Aluminum and alumina/MoS2/cellulose derivative composite: design and performance

Shih-Chen Shi1,∗, Shia-Seng Pek1 and Yue-Feng Lin2

1 Department of Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan
2 Department of Mechanical Engineering, National Chih-Yi University of Technology, No. 57, sec. 2, Zhongshan Rd., Taiping Dist., Taichung 411030, Taiwan
∗ Author to whom any correspondence should be addressed.
E-mail: scshi@mail.ncku.edu.tw

Abstract
Nanoparticles were added to improve the tribological performance of the biopolymer-based composite films. Aluminum and alumina were used as additives. The matrix of the composite was MoS2/hydroxypropyl methylcellulose (HPMC). The ternary additive/MoS2/HPMC hybrid composites were successfully prepared via solvent evaporation. The surface morphology, thickness, microstructure, and wear scars were analyzed using scanning electron microscopy. X-ray diffraction was used to analyze the crystal structures of the nanoparticles in the composite films. Finally, a wear test was conducted to determine the tribology behavior and was discussed using the third-body theory. Because of the high surface-area-to-volume ratio of the additives, nanoparticles were exposed and densely distributed on the composite surface. Disclosed nanoparticles caused peaks and valleys and showed more significant undulations, prompting a highly rough surface. The addition of nanoparticles enhanced the load capacity of the composite films by 155%. In the meantime, nanoparticle additives significantly reduced the coefficient of friction by 50% and improved anti-wear performance by five times. The nanoparticles in the wear scar exhibited an excellent third-body mechanism during the wear process, coordinating the velocity accommodation mode between the two rubbing surfaces and the transfer load.

1. Introduction

The field of tribology studies the control of friction, abrasion, and lubrication effect. Green tribology, which has recently attracted the scientific community’s attention, emphasizes the development of tribology technology from the perspective of ecological balance and environmental protection. The most important aspects of green tribology are reducing energy consumption, reducing carbon dioxide emissions, reducing environmental costs, and improving quality of life [1].

Packaging materials are commonly used in daily life, and traditionally, plastics such as polyethylene and polypropylene are widely used as packaging materials. However, a large amount of indecomposable waste may cause environmental damage and biotoxicity accumulation. Therefore, it is reasonable to develop biodegradable materials as packaging materials. Biopolymer-based composite films can be used as the raw material for packaging. Many scholars continue to explore available biomaterials and test their gas barrier and moisture barrier properties [2]. Among biopolymers, cellulose is a potential green tribology material [3, 4], which is bio-friendly and biodegradable. Cellulose is often used as a packaging material for its superior anti-wear properties [5, 6].

Hydrophobic stearic acid was added to hydroxypropyl methylcellulose (HPMC). As a result, reduced surface energy, adhesion, friction coefficient, and a film with anti-wear behavior were obtained [7]. Further, an HPMC film was prepared using an optimal water ratio and HPMC on silicon to reduce friction and wear. Raman spectroscopy was used to observe the transfer layer formed during abrasion [8]. To enhance the anti-wear performance of HPMC, MoS2 particles that are biofriendly and exhibit good lubricating properties are added to
2.1. Preparation of composite medium-, and long-range wear.

of 200 m, the third-body wear mechanism caused by the additives was discussed based on the evidence of short-,

nanoparticles were used as additives to improve the service life of the composite materials. With a wear distance

HPMC, which are evenly distributed onto the matrix material owing to the excellent dispersion effect of HPMC;

additive

HPMC solution to obtain the MoS2

The schematic of the preparation of composites is illustrated in

Further, a similar morphology is obtained in response to an abrasion test of 80–870 laps. This speed coordi-
nation mode is M3 (shearing), the velocity accommodation mechanism of interfacial sliding, which is the fric-
tion behavior between the MoS2 transfer layers. Based on Raman real-time spectroscopy, the phenomenon of

MoS2 transfer layers can be observed [10]. It was reported that when the molybdenum disulfide composite film
has multiple degrees of freedom, it can avoid intercrystalline slippage. During the wear process, the surface

morphology of the columnar composite film can form a third-body flow and promote the speed coordination
mode, which can form a superficial tribological transformation (STT). This prevents excessive wear of the com-
posite film, promotes the formation of fine third-body particles, and leads to a third-body layer that reduces

wear and tear [11]. The MoS2 additive positively affects cellulose-based composite materials, but MoS2 particles
can quickly oxidize in the environment to form oxides that compromise the tribological characteristics [12].

