

Full Length Article

Achieving macroscopic superlubrication in compressor applications via carbon-based coatings

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ABSTRACT

This study achieved friction reduction in compressor component friction pairs by applying carbon-based coating materials, exploring their tribological behaviors, and demonstrating their engineering applicability. Surface studies indicated that the coating incorporating the 2D shear layer exhibited a lower COF and reduced wear. Furthermore, wear scar analysis revealed that the shear layer was rapidly transferred to the counterface during initial sliding, where it formed a self-lubricating transfer film and frictional heat and shear forces induced the in-situ generation of graphitic carbon tribofilm. Notably, the SiMo-DLC coating exhibited strong substrate adhesion and resisted delamination, thereby significantly improving the tribological performance of metallic friction pairs under compressor operating conditions. Component testing confirmed that the DLC-based coatings reduced the compressor input power and enhanced energy efficiency by up to 4%, with the best performance observed when using the SiMo-DLC coating. These results elucidate the mechanism of engineered superlubricity arising from in-situ formation of graphitic structures within the transfer film, and provide experimental and theoretical support for the engineering application of carbon-based coatings in long-term service compressors.

1. Introduction

Compressors serve as core power units in critical applications including refrigeration, air conditioning, and vehicle thermal management systems. Although long-term stability and efficiency are critical for ensuring compressor system performance while minimizing energy consumption [1], internal moving components (e.g., pistons, vanes, and crankshafts) inevitably experience severe friction and wear under high-speed operation, high-pressure loads, cyclic stresses, and complex lubrication conditions [2–4]. This degradation manifests as growing dimensional inaccuracy, increased clearances between mating parts, reduced volumetric efficiency, elevated frictional power losses, and ultimately, diminished overall energy efficiency. These issues are further compounded by increased noise and vibration as well as reduced reliability and service life. Therefore, the wear between critical friction pairs must be reduced and friction surface properties enhanced to

advance compressor technology.

Conventional compressor vane surface treatments (e.g., nitriding, carburization, and heat treatment) provide limited improvement in wear resistance [5,6] and often fail to meet modern requirements for high energy efficiency, extended lifespan, ultralow friction, and environmental sustainability. Consequently, diamond-like carbon (DLC) films have emerged as promising materials for surface treatment owing to their exceptional combination of high hardness, low coefficient of friction, superior wear resistance, and chemical stability [7–9]. Extensive laboratory studies have confirmed the outstanding tribological performance of DLC coatings in various refrigerant environments, including research specifically examining their behaviors considering refrigerant interactions [10,11]. Regarding research on carbon-based coatings for compressors, investigations by De Mello et al. [12] investigated atmospheric influences on Si-doped DLC coatings, confirming reduced friction coefficients (0.3 in air) and enhanced wear resistance

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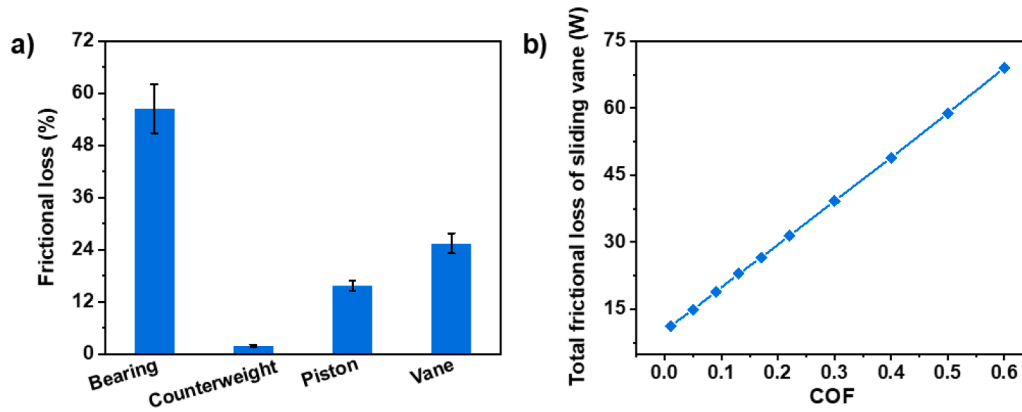


Fig. 1. a) Frictional loss distribution in compressor pump; b) Relationship between COF of the vane and its total frictional losses.

Table 1

Friction condition.

Upper sample coating	Lower sample coating	Load (N)	Speed (m/s)	Medium	Time (min)
Si-DLC or SiMo-DLC	Si/O-DLC	1	0.1	dry-friction	30
		2			
		1	0.04	refrigerating oil	
		2			
		200			

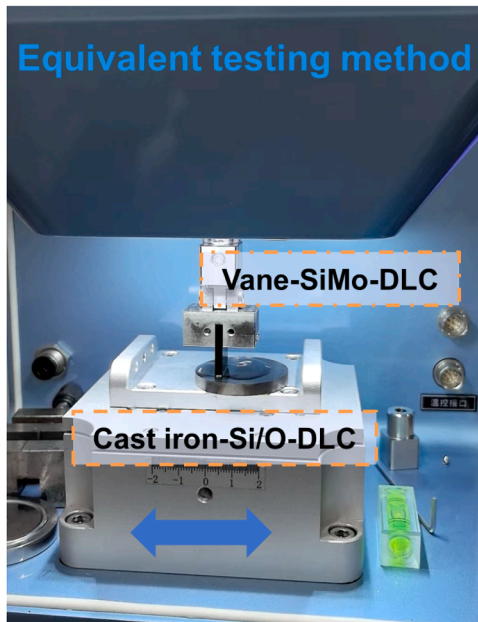


Fig. 2. Experimental setup for laboratory equivalent vane tests.

under refrigerant conditions. Similarly, He et al. [13] developed an unbalanced magnetron sputtering technology to deposit DLC films on orbiting scroll surfaces, demonstrating reduced friction coefficients to 0.1 with improved film-substrate adhesion. Notably, Lee et al. [14] achieved a remarkably low COF of 0.02 for tetrahedral amorphous carbon nitride coatings in R32 refrigerant. These low friction values approach engineering superlubricity regimes ($\text{COF} \leq 0.01$), potentially reducing friction by an order of magnitude compared with conventional lubrication [15]. Theoretical advances have paralleled experimental findings, with mechanistic understanding of DLC superlubricity significantly advanced through models addressing interface passivation,

stress-induced graphitization, and tribofilm formation [16–19]. These advances highlight the considerable potential of engineered carbon-based coatings for enhancing compressor energy efficiency and operational durability. In most engineering implementations, DLC coatings predominantly rely on transfer film generation for lubrication, where establishing such interfacial layers during sliding contact is essential for achieving low friction coefficients and extended service lifetimes. This understanding led to a targeted hypothesis: depositing carbon-based coatings featuring an outermost layer specifically engineered to facilitate transfer film formation may improve lubrication performance on compressor surfaces. Crucially, while substantial research exists on DLC films for compressors, the tribological behavior of compressor materials coated with functional gradient coatings, particularly the relationship linking their friction characteristics to compressor energy efficiency, the design criteria for ultralow-friction coatings, and their corresponding lubrication mechanisms, remains insufficiently studied. A systematic investigation into this relationship is therefore necessary both to validate the proposed coating design and quantify its impact on compressor performance.

Therefore, this study systematically investigated the mechanisms and application potential of carbon-based coatings to enhance the energy efficiency and wear resistance of critical compressor friction pairs. Two advanced coatings, $\alpha\text{-C:H:Si}$ (named Si-DLC) and $\alpha\text{-C:H:Si/MoS}_2$:GLC (named SiMo-DLC), were developed using a targeted compositional design and deposition process, and their physical properties, tribological performances under various conditions, wear scar morphologies, and chemical compositions were characterized. Furthermore, the roles of the engineered two-dimensional (2D) functional shear layer in tribological behavior regulation and the corresponding superlubrication mechanisms were elucidated. Finally, practical friction-reduced performance was validated by conducting compressor installation tests using the optimized coatings. The results of this study establish essential theoretical and experimental frameworks for implementing carbon-based coatings in compressor systems and provide critical insights for developing energy-efficient and reliable compressor technologies.

2. Theoretical explanation of carbon-based coating application in compressors

The movement of compressor components is relatively complex and involves multiple lubrication states. Taking a small rotary air-conditioning compressor as an example, Meizhi Compressor Co. (named GMCC) reporting and self-developed software indicate that frictional losses of vane and piston account for approximately 40% in compressor pump (Fig. 1a). Considering the costs associated with the coating process, carbon-based coating treatments should be applied only to the vanes and pistons accordingly.

Note that the improvement in energy efficiency provided by the

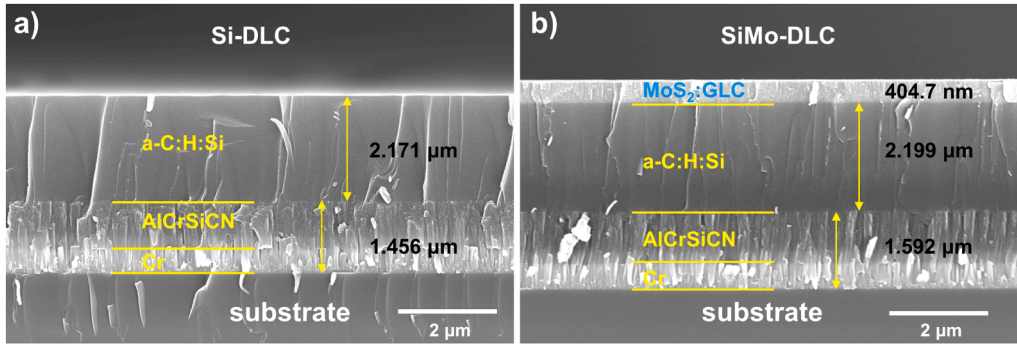


Fig. 3. Structure of a) Si-DLC and b) SiMo-DLC coatings.

