Tribological behaviour of fused deposition modelling printed short carbon fibre reinforced nylon composites with surface textures under dry and water lubricated conditions

Ming LUO¹, Siyu HUANG¹,², Ziyan MAN¹, Julie M. CAIRNEY¹,², Li CHANG¹,*
¹ School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, Sydney NSW 2006, Australia
² Australian Centre for Microscopy and Microanalysis, The University of Sydney, Sydney NSW 2006, Australia
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Abstract: Fused deposition modelling (FDM) printed short carbon fibre reinforced nylon (SCFRN) composites were fabricated. The friction and wear behaviour of printed materials were systematically investigated under both dry sliding and water lubricated conditions. The results showed that with short fibre enhancements, the printed SCFRN achieved a lower friction coefficient and higher wear resistance than nylon under all tested conditions. Further, under water lubricated conditions, the printed SCFRN exhibited a low, stable friction coefficient due to the cooling and lubricating effects of water. However, the specific wear rate of the printed specimens could be higher than that obtained under dry sliding conditions, especially when the load was relatively low. The square textured surface was designed and created in the printing process to improve materials’ tribological performance. It was found that with the textured surface, the wear resistance of the printed SCFRN was improved under dry sliding conditions, which could be explained by the debris collection or cleaning effect of surface texture. However, such a cleaning effect was less noticeable under lubricated conditions, as the liquid could clean the surface effectively. On the other hand, surface textures could increase the surface area exposed to water, causing surface softening due to the higher water absorption rate. As a result, the samples having surface textures showed higher wear rates under lubricated conditions. The work has provided new insights into designing wear resistant polymer materials using three-dimensional (3D) printing technologies, subjected to different sliding conditions.

Keywords: fused deposition modelling (FDM); short carbon fibre reinforced nylon (SCFRN) composites; transfer film; friction and wear

1 Introduction

Additive manufacturing (AM, also known as three-dimensional (3D) printing) is a promising technology for fabricating rapid prototyping owing to its flexibility and low cost in creating complex engineering structures [1, 2]. 3D printing technology is being implemented in a wide variety of industries such as aerospace, mechanical, architectural, and marine industries with the use of all different types of engineering materials such as polymers, metal, ceramic, and concrete [3]. In particular, the production of polymer materials fabricated by the 3D printing technique has received vital attention due to their tremendous versatility and ease of use. Nevertheless, due to the intrinsically weak mechanical properties of pure polymers, there is a critical need to develop printable, high-performance polymeric composite materials using reinforcements and fillers, especially fibres [4, 5]. Fused deposition modelling (FDM) has become one of the most popular methods for fabricating polymer materials. Further, the filament
technique allows using various fillers including both short and continuous fibres, which enables to tailor the mechanical properties and functions of the printed materials/structures.

Many studies reported the mechanical properties such as strength and fracture toughness of printed polymeric composites [6, 7]. However, the tribological behaviour of printed composites has not been evaluated clearly, although fibre reinforced composites are often used in the tribo-applications such as bearing, gears, and rollers [8]. On the other hand, the composites fabricated using the FDM printing technology still have some disadvantages, including the lack of controlling fibre placement and the poor interface [2, 9], limiting their mechanical properties and tribological performance. To overcome such a shortage of printing technology, in our previous studies, surface textures were created on the printed specimens to improve their friction and wear performances [10]. The results showed that the induced surface texture could further improve the wear resistance of the fibre-reinforced composites by collecting large, abrasive debris. It is worth mentioning that FDM printing technology provides outstanding shape flexibility of fabricating the specimen with complex shapes of surface structures, comparing with traditional texturing methods such as micro-machining and laser surface cutting [11–13].

In the present work, the wear behaviour of composite materials with surface textures were further studied under lubricated conditions. It is known that polymers and their composites are often used in fluid environments as alternatives to metals, thanks to their superior corrosion resistance. However, many researchers reported that the friction and wear behaviour of polymer materials in fluid environments could be significantly different from that under dry sliding condition [14, 15]. Normally, under water lubricated conditions, the polymer/metal sliding system would exhibit the lower friction coefficients than those obtained under dry sliding conditions. This was often explained by the lubricating and cooling effects of water [16–18]. However, the wear performance of polymers in water can be complicated. Unal and Mimaroglu [17] reported that pure polyetheretherketone (PEEK) and 30% carbon fibre reinforced PEEK composites showed lower wear rate under water lubricated conditions, owing to the cooling effect of water. Others, however, have observed the increased wear rate of polymer specimens under lubricated conditions [16, 18–20]. It is noticed that lubricants such as water would generally inhibit the formation of transfer films on the metal counterparts, which may lead to lower wear resistance than those under dry sliding conditions [19, 20]. Further, the wear performance of polymer materials could also be impaired by water because water absorption would reduce the strength/hardness, modulus of elasticity, and swelling of the polymer surface layers [21, 22].

