not affected by the load fluctuation. The tested samples were maintained in a reciprocating motion at dry conditions, and each test was repeated. The counterpart ball (Si_3N_4 , diameter: 6.3 mm) has the highest hardness among

the samples, which means that it could evaluate the tribological characteristics of samples more accurately. To obtain stable tribological properties of self-lubricating materials, the tribological standard test procedures were adopted. The test conditions were set based on the practical working conditions and tribological properties of the materials, as presented in Table 4.

Meanwhile, the vibration acceleration signals during the tests were recorded by the acceleration sensor (PCB352C33, Sensitivity of 50 mV/g, USA), which was installed on the loading rod and kept in the horizontal direction to the friction. In addition, the distance from the friction interface was approximately 15–20 mm. The friction-induced noise was recorded by the microphone (PCB378B02, USA) with a sensitivity of 50 mV/Pa and the dynamic measurement range of 15–137 dB, with a horizontal distance from the friction interface at approximately 80–100 mm. The data acquisition system (Iptest-08) was used to synchronously collect the vibration acceleration and noise signals. The sampling rate of the system was 10 ksp/s. It was verified that the sound pressures of measured signals in the tests were more than 10 dB larger than that of the environmental noise. The precision of measured signals was not influenced by the environment.

After the tests, the power spectral density (PSD), spectrum rules, and coherence of vibration acceleration and sound pressure signals were analyzed by the MATLAB software (USA). Meanwhile, the profile parameters on the worn out surfaces of the samples were measured by the white light interference profilometer (UP-3D Rtec, USA). Each parameter was measured ten times, and an average value was taken as the measurement result. In addition, the microstructural morphology and elemental distributions of Ti_3C_2 were observed using a scanning electron microscope (SEM,

Fig. 2 Photograph of comprehensive test system.

Table 4 Test conditions for tribological experiments.

Reciprocating displacement (mm)	Reciprocating frequency (Hz)	Each test time (min)	Test temperature (°C)	Relative humidity (%)
8	1	30	20–25	50 ± 10

JSM-IT300/EDS-X-MaxN20, Japan). Furthermore, the morphological characteristics on the worn surfaces were observed by a electronic probe microanalyser (EPMA, JAXA-8230, Japan), and the friction and wear mechanisms were analyzed. An field emission scanning electron microscope (FESEM, ULTRA PLUS, Germany) was utilized to observe the internal morphology of materials in the worn surface section, which analyzed the material damage characteristics. The phase analyses on the surfaces were performed using a rotation anode high power X-ray diffractometer (XRD, D-MAX-RB, Japan) and an energy dispersive spectrdmeter (EDS, Inca-X-ACT, UK), and the crystallinity, residual stress, and grain diameter were calculated using the MDI Jade 9 software (USA).

3 Results and discussion

3.1 Tribological behavior and friction-induced noise of samples

As illustrated in Fig. 3, the friction coefficient and equivalent sound pressure increase with the increase in applied load. As illustrated in Figs. 3(a) and 3(b), at the stable friction stage (10 N), the average friction coefficients of SSs, GSs, GSs-SAC, and GSs-SACT were 0.521, 0.501, 0.453, and 0.335, respectively. Compared to SSs, the average friction coefficients decreased by 3.8% (GSs), 13.1% (GSs-SAC), and 35.7% (GSs-SACT). Meanwhile, the average equivalent sound pressures of SSs, GSs, GSs-SAC, and GSs-SACT were 91.06, 77.22, 75.91, and 70.63 dB, respectively. However, the average equivalent sound pressures decreased by 15.2% (GSs), 16.6% (GSs-SAC), and 22.4% (GSs-SACT).

As presented in Figs. 3(c) and 3(d), the average friction coefficients of SSs, GSs, GS-SAC, and GSs-SACT were 0.525, 0.507, 0.468, and 0.353, respectively. Compared to SSs, the average friction coefficients decreased by 3.4% (GSs), 10.9% (GSs-SAC), and 32.8% (GSs-SACT). Meanwhile, the average equivalent sound pressures of SSs, GSs, GSs-SAC, and GSs-SACT were 96.21, 80.02, 78.32, and 72.59 dB, respectively.

Meanwhile, the average equivalent sound pressures decreased by 16.8% (GSs), 17.9% (GSs-SAC), and 24.6% (GSs-SACT), in comparison to SSs. Nevertheless, the average friction coefficients of SSs, GSs, GSs-SAC, and GSs-SACT were 0.541, 0.535, 0.523, and 0.385, respectively, under an applied load of 30 N. Moreover, the average friction coefficients decreased by 1.1% (GSs), 3.3% (GSs-SAC), and 28.8% (GSs-SACT), with SSs as the reference for the comparison. The average equivalent sound pressures of SSs, GSs, GSs-SAC, and GSs-SACT were 103.03, 90.65, 87.85, and 77.01 dB, respectively. Compared with SSs, the average equivalent sound pressures decreased by 12.0% (GSs), 14.7% (GSs-SAC), and 25.2% (GSs-SACT).