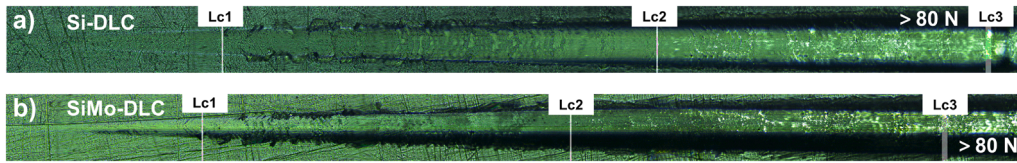


Fig. 4. Scratch test of adhesion between a) Si-DLC and b) SiMo-DLC coatings on vane substrate.

Table 2

Hardness and elasticity modulus of Si-DLC and SiMo-DLC according to test depth.

	50 nm indentation		100 nm indentation		300 nm indentation	
Coating	Hardness (GPa)	Elastic modulus (GPa)	Hardness (GPa)	Elastic modulus (GPa)	Hardness (GPa)	Elastic modulus (GPa)
Si-DLC	12.1	91.5	12.38	105.6	12.7	99.0
SiMo-DLC	6.5	86.9	6.39	89.1	7.8	107.5

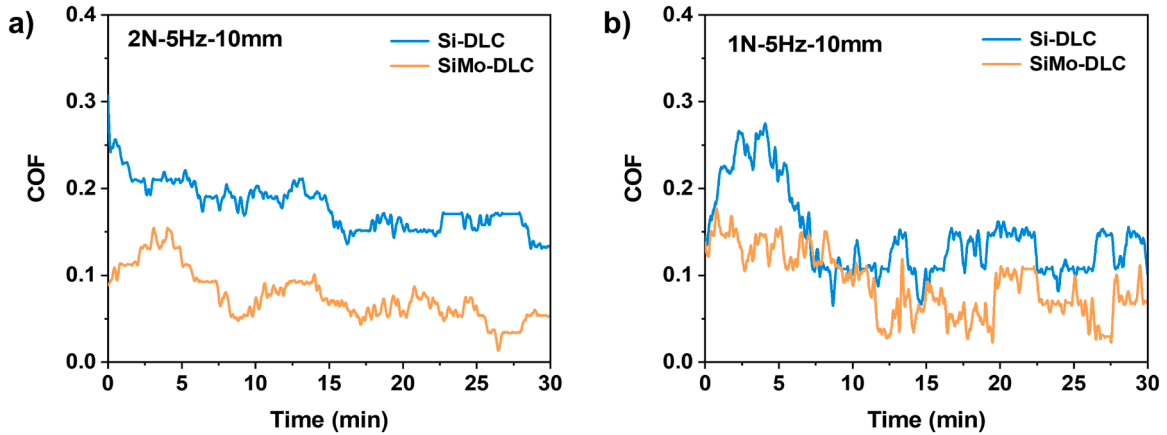


Fig. 5. Variation in COF over time using Si-DLC and SiMo-DLC coatings in dry-friction conditions with a) 2 N and b) 1 N loads.

coating is inversely proportional to the input power. For example, the total frictional losses at the vane tip contact [20] are given by

$$L = \mu_v F_n (r\omega_p + e\omega \cos\theta / \cos\alpha) \quad (1)$$

Where μ_v is COF between the vane tip and piston, r is piston outer ring radius, F_n is the normal force, ω_p is the rotation angular velocity of the piston, e is eccentricity of crankshaft, ω is the revolution angular velocity of the piston, θ is angle of piston, and α is the angle between the center at the end of the vane and the connecting line between the piston center and the center line of the vane.

As an example, the calculation results from one trial are shown in Fig. 1b. The results indicate that reducing the COF will decrease the frictional power loss, thereby reducing the input power and ultimately

improving energy efficiency, suggesting the potential benefits of carbon-based coatings.

3. Materials and methods

3.1. Carbon-based coatings design

For coating design, the doping of Si element and the design of Mo element are based on research reported in the literature: The doping of Si elements is relatively common in DLC coatings, and its lubrication mechanism is also clear [21]. On one hand, since the bond energy of C-C bonds is higher than that of C-Si and Si-Si bonds, Si doping can effectively reduce atomic interactions at the friction interface of the thin film, thereby decreasing sliding resistance and friction coefficient. On the

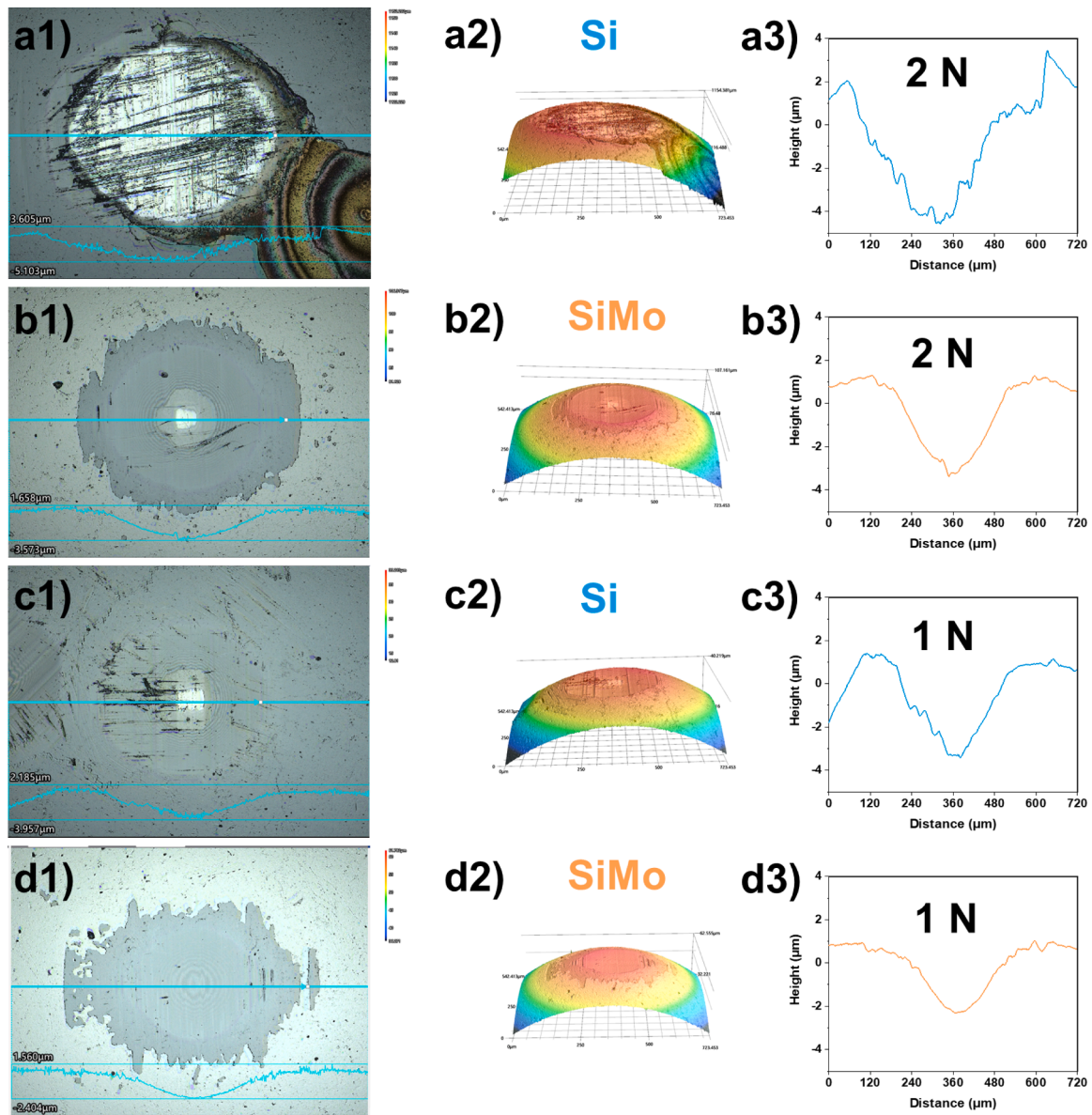


Fig. 6. Wear morphologies and corresponding depth profiles of upper counterpart balls coated with: a) Si-DLC and b) SiMo-DLC at 2 N; c) Si-DLC and d) SiMo-DLC at 1 N.

other hand, Si doping promotes the transformation of sp^3 -C bonds into sp^2 -C bonds, increasing the graphitization degree of the carbon-based film and endowing it with easy-shear properties, thus further reducing friction. Molybdenum disulfide (MoS_2) exhibits a typical layered structure. Within each layer, atoms are bonded together by covalent bonds, while the van der Waals forces between adjacent layers are weak. This characteristic facilitates easy shearing during friction, thereby reducing the friction coefficient [22,23]. The purpose of incorporating functional layers with MoS_2 and GLC (graphite-like carbon) at the outermost surface is to allow the sliding piece to rapidly form an easy-shear pre-transfer film.

The coatings were prepared by the composite ion beam high-power pulsed magnetron sputtering technology, using acetylene (C_2H_2), tetramethylsilane (TMS) and hexamethyldisiloxane (HDMSO) as the precursor gases. The preparation of Si-DLC or Si/O-DLC comprises the first four steps, while SiMo-DLC adds an additional shear layer deposition process. The detailed process is as follows:

- (1) Using compressor vanes and 304 stainless steel balls as substrates, ultrasonically clean and dry them before placement in a vacuum chamber. After evacuating to below 3×10^{-3} Pa, clean all substrates via Ar plasma etching for 60 min.
- (2) Introduce Ar gas and activate the high-power pulsed magnetron sputtering power supply for the Cr target. Set working voltage to 600 V (1000 Hz) with 400 V negative bias voltage for 20 min deposition.
- (3) Maintain step (2) conditions while introducing C_2H_2 for gradient transition layer deposition. Gradually increase acetylene flow rate by 2 sccm throughout the 25 min sputtering process. Terminate all gases and power supplies after completion.
- (4) Introduce TMS or HDMSO and C_2H_2 gases. Activate the linear anode layer ion surge at 600 V with 300 V negative bias voltage to deposit Si-doped DLC coating for 600 min. Shut down gases and power after deposition.
- (5) Introduce Ar and activate sputtering power supplies for MoS_2 and graphite targets. Set working currents to 5 A and 1 A respectively

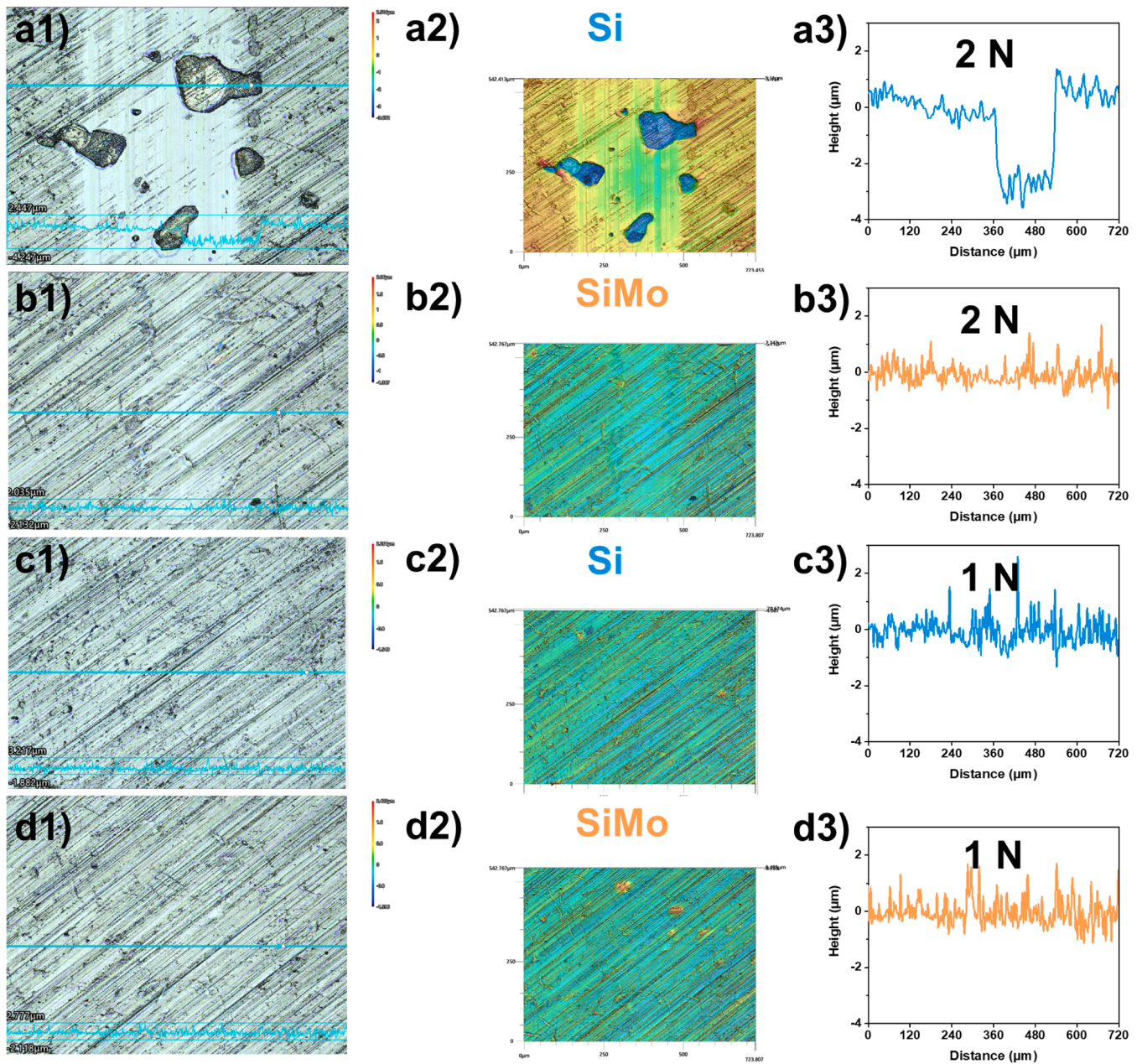


Fig. 7. Wear morphologies and corresponding depth profiles of bottom disks paired with balls coated with: a) Si-DLC and b) SiMo-DLC at 2 N; c) Si-DLC and d) SiMo-DLC at 1 N.

with 50 V negative bias voltage. Deposit surface functional layer for 120 min.

3.2. Friction testing

The selected compressor exhibits vane-piston interface contact pressures ranging from 200 to 450 MPa. Under typical operating conditions, the rotational frequency of the crankshaft falls within 20 Hz, while the piston operates at approximately 1/12 of this crankshaft frequency (the transmission ratio was calculated based on the crankshaft eccentricity and piston dimensions). With a piston diameter of 25 mm, the tangential linear velocity during motion reaches approximately 0.13 m/s. Based on these parameters, the applied loads and sliding velocities in subsequent friction tests were designed to closely replicate actual operating conditions.

The influence of each surface coating on tribological behavior was

investigated by conducting friction tests using tribometer (Table 1). Under ambient air, the upper component of the tribometer comprised a 6 mm diameter 304 stainless steel ball coated with either Si-DLC or SiMo-DLC, and the bottom component comprised a 10 mm thickness cast iron disk coated with α -C:H:Si/O (named Si/O-DLC). Tribological tests were conducted at room temperature using applied loads of 1 and 2 N (Hertz contact pressures of 350 and 440 MPa, respectively) at 5 Hz (linear speed: 0.1 m/s) for 30 min under both dry-friction and oil-lubricated (commercial refrigerating oil, Polyol Ester) conditions to measure the COF. Each test coating specimen was sonicated before friction testing. Each test was conducted in triplicate to ensure reliable results. The ball and disk from each test were washed in petroleum ether before observation. The wear rate (δ) of the upper ball was calculated as follows [24]:

$$\delta = \frac{V}{F_n v t} \quad (2)$$

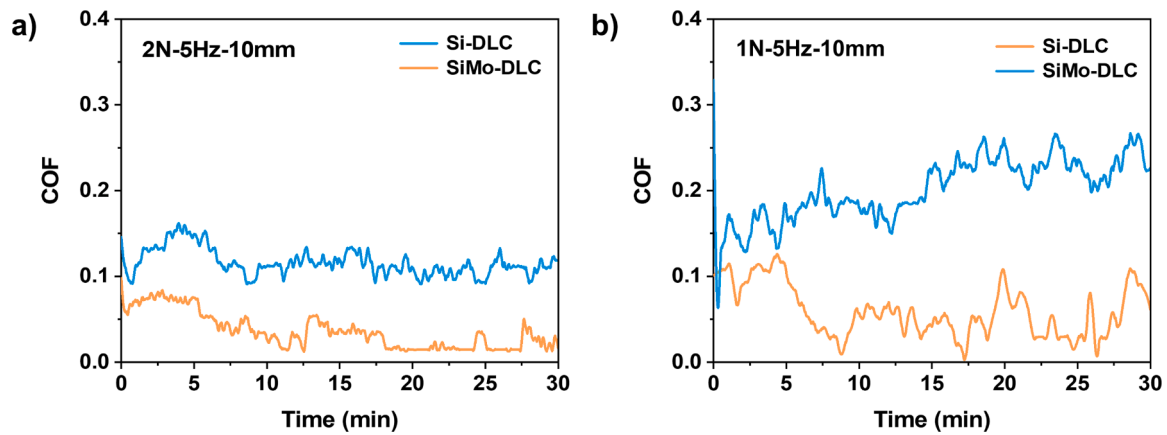


Fig. 8. Variation in COF over time using Si-DLC and SiMo-DLC coatings in oil-lubricated conditions under a) 2 N and b) 1 N loads.

where V is the wear volume of the upper ball, measured using a laser confocal microscope; F_n is the applied load (normal force); v is the linear speed; and t is the friction processing time.

Friction testing was also conducted using a laboratory equivalent test method replicating the contact between the compressor vane tip and piston ring using an upper steel vane (uncoated or coated with Si-DLC or SiMo-DLC) and a lower cast iron disk (uncoated or coated with Si/O-DLC) to better simulate friction performance in actual compressor applications (Fig. 2). Note that the surface roughness (R_z) of the disk matched that of the outer ring of the piston in the compressor. The vane was secured using a specialized fixture such that its R-surface (convex side) contacted the disk. Each test was conducted for 30 min at room temperature under a load of 200 N (Hertz contact pressure: 240 MPa) at a frequency of 2 Hz (linear velocity: 0.04 m/s) using commercial refrigeration oil as the lubricant.

3.3. Characterization

Coating hardness was determined before testing using a KLA nano-indenter in continuous stiffness measurement mode. Substrate interference was eliminated by performing indentations at controlled depths within 0–300 nm; ten measurements were collected at each depth on each coating and averaged to ensure statistical reliability. After testing, a laser confocal microscope was used to characterize coating morphology. Furthermore, the chemical compositions of the wear scars were determined by conducting X-ray photoelectron spectroscopy (XPS, Thermo Scientific ESCALAB 250Xi) using an Al $K\alpha$ excitation source and collecting Raman spectra (Evolution, HORIBA, France) from 150 to 2000 cm^{-1} using a 532 nm laser with a power of 3.25 mW for 40 s via two accumulations. The adhesion strength of the coating was measured by scratch testing with a load of 100 N at a loading rate of 100 N/min.