However, various additives may provide more diversified lubricating mechanisms, allowing the composite mat-
erial to have better abrasive properties [13].

Nanoparticles have a higher surface area-to-volume area than microparticles, the hardness and surface activ-
ity of nanoparticles are the main influencing factors in nanomaterials [14]. Owing to the high interfacial area
ratio between the matrix and the additives (nanoparticles), the bonding between the matrix and nanoparticles of
the polymer nanocomposite strengthens, resulting in a polymer nanocomposite with higher strength and toughness
than matrices in general. When metallic nanoparticles and non-metallic oxides, such as Al [15], Cu [13],

Al2O3 [16], SiO2 [17], CuO [18], and ZnO [19], are added to the polymer, they can enhance the load capacity and
toughness of the material. Various morphologies, sizes, and compositions of additives have different

strengthening effects on the mechanical properties of composites, such as ZnO nanorod [20], graphene oxide [21],

Y2O3 [22], and TiB2 [23]. Numerous studies show that to obtain a good anti-wear effect, the additive

volume of the microparticles must reach 25–35 vol%, while only 1–5 vol% of nanoparticles is sufficient to

reduce the coefficient of friction and abrasion rate [24].

Spherical and nearly spherical particles can exhibit a rolling effect instead of the original sliding friction,

which effectively reduces the coefficient of friction and abrasion rate [25]. Hard and polygonal particles, such as

Al2O3, SiC, and diamond, cause grooving [26] or rolling to different additive concentrations and load sizes. With

a low concentration of additives and a large load, these hard particles will penetrate the relatively soft surface
of the part exposed to wear to form two-body wear [27]. This is because they bear considerable stress on their unit
area, which causes the frictional resistance and abrasion rate to increase instead. With a high concentration and a

small load, they behave in the same manner as spherical particles. The abrasion changes from two-body rolling
to third-body rolling [28].

Al is the third most abundant element in the Earth’s crust and is the most abundant metal [29]. It is also easily
recyclable and reusable. In addition, Al2O3 has a high melting point, high hardness, good corrosion resistance,

and good insulation properties. Therefore, we hypothesize that aluminum-based nanoparticles could form a
good dispersion state with the hybrid matrix of MoS2/HPMC, thereby improving the mechanical properties of
ternary composites [30]. In this study, MoS2/HPMC was used as the hybrid matrix material, while Al and Al2O3
nanoparticles were used as additives to improve the service life of the composite materials. With a wear distance
of 200 m, the third-body wear mechanism caused by the additives was discussed based on the evidence of short-,
medium-, and long-range wear.