Therefore, the tribological properties are not real material properties but system responses, depending on the contact conditions of the system in which these materials are required to perform. There is still a lack of publications on designing the printed polymers and composites recently, e.g., considering their compositions and geometric design for the high wear resistance subjected to different sliding conditions. Therefore, this study aims to systematically investigate the friction and wear behaviour of FDM printed short carbon fibre reinforced nylon (SCFRN) under different sliding conditions. Toward that, a series of polymer composites were printed by using the FDM printing technology. The tribo-effects of fibre fillers and surface textures were studied under both dry and water lubricated conditions. The work strives to shed some light on the development of high wear resistant polymer composites subjected to various tribo-applications by using novel printing technologies.

2 Materials and experiments

2.1 Materials

The polymer and composite materials used in this study were fabricated using a commercial 3D printer (Markforged Mark Two system, USA) with a 0.1 mm layer height. Two filaments named Markforged nylon white (neat nylon) and Markforged Onyx (SCFRN) were applied to print the specimens. The short carbon fibres in the SCFRN filament have a diameter of 7.11±0.07 μm, with the average length of 105.43±61.83 μm. The fibre volume fraction of the short carbon fibre
filament is 9.6% ± 0.3%, which was measured by using the thermogravimetric analysis (TGA) method [23]. All specimens were fabricated with a solid infill at room temperature (25 °C). The printing speed of the printer was about 30 mm/s and the filament printing temperature was approximately 275 °C.

The dimension of the printed specimen for wear tests was 4 mm × 4 mm × 12 mm. Two surface structures including flat surface and square textured surface were printed. The square textured surface was designed with the width of 0.8 mm and the depth of 2 mm, as shown in Fig. 1(a). The printed textured surfaces of neat nylon and SCFRN are shown in Figs. 1(b) and 1(c), respectively. It is noticed that more accurate texture shapes were achieved with SCFRN filaments than those with neat nylon. This can be explained by the higher stiffness of SCFRN filaments [3, 10]. There are additional voids on the specimens, which often occur by printing more complex shapes with the FDM printing method [2, 10].

2.2 Experiments

The mechanical properties of printed samples were characterised by tensile tests using a universal testing machine (Instron 5567, USA) with a loading rate of 5 mm/min following ASTM standard D3039. Further, the surface hardness of the samples was measured on a UMIS Ultra nanoindentation system (CSIRO, Australia) with a diamond Berkovich indenter. The maximum load was 10 mN with 5 s holding time at peak load and 1 mN/s loading/unloading rate. At least five indentation points were collected to determine the average hardness value for FDM printed polymer and composite materials. In particular, the hardness of samples with water absorption was measured after immersing the specimens into distilled water for 20 h. In this case, the samples were prepared under the same condition for lubricated wear tests. Thus, the measured hardness can be used for understanding the effect of water absorption on the wear performance of the printed samples under lubricated conditions.

Wear tests were conducted at room temperature via a pin-on-disk configuration using a commercial tribometer (NANOVEA-MT/60/NI, Nanovea, USA) to investigate the friction and wear performance of printed polymer and composite materials under dry sliding and water lubricated conditions. During the wear tests, different loading conditions (20, 30, and 40 N) were applied to determine the wear behaviour of the printed composite materials. Correspondingly, the normal contact pressures were 1.25, 1.875, and 2.5 MPa, respectively. Each test was performed at a duration of 20 h with a 0.1 m/s linear speed, and the specimen and steel counterparts were immersed into distilled water under the water lubricated conditions. The steel counterparts were stainless steel disks (LS2542, SKF) which have a hardness of approximately 13,000 MPa and a surface roughness (Ra) of approximately 220 nm. The internal and external diameters of the steel counterpart were 25 mm and 42 mm, respectively. The specimens were cleaned and dried in a vacuum oven at 80 °C for 2 h after the tests to calculate the original weight. The specific wear rate ($W_s$) was calculated according to Eq. (1) [24]:

$$W_s = \frac{\Delta m}{\rho \times F_N \times L} \left( \frac{m \cdot m^3}{N \cdot m} \right)$$

where $\Delta m$ (g) is the mass loss of the printed
specimen, \( \rho \) (g/cm\(^3\)) represents the density of the specimen, \( F_n \) (N) is the normal load, and \( L \) (m) is the total sliding distance. Each wear test was repeated for at least three times to provide the scatter of the data.