4. Results and discussion

4.1. Coating characteristics

Two types of carbon-based thin-film coatings were evaluated in this study: Si-DLC and SiMo-DLC. These coatings were obtained through element doping and composition control to realize long-term stable superlubricity with a COF below 0.01. As shown in Fig. 3, the two carbon-based coatings were exclusively differentiated by the 400 nm-thick soft 2D molybdenum disulfide-carbon (MoS_2/GLC) co-doped shear layer present in SiMo-DLC (Fig. 3b) but not in Si-DLC (Fig. 3a).

Scratch testing of coating–vane substrate adhesion surfaces revealed Lc3 values exceeding 80 N for both coatings (Fig. 4), indicating superior interfacial bonding.

Finally, the nanoindentation results indicated that the Si-DLC

coating exhibited hardnesses of 12.1, 12.38, and 12.7 GPa at 50, 100, and 300 nm (Table 2), respectively. Notably, because the testing depths were confined within the outermost layer of the SiMo-DLC coating, the measured hardnesses (6.5, 6.39, and 7.8 GPa at 50, 100, and 300 nm, respectively) specifically characterize the co-doped 2D material layer.

4.2. Coating behavior under dry-friction conditions

The results of the ball-on-disk tribological tests conducted under dry-friction atmospheric conditions are shown in Fig. 5, which indicates that SiMo-DLC exhibited a lower COF and a more stable friction process than Si-DLC under both 2 and 1 N loads. Note that the run-in process was completed within a short period of time. Critically, the lower initial COF indicates that SiMo-DLC played a particularly critical role in the tribo-reaction under the 2 and 1 N load.

The wear scars on the ball and disk contact surfaces after testing using the two coatings revealed distinct morphologies, as shown in Fig. 6. Under the 2 N loading, the Si-DLC coating exhibited prominent plowing grooves with the coating worn off in places to expose the metal substrate, suggesting interfacial asperity failure and severe wear owing to nonconformal contact (Fig. 6a). By contrast, the SiMo-DLC coating exhibited a relatively shallow wear depth of 3 μm with no obvious plowing grooves and a layer of grey material on its surface (Fig. 6b). Furthermore, the disks paired with the Si-DLC-coated balls exhibited coating delamination ($\sim 3 \mu\text{m}$ deep), whereas those paired with the SiMo-DLC-coated balls exhibited only shallow scratches within allowable surface roughness limits (Fig. 7).

Under the 1 N loading, the SiMo-DLC coating exhibited shallower wear depths and smaller scar diameters than the Si-DLC coating, with no observable coating detachment in the central wear zone of either ball (Fig. 6c and d). The disks exhibited negligible wear marks that remained within the allowable surface roughness limits regardless of coating type (Fig. 7c and d).

4.3. Coating behavior under oil-lubricated conditions

Friction experiments were also conducted incorporating a widely used commercial refrigerating oil to better align the test conditions with actual compressor operating conditions. The results in Fig. 8 indicate that SiMo-DLC provided a lower COF with reduced fluctuations compared with Si-DLC under both 2 N and 1 N loads, while also exhibiting enhanced process stability throughout the tests. Notably, SiMo-DLC exhibited a lower COF under oil-lubricated conditions than under dry-friction conditions.

The wear morphology analysis revealed distinct differences between coatings under the 2 N loading: the Si-DLC-coated balls exhibited morphologies similar to those obtained in dry-friction conditions, with

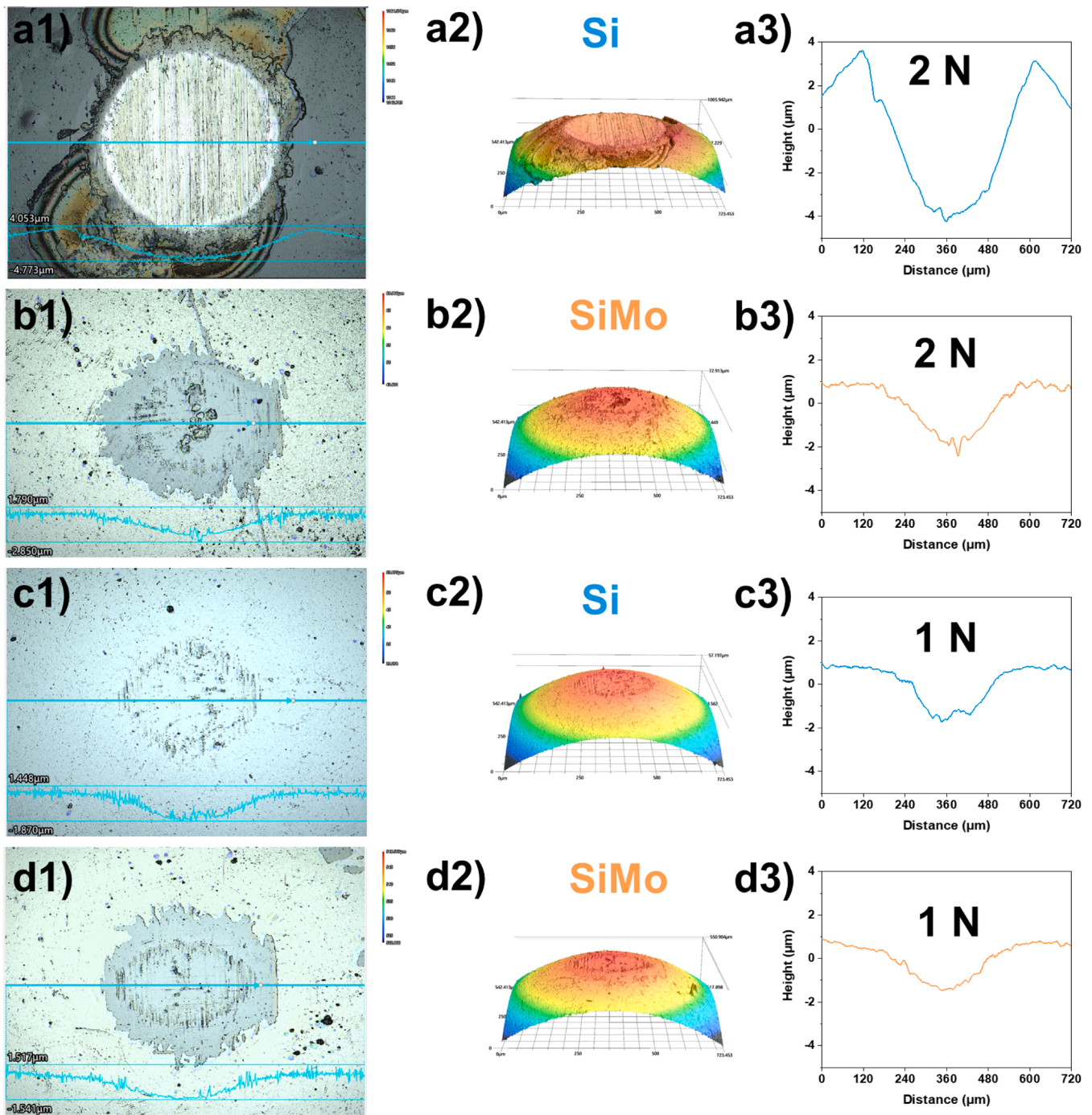


Fig. 9. Wear morphologies and corresponding depth profiles of upper balls coated with: a) Si-DLC and b) SiMo-DLC at 2 N; c) Si-DLC and d) SiMo-DLC at 1 N after oil-lubricant condition.

flattening of the spherical crown and removal of the entire coating layer through wear, resulting in a maximum wear depth in excess of 6 μm (Fig. 9a). By contrast, the SiMo-DLC-coated balls exhibited shallower wear depths ($\sim 2 \mu\text{m}$) within the coating thickness and acceptable surface roughness parameters, with no observable plowing grooves or coating delamination in the contact zone (Fig. 9b).

Under 1 N loading, the wear depths on the coated balls exhibited no significant differences, although gray material was again present on the surface of the SiMo-DLC-coated balls (Fig. 9c). Notably, the disks paired with both coating types exhibited no discernible wear marks under oil-lubricated conditions, and all measured wear depths remained within the allowable surface roughness limits (Fig. 10).

Fig. 11 compares the COFs and ball surface δ values for the Si-DLC and SiMo-DLC coatings under dry-friction and oil-lubricated conditions according to the applied load. The SiMo-DLC coating consistently exhibited a lower COF and δ than the Si-DLC coating. In dry-friction conditions, the δ values of the Si-DLC- and SiMo-DLC-coated balls reached 3.983 and $1.373 \times 10^{-8} \text{ mm}^3/\text{N}\cdot\text{m}$, respectively, under the 2 N load and 1.257 and $0.840 \times 10^{-8} \text{ mm}^3/\text{N}\cdot\text{m}$, respectively, under the 1 N load. In oil-lubricated conditions, the δ values of the Si-DLC- and SiMo-DLC-coated balls reached 3.067 and $0.423 \times 10^{-8} \text{ mm}^3/\text{N}\cdot\text{m}$, respectively, under the 2 N load and 0.677 and $0.480 \times 10^{-8} \text{ mm}^3/\text{N}\cdot\text{m}$, respectively, under the 1 N load. A comparative analysis revealed that SiMo-DLC outperformed Si-DLC under both dry-friction and oil-