2. Experimental details

2.1. Preparation of composite film

The schematic of the preparation of composites is illustrated in figure 1. First, 1 g HPMC (Pharmacoat 615,
Shin-Etsu, Tokyo, Japan) powder was mixed in 9 g solvent (7.2 g ethanol and 1.8 g water) to prepare the HPMC
solution. Then, 0.5 g MoS2 particles (average size: 2 μm; Sigma-Aldrich, St. Louis, MO, USA) were added to the
HPMC solution to obtain the MoS2/HPMC slurry. Polygonal Al2O3 particles (diameter: 432 ± 84 nm) and
spherical Al particles (diameter: 113 ± 41 nm) were used as additives. The additive slurry was prepared by adding
0.2 g (1 wt%), 0.4 g (2 wt%), and 0.6 g (3 wt%) additive (Al2O3 or Al nanoparticle) to the solvent (9.2 g
ethanol and 0.1 g Span 80). Subsequently, the MoS2/HPMC and additive slurries were mixed, and 486 μl of the
mixed solution was sampled and dropped onto a glass (100 mm in diameter, Corning, New York, NY, USA)
using a micropipette. This specimen was placed at 30 °C and relative humidity (R.H.) of 40% for 6 h to yield the
additive/MoS2/HPMC composite film.
2.2. Characterization of the composite film
The load capacity of the film was based on ISO 6506–1. Using an AISI 52100 chrome steel ball (diameter: 2.36 mm) as the indenter, a force of 15 N was continuously applied to the specimen for 3 min. Each sample was measured at five points (four corners and the center). Once the force was removed, the sample was allowed to stand for 12 h to avoid errors caused by short-term rebound. The indentation was further analyzed using three-dimensional (3D) laser scanning microscopy (VK9700, Keyence, Osaka, Japan) to obtain the diameter and depth. The reference value of the load capacity was obtained by calculating the Brinell hardness. The surface roughness was measured using 3D laser scanning microscopy. The thickness of the composite film was measured by observing the cross-section of the film using scanning electron microscopy (SEM, SU-5000, Hitachi, Tokyo, Japan). For the x-ray diffractometer (XRD, D8, Bruker AXS Gmbh, Karlsruhe, Germany), crystallization parameters were collected using a Bruker diffractometer (Model D2 phaser) with CuKα (Kα1, 0.15406 nm) at an operating voltage and current of 30 kV and 10 mA, respectively. The blank scan was carried out using a clean zero background plate with no applied sample. The blank scan was subtracted from the analysis.

2.3. Tribology behavior of composite film
The tribological performance was evaluated using a ball-on-disk tribometer (POD–FM406–10NT, Fu Li Fong Precision Machine, Kaohsiung, Taiwan) under a load of 2 N and disk speed of 0.03 m s⁻¹. A chrome steel ball (AISI 52100) with a diameter of 6.31 mm was employed as the upper ball, and the composite films were employed as the lower disk test piece. The wear test was performed at 25 °C and an RH of 70%. The wear distances were 30 m, 100 m, and 200 m. The friction coefficient of the film was monitored and recorded in real-time, and the wear volume was measured using 3D laser scanning microscopy.

The third-body theory describes the interaction between two contacted materials involved in dry friction conditions [31, 32]. The velocity accommodation mechanism refers to the location and motion state of the Wear as sites (S) and modes (M), respectively. S1 and S5 are called the first bodies (representing two counter-wear parts); S3 refers to the natural wear debris generated by abrasion or a lubricant additive; and S2 and S4 are the interface layers between S1–S3, and S5–S3. Mode (M) represents the mode of velocity accommodation. M1–M4 represent elastic deformation, normal breaking/rupture, hearing/sliding, and rolling mechanisms, respectively. The third body comes from two sources: the natural third body (Q₁), which represents the detached particles due to abrasion, and the artificial third body (Q₂), which represents the additional solid lubricants. There are four types of third-body flow: internal flow (Q₁), representing the flow that can be maintained in the contact zone during the wear cycles; external flow (Q₄), representing the flow that is removed from the contact area in the wear cycles; recirculated flow (Q₃), representing the flow of the third body that is returned to the contact area after the external flow, and wear flow (Q₅), representing the third body that is removed completely from the contact area and no longer participates in the wear cycles [33, 34]. The purpose of the third-body theory is to supplement previous theories of tribology to completely describe a wear system.

3. Results and discussion

3.1. Surface morphology and characterization of the composite films
The SEM images indicate that as the nanoparticle content increased, the nanoparticles aggregated on the surface of the Al₂O₃/MoS₂/HPMC composite film, forming larger particles (figures 2(a)–(c)). In the case of the Al/MoS₂/HPMC composite film, increasing the additive content led to denser distribution of the nanoparticles
Under high magnification, no aggregation was observed and the sizes of the nanoparticles remained at the nanoscale. Owing to the good dispersion effect of HPMC, the aggregation of the nanoparticles was mitigated when they were added to MoS₂/HPMC mixture to prepare the composite film. The morphology of the composite film revealed that MoS₂ was mainly encapsulated in the HPMC, while more nanoparticles were suspended on the surface of the composite film, covering a relatively large surface area. It was also observed that the density of the additive affected the distribution of the nanoparticles in the composite film. Compared with Al₂O₃ nanoparticles, Al nanoparticles were lighter with a lower volumetric density, preventing them from easily sinking into the MoS₂/HPMC matrix. This led to a wider distribution with the same mass of nanoparticles. On the other hand, the strongly hydrophilic Al₂O₃ nanoparticles did not easily disperse into organic solvents. Therefore, as the amount of Al₂O₃ nanoparticles increased, the phenomenon of aggregation became more severe, eventually forming sub-micron-sized particles.