After the wear test, the worn surface of each specimen was examined using a scanning electron microscope (SEM; Zeiss Ultra Field Emission Gun SEM, Germany) to investigate the wear mechanisms and the formation of transfer films. To further investigate the transfer film behaviour under dry sliding and water lubricated conditions, cross-section samples were provided by cutting out a cross-section of the steel counterparts. Then, the same was mounted in resins (25 mm) and polished by using a Struers Tegrapol polishing machine (1 \( \mu \)m) (Struers Dap-7, Denmark)[25]. This allows us to directly observe the cross-section of formed transfer films.

3 Results and discussion

3.1 Mechanical characterization

The mechanical properties of the printed nylon and SCFRN samples were characterized with tensile tests. The typical stress–strain curves are shown in Fig. 2(a). After the test, the fracture surface of SCFRN was examined using SEM, as given in Fig. 2(b). It is noticed that the printed SCFRN exhibited a higher tensile strength and modulus but lower elongation rate than those of pure nylon, i.e., SCFRN became stiff and brittle. This can be explained by the high stiffness and strength of short carbon fibres, which restrict the motion of nylon chains under loading conditions. Further, as shown in Fig. 2(b), numerous fibres were pulled out from polymeric matrix with smooth surfaces, indicating the poor interfacial strength between fibres and nylon. This would also contribute to the brittleness, i.e., the low elongation rate of SCFRN samples.

Table 1 summarizes the mechanical properties of the printed nylon and SCFRN. It can be seen that the printed SCFRN showed less water absorption than nylon. This may be explained by the high crystallinity of nylon in short carbon fibre reinforced nylon composites [26]. In this case, it would be more difficult for water to diffuse into the polymer matrix [26, 27]. To further examine the effects of water absorption on the mechanical performance of printed materials, hardness tests were conducted on the samples before and after water immersion conditions. All the indentation tests were carried out on polymers, as water absorption would be mainly taken by the polymer matrix. The representative load–displacement curves are given in Fig. 3. As shown in Fig. 3, the residual indention depth ranges from 1 to 2 \( \mu \)m, with the indents’ size of ~150 \( \mu \)m\(^2\). The average values of the measured hardness are also summarized and compared in Table 1. For the materials used in this work, it is noticed that the hardness of polymer specimens decreased proportionally to the absorption rate.

3.2 Friction coefficient

The friction coefficients of the printed polymer and composite materials tested under both dry and water lubricated conditions are summarized in Fig. 4. The given values were the average values of friction coefficient during the steady stage. It is noticed that under water lubricated conditions, both nylon and
Table 1  Mechanical properties of the FDM printed nylon and SCFRN.

| Mechanical property       | Markforged nylon | Markforged SCFRN |
|---------------------------|-------------------|-------------------|
| Tensile strength (MPa)    | 35.35±0.49        | 47.60±0.42        |
| Tensile modulus (GPa)     | 1.10±0.10         | 2.26±0.15         |
| Tensile elongation        | 0.65±0.08         | 0.16±0.01         |
| Density (g/cm³)           | 1.1               | 1.2               |
| Water absorption (%)      | 4.8±0.1           | 3.5±0.4           |
| Hardness (MPa)            |                   |                   |
| —Dry specimens            | 100.8±5.6         | 109.5±18.8        |
| —Water absorbed specimens| 51.7±4.6          | 74.1±10.3         |

SCFRN composites achieved lower friction coefficients than those under dry sliding conditions. Further, the friction coefficient of the printed SCFRN tended to increase with the normal load but was rather stable under water lubricated conditions. This can be explained by the cooling and lubrication effect of water, which contributes to a lower, stable friction coefficient. As shown in Fig. 4(b), the square textured surface showed a little influence on the friction coefficient with the flat surface under both dry sliding and water lubricated conditions. In general, the friction coefficient depends on the real contact area between the sliding surfaces and the shear strength of the sliding materials [28–31]. In our case, the induced textures would reduce ~16% of the nominal surface area of the printed samples. However, the real contact area between polymer specimen and steel disc during friction may not be affected, as it is normally less than 10% of the apparent contact area. This can explain the results that friction coefficients of the samples with and without textures showed similar trends, responding to the changes in loading conditions (cf. Fig. 4).

Figure 5 compared the representative friction processes of the printed materials tested under different conditions. As shown in Fig. 5, the running-in stage can take 2–10 h, depending on the types of materials and sliding conditions. SCFRN showed a much lower and stable friction coefficient under lubricated conditions, which can be explained by the effective lubricating effects of the distilled water [15, 22, 32]. It is also noticed that under dry sliding conditions, the friction can be greatly affected by the increased pressures, possibly due to the frictional heating in the contact region. However, owing to the cooling and lubricating effects of water, the friction behaviour of SCFRN was less dependent on the external loads as shown in Fig. 4(b).

For neat nylon, the measured friction coefficient showed significant fluctuations in the steady stage, varying from ~0.2 to ~0.8. It is noticed that the highest value matches those measured for neat nylon tested under dry sliding conditions, which ranges

Fig. 3  Representative load–displacement curves for nylon and SCFRN before (dry) and after (water) 20 h water absorption tests.

Fig. 4  Average friction coefficient: (a) nylon and SCFRN tested under dry and water lubricated conditions with a constant load of 20 N and (b) SCFRN tested under dry and water lubricated conditions with various loads.

![Figure 3](image-url)

![Figure 4](image-url)
from 0.6 to 0.7. On the other hand, the lowest value of the friction coefficient agrees with the results from the SCFRN under lubricated conditions. As aforementioned, the low friction coefficient for SCFRN is due to the lubricating effects of water. In this case, the lubricants at the interface will govern the friction between sliding pairs. Therefore, the results suggest that the low friction coefficient for neat nylon was also caused by boundary lubrication of water, as observed for SCFRN. However, for neat nylon, water could only temporarily form an effective lubricating film in the contact range, which would be easily broken or even squeezed out due to the smooth contact. Once it occurs, the friction would be mostly determined by the direct contact between solid surfaces. Correspondingly, the recorded friction coefficient is more comparable with those measured under dry conditions. Nevertheless, water can still be periodically brought into the contact area due to the wear process of contact surfaces. As a result, the friction coefficient varied between the values obtained from lubricating film and dry sliding conditions. With the fibre reinforcements, stiff fibres would undertake the most load during the wear process and stand out from the polymer matrix [33, 34]. Those protruded fibres can create a gap (typically at a submicron scale [35]) for water lubricants between sliding counterparts. As a result, a lower and stable friction coefficient can be achieved thanks to such a mixed-lubrication effect.

### 3.3 Wear behaviour

The specific wear rate of FDM printed polymer and composite materials under both dry and water lubricated conditions are shown in Fig. 6(a). In general, the printed SCFRN can achieve a significantly lower specific wear rate than neat nylon under all tested conditions, owing to the enhanced mechanical properties of composite materials. Under dry sliding conditions, for both neat nylon and SCFRN, the specific wear rates were reduced by the induced surface textures. In this case, the square textured...
surface provided a discontinuous contact surface, thereby reducing the adhesion force between the specimen and counterpart [36]. Surface textures would also collect the wear debris during the wear process, thus reducing the abrasive wear [37]. Further, it is noticed that for both samples under water lubricated conditions, the specific wear rates were higher than that under dry sliding condition, despite the lower friction coefficient with water. This may be due to the softening effect of water absorption on polymers. As given in Table 1, the mechanical properties of printed polymer specimens would be clearly reduced after immersed in water. Nevertheless, with fibre reinforcements, the absorption rate would be decreased. Accordingly, the mechanical properties were less affected. This agrees with the results shown in Fig. 6(a), i.e., SCFRN showed more stable wear behaviour under dry and lubricated conditions.

Figure 6(b) compares the specific wear rates of SCFRN with the increasing normal loads from 20 to 40 N. It is noticed that the specific wear rate of SCFRN increases with the increasing normal load under dry sliding conditions but decreases under lubricated conditions. Also, the specific wear rate of SCFRN significantly increased with the induced surface textures under water lubricated conditions. The surface textures were helpful for improving the wear resistance under dry sliding conditions, by reducing adhesive and abrasive wear. Water could clean the worn surfaces of the specimens and washed the wear debris away from the contact region. In this case, the beneficial effects of surface textures such as the collection of wear debris became less noticeable. On the other hand, the surface texture would increase the real contact surface area exposed in water and thereby, increasing the water absorption, which would impair the mechanical properties of the printed composite materials. Therefore, the printed composite materials with surface textures provided an even higher specific wear rate than those without surface textures under water lubricated conditions.

