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Review

Tribological Investigations of 3D Printed Polymers and Their Applications: A Review

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Abstract

In latest years, 3D printing has progressed significantly. Studies in numerous fields (medical, automotive, aerospace, construction, electrical, etc.) were conducted to reap fruits from the progress of 3D printing. In this work, some previous studies on the use of 3D printing for tribological applications were highlighted. This study contributes to enriching relevant information about the various materials and 3D printing processes utilized and also facilitates the comprehension of the findings of these research and future issues. Accordingly, a comprehensive study of the tribological properties of 3D-printed polymers was conducted.

Keywords: 3D printing, tribological properties, 3D printed techniques, 3D printed polymers applications, 3D printed materials

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1 INTRODUCTION

The development of precision, reliability and material range of 3D printing has resulted in the competitiveness of 3D printing as an industrial-production technique, and the term additive manufacturing is now interchangeable with it[1]. 3D printers are one of the most recent technological revolutions in industrialization. Layers are stacked on top of each other to form the desired 3D objects utilizing a particular technique and different materials. The current high demand for 3D printing processes is attributed to the excellent precision and quality of the items produced with this technology. It is also more efficient, cost-effective, and simple for utilization than other fabrication techniques. In addition to the production of complicated and large-scale components, prominent, overlapping, and printing pieces with various mechanical and physical characteristics are also feasible, which, therefore, led to the extensive use of additive manufacturing, including medical, aerospace, automotive, and electronics[2-6].

The majority of previous research focused on the mechanical properties of 3D printed materials, while investigations on their tribological characteristics are little[7,8]. Previous studies on 3D printing for polymers were analyzed statistically (Figure 1). Only 3% of such studies addressed the tribological aspects of the printed polymers. In addition, 12% of these studies have focused on the mechanical properties of printed polymers. Photopolymer charge transfer, biological systems, optical elements, biomedical, and pharmaceutical applications were among the remaining disciplines (85%). Accordingly, the goal of this research is to enlighten existing research onthe tribological properties of 3D printed polymers and possible challenges, to maximize the benefits of 3D printing technology in the field of tribology.

Polymer matrix composites as 3D printing materials will be the subject of future research. In light of the positive tribological properties observed in a prior investigation[9-11], an epoxy matrix composite will be examined as well.

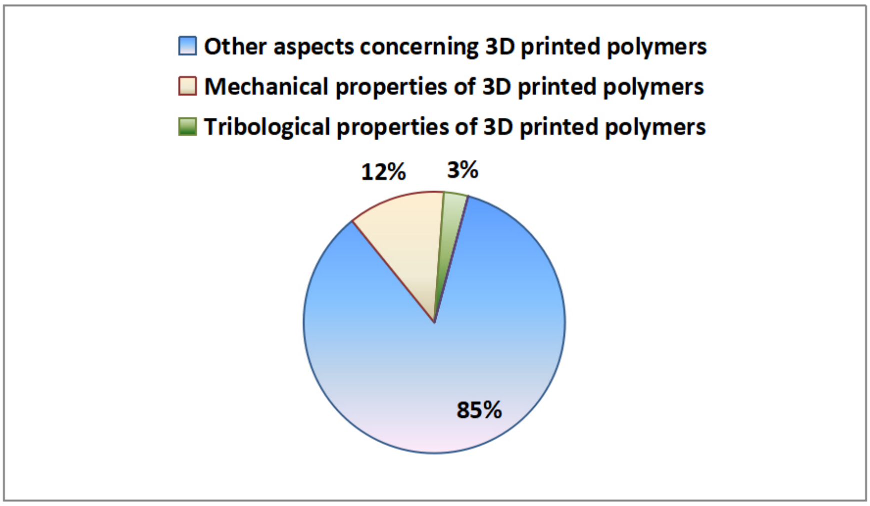

Figure 1. Statistic analysis of previous studies on 3D printed polymers.

2 MATERIALS AND 3D PRINTING TECHNIQUES

ABS and PLA are two of the most common polymers used as 3D print materials. Because ABS is tougher than other polymers and more flexible even at low temperatures, it is ideal for applications requiring both strength and flexibility, such as shock resistance. It is also resistant to corrosion caused by acids, alcohols, and alkalis[12]. PLA, on the other hand, features a low melting point, a low price, and medically suitable qualities, due to which it is mostly applied in the medical field[13,14]. Fused deposition modeling (FDM) is a contemporary fast prototyping technology widely utilized thanks to its ability to create useful components in a reasonable amount of time. It is a process in which the components are printed layer by layer using a print head nozzle with the addition of the heated engineering plastic material. In this field, engineered thermoplastics such as Acrylonitrile Butadiene Styrene (ABS), carbon fiber polylactic acid (CFPLA), polyamide[12,15-21], PETG, and Epoxy nanoclay have been employed for parts manufacture. Printing factors such as printing direction, layer thickness, orientation angle, filling ratio, and filament feed rate affect the quality and effectiveness of FDM manufactured products. Polymeric specimens utilized in earlier research were created using different printing parameters, comprising the orientation of the printed specimen with relation to the printer's building tray and the thickness of a single layer of deposited material[22-26].

Direct ink writing of poly (amide acid) (PAA) precursor ink, followed by post thermal treatment and template removal, results in three-dimensional (3D) printing of porous polyimide (PI) with good oil storage potential for self-lubrication. PAA and polymethyl methacrylate (PMMA) microspheres are used in the ink, where the PMMA microspheres act as both a pore-forming agent and a rheology modifier to achieve high-precision porous PI objects, as shown in Figure 2[27].

Due to the difficulties in recycling carbon fiber reinforced polymer (CFRP) waste, its annual production is tremendous. Some studies offered a new additive manufacturing-based recycling technique for reclaiming CFRP waste and re-manufacturing CF into printed composite components. Carbon fiber (CF) was initially recovered from CFRP waste using supercritical fluid, then combined with Poly-Ether-Ether-Ketone to make composite filaments in a trial of this technique, see Figure 3. The filaments were then put into a fused deposition modeling printer, where the recycled CFRP pieces were fabricated. Experiments utilizing recycled carbon fiber in engineering applications revealed that it may successfully improve mechanical strength, electrical conductivity, heat conduction, and wear resistance of printed parts[28].

Prior research looked at the function of nanodiamonds (NDs) as fillers in the creation and testing of 3D-printed nanocomposite samples to improve friction and wear resistance. 0.1 wt.% ND was added into the PMMA using a solution-based mixing method, and samples were 3D-printed for tribological and microbiological examination. Control specimens were compared to specimens containing both amine-functionalized NDs (A-ND) and pure non-functionalized NDs (ND). During the surface hardness test, the Vickers micro-hardness of the nanocomposite groups improved significantly (p 0.001). Refined ND and A-ND were utilized at a concentration of 0.1wt. % in the polymer to preparethe ND-incorporated and A-ND-integrated nanocomposites. The pre-weighted ND powders were mixed with resin oligomers to achieve a uniform dispersion of the ND and A-ND, for which a solution-based mixing approach was utilized with the aid of high-power probe sonication in conjunction with magnetic stirring[29]. The resin was degassed in a vacuum for two hours before being applied to print the substrate samples. The specially designed cubed samples were printed using a digital light processing (DLP) 3D printer. The specimens

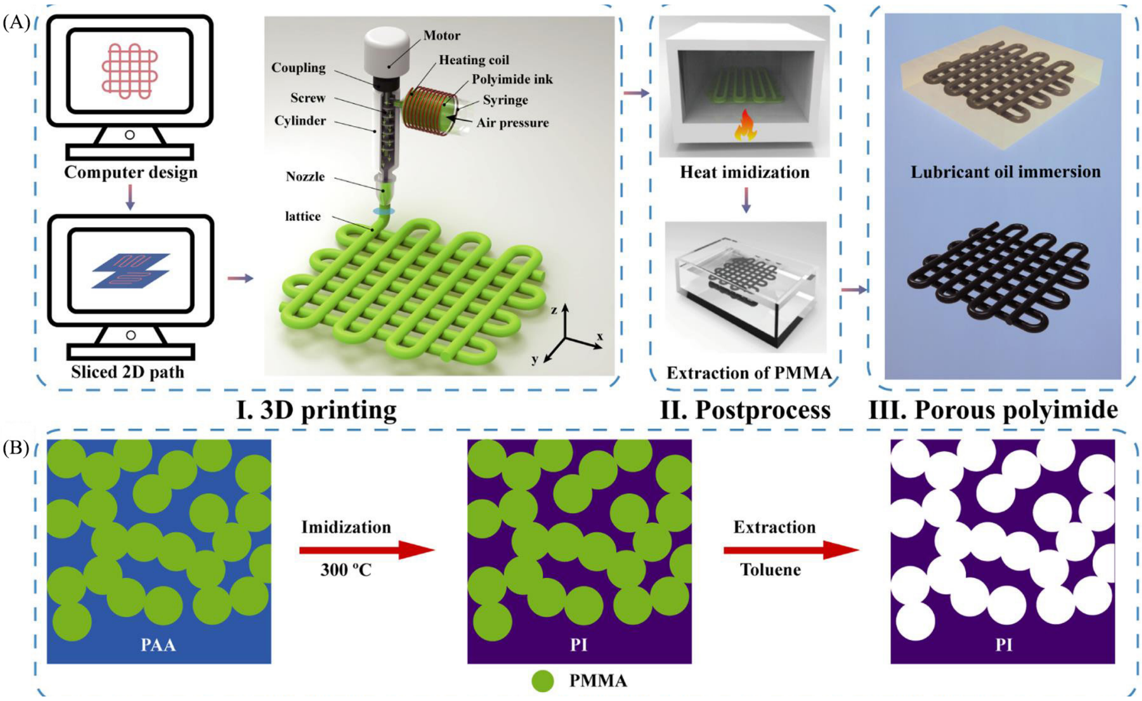

Figure 2. 3D printing porous PI schematic diagram. A Porous PI is fabricated by combining 3D printing of the PAA precursor ink with postprocessing; B Pore formation mechanism diagram[27].

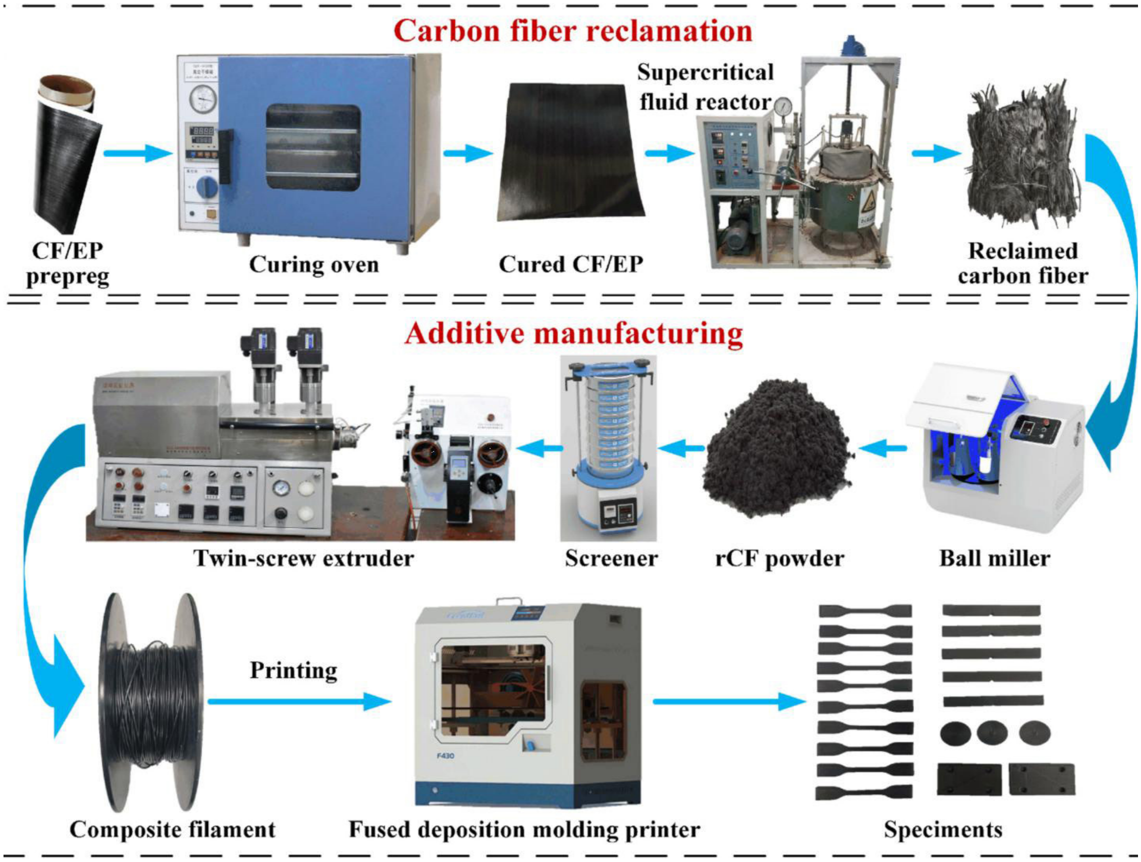

Figure 3. The integrated CFRP recycling technique's experimental procedure using additive manufacturing-based re-manufacturing[28].

were printed with a100μm z-axis (parallel to printing direction) spacing, a build angle of 0º, and the side to be tested parallel to the platform. The samples were polymerized under 405nm light at a maximum printing speed of 140mm/h, then post-cured (15 minutes) in a UV oven according to the kits' instructions[29]. The samples were completely dried at 37 degrees Celsius before testing and polished with SiC paper (1200, 1500, and 2000grit) (Figure 4).

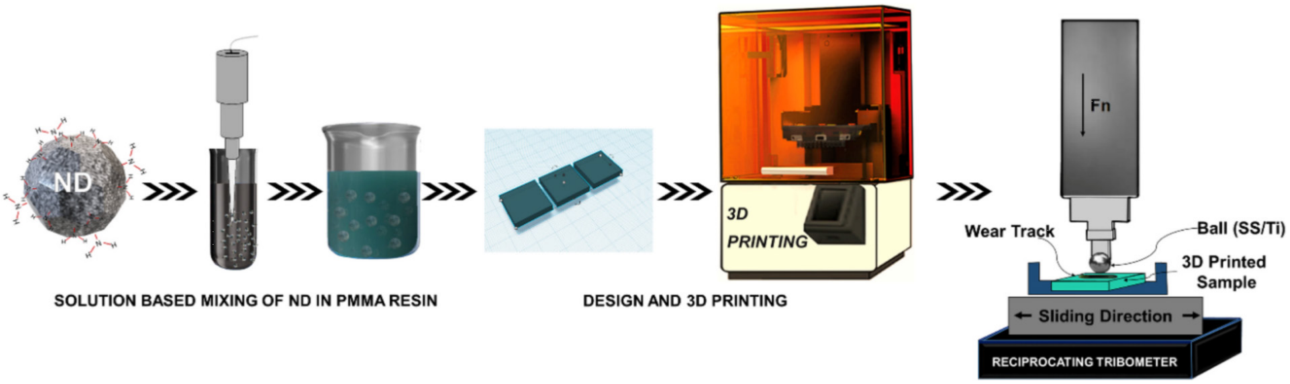

Figure 4. Schematic illustration of the 3D-printed nanocomposite specimen fabrication and testing process[29].

3 TRIBOLOGICAL PROPERTIES OF 3D PRINTED POLYMERS AND THEIR APPLICATIONS

3D printing has recently become popular for the design and manufacture of various system and mechanism components. Part orientation affects surface quality and, as a result, tribological characteristics of tribopairs during the printing process. However, little study has been carried out on the tribological behavior of 3D printed materials which may lead to uncontrolled wear of tribopair surfaces. The tribological properties of acrylonitrile butadiene styrene (ABS), a commonly used polymer in 3D printing, were studied by many researchers. The ABS sample was created using fused deposition modeling (FDM). The tribology test was performed on a paraffin-lubricated ball-on-disc tribometer. With a constant sliding distance, speed, and temperature, the test was maintained at various applied loads[24]. The results showed that as the load increased, the wear rate of the 3D-printed ABS reduced. In either case, a significant coefficient of friction was observed with the applied force.

The effect of varying the contact load on the friction and wear mechanisms of additively manufactured acrylonitrile butadiene styrene (3D ABS) and Verogray polymers fabricated using Polyjet technology was investigated via a Bruker Universal Material Test with the linear reciprocating module in a ball-on-plate configuration under dry sliding conditions. At room temperature, loads of 1, 5, and 10N were applied in dry sliding contact with a 52100 steel counterface. The findings showed that for 1N load, the friction coefficient was largely determined by the surface's orientation to the sliding direction. However, for greater weights of 5N and 10N, this dependency was shown to be caused by bulk material properties rather than surface roughness. The bulk material characteristics and the applied load were also shown to influence the relationship between surface morphology and wear rate[23]. Polyjet materials can be applied in metal-polymer tribo-contacts to improve friction and wear behavior, according to the findings of this study.

The ball-pin tribometer was used to investigate the tribological characteristics of 2D layered materials (2DLMs), such as MoS2 and WS2, as well as three-dimensional (3D) graphite, which were infused in thermoplastic polymer matrices made of ABS and PETG. The dynamic friction characteristics of the composites were examined to make use of the graphite and 2DLM fillers' solid-phase lubricating capabilities. In the situations of 3D printed PETG and injection moulded ABS, Graphite was revealed to have the lowest dynamic friction, whereas MoS2 and WS2 were shown to have the lowest friction in 3D printed PETG and ABS[30]. With low-cost additive manufacturing techniques, this study encompassed a wide range of applications, such as wearable electronics and sensors.

The tribological properties of different printed polymers, such as PLA, high tensile/high temperature-PLA, and polyethylene terephthalate-glycol, have been investigated to develop tribological applications. The tribological experiments were performed in a reciprocating sliding and dry environment. The findings revealed that the presence of different orientations during the 3D-printing process affected the coefficient of friction and wear depth values[31]. Moreover, the printing structure in the horizontal direction (X) facilitated the reduction of friction and wear. PLA samples printed using the Fused Deposition Modeling process had their hardness, friction coefficient, and wear properties investigated as a function of layer (thickness and orientation) parameters. Samples were printed in two distinct construction orientations with three different layer thicknesses. The hardness of the materials was assessed using a D-type shore hardness durometer, and a pin-on-disc setup was employed to determine the friction coefficient and wear rate. The 3D manufacturing parameters of layer (orientation and thickness) have a spectrum of effects on the polymer behavior, according to hardness, friction, and wear studies[32]. However, those factors had little effect on the friction coefficient, which might have been quite relevant depending on the normal load. The effect of layer orientation on a normal load of 100N was uncertain, although the wear rate changed with the layer thickness.

Other research investigated the tribological behavior of ABS composite parts made of FDM. The friction and wear behavior of ABS composite was compared to that of the FDM machine's current acrylonitrile butadiene styrene filament. Carbon fiber reinforced ABS demonstrated less wear than pure ABS in the test specimens, as carbon fiberenhancedthe wear resistance of polymer materials given its high load-carrying capability[33]. The applied load and run time substantially affect the material's wear rate and frictional behavior under dry sliding circumstances.

Using the Dimension 1200es machine, the ring-shaped samples were produced with ABS P430 materials. The disc-shaped counter-samples were made from C45 steel. The "printing" orientation (between the friction surface of the sample and the construction platform), determined at three degrees of variability (0°, 45°, and 90°), is the technical parameter of the construction process of the examinedsample models. The impact of printing orientation on friction force and total friction wear was investigated using the T-15 tribological tester of the ring-on-disc type. When employing FDM technology, the sample models created at the provided angle Pd-0° against the building platform exhibited maximum wear. The magnitude of friction force between ABS samples and C45 steel had no significant influence on the printing direction of ABS samples manufactured using FDM technology[34]. Because of the extremely inadequate strength of models that were damaged during the tests, it was difficult to achieve an appropriate closure of measurements with the sample distribution at the required Pd angle of 90°.

The carbon acquired from trees, plants, and soils is used to absorb and store carbon dioxide from the atmosphere in a natural way. Regeneration is one of the most crucial characteristics. Therefore, PLA was fortified with biocarbon to produce a material that is 100 percent recyclable. In spite of the long-term use of PLA in 3D printing, the enhancement of mechanical and tribological characteristics can still enable additional applications such as housings or structural interiors of automobiles or other vehicles. Although the COF remains high, approximately 0.5, the friction values in the case of reinforcement exhibit less variation. PLA with 30 vol. % biocarbon has the smoothest and most homogeneous COF. However, it exhibited the lowest producibility in 3D printing with nozzle chocking. After a dry sliding test against an Al2O3 ball, the PLA sample with 30 vol. % carbon was shown to have the lowest wear volume. Several wear mechanisms, including fatigue and abrasion, were observed. Both methods are impacted by the biocomposites' materials characteristics, particularly stiffness change and embrittlement owing to reinforcement. Biocarbon reinforced PLA applications are considered for the automobile components of green cars[35]. Both biocarbon and PLA biopolymers are derived from natural resources. Another benefit is the second use of such biogenic automobile components after its service lifespan. Downcycling is used as a soil improvement ingredient in agriculture. Table 1 summarizes research on the tribological behavior of 3D printed polymers. Figure 5 depicts the uses of numerous 3D printed polymers reported in previous studies. Automotive, Aerospace, Medical, Construction,

Table 1. Summary of Studies on the Tribological Properties of 3D Printed Polymers

No.	Materials	Findings	Ref
1	Porous Polyimide	The printed porous PI demonstrated good oil storage capabilities, and it holds the promise ofcreating high-performance lubricated components, particularly those with a high level of complexity.	[27]
2	Wanhao UV resin	In contrastto non-post treated samples, tribological testing revealsthat post-processing results in a reduced wear depth and a higher coefficient of friction for the specimens.	[36]
3	Porous polycarbonate-urethane (PCU) and (UHMWPE) blend	Due to retained fluid in its porosity, 3D printed PCU exhibits 27 % less wear depth than molded PCU in rotational oscillation testing under conditions that replicate the knee action. As a result, 3D printing renders the creation of porous, customized PCU implants that imitate meniscus lubrication a breeze.	[37]
4	3D-P ABS and PETG matrix infused with graphite, MoS2, and WS2	Graphite is shown to diminish dynamic friction in 3D printed PETG and injection moulded ABS, whilst MoS2 and WS2 are found to lower friction in 3D printed PETG and ABS.	[30]
5	PLA, HT-PLA, and PETG	The findings reveal that the presence of different orientations during the 3D-printing process affects the coefficient of friction and wear depth values. Furthermore, printing structure in the horizontal orientation (X) helps to reduce friction and wear.	[31]
6	PLA and PLA composites	After a dry sliding test against an Al2O3 ball, the PLA sample made with 30% carbon is shown with the lowest wear volume.	[35]
		The layer thickness had little influence on the friction coefficient, but the layer orientation might be of great significance depending on the normal load. The wear rate varies with layer thickness under a normal load of 100 N, but the impact of layer orientation is ambiguous.	[32]
		Experiments demonstrate that the material filler has a significant impact on the tribological properties of pairs of PLA polymer samples created by 3D printing. For tribopair design in medical applications, components with 100 percent filling areused.	[18]

		Under dry sliding circumstances, the coefficient of friction for texture T2 is found at the lowest at both high and low speeds. Wear debris is more efficiently captured, which contributes to the creation of a solid lubricant transfer layer. At low speeds, texture T3 exhibits the lowest coefficient of friction when lubricated, whereas texture T1 has the lowest coefficient of friction at high speeds.	[26]
		The nanocomposites with 25% wt ALM and 75% wt CB have improved mechanical and wear characteristics, implying the collaboration of the nanofillers and the role of CB as a compatibilizer between PLA and ALM.	[38]
7	Epoxy-nanoclay-PTFE-SiCnanocomposites	The best wear result is achieved in nanocomposites withwhiskers aligned perpendicular to the sliding steel counter-surface and slid orthogonally to the build direction and print path direction. All the nanocomposites outperform the unfilled epoxy sample in terms of wear.	[39]
8	ABS and PLA	The discrepancies between the white ABS and PLA materials are considered to represent changes in the raw ingredients' characteristics. PLA samples made with the same approach but different color additives reveal a substantial variation.	[17]
		PLA and ABS samples have similar tribological characteristics when being printed under the same circumstances.	[21]
9	PA6-TiO2	The results reveal that at a maximum applied load of 20N and a run period of 10 minutes, PA6-30 wt. % TiO2 samples havethe lowest wear rate.	[40]
10	ABS and ABS composites	The surface texture generated by AM decreases particle erosion by half in the same erosion direction, and the influence of blasting direction on the texture of the prepared surface is substantial, with a noticeable change in wear rate when the surface texture is smaller than the particle size.	[25]
		The results reveal that the wear rate of the 3D-printed ABS decreases as the load rises. In any case, a high coefficient of friction is seen under the action of the applied force.	[24]
		The study reveals that the friction coefficient for a 1 N load is highly influenced by the surface's orientation to the sliding direction. At greater weights of 5 N and 10 N, however, this reliance is shown to be attributed to bulk material properties rather than surface roughness. The bulk material properties, as well as the applied load, are shown to affect the relationship between surface morphology and wear rate.	[23]
		The wear rate and coefficient of friction of FDM printed components may be adjusted by adjusting the process parameters to achieve the ideal condition, which is difficult with traditional techniques. The infill pattern, when combined with the density of the infill, results in a fast change in wear performance.	[22]
		Wear is affected by the printing position (the orientation of the print layers). The decrease in the roughness of the polymeric specimen and the production of a pulverized polymeric as a wear product, which may function as a lubricant and reduce frictional resistance, may be linked to the stability of the frictional moment as the test progresses.	[15]
		The results show that the percentages of butadiene in the specimens as well as the density of the infill influence the ABS wear rate.	[14]
		Carbon fiber reinforced ABS wears out less quickly than pure ABS. Carbon fiber has improved the wear resistance of polymer materials with its high load-carrying capability. The applied load and run time prominently impact the material's wear rate and frictional performance under dry sliding environments.	[33]
		The sample models created at the required angle Pd – 0° against the building platform display the highest wear for the samples producedby FDM.	[34]
		The coefficient of friction (COF) and wear rates are considerably decreased when silicon oil lubricants are utilized in the ball-on-disctest, and the greater the viscosity of the lubricant, the lower the COF and wear rates. It is also confirmed that the temperature of the specimen caused by friction reduces as the viscosity of the lubricant increases.	[16]
11	PEEK/CF composite	The findings show that the friction coefficient and wear rate are substantially influenced by the sliding direction. More importantly, incorporating nano-silica into the interface enhances the coating material's friction performance substantially. It is noted that using the FDM process, oriented short CF reinforced PEEK tribo-coatings can be produced, and external nano-silica can be added to the sliding interface to improve tribological performance.	[41]
12	Carbon fiber reinforced polymer (CFRP) waste	This research shows that an additive manufacturing-based recycling technique demonstrates great potential to recover CFRP waste and produce high-performance engineering components with complicated geometries that are both cost-effective and ecologically acceptable.	[28]
13	CF-PETG COMPOSITES	The results show that increasing the percentage of infill density improves the wear characteristics of CF-PETG specimens at all test parametric circumstances.	[42]
14	UHMWPE based composites	In terms of mechanical and tribological characteristics (wear resistance, friction coefficient, Young's modulus, and yield strength), extrusion compounded UHMWPE-based composites (hot compression of granules and 3D printing) outperform those made by hot pressing powder mixes.	[43]
15	Poly(methyl methacrylate) (PMMA)-based appliances	When comparing the ND and A-ND nanocomposites to stainless steel (SS) counter surfaces, the coefficient of friction (COF) is significantly reduced (p 0.01). The COF of the control group is similar to A-ND but lower than ND for titanium (Ti)-based specimens. For both SS and Ti counter-surfaces, wear resistance testing indicates that the ND and A-ND groups outperform the controls (p 0.001).	[29]

16	ABS and 20% carbon fibre PLA	The thickness of the layer has a direct association with wear in this study since the thicker one will stay longer and reach the substrate due to its size. The wear rate is indirectly related to the infill pattern. Because of the discontinuous beads, specimens printed with a grid pattern exhibita comparably low wear rate, specific wear rate, and coefficient of friction amongst infill patterns. CFPLA material has a very high wear strength because of the incorporation of carbon fiber, which increases strength and improves stiffness and hardness when compared to ABS. Layer thickness and infill density have a significant influence on wear strength in both CFPLA and ABS.	[19]
17	Polybutylene Terephthalate	The results demonstrate a substantial impact of the direction and density of the infill on the tribological characteristics.	[44]
18	PC-ABS	The findings show that the FDM process parameters have a significant impact on the wear behavior of manufactured parts owing to a variety of microstructural changes that occur throughout the manufacturing process, resulting in variations in wear characteristics, which is perfectly compatible with practical observation. The wear rate of FDM-made components reduces with decreasing layer thickness and build orientation, but increases with increasing raster angle and air gap, according to the experimental data.	[13]
19	REC PLA	Experiments have demonstrated that the filling factor affects the tribological characteristics of plastic tribopairs for 3D printing.	[45]

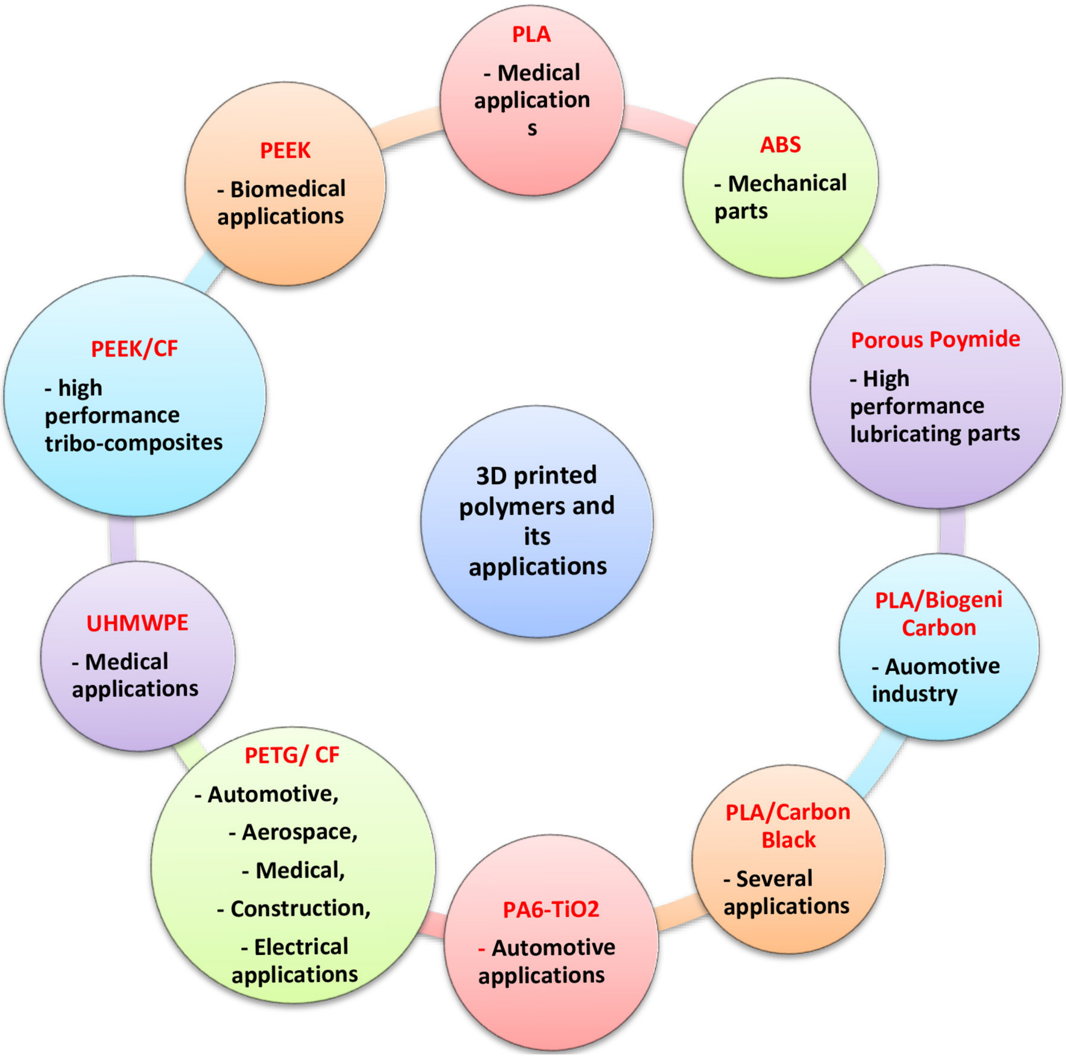

Figure 5. The applications of 3D printed polymers during the priorinvestigations.

Electrical, and other applications were among those considered.

4 CONCLUSION

3D printing gains more and more extensive use as it bridges the gap between concept and product development. In addition to 3D printed polymers, researchers created 3D printed composites, and their characteristics are being investigated for potential applications in certain fields such as automotive and aerospace. Although numerous researchhasbeen conducted on 3D printed polymers, only little focused on their tribological characteristics. The tribological properties of 3D printed polymers and composites, as well as 3D printing processes, were explored, and the tribological properties of several 3D printed materials were compared.

Acknowledgments

Not applicable.

Conflicts of Interest

These authors declare no conflict of interest.

Author Contribution

Ramadan MA collected the data, performed the statistical analysis, designed this study, wrote the article and approved the final version.

Abbreviation List

ABS, Acrylonitrile butadiene styrene
ALM, Carbon fiber-reinforced polyamide
AM, Additive manufacturing
CB, Carbon black
CF, Carbon Fiber
CFPLA, Carbon fibre poly lactic acid
CFRP, Carbon fibre reinforced polymer
COF, Coefficient of friction
DLP, Digital light processing
FDM, Fused deposition modeling
HT-PLA, High temperature PLA
NDs, Nanodiamonds
PAA, Poly amide acid
PC, Polycarbonate
PCU, Polycarbonate-urethane
Pd, Provided angle
PEEK, Polyether ether ketone
PETG, Polyethylene terephthalate glycol
PI, Polyimide
PLA, Poly lactic acid
PMMA, Polymethyl methacrylate
PTFE, Polytetrafluoroethylene
REC, Recycled
UHMWPE, Ultra-high-molecular-weight polyethylene
2DLMs, 2D layered materials

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