The thickness and surface roughness of the composite films are shown in figure 3. When the nanoparticle content increased, the thickness of the composite film also increased. Holmberg et al. suggested that the coefficient of friction of a thin film increases because of the influence of the substrate when the worn parts come into contact with the parts that have a relatively high shear strength. In this study, owing to the moderate thickness of the film, the coefficient of friction was not affected by this phenomenon [36].

Further, the nanoparticles significantly increase the surface roughness. The addition of 3% Al increased the surface roughness of MoS₂/HPMC composites the most, compared to the other composite films, which was attributed to their dense and uniform distribution on the film surface. The increase in surface roughness contributes to the abrasion in the initial stage, as fewer rough peaks are in contact with the abrasive counterparts, which can reduce the effect of surface adsorption. Increasing the surface roughness under dry friction conditions can reduce the coefficient of friction and extend the run-in period [36].

The load capacities of the composite materials are shown in figure 4. The load capacity of the pure HPMC film was 9.6 kgf mm⁻². Among the composite films, the highest load capacity was exhibited by the 3% Al₂O₃ composite film (24.5 kgf mm⁻²). The mechanical properties of the composite materials were improved, compared to the mechanical properties of the HPMC films and the additives. It is essential that the material can transfer the stress effectively from the substrate to the additive under stress. Therefore, the adsorption strength between the substrate and the additive is important. The high load capacity of the Al₂O₃ composite film was likely attributed to the effective adsorption of the uniformly dispersed Al₂O₃ by HPMC. Notably, an overall
trend of an improved load capacity with increasing nanoparticle concentration in all films was observed. This indicated that the nanoparticles in the composite film were able to withstand a certain load. According to the load curves and load capacities of the composite films, it can be deduced that the true contact area of the composite film increased with the deformation of the rough peaks under load. In addition, composite films with 1% and 2% of the same nanoparticle additive were compared. It was found that the composite film with 1% additive had a poorer load capacity, indicating that under the same load, it had a larger true contact area than the 2% composite film.

As shown in figure 5 (2H-MoS₂, JCPDS 37–1492), the characteristic peak of MoS₂ is clearly observed in all the nanocomposite coatings [37]. In particular, the highest intensity diffraction peak was 2θ = 14.4°, indicating that the MoS₂ crystals were mainly stacked on the (002) crystal plane. It was found that the (002) crystal plane is favorable for the shear/slip behavior of MoS₂. The (104), (110), (113), (116), (214), and (300) crystal planes in the Al₂O₃/MoS₂/HPMC composite film were consistent with the characteristic peaks of Al₂O₃ (JCPDS 46–1212). The (111), (200), (220), and (311) crystal planes observed in the Al/MoS₂/HPMC composite film were also consistent with the characteristic peaks of Al (JCPDS 04–0787) [38]. This means that the Al nanoparticles remained in the powdered state, and the diffraction peaks of the Al nanoparticles increased significantly with increasing content. From the sharp and multiple single-peak XRD patterns, it can be seen that both the nanoparticles and molybdenum disulfide maintained a stable crystalline state in the composite film, and the addition of the nanoparticles did not influence the original structure and preferred direction of molybdenum disulfide. The characteristic peak intensity of the nanoparticles was compared with the characteristic peak intensity of the composite film with a fixed ratio of MoS₂, that is, the (002) crystal plane. It can be observed that when the nanoparticle content increased, the intensity of the diffraction peak significantly increased, which also indicates
that no chemical reaction occurred in the material. Therefore, nanocomposite films with varying content and good crystal structures were successfully prepared.

