DOI: 10.46793/41DAS2025.171S

CHALLENGES OF ADDITIVE MANUFACTURING IN MACHINE ELEMENT APPLICATIONS

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1. Introduction

Additive manufacturing, also known as 3D printing, has become increasingly relevant in science as well as industrial applications, thanks to its ability to produce complex geometries that are difficult to achieve with conventional methods. Sliding bearings are essential machine parts, characterized by great reliability, constant performance, and minimal noise [1]. In machine systems, sliding bearings allow shaft rotation with minimal friction and heat dissipation. The use of additive technologies to make machine parts, especially sliding bearings, allows for on-demand manufacturing without large series or expensive tools and the use of a variety of materials, from engineering polymers to metals. Industries that need customized solutions benefit from mass personalization and customized production enabled by these technologies [2]. Additive manufacturing contributes to environmentally friendly production by reducing material waste, lowering energy consumption, and minimizing the carbon footprint, thus supporting strategies of circular economy [3]. One of the disadvantages of additive technologies is the higher price per unit of the product compared to conventional methods, as well as the longer time for manufacturing the part. In addition, parts made with additive technologies often require additional machining using traditional methods, such as turning or grinding, in order to achieve the appropriate finish and surface quality. The need to evaluate tribological properties, primarily the coefficient of friction and wear of additively produced parts, arose from the increasing application of additive technologies in the production of sliding bearings. The aim of this paper is to provide an overview of additive manufacturing technologies that can be applied to the production of machine elements, with special reference to sliding bearings, as well as to analyse the tested tribological properties of the relevant materials.

2. Overview of additive manufacturing technologies

The additive manufacturing paradigm involves manufacturing a part based on a CAD model, whereby material is deposited layer by layer using controlled and automated tools [4]. Sheet lamination, material extrusion, powder bed fusion, direct energy deposition, binder jetting, material jetting, and vat photopolymerization are some of the most frequently used categories of AM technology. Each technology, thanks to its specific features, is adapted to specific applications [5]. The process of creating a part begins with the creation of a CAD model and the generation of an stereolithography (STL) file of the desired object, which is a standard procedure in almost all AM processes [6]. The 3D model is converted into a series of 2D slices, which are suitable for printing as they contain information about the lateral profiles of each layer. Based on those slices, the model is created layer by layer, following those slices. The STL format of the model consists of several triangular facets, which approximate the geometry of the object [7].

2.1 Fused Deposition Modeling (FDM)

In FDM technology shown on Fig.1., thermoplastic extrusion is done through a heated nozzle and the material is applied in layers to form a 3D object based on the STL file. The properties of the manufactured part can be influenced by several printing parameters, including layer thickness, infill shape and density, raster angle, build orientation, number of contours, as well as other factors [8]. Process parameters influence the tribological characteristics of parts made by the FDM method. Wear rate can be reduced by reducing the thickness of the layer or by a certain orientation of the print, while increasing the roster angle and air gap can lead to the opposite effect. Road width and number of contours can also affect the wear rate [9].

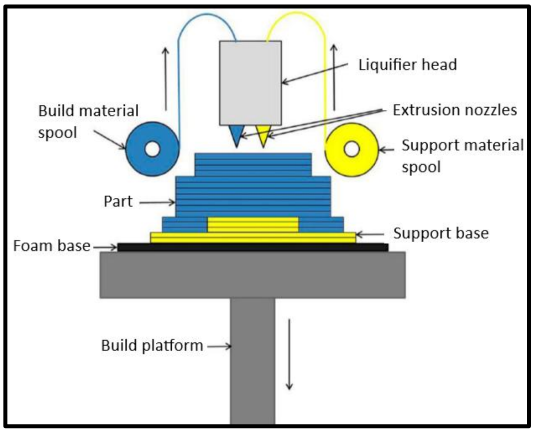

Fig. 1. Fusion Deposition Modeling method [5]

2.2 Selective Laser Sintering (SLS)

The selective laser sintering (SLS) method uses a directional laser beam to selectively irradiate and sinter powder layers, as illustrated in Fig.2., forming the desired three-dimensional product [10].