Under all load conditions, as the applied load increases, the friction coefficient takes a shorter time to reach the steady state. Moreover, the friction coefficients and friction-induced noise sound pressures increase; however, the increase in sound pressures is more significant. The friction coefficients of GSs and GSs-SAC gradually approach those of the SSs, and the noise sound pressures of GSs and GSs-SAC exhibited the same trend. However, the friction coefficients and noise sound pressures of GSs-SACT could be maintained at the lowest levels. Therefore, loads exhibit the least effect on the anti-friction and noise reduction performances of GSs-SACT. Although the effects of grooves on the friction coefficients are not significant, the noise sound pressures are significantly affected. At a load of 10 N, the friction coefficients and sound pressures of GSs-SAC exhibited lower values than GSs. However, as the applied load increased, the lubricating performance of Sn-Ag-Cu exhibited a limited effect, while the anti-friction and friction-induced noise reduction performances of GSs-SAC exhibited the same trend as those of GSs. Under high loads, GSs-SACT could obtain lower friction coefficients and sound pressures than GSs-SAC.

Analyses on the instantaneous changes in the friction coefficient and force could highlight unique tribological characteristics, and the test results presented in Fig. 4 illustrate the relationship between noise and friction

Fig. 3 Changes in equivalent noise pressures and average friction coefficients of samples with time.

force. The friction coefficients increase with the increase in frictional forces. The inconsistent rules of frictional forces and coefficients are similar. Nonetheless, at the turning positions of the reciprocating process, the curves of frictional forces and friction coefficients indicate a significant step-jumping. Moreover, a higher friction-induced noise is recorded at the large jump region in the amplitude. The step-jumping amplitudes of GSs, GSs-SAC, and GSs-SACT decrease more

significantly than SSs. The curves of frictional forces and coefficients reflect tooth-jumping, and the jumping number is typically equal to the groove number. Therefore, the step-jumping amplitudes of frictional forces are weakened by tooth-jumping, thereby suppressing the friction-induced noise. Moreover, with the increase in tooth-jumping amplitudes, the friction-induced noise becomes more significant. The tooth-jumping of curves is triggered by the grooves,

Fig. 4 Changes in frictional forces and friction coefficients of samples with time at the stable stage.

and the amplitudes could be reduced by the lubricants in the grooves. Therefore, compared with other samples, the frictional forces, coefficients, and friction-induced noises on GSs-SACT are the least.

With the increase in the load, the frictional forces and coefficients, step-jumping amplitudes of curves, and sound pressures of friction-induced noise increase. The noise reduction effects of grooves could be minimized with the increase in the load. At an applied load of 10 N, taking GSs as the reference, the

jumping of frictional forces and friction coefficients of GSs-SAC is improved by the grooves and Sn-Ag-Cu. Nevertheless, the inconsistent rules of frictional forces and friction coefficients of GSs-SAC and GSs are similar, and the effects of grooves and Sn-Ag-Cu are reduced at higher load (30 N). However, under the high load (30 N), the jumping amplitudes of frictional forces and friction coefficients could be significantly reduced by the composite lubricants and grooves on GSs-SACT.

Furthermore, a practical engineering application is adopted as an analogy to illustrate the effects of grooves on frictional force, which elucidates the explanation better. Nevertheless, the amplitude reduction mechanisms of surface friction and liquid flow differ. As illustrated in Fig. 5, tanker speed always changes, and the oil in the tank fluctuates constantly. The fluctuation force of oil would make the tanker run in an unstable state, which could trigger accidents. Therefore, “wave damping plates” are installed inside the tank to minimize the large fluctuation of oil, thereby decreasing the fluctuation force. The wave damping effect can be realized on GSs–SACT to reduce the fluctuation of friction force. Moreover, surface profiles at the friction interface are not uniform, which could affect the change in the frictional force. Meanwhile, the counterpart ball sliding speeds are altered, and the frictional forces also fluctuated constantly. Therefore, the friction-induced vibration and noise are induced by the instability of the friction system. The grooves are equivalent to the “wave damping plates”, which could reduce the larger fluctuation of friction force. Furthermore, the frictional force fluctuations are weakened by the grooves. In addition, the jumping amplitudes of frictional forces are minimized by SACT. In contrast, the friction-induced vibration and noise could be suppressed by the “wave damping effects” of grooves and SACT. The synergistic effects of grooves and SACT can improve the inconsistent rules of frictional forces, which enhance the friction-induced noise reduction ability of GSs–SACT.

Fig. 5 Wave damping effect of GSs–SACT.

3.2 Friction-induced vibration and noise characteristics of samples

Power spectrum density analyses of noise and vibration signals of the samples are presented in Fig. 6. The inconsistent rules of vibration PSD curves and noise are similar. Meanwhile, the vibration and noise of SSs have high power distributions in the entire spectra, thereby producing the high-frequency noise (high-pitched noise) during the tests. Compared with those of SSs, more peaks in the PSD curves of GSs, GSs–SAC, and GSs–SACT are generated by the “wave damping effect” of grooves and composite lubricants. The power distributions in the entire spectrum and friction-induced noises are significantly reduced. Moreover, the peak spectrum intensities of GSs are significantly reduced, thereby inhibiting the high-frequency noise, and producing low-frequency chattering (low-intensity impact noise accompanied by rapid vibration). The spectrum intensities in the local frequencies of GSs–SAC are lower, which is attributed to the chattering, and hence they generate the low-noise. Furthermore, the spectrum intensities of GSs–SACT are the lowest, and the peak distributions in its PSD curves are the least. In addition, no significant friction-induced noise was observed during the tests.

As illustrated in Figs. 7 and 8, the spectrum distributions and compositions of vibration and noise are similar. Meanwhile, the spectra of SSs contain the highest frequencies and the largest intensities, while GSs–SACT spectra contain the least frequencies and the smallest intensities. The spectra of SSs, GSs, and GSs–SAC are distributed in frequencies of 500–3,000, 500–4,000, and 0–1,500 Hz, respectively, whose noises are the high-pitched noise, chattering, and low-noise, respectively. Moreover, the spectra of GSs–SACT without the obvious friction-induced noise are primarily distributed in 0–500 Hz. Therefore, the forms of the friction-induced noises are affected by the surface contact characteristics. The surface contact characteristics are improved by the grooves and lubricants, which could suppress the friction-induced vibration and noise.