3.2. Tribology behavior and third-body observation of Al₂O₃/MoS₂/HPMC films

Figures 6(a)–(b) show the coefficients of friction at a wear distance of 200 m and the wear volume at different wear distances for the Al₂O₃/MoS₂/HPMC composite films. The coefficient of friction significantly decreased upon adding the Al₂O₃ nanoparticles (1%–3%), with an average between 0.24 and 0.27. The uneven distribution of the Al₂O₃ nanoparticles on the surface of the composite film caused the coefficient of friction to significantly fluctuate. At the wear distance of 200 m, the composite film with 1% Al₂O₃ effectively reduced the wear volume. However, the wear volume increased for 2 and 3% Al₂O₃ addition, which was because of its hydrophilicity; the hydrophilicity enabled the Al₂O₃ nanoparticles to agglomerate, and prevented their dispersion in organic solvents, forming sub-micron particles. As such, an increase in the angularity will cause abrasion, and an excessive amount of additive will cause the material to become brittle and enable its removal.

In Figure 7, the SEM image of the composite film with 1% Al₂O₃ indicates that it exhibited chipping (as indicated by the arrow) and the formation of debris around the wear scar. In contrast, the composite film with 2% Al₂O₃ exhibited aggregation of the nanoparticles in the wear scar, as well as a relatively large amount of debris around the wear scar. In comparison, the composite film with 3% Al₂O₃ had a wider wear scar with severe nanoparticle aggregation.

Compared to the MoS₂/HPMC composite film, the composite film with Al₂O₃ had a relatively higher surface roughness; thus, it had a lower coefficient of friction. Nevertheless, during the wear process, all coefficients of friction values significantly fluctuated, which was presumed to be the cause of a large amount of wear debris. Because Al₂O₃ nanoparticles had a relatively small volumetric density, when the added amount reached 2%–3%, the structure of the composite film loosened and the nanoparticles became prone to aggregation. As such, the corresponding wear volume of the Al₂O₃/MoS₂/HPMC composite films was larger than that of the HPMC/MoS₂ composite film; the 1% film was an exception.

In figure 7, Mark A to C indicated the flattened nanoparticles tend to aggregate. The debris was thought to be the Al₂O₃ nanoparticles with relatively high hardness, causing abrasive wear behavior. Further, the Al₂O₃ nanoparticles also squeezed out of the wear scars (figure 8(a), mark D). At the interface of the Wear, the main velocity accommodation mode for the interface layer of the wear part (S5) was particle fracture (M2), that is, the phenomenon (mark E) in which the additive nanoparticles were fractured by the positive force and accumulated (figure 8(b)). The third-body wear mechanism of the Al₂O₃/MoS₂/HPMC composite film is shown in figure 8(c). During Wear, the wear flow (Qw) that pushes the nanoparticles away from the interface is relatively large; hence, the debris remaining in the wear scars is relatively small [33].
3.3. Tribology behavior and third-body observation of Al/MoS$_2$/HPMC films

The composite film with 1% Al additive showed a significant increase in the value of the coefficient of friction when wear proceeded for 20 m. At 30 m, the composite film cracked and peeled off from the glass substrate, which was visible to the naked eye (figure 9(a)). For the composite film with 2% Al, wear occurred from the 30 m mark to 200 m, during which the coefficient of friction continued to increase. It was speculated that the composite film was partially broken because of the generated wear debris. For the composite film with 3% Al, the coefficient of friction was significantly smaller and relatively stable. Overall, the coefficient of friction gradually decreased with the addition of nanoparticles. Further, as the content of powdered Al nanoparticles increased, the wear volume gradually decreased. Figure 9(b) shows that the composite with 1% Al was easily peeled off in the early stage of wear. Above 2%, there were sufficient Al nanoparticles; thus, the composite film was able to bear the load and resist the effect of the chromium steel ball. From the wear interface of the composite film with 3% Al, it was observed that in the ranges of 30–100 m and 100–200 m, the rate of increase of the wear volume decreased.

