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Review

Development of Wear-Resistant Polymeric Materials Using Fused Deposition Modelling (FDM) Technologies: A Review

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Abstract: The advancement of 3D printing technology has changed material design and fabrication across various industries. Among its many applications, the development of high-wear-resistance polymer composites, particularly using Fused Deposition Modelling (FDM), has received increasing interest from both academic and industrial sectors. This paper provides an overview of recent advances in this field, focusing on the selection of key printing parameters (such as layer thickness, print speed, infill density, and printing temperature) and material compatibility optimisation to enhance print quality and tribological performance. The effects of various tribo-fillers, such as fibres and nanoparticles, on the tribological properties of the printed polymer composites were studied. Generally, in the case of nano-sized particles, the wear rate can be reduced by approximately 3 to 5 times when the nanoparticle content is below 5 vol.%. However, when the nanoparticle concentration exceeds 10 vol.%, wear resistance may deteriorate due to the formation of agglomerates, which disrupts the uniform dispersion of reinforcements and weakens the composite structure. Similarly, in short fibre-reinforced polymer composites, a fibre content of 10–30 vol.% has been observed to result in a 3 to 10 times reduction in wear rate. Special attention is given to the synergistic effects of combining micro- and nano-sized fillers. These advancements introduce novel strategies for designing wear-resistant polymer composites without requiring filament fabrication, making 3D printing more accessible for tribological applications. In the last part of the review, the impact of emerging AI technologies on the field is also reviewed and discussed. By identifying key research gaps and future directions, this review aims to drive further innovation in the development of durable, high-performance materials for wide industry applications in aerospace, biomedical, and industrial engineering.

Keywords: 3D printing; wear-resistant; polymer composites; tribology

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1. Introduction

Over the past decade, the development of 3D printing technology has had a major impact on many engineering fields, from biomedical to automotive to aerospace. The advancement is changing the traditional material design and fabrication process. One important area of focus in this field is the development of wear-resistant polymer materials/structures using 3D printing methods [1].

Wear-resistant polymer composites are crucial in a wide range of applications, from industrial machinery components to dental restorations. Among those applications, components are subjected to friction, abrasion, and repetitive mechanical stresses. As friction and wear contribute significantly to global energy consumption and material waste, friction

alone accounts for nearly one-third of total primary energy use, and by implementing tribological strategies, significant reductions in energy consumption and greenhouse gas emissions can be achieved. It estimates that applying existing tribological technologies could reduce global CO_2 emissions by 6–10 gigatons, accounting for over 15–26% of total emissions [2].

In addition, the performance and durability of engineering components are mostly dependent on the friction and wear properties of the materials. As such, the design and selection of wear-resistant materials is critical for these specialised industrial applications [3]. On the other hand, 3D printing has emerged as a technology that may change materials design and manufacturing, owing to its ability to create complex geometries that offer design freedom and the manufacturing process, such as placing a particular reinforcement at a certain part of printed composites. Accordingly, several attempts have been made to develop high-wear-resistance composite materials [4–9]. Good mechanical and tribological properties can be achieved by using different reinforcement fillers, including continuous fibres [10]. Further, the 3D printing method provides great shape flexibility in fabricating the specimen with complex shapes of surface structures, which is another promising approach to enhance the tribological performance of the printed structures [11,12]. In addition to design flexibility and reinforcement incorporation, the layer-by-layer extrusion method of FDM provides unique advantages over traditional polymer manufacturing techniques, such as moulding and casting, in the context of wear-resistant polymer composites. FDM enables precise control over reinforcement alignment, allowing for optimised fibre orientation and filler distribution, as reported in previous studies [13,14], which directly influences wear resistance. Additionally, the ability to control surface texture provides further opportunities to tailor wear performance. These advantages position FDM as a promising alternative for developing wear-resistant polymer composites with tunable mechanical and tribological properties. Other 3D printing techniques such as material jetting is also gaining popularity due to its capability to produce multi-material parts by UV curing in a single process [15]. Nevertheless, they remain dominant in producing functional materials instead of wear-resistant polymer composites.

However, the application of 3D printing technology for high-wear-resistance composites presents several challenges that must be addressed. First, it is practically difficult to fabricate filaments with high-volume fraction reinforcements, e.g., the highest volume fraction of fibres achieved for FDM is ~40 vol.% compared with >65 vol.% using the traditional autoclave technique. High-volume fractions of reinforcements can enhance mechanical properties but may complicate processing due to increased viscosity and poor flowability. Printability issues also arise with higher reinforcement content, often resulting in nozzle clogging and inconsistent extrusion, inducing more complexity in selecting and optimising print parameters [16,17]. Secondly, there is still a lack of automated methods for determining the printing parameters to achieve the desirable wear properties of printed parts. In practice, the selection of printing parameters is still largely based on a trial–error process, which is time-consuming and potentially lacks reliability [12,18,19]. Another issue is the anisotropic structures created by using FDM technology. In general, the material can show distinctive properties along and against printing directional, which can sometimes negatively impact the mechanical properties of the printed components [20,21]. Finally, the quality of prints, such as void formation and surface finishing in the FDM, presents a significant challenge for practical applications, as achieving consistent material distribution remains difficult. Addressing these challenges requires a systematical design and process strategy by optimising printing parameters, understanding material formulations, and applying post-processing techniques to enhance structural integrity and functionality [16].

This review provides a comprehensive examination of recent advancements in the development of high-wear-resistance polymer composites using 3D printing technologies. A primary focus is placed on Fused Deposition Modelling (FDM), the most popular technology for developing high-wear-resistance polymer composites. In Section 2, a broad view is provided of the distinct advantages, limitations, and suitability for fabricating wear-resistant composites by comparing with another important printing technology, the selective laser sintering (SLS) processing method. In particular, the tribo-effects of various 3D printing parameters were reviewed. In Section 3, the selection criteria for base materials and reinforcements are discussed, with specific attention given to the critical role of various tribo-fillers in determining the wear performance of the printed composite materials. In Section 4, recent advances in developing high-wear-resistance polymer composites are highlighted, including the attempts to explore synergistic effects of micro-sized and nano-sized fillers, the design and fabrication of complex surface textures to optimise the friction and wear properties, and the impact of emerging AI technology in the field. By identifying existing research gaps and proposing potential future directions, this review aims to contribute to the advancement of the field and inspire further investigations into novel 3D-printed wear-resistant materials.

2. Considerations for Selecting the 3D Printing Technologies for Wear-Resistant Composites

2.1. Popular 3D Printing Technologies for Polymer Composites

The selection of 3D printing technology is a crucial factor in the development of wear-resistant composite materials, as each technique offers distinct advantages and faces unique challenges in designing and fabricating polymeric materials. This section focuses on two widely used 3D printing methods: Fused Deposition Modelling (FDM) and Selective Laser Sintering (SLS). By analysing these technologies, their role in controlling material properties to specific requirements will be explained, providing a comprehensive understanding of their contributions to this field.

2.1.1. Fused Deposition Modelling (FDM)

FDM, a widely used 3D printing technology, operates through the layer-by-layer deposition of molten thermoplastic filaments. Known for its simplicity, cost-effectiveness, and accessibility, FDM is a popular choice for fabricating polymer composites using different polymers such as ABS, PLA, or specialised filaments infused with reinforcing agents. Despite its advantages, achieving uniform distribution and alignment of reinforcements within the printed layers remains a significant challenge. To enhance the wear resistance of FDM-printed components, optimisation of key printing parameters, including nozzle temperature, layer height, and extrusion speed, is essential. These adjustments ensure better interlayer adhesion and reinforcement integration, improving the performance and durability of the final product [22,23].

2.1.2. Selective Laser Sintering (SLS)

SLS is another additive manufacturing technique that uses a high-powered laser to selectively fuse powdered materials. This process enables the fabrication of complex geometries and highly durable components. SLS is particularly effective in producing functionalised composites, as it allows for the integration of various fillers, such as short fibres or particulate fillers, into the powder bed. By selectively sintering the powdered composite, SLS produces robust and homogeneous structures with enhanced properties such as wear resistance. The versatility of SLS extends to a wide variety of polymers,

enabling the creation of components with tailored material properties to meet specific application requirements [24].

Table 1 compares the two printing techniques. The contents of the table and the subsequent summary were derived from various research articles [25–30]. As shown in the table, FDM, with its affordability, accessibility, and versatility, is ideal for prototyping and small-scale production, particularly when cost-efficiency and ease of use are priorities. On the other hand, SLS provides superior accuracy, smoother surface finishes, and the ability to produce larger and more complex parts, making it suitable for applications demanding high precision and scalability. However, these advantages come at a higher cost, emphasising the need to align the choice of technology with the demands. Thus, the choice between FDM and SLS depends on the specific requirements of the application.

Table 1. Comparison of FDM and SLS technology.

Printing Type	FDM	SLS
Print accuracy	Medium	High
Maximum printing size	Low	High
Capability for post-processing	Medium	Medium
Choice of raw materials	Medium	High
Machine size	Low	High
Affordability of the machine	High	Low
Affordability of the operation	High	Low

The terms "Low", "Medium", and "High" in this table indicate the relative performance or desirability of each characteristic when comparing FDM and SLS. The classification is based on commonly reported values in the literature. For instance, print accuracy is the dimensional precision of printed parts relative to the original CAD model. "High" means minimal deviations, while "Medium" suggests the need for calibration or post-processing to achieve tight tolerances.

2.2. The Role of 3D Printing Parameters in Achieving High Wear Resistance

The effectiveness of 3D printing technologies in creating wear-resistant components is not only dependent on the choice of technology but also relies on various printing parameters. This section focuses on FDM technology by considering the critical role of 3D printing parameters—such as layer thickness, printing speed, infill density, and temperature—in achieving high wear resistance of the final printed components.

2.2.1. Layer Thickness

Layer thickness, defined as the height of each deposited layer in the 3D printing process, plays an important role in determining the mechanical properties of printed components. Rankouhi et al. [31] concluded that minimising layer thickness is normally beneficial for enhancing the mechanical strength of 3D-printed parts. Their study emphasised that reducing layer thickness minimises the gaps between thermal interlayers, resulting in a smaller air gap-to-material ratio. This leads to a denser structure with fewer voids, allowing the printed part to withstand higher loads and exhibit greater elasticity. Further, smaller layer thickness will also create stronger interlayer adhesion and, thus, better mechanical performance. In a similar manner, layer thickness can have a large impact on tribological properties. For instance, Norani et al. [32] investigated the effects of 3D printing parameters on the wear characteristics of ABS. Their findings suggested that a decrease in layer thickness correlated with a lower wear rate. Additionally, an optimal extrusion temperature was identified to yield optimal wear performance for ABS. Notably, the study identified line infill type as the most effective infill pattern for achieving optimal wear resistance [32]. Likewise, Srinivasan and colleagues observed improved wear resistance as

layer thickness decreased across a range of infill densities (40% to 80%) for grid, rectilinear, and triangular infill patterns in ABS [33]. Other comparable results can also be found in Table 2. Furthermore, this trend extends to carbon fibre-reinforced PLA, as investigated in a study by the same group [34]. The authors noted a consistent decrease in wear rate with smaller layer thickness across various infill densities. It is suggested that smaller layer thickness resulted in fewer air gaps within the components, which increased the mechanical strength and, thus, better tribological performance. In the scenario involving continuous glass fibre-reinforced PLA [35], the thickness of each layer has a considerable influence on the flexural strength, flexural modulus, impact strength, and interlaminar shear strength. Notably, all these properties exhibit improvement with a decrease in layer thickness. A similar study [36] demonstrates that reducing layer thickness in FDM-printed components significantly enhances mechanical and tribological properties by improving interlayer adhesion and minimising voids between layers. Smaller layer thickness allows for better thermal fusion between adjacent layers, which strengthens the interfacial bonding and reduces the likelihood of delamination under mechanical or tribological stress. This results in improved wear resistance and a lower coefficient of friction as the smoother surface quality reduces abrasive interactions during sliding contact. However, lower porosity can sometime be achieved by increasing the layer thickness during 3D printing, which can also influence the overall mechanical and tribological properties of the printed materials. As highlighted in the investigation by Amirruddin et al. [37], by increasing the layer thickness, the total number of layers in the build is reduced, thereby minimising void formation and enhancing the mechanical integrity of the final product. This approach highlights the importance of optimising printing parameters to achieve desired material properties.

2.2.2. Printing Speed

Printing speed is another important printing parameter that can significantly impact the quality and performance of 3D-printed components. Faster printing speeds would reduce production times but often negatively affect print quality due to different temperature profiles resulting from the printing process [38]. Chithambaram et al. [12] studied the wear behaviours of printed PEEK materials. It was found that the mechanical properties of PEEK are significantly influenced by printing speed, as it directly affects the interlayer adhesion and surface quality of the printed materials. In particular, the study showed that a printing speed of 20 mm/s combined with a layer thickness of 0.15 mm resulted in superior mechanical performance, with the highest microhardness value (26.3 HV) and the lowest wear rate (0.17×10^{-9} mm^3/Nm) under a maximum load of 60 N. The desirable performance was attributed to the slower printing speed, which provides sufficient time for polymer chain diffusion across adjacent layers, ensuring strong interlayer bonding and minimising defects such as voids and weak interfaces. Conversely, higher printing speeds, such as 25 mm/s, limit the diffusion process, reducing interlayer adhesion and increasing the likelihood of surface defects such as pitting and microcracks. These defects compromised the mechanical integrity of the printed material, leading to lower hardness and, thus, higher wear rates. The findings emphasise the importance of printing speed in determining the wear performance of 3D-printed components [12]. The positive effects of printing speed on mechanical and tribological properties were well reviewed in [13]. It was summarised that lower printing speeds would enhance interlayer bonding and mechanical strength by allowing more time for the diffusion of polymer chains between layers, leading to better crystallinity of thermoplastics such as PEEK and fewer voids. Higher printing speeds tend to result in more structure defects and poor mechanical properties, i.e., lower tensile strength and toughness. It was also noticed that the printed materials with lower printing speeds could reach better wear resistance by facilitating the formation of uniform

transfer films on counter surfaces during frictional contact. However, it is worthwhile mentioning that excessive reduction in speed could also lead to thermal accumulation, potentially affecting part dimensions. Therefore, in practice, it is important to select the optimised printing speed by considering its interactions with other printing parameters. For instance, He et al. reported that the optimal combination of FDM parameters, including printing speeds around 40 mm/s and higher nozzle temperatures, yielded the best mechanical properties profile with improved tensile, compressive, and flexural strength [18]. Pulipaka et al. [19] conducted a systematic study on the impact of various 3D printing parameters on the mechanical properties of PEEK. The authors concluded that although high printing temperatures required for PEEK (390–420 °C) mitigate some negative effects by enhancing material fusion, slower print speeds allow for more thorough bonding and reduced thermal stresses. The study highlights that while print speed itself was not statistically significant in determining ultimate tensile strength or elastic modulus, trends indicate improved performance at moderate speeds, particularly when combined with optimised nozzle and platform temperatures. This mechanism again highlights the importance of selecting the proper print speed to maintain a stable thermal gradient and ensure strong layer adhesion.

In conclusion, printing speed is a critical parameter in 3D printing that significantly influences the mechanical properties and wear resistance of polymer composites by affecting interlayer adhesion, microstructural uniformity, and surface quality. Slower printing speeds provide longer time for polymer chain diffusion and fusion between layers, enhancing interlayer adhesion and reducing defects such as voids and microcracks. This results in higher tensile strength, hardness, and enhanced elongation at break. Additionally, heat retention at slower speeds promotes higher crystallinity in semi-crystalline polymers, further improving the mechanical performance of the printed material. In terms of wear resistance, slower speeds facilitate the formation of smoother surfaces and are more likely to produce uniform transfer films during frictional contact, which reduces wear rates and increases durability. However, excessively slow speeds can lead to thermal accumulation, causing residual stress and potential distortions. Moreover, the final structure/properties of the printed materials are also affected by other printing parameters, such as layer thickness and nozzle temperature, as well as the complex interactions between those parameters. Hence, it is important to select and optimise all the printing parameters from a systematic point of view.

2.2.3. Infill Density

Infill density is another important parameter in 3D printing that directly affects the internal structure of the printed material and, thus, its mechanical and tribological properties. For example, studies on polyamide (PA6 and PA66) demonstrated that increasing the infill density from 50% to 100% contributed to substantial improvements in ultimate tensile strength (UTS) and yield strength due to a denser internal [39]. Accordingly, the tribological performance of 3D-printed materials can also be effectively improved with infill density. Portoacă, A.I. et al. [36] reported that higher infill densities enhance structural integrity by reducing void content. This facilitates more uniform load distribution during sliding contact and, thus, reduces localised stress concentrations and wear loss. Higher infill percentages also strengthen the layer interface, minimising material deformation and mitigating abrasive interactions with the counter surface. On the contrary, low-density infill structures exhibit higher void contents, causing more stress concentrations and earlier failure of the structure. As a result, the specimens showed accelerated wear loss. Roy and Mukhopadhyay [40] investigated the effects of infill densities on ABS and PLA materials and confirmed that higher infill densities significantly enhance the tensile strength, hard-

ness, and wear resistance of the printed specimens. The improvement is also attributed to the reduced porosity and stronger interlayer bonding provided by increased infill density. The authors observed that components with higher infill density exhibited enhanced tribological performance with the improved wear resistance and frictional stability. In addition, Sirin et al. [41] studied the effects of infill density on the wear resistance and mechanical behaviour of 3D-printed PLA specimens. Higher infill densities, particularly at 70%, showed improved wear resistance, reduced weight loss, and lower coefficients of friction compared to specimens with lower infill densities. Increasing infill density reduces void content within the structure, leading to higher hardness and, thus, smaller contact area and friction. Further, the improved interlayer bonding at higher infill densities creates a more cohesive structure, effectively resisting delamination and material detachment during wear processes.

In conclusion, infill density plays a crucial role in determining the mechanical and tribological performance of printed components. Higher infill densities normally result in enhanced mechanical properties, thanks to less internal porosity and stronger interlayer bonding. Such a denser internal structure also contributes to better stress distribution, resulting in a better load-bearing capacity under both normal and frictional loading. From a tribological perspective, increased infill density improves wear resistance by creating a more compact and uniform surface that enhances material stability during sliding or abrasive contact. The improved bonding between layers and the reduction in voids prevent the formation of wear-induced damage, ensuring reliable, longer-lasting performance.

2.2.4. Print Orientation and Raster Angle

Printed materials often show significant anisotropic behaviour depending on building direction and printing strategy. In particular, the two key parameters, namely printing orientation and raster angle, have pronounced effects on the anisotropic behaviour of printed parts. Here, a raster angle is the angle of the tool path with respect to the x-axis of the print bed. Printing orientation refers to the alignment of the printed layer(s) within the space of the build volume. Hanon et al. comprehensively investigated the important roles of print orientation and raster angle in determining the mechanical and tribological properties of 3D-printed polylactic acid (PLA) [42]. It was found that print orientation significantly impacts tensile strength, wear resistance, and frictional behaviour due to variations in layer bonding and stress distribution. As the layers were built parallel to the applied load, horizontally printed specimens demonstrated superior mechanical properties, attributed to enhanced interlayer bonding and uniform stress distribution, which mitigated the formation of voids and cracks under a given load. Conversely, vertically printed specimens (i.e., layers built perpendicularly to the applied load) exhibited weaker interlayer adhesion and higher susceptibility to wear and delamination due to stress concentration at perpendicular layer interfaces. The work also studied the effects of raster angles on tribological performance. Oblique raster angles were associated with increased voids and gaps, reducing the load-bearing capacity and wear resistance. These gaps act as stress concentrators, promoting material removal during frictional contact. The results showed that optimising print orientation and raster angle would effectively enhance the uniformity of stress distribution and minimise the internal defects in printed specimens, thus improving both mechanical integrity and tribological performance. In their later studies, the authors further concluded that the on-edge orientation provided the highest tensile strength, as the alignment of short inner lines and interlocked layers enhanced structural support and resistance to applied forces [8]. In contrast, the upright orientation exhibited the weakest mechanical properties due to the weaker interlayer adhesion, as the layers were built perpendicular to the applied load, making the structure more prone to

delamination. The flat orientation showed moderate tensile strength and ductile behaviour, indicating its suitability for applications requiring some flexibility. In terms of tribological performance, print orientation affected both wear resistance and the coefficient of friction (COF). Horizontally oriented specimens demonstrated smoother surfaces, which reduced COF but increased wear rates due to the larger contact area during sliding. On the contrary, vertically oriented samples exhibited superior wear resistance despite higher COF values, as their smaller contact areas and rougher surfaces concentrated pressure and minimised material removal. The wear test results are summarised and compared in Figure 1.

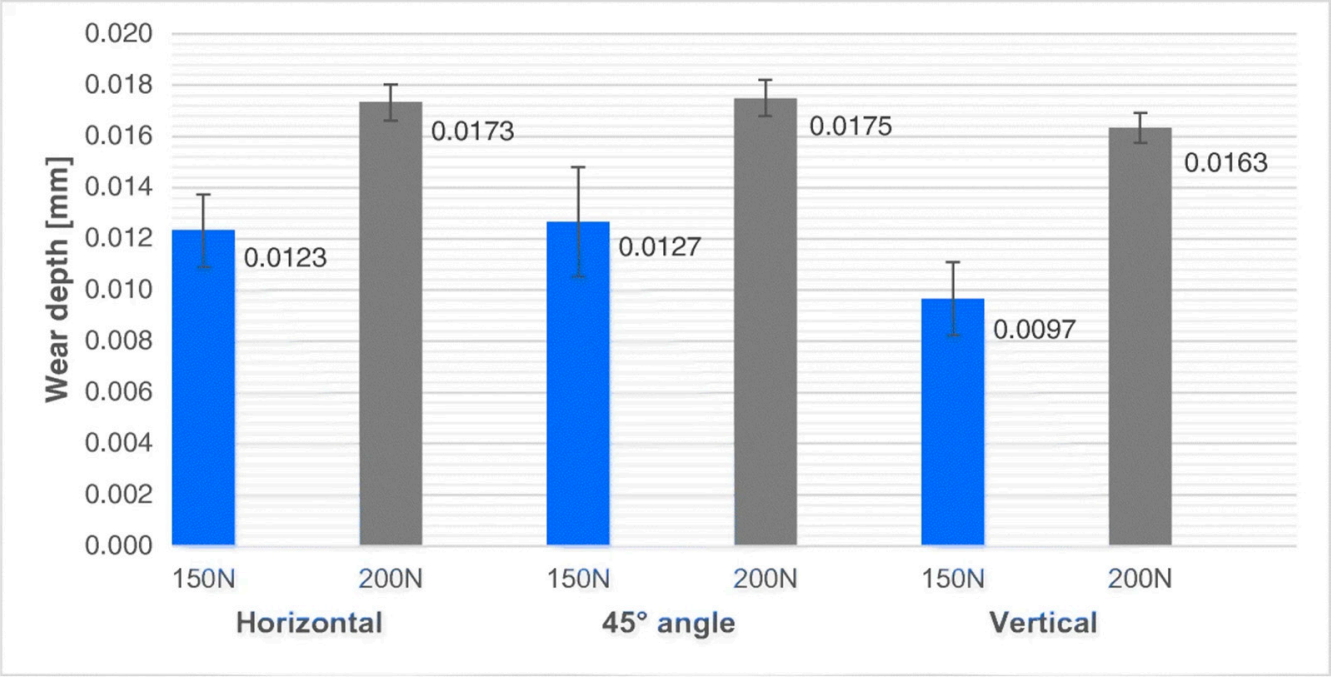


Figure 1. Comparison of average wear depth for each print orientation (here, "horizontal", "45° angle", and "vertical" refer to the orientation of printed layers with respect to the sliding direction) [8].

Amirruddin et al. investigated the influence of raster angle and layer thickness on the mechanical and tribological properties of 3D-printed ABS and PLA [37]. In Figure 2, the wear results of ABS and PLA against a raster angle are depicted under a fixed layer thickness. Owing to limitations in the weighing machine's resolution, only the general trend is discussed. Pins printed at a 0° raster angle exhibited the highest wear (mass loss), while those printed at a 45° angle. Additionally, it indicates that at the highest layer thickness of 0.32 mm, the raster angle has an insignificant effect on ABS wear. Notably, a raster angle of 45° was observed to have the least friction compared to 0° and 90° (4–16% lower compared to friction at 0° or 90°). The study revealed that a raster angle of 45° provided the best tribological performance, with the lowest friction force and wear rates. This superior performance is attributed to the optimal alignment of raster patterns at 45°, which facilitated more effective load distribution and reduced stress concentrations at the sliding interface.

In conclusion, the influence of raster angle and print orientation on the mechanical and tribological properties of 3D-printed components is closely linked to the anisotropic nature of additive manufacturing. Optimal raster angles and printing orientation would lead to better load distribution, less interfacial defects, higher interlayer bonding, and, thus, superior mechanical and tribological properties. In practice, it is also important to design and use the printed tribological components by considering layer orientation

against the loading and/or sliding directions based on application-specific mechanical and tribological requirements.

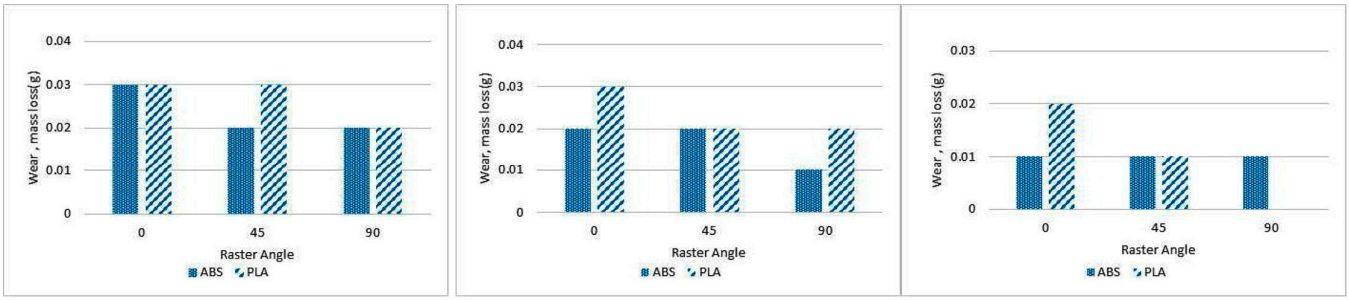


Figure 2. Wear of ABS and PLA pins printed at three different raster angles and constant layer thicknesses of (**a**) 0.127 mm, (**b**) 0.254 mm, and (**c**) 0.32 mm [37].

2.2.5. Extrusion and Bed Temperature

Printing temperature refers to the temperature at which thermoplastic filament or resin is melted during the 3D printing process. Achieving the optimal printing temperature is critical for ensuring proper material flow, adequate interlayer adhesion, and, ultimately, improved wear resistance. Temperatures below the recommended range can result in insufficient melting, poor bonding, and weak structural integrity, whereas excessively high temperatures may cause material degradation or uneven deposition. Maintaining the appropriate printing temperature is essential for achieving the desired mechanical and tribological properties in 3D-printed components [43,44].

Zainal et al. investigated the tribological properties of PLA 3D printed at various extrusion temperatures. In Figure 3, the specific wear rate of the pin extruded at temperatures ranging from 190 °C to 230 °C is presented [45]. The results showed that pins printed at 190 °C exhibit the highest specific wear rate, while those printed at 230 °C achieve the lowest wear loss. Moreover, the specific wear rate exhibits a linear decrease with increasing extrusion temperature within the investigated range. After examining the surface morphology, the authors noted that more deformation and material transfer took place with pins printed at lower temperatures. This phenomenon can be attributed to the weakened joints between layers, as evident from delamination observed on the adjacent layers. Given that FDM 3D-printed parts are constructed layer by layer, each interface between layers introduces a potential weak point in the object. This weak region is amplified when the pin is printed in an orientation perpendicular to the sliding direction during testing. Additionally, the extrusion temperature during printing was notably higher than the working temperature during the tribological test. This implies that the deposited PLA material retained the capability to diffuse and homogenise with the surrounding material for an extended period after extrusion. Hence, an elevated extrusion temperature contributed to the enhanced interlayer bonding. Such a strengthened bond is more resistant to wear by withstanding the shear stress associated with relative movement. Vanaei et al. particularly investigated the impact of printing temperature on the bonding strength of 3D-printed materials and highlighted its critical role in determining interlayer adhesion and overall structural integrity [46]. The study demonstrated that good bonding strength could be achieved when the temperature of the previously deposited filament remains near or above the crystallisation temperature. It facilitates the diffusion process of polymer chains, allowing for better interlocking between layers and increased material crystallinity at the interface. As a result, the printed materials show stronger interlayer adhesion with improved mechanical performance. Conversely, when the previously deposited layer cools too quickly or the printing temperature falls below the crystallisation temperature, the

molecular chains lose mobility, resulting in weak bonds and reduced structural stability. It was also noted that excessively high temperatures can cause material deformation and surface defects due to uncontrolled molten flow, further compromising bonding quality and overall mechanical integrity [37,38].

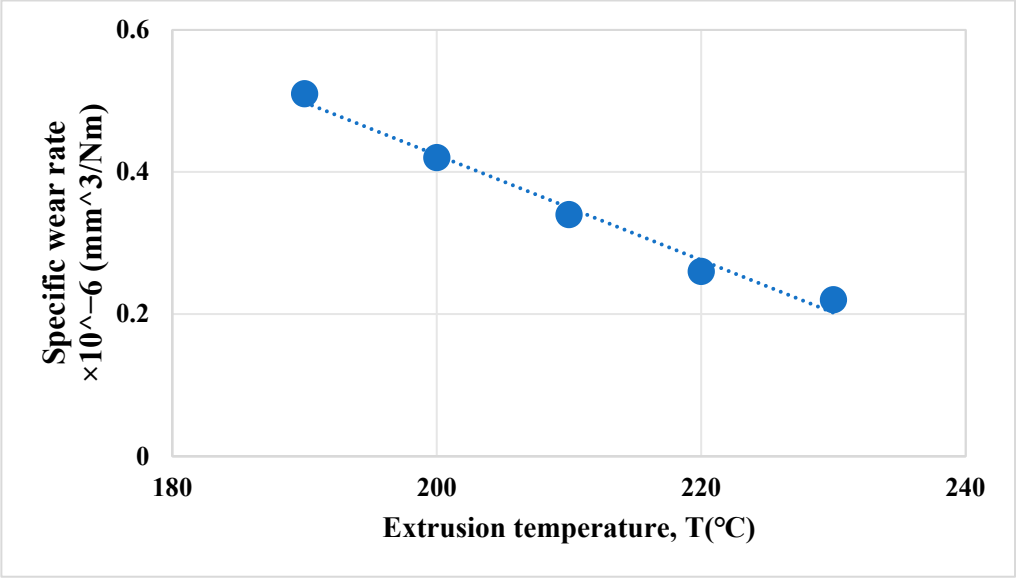


Figure 3. Specific wear rate of FDM-printed PLA pins extruded at different extrusion temperatures [45].

Another important temperature parameter is bed temperature, i.e., the temperature of the build platform in 3D printing. Maintaining an optimal bed temperature is crucial for preventing warping and ensuring proper adhesion between the print and the build surface. Several studies have reported that an optimal bed temperature can be identified within a specific range. It is noteworthy that the identified value could change with other printing parameters [18,19]. It was also noted that the surface roughness increased as the heating bed temperature rose, a consequence of the thermal deformation of the manufactured part. It was suggested that when the platform temperature was lower, the heat transfer speeded up, resulting in a higher thermal gradient and a rapid decrease in the material's temperature, which could adversely affect interlayer bonding. Hence, a proper platform temperature should be chosen, together with the extrusion temperature, to achieve good interlayer bonding by controlling the steady-state temperature within the printed material.

In summary, the internal structure and overall performance of the printed materials are essentially determined by several printing parameters used in printing. Table 2 summarises printing parameters that have been investigated for desirable mechanical properties. Although significant efforts have been made, it remains challenging to fully understand the complex effects of multiple printing parameters on the time-related wear behaviour of printed parts. To address this issue, computing methods such as the Artificial Neural Network (ANN) method have been recently adopted in the field. For instance, Pant et al. utilised the Taguchi method and Artificial Neural Network (ANN) to assess process variables in the FDM process for estimating wear rates in PLA material. A comprehensive comparison of experimental results, Taguchi method, and ANN outcomes was conducted. The work suggested that ANN is more suitable than the Taguchi method for wear prediction. It is worth mentioning that the reliability of the ANN model is largely dependent on the size of the database [47]. With the rapid development of data science and AI technology, it is expected that the data-based computing technology will shed new light on further research in the optimisation of printing parameters for the design and fabrication of wear-resistant polymer composites.

Table 2. Summary of the effects of varying 3D printing settings parameters.

Polymer/ Reinforcement	3D Printing Type	3D Printing Parameters	Reference
ABS/Carbon fibre	FDM	Layer thickness: 0.25 mm Print orientation: 0° Infill density: 90%	[48]
ABS	FDM	Layer thickness: 0.18 mm Print speed: 60 mm/s Print orientation: 0° Infill density: 100% Extrusion temperature: 220 °C	[49]
ABS	FDM	Layer thickness: 0.2–0.25 mm Print speed: 120 mm/s Extrusion temperature: 220–260 °C	[50]
ABS	FDM	Layer thickness: 0.1–0.15 mm Extrusion temperature: 225–235 °C Infill pattern: line hexagon, triangle	[32]
ABS	FDM	Layer thickness: 0.1–0.2 mm Infill density: 40–80% Infill pattern: rectilinear, grid triangular	[33]
ABS	FDM	Layer thickness: 0.127–0.32 mm Raster angle: 0–90°	[37]
ABS/Nano-clay	FDM	Layer thickness: 0.2 mm Infill density: 99% Print orientation: ±45°	[51]
ABS	FDM	Layer thickness: 0.4 mm Print speed: 60 mm/s Infill density: 100% Extrusion temperature: 245 °C Bed temperature: 85 °C	[52]
ABS/Graphene	FDM	Layer thickness: 0.1 mm Print speed: 5 mm/s Infill density: 100% Extrusion temperature: 245 °C	[53]
ABS/Graphene	FDM	Layer thickness: 0.16 mm Print speed: 100 mm/s Infill density: 100% Extrusion temperature: 250 °C	[54]
Nylon PA12	SLS	Build orientation: X, Y, Z axes	[55]
Nylon PA6/CCF	FDM	Layer thickness: 0.125 mm Print speed: 15 mm/s Extrusion temperature: 275 °C	[56]
Nylon PA6/SCF	FDM	Layer thickness: 0.1 mm Print speed: 30 mm/s Extrusion temperature: 275 °C	[57]
Nylon PA6 PA66	FDM	Layer thickness: 0.1 mm Print speed: 30 mm/s Infill density: 50–100% Extrusion temperature: 180 °C	[39]

Table 2. *Cont.*

Polymer/ Reinforcement	3D Printing Type	3D Printing Parameters	Reference
Nylon PA6 PA66/Glass fibre	FDM	Layer thickness: 0.2 mm Print speed: 60 mm/s Infill density: 60–100% Extrusion temperature: 275 °C	[58]
Nylon/CF, GF	FDM	Layer thickness: 0.2 mm Print speed: 60 mm/s Infill density: 100% Extrusion temperature: 250 °C	[59]
PEEK	FDM	Layer thickness: 0.1–0.15 mm Print speed: 20–25 mm/s Infill density: 100% Extrusion temperature: 420 °C	[12]
PEEK	FDM	Layer thickness: 0.1–0.15 mm Print speed: 30–50 mm/s Extrusion temperature: 420–440 °C Bed temperature: 100–120 °C	[18]
PEEK/SCF	FDM	Layer thickness: 0.2 mm Print speed: 30 mm/s Infill density: 100% Print orientation: 0–90° Extrusion temperature: 440 °C Bed temperature: 120 °C	[60]
PEEK	FDM	Layer thickness: 0.1–0.3 mm Print speed: 15–25 mm/s Infill density: 70–100% Extrusion temperature: 390–420 °C Bed temperature: 136–150 °C	[19]
PLA/CF	FDM	Layer thickness: 0.075–0.125 mm Infill density: 60–80% Infill pattern: rectilinear, grid triangular	[34]
PLA	FDM	Layer thickness: 0.2 mm Print speed: 60 mm/s Infill density: 100% Extrusion temperature: 210 °C Bed temperature: 60 °C	[52]
ABS, PLA, Nylon	FDM	Layer thickness: 0.12 mm Print speed: 30 mm/s Infill density: 50% Bed temperature: 70 °C	[61]
PLA/Graphene	FDM	Layer thickness: 0.2 mm Print speed: 110 mm/s Infill density: 100% Extrusion temperature: 200 °C	[4]

Table 2. *Cont.*

Polymer/ Reinforcement	3D Printing Type	3D Printing Parameters	Reference
PLA	FDM	Layer thickness: 0.06 mm Print speed: 35 mm/s Infill density: 100% Extrusion temperature: 210 °C Bed temperature: 60 °C	[11]
PLA/Glass fibre	FDM	Layer thickness: 0.5–0.8 mm Print speed: 2–6 mm/s Extrusion temperature: 190–230 °C	[35]
PLA/Bronze	FDM	Layer thickness: 0.2 mm Raster angle: 45/135°, Extrusion temperature: 195 °C Bed temperature: 60 °C	[8]
PLA	FDM	Layer thickness: 0.2 mm Print orientation: X and Z axes Extrusion temperature: 200 °C	[62]
PLA/PA6+TiO_2	FDM	Print speed: 90 mm/s Infill pattern: triangular	[63]
PLA	FDM	Layer thickness: 0.07–0.3 mm Print orientation: 60–90° Extrusion temperature: 220–230 °C	[47]
PLA/Graphene	FDM	Layer thickness: 0.10–0.18 mm Print speed: 30–40 mm/s Infill density: 16–30%, Extrusion temperature: 200 °C	[64]
PLA	FDM	Layer thickness: 0.1–0.2 mm Print orientation: X and Z axes	[65]
PLA	FDM	Layer thickness: 0.2 mm Print speed: 60 mm/s Infill density: 100% Print orientation: 45/135° Extrusion temperature: 195 °C Bed temperature: 60 °C	[42]
PLA	FDM	Layer thickness: 0.2–0.3 mm Infill density: 25–100% Infill pattern: triangle, hexagon, lines, concentric Raster angle: 0–60°	[66]
ABS, PLA	FDM	Layer thickness: 0.18–0.33 mm Infill density: 45–80% Print orientation: 45–90°	[40]
PLA	FDM	Layer thickness: 0.1 mm Print speed: 60 mm/s Infill density: 20–100% Extrusion temperature: 200 °C Bed temperature: 60 °C	[67]

Table 2. *Cont.*

Polymer/ Reinforcement	3D Printing Type	3D Printing Parameters	Reference
ABS, PLA	FDM	Wall thickness: 0.8–1.2 mm Print speed: 47–60 mm/s Infill density: 40–100% Raster angle: 0–90° Extrusion temperature: 220–240 °C	[68]
PLA/Nano-silicon	FDM	Layer thickness: 0.3 mm Print speed: 50 mm/s Infill density: 100% Extrusion temperature: 210 °C	[9]
ABS, PLA	FDM	Layer thickness: 0.2 mm Print speed: 60 mm/s Infill density: 100% Extrusion temperature: 220 °C Bed temperature: 30 °C	[69]
PLA	FDM	Layer thickness: 0.2–0.4 mm Print speed: 30–80 mm/s Infill density: 25–100%	[70]
PLA	FDM	Layer thickness: 0.2 mm Print orientation: 45° Extrusion temperature: 240 °C Bed temperature: 90 °C	[71]
PLA	FDM	Layer thickness: 0.15 mm Infill density: 30–70% Extrusion temperature: 200 °C Bed temperature: 50 °C	[41]
PLA	FDM	Layer thickness: 0.2 mm Infill density: 15% Extrusion temperature: 190–230 °C Bed temperature: 60 °C	[45]

3. Materials Utilised in 3D Printing Wear-Resistant Composites

3.1. Overview of Common Polymers and Reinforcement Materials Used in Wear-Resistant Composites

3.1.1. Commonly Used Polymers in 3D Printing

1. Acrylonitrile Butadiene Styrene (ABS)

Acrylonitrile Butadiene Styrene (ABS) is widely recognised in 3D printing for its high impact resistance, toughness, and elevated glass transition temperature. ABS is also a popular material for manufacturing wear-resistant components in various industries. Common applications include the production of gears, bearings, and functional prototypes [72]. The versatility of ABS in 3D printing enables the production of durable parts suitable for use in different environmental conditions. However, ABS is prone to shrinkage and expansion due to temperature fluctuations during the printing process, often resulting in defects such as warping or complete print failures. To address these challenges, it is particularly important to control printing temperature and bed temperature. In practice, it often requires enclosing the print area to minimise temperature gradients for good surface quality and dimensional accuracy [73,74].

2. Polylactic Acid (PLA)

Polylactic Acid (PLA) is one of the most used materials in 3D printing due to its ease of use, low cost, and environmentally friendly nature. Up to now, PLA has been widely used in non-functional prototypes, low-stress components, and engineering parts where mechanical strength and wear resistance are not primary concerns [75]. Despite these advantages, PLA is generally not well suited for wear-intensive applications due to its poor mechanical properties and low wear resistance. PLA is associated with several intrinsic drawbacks, including low toughness, high brittleness (characterised by less than 10% elongation at break), and low melting point (60–65 °C), which leads to easily friction-generated heat softening with a high wear loss. These limitations constrain its applicability in various industrial contexts [65,76]. However, its performance can be improved, e.g., by using reinforcement fillers such as fibres, metal particles, etc. [63,77,78].

3. Polyether Ether Ketone (PEEK)

Polyether ether ketone (PEEK) emerges as a high-performance polymer with exceptional mechanical properties and chemical resistance, making it a standout choice in many engineering applications. Several case studies have also shown that PEEK is a promising candidate for printing materials for creating wear-resistant components [19]. Nevertheless, investigations into the 3D printing of PEEK are limited due to the high printing temperatures required by the high melting temperature of PEEK at approximately 340 °C, apprehensions regarding inadequate adhesion between layers, the time-consuming and economically impractical nature of the associated processing steps [79].

4. Nylon

Nylon, a versatile and thermoplastic polyamide, stands as an excellent candidate for wear-resistant composites through 3D printing. Renowned for its excellent mechanical properties, including high tensile strength and impact resistance, nylon offers a compelling foundation for fabricating durable components. Its inherent toughness and chemical stability make it an ideal base material. Its compatibility with various reinforcing agents, such as carbon fibres and nanoparticles, further enhances its wear resistance. The combination of nylon and 3D printing technologies presents a promising avenue for creating robust, customised components tailored to meet the rigorous requirements of various engineering applications. The primary drawback associated with nylon groups is their sensitivity to moisture, leading to a decline in mechanical properties. The presence of moisture or water acts as a plasticiser, contributing to a reduction in tensile strength by more than 50% [80].

3.1.2. Reinforcement Materials for 3D-Printed Composites

1. Carbon Fibres

Carbon fibres play a crucial role in reinforcing wear resistance in 3D-printed parts. Their integration into polymer matrices significantly enhances the load-carrying capacity and wear performance of components. This has been successfully achieved in applications such as aerospace components and automotive parts, where durability and high performance are essential. Furthermore, the incorporation of carbon fibres into polymer composites promotes the formation of a transfer film on the counterpart surface during operation. The transfer film reduces direct surface interaction, thereby improving friction and wear properties [56]. However, challenges exist in optimising the distribution and alignment of carbon fibres during the 3D printing process and their interface bonding strength [81,82].

2. Glass Fibres

Glass fibres, with their cost-effectiveness, are widely used to improve the mechanical and tribological properties of polymer composites. Industries such as electronics and

automotive have witnessed the positive impact of glass fibres in improving wear resistance in various service conditions. For printed materials, the main challenge is to improve interfacial adhesion by selecting proper printing parameters [35,83]. Furthermore, during the wear process, the breakage of glass fibres may take place, especially with a poor interfacial bond with the polymeric matrix. The resultant fibre debris can increase wear loss due to the high abrasiveness of glass debris [84].

3. Nanoparticles

Nanoparticles, including nano-sized graphene, nanotubes, and other inorganic fillers, offer a pathway to creating nanocomposites with superior wear resistance in 3D-printed materials. Nanoparticles have a high specific interfacial surface ratio, enabling desirable reinforcement effects even with a very low volume fraction (e.g., <1 vol.%). Ongoing innovations in incorporating nanoparticles into polymer matrices showcase promising advancements. Practical considerations, such as dispersion and printing process compatibility, play a crucial role in maximising the benefits of nanomaterials for wear-resistant 3D-printed components. Nanomaterials can achieve good wear resistance through different mechanisms such as nano-polishing and surface modifications facilitated by chemical reactions. In contrast to micro-sized fillers, nanocomposites attain their peak wear resistance at a relatively lower volume fraction, typically below 5%, and it will be discussed in the following section. Table 3 summarises commonly used polymer matrix and reinforcement materials, including the corresponding 3D printing types and studied volume fraction value/range.

Table 3. Summary of common high-wear-resistance polymer composites fabricated using 3D printing technology.

Polymer Matrix	Reinforcement	3D Printing Type	Volume Fraction (wt.%)	Reference
ABS		FDM		[48]
ABS	Carbon fibre	FDM	10	[48]
ABS		FDM		[49]
ABS		FDM		[50]
ABS		FDM		[32]
ABS		FDM		[33]
ABS		FDM		[37]
ABS	Nano-clay	FDM	0–2	[51]
ABS		FDM		[52]
ABS	Glass fibre	FDM	5, 10	[85]
ABS	CNT	FDM		[86]
ABS	Graphene	FDM	0–5	[53]
ABS	Graphene	FDM	1–2	[54]
ABS		FDM		[40]
ABS		FDM		[66]
ABS		FDM		[68]
ABS		FDM		[69]
ABS		FDM		[61]
Nylon PA12		SLS		[55]

Table 3. *Cont.*

Polymer Matrix	Reinforcement	3D Printing Type	Volume Fraction (wt.%)	Reference
Nylon		FDM		[61]
Nylon	SiC, Al_2O_3	FDM	0–25, 25–45	[87]
Nylon		FDM		[88]
Nylon PA6	CCF	FDM	35	[56]
Nylon	SCF	FDM	10	[57]
Nylon PA12		SLS		[89]
Nylon	ZrO_2	FDM	0–30	[90]
Nylon		FDM		[61]
Nylon	CF, GF	FDM	25	[59]
Nylon PA6 PA66		FDM		[39]
Nylon PA6 PA66	Glass fibre	FDM	30	[58]
Nylon PA 12	SiC	SLS	10	[91]
Nylon PA 12	SiC, nano-SiO_2	SLS	4, 2.5	[92]
Nylon PA 12		SLS		[27]
PEEK		FDM		[12]
PEEK	CF, nanosilica	FDM	30, 20	[93]
PEEK		FDM		[18]
PEEK	SCF	FDM	5	[60]
PEEK		FDM		[19]
PLA	CF	FDM	20	[34]
PLA		FDM		[37]
PLA		FDM		[52]
PLA		FDM		[61]
PLA	Graphene	FDM		[4]
PLA		FDM		[11]
PLA	Glass fibre	FDM	45	[35]
PLA	Carbon fibre	FDM	5–30	[94]
PLA	Graphene	FDM	10–30	[95]
PLA	Graphene	FDM	50	[96]
PLA		FDM		[97]
PLA	Wood	FDM	0–50	[98]
PLA	Bronze	FDM	8	[8]
PLA		FDM		[62]
PLA	PA6/TiO_2	FDM	30–50	[63]
PLA		FDM		[47]
PLA	MoS_2	FDM	1, 2.5	[99]
PLA	Graphene	FDM	1–10	[64]
PLA		FDM		[100]

Table 3. *Cont.*

Polymer Matrix	Reinforcement	3D Printing Type	Volume Fraction (wt.%)	Reference
PLA		FDM		[65]
PLA		FDM		[42]
PLA		FDM		[66]
PLA		FDM		[40]
PLA		FDM		[67]
PLA		FDM		[68]
PLA	Nano-silicon	FDM	0–7	[9]
PLA		FDM		[101]
PLA		FDM		[69]
PLA		FDM		[70]
PLA		FDM		[71]
PLA	Nano-clay	FDM	10–20	[102]
PLA		FDM		[41]
PLA		FDM		[45]

3.2. Design Wear-Resistant Polymer Composites Using Different Fillers

For polymeric composites, the base material governs the printing parameters, such as printing temperature and printing speed, whereas the reinforcement fillers largely determine the mechanical and tribological performance of the composites. Thus, to design wear-resistant polymer composites, it is crucial to select the reinforcement materials by considering their type, geometry shape, size, and volume fractions, as well as their effects on the printing properties of filaments. The understanding of these factors is crucial for optimising the final production of wear-resistant components by using 3D printing technology, ensuring improved performance and durability in demanding applications.

3.2.1. Micro-Sized Particles

Micro-sized hard particles are the most widely used fillers to enhance the hardness and wear resistance of polymer matrices. In general, with a higher volume fraction of reinforcements, the mechanical and tribological properties tend to be improved according to the rule of mixtures. For instance, Ertane et al. [94] studied the effects of biocarbon particles on the tribological properties of PLA composites. They discovered that both the wear and friction performance were enhanced with the volume fraction of biocarbon particles up to 30 vol.%, as shown in Figure 4. Within such a range of volume fractions, the reinforcement could effectively strengthen the PLA matrix by increasing stiffness and reducing elastic recovery, which minimises deformation under load and limits material removal during sliding interactions. Accordingly, during the wear process, surface wear is characterised by reduced polymeric debris and the accumulation of particles within surface voids, stabilising the coefficient of friction and slowing down wear progress. However, it was noted that the increased brittleness introduced by higher biocarbon content can lead to microcracking, particularly in zigzag patterns, as the material's elongation and flexibility decrease. Further, high contents of biocarbon also presented challenges in terms of manufacturability, leading to issues such as nozzle clogging during the 3D printing process. Therefore, it may be practically difficult to further increase the volume fraction of particle fillers. In fact, it is known that there is usually an optimal range of volume fraction for each type of reinforcement material, beyond which wear resistance may remain similar

or even decline, as reported in many traditionally manufactured polymer composites [103]. The trend has also been observed in some 3D-printed composites. In another study of wood-reinforced PLA [98] with reinforcement content ranging from 0 to 50%, the tensile modulus reached its peak at 20%. Further increasing the wood reinforcement not only lowered the mechanical performance but also adversely affected the printability.

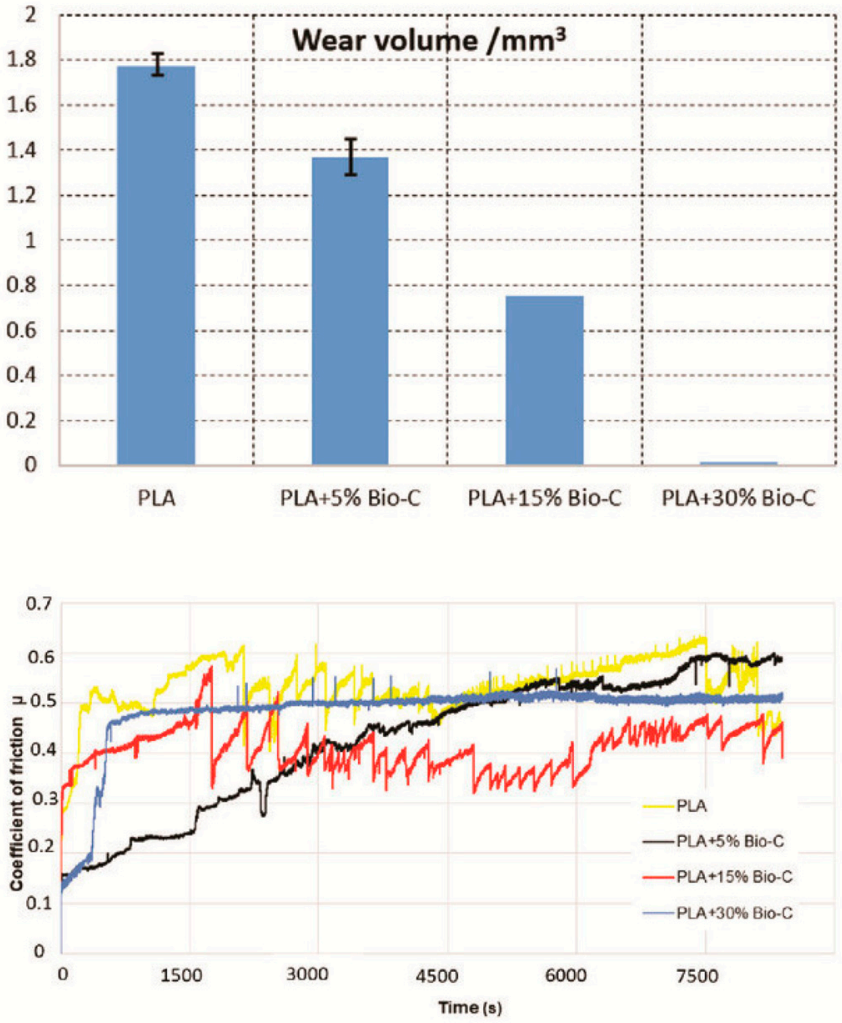


Figure 4. Tribological performance of different volume fraction biocarbon-reinforced PLA [94].

More recently, Vishal, K. et al. studied the effects of silicon particles on the mechanical and tribological properties of PLA composites [9]. It was found that the tensile strength, modulus, flexural strength, and impact strength were optimised at 5 wt.% silicon within the studied range of 0–7%, while the specific wear rates for both 5% and 7% silicon content remained almost identical (see Figure 5). This may explain the fact that while high-volume reinforcement in polymer composites has the potential to enhance mechanical properties and wear performance, high-volume content fillers are not commonly used in 3D printing due to several significant challenges. First, high reinforcement content can result in processing difficulties, including poor flow properties, nozzle clogging, and reduced layer adhesion, which compromise the quality and consistency of printed parts. Additionally, excessive reinforcement may result in brittleness, reducing flexibility and impact resistance [104]. Thus, practical limitations such as printability, material properties, and cost-effectiveness often necessitate a careful balance between reinforcement content and performance in 3D-printed composites.

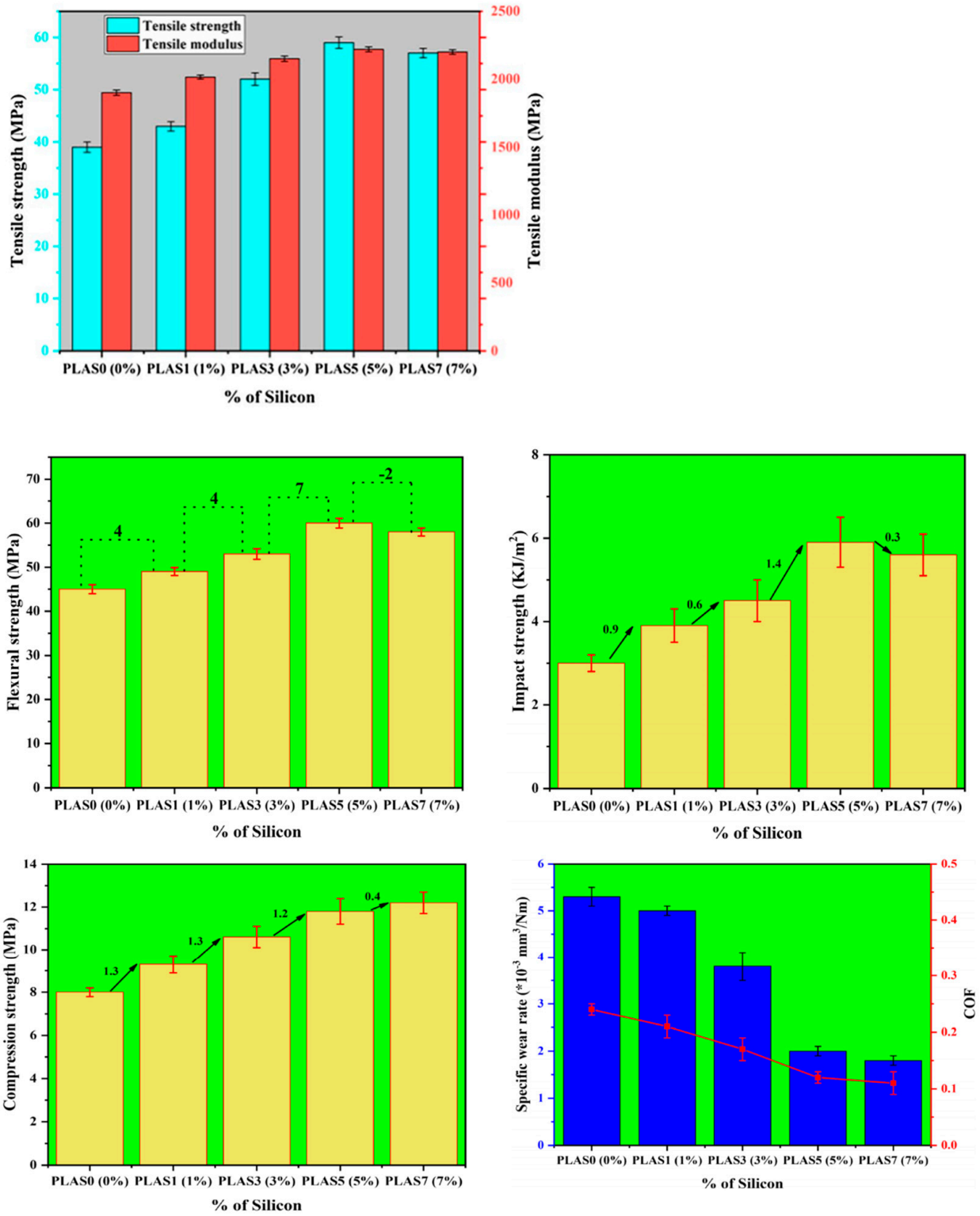


Figure 5. Mechanical and wear properties in 3D-printed PLA silicon composites [9].

3.2.2. Nano-Sized Fillers

Nano-sized fillers, or nanofillers, have a geometric size of less than 100 nm at least in one dimension. Thanks to their large surface–volume ratio, nanofillers can effectively improve the property files of polymer composites even with a very low volume fraction. As an illustration [51], the study explores the tribological properties of ABS nanocomposites reinforced with nano-clay particles, emphasising the relationship between nano-clay content, wear resistance, and material performance. Increasing the nano-clay loading

significantly improved the wear resistance of 3D-printed ABS components, with 2 wt.% nano-clay providing the most effective reduction in wear rate and stabilisation of the coefficient of friction. The nano-clay particles enhance the thermal and mechanical properties of the composite by forming a strong interfacial bond with the ABS matrix. This interaction creates an interlocking layered structure that reduces material deformation and delamination during sliding. In terms of wear mechanisms, the homogeneous dispersion of nano-clay in the polymer matrix contributes to the formation of a protective tribo-layer on the material's surface, minimising direct contact with the counterpart and reducing abrasion. The nanocomposite's ability to dissipate frictional heat further contributes to its improved wear performance by preventing thermal softening of the ABS matrix. Notably, the study observed anisotropic behaviour based on the abrasion layer orientation, with transverse orientations exhibiting superior wear resistance compared to parallel orientations, attributed to enhanced nanoparticle–matrix interconnectivity. In a similar way, a study investigates the tribological and mechanical properties of 3D-printed PLA composites reinforced with short carbon fibres (SCFs) and graphene nanoparticles (GNPs) [105]. The results demonstrate that the inclusion of these fillers significantly enhances the wear resistance and mechanical performance of the composites. The primary mechanism driving the improved tribological behaviour is the synergistic effect of SCFs and GNPs. SCFs contribute by reinforcing the matrix and distributing applied loads over a larger surface area, reducing stress concentrations and material deformation. Concurrently, GNPs act as a solid lubricant, forming a protective tribo-layer on the surface that minimises direct contact with abrasive counterparts. This dual functionality of the fillers reduces wear rates and stabilises the coefficient of friction under sliding conditions. The SCFs enhance hardness and elastic modulus, which contributes to the material's resistance to wear-induced plastic deformation. Additionally, the dispersed GNPs promote thermal stability by dissipating heat generated during friction, further preventing matrix softening. Similarly, the tribological analysis case study of CNT-reinforced polyphenylene sulfide (PPS) composites [106] demonstrates a significant improvement in wear resistance and frictional behaviour due to the inclusion of CNTs. The addition of CNTs reduces wear rates and stabilises the coefficient of friction, with the effect becoming more pronounced at higher CNT concentrations. CNTs enhance the formation of a protective tribo-layer on the contact surface, which reduces material loss during sliding. This layer acts as a barrier, preventing direct interaction between the PPS matrix and the counter face, thereby mitigating adhesive and abrasive wear. Moreover, the CNTs improve the thermal conductivity of the composite, enabling efficient dissipation of frictional heat generated during sliding. This reduces the risk of localised thermal softening, which can compromise wear resistance. The enhanced interfacial bonding between CNTs and the PPS matrix also contributes to the overall structural integrity of the composite, limiting particle detachment and surface degradation.

Apart from the investigations mentioned, other findings stated that nanocomposites have better wear performance compared to the rolling effects of nanofillers. The study focused on enhancing the wear performance of PEEK using inorganic fullerene-like tungsten disulfide (IF-WS2) nanoparticles and demonstrated remarkable improvements [107]. The wear rate of PEEK decreased by approximately 50% with the incorporation of 2 wt.% IF-WS2. This enhancement is attributed to the lubricating properties of the IF-WS2 nanoparticles, which function as solid lubricants and significantly reduce the coefficient of friction. The static coefficient of friction decreased by 10% with 1 wt.% IF-WS2, highlighting its role in improving tribological performance. The mechanism behind the improved wear resistance involves the spherical morphology of IF-WS2 nanoparticles, which enables a rolling effect akin to ball bearings during sliding interactions. Additionally, the nanoparticles' outer layers are worn off and form a protective tribo-film on the contact surfaces, minimising

direct material abrasion. The synergistic action of sliding, rolling, and film formation effectively reduces wear and friction. For example, a study on multiwalled carbon nanotubes (MWCNTs)-reinforced high-density polyethylene (HDPE) nanocomposites demonstrated a direct correlation between enhanced wear performance and increased hardness [108]. The wear resistance improved significantly with the inclusion of MWCNTs, attributed to their ability to uniformly disperse within the polymer matrix, enhancing load distribution and reducing material removal during abrasive interactions. The uniform dispersion of MWCNTs up to 2 wt.% ensured effective load transfer and minimised localised stress, leading to reduced wear rates. Beyond this concentration, agglomeration occurred, which impaired wear performance. The increased hardness of the composites, which peaked at 2.5 wt.% MWCNTs, played a critical role in the observed improvements in wear resistance. The elevated hardness was due to the strengthening effect of the MWCNTs, which limited plastic deformation and contributed to the durability of the surface under applied loads. However, the transition from ductile to brittle behaviour at higher MWCNT concentrations (beyond 2 wt.%) reduced toughness, which in turn affected the wear performance under high-stress conditions.

In summary, the introduction of nanoparticles at different volume contents has a large impact on the friction and wear behaviours of additively manufactured polymer nanocomposites. This is evident through the varied effects observed in different cases, as outlined in Table 4 for comparative analysis. It is crucial to emphasise that achieving the optimisation of friction and wear performance may yield different optimal volume content values for nanoparticles. This implies that an improvement in friction behaviour does not necessarily align with enhanced wear performance.

Table 4. Summary of the tribological performance of some additively manufactured polymer nanocomposites.

Matrix/ Nanoparticles	Nanoparticle Size (nm)	Friction Coefficient Trend Against Increasing Volume Content	Minimum Wear Rate (mm^3/Nm)	Best Volume Content for Wear Performance (wt.%)	Reference
PLA/SiO_2	20	↓	1.02×10^{-3}	8	[109]
Al_2O_3, CB	15–20/ 30–60	↓	6.9×10^{-4}	0.75/2.25	[110]
	NA	↑	2.0×10^{-6}	10	[64]
PLA/Nanoclay	NA	↑	1.12×10^{-5}	10	[102]
PLA/ SCF + GNP	5	↑	6.14×10^{-4}	5/5	[105]
ABS/SiO_2	<100	↓	2.55×10^{-5}	2	[51]
ABS/CNTs	10–20	↓	2.78×10^{-7}	4	[86]
ABS/Graphite	NA	↓	1.48×10^{-5}	5	[53]
ABS/Graphene	2–10	↓	3.1×10^{-3}	2	[54]
PEEK/WS_2	80	↓	9×10^{-4}	10	[107]
PA12/micro SiC + SiO_2	NA	↑	5.89×10^{-6}	4/2.5	[92]
PPS/CNTs	60–100	↓	1.8×10^{-5}	0.9	[106]

The symbols "↑" means increase and "↓" means decrease; the term 'NA' here represents the nanoparticle size information is not available or not provided in the corresponding papers.

3.2.3. Fibre Reinforcements

Fibres are the more effective reinforcement fillers to enhance the mechanical properties of polymer composites. Owing to their large radius/length ratio, fibres are more effective for load transferring compared to particulate fillers. Also, better reinforcement effects can be expected with high-volume fractions of fibres. Dhakal et al. [111] investigated the impact of carbon fibre volume fraction on the wear performance of PEEK composites produced via fused filament fabrication (FFF). The findings revealed that the addition of carbon fibres significantly enhances the wear resistance of PEEK by improving load-bearing capacity and reducing surface deformation during sliding. The authors concluded that the fibres act as reinforcements, distributing stresses more evenly across the material and protecting the polymer matrix from direct contact with abrasive surfaces. The study also noted that increasing fibre content further improves stiffness and reduces friction. The wear mechanisms in carbon fibre-reinforced PEEK composites include fibre–matrix debonding and crack propagation, depending on the fibre–matrix interfacial bond. Further, carbon fibres could improve the thermal conductivity of polymer composites and, thus, reduce thermal deformation and adhesive wear with a lower friction force. However, excessive loading of fibres can lead to fibre agglomeration, which compromises uniform dispersion and creates stress concentrators, reducing the material's overall tribological performance. In addition, higher fibre contents may cause higher void formation during the printing process, which can weaken the material structure and contribute to delamination failure in the material under cyclic loading conditions.

For unidirectional continuous fibres, fibre orientation is another important factor that influences the wear performance of polymer composites. For instance, Man and colleagues' study on the wear behaviour of additively manufactured continuous carbon fibre-reinforced PA6 composites [56]. In general, carbon fibre demonstrated its effectiveness in enhancing the wear resistance of the polymer composite. However, the fibre orientation relative to the sliding direction significantly influences wear mechanisms. Parallel and anti-parallel fibre orientations improve wear performance by promoting fibre thinning and the development of a protective transfer film. In contrast, normal fibre orientation results in higher stress concentration on fibre tips, causing fibre breakage and leading to abrasive wear, especially under a higher loading condition. The failure of fibre, i.e., fibre breakage and/or fibre removal, mostly depends on the interfacial bonding between fibres and the polymer matrix. Poor bonding facilitates fibre–matrix debonding, exacerbating the wear process under sliding conditions. Microstructural defects such as voids further contribute to stress concentration and localised failures. Post-processing techniques like compression moulding can reduce void content and enhance interfacial bonding, thereby improving the wear performance and load-bearing capacity of the composite. It was summarised that when the applied load is high, the wear process transitions from adhesive wear in parallel orientations to abrasive wear in normal orientations. Lv et al. also studied the wear performance of PEEK composites reinforced with highly oriented carbon fibres and highlighted the critical role of fibre orientation in influencing friction and wear mechanisms [60]. Three orientations, parallel (P), tilted (T), and anti-parallel (AP), were analysed under varying contact pressures. The findings showed that tilted orientations generally exhibit superior wear resistance compared to parallel and anti-parallel orientations under most conditions. The enhanced performance of tilted fibres arises from their ability to balance interfacial stress distribution and limit excessive fibre damage. In contrast, parallel fibres tend to suffer from stress concentration at fibre edges, leading to higher wear rates and fibre–matrix debonding. The authors concluded that the mechanism is that fibre orientation influences the interaction between the composite and the counter surface. Anti-parallel fibres reduce the accumulation of wear debris and promote the formation of protective tribo-films,

which enhance wear resistance. However, at higher pressures, all orientations exhibit an improvement in wear resistance due to the formation of more uniform and robust transfer films, which shield both the fibres and the polymer matrix from direct abrasive forces.

Other than fibre volume and orientation, the type of fibres can also change the wear mechanism completely. The study by Bodaghi et al. examines the tribological and mechanical performance of glass fibre-reinforced acrylonitrile butadiene styrene (ABS) gears with fibre volume varied from 0 to 15% [85]. The optimal volume fraction of glass fibre was determined as 5 vol.%, which resulted in the best overall mechanical and tribological performance of fibre-reinforced composites. It was indicated that the fibre reinforcements reduce material deformation and increase the resistance to abrasive wear, particularly in high-stress gear applications. However, higher fibre concentrations (e.g., 10% and 15%) result in fibre agglomeration and increased porosity, which could reduce the bonding efficiency and wear resistance of the composites. Liow and colleagues [112] investigated the wear behaviour of 3D-printed glass fibre-reinforced PLA (PLA-GF) composites under different sliding speeds and directions. It was found that glass fibres effectively enhance the wear resistance of PLA by increasing the material's hardness and load-bearing capacity. All the printed fibre-reinforced PLA composites exhibited a lower wear rate but a higher friction coefficient compared to the neat PLA. With the increase in sliding speeds, the PLA transfer film was more developed due to thermal softening. As a result, the governing wear mechanism changed from abrasion to adhesion. It was also noted that with parallel orientations achieving superior wear resistance due to aligned load transfer and minimised fibre–matrix debonding. Conversely, perpendicular orientations experience higher wear rates due to increased interfacial stress and fibre pull-out.

Based on the cited literature, micro-sized fibres have been shown to enhance wear resistance by up to tenfold, whereas nano-sized particles typically improve wear resistance by approximately threefold to fivefold. This finding aligns with observations from traditional moulding processes, where micro-sized fibres have been demonstrated to be more effective than nano-sized particles in reinforcing polymer composites. This difference is likely due to the superior reinforcement of mechanical properties provided by micro-sized fibres. Also, it is important to note that most wear tests are conducted under abrasive wear conditions, where the wear resistance of the tested samples is primarily governed by their hardness [113,114]. Their improved load transfer capability contributes to higher tensile strength, stiffness, and hardness, which in turn enhance the composite's resistance to wear. In contrast, while nano-sized particles contribute to surface hardening and reduced friction, their smaller size limits their effectiveness in significantly reinforcing the bulk mechanical properties of the polymer matrix.

Therefore, to design wear-resistant polymer composites using 3D printing technology, it is important to take all the abovementioned factors into consideration and to combine the favourable factors according to the service conditions where the components need to function. In addition, to ensure the printing quality, it is also necessary to control and optimise the printing properties of filament materials with the selected fibres, as well as bonding efficiency between the fibre and base materials.

4. Recent Advances in Developing Wear-Resistant Polymer Composites Using 3D Printing Technology

4.1. Discussion on the Synergistic Effects of Combining Different Reinforcements in 3D Printing for Enhanced Wear Resistance

To achieve superior wear resistance in 3D-printed components, researchers and engineers are increasingly investigating the synergistic effects of combining multiple reinforcements. The strategic integration of materials such as fibres, nanoparticles, and additives

offers a new route to further enhance mechanical properties and wear performance beyond what individual reinforcements can achieve. This section examines the critical considerations and emerging trends in leveraging these synergistic effects, focusing on how the combination of reinforcements in 3D printing can optimise the design and functionality of wear-resistant components for advanced applications.

The integration of nanoparticles into polymer materials through additive manufacturing has shown promising outcomes in enhancing wear performance. However, in specific engineering applications, composites reinforced with micro-sized particles continue to be favoured for their superior wear resistance and mechanical characteristics [30,115]. The overall performance of multi-filler-reinforced composites is generally derived from the collective impact of each distinct filler, including its influence on wear properties.

Notably, examples of injection-moulded polymer nanocomposites have demonstrated synergistic effects, wherein the combination of nanoparticles with traditional fibres results in excellent wear resistance, as detailed in a study [116].

Recently, research efforts have been dedicated to developing hybrid polymer nanocomposites by using 3D printing technology. For instance, Lin et al. [93] printed fibre-reinforced PEEK coating material on a pure PEEK via the FDM technique. During the wear process, nanoparticles were fed into the contact region to investigate the interactions between nanoparticles and carbon fillers, as well as their effects on the tribological performance of PEEK coating material. It was found that with the presence of nanoparticles, the friction coefficient of the sliding system was significantly reduced in both sliding directions. However, the wear rate was little affected, which displayed a consistent pattern with sliding time. Initially, there was a gradual increase with a higher loss rate, followed by reaching a steady state, as shown in Figure 6. After the tests, the worn surfaces of PEEK composites were further analysed using microscopy techniques, as depicted in Figure 7. Silica nanoparticles covering the carbon fibre surface were evident from the distribution of Silicone elements on fibres. It was proposed that these nanoparticles came into direct contact with the carbon fibres, which significantly enhanced the friction performance by the rolling process of nanoparticles and reduction in adhesion between the tribo-pair. However, the beneficial effect of such a friction reduction on wear was counteracted by the abrasive wear induced by hard silica particles. As a result, the overall wear rate was changed little with the addition of nanoparticles.

A study explored the impact of varying volume content of nano-clay particles in conjunction with SCF-reinforced PETG composites under different loading and sliding velocities [117], and the composition of the nanocomposites is depicted in Figure 8. The tribological outcomes under distinct loading conditions are presented in Figure 9, while those under different sliding velocities are shown in Figure 10. The incorporation of nano-clay particles resulted in a substantial enhancement in the tribological characteristics of 3D-printed PETG nanocomposites, demonstrating notably improved performance compared to SCF-reinforced PETG composites.

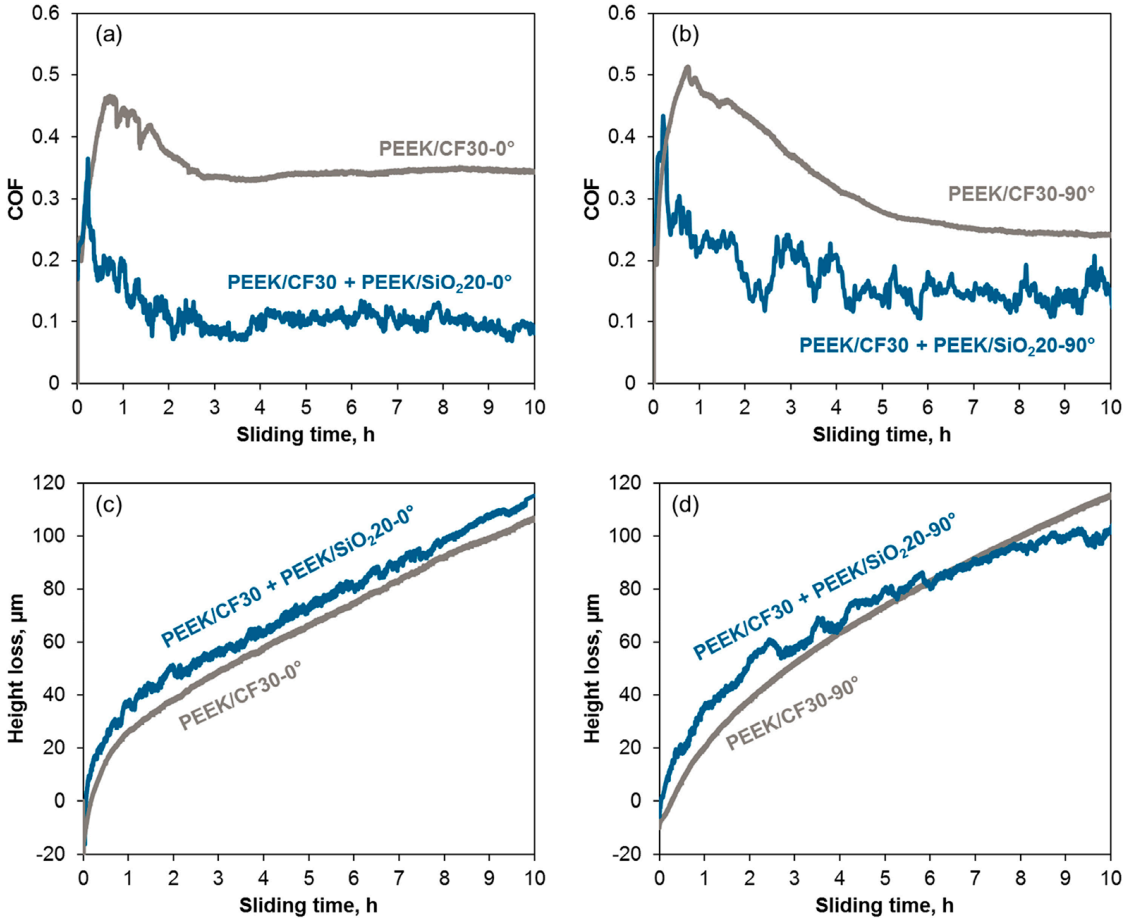


Figure 6. Typical evolutions of the COF and height loss as a function of the sliding time under different testing conditions: (**a**) COF with and without nanosilica taking in 0°-direction; (**b**) COF with and without nanosilica taking in 90°-direction; (**c**) height loss with and without nanosilica taking-in in 0°-direction and (**d**) height loss with and without nanosilica taking-in in 90°-direction [93].

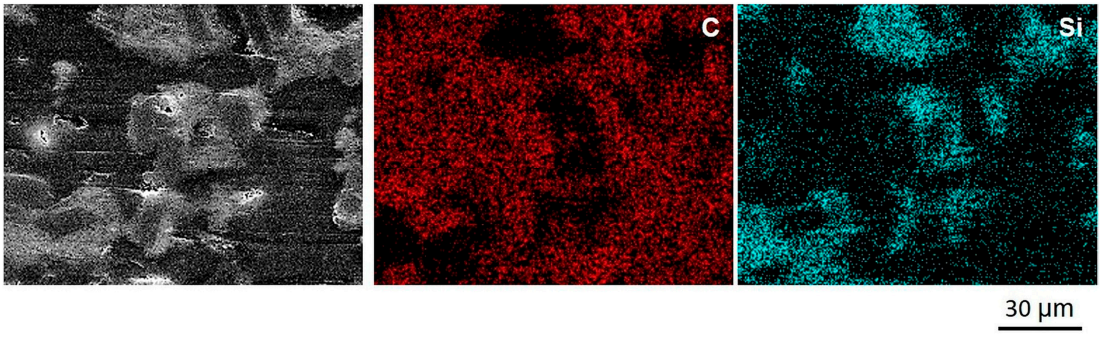


Figure 7. EDX mappings of C- and Si-element of PEEK/CF30 after releasing PEEK/SiO220 in 90 direction. The sliding direction is from left to right [93].

Composite Configuration	Constituents
PC5	PETG + 5% SCF
PC10	PETG + 10% SCF
PO1C5	PETG + 1% OMMT + 5% SCF
PO3C5	PETG + 3% OMMT + 5% SCF

Figure 8. Composition of printed PETG composites reinforced with SCFs and nano-clay particles [117].

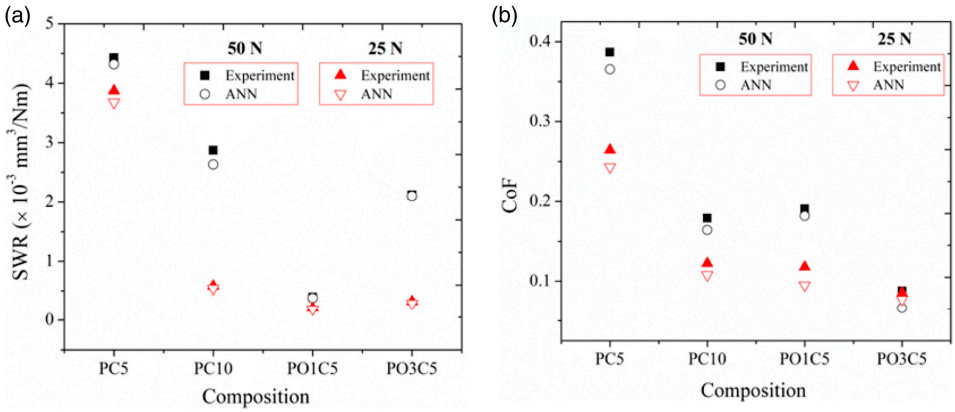


Figure 9. Effect of load on the (**a**) SWR and (**b**) CoF of different PETG/SCF/OMMT nanocomposite samples (300 r/min, 500 m) [117].

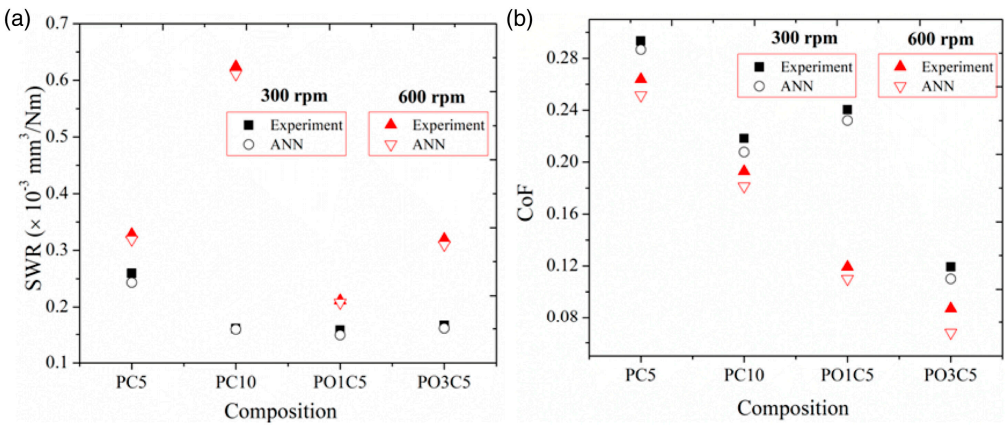


Figure 10. Effect of sliding velocity on the (**a**) SWR and (**b**) CoF of different PETG/SCF/OMMT nanocomposite samples (25 N, 500 m) [117].

This synergistic effect was particularly pronounced under more demanding loading conditions. The author pointed out that SCFs primarily enhance tensile strength and stiffness by improving stress transfer and bridging potential sites of crack propagation, effectively reducing the likelihood of failure under applied mechanical loads. OMMT nano-clay complements this effect by filling micro-voids, reducing porosity, and strengthening the interfacial adhesion within the composite. The nano-clay's high specific surface area facilitates enhanced bonding with the matrix, increasing energy dissipation during deformation and contributing to improved toughness and load-bearing capacity. In terms of tribological performance, OMMT nano-clay enhances wear resistance by forming a stable transfer film at the sliding interface, which reduces material loss and stabilises the coefficient of friction (COF). Additionally, the rolling effect of nano-clay particles minimises shear stresses and contact temperature during sliding, further lowering wear rates. SCFs contribute to wear resistance by providing macro-scale reinforcement and distributing loads more effectively, preventing excessive deformation under frictional forces. The combined effect of SCFs and OMMT creates a composite with superior mechanical integrity and tribological behaviour, where SCFs reinforce the structural performance and nano-clay addresses micro-scale tribological challenges, highlighting the potential of this hybrid reinforcement strategy for advanced 3D-printed composites.

4.2. Numerical Modelling in Developing Wear-Resistant Polymer Composites Using 3D Printing Technology

Numerical simulation plays a pivotal role in the development and optimisation of high-wear-resistance polymer composites produced via 3D printing. It offers several key

advantages, including the ability to predict the mechanical behaviour and performance of composites before manufacturing physical prototypes. This early-stage analysis helps identify potential issues and optimise designs, reducing development time and cost. Simulation tools also enable researchers to investigate various combinations of polymer matrices and reinforcing materials, facilitating the design of composites tailored for specific applications. Moreover, numerical simulations provide critical insights into wear mechanisms at both microscopic and macroscopic levels, helping us to understand how composite components interact under conditions of abrasion, friction, and fatigue. By comparing simulation results with experimental data, researchers can validate and refine their models, increasing confidence in their predictive accuracy. This process not only enhances material design but also strengthens the role of simulation in advancements in wear-resistant polymer composites.

Zhang et al. [118] explored the impact of process conditions on temperature variation in Fused Deposition Modelling (FDM) using a numerical model. They observed a universal reheating phenomenon primarily in the layer thickness direction. A higher temperature difference between adjacent layers, influenced by factors like temperature settings, cross-section area, printing speed, or layer thickness, intensified the reheating effect. Temperature settings, including the printing nozzle, heat plate, and environment, are critical factors affecting temperature variation. Precise control of these temperatures reduces the gradient, regulates cooling, alleviates internal stress, strengthens interlayer bonding, and enhances FDM feasibility. In FDM, higher layer thickness or printing speed leads to a lower overall cooling rate. Moreover, a positive correlation between printing speed and the mechanical properties of FDM-constructed components is predicted. Similarly, the temperature and stress field were modelled by a numerical simulation by Yang et al. [119]. Furthermore, the influence of various processing parameters on the mechanical performance of both pure PLA and PLA reinforced with graphene nanoparticles (GNPs) was investigated through numerical simulation and subsequently validated by experimental studies. In the GNP/PLA case, both the numerical simulation and experimental results indicate that an increase in nozzle temperature and velocity leads to a decrease in the thickness, area, and compactness of the deposited filament. Conversely, the width of the deposited filament increases with higher nozzle temperature and reduced nozzle velocity. These changes in process parameters result in a 10.5% decrease in thickness and a 24.7% increase in width. Under higher nozzle temperatures and velocity conditions, the tensile strength of the printed PLA/GNPs specimen reaches approximately 61.8 MPa, marking an 18.6% improvement compared to the specimen with a tensile strength of 52.1 MPa under lower nozzle temperatures and velocity conditions [120,121]. In addition, other properties, such as the porosity of FDM-fabricated parts, were also studied. The study examines the influence of porosity on the mechanical properties of parts fabricated using FDM and highlights the critical role of printing parameters in determining porosity levels. The findings reveal that porosity is closely linked to parameters such as layer thickness and strand-to-strand distance, which govern the contact area and bonding quality between adjacent layers. Lower porosity, achieved by reducing layer thickness and strand-to-strand distance, enhances tensile strength and stiffness by increasing the contact area and facilitating molecular diffusion across layer interfaces. This results in stronger interlayer bonding and greater structural integrity. Conversely, higher porosity, caused by larger strand gaps or thicker layers, leads to weaker interlayer adhesion and the formation of voids, which act as stress concentrators and reduce the material's ability to withstand mechanical loads. However, the study also notes that excessive reductions in strand-to-strand distance may compromise dimensional accuracy due to material overlap [122].

When it comes to the numerical simulation of the wear performance of 3D-printed components, there is a lack of studies in the field so far. A study [123] examined the

wear behaviour of PLA spur gears under varying coefficients of friction and temperatures, highlighting the mechanisms influencing wear performance. The findings, as shown in Figure 11, indicate that reducing COF significantly decreases wear propagation, as lower friction reduces the stress concentration and sliding forces at the gear interface. This is primarily attributed to reduced energy dissipation, such as heat and lower material removal rates during operation. However, the effect diminishes beyond a threshold COF, indicating a convergence towards steady-state wear behaviour. Temperature plays a more pronounced role, with even a modest increase causing a sharp rise in wear propagation. Elevated temperatures soften the PLA material, reducing its ability to resist deformation and increasing the material removal rate. The mechanism involves temperature-induced reductions in the mechanical strength and stiffness of the material, which accelerates wear and increases susceptibility to thermal damage. The study focuses on the critical importance of managing operational parameters such as COF and temperature, as well as considering cooling mechanisms to maintain gear performance and durability in PLA-based applications [123,124].

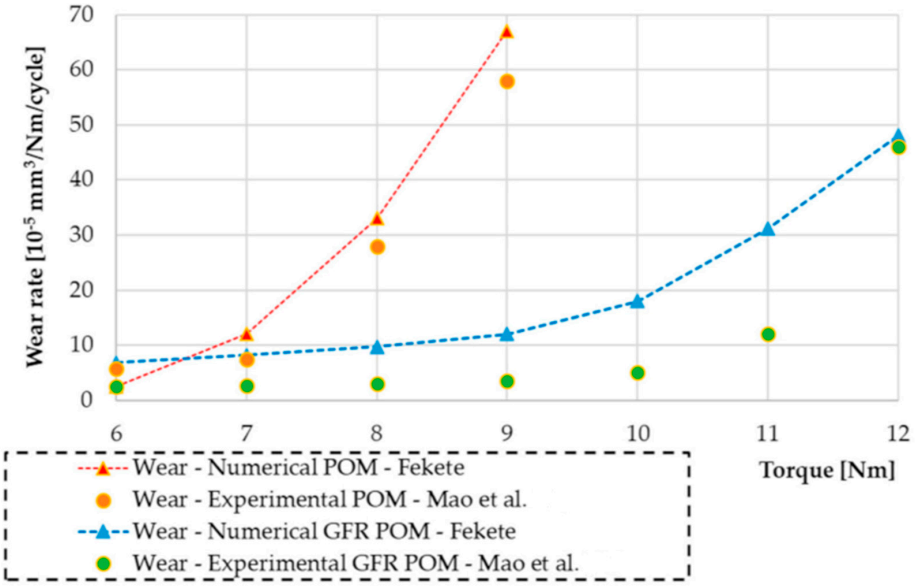


Figure 11. Comparison of experimental and numerical wear rates in the case of POM and glass fibre-reinforced (GFR) POM gear pairs [123,124].

4.3. Surface Texture Technique for Optimising Wear-Resistant Properties

Compared to conventional processing technologies, AM technology presents new opportunities and challenges in developing wear-resistant composite materials. For instance, 3D printing technology enables us to create complex 3D or 2D structures to further enhance the tribological properties of printed components, e.g., by creating textured surfaces. On the other hand, post-processing treatments may be required to migrate internal defects and improve the durability and performance of wear-resistant materials.

4.3.1. Surface Texture

Surface texture refers to the characteristics of a material's surface, including roughness, waviness, and lay. Surface texture influences friction, adhesion, and overall wear resistance. A smooth surface texture generally reduces friction and wear, enhancing the wear resistance of components. However, in certain applications, a controlled level of roughness may be beneficial for promoting lubrication and reducing adhesive wear. For instance, Aziz et al. [11] investigated the effect of surface texturing on the friction behaviour of 3D-printed PLA, and the coefficient of friction reached a minimum for textured PLA at both high and

low speeds in dry sliding conditions. Surface texturing plays a critical role in enhancing the tribological performance of 3D-printed PLA under both dry and lubricated conditions by influencing mechanisms such as wear debris entrapment, contact area modification, and lubricant retention. Under dry sliding conditions, textures with moderate dimensions facilitated optimal wear debris entrapment and transfer layer formation, which acted as a solid lubricant to reduce the coefficient of friction (COF) and wear. Smaller textures were less effective in trapping debris, while larger textures exhibited inadequate transfer layer formation, resulting in higher COF and increased material removal. Surface texturing reduces the real contact area, thereby lowering frictional forces and mitigating abrasive damage through debris entrapment. In lubricated conditions, the performance of textures varied with sliding speed. Larger textures demonstrated superior lubricant retention at low speeds, reducing direct asperity contact, while smaller textures enhanced hydrodynamic effects at high speeds, further lowering COF. The ability of textured surfaces to act as reservoirs for lubricants improves sliding interactions by dissipating frictional energy and minimising wear. Surface analysis indicated that adhesive and abrasive wear dominated under dry conditions, whereas lubricated conditions significantly reduced surface damage.

Likewise, Luo et al. [57] investigated the tribological behaviour of FDM-printed short carbon fibre-reinforced nylon composites with surface textures under both dry and water-lubricated conditions. The employed textures and relevant details are depicted in Figures 12 and 13. The authors point out that the positive impact of surface textures is attributed to the reduction in friction and wear rate during dry sliding conditions by collecting wear debris and fibre debris, thereby minimising three-body abrasive wear. However, under water-lubricated conditions, these advantageous effects become less pronounced. Conversely, surface texture contributes to an increase in the real surface area exposed to distilled water. This heightened exposure, coupled with increased water absorption, significantly compromises the mechanical properties and wear resistance of the printed composite materials under lubricated conditions. The authors pointed out that the fibres restrict polymer chain mobility, improving load transfer and reducing deformation under mechanical stress while also serving as load-bearing elements during sliding. The incorporation of surface textures further enhanced wear resistance under dry conditions by collecting wear debris and reducing three-body abrasive wear, as the textured surfaces minimised contact adhesion and frictional heating. However, under water-lubricated conditions, the effectiveness of surface textures diminished, as the lubricating and cooling effects of water cleaned the contact surfaces and reduced debris accumulation. Additionally, water absorption impaired the mechanical properties of the polymer matrix, particularly in textured samples, as increased exposed surface areas facilitated swelling and softening of the material.

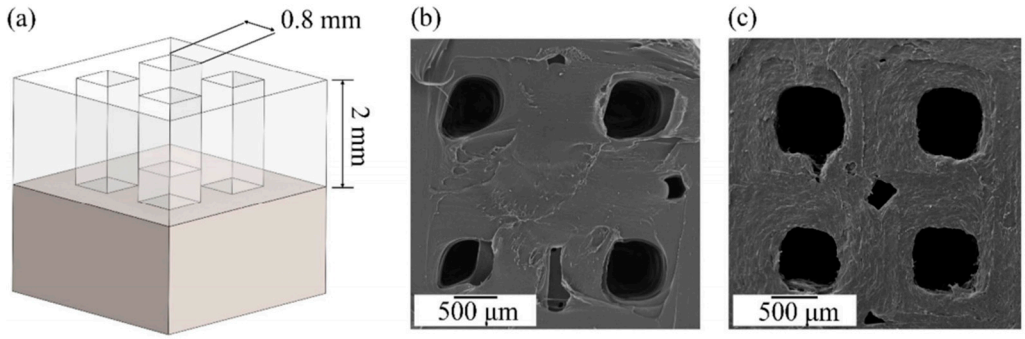


Figure 12. (**a**) Designed textured surface, (**b**) top-view of the printed textured surface of neat nylon, and (**c**) top-view of the printed textured [57].

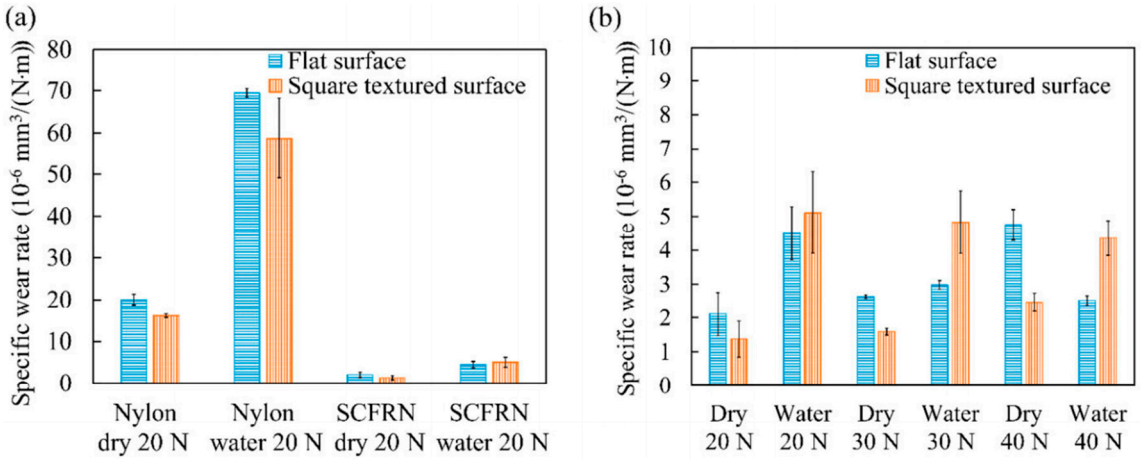


Figure 13. Average specific wear rate: (**a**) nylon and SCFRN tested under dry and water lubricated conditions with a constant load of 20 N and (**b**) SCFRN tested under dry and water lubricated conditions with various loads [57].

The concept has also found application in practical scenarios, as evidenced by the work of Mourya and colleagues [61]. Their study investigates the wear properties of 3D-printed textured journal bearings (TJBs) fabricated using different polymers, including ABS, PLA, and nylon, focusing on process parameters such as texture depth, rotor speed, and load. Findings reveal that nylon exhibits superior wear resistance due to its higher toughness and lower surface roughness compared to ABS and PLA. The material properties of nylon minimise the wear rate and thermal deformation, even under high operating loads. For PLA, however, its lower thermal resistance leads to significant thermal deformation at higher speeds and loads, reducing its reliability. ABS displayed moderate wear resistance but exhibited higher wear rates compared to nylon. The incorporation of surface textures, particularly hexagonal shapes, played a crucial role in enhancing the tribological properties of the TJBs. The mechanism involves increased hydrodynamic effects due to texture depth, which creates a lubricating air film that reduces direct contact between the rotor and the bearing surface. This leads to a lower rubbing temperature and wear rate.

4.3.2. Heat Treatment

Heat treatment processes, such as annealing, can alter the material's microstructure, enhancing its hardness and wear resistance. Proper heat treatment can mitigate wear and improve the longevity of 3D-printed components. For example, a study conducted by He et al. [18] pointed out that annealing proved to be beneficial in enhancing the mechanical strength of FDM-fabricated PEEK, with the improvement escalating with higher temperatures and reaching a peak at 300 °C. The tribo-properties of PEEK were found to be influenced by a combination of crystallinity and filament orientation. Findings indicate that higher nozzle temperatures and lower printing speeds significantly improve the mechanical properties by enhancing interlayer bonding. Increased nozzle temperatures reduce melt viscosity, improving the flowability of extruded PEEK and facilitating better molecular diffusion at layer interfaces. This leads to stronger bonding and fewer voids between layers, as evident in tensile and compressive strength improvements. Lower printing speeds allow more time for interlayer diffusion and recrystallisation, further strengthening the material. Annealing was also found to enhance both mechanical and tribological properties by increasing crystallinity and reducing residual stress in the printed parts. The mechanism involves isothermal crystallisation, where annealing at optimal temperatures rearranges molecular chains, improving their alignment and forming a denser structure. In terms of wear resistance, annealing promotes the formation of uniform transfer films on sliding

surfaces, reducing friction and wear rates. However, excessive annealing temperatures decrease ductility, indicating a trade-off between stiffness and flexibility.

These findings highlight the importance of optimising FDM parameters and post-processing techniques like annealing to achieve tailored mechanical and tribological properties in high-performance 3D-printed PEEK components, particularly for applications requiring durability and wear resistance.

4.4. Implications for the Advancement of Wear-Resistant Composite Materials

The development of wear-resistant composite materials through 3D printing has the potential to impact various industries significantly. This section examines the implications of integrating new materials, using advanced technologies, and applying methods in creating wear-resistant composites. These advancements aim to address challenges in demanding applications, improve durability, and enable customised and efficient solutions in sectors such as aerospace, automotive, healthcare, and manufacturing.

4.4.1. Improving Industrial Applications

1. Extended Component Lifespan

The development of wear-resistant composite materials extends the lifespan of critical components in industrial machinery and equipment, reducing maintenance costs and improving operational efficiency. Reinforcing polymer composites with materials like glass fibres and carbon fibres through 3D printing offers benefits such as rapid prototyping and improved wear resistance. The increasing demand for customised polymer composite structures is driving innovations in manufacturing, enabling faster development and cost-effectiveness—advantages that are often difficult to achieve with traditional moulding processes. Extended component lifespan in 3D-printed composites is achieved through the optimisation of material properties and processing parameters that enhance durability and resistance to wear and mechanical degradation. By incorporating reinforcements such as short and continuous fibres or nanoparticles, the structural integrity and load-bearing capacity of the printed components are significantly improved. These reinforcements distribute stresses more evenly across the material, reducing the risk of localised failures such as cracking or delamination. Furthermore, surface texturing and controlled porosity minimise wear by enhancing lubricant retention and reducing frictional forces during operation. Optimised printing parameters, such as layer thickness, raster orientation, and infill density, further contribute by ensuring robust interlayer bonding and uniform material distribution, which mitigate weak points prone to failure under cyclic or prolonged loading. These advancements in material design and processing strategies enable 3D-printed components to withstand harsher operational conditions, thereby extending their functional lifespan and making them viable for demanding applications in industries like aerospace, automotive, and medical devices [81,83].

2. Enhanced Performance in Harsh Environments

Wear-resistant composites with advanced reinforcements are essential for demanding environments, including aerospace, automotive, and marine applications. These materials enhance system performance and reliability by improving the durability of critical components. The oil sands industry, faced with severe operational challenges such as abrasion, erosion, and corrosion, has increasingly turned to additive manufacturing (AM) to enhance equipment reliability and reduce downtime. AM technologies enable the fabrication of complex geometries that are difficult to achieve with conventional manufacturing while also allowing for rapid prototyping and iterative design improvements directly from 3D CAD models in a cost-effective manner. Materials such as cemented carbide and other wear-resistant composites have been explored for their potential to improve performance

and lower production costs. Current efforts focus on slurry transport applications, wear-resistant overlays, sintered metal carbides, and composite materials, with AM playing an increasingly vital role. While AM remains in its early stages of adoption in the industry, its ability to produce tailored, high-performance components has positioned it as a promising solution for overcoming the harsh environmental and operational conditions inherent to oil sand production [125].

4.4.2. Innovations in Medical Implants

1. Biocompatible Wear-Resistant Materials

The advancement of wear-resistant composites presents opportunities for the development of biocompatible materials suitable for medical implants. Specifically, orthopaedic implants and prosthetics [126], particularly in dentistry, stand to benefit from materials that possess both wear resistance and compatibility with the human body. In a study focusing on carbon fibre (CF)-reinforced polyether ether ketone (PEEK), the CF-PEEK composite, with its improved mechanical properties, holds significant potential for application as a material for orthopaedic or dental implants. This extends to areas such as bone repair, regeneration, and tissue engineering applications [127]. The study systematically investigated the mechanical, tribological, and biological properties of FDM-printed carbon fibre-reinforced PEEK (CFR-PEEK) composites and their potential for biomedical applications. The findings reveal that CFR-PEEK exhibits significantly improved mechanical properties, including tensile, bending, and compressive strength, compared to pure PEEK. This enhancement is attributed to the incorporation of carbon fibres, which improve the composite's stiffness and load-bearing capacity, making it suitable for applications such as dental implants and bone replacement. Carbon fibres provide reinforcement at the molecular level, enhancing stress distribution and minimising deformation. Tribologically, the surface topography of FDM-printed CFR-PEEK, characterised by its highly roughened structures, contributes to its superior cell adhesion and biocompatibility. The study found that these rough surfaces offer more binding sites for cells, promoting adhesion and spreading, which are critical for tissue integration. Unlike polished or sandblasted surfaces, the as-printed rough structures retain their manufacturing-induced features, which enhance bioactivity. Additionally, the research confirmed that the FDM process did not introduce toxic substances, ensuring the material's safety for biomedical use. These results demonstrate the potential of CFR-PEEK composites in orthopaedic and dental implants, particularly in applications requiring high mechanical strength and biocompatibility. The study emphasises the importance of optimising FDM parameters and material composition to fully leverage the capabilities of 3D-printed CFR-PEEK in clinical applications.

2. Customisation and Patient-Specific Solutions

Three-dimensional printing offers the potential for customised medical implants tailored to individual patient needs, ensuring a precise fit, reduced wear, and extended implant longevity. However, challenges remain that limit its broader adoption in medical applications. The time required to generate digital files and the high costs of materials and processing are significant barriers, particularly in emergency situations. Accuracy issues with wear-resistant composites, along with time-intensive post-processing and a shortage of trained operators, further hinder its use. Additionally, many 3D printers lack the specialisation needed for dentistry, making them less suitable for medical professionals. Compared to traditional bulk manufacturing, these limitations place 3D printing at a competitive disadvantage. To address these issues, advancements in 3D printing technology for dentistry should prioritise cost reduction, faster production times, improved surface quality, and greater process reliability. Future developments are likely to make 3D printing in dentistry more specialised and efficient, with enhanced material performance and

application-specific designs [128]. The review highlights the transformative role of 3D printing in dentistry, particularly in enabling customisation and patient-specific solutions. The ability of 3D printing technologies to utilise digital data from intraoral or extraoral scans allows for the fabrication of complex geometries tailored to individual patient needs. This customisation extends across prosthodontics, orthodontics, and maxillofacial surgery, enabling the production of dental crowns, surgical guides, implants, and orthodontic models with high precision and minimal material waste. In addition, digital workflows facilitate rapid and accurate design iterations, reducing reliance on manual processes and ensuring better adaptation to patient anatomy. For example, personalised prosthetics and implants not only enhance functional outcomes but also improve patient comfort and satisfaction by precisely matching anatomical features. This integration of CAD software and 3D printing technologies allows dentists to streamline treatment processes, minimise errors, and provide cost-effective and tailored care, underscoring the significant potential of 3D printing to advance precision medicine in dentistry.

3. Advancements in Sustainable Practices

The integration of sustainable polymers and reinforcements in wear-resistant composites highlights a growing focus on environmental sustainability, enabling the development of eco-friendly materials for a range of applications [129]. A review by Faludi et al. used life-cycle assessment to compare the environmental impacts of additive manufacturing and traditional machining. The study highlighted that designers and engineers seeking to reduce environmental impacts should prioritise high-utilisation machines. It further suggested that, where applicable, Fused Deposition Modelling (FDM) machines should be favoured over CNC mills if they meet the necessary quality standards for surface finish due to their lower environmental effects [130]. The findings from the study emphasise significant advancements in sustainable practices through the application of additive manufacturing (AM). The research highlights how AM can significantly reduce material waste compared to traditional subtractive manufacturing processes, such as computer numerical control (CNC) machining. The mechanism behind this lies in the layer-by-layer construction technique of AM, which minimises excess material use and eliminates the need for cutting fluids, a notable source of environmental toxins in CNC processes. Additionally, AM's capability to optimise designs for material efficiency, such as creating hollow structures or integrating multi-functional components, further reduces resource consumption. The study also notes that the environmental impact of AM is highly influenced by energy consumption during operation. While AM may have higher energy requirements compared to traditional methods, its overall ecological footprint can be mitigated through efficient machine utilisation and renewable energy sources. Life-cycle assessments (LCAs) reveal that AM has the potential to lower greenhouse gas emissions and reduce waste production, especially when machines are shared or operated at high utilisation rates, reducing idle energy consumption. Finally, wear-resistant polymer composite plays a crucial role in sustainability by directly influencing energy consumption, resource efficiency, and environmental impact. The study highlights that tribological interactions account for approximately 23% of global energy consumption, with 20% used to overcome friction and 3% required for remanufacturing worn components, as reported in a study [131]. By implementing advanced surface engineering, material innovations, and lubrication technologies, energy losses due to friction and wear could be reduced by 40% in the long term and 18% in the short term. This reduction translates into significant sustainability benefits, including an 8.7% decrease in total global energy consumption and a substantial cut in CO_2 emissions—up to 3140 megatons of CO_2—by minimising inefficiencies in transportation, manufacturing, power generation, and residential applications. Moreover, these advancements could generate economic savings of nearly one trillion Euros annually

while extending the lifespan of critical components and reducing material waste. The findings emphasise that improving wear resistance and friction management is essential for achieving energy efficiency, lowering reliance on finite resources, and supporting long-term environmental sustainability through reduced emissions and lower material demand.

4.4.3. Challenges and Future Directions

Three-dimensional printing, also known as additive manufacturing (AM), faces several challenges that impede its widespread adoption, particularly in industrial applications. A major limitation is the high cost of equipment, materials, and post-processing, which is especially restrictive in developing economies with limited financial resources. Scalability is another significant challenge, as 3D printing is less efficient for mass production due to extended build times and restrictions on part dimensions. Material limitations, particularly the narrow range of high-performance polymers and metals, further constrain its applications. Additionally, technical issues such as porosity, inconsistent product quality, and residual stresses during metal printing compromise the durability and reliability of components, often necessitating extensive post-processing to meet functional standards [132]. Environmental and health concerns add to these challenges. Although 3D printing typically generates less material waste than traditional manufacturing, certain processes emit harmful fumes and consume substantial energy, diminishing its environmental benefits.

Moreover, a recent study [133] reported that the development of wear-resistant materials plays a crucial role in promoting sustainability and scalability by reducing material loss, energy consumption, and environmental impact while ensuring manufacturability for large-scale applications. Advances in surface engineering, such as coatings, texturing, and self-lubricating materials, enhance wear resistance without altering bulk properties, leading to more efficient material utilisation and extended component lifespan. The incorporation of nanostructured reinforcements, including graphene and carbon nanotubes, improves durability while enabling lightweight, high-performance composites that reduce resource consumption. Additive manufacturing and advanced processing techniques, such as plasma treatment and laser surface modification, provide scalable solutions for integrating wear-resistant materials into industrial applications. However, maintaining uniform material properties at scale remains a challenge, necessitating precise control over microstructures and reinforcement dispersion. Computational modelling and machine learning are emerging as valuable tools to optimise wear resistance and production efficiency. Future research should focus on refining processing techniques, improving recyclability, and developing sustainable materials that balance performance with environmental responsibility, ensuring the large-scale implementation of wear-resistant technologies across diverse industries.

Despite these problems, 3D printing presents numerous opportunities and emerging trends that have the potential to revolutionise manufacturing. Sustainability initiatives are driving the development of eco-friendly materials, such as biodegradable polymers like polylactic acid (PLA), and promoting zero-waste manufacturing principles. These efforts align with broader environmental goals, including reducing carbon emissions and incorporating recycled materials into production. Technological advancements, such as hybrid manufacturing that combines additive and subtractive techniques, address limitations in surface quality and mechanical performance.

Finally, it is worth mentioning that the incorporation of Industry 4.0 principles into additive manufacturing (AM) has revolutionised the production of smart, wear-resistant materials, creating opportunities for highly customised, efficient, and durable manufacturing processes. Industry 4.0 emphasises interconnected systems, including IoT, cloud computing, and real-time data processing, to optimise manufacturing workflows. In the

context of wear-resistant materials, AM enables the fabrication of complex geometries and multi-functional structures with precision, allowing manufacturers to tailor material properties to specific wear conditions. Smart materials, integrated with sensing capabilities, can monitor their performance in real time, providing critical feedback to improve operational reliability and lifespan. These advancements, supported by interdisciplinary research in materials science and engineering, are expanding the applications of 3D printing across industries such as aerospace, healthcare, and automotive. Economic opportunities also arise from the potential of 3D printing to reduce production costs and shorten supply chains. Localisation of production through AM minimises logistics expenses and decreases the environmental footprint of manufacturing. Innovations in materials, such as functionally graded and multi-material composites, further improve the feasibility of 3D printing technologies. By investing in these areas, industries can have the full potential of 3D printing to create sustainable and efficient solutions for the future [134]. Furthermore, a study [135] reported that the integration of artificial intelligence (AI) and machine learning (ML) into the fabrication of polymer composites has revolutionised material design, manufacturing, and performance optimisation by enabling data-driven predictions and process control. AI-driven techniques facilitate the precise optimisation of key parameters such as fibre orientation, reinforcement dispersion, and curing conditions, ensuring enhanced mechanical, thermal, and tribological properties while minimising material defects and experimental costs. Machine learning models, including neural networks and Gaussian process modelling, have proven effective in predicting composite behaviour, optimising wear resistance, and quantifying uncertainties in fabrication processes. Moreover, deep learning approaches, such as convolutional neural networks, enable microstructural analysis and defect detection, further improving the consistency and scalability of composite production. By leveraging AI, researchers can accelerate the discovery of novel bio-based and high-performance polymer composites while advancing sustainable and scalable fabrication methods for applications in various engineering fields. Future research should address challenges related to available data, model interpretability, and real-time AI adaptation in manufacturing to ensure widespread industrial implementation of intelligent polymer composite fabrication.

5. Conclusions

The development of wear-resistant polymeric materials through 3D printing technologies has emerged as a significant advancement in materials engineering, offering customised solutions for a wide range of wear-critical applications. Additive manufacturing (AM) methods, particularly Fused Deposition Modelling (FDM) and selective laser sintering (SLS), have provided a certain level of control over design parameters, enabling the optimisation of mechanical and tribological properties. Parameters such as layer thickness, printing speed, infill density, raster angle, and print orientation critically influence interlayer bonding, porosity, and surface texture, all of which directly affect wear resistance and overall performance. Optimising these parameters has demonstrated the ability to improve material durability, enhance surface smoothness, and reduce wear rates under varying operational conditions.

The incorporation of reinforcement strategies, such as short and continuous fibres and nanoparticles, has further improved the performance of 3D-printed composites. Fibres contribute macro-scale reinforcement, improving tensile strength and load-bearing capacity, while nanoparticles address micro-scale tribological challenges by enhancing interfacial bonding, reducing porosity, and forming protective tribo-layers that minimise friction and wear. The synergistic combination of these reinforcements results in hybrid composites with superior wear resistance and mechanical strength, demonstrating their potential for

advanced applications in the aerospace, automotive, and biomedical sectors. Additionally, surface texturing and the use of smart materials have added new dimensions to tribological performance, enabling adaptive responses to operational conditions and self-monitoring capabilities. Post-processing techniques, such as annealing, have also proven effective in reducing residual stress and improving crystallinity, further enhancing wear resistance and mechanical integrity. Furthermore, digitalisation and the integration of Industry 4.0 principles, such as real-time monitoring, digital twins, and AI-driven optimisation, have enabled greater customisation, improved efficiency, and smarter manufacturing workflows for wear-resistant components.

Despite these advancements, significant challenges remain. Achieving uniform reinforcement dispersion, scaling up production for industrial applications, and balancing cost-efficiency with performance are critical hurdles. Environmental concerns associated with polymer waste and the limited availability of sustainable materials are additional barriers. Future research should focus on addressing these challenges by exploring biodegradable polymers, recycled composites, and environmentally friendly printing processes. Advances in computational modelling and machine learning could further enhance predictive capabilities, enabling the design of materials with optimised properties for specific wear conditions.

In conclusion, the development of wear-resistant polymeric materials using 3D printing technologies has demonstrated the potential to create durable, efficient, and application-specific solutions. By addressing existing challenges and emerging trends, this review highlights the remarkable progress in 3D-printed wear-resistant polymers and serves as a foundation for future exploration and innovation in this field.

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