The coherence analyses of the vibration accelerations and sound pressures of the samples are presented in Fig. 9. The coherence coefficients of SSs, GSs, and

Fig. 6 Power spectrum density analyses of noise and vibration signals of the samples.

Fig. 7 Time history records of vibration accelerations and (a) sound pressures and (b) signals at the friction stable-stage of samples.

Fig. 8 Frequency spectrum analyses of vibration acceleration (a) sound pressures and (b) signals at the friction stable-stage of samples.

Fig. 9 Coherence analyses of vibration accelerations and sound pressures of samples.

GSs-SAC with the obvious friction-induced noises are all approximately 0.7, thus indicating that the vibration acceleration and noise signals are highly correlated. The coherence coefficients of GSs-SACT without the significant friction-induced noise are in the range of 0–0.1, thereby indicating that the signals are slightly correlated. Therefore, the friction-induced noise is closely related to the local vibration on surfaces triggered by the sliding friction. Moreover, the high-pitched noise is produced by the friction-induced vibration on SSs. The friction-induced vibration and noise are effectively reduced by the grooves on GSs. However, the low-frequency chattering is generated by the periodic impacts between counterpart ball and groove edges during the reciprocating sliding. Meanwhile, the synergistic effects of lubricants and grooves suppress the periodic vibration at the friction interface, thus inhibiting the friction-induced noise.

3.3 Worn surface analysis

As illustrated in Fig. 10, spalling and larger wear

Fig. 10 Morphology images (electronic probe microanalyzer) of worn surfaces of SSs, GSs, GSs-SAC, and GSs-SACT under the 20 N load.

debris are evident on the SSs, which clearly indicate that the dominant wear mechanism is adhesion. Furthermore, narrow furrows and wear debris can be observed on GSs. The spalling phenomena on groove edges are triggered by the impact of the counterpart ball. However, the presence of the micro-grooves on the contact surfaces indicated that abrasion is the wear mechanism. The furrows, smaller wear debris, and Sn-Ag-Cu could be observed on GSs-SAC; however, no obvious furrow and spalling exists on the GSs-SACT. Furthermore, the cracking and deformation of Sn-Ag-Cu- Ti_3C_2 in the grooves are observed. Consistently, GSs-SACT exhibited the best anti-friction performance, which alters the wear mechanisms and extends the service life of materials.

As presented in Fig. 11, the depths of SSs, GSs, GSs-SAC, and GSs-SACT are approximately 20.05, 19.91, 19.79, and 3.26 mm, respectively, and the worn surface widths are approximately 1009.5, 926.3, 872.5, and 606.7 mm, respectively. The wear loss and surface roughness of SSs exhibited maximum values, while those for GSs-SACT are the minimum. Meanwhile, it

is observed that the cross-sectional profile of SSs exhibits apparent convex edges with parabolic plastic deformation while the plastic deformation of GSs is the inverted triangle shape. The profile of GSs-SAC depicts a clear fluctuation, and the profile of GSs-SACT exhibits a smooth curve. Therefore, the wear debris is trapped by the grooves, thus reducing the damage of wear debris to the surfaces. Sn-Ag-Cu spreads out over the contact surface, and fills the pits on GSs-SAC. Consequently, the low-shear conjunction layer and relative smooth surface trigger a remarkable reduction in the wear rate. The elemental distributions on GSs-SACT before and after friction tests are presented in Fig. 12. Under the influence of frictional force and heat, the composite lubricants with MXene- Ti_3C_2 are presented and distributed uniformly on the worn surface. Moreover, the oxygen element significantly increases on the worn surface, which indicates that tribo-chemical reactions occur during the friction process. In addition, oxides and intermetallic compounds are produced, which could affect the wear resistance performances of materials.

Fig. 11 3D surface mappings, 2D profiles, and roughness of worn surfaces under the 20 N load.

As presented in Fig. 13, the SSs with noticeable bulges have severe sub-surface defects. In addition, plastic deformations, grain refinements, transverse cracks, and micro-pores can be detected. The plastic deformations, grain refinements, and cracks also appear in the GSs sub-surface. However, the groove edges are broken by impacting, and the wear debris caused by the furrows are collected in the grooves. As Sn–Ag–Cu spreads out and fills the worn pits, it smoothens the worn surface of GSs–SAC. A damaged layer with the cracks and micro-pores is distinguished

in the sub-surface close to the worn GSs–SAC. The Sn–Ag–Cu– Ti_3C_2 alloy with MXene– Ti_3C_2 diffuses on the worn GSs–SACT, which reduces the friction-induced damage. Therefore, under the influence of frictional force and heat, Sn–Ag–Cu can cover the surface cracks and fill the surface pits, which facilitates a self-healing effect for the surface damages. Therefore, the “nano-nail effect” of 2D MXene– Ti_3C_2 improves the anti-friction property of Sn–Ag–Cu, which makes the repairing effect of composite lubricants completely feasible.

Fig. 12 Elemental distribution analyses of GSs-SACT (a–g) before and (h–n) after friction tests under the 20 N load.

As illustrated in Fig. 14, XRD patterns of SSs, GSs, and the initial surface (smooth surface before the friction test) are similar, thereby indicating that no significant tribo-chemical reaction occurs on the worn surfaces after the friction tests. Meanwhile, XRD patterns of GSs-SAC and GSs-SACT exhibit new crystal peaks, and the tribo-chemical reactions occur at the interfaces. The intermetallic compounds of Ag_4Sn , FeSn , and Fe_3Sn_2 , as well as Ag_2O , CuO , and SnO_2 oxides are produced on GSs-SAC and GSs-SACT. Moreover, some titanium products such as TiC , SnTi_2 , and TiO_2 could be detected on the GSs-SACT. As presented in Table 5, several hexagonal crystal structures are produced by the tribo-chemical reactions. The hexagonal systems with low shear stress and strong bearing capacities exhibit better tribological properties. Moreover, the hard phases with small diameters and high densities are produced

by the tribo-chemical reactions on GSs-SAC and GSs-SACT, which improve the mechanical properties of lubricating films. During the sliding process, the lubricating films with excellent anti-friction properties on the worn surface are formed by the tribo-chemical reactions, which inhibit the frictional damage and enhance the bearing capacity of GSs-SACT.

The crystallinities of sample surfaces significantly decreased, and the average grain diameters increased after the sliding tests. Several damages of the material crystal structure were caused by friction. Moreover, the crystallinity of GSs-SAC exhibits the lowest damage, and the average grain diameter is the largest. Sn-Ag-Cu on GSs-SAC could activate the surface chemical energies of materials and promote the tribo-chemical reactions. However, MXene- Ti_3C_2 in Sn-Ag-Cu- Ti_3C_2 exhibits “nano-nail effect”, which increases the worn surface crystallinities and average

Fig. 13 (a–e) Microphotographs and (f–j) elemental content analyses of cross-sections of the samples.

Fig. 14 XRD patterns of the samples.

grain diameters; hence, it improves the lubrication performance. The residual strains are eliminated by Sn–Ag–Cu–Ti₃C₂, which improves the stress field distributions on GSs–SACT. The results indicated that the synergistic effects of MXene–Ti₃C₂ and Sn–Ag–Cu triggered a significant enhancement in the anti-friction property.

SSs with severe material damage are primarily characterized by adhesive wear, and the high-frequency noises are produced during the tests. However, the existence of narrow furrows on GSs verifies that the dominant wear mechanism is abrasion. In addition, the sliding of Si₃N₄ against GSs exhibited low-frequency chattering. The wear debris settled in the surface grooves, which minimizes the wear rate of

Table 5 Physical properties of chemical reaction products on worn surfaces.

Chemical formula	JCPDS file No.	Crystal system	Grain size (nm)	Density (g/cm ³)
Ti	00-044-1288	Cubic	22.9	4.401
Sn	00-004-0673	Tetragonal	189.2	7.287
C	01-071-3739	Hexagonal	164.6	2.271
TiC	01-074-1219	Cubic	66.7	4.088
FeSn	03-065-3478	Hexagonal	65.8	7.986
Fe ₃ Sn ₂	97-000-0071	Hexagonal	33.9	8.219
SnTi ₂	00-010-0226	Hexagonal	6.2	6.665
Ag ₄ Sn	00-029-1151	Hexagonal	12.8	10.03
TiO ₂	01-072-4815	Tetragonal	34.3	4.252
Ag ₂ O	00-012-0793	Cubic	3.2	7.245
CuO	01-070-6831	Monoclinic	5.2	6.509
SnO ₂	01-046-1088	Tetragonal	2.7	6.936

GSs. Because Sn–Ag–Cu repairs the worn cracks on GSs–SAC, the friction damages are significantly reduced, and the friction processes are accompanied by the lower friction-induced noise. The surface defects (cracks and pores) on SSs produced during the rubbing of the sliding surfaces trigger the spalling and wear debris on the worn surface. Nevertheless, the wear mechanism turned to the tribo-chemical wear by Sn–Ag–Cu, which produces oxides and intermetallic compounds with anti-friction effects to improve the tribological properties. Moreover, MXene–Ti₃C₂ could enhance the anti-friction property of the Sn–Ag–Cu lubricant on GSs–SACT.

3.4 Characteristics of composite lubricant Sn–Ag–Cu–Ti₃C₂

No adhesive trend exists for tin-based alloy lubricants on the iron-based materials caused by the immiscibility between tin (Sn) and iron (Fe), which could inhibit the adhesive wear on the surfaces. Therefore, tin-based alloys are widely used as lubricants (bearing alloy) on the surface of iron-based materials. The immiscibility between tin (Sn) and iron (Fe) is an important advantage of bearing alloy. The common bearing alloys are Babbitt alloys, such as ZChSnSb11-6 (Sb: 10.0–12.0 wt%, Cu: 5.5–6.5 wt%, Sn: Balance) and ZChSnSb8-4 (Sb: 7.0–9.0 wt%, Cu: 3.5–5.5 wt%, Sn: balance). As illustrated in Fig. 15, the contact angles of Sn–Ag–Cu and Sn–Ag–Cu–Ti₃C₂ on the smooth and groove surfaces of CSS-42L steel at 500 °C are

investigated under vacuum condition using the contact angle measuring instrument. All contact angles are larger than 90°. Therefore, Sn–Ag–Cu and Sn–Ag–Cu–Ti₃C₂ guarantee the immiscibility properties of the tin-based alloy on iron-based materials, which are beneficial in minimizing the adhesive wear.

The worn surface with the higher microhardness would exhibit the best wear resistance. As presented in Fig. 16, the microhardnesses of worn surfaces are larger than those of surfaces before tests. The microhardnesses of worn surfaces are increased with the increase in the loads, thus indicating that the frictional behaviors could increase microhardnesses, as a rational result of the strain hardening, owing to the plastic deformation after the sliding. Moreover, the microhardnesses on worn surfaces could be increased by the composite lubricants of Sn–Ag–Cu–Ti₃C₂. Compared with SSs, GSs, and GSs–SAC, the microhardnesses of GSs–SACT under loads of 10, 20, and 30 N are increased by 32.8%, 27.6%, and 30.0%, as well as by 18.3%, 24.2%, and 12.5%, and by 10.7%, 16.0%, and 6.3%, respectively. Furthermore, the worn surfaces are repaired by Sn–Ag–Cu–Ti₃C₂, thereby improving the microhardness and wear resistance of worn surfaces. As illustrated in Fig. 17, after the friction tests, clusters of surface cracks could be observed on Sn–Ag–Cu and Sn–Ag–Cu–Ti₃C₂ surfaces. Sn–Ag–Cu has significantly larger cracks than Sn–Ag–Cu–Ti₃C₂. Moreover, with the increase in the load, the cracks on Sn–Ag–Cu are increased, such that the lengths and widths become longer and wider. However, the effects

Fig. 15 Miscibility analyses of lubricants and CSS-42L substrate.

Fig. 16 Microhardness analyses of the samples.

of the applied load on Sn-Ag-Cu-Ti₃C₂ are limited. With its unique micro-nano size-effects, MXene-Ti₃C₂

could enhance the integrity and anti-friction property of lubricating films.

Fig. 17 Microscopic images of lubricant cracks.

3.5 Surface profile characteristics

As illustrated in Figs. 18(a)–18(c), with the increase in the load, the roughness (R_a) of samples and surface damages are increased. In addition, the surface damages and minimal surface roughness are observed for GSs–SACT. Furthermore, the kurtosis (R_{ku}) of profile is approximately 3, which indicates that the amplitude curves of surface profiles are uniform. Nevertheless, R_{ku} decreases with the increase in the load. Because the R_{ku} of GSs–SACT exhibited a value of 3, the profile sharpness and wear reduction of GSs–SACT exhibited the best performance. Meanwhile, with the increase in the load, the skewness (R_{sk}) of SSs increases, while those of GSs and GSs–SAC decrease, and that of GSs–SACT is maintained at approximately 0.6. However, the skew levels of surface profiles can be characterized by R_{sk} . A larger R_{sk} implies a larger proportion of valleys in the profiles. When R_{sk} is negative, the proportion of peaks in the profiles is larger than that of valleys. Furthermore, the valleys are more than the peaks in SSs profiles, whose proportion in the profiles is increased with the increase in the load. Because the valleys considered the starting points of cracks, the surfaces that have more valleys exhibit a higher tendency to be cracked.

Moreover, the peaks are more than the valleys in the profiles of GSs and GSs–SAC, and the proportion of peaks and valleys in the profiles increases with the increase in the load. The peaks are the stress concentration points, and the increase in the peaks would trigger surface damages. Meanwhile, the R_{sk}

of GSs–SACT is the smallest, which indicates that the valleys with the shallow depth are uniformly distributed in the profiles. When the loads are increased, it is observed that the profiles on GSs–SACT are smoother and more uniform.

As presented in Figs. 18(d)–18(f), the steep shape of the surface profiles is characterized by the average absolute slope (Δa). The profiles of SSs are the steepest, and those of GSs–SACT exhibit the least steepness. Moreover, with the increase in the load, the steepness of the profiles increases. During the friction, the stress concentrations could be caused by the profiles with the larger steepness. Accordingly, the surface damages increase. Meanwhile, the wrinkle levels of the surface profiles are characterized by the length ratio (l_r). The wrinkle levels of surface profiles increase with the increase in the load, which indicates that the deformations and damages on the surfaces increase. Furthermore, λ_a represents the average wavelength of the profile. The profile wavelengths increase with the increase in the load. The smaller wavelength could improve the bearing capacity and wear resistance of profiles. In addition, GSs–SACT exhibited the minimum values of Δa , l_r , and λ_a . Correspondingly, GSs–SACT exhibited the highest wear resistance and bearing capacity owing to the uniform profile shape and limited presence of the stress concentration zones.

The amplitude distribution function (ADF) represents the probability density functions of profile amplitudes within the evaluated length. ADF distribution areas of the samples increase with the increase in the load,

Fig. 18 Changes in profile parameters of the worn surfaces.

which indicates that the sharp peaks and deep valleys in the profiles increase. As presented in Figs. 19(a)–19(c), the distributions of sharp peaks and deep valleys on GSs–SACT with the uniform profile heights are the least, which would reduce the probabilities of damages. Peak count (PC) represents the quantitative distribution of peaks within the evaluated length, which influences the wear resistance performance of surfaces. When the load is increased from 10 to 20 N, the peaks in the profiles increase. Although the low-amplitude peaks decrease as the load is increased from 20 to 30 N, the high-amplitude peaks increase. Therefore, under all loads, GSs–SACT profiles exhibit the lowest number of total and high-amplitude peaks, which could improve the wear

resistance of the surfaces. Bearing ratio (BR) represents the ratios of profile lengths to the evaluated lengths at the horizontal sections, which reflect the bearing capacity of the surface. Moreover, the sharp peaks are the stress concentration points of interface interaction, and the deep valleys represent the starting points of the cracks. The sharp peaks and deep valleys promote the damages to the material surface. Furthermore, the larger BR curve slopes lead to lower proportions of sharp peaks and deep valleys in the profiles. The sharp peaks and deep valleys increase with the increase in the load, which would reduce the bearing capacity of the profiles. Meanwhile, the effects of loads on the BR curves of GSs–SACT are the minimum, thus indicating that the bearing capacity of GSs–SACT

Fig. 19 (a, c, e) Amplitude distribution functions, and (b, d, f) bearing ratios and peak counts of the surface profiles.

profiles is the best.

GSs-SACT profiles are described by the amplitude parameters (R_a , R_{ku} , and R_{sk}), spatial parameter (λ_a), hybrid parameters (Δa and l_r), and statistical curves (ADF, PC, and BR), which show the contact characteristics and wear resistance mechanisms of GSs-SACT. Moreover, the profiles with several sharp peaks and deep valleys on the worn SSs are steep and wrinkled, which indicate the poor wear resistance and high-frequency noise during the drying friction. The grooves on GSs could reduce the wear and friction-induced noise. However, abrasive wear is

observed on GSs, whose profiles have not been improved. The anti-friction effects of grooves and Sn-Ag-Cu on GSs-SAC could improve the profiles and suppress the friction-induced noise. However, with the increase in the load, the anti-friction effects on GSs-SAC are reduced. The better contact characteristics are produced by the synergistic effects of grooves and Sn-Ag-Cu-Ti₃C₂ on GSs-SACT, which obtains the best bearing capacity and anti-friction property. Meanwhile, the profile characteristics on GSs-SACT are difficult to induce the self-excited vibrations of friction system; therefore, no obvious

friction-induced noise exists at the interface.

3.6 Anti-friction and friction-induced noise reduction mechanisms of GSs–SACT

As presented in Fig. 20, the friction system on GSs–SACT could be represented as the sphere (M) moving with the velocity (V) on the horizontal plane, with the grooves and lubricants under the applied load (F_N) and frictional force (F_X). Meanwhile, tribo-chemical wear occurs on GSs–SACT during the sliding process. The lubricating films containing Sn–Ag–Cu, MXene– Ti_3C_2 , oxides, and intermetallic compounds are spread out on the worn surface to repair the defects. The “nano-nail effect” of MXene– Ti_3C_2 improves the crystallinities and reduces the residual strains on the worn surfaces, which enhances the tribological performances of GSs–SACT.

The friction-induced vibration and noise system could be represented as the sphere (M) moving with

the velocity (V) under the applied load (F_N). The contact interface is equivalent to the thin elastomer layer with the damping (C) and spring (K). During the sliding process, the friction-induced noises with the various frequencies are induced by the self-excited vibration at the interface. The synergistic effects of grooves and Sn–Ag–Cu– Ti_3C_2 improve the inconsistent rules of frictional forces, which enhance the noise reduction performance on GSs–SACT. Meanwhile, the wear and noise reduction mechanisms are investigated by the profile characteristics. The relationships between noise and lubricants are established by analyzing the changes in frictional force and the surface profiles. The best profile characteristics are obtained by the synergistic effects of grooves and Sn–Ag–Cu– Ti_3C_2 . The amplitude parameters (R_a , R_{ku} , and R_{sk}), spatial parameter (λ_a), hybrid parameters (Δa and l_r), and statistical analysis curves (ADF, PC, and BR) provide the comprehensive characterizations of the profile information. The surface profiles after the abrasive and

Fig. 20 Anti-friction and noise reduction mechanisms of GSs–SACT.

adhesive wears are steeped and wrinkled, respectively. The surface profiles with the sharp peaks and deep valleys result in the fluctuation of frictional forces, which trigger friction-induced vibration and noise. The GSs–SACT with uniform profiles could effectively suppress the self-excited vibrations and friction-induced noise. This study could provide the experimental bases for the applications of anti-friction and friction-induced noise reduction performance of CSS-42L in the field of tribology.

4 Conclusions

In this study, the effects of textured surfaces filled with Sn–Ag–Cu and MXene–Ti₃C₂ on the friction, wear, and friction-induced noise of CSS-42L steel were investigated. According to the test results, the following conclusions were drawn:

1) GSs–SACT exhibited the lowest friction coefficients and friction-induced noise among SSs, GSs, and GSs–SAC. The synergistic effects of textures and Sn–Ag–Cu–Ti₃C₂ significantly improve the changing rules of frictional forces, which enhance the noise reduction ability on GSs–SACT.

2) The wear mechanism of SSs is adhesive wear, which produces high-frequency noise during the tests. The abrasive mechanism of GSs triggered low-frequency chattering. The low-noise induced by GSs–SAC is attributed to the tribo-chemical wear. However, GSs–SACT exhibited the minimum noise and wear.

3) Sn–Ag–Cu–Ti₃C₂ exhibited immiscibility properties with tin-based alloy on CSS-42L, which could restrict adhesive wear. The tribo-chemical reactions on GSs–SACT produced oxides and intermetallic compounds with strong bearing capacities and excellent wear resistance. The crystallinities on the worn surfaces were improved by the “nano-nail effect” of MXene–Ti₃C₂, which enhances the anti-friction performance of composite lubricants. The tribological properties of GSs–SACT were remarkably improved.

4) When the profiles were steeped and wrinkled, the friction-induced noise could be clearly observed. The synergistic effects of grooves and Sn–Ag–Cu–Ti₃C₂ on GSs–SACT are beneficial in forming uniform profiles with excellent bearing capacities and wear resistance, which prevents the self-excited vibration of friction system, as well as the friction-induced noise.

Acknowledgements

This work was supported by the Guangdong Basic and Applied Basic Research Foundation. Authors are also grateful to Xiaolei NIE, Yumei LI, Meijun YANG, Wanting ZHU, Suling ZHAO, and Linqing QIN in the Material Research and Test Center of WUT for their kind help with SEM, EPMA, FESEM, and XRD.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made.

The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- [1] Qiu Z F, Wang F F, Li Q S, Zheng L J, Zhang F X, Zhang H. Corrosion and mechanical properties for Cr-coated CSS-42L bearing steel after Ti and C ions co-implantation. *Appl Surf Sci* **509**: 145293 (2020)
- [2] Wang F F, Zheng L J, Li Q S, Zhang F X, Chen X H, Zhang H. Corrosion properties of carbon ions implanted chromium coating prepared on CSS-42L aerospace bearing steel. *Surf Coat Technol* **349**: 392–399 (2018)
- [3] Wang F F, Zhou C G, Zheng L J, Zhang H. Improvement of the corrosion and tribological properties of CSS-42L aerospace bearing steel using carbon ion implantation. *Appl Surf Sci* **392**: 305–311 (2017)
- [4] Ji Z J, Zhang L, Xie G X, Xu W H, Guo D, Luo J B, Prakash B. Mechanical and tribological properties of nanocomposites incorporated with two-dimensional materials. *Friction* **8**(5): 813–846 (2020)
- [5] Zhai W Z, Bai L C, Zhou R H, Fan X L, Kang G Z, Liu Y, Zhou K. Recent progress on wear-resistant materials: Designs, properties, and applications. *Adv Sci* **8**(11): 2003739 (2021)

- [6] Mai Y J, Li Y G, Li S L, Zhang L Y, Liu C S, Jie X H. Self-lubricating Ti_3C_2 nanosheets/copper composite coatings. *J Alloys Compd* **770**: 1–5 (2019)
- [7] Cheng H, Zhao W J. Regulating the Nb_2C nanosheets with different degrees of oxidation in water lubricated sliding toward an excellent tribological performance. *Friction*: 1–13 (2021)
- [8] Meng F N, Zhang Z Y, Gao P L, Kang R Y, Boyjoo Y, Yu J H, Liu T T. Excellent tribological properties of epoxy— Ti_3C_2 with three-dimensional nanosheets composites. *Friction* **9**(4): 734–746 (2021)
- [9] Ronchi R M, Arantes J T, Santos S F. Synthesis, structure, properties and applications of MXenes: Current status and perspectives. *Ceram Int* **45**(15): 18167–18188 (2019)
- [10] Zhang H, Wang L B, Chen Q, Li P, Zhou A G, Cao X X, Hu Q K. Preparation, mechanical and anti-friction performance of MXene/polymer composites. *Mater Des* **92**: 682–689 (2016)
- [11] Lian W Q, Mai Y J, Liu C S, Zhang L Y, Li S L, Jie X H. Two-dimensional Ti_3C_2 coating as an emerging protective solid-lubricant for tribology. *Ceram Int* **44**(16): 20154–20162 (2018)
- [12] Rosenkranz A, Grützmacher P G, Espinoza R, Fuenzalida V M, Blanco E, Escalona N, Gracia F J, Villarreal R, Guo L C, Kang R Y, et al. Multi-layer $\text{Ti}_3\text{C}_2\text{T}_x$ -nanoparticles (MXenes) as solid lubricants—Role of surface terminations and intercalated water. *Appl Surf Sci* **494**: 13–21 (2019)
- [13] Guo L H, Zhang Y M, Zhang G, Wang Q H, Wang T M. MXene— Al_2O_3 synergize to reduce friction and wear on epoxy-steel contacts lubricated with ultra-low sulfur diesel. *Tribol Int* **153**: 106588 (2021)
- [14] Xue Y W, Shi X L, Lu G C, Zhou H Y, Chen Y, Shu J P. Tribological behavior of M50—Sn—Ag—Cu composites with curved microchannels. *J Mater Eng Perform* **29**(4): 2190–2201 (2020)
- [15] Liu X Y, Shi X L, Huang Y C, Deng X B, Yan Z, Xue B. Anti-friction and wear properties of the friction surface of M50—10 wt%(50Sn₄₀Ag₁₀Cu) composite. *J Alloys Compd* **765**: 7–17 (2018)
- [16] Lu G C, Shi X L, Zhang J, Zhou H Y, Xue Y W, Ibrahim A M M. Effects of surface composite structure with micro-grooves and Sn—Ag—Cu on reducing friction and wear of Ni_3Al alloys. *Surf Coat Technol* **387**: 125540 (2020)
- [17] Liu X Y, Shi X L, Huang Y C, Deng X B, Lu G C, Yan Z, Xue B. Tribological behavior and self-healing functionality of M50 material covered with surface micropores filled with Sn—Ag—Cu. *Tribol Int* **128**: 365–375 (2018)
- [18] Hu T C, Hu L T, Ding Q. Effective solution for the tribological problems of Ti—6Al—4V: Combination of laser surface texturing and solid lubricant film. *Surf Coat Technol* **206**(24): 5060–5066 (2012)
- [19] Arenas M A, Ahuir-Torres J I, García I, Carvajal H, de Damborenea J. Tribological behaviour of laser textured $\text{Ti}_6\text{Al}_4\text{V}$ alloy coated with MoS_2 and graphene. *Tribol Int* **128**: 240–247 (2018)
- [20] Sadeghi M, Kharaziha M, Salimijazi H R. Double layer graphene oxide-PVP coatings on the textured $\text{Ti}_6\text{Al}_4\text{V}$ for improvement of frictional and biological behavior. *Surf Coat Technol* **374**: 656–665 (2019)
- [21] Li X, Liu Q, Dong G N. Self-assembly membrane on textured surface for enhancing lubricity of graphene oxide nano-additive. *Appl Surf Sci* **505**: 144572 (2020)
- [22] Zhou H Y, Shi X L, Yang Z Y, Wu C H, Lu G C, Xue Y W. Tribological property and frictional noise performance of titanium alloys with Sn—Ag—Cu and TiC filled into surface dimples. *Tribol Int* **144**: 106121 (2020)
- [23] Hua X J, Paoza J C, Sun J G, Zhang P Y, Ji J H, Wang H, Fu H, Kang Z Y. Experimental analysis of friction and wear of laser microtextured surface filled with composite solid lubricant and lubricated with grease on sliding surfaces. *J Tribol-T ASME* **139**: 021609 (2017)
- [24] Zhang Q, Mo J L, Lu X D, Zhao J, Wang D W, Zhou Z R. Grooved-structure design for improved component damping ability. *Tribol Int* **123**: 50–60 (2018)
- [25] Yang J, Liu Z L, Cheng Q C, Liu X K, Deng T Y. The effect of wear on the frictional vibration suppression of water-lubricated rubber slat with/without surface texture. *Wear* **426–427**: 1304–1317 (2019)
- [26] Wang D W, Mo J L, Liu M Q, Ouyang H, Zhou Z R. Noise performance improvements and tribological consequences of a pad-on-disc system through groove-textured disc surface. *Tribol Int* **102**: 222–236 (2016)
- [27] Massi F, Berthier Y, Baillet L. Contact surface topography and system dynamics of brake squeal. *Wear* **265**(11–12): 1784–1792 (2008)
- [28] Chen G X, Zhou Z R, Kapsa P, Vincent L. Effect of surface topography on formation of squeal under reciprocating sliding. *Wear* **253**(3–4): 411–423 (2002)
- [29] Sherif H A. Investigation on effect of surface topography of pad/disc assembly on squeal generation. *Wear* **257**(7–8): 687–695 (2004)
- [30] Lu G C, Shi X L, Liu X Y, Zhou H Y, Chen Y. Effects of functionally gradient structure of Ni_3Al metal matrix self-lubrication composites on friction-induced vibration and noise and wear behaviors. *Tribol Int* **135**: 75–88 (2019)
- [31] Wang D W, Mo J L, Zhang Q, Zhao J, Ouyang H, Zhou Z R. The effect of the grooved elastic damping component in reducing friction-induced vibration. *Tribol Int* **110**: 264–277 (2017)
- [32] Mo J L, Wang Z G, Chen G X, Shao T M, Zhu M H, Zhou Z R. The effect of groove-textured surface on friction and wear and friction-induced vibration and noise. *Wear* **301** (1–2): 671–681 (2013)
- [33] Xue Y W, Shi X L, Zhou H Y, Lu G C, Zhang J. Effects of groove-textured surface combined with Sn—Ag—Cu lubricant on friction-induced vibration and noise of GCr15 bearing steel. *Tribol Int* **148**: 106316 (2020)