The wear scar of the composite film with 1% Al at a wear distance of 200 m showed a relatively smooth surface, the surface morphology did not change, and the Al nanoparticles were observed on the surface as shown in figure 10(a). The composite film with 2% Al showed cracks at a wear distance of 200 m as shown in figure 10(b). The wear debris around the wear scar was apparent, and the nanoparticles in the wear scar appeared to be squashed. The composite film with 3% Al showed many cracks, which was confirmed by the high-magnification SEM image (figure 10(c)).

Above 2%, the densely distributed Al nanoparticles in the composite film effectively improved the load capacity of the material and prevented the direct wear caused by the chrome steel ball on the HPMC substrate and MoS$_2$. However, the Al nanoparticles deformed under the stress of the chromium steel ball during the wear.

Figure 8. SEM images of the (a) 1% Al$_2$O$_3$/MoS$_2$/HPMC composites (2 N, 200 m) and (b) enlarged area indicated by arrow D (red dot circle and mark E represent the accumulated flattened nanoparticles. (c) Schematic of the wear mechanism of the Al$_2$O$_3$/MoS$_2$/HPMC composites.

Figure 9. (a) Friction coefficient and (b) wear volume of the Al/MoS$_2$/HPMC composites (X represents the film broken during wear).
process, becoming squashed. Furthermore, they remained in the wear scars, forming a protective layer together with the debris to reduce the resistance to friction (figures 11(a)–(b), mark F). When the wear process began, the Al nanoparticles underwent plastic deformation under the action of frictional stress, while remaining in the wear scars, and the surface structure underwent STT. As the squashed nanoparticle and the neighboring nanoparticle ($\Delta$) approached each other, the nanoparticles gradually condensed into a thin film, also referred to as first body film (figure 11(c)). The first body film exhibited the first body plastic flow in the wear scars. Since the first body film is caused after the first body (SS) is subjected to local stress, it occurs at the interface of the wear part (SS), which uses shear behavior (M3) as the main mode to coordinate the speed difference during the wear process. In this wear experiment, neither the wear flow ($Q_w$) nor the third-body flow ($Q_s$) was significant.

### 4. Conclusion

In this study, Al$_2$O$_3$ and Al nanoparticles were added to MoS$_2$/HPMC composites with the objective to improve their tribological characteristics. Upon the addition of the nanoparticles, the surface roughness increased, which effectively reduced the occurrence of surface adsorption and local stress. The composite films also benefited from the nanoparticles being exposed on their surface as they avoided the occurrence of furrowing. The addition of the Al$_2$O$_3$ particles significantly decreased the coefficient of friction of the composite films. However, the nanoparticles displayed a tendency to aggregate; thus, the uneven distribution caused the coefficient of friction to significantly fluctuate. At 3% addition of Al$_2$O$_3$ nanoparticles, the coefficient of friction for the MoS$_2$/HPMC composite films decreased by 60%. Owing to the large surface area-to-volume ratio, small size, and angularity of the nanoparticles, the composite films were protected from abrasive Wear during the wear process. In addition, the nanoparticles remained in the wear scars for a long time, which provided the effects of load bearing and velocity accommodation in the wear scars.

Adding 1% Al$_2$O$_3$ nanoparticles significantly decreased the wear volume to 25% (2N, 30 m). In addition, the Al$_2$O$_3$ aggregated nanoparticles that remained in the wear scar caused abrasive wear owing to their high...
hardness. This generated a relatively large number of debris and increased the wear volume. In contrast, owing to their low hardness, the Al nanoparticles subjected to the stress of the chromium steel ball underwent plastic deformation and became squashed. Under the action of the flow of MoS₂, these squashed nanoparticles condensed with the debris to form a first-body layer, which could separate and recombine. The separated wear debris and nanoparticles remained in the wear scars to provide the effect of load bearing. Simultaneously, the fine debris could fill the rough peak of the grinding ball and reduce the frictional resistance. As a sequence, at 3% addition of Al nanoparticles, the wear volume compared to that of the pure MoS₂/HPMC composite film decreased by 80%.