### 3.4 SEM analysis

Figure 7 presents the SEM images of the worn surfaces of FDM printed nylon under 20 N in dry sliding conditions. The results showed that worn surfaces of the neat nylon were rather smooth, without noticeable abrasives grooves. The quality of surface finishing has been comprised with the induced surface textures during the printing process [10]. As a result, more wear debris was observed around textures and other voids at surfaces.

![Fig. 7](image-url)
Figure 8 shows the SEM images of the worn surfaces of printed nylon under water lubricated conditions. Compared with Fig. 7, more surface damages are observed under water lubricated conditions. In particular, there are more exfoliations and cracks at the worn surface, especially around the induced textures and the voids. This may be attributed to the water absorption, causing the swelling of the surface associated with the weakened surface properties of nylon [22]. As a result, the wear rate of neat nylon was significantly increased under water lubricated conditions (cf. Fig. 6).

Figure 9 shows the SEM images of the worn surfaces of printed SCFRN under 20 N in dry sliding conditions.
conditions. It is noticed that the worn surface of the flat surface was rough. Fibre breakage and fibre removal can be seen, especially in the middle region of the worn surface. This may be due to the relatively high contact temperature in the central area. On the other hand, the fibre debris can sometimes be trapped in the contact region and serve as the third abrasive medium, resulting in grooves on the worn surface (Fig. 9(b)). Compared with the flat surface, the worn surface of square textured surface was rather smooth. The square textured surface provided a discontinuous contact surface, reducing the concentration of adhesion force and thus frictional heating at the central region. Also, the collection of wear debris in textures was noticed (Fig. 9(d)), which contributed to a lower wear rate by reducing severe three-body abrasive wear [10]. In this case, some abrasive grooves were only observed at texture regions due to the agglomerated debris trapped in the squared textures.

Figure 10 shows the SEM images of the worn surfaces of printed SCFRN under water lubricated conditions. Unlike the worn surfaces of the printed nylon under water lubricated conditions, the worn surfaces of printed SCFRN were clean and smooth. Accordingly, for the flat surface, there was much less micro-sized grooves caused by fibre debris. Whilst, for the surfaces with textures, the worn surface was smooth and there was no observable debris collected in the textures (Figs. 10(c) and 10(d)), which also confirmed the cleaning effect of water.

3.5 Transfer film layers

During the wear processes of polymers against metal counterparts, the material transfer occurs, i.e., polymer debris would transfer and attach on the metal surface, which sometimes results in continuous films on metals. The influence of such transfer films in polymer tribology is well-discussed in Refs. [38, 39]. Many studies reported that water lubricant may hinder the formation of continuous transfer films on steel counterpart, as the main reason explaining the poor wear performance of polymers under lubricated conditions. Therefore, to further investigate the underlying wear mechanisms, the formation of transfer films on steel counterpart were further examined. Figure 11 shows the SEM images of the transfer film layers formed on the steel counterparts of SCFRN and nylon under different lubricated conditions at a normal load of 20 N. Both printed nylon and SCFRN could effectively form the uniform and tenacious transfer film layers on the steel counterpart under dry sliding conditions, which would be beneficial for decreasing friction coefficient.
and specific wear rate [20]. Under water lubricated conditions, the surface profile of wear tracks has been clearly changed compared to the original steel disk, suggesting the presence of transfer film. However, it is difficult to quantitatively evaluate the transfer film using the top-view SEM images. Hence, the cross-sectional SEM analysis of the wear tracks on the steel counterpart was carried out to further examine the distribution and thickness of transfer film layers, as shown in Fig. 12.

It is noticed that the transfer film layers were continuously formed on the steel disk under all the tested conditions. Both printed nylon and SCFRN provided continuous transfer films under water lubricated conditions. In the case of water lubrication, there is a complementary effect between water and solid transfer film for polymer specimens. Due to its low viscosity, water normally shows poor load-carrying capacity. Thus, solid transfer film would be more effective to reduce wear by reducing the abrasiveness of the asperities of hard steel disk. On the other hand, water would clean the wear debris and reduce frictional heating. This explains the results that under relatively high loading conditions, the flat surface shows an even better wear performance in water than that obtained from dry sliding conditions, despite the weakened mechanical properties due to water absorption. However, the textured samples are not desirable for lubricated conditions, probably due to the significant reduction of the mechanical properties.

Fig. 11 SEM images of the wear tracks on the steel counterpart of FDM printed SCFRN and nylon: (a) SCFRN under dry sliding condition, (b) SCFRN under water lubricated condition, (c) nylon under dry sliding condition, and (d) nylon under water lubricated condition, compared to (e) the virgin steel counterpart.
Friction at the surface. Therefore, the design and selection of materials for tribological applications should consider both internal mechanical properties and external sliding conditions.

Finally, it is worthwhile pointing out that the effectiveness of textures is greatly dependent on the shape and dimensions of texture structures. In the present work, the dimensional accuracy and resolution of the FDM printing method were limited by the fabrication parameters of the used equipment. The wear performance of the textured materials can be possibly enhanced by further optimizing the shape and size of textures, which can be further studied in future work.

4 Conclusions

In this study, the friction and wear behaviour of the FDM printed SCFRN composites with the designed surface textures have been comparatively investigated under dry sliding and water lubricated conditions. It is found that the sliding wear process of the printed polymeric materials is normally affected by a number of parameters such as the properties of base materials, the removal process of fibers, the formation of transferred film, the presence of the third body debris, and the evolution of surface profiles, as well as the interactions between those factors. Hence, the design and selection of tribo-materials using AM technology would require a systematic approach by considering multiple parameters. In particular, the following conclusions can be drawn:

1) The FDM printed composite materials (SCFRN) exhibited a lower friction coefficient and significantly higher wear resistance than printed polymer materials (neat nylon) under dry sliding and water lubricated conditions. Short carbon fibres contributed to various beneficial effects such as the enhancements of mechanical properties and the diminution of water absorption under water lubricated conditions.

2) The beneficial effects of surface textures were attributed to reducing friction and wear rate under dry sliding conditions by collecting wear debris and fibre debris, therefore minimising the three-body abrasive wear. Under water lubricated conditions, however, those beneficial effects became less noticeable. On the other hand, the surface texture would increase the real surface area exposed in the distilled water. With the increase in water absorption, the mechanical properties and the wear resistance of the printed composite materials were significantly impaired under lubricated conditions.

3) It is found that both printed nylon and SCFRN can form continuous transfer films under water lubricated conditions. In this case, there is a complementary effect between water and solid transfer film for polymer specimens, especially under extreme conditions such as at high temperatures and/or under high loads. In particular, solid transfer film would be effective to reduce abrasive wear by covering the asperities of hard steel disk. Whilst, water would reduce adhesion and frictional heating. As a result, when the normal load reached 40 N, the printed SCFRN showed higher wear resistance under lubricated conditions.

Fig. 12 Cross-sectional SEM images of the steel counterpart: (a) SCFRN under dry sliding condition, (b) nylon under dry sliding condition, (c) SCFRN under water lubricated condition, and (d) nylon under water lubricated condition.
conditions, compared to the result under dry sliding conditions.

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References

[1] He Q H, Wang H J, Fu K K, Ye L. 3D printed continuous CF/PA6 composites: Effect of microscopic voids on mechanical performance. Compos Sci Technol 191: 108077 (2020)

[2] Heidari-Rarani M, Rafiee-Afarani M, Zahedi A M. Mechanical characterization of FDM 3D printing of continuous carbon fiber reinforced PLA composites. Compos B: Eng 175: 107147 (2019)

[3] Wickramasinghe S, Do T, Tran P. FDM-based 3D printing of polymer and associated composite: A review on mechanical properties, defects and treatments. Polymers 12(7): 1529 (2020)

[4] Lancaster J K. Polymer-based bearing materials: The role of fillers and fibre reinforcement. Tribology 5(6): 249–255 (1972)

[5] Voss H, Friedrich K. On the wear behaviour of short-fibre-reinforced peek composites. Wear 116(1): 1–18 (1987)

[6] Ning F D, Cong W L, Qiu J J, Wei J H, Wang S R. Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling. Compos Part B–Eng 80: 369–378 (2015)

[7] Dizon J R C, Espira JR A H, Chen Jr Q Y, Advincula R C Jr. Mechanical characterization of 3D-printed polymers. Addit Manuf 20: 44–67 (2018)