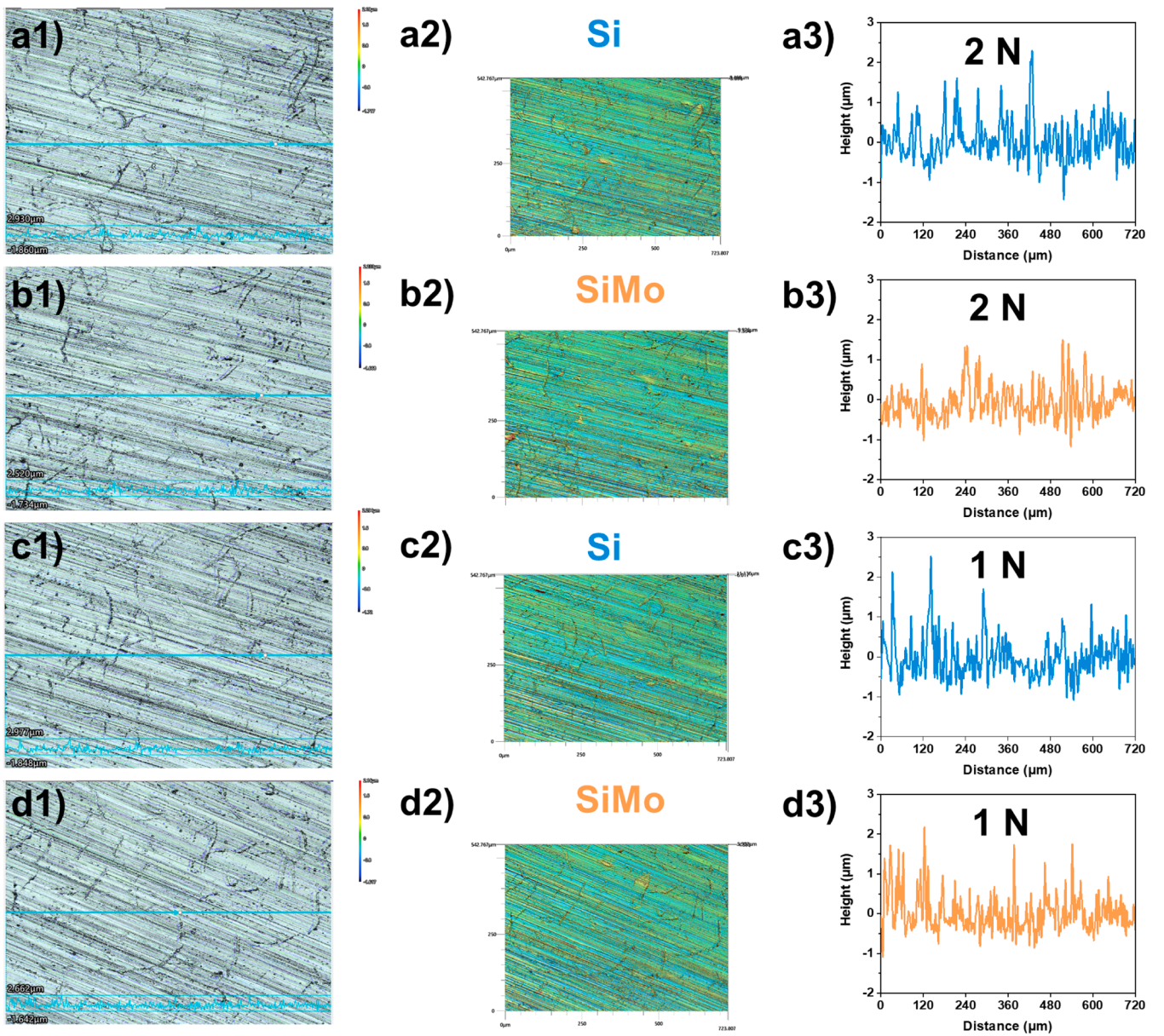


Fig. 10. Wear morphologies and corresponding depth profiles of bottom disks paired with balls coated with: a) Si-DLC and b) SiMo-DLC at 2 N; c) Si-DLC and d) SiMo-DLC at 1 N after oil-lubricant condition.

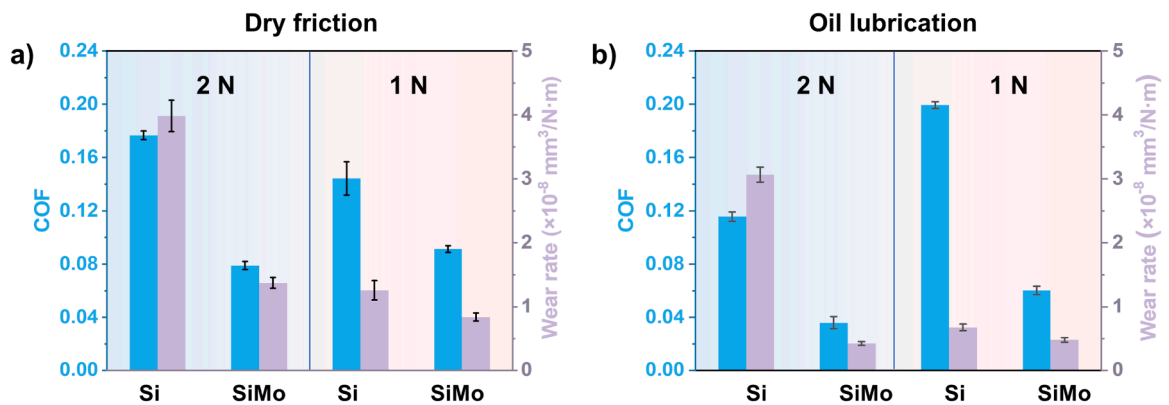


Fig. 11. COF and δ of upper balls coated with Si-DLC and SiMo-DLC according to applied load in a) dry-friction and b) oil-lubricated conditions.

lubricated conditions, with a 70% lower COF and 86% lower δ . The two coating systems exhibited different δ values because the addition of the

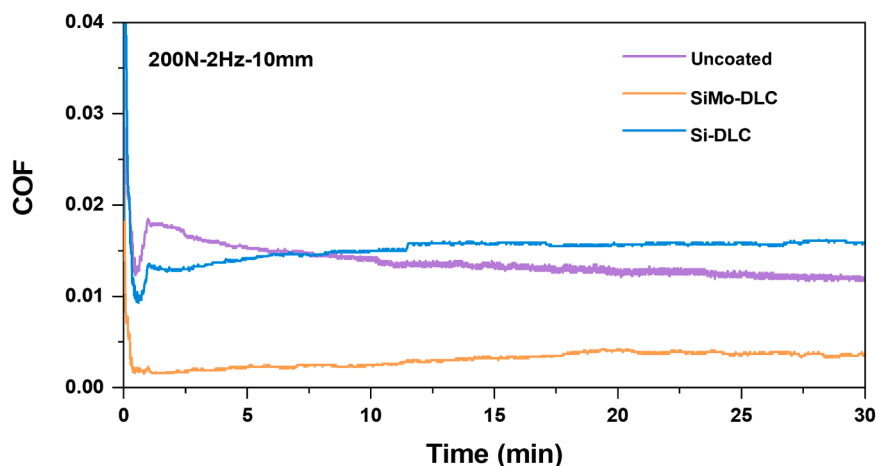


Fig. 12. COF over time for uncoated, Si-DLC-coated, and SiMo-DLC-coated vanes under 200 N load at 2 Hz in oil-lubricated conditions.

soft, co-doped MoS₂-GLC outer layer in the SiMo-DLC coating significantly improved tribological performance; the mechanisms underlying this improvement are discussed in Section 5.

4.4. Laboratory equivalent test results

As shown in Fig. 12, all laboratory equivalent test specimens exhibited a low COF, with the SiMo-DLC-coated vane exhibiting an average COF of approximately 0.003, reflecting macroscopic superlubricity under ambient atmospheric conditions. Furthermore, the COFs of the uncoated and Si-DLC-coated vanes first decreased, then increased within the first minute, i.e., during the initial stage of friction, whereas no such change was observed for the SiMo-DLC-coated vane.

The wear morphologies on the R-surfaces of the uncoated vanes revealed no significant wear traces (Fig. 13a) and only partial smoothing of surface asperities in the friction contact area, whereas the Si-DLC-coated vanes exhibited minor wear with a maximum depth of 2 μm (Fig. 13b), which was within the acceptable range of coating thickness and surface roughness. Notably, the SiMo-DLC-coated vanes (Fig. 13c) exhibited significantly reduced COFs compared with the uncoated and Si-DLC-coated vanes while mitigating the wear characteristics observed on the latter. These results suggest optimized interfacial interactions and improved wear resistance inherent to the SiMo-DLC structure.

Fig. 14 compares the COFs and wear depths of vane surfaces for uncoated, Si-DLC-coated, and SiMo-DLC-coated vanes under oil-lubricated conditions. The average COF values for uncoated, Si-DLC- and SiMo-DLC-coated vanes were 0.018, 0.017 and 0.003, respectively. The maximum wear depths reached approximately 1.61, 2.53 and 1.24 μm for uncoated, Si-DLC- and SiMo-DLC-coated vanes, respectively.

4.5. Chemical compositions of wear regions

The lubrication mechanisms associated with the carbon-based coatings evaluated in this study were explored and the mechanisms by which SiMo-DLC achieved superlubricity under atmospheric conditions were investigated using nanoindentation, XPS, and Raman spectroscopy to analyze the mechanical properties and chemical compositions of the wear regions. Nanoindentation tests were conducted to a depth of 150 nm on the friction contact zones of the uncoated and Si/O-DLC-coated disks before friction testing, as well as the Si/O-DLC-coated disks after friction experiments against Si-DLC-coated balls and SiMo-DLC-coated balls and vanes. The nanoindentation results presented in Fig. 15 indicate that the materials formed in the friction contact zones on the disks were slightly harder after friction against SiMo-DLC-coated balls than Si-DLC-coated balls but had lower elastic moduli.

The Raman spectroscopy results for the wear scars on the disks are shown in Fig. 16. In Raman spectroscopy, the peaks at 1360 cm^{-1} (D peak, intensity I_D) and 1580 cm^{-1} (G peak, intensity I_G) correspond to characteristic carbon atomic vibrations; thus, a higher I_D/I_G ratio indicates a greater degree of graphitization, which enhances lubrication and reduces the COF [25,26]. Fig. 16a indicates that no graphitized carbon materials were present on the uncoated cast iron disks before or after friction, whereas graphitized carbon materials were observed on the coated disks before and after friction against Si-DLC- and SiMo-DLC-coated vanes. Furthermore, the I_D/I_G ratio for the coated disks increased from 0.44 before friction to 0.56 after friction against the Si-DLC-coated vanes (Fig. 16b) and increased from 0.45 before friction to 0.77 after friction against the SiMo-DLC-coated vanes (Fig. 16c). These results indicate that the newly formed substances observed on the coated disks after friction against the SiMo-DLC-coated balls exhibited a higher degree of graphitization.