Yawen XUE. He received his B.S. degree in mechanical engineering and automation in 2011 from Xinjiang Agricultural University, Urumqi, China. He received his M.S. degree in mechatronic engineering

in 2014 from Taiyuan University of Science and Technology, Taiyuan, China. He is now a Ph.D. student in Wuhan University of Technology, Wuhan, China. His research areas cover surface modification and tribology.

Chaohua WU. He received his B.S. degree in mechanical engineering and automation in 2003 from Wuhan University of Technology, Wuhan, China. He received his M.S. degree in mechanical manufacture and automation in 2006 from

Wuhan University of Technology, Wuhan, China. He

received his Ph.D. degree in industrial engineering from Wuhan University of Technology, Wuhan, China, in 2020. His current position is an assistant professor and a supervisor of graduates at the School of Mechanical and Electronic Engineering, Wuhan University of Technology. His research areas cover surface modification and process optimization.

Xiaoliang SHI. He received his B.S. degree in geological engineering in 1997 from China University of Geosciences, Wuhan, China. He received his M.S. and Ph.D. degrees in geological engineering from China University of Geosciences,

Wuhan, China, in 2000 and 2003, respectively. His current position is a professor and a Ph.D. supervisor at the School of Mechanical and Electronic Engineering, Wuhan University of Technology. His research areas cover tribology and surface interface technology of high-end equipment.

Qipeng HUANG. He received his B.S. degree in process equipment and control engineering in 2017 from Henan University of Technology, Zhengzhou, China. He received his

M.S. degree in mechanical engineering in 2020 from Henan University of Technology, Zhengzhou, China. His research interests focus on surface engineering, design of functional materials, and tribology.

Ahmed Mohamed Mahmoud IBRAHIM. He received his B.S. degree in production engineering and mechanical design in 2007 from Minia University, Egypt. He received his M.S. degree in the non-conventional machining processes

in 2011 from Minia University, Egypt. He received his Ph.D. degree in tribology and surface engineering

in 2016 from Wuhan University of Technology, China. He is currently an assistant professor in the Department of Production Engineering and Mechanical Design, Minia University, Egypt. His research interests are tribology, surface engineering, self-lubricating materials, non-conventional machining processes, green cutting fluids, additive manufacturing, and artificial intelligence applications in manufacturing processes.