[8] Zhang Y, Purssell C, Mako K, Leigh S. A physical investigation of wear and thermal characteristics of 3D printed nylon spur gears. Tribol Int 141: 105953 (2020)

[9] Prusinowski A, Kaczyński R. Tribological behaviour of additively manufactured fiber-reinforced thermoplastic composites in various environments. Polymers 12(7): 1551 (2020)

[10] Luo M, He Q H, Wang H J, Chang L. Tribological behavior of surface textured short carbon fiber-reinforced nylon composites fabricated by three-dimensional printing techniques. J Tribol 143(5): 051105 (2021)

[11] Wang M L, Wang X J, Liu J Y, Wei J C, Shen Z W, Wang Y. 3-Dimensional ink printing of friction-reducing surface textures from copper nanoparticles. Surf Coat Technol 364: 57–62 (2019)

[12] Zhang P, Liu X J, Lu W L, Zhai W Z, Zhou M Z, Wang J. Fretting wear behavior of CuNiAl against 42CrMo4 under different lubrication conditions. Tribol Int 117: 59–67 (2018)

[13] Bhaduri D, Batal A, Dimov S S, Zhang Z, Hong H, Fallqvist M, M’Saoubi R. On design and tribological behaviour of laser textured surfaces. Procedia CIRP 60: 20–25 (2017)

[14] Sumer M, Unal H, Mimaroğlu A. Evaluation of tribological behaviour of PEEK and glass fibre reinforced PEEK composite under dry sliding and water lubricated conditions. Wear 265(7–8): 1061–1065 (2008)

[15] Chauhan S R, Kumar A, Singh I. Sliding friction and wear behaviour of vinylester and its composites under dry and water lubricated sliding conditions. Mater Des 31(6): 2745–2751 (2010)

[16] Tanaka K. Friction and wear of semicrystalline polymers sliding against steel under water lubrication. J Lubr Technol 102(4): 526–533 (1980)

[17] Unal H, Mimaroğlu A. Friction and wear characteristics of PEEK and its composite under water lubrication. J Reinf Plast Compos 25(16): 1659–1667 (2006)

[18] Yu S R, Hu H X, Yin J. Effect of rubber on tribological behaviors of polyamide 66 under dry and water lubricated sliding. Wear 265(3–4): 361–366 (2008)

[19] Lancaster J K. Lubrication of carbon fibre-reinforced polymers part I—Water and aqueous solutions. Wear 20(3): 315–333 (1972)
[20] Meng H, Sui G X, Xie G Y, Yang R. Friction and wear behavior of carbon nanotubes reinforced polyamide 6 composites under dry sliding and water lubricated condition. Compos Sci Technol 69(5): 606–611 (2009)

[21] Lutton M D, Stolarski T A. The effect of water lubrication on polymer wear under rolling contact conditions. J Appl Polym Sci 54(6): 771–782 (1994)

[22] Alomayri T, Assaedi H, Shaikh F U A, Low I M. Effect of water absorption on the mechanical properties of cotton fabric-reinforced geopolymer composites. J Asian Ceram Soc 2(3): 223–230 (2014)

[23] Pascual-González C, Iragn M, Fernández A, Fernández-Blázquez J P, Aretxabala L, Lopes C S. An approach to analyse the factors behind the micromechanical response of 3D-printed composites. Compos Part B–Eng 186: 107820 (2020)

[24] Chang L, Zhang Z, Breidt C, Friedrich K. Tribological properties of epoxy nanocomposites: I. Enhancement of the wear resistance by nano-TiO2 particles. Wear 258(1–4): 141–148 (2005)

[25] Kurdi A, Kan W H, Chang L. Tribological behaviour of high performance polymers and polymer composites at elevated temperature. Tribol Int 130: 94–105 (2019)

[26] Tan J K, Kitano T, Hatakeyama T. Crystallization of carbon fibre reinforced polypropylene. J Mater Sci 25(7): 3380–3384 (1990)

[27] Srinath G, Gnanamoorthy R. Sliding wear performance of polyamide 6-clay nanocomposites in water. Compos Sci Technol 67(3–4): 399–405 (2007)

[28] Chung C I, Hennessey W J, Tusim M H. Frictional behavior of solid polymers on a metal surface at processing conditions. Polym Eng Sci 17(1): 9–20 (1977)

[29] Saikko V. Effect of contact pressure on wear and friction of ultra-high molecular weight polyethylene in multidirectional sliding. Proc Inst Mech Eng H 220(7): 723–731 (2006)

[30] Du S R, Mullins M, Hamdi M, Sue H J. Quantitative modeling of scratch behavior of amorphous polymers at elevated temperatures. Polymer 197: 122504 (2020)

[31] Du S R, Zhu Z W, Liu C, Zhang T, Hossain M M, Sue H J. Experimental observation and finite element method modeling on scratch-induced delamination of multilayer polymeric structures. Polym Eng Sci 61(6): 1742–1754 (2021)

[32] Wu J, Cheng X H. The tribological properties of Kevlar pulp reinforced epoxy composites under dry sliding and water lubricated condition. Wear 261(11–12): 1293–1297 (2006)

[33] Chang L, Friedrich K. Enhancement effect of nanoparticles on the sliding wear of short fiber-reinforced polymer composites: A critical discussion of wear mechanisms. Tribol Int 43(12): 2355–2364 (2010)

[34] Li D X, You Y L, Deng X, Li W J, Xie Y. Tribological properties of solid lubricants filled glass fiber reinforced polyamide 6 composites. Mater Des 46: 809–815 (2013)

[35] Wang J Z, Chen B B, Liu N, Han G F, Yan F Y. Combined effects of fiber/matrix interface and water absorption on the tribological behaviors of water-lubricated polytetrafluoroethylene-based composites reinforced with carbon and basalt fibers. Compos A: Appl Sci Manuf 59: 85–92 (2014)

[36] Zeng S S, Li J B, Zhou N N, Zhang J Y, Yu A B, He H B. Improving the wear resistance of PTFE-based friction material used in ultrasonic motors by laser surface texturing. Tribol Int 141: 105910 (2020)

[37] Qi X W, Wang H, Dong Y, Fan B L, Zhang W L, Zhang Y, Ma J, Zhou Y F. Experimental analysis of the effects of laser surface texturing on tribological properties of PTFE/Kevlar fabric composite weave structures. Tribol Int 135: 104–111 (2019)

[38] Higgs C F, Warnyoh E Y A. An in situ mechanism for self-replenishing powder transfer films: Experiments and modeling. Wear 264(1–2): 131–138 (2008)

[39] Chang L, Friedrich K, Ye L. Study on the transfer film layer in sliding contact between polymer composites and steel disks using nanoindentation. J Tribol 136(2): 021602 (2014)

Ming LUO. He received his B.S. degree in mechanical engineering in 2018 from the University of Sydney, Australia. Then, he received his M.S. degree in the Centre for Advanced Materials Technology, School of Aerospace, Mechanical and Mechatronic Engineering from the University of Sydney, Australia, in 2021. He is currently a Ph.D. candidate in the Department of Materials Science and Engineering at the University of New South Wales, Australia. His research interests include microstructures and properties of additively manufactured materials.
Siyu HUANG. He received his M.Phil. degree in 2019 from the University of Sydney, Australia. Currently, he is a Ph.D. candidate at the University of Sydney. His research interests cover the hydrogen embrittlement, microscopy techniques, and tribology.

Ziyan MAN. She received her M.S. degree in biomedical engineering in 2018 from the University of Sydney, Australia. She is currently a Ph.D. candidate at the University of Sydney. Her research interest includes tribology, polymer composites, and additive manufacturing.

Julie M. CAIRNEY. She is a professor of Materials Engineering at the University of Sydney, Australia. She leads a research group that specialises in using advanced microscopy to study the 3D structure of materials at the atomic scale. Her projects cover steels, corrosion products, hydrogen embrittlement, and microscopy technique development. She serves as the vice president of the International Field Emission Society, which supports the atom probe microscopy community. She is also a passionate contributor to the broader scientific community and was selected as one the World Economic Forum (WEF)’s 50 Young Scientists of 2016.

Li CHANG. He is a senior lecturer in the School of Aerospace, Mechanical, and Mechatronic Engineering, at the University of Sydney, Australia. He received his B.S. and M.S. degrees from Tsinghua University, China, in 1999 and 2002, respectively. In 2005, he received his Ph.D. degree from the Institute for Composite Materials (IVW GmbH), Technical University of Kaiserslautern, Germany. His main research areas are tribology, polymer nanocomposites, nanoindentation, and additive manufacturing.