The results of the XPS analysis, which was conducted using a shallower probing depth than the Raman spectroscopy, provide additional insights into the chemical composition of the near-surface materials. No sp^2 peaks were observed on the uncoated disks (Fig. 17a), whereas sp^2 hybridized peaks were detected on the coated disks before and after friction against the Si-DLC- and SiMo-DLC-coated vanes (Fig. 17b). Notably, the intensity of the sp^2 peaks increased after friction against the SiMo-DLC-coated vanes, confirming the generation of additional graphitic structures [27] during the friction process (Fig. 17c). Furthermore, deconvolution of Mo peaks before and after friction revealed the formation of MoS₂ on the near-surface of the disks after friction against the SiMo-DLC-coated vanes (Fig. 18), confirming that MoS₂ from the vane coating was transferred to the disk to form new Mo-based compounds [28,29]. Therefore, the results of the chemical composition analyses indicate that MoS₂ as well as a larger quantity of graphitized materials were generated on the surface of the coated disks after friction against the SiMo-DLC-coated vanes. This likely occurred during the initial period of friction, when the oil film thickness was insufficiently established, causing the outermost MoS₂ to be rapidly transferred to the disk, where it filled surface asperities and accelerated conformal contact, thereby reducing initial wear. Concurrently, the carbon materials doped into the coating generated more graphitic carbon tribofilm under frictional heat and shear, ultimately leading to a lower COF.

5. Lubrication mechanism

In summary, different friction conditions are categorized as point contact or line contact based on contact forms. The point contact friction test serves to demonstrate that, for the same coating composition,

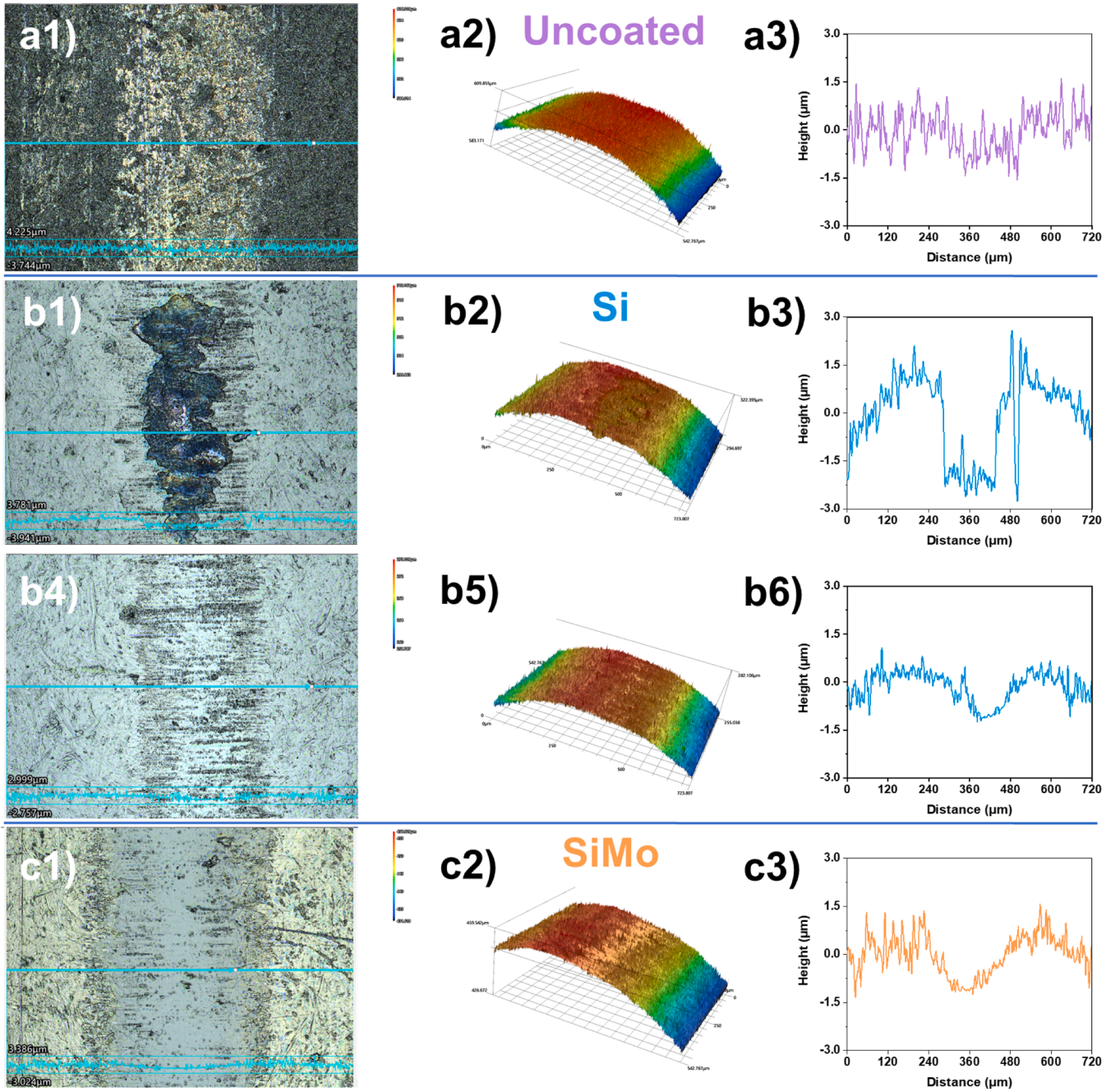


Fig. 13. Wear morphologies and corresponding depth profiles under 200 N in oil-lubricated conditions for the a) uncoated, b) Si-DLC-coated, and c) SiMo-DLC-coated vanes.

adding an outermost shear layer (MoS₂/GLC) significantly reduces friction and wear. Under higher applied loads, whether in dry or lubricated conditions, SiMo-DLC-coated spherical surfaces maintain better structural integrity and lower wear levels. Similarly, the wear results from equivalent friction tests resemble those of point contact tests: both show greater wear in Si-DLC-coated samples, exhibiting consistent wear trends. Consequently, the equivalent friction test results, which use materials identical to those in actual compressors, are used to analyze the lubrication mechanisms, with morphology and chemical composition characterized on both coated vanes and coated gray iron before and after friction tests.

Critical factors that have been identified as influencing the superlubricity of element-doped DLC films include the bonding between the doped elements and carbon, the catalytic roles of these elements in

shear-induced graphitization, and their tribo-oxidation products. Furthermore, the relationship between the COF, contact stress, and interfacial shear stress is given by [30]

$$\text{COF} = \frac{F_f}{F_n} = \frac{A\tau}{F_n} = \frac{\tau}{P} \quad (3)$$

where F_f denotes the frictional force, A denotes the contact area, τ denotes shear stress in the interfacial material, and P denotes contact pressure. Thus, Eq. (3) indicates that the COF decreases with the interfacial shear stress.

Based on these principles, the tribological behaviors, wear morphologies, and wear scar compositions obtained in this study using the two evaluated coatings were comprehensively analyzed to elucidate the superlubricity mechanism for the engineering materials coated with

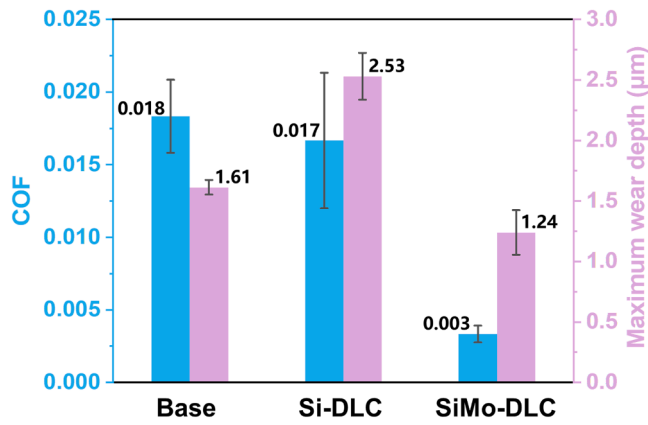


Fig. 14. COF and corresponding maximum wear depth under 200 N in oil-lubricated conditions for a) uncoated, b) Si-DLC- and c) SiMo-DLC-coated vanes.

SiMo-DLC under atmospheric conditions, which is schematically illustrated in Fig. 19. The Si element and MoS₂/GLC layer governed two pivotal processes during friction: transfer film formation and shear-induced graphitization. On the one hand, Si doping not only reduced the internal film stress to enhance coating adhesion but also exhibited stronger reactivity with oxygen and water than carbon, effectively suppressing graphitic layer oxidation and thereby maintaining lubricative integrity. Concurrently, the outermost MoS₂/GLC layer protected the surface by filling asperities in the counterpart (disk) during the initial friction stages to mitigate severe wear. Under continued frictional heating and shear force, graphitic carbon tribofilms were generated at the friction interface, while the inherent interlayer shearability of the coating further lowered the COF. Additionally, oxides generated through tribo-oxidation were encapsulated within the coating layer. Shielded by the carbon-rich layer, these oxides were prevented from directly participating in friction, thereby sustaining favorable tribological performance. Thus, the synergistic interaction between transfer film formation and shear-induced graphitization stabilizes superlubricity. Specifically, for MoS₂ and GLC, the pre-transfer film plays a critical role in tribological behavior. This understanding is particularly important for coating design in critical interfaces like those between compressor vane tips and piston outer rings, where even minor wear can lead to refrigerant leakage and reduced energy efficiency.

6. Installation verification

The feasibility of applying the laboratory test results to practical friction pairs was verified in this study by conducting installation tests in constant- and variable-frequency compressors. The cooling capacity, input power, and coefficient of performance (COP) data were collected from each compressor after initial run-in.

6.1. Constant-frequency compressor

The constant-frequency compressor was operated at 50 Hz and comprised vanes coated with one of the two evaluated coatings and piston rings coated with Si/O-DLC, as well as R32 refrigerant and commercial refrigerant oil. The resulting cooling capacity, input power, and COP for the compressor are shown in Fig. 20. These results indicate that the Si-DLC-coated vanes maintained an efficiency equivalent to the baseline (uncoated) condition, whereas the SiMo-DLC-coated vanes reduced the input power and improved efficiency by approximately 0.7%.

6.2. Variable-frequency compressor

The variable-frequency compressor comprised vanes coated with SiMo-DLC, pistons coated with Si/O-DLC, and a crankshaft coated with SiMo-DLC, as well as R134a refrigerant and commercial refrigerant oil. Before installation test, to evaluate the potential impact of friction coefficient reduction on frictional losses, the COF values of uncoated and coated vanes under oil-lubricated conditions were extracted from component friction tests. Theoretical calculations indicate an approximate 14% reduction in total vane frictional losses.

In installation test, the cooling capacity, input power, and COP of the compressor were evaluated at frequencies of 35, 50, and 75 Hz. The results in Fig. 21a indicate that the use of coated components significantly reduced the input power when compared with the use of uncoated components, with the maximum improvement in COP reaching 4.16% across frequencies (Fig. 21b). Generally, the results of the installation tests conclusively demonstrated that the SiMo-DLC coating effectively reduced the intercomponent COF, decreased the system input power, and ultimately enhanced energy efficiency.

In summary, compressor energy efficiency represents a comprehensive reflection of system integration. Factors including motor efficiency, mechanical losses, frictional dissipation, and anomalous compression collectively influence input power, thereby determining overall energy efficiency. In general, frictional losses typically account for approximately 14.8% of total input power [31,32]. When the friction coefficient reaches superlubricity levels, vane frictional dissipation is substantially

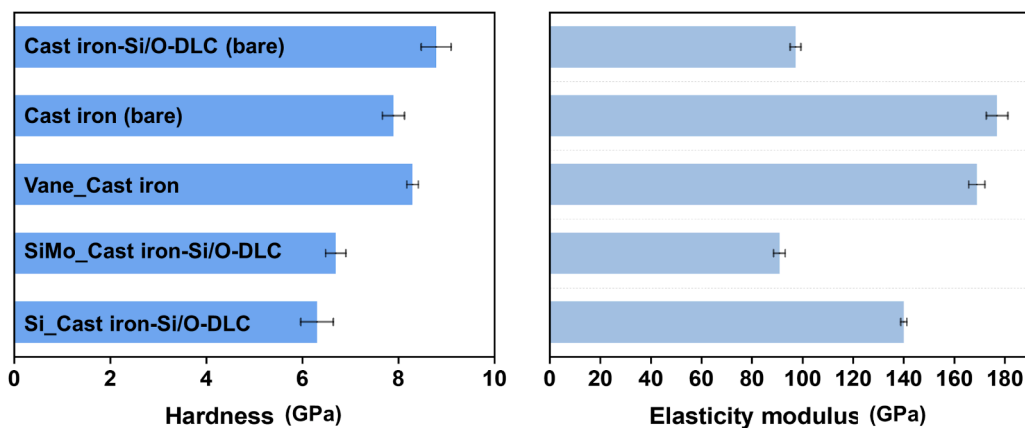


Fig. 15. a) Hardnesses and b) elastic moduli of cast iron disk surfaces before and after friction testing. Vane_Cast iron indicates that the upper component was a vane and the bottom was cast iron. SiMo_Cast iron-Si/O-DLC indicates that the upper component was a vane coated with SiMo-DLC and the bottom was cast iron coated with Si/O-DLC after friction.

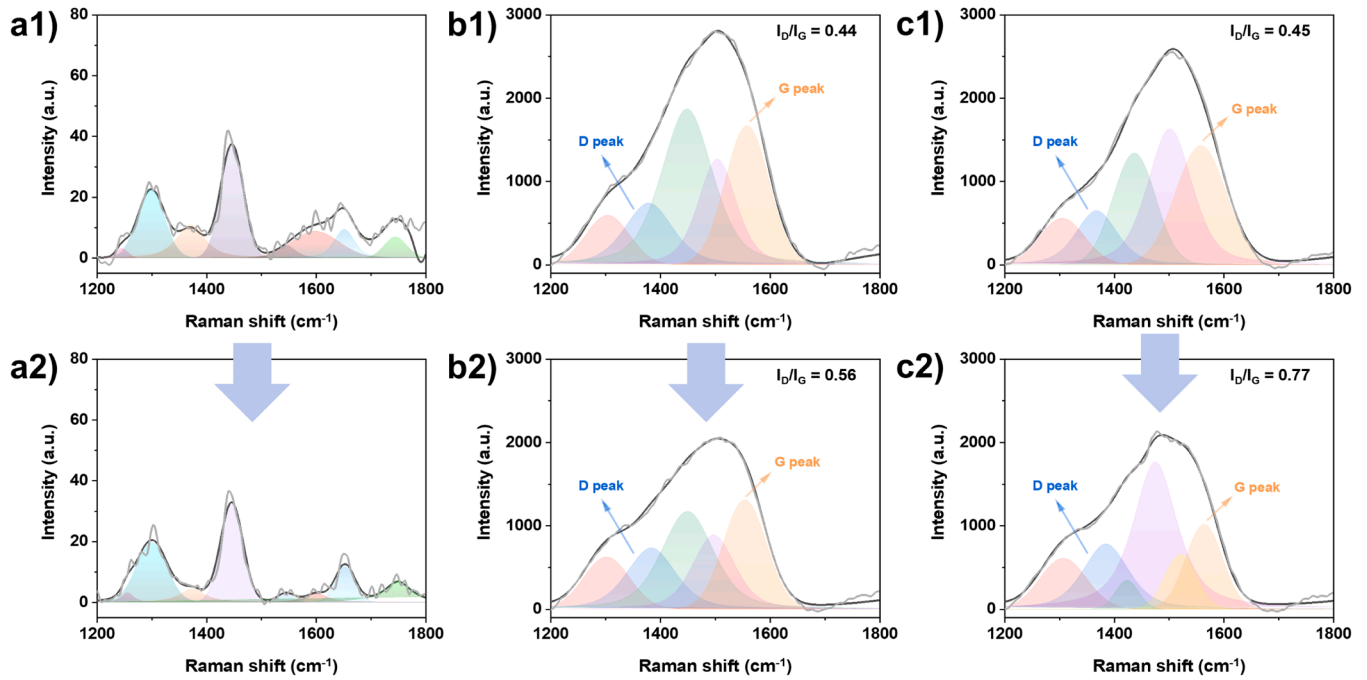


Fig. 16. Raman spectra of disks before (a1, b1, c1) and after (a2, b2, c2) friction between: a) uncoated vane and uncoated disk, b) Si-DLC-coated vane and coated disk, c) SiMo-DLC-coated vane and coated disk.

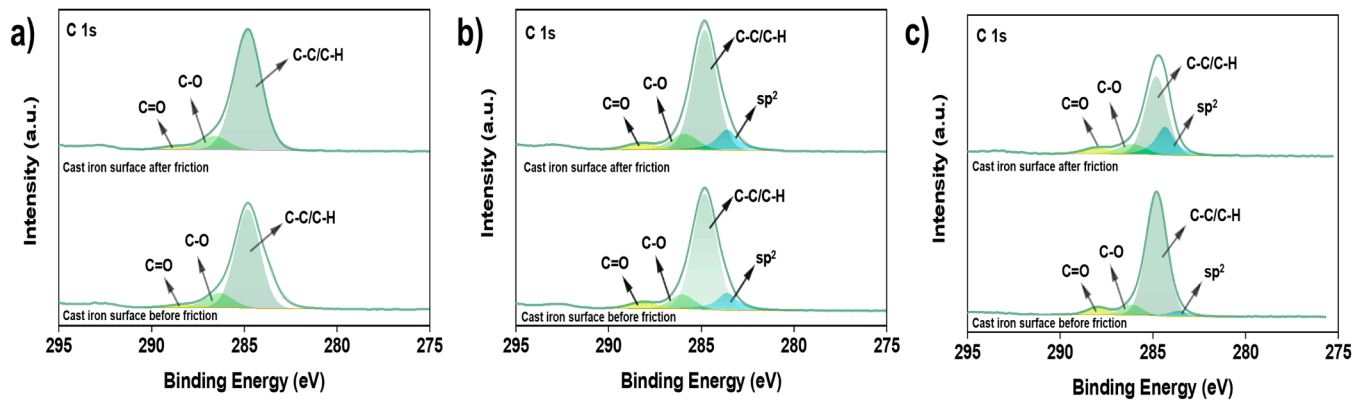


Fig. 17. High-resolution XPS spectra of disks before and after friction: a) uncoated vane and uncoated disk, b) Si-DLC-coated vane and coated disk, c) SiMo-DLC-coated vane and coated disk.