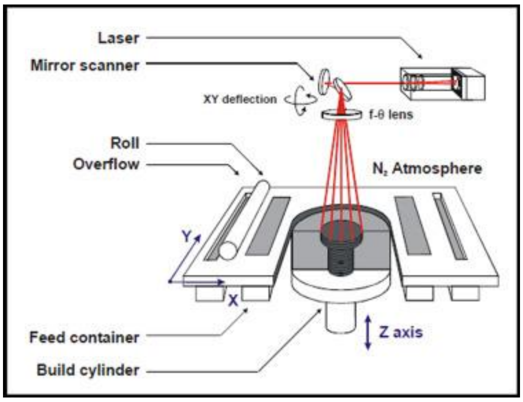

Fig. 2. Selective Laser Sintering method [12]

Before starting the laser beam, it is necessary to heat the powder to the appropriate temperature. This method fulfils the basic principle of additive technologies, adding material layer by layer to create a part directly based on the 3D model and the corresponding STL file. The recoating roller first uniformly applies a thin layer of powder to the working surface inside the chamber, which is later selectively sintered under the influence of a laser. After the formation of one layer, the working platform is restrained by a predefined layer height, and a new layer of powder is again applied to the surface. This process is repeated until the part is completely finished [11].

2.3 Stereolithography (SLA)

SLA is a vat polymerization technique in which layers of a liquid precursor in a vat are consecutively subjected to ultraviolet (UV) radiation, resulting in selective solidification, as shown in Fig.3. A photoinitiator (PI) molecule in the resin reacts to incoming light and, upon irradiation, locally initiates the chemical polymerization reaction, resulting in curing exclusively in the exposed regions. Subsequent to the formation of the initial layer, a new resin film is placed, irradiated, and cured [13].

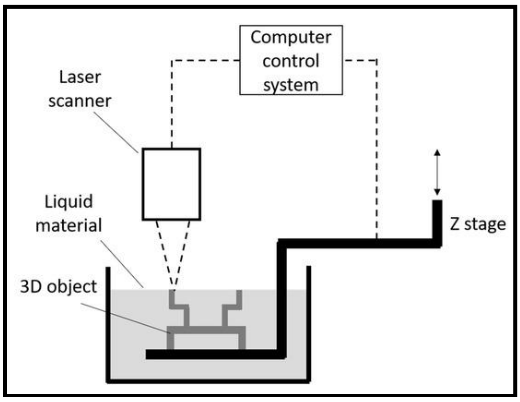

Fig. 3. Stereolithography method [7]

3. Tribological behavior of common 3D printing materials

Tribological properties and behaviour of 3D printed materials is important for optimizing materials and parts performance in applications where friction and wear are significant concerns. The most commonly used materials in additive manufacturing are engineering polymers, metals and ceramics. The most common polymers are Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Polyethylene Terephthalate Glycol (PETG) and Polyamide (PA), as well as composites based on these polymers. Composites are mainly reinforced with fibers, such as carbon fibers or glass, which improves the mechanical, tribological and thermal properties of the manufactured parts [14]. PLA is characterized by greater mechanical strength and is environmentally more stable, while ABS is more flexible and more resistant to higher temperatures, although on average it has lower strength. The properties of these materials can be influenced by printing parameters, such as layer thickness, infill density and shape, as well as printing orientation [15]. In the paper [16] ABS and PLA materials were tested. Layer thickness, infill angle and orientation of deposition were chosen as the main printing parameters. Under identical printing conditions, PLA and ABS did not show significant differences in tribological properties. The materials predominantly utilized in Selective Laser Sintering (SLS) include thermoplastics such as Polyamide 12 (PA12), Polyamide 11 (PA11), and their composite variants. Additional materials comprise Thermoplastic polyurethane (TPU), Polypropylene (PP), Polystyrene (PS), Polyethylene (PE), Polycaprolactone (PCL), and high-performance polymers such as Polyetheretherketone (PEEK) [11]. Polyamides are the most widely used materials in commercial systems. They can be found in the most famous form PA12 as well as in forms with particles like glass or carbon. Tribological properties of SLS-made PA12 depend on sintering orientation and additives. Parallel orientation reduces wear and friction [17,18], while reinforcements with graphite, MoS_2, carbon fibers and SiC significantly improve wear resistance and reduce the coefficient of friction [19–21].

Recent studies have increasingly examined the tribological properties and the possibility of using sliding bearings manufactured using additive technologies. In the work [22] authors investigated the effect of texture on plain bearings fabricated by FDM technology using ABS, PLA and nylon. The focus of testing was the effect of texture depth, rotation speed and load, with optimization using Gray Relational Analysis. The authors in [23] compared the performance of sliding bearings made by different methods, SLS and FDM, where SLS nylon bearings showed lower friction, but limited application at higher temperatures. In [24] investigated bearings were made with MultiJet technology, where the load and joint of the bearing showed significant influence.

4. Challenges and limitations of 3D-printed bearings

Bearings produced by additive technologies have their own advantages, which are primarily reflected in the design and economy of production. Compared to traditionally produced bearings, there are numerous challenges. Most often, the problems are due to anisotropy, layered structure effects, reduced dimensional accuