International Tribology Council
Vytautas Magnus University
Lithuanian Scientific Society Department "Tribologija"

The 11th International Conference BALTTRIB'2022
22–24 September 2022
Akademija, Kaunas, Lithuania

Proceedings of BALTTRIB'2022 edited by prof. J. Padgurskas
eISSN 2424-5089 (Online)

DOI: 10.15544/balttrib.2022.7

TRIBOLOGICAL ASPECTS OF POLYMERS AND THEIR COMPOSITES USED IN ADDITIVE MANUFACTURING - A REVIEW

***A. Mukhopadhyay* [1]*, *S. Banerjee* [2]**
[1] Mechanical Engineering Department, Jadavpur University, Kolkata, India
[2] West Bengal State University, Kolkata, India

Abstract. In the recent time different polymers as well as polymer composites are becoming the major in contender over the conventional engineering materials owing to the enhanced utility and cost advantages. Further, with the advent of different additive manufacturing techniques the uses of such polymers are also gaining priority. It is also needless to mention that tribo pairs are dominant part in all the major fields of applications. The tribology of polymer at large is very complex and there is hardly any governing mechanism. Hence, case based individual studies on tribology are an essential minimum requirement for each and every type of polymeric materials. A tribological study, that is, understanding friction and wear characteristics under relative movements have also been made for various virgin polymers. However, more studies and related data are steel needed particularly for newly developed composites. This paper intends to review, in brief, the research trends on tribological characterization including mainly the coefficient of friction and wear in tribo pairs made up of polymers and polymer composites. Sample preparation through additive manufacturing technologies, more generally by 3D printing process, have been considered. Effect of micro and nano fillers on the composites have also been discussed and compared with the tribology over their virgin counterparts. Some laboratory based results on tribological characterizations of 3D printed parts using conventional polymers have also been discussed.

Keywords. Polymer, composite polymer, additive manufacturing, 3D printing, optimization.

1. INTRODUCTION

Use of polymers and their composites in today's engineering world is enormous starting from commodity polymers, engineering polymers, high performance and ultra-high performance polymers [1]. All such polymers may be classified in two broad categories like amorphous and semi-crystalline. Conventional engineering polymers mainly include but not limited to acrylonitrile butadiene styrene (ABS), PLA, acrylonitrile styrene acrylate (ASA), polyesters like PET and PBT, polyamide. They possess higher mechanical strength and high operating temperature (110–120 ℃). However, for very high temperature applications with good chemical resistance and enhanced tribological characteristics both high and ultra-high performance polymers are highly demanding. Recent researches focus on the development of various polymeric composites for enhanced mechanical as well as tribological properties. Use of polymers for tribological applications has a wide range of benefits which include but not limited to long lasting endurance, low friction, ability to withstand high loads and speeds, comparatively lower cost of production and like others. All the major fields like machine elements application, aviation industry, frictional components in vehicle, implants for hip and other joints in medical applications, friction reducing coatings for MEMS devices and many more may be benefitted by using polymeric compounds as tribological materials [26].

3D printing is one of the dominant additive manufacturing processes, which utilizes a computer aided design (CAD) based 3D model to fabricate any complex contour including very thin sections. Unlike conventional machining, this process is based on deposition of material layer after layer. Since 1990s, 3D printing has been used progressively as a learning tool and to generate functional parts, which has created the need for a better understanding of the mechanical behaviour of 3D printed parts and the

---

[*] Author for contacts: Assoc. Prof. Abhijit Mukhopadhyay
E–mail: m_obiji@yahoo.com

development of analytical models and design parameters for engineers. Fused Deposition Modelling (FDM), one of the Rapid Prototyping (RP) processes, utilizes controlled extrusion of melted thermoplastic polymer filaments, which are ejected through the tip of nozzle under controlled temperature to 3D print layers of materials and then solidifies into final parts [2]. Varied advanced polymers are used now a day due to their positive advantages like lower weight, self-lubricating property, ease of manufacturing using computer based models, shock dampening capability, low noise in operation and like others. The uses of different thermoplastics are not limited to mere prototype development. On the contrary mechanical components like gears, links, and lead screws are also produced and utilized in different machining operations. However, due to low mechanical properties their applications are restricted to non-severe applications. Tribological components may also be replaced by suitable polymer parts [2, 3]. However, FDM has still many drawbacks such as quality, surface finish and dimensional accuracy of the finished components. As FDM process depends on many process parameters it is of utmost important to identify the optimum parametric combination that provide the ideal surface finish and quality of the 3D printed parts. The present authors have studied the effect of factors like layer thickness, infill factor and deposition orientation in printing of ABS and PLA polymeric [2]. Printed parts have been tested for their wear and friction behaviour using a multi tribo tester (TR-25) at low loads. It has been revealed from the experimental results that a dimensionally accurate and higher surface quality were obtained with lower layer thickness and orientation angle had no significant effect on the overall surface finish. Surface texturing in case of 3D printing has various positive advantages also in spite of the above-mentioned drawbacks. In fact several researchers have studied the effect of micro-texturing, including laser texturing on the surface of metallic parts on various tribological properties like lubrication, adhesive wear, abrasive wear, cavitation wear and so on [4]. Magdalena et al. (2017) had demonstrated the effect of surface roughness in case of a metal-polymer tribo pair in ringer's solution. The study was made for a medicinal application and superior surface roughness (Ra value) of the polymeric pin showed improved wear resistance against metallic counterpart [5].

Development of polymeric parts is gaining importance with the advent and rapid growth in additive manufacturing technologies. Injection molding, casting and other conventional methods of plastic parts manufacturing are associated with increased time, more defects, high surface deviations/tolerances and difficult control over the process. 3D printing is one of the popular amongst various additive manufacturing (AM) techniques due to its ease of operation, flexibility, user friendliness and almost negligible health hazard problems. The comparatively lower price of 3D printers facilitates its application in different public domain like schools, homes, libraries, universities and laboratories etc. Now a day 3D printing is not only limited to prototype development. Customization of products is a difficult task on behalf of the manufacturers owing to high cost involvement in such process. This bottleneck can easily be managed with 3D printing as smaller quantities of customized products can be produced at a comparatively lower manufacturing cost and there is also the possibility for change in design and other requirements as per the need of the customers. This process is particularly useful in varied medical applications where unique products and wide variety of medical implants are required for patients in particular. Additional cost of mold preparations and other special tooling is not required in 3D printing. This reduces the additional cost of production. A major advantage of 3D printing is mass customization, that is, a series of personalized goods are produced at a lower price. Example reveals that a China based construction house has successfully assembled 3D printed ceramics within a day. Various major commercial applications have been accomplished in the recent time utilizing conventional modelling materials [2]. On the contrary, advanced metals and metal alloys have been successfully experimented and implemented by the aerospace industries. Needless to be mentioned here, that the traditional manufacturing processes are more expensive, inefficient, challenging and may lead to the quality concern. However, the anisotropic behaviour of 3D printed parts is the major limitation of its commercial application in a large scale. Printing environment also pose a challenge on the quality of the finished parts.

Commonly used polymeric materials in the fused deposition modelling (FDM) technique include but not limited to ABS, PLA, polyamide or nylon (PA), polycarbonate (PC), polymethyl methylacrylate (PMMA) and many more. ABS is an oil-based plastic used widely for the manufacturing of car parts, musical instruments and the popular Lego building blocks. ABS polymer requires a heated surface on which printing may be continued. This is needed due to the high melting point of ABS. During cooling of the printed parts warping may result as a major defect. PLA, which is made from organic materials like corn starch and/or sugarcane, is a user-friendly thermoplastic. PLA is considered superior over ABS and nylon in 3D printing due to its higher strength, stiffness, easiness to use as well as minimum warping property. However, the durability and impact resistance of PLA is very poor owing to its brittleness and cannot be stored at high temperatures. Thermoplastic elastomer (TPE) materials have high impact strength and resistance to vibration. They are durable too and can be deformed easily by compressive counter loads. Some common application areas of TPE include but not limited to vibration dampeners, phone cases, automobile parts, varied household appliances and like others. In the recent time attempts have been made to reinforce traditional printing materials like ABS, PLA, ASA etc. with composite fibres. Carbon fibres are added to several common filaments to increase their strength and stiffness. The materials become much lighter and stable due to the addition of fibres which prevent shrinkage during cooling. Fine metal powders are added with PLA to provide metallic lustre to the finished part. This also improves the weight of the part. Printing parameters like temperature, speed, bed adhesion, extrusion rates will be almost similar to those of normal settings used for base materials. Kai Parthy has developed a new series of advanced materials. Laywood-3, a wood-polymer composite, has been developed by mixing about 40% recycled wood particles with some binding polymers. However, it is a brittle material and is used for printing unique parts with a wooden texture. Laybrick, an expensive 3D printing material, is made up of a mixture of grounded minerals like powdered chalk and thermoplastics. Sandstone like texture of this composite makes it popular for large architectural models and sculptures. Combination of ceramic powder and polymers leads to the development of a unique filament known as Layceramic, which can withstand high temperature and widely used to make roof tiles, home decorative items, tableware and like others.

On the other side, tribology is responsible for approximately 23% of global total energy consumption out of which 20% is to overcome friction and rest 3% is for loss of manufactured parts due to wear and tear, remanufacturing etc. [1]. It is not out of place to mention here that tribology is the subject of interdisciplinary studies of friction, wear and associated lubrication, if any. The subject was known in the ancient times also but came into lime light with renewed interest after the publication of Professor Peter Jost important research reports in the year 1966. This report basically emphasized the enormous cost involvement and ultimate loss due to friction and corresponding wear [6, 7]. Several research findings have been obtained and several other researches are going on around the globe regarding tribology of metal-metal, metal-ceramic and metal-composite contact pairs. However, quantum of tribological works in case of metal-polymer and polymer-polymer tribo pairs or the development of various polymer composites are yet to be nurtured, particularly in this juncture of renewed interest and application possibilities of polymeric materials and polymer composites in engineering and other areas at large.

2. LITERATURE REVIEW

Since 1990s, 3D printing has been used progressively as a learning tool and to generate functional parts, which has created the need for a better understanding of the mechanical behavior of 3D printed parts and the development of analytical models and design parameters for engineers. Fused Deposition Modeling (FDM), one of the leading rapid prototyping (RP) processes, utilizes controlled extrusion of thermoplastic polymer filaments which are ejected through the tip of nozzle under controlled temperature to deposit layers of materials and then allowed to solidify into final parts. Due to several positive conditions, RP has assembled numerous components to cater the needs of clients and fast changes in manufacturing in less time and have competitive edge over other conventional manufacturing methods. However, FDM had still few drawbacks such as quality, surface finish, dimensional accuracy and so forth, of the finished components. As FDM process depends on many process parameters, it is of utmost importance to identify the optimum parameters that provide the ideal surface finish and quality of the 3D printed parts [8]. Tribological components are also replaced by suitable polymer parts [9, 10]. Due to several positive conditions, RP has assembled numerous components to cater the needs of clients and fast changes in manufacturing in less time and have competitive edge over other manufacturing methods. The most commonly used materials for RP technologies are ABS (acrylonitrile butadiene styrene) and PLA (poly lactic acid) [9] due to their low melting temperature, diversity and ease of adoption to different 3D printing processes.

Sun Q. et al. [8] and Ahn D. et al. [10] presented many reports related to the surface roughness and cross sectional shape of the FDM fabricated parts and the bonding mechanism along cross-section of printed parts in their respective papers. Ahn S. H. et al. [11] had investigated the effects of raster orientation, another important process parameter in 3D printing, on the tensile and compression properties comprehensively. In their studies Miguel Fernandez-Vicente et al. [12] had demonstrated that maximum tensile strength was associated with rectilinear patterns with infill density of 100%. They utilized statistical tool ANOVA for their study. They considered three levels of infill parameter (20, 50 and 100%) and three most commonly used patterns (line, rectilinear and honeycomb). P.J. Nuñez et al. [13] performed experimental studies on dimensional accuracy, flatness error, and surface texture in manufactured products obtained from FDM with ABS as the model material considering layer thickness and density as the major printing parameters. Anoop Kumar Sood et al. [14] explored Taguchi's technique to optimize percentage change in length, width and thickness. They considered five principal process parameters like layer thickness, raster width, raster angle, and air gap and part orientation. The effect of the main factors along with their interactions had been considered on the dimensional accuracy of the parts. Model material was ABS in their study. The same authors had demonstrated the effect of five FDM process parameters like slice thickness, raster width, raster angle, air gap between two layers and part orientation on three mechanical properties tensile, flexural and impact strength of ABS test specimen in another paper [15]. Hanon et al. compared the tribological properties of 3D printed ABS and PLA materials by studying the difference between static and dynamic friction factors and the examination of wear values through numerous experiments [16]. The effect of applied load and sliding speed on the tribological aspects of the polymer to metal sliding combinations under dry sliding, water absorbed and EP conditions had been investigated by Kulkarni et al. [17]. Assessment of wear of 3D printed ASA parts is commonly performed by visual inspection. Authors of the present paper conducted quantitative studies through the measurement of weight loss in a predetermined tribological study using multi tribo tester TR-25 (Ducom) [2]. Daniel Horvath et al. used design of experiments (DOE) to identify the optimum combination of the printing factors for the improvement of the surface roughness of ABS 400 polymer [18].

3. EXPERIMENTAL RESEARCH AND ANALYSIS

Long-time back, being inspired by the concept that wear rate of metals, carbon or graphite is related with their mechanical properties, Lancaster J.K (1968) conducted experimental studies on several polymers to understand the effect of varied proportions of plastic and elastic deformation on the wear rate. An index 'H/E' had been used for the study, where 'H' and 'E' stands for the hardness and elastic modulus respectively. Lower value of this index means greater wear. In general, elastic moduli of polymers are low. Lancaster conducted the wear studies at different temperatures as mechanical properties of polymers depend on temperature [27]. Figure 1 indicates the comparative graphs of wear against temperature of six different polymers. Samples had been slid against a 1.2 µm rough (Ra) steel surface counterpart using silicone fluid as lubricant.

Comparative studies of various tribological characteristics had been made between pure ABS and reinforced nylon 6 (reinforced by Al and Al_2O_3) as per ASTM G 99 standard in dry sliding condition using pin-on-disc tribometer at loads of 5, 10, 15 and 20 N at a speed of 1.36 m/s for 5 and 10 minutes respectively [19]. Aluminium has been selected for its self-lubricating property and high thermal conductivity whereas Al_2O_3 is abrasive in nature. Studies suggest that reinforcement of nylon gives improved wear resistance over pure ABS.

Gregory Sawyer W. et al. [20] studied the friction and wear behaviour of PTFE filled with nano particles of alumina. It may be mentioned here that polymer nano-composite contains the polymer as matrix and at least one dimension of the reinforcement material is having less than 100 nanometre size. They used one reciprocating pin-on-disc tribometer where the counter face reciprocates beneath the pin made up of composite material with 50 mm stroke at a speed of 50 mm/s at an average load of

260 N on the job. Mass loss has been used to calculate the loss of volume and rate of wear. They observed that 20 % wt. of 40 nm alumina had increased the wear resistance of the composite by 600 times over the unfilled material.

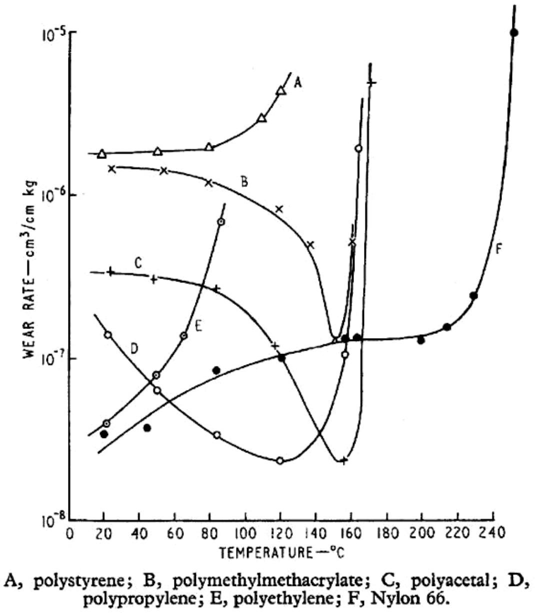


Figure 1. Wear of different polymers with temperature variation in lubricated condition [courtesy: 27].

Addition of carbon nanotube (CNT) to epoxy resin had demonstrated superior wear resistance of the composite over pure epoxy [21]. Test for wear of CNT-epoxy composites had been carried out on a Plint-Cameron pin-on-disc machine in dry condition. For the study, a fixed track diameter of 80 mm and normal stress of 1 MPa had been considered at a sliding velocity of 0.98 m/s. The authors considered the coverage area ratio of CNT to matrix material (Rc/m) and observed that coverage ratio more than 25% furnished a much reduced wear rate than pure epoxy. This was attributed due to the fact that the CNTs had been exposed to the sliding interface and thus protecting the mother epoxy.

Yetgin S H (2020) had investigated the impact of multi-walled carbon nanotube (MWCNT) and graphene oxide (GO) on abrasive wear performance of polypropylene (PP) [28]. Addition of different weight percentages of both the filler materials reduced the coefficient of friction of the nano composites by 19% and 23% compared to the unfilled PP. It has been revealed from the study that graphene oxide can be used as an effective modifier for the improvement of the wear of PP polymer under harsh tribological atmospheres. Figure 2 indicates the comparative worn surfaces of the samples.

A comparative study of pure ABS vs. ABS reinforced with micro flex graphite (23 µm) had demonstrated marked increase of both coefficient of friction as well as specific wear rate. Hence, this composite may be utilized where such increased values may be tolerated [22]. The applied load in that experiment had been selected as 35 N. The said value had been considered due to its suitability of detecting wear amount which had been obtained from several research works in the related area.

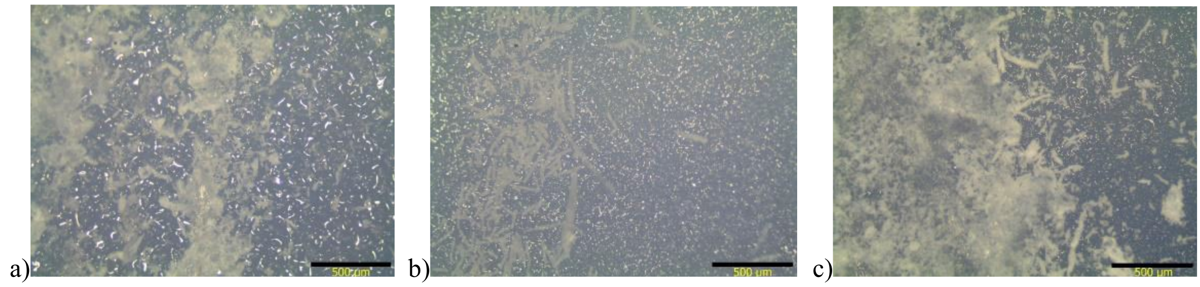


Figure 2. Worn surfaces due to abrasive wear of: a) PP; b) PP–0.3% MWCNT, c) PP–0.3% GO composites.

Interestingly some major breakthroughs in the field of composite development for additive manufacturing application have been accomplished in the past couple of years followed by their mechanical and other relevant characterization except tribology studies. It is not out of place to mention about some of the important work in the regime of such composite development. Hwang et al. (2015) had developed new metal-polymer composite filaments for the use of 3D printing machine using fused deposition modeling (FDM) processes. In that study acrylonitrile butadiene styrene (ABS) thermoplastic was mixed with copper and iron particles in different weight percentages. Metal particles had been added to enhance the properties like tensile strength and thermal conductivity. Some printing parameters had also been varied to understand the effects of the parameters on those properties. However, they ended up with the conclusion that the tensile strength of the composites had been decreased by increasing the loading of metal particles. Thermal conductivity of the metal-polymer composite filament was improved by increasing the metal content [23]. Ryder et al. (2018) developed a polymer-metal composite using ABS and SS 420 powder. 10, 15 and 23% weight percentage had been considered in there fabrication and the resultant mixtures had been extruded into composite filaments for the printing of parts using fused deposition modeling technique [24]. The printed parts then compared for different mechanical and thermal properties over those of the pure ABS polymer. The new polymer-metal composite demonstrated promising results. The properties were at par with those of the base polymer if not superior for all the weight percentages of metal powder. On the contrary magnetic property had been enhanced. Kürşad Sezer H et al. (2019) had recently fabricated a composite with ABS as the matrix reinforced with maximum of 10% multiwall carbon nanotubes (MWCNTs). Mechanical properties like tensile strength, ductility and the elastic modulus along with the electrical conductivity had been studied. Tensile strength of the new composite had been increased up to 288% for 7 weight percentage of filler addition. However, ductile to brittle transition had been noticed with increasing weight percentages of MWCNT. Quite obviously, due to the presence of carbon nano tubes in the composite, the electrical conductivity had been increased to approximately 7 times [25].

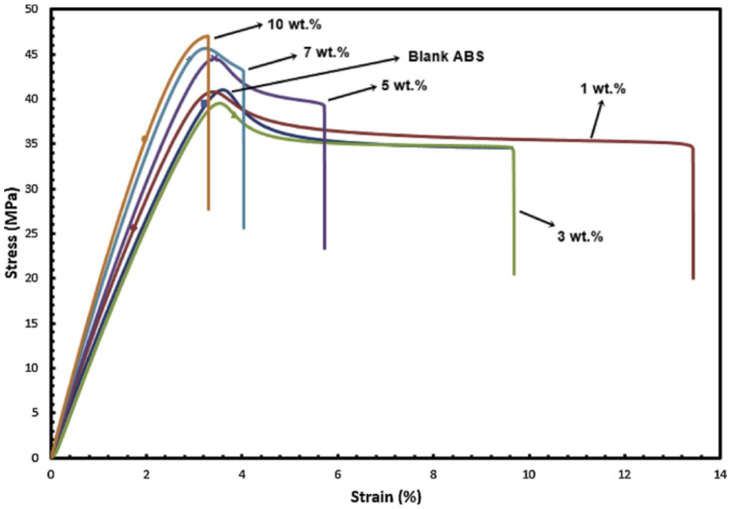


Figure 3. Stress-vs-strain curve ABS-MWCNTs specimens under tension [ref. 25].

Mohamed O.A. et al. (2018) had utilized a new optimization technique, definitive screening design (DSD), to find the optimum combinations of printing parameters in fused deposition modeling (FDM) for specific wear rate of PC-ABS (Polycarbonate-Acrylonitrile Butadiene Styrene) material. Six FDM parameters like layer thickness (A), air gap (B), raster angle (C), build orientation (D), road width (E) and number of contours (F) had been considered in their study. The legends used for each factors have been reflected as per their literature. They had introduced the new algorithm for optimization. At the same time they had also concluded that the wear rate decreased with decreasing layer thickness and build orientation but with the increase in air gap and raster angle. Wear tests had been conducted in dry conditions with a normal load of 10 N on the job and 300 rpm of the wheel. A total of 10,000 cycles with the wear track diameter of 14 mm had been set [29].

Research work has also been done by the present author on tribological studies of 3D printed ABS and PLA plastics [2]. Samples for the said experimental research work have been prepared in a 3D printing machine (Stratasys F170). Printing factors like material deposition, layer thickness, infill angle, infill pattern and orientation of deposition have been selected at different levels based on the literature surveys as well as standards in that regard. The printed parts have been tested for their friction and wear behavior utilizing a multi tribo tester (TR- 25). Samples of size 20×20×8 mm have been sled against EN 8 steel roller (50ϕ and 55 HRC) at fixed load of 25 N, fixed rotational speed of 300 min^{-1} of the roller and fixed rolling time of 600 sec in dry condition. Block-on-roller configuration of the multi tribo tester has been selected for the tribological studies. The results have been tabulated and graphed with adequate discussion to analyze the effects of the printing parameters on tribological and friction behavior of 3D printed ABS and PLA samples. The printing parameters at different levels and corresponding tribological characteristics of ABS plastic have been tabulated in Table 1.

Table 1. Dimensional deviation, weight loss, friction and wear of ABS plastic.

Experiment No.	Infill Factors				Dimensional Deviations			Weight Loss, gm	COF	Wear, µm
	Angle, degree	Density, %	Thickness, inch	Pattern	Δx, mm	Δy, mm	Δz, mm			
1	90	45	0.007	Single	+0.07	+0.01	+0.06	0.005	0.042	122
2	90	45	0.007	Double	0	+0.03	+0.03	0.007	0.241	84
3	90	45	0.013	Single	+0.10	+0.02	+0.30	0.002	0.280	110
4	90	45	0.013	Double	+0.09	+0.06	+0.31	0.005	0.046	134
5	90	80	0.007	Single	+0.05	0	+0.08	0.004	0.132	154
6	90	80	0.007	Double	-0.05	0	+0.07	0.006	0.210	131
7	90	80	0.013	Single	0	-0.07	+0.34	0.003	0.311	140
8	90	80	0.013	Double	+0.02	-0.04	+0.44	0.003	0.245	131
9	45	45	0.007	Single	-0.03	-0.01	+0.17	0.004	0.308	90
10	45	45	0.007	Double	+0.12	+0.20	+0.01	0.004	0.17	85
11	45	45	0.013	Single	+0.05	+0.01	+0.26	0.002	0.294	77
12	45	45	0.013	Double	-0.07	+0.02	+0.26	0.005	0.268	111
13	45	80	0.007	Single	+0.01	+0.02	+0.16	0.004	0.212	108
14	45	80	0.017	Double	+0.06	+0.09	-0.03	0.004	0.202	99
15	45	80	0.013	Single	-0.06	-0.17	+0.33	0.003	0.198	143
16	45	80	0.013	Double	-0.23	-0.05	+0.47	0.006	0.239	83

In the same research study, parts have also been printed using PLA plastic as base material. However, due to some default setting of the printer (Stratasys F170) all the combinations of working parameters as used in case of ABS material could not have been utilized. Due to this practical limitation of the 3D printer, only the following factors have been considered:

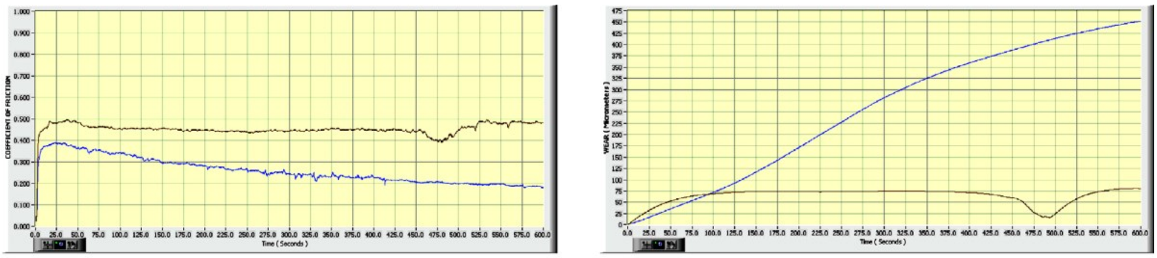
- Angle of deposition: (i) 45° and (ii) 90°;
- Deposition layer thickness – 0.01 inch;
- Infill density – 22%.

Thus, the above-mentioned parameters have been utilized for printing and comparisons of the tribological and dimensional deviation values of ABS and PLA plastics. Table 2 indicates the test results.

Table 2. The tribological test results of ABS and PLA printings

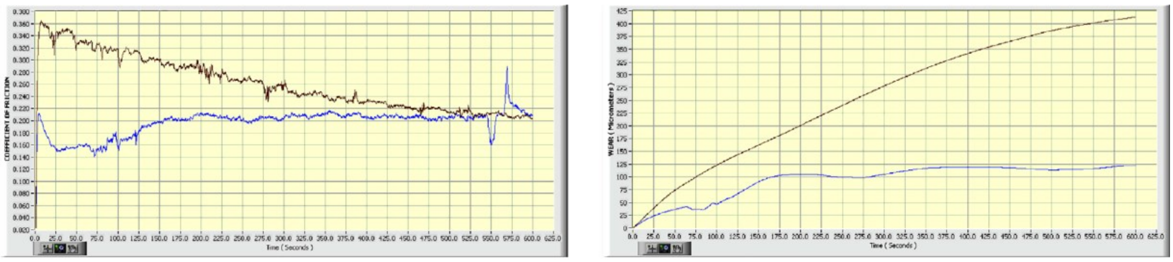
Material	Infill Factors			Dimensional Deviations			Weight Loss, gm	COF	Wear, µm
	Angle, degree	Density, %	Thickness, inch	Δx, mm	Δy, mm	Δz, mm			
PLA	45	22	0.01	+0.183	+0.156	+0.49	0.008	0.162	452
	90	22	0.01	+0.083	+0.146	+0.486	0.006	0.189	413
ABS	45	22	0.01	+0.02	+0.03	+0.16	0.006	0.484	81
	90	22	0.01	+0.02	+0.07	+0.18	0.004	0.163	122

Comparative coefficient of friction (COF) and wear curves have been depicted in Figure 4 (a) - (b) and Figure 5 (a) - (b) for 45° and 90° infill angle respectively. The curves have been generated from 'Winducom-6" software. The nature of friction and wear are self-explanatory from the curves.



(a) (b)

Figure 4. Printing with 45° infill angle (a) COF and (b) wear curves of ABS (maroon line) and PLA (blue line).



(a) (b)

Figure 5. Printing with 90° infill angle (a) COF and (b) wear curves of ABS (maroon line) and PLA (blue line).

4. RESEARCH GAP

Additive manufacturing (AM) technology is gradually progressing in terms of new application possibilities and incorporating newer development in composite materials for printing machineries. Majority of the research works in the recent time are mainly confined to the optimizing of the process parameters of the FDM process considering standard printing materials like ABS, PLA and PC to enhance mechanical properties, thermal properties, surface roughness, reduce material wastage and build time. Thus, it reveals that there is an enormous opportunity of improvement in the development of newer materials. Sufficient research has not been done on the interdependence of the process parameters on the material and mechanical properties for different kinds of materials that are used in the AM process. It is also necessary to establish work standards for different work materials used in the FDM process. Most of the materials used in AM may be affected by several environmental conditions such as temperature, pressure, humidity and other noise factors which may ultimately affect the accuracy of the fabricated parts. Hence, in the future works robustness of the design and manufacturing may also be considered keeping in mind the environmental factors at large. There is a need to conduct exhaustive research works on different combinations of natural fiber reinforced composites and polymers as they have a huge potential in replacing glass filled reinforced composites, which are not ecofriendly.

5. CONCLUSION

Polymer based materials are upcoming for several industrial and engineering application owing to their attractive characteristics like self-lubricating property, low corrosion and wear, light weight and low cost compared to metals, low frictional property and like others. In the recent time with the development of additive manufacturing technologies polymeric parts can be produced with much flexibility and confirming the needs of the customer with minimum time. However, there are several issues in preparing parts through some suitable additive manufacturing process. 3D printing is a popular choice amongst various AM techniques and utilizes some conventional modeling materials. However, with the increased demand in major industrial concerns the need of the hour is to develop superior quality polymer composites. Researches are going on towards this direction where both micro as well as nano particles are used as reinforcement material. Several alternatives have been researched in this regard and the field is quite vast and open till date. It is also difficult to observe the exact governing tribo mechanisms in case of polymer tribology which itself is a complex entity and there exist no generalized and simple rule. Proper protocol in tribo testing should also be developed.

Additive manufacturing techniques have the potential for mass production of complicated geometries where conventional methods require time consuming tooling and post processing. Focus has already been given on the production of complex lattice structure using AM methods for future applications in buildings to protect against impulsive loadings and maximize the efficiency of structures in terms of weight. A metallic hollow walled micro lattice structure can be developed using AM for energy absorption. Biomedical fields have the potential to implement AM technologies combining with CT scan results for the production of need specific implants which will tailor suit the particular requirement of a patient. Optimization of important factors such as cell attachment and growth, nutrient transportation for the biomedical implants etc. can also be accomplished. Research and development in 3D printing may help to improve bio-printed scaffolds, artificial organs and tissues for clinical applications and tissue engineering. Additive manufacturing of ultra-high strength ceramic with complex geometry is being studied as they are used frequently for space flights at high temperatures. Future prospects in AM include manufacturing complex parts with multiple functions to enhance design freedom; integrate sensors, circuits, wiring or combine thermal and acoustic insulation functions in the structure; combining multiple alloys, metals and ceramics to reduce brittleness of ceramics; thermal shield used during re-entry of space vehicles into the atmosphere; development of automatic means for the detection of defects and automate repair process and many more.

It is also needless to be mentioned that all such application of polymeric parts need to be studied for tribological characterizations including bio and nano tribology, corrosion, bio-mimetics and so on. Hence, there are ample scopes of future studies to further the subject at large.

REFERENCES

[1] Friedrich K. Polymer composites for tribological applications. Journal of Advanced Industrial and Engineering Polymer Research 1, (2018) 3–39.

[2] Mukhopadhyay A., Roy R. Tribological studies of 3D printed ABS and PLA plastic parts. Materials Today: Proceedings 41 (2020) 856–862.

[3] Mirza Danish Beg, Md. Shadab Khan, Abdul Ahed Khan. Investigation on tribological behavior of FDM printed ABS polymer. IJTRA 5, 3 (2017) 75-77.

[4] Tamer S., Sinan F., Satılmış Ü. Effects of 3D printed surface texture on erosive wear. Tribology International 144 (2020) 106-110.

[5] Niemczewska-Wójcik M., Pielzoszewski W. The surface texture and its influence on the tribological characteristics of a friction pair: metal–polymer. Archives of Civil and Mechanical Engineering 17, 2 (2017) 344-353. [https://doi.org/10.1016/j.acme.2016.10.011.]

[6] Jost H.P. Lubrication (Tribology) – A report on the present position and industry's needs. Department of Education and Science, London. 1996. UK. [Available at http://www.skf.com/binary/68-33957/SKF-filament-wound-bushings.pdf.]

[7] Kenneth H., Ali E. Influence of tribology on global energy consumption, costs and emissions. Friction 5, 3 (2017) 263–284.

[8] Sun Q., Rizvi G. M., Bellehumeur C. T., Gu P. Effect of processing conditions on the bonding quality of FDM polymer filaments. Rapid Prototyping Journal 14 (2008) 72–80. [DOI: 10.1108/13552540810862028]

[9] Tymrak B.M., Kreiger M., Pearce J.M. Mechanical properties of components fabricated with open- source 3-D printers under realistic environmental conditions. Materials and Design 58 (2014) 242–246. [DOI: 10.1016/j.matdes.2014.02.038]

[10] Ahn D., Kweon J.-H., Kwon S., Song J., Lee S. Representation of surface roughness in fused deposition modeling. J Mater Process Technol. 209 (2009) 5593–600.

[11] Ahn S.H., Montero M., Odell D., Roundy S., Wright P.K. Anisotropic material properties of fused deposition modeling ABS. Rapid Prototyping J 8(2002) 248–57.

[12] Fernandez-Vicente M., Calle W., Ferrandiz S., Conejero A. Effect of infill parameters on tensile mechanical behavior in desktop 3D printing. 3D Printing and Additive Manufacturing 3, 3 (2016).

[13] Nuñez P.J., Rivas A., García-Plaza E., Beamud E., Sanz-Lobera A. Dimensional and surface texture characterization in Fused Deposition Modelling (FDM) with ABS plus. The Manufacturing Engineering Society International Conference, MESIC 2015, Procedia Engineering 132. 2015. 856 – 863.

[14] Sood A.K., Ohdar R.K., Mahapatra S.S. Improving dimensional accuracy of Fused Deposition Modelling processed part using grey Taguchi method. Materials and Design 30 (2009) 4243–4252.

[15] Sood A.K., Ohdar R.K., Mahapatra S.S. Parametric appraisal of mechanical property of fused deposition modeling processed parts. Materials and Design 31(2010) 287–295.

[16] Hanon, Muammel M., Márk Kovács, László Zsidai. Tribology behaviour investigation of 3D printed polymers. International Review of Applied Sciences and Engineering 10, 2 (2019) 173-181.

[17] Kulkarni, Mithun V., et al. Tribological behaviours of ABS and PA6 polymermetal sliding combinations under dry friction, water absorbed and electroplated conditions. J Eng Sci Technol 11, 1 (2016) 68-84.

[18] Horvath Daniel, Rafiq Noorani, Mel Mendelson. Improvement of surface roughness on ABS 400 polymer using design of experiments (DOE). Materials Science Forum 561. 2007. Trans Tech Publications Ltd.

[19] Kamaljit Boparai, Rupinder Singh, Harwinder Singh. Comparison of tribological behavior for Nylon6-Al-Al_2O_3 and ABS parts fabricated by fused deposition modeling.Virtual and Physical Prototyping 10, 2, (2015) 59-66.

[20] W. Gregory Sawyer, Kevin D. Freudenberg, Praveen Bhimaraj, Linda S. Schadler. A study on the friction and wear behavior of PTFE filled with alumina nanoparticles. Wear 254 (2003) 573-580.

[21] Zhang L.C., Zarudi I., Xiao K.Q. Novel behavior of friction and wear of epoxy composites reinforced by carbon nanotubes. Wear 261 (2006) 806-811.

[22] Dawoud M., Taha I., Ebeid S.J. Effect of processing parameters and graphite content on the triblogical behavior of 3D printed acrylonitrile butadiene styrene. Mat.-wiss. u. Werkstofftech 46, 12 (2015) 1185-1195.

[23] Hwang S., Reyes E.I., Moon K.S., Rumpf R.C., Kim N.S. Thermo-mechanical characterization of metal/polymer composite filaments and printing parameter study for fused deposition modeling in the 3D printing process. J. Electron. Mater. 44 (2015) 771-778.

[24] Ryder M.A., Lados D.A., Iannacchione G.S., Peterson A.M. Fabrication and properties of novel polymer-metal composites using fused deposition modeling. Composites Science and Technology (2018) 1-23. [doi: 10.1016/j.compscitech.2018.01.049].

[25] Kürşad Sezer H., Eren O. FDM 3D printing of MWCNT re-inforced ABS nano-composite parts with enhanced mechanical and electrical properties. Journal of Manufacturing Processes 37 (2019) 339–347.

[26] Gimenez J. Fatigue wear of polymer composites having nano-engineered interfaces. Master of Science and Technology Thesis in Engineering Materials, The University of New South Wales School of Materials Science and Engineering. 2014. 74p. [DOI: 10.13140/2.1.1966.6243; available at https://www.researchgate.net/publication/271703673].

[27] Lancaster J.K. Relationships between the wear of polymers and their mechanical properties. Proc. Inst. Mech. Engineers 183, 16 (1968) 98-106. [doi.org/10.1243/PIME_CONF_1968_183_283_02]

[28] Yetgin S.H. Impact of multi-walled carbon nanotube and graphene oxide on abrasive wear performance of polypropylene. Res. Eng. Struct. Mater.7, 1 (2020) 157-171.

[29] Mohamed O. A, Masood S. A, Bhowmik J. L. Analysis of wear behavior of additively manufactured PC-ABS parts. Materials Letters (2018) 1-9. [doi: https://doi.org/10.1016/j.matlet.2018.07.139]

[30] Gholamhossein Sodeifiana, Saghar Ghaseminejad, Ali Akbar Yousefi. Preparation of polypropylene/short glass fiber composite as Fused Deposition Modeling (FDM) filament. Results in Physics. 12 (2019) 205–222.