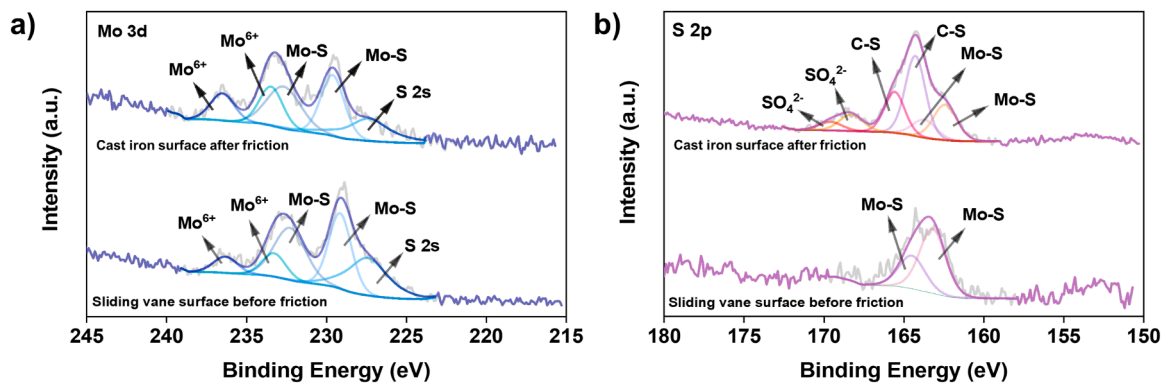


Fig. 18. High-resolution XPS spectra of vane surfaces before friction and disk surface after friction: elemental a) Mo and b) S.

minimized, approaching theoretical limits. This study achieved a 4.16% improvement in energy efficiency through carbon-based coating

implementation. This already represents a significant breakthrough in the refrigeration engineering industry, particularly as a 3.2% efficiency

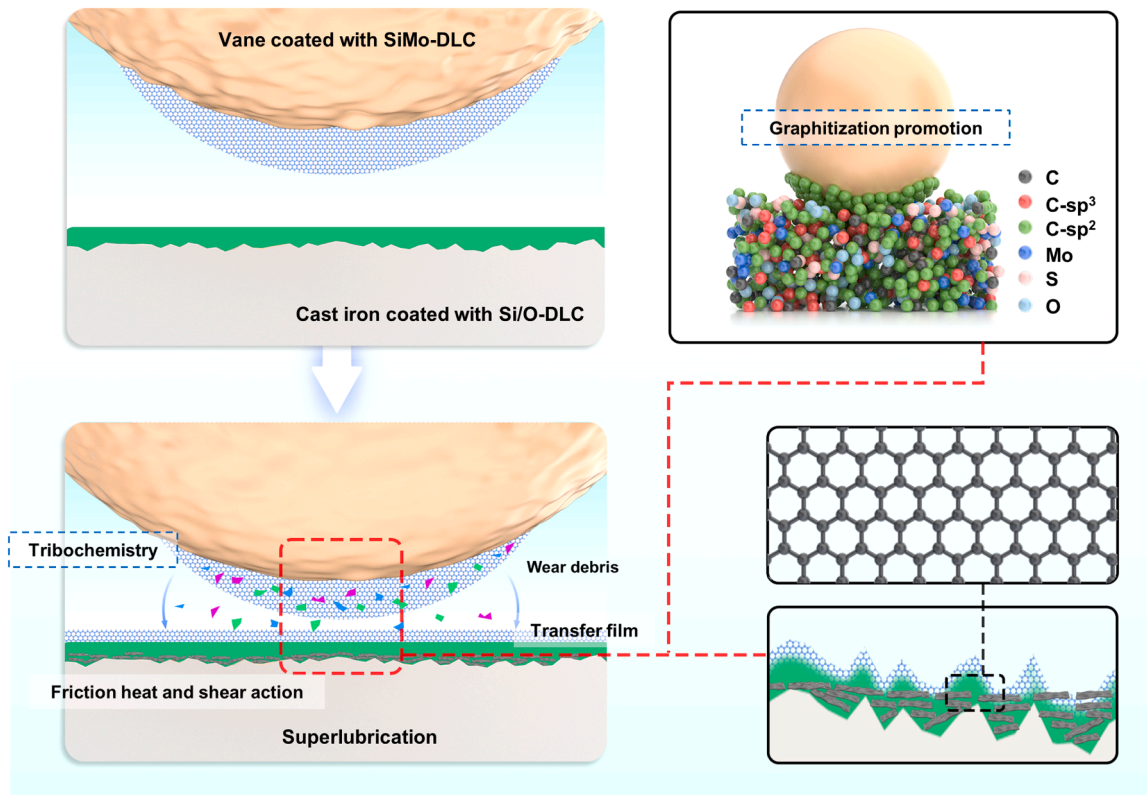


Fig. 19. Schematic model of SiMo-DLC superlubrication for the vane-to-cast iron friction pair.

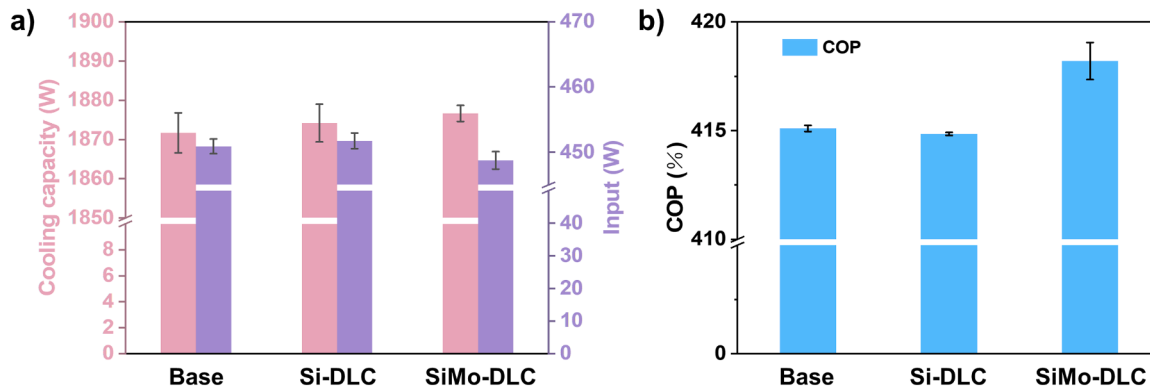


Fig. 20. Installation performance test using a constant-frequency compressor: a) cooling capacity and input power, and b) COP of the uncoated, Si-DLC-coated, and SiMo-DLC-coated vanes.

improvement had been documented as a major breakthrough in prior studies [33]. More importantly, these results confirmed that DLC-based coatings can be achieved not only at the laboratory scale, but also in actual mechanical components. Indeed, these coatings were shown to provide surface wear protection, reduce the COF, and ultimately enhance the energy efficiency of compressor systems.

7. Conclusion

This study addressed the issue of friction and wear between compressor component friction pairs by developing two carbon-based coatings (Si-DLC and SiMo-DLC) through interfacial composition optimization. Both coatings demonstrated strong adhesion while maintaining low COF and δ values. A comparative analysis revealed that SiMo-DLC outperformed Si-DLC under both dry-friction and oil-lubricated conditions, with a 70% lower COF and 86% lower δ . Critically, the

SiMo-DLC coating enabled macroscopic superlubricity between components under ambient atmospheric conditions. This coating design effectively minimized abrasive wear by continuously forming a carbon transfer film during operation while simultaneously inhibiting interfacial oxidation. Friction-induced thermomechanical activation promoted the in-situ generation of graphitic carbon tribofilm within the contact zone, whose lamellar shear characteristics contributed to additional friction reduction. Finally, practical compressor tests demonstrated that SiMo-DLC coating reduced the system input power, resulting in a maximum energy efficiency improvement of 4.16% in the selected compressor. Therefore, this work establishes a quantitative relationship between compressor pump frictional losses and COFs, highlights the key role of the pre-transfer film in energy efficiency enhancement, and provides theoretical basis and experimental support for the development of highly reliable energy-efficient compressors. Future research should integrate multiscale simulations to optimize the coating microstructure

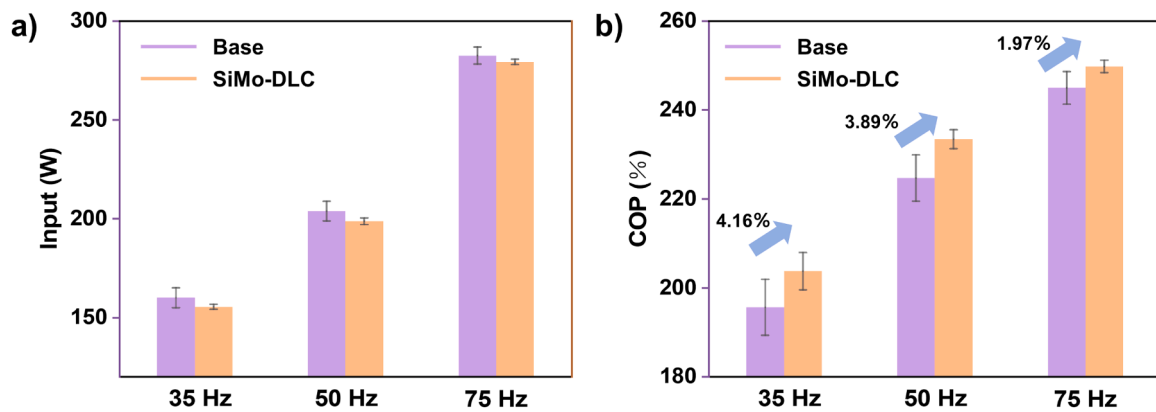


Fig. 21. Installation performance test using a variable-frequency compressor: a) input power and b) COP for the uncoated and SiMo-DLC-coated vanes.

under extreme operating conditions, thereby expanding the industrial application potential of DLC-based coatings.

CRedit authorship contribution statement

Gang Wen: Methodology, Conceptualization, Writing - original draft, review & editing. **Ming Qin:** Supervision, Resources, Conceptualization. **Wukui Tang:** Investigation. **Jinrui Zhang:** Methodology. **Yupeng Zhang:** Data curation. **Rende Chen:** Methodology. **Peng Guo:** Data curation. **Aiying Wang:** Writing - review & editing, Supervision, Resources, Funding acquisition.

Declaration of Competing Interest

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

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Data availability

The data that has been used is confidential.

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