Depending on the wear conditions, nanoparticles with the appropriate hardness can be selected as additives. When in abrasive contact with a relatively hard material, Al₂O₃ can be selected as an additive, which can serve as a load-capacity supporting layer. In contrast, Al is a relatively soft material that is usually used as a sacrificial layer to protect the substrate. In addition, the wear part that is in contact with Al is not scratched, simultaneously protecting both the substrate and the object in contact. Thus, for interlayer protection, a composite film with Al nanoparticles can be selected.

This study demonstrated significant improvement in the anti-wear characteristics and service life by adding minimal additives and the importance of understanding the wear mechanism of various additives to choose suitable composite formulations for different applications.

However, the composites using multi-additive materials are susceptible to deterioration due to particle agglomeration. In the future, the composites can be further developed in conjunction with dispersants to obtain a stable anti-wearing layer.

Acknowledgments

The authors gratefully acknowledge the use of EM000700 of MOST 110–2731-M-006–001 belonging to the Core Facility Center of National Cheng Kung University.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Funding

This work was supported by the National Science and Technology Council, Taiwan (grant number MOST 110–2221-E-006–150, 111–2221-E-006–145, 111–2221-E-006–147-MY2, and 111–2221-E-006–133).

Ethical statements

This material is the authors’ own original work, which has not been previously published elsewhere.

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.

ORCID iDs

Shih-Chen Shi https://orcid.org/0000-0002-4163-2552

References

[1] Zhang SW 2013 Friction 1 186
[2] Rastogi V K and Samyn P 2015 Coatings 5 887
[3] Li J W, Lin N, Du C, Amann T, Feng H, Yuan C Q and Li K 2022 Carbohydrate Polym. 290 119478
[4] Fuenmayor C et al 2022 Surface Topography: Metrology and Properties 10 034001
[5] Shi S-C and Liu G-T 2021 Cellulose 28 6147
[6] Shi S-C and Peng Y-Q 2020 Prog. Org. Coat. 138 105304
[7] Fahs A, Brogly M, Bistac S and Schmitt M 2010 Polymers 80 105
8. Shi S-C, Wu J-Y and Peng Y-Q 2018 Wear 408 208
9. Shi S-C, Tsai X-N and Pek S-S 2020 Surf. Coat. Technol. 389 125617
10. Dvorak S, Wahl K and Singer I 2007 Tribol. Lett. 28 263
11. Colas G, Saulot A, Godreau C, Michel Y and Berthier Y 2013 Wear 305 192
12. Centers P W 1988 Wear 122 97
13. Shi S-C and Jiang S-Z 2020 Surf. Coat. Technol. 389 125655
14. Dvorak S, Wahl K and Singer I 2007 Tribol. Lett. 28 263
15. Colas G, Saulot A, Godeau C, Michel Y and Berthier Y 2013 Wear 305 192
16. Chou R, Battez A H, Cabello J, Viesca J, Osorio A and Sagastume A 2010 Tribol. Int. 43 2327
17. Terezona R, Allsopp D and Hutchings I 1999 Wear 225 205
18. Calafiglia S, Carbone S, Di Mauro A and Valentini P 2011 Wear 262 949
19. Holmberg K and Mathews A 1994 Thin Solid Films 253 173
20. Ehrenberg B, Westman L and Tronko J 2009 Wear 266 482
21. Wohlfahrt C, Denekamp A and Wehrmann K 2010 Wear 268 482
22. Xue Q, Wang D, Wang Y and Sun A 2010 Adv. Eng. Mater. 12 534
23. Shabana S, Sonawane S, Ranganathan V, Pujjalwar P, Pinjari D, Bhanvase B, Gogate P and Ashokkumar M 2017 Ultrason. Sonochem. 36 59
24. Friedrich K and Schlirnb A K 2011 Tribology of Polymeric Nanocomposites: Friction and Wear of Bulk Materials and Coatings (Oxford: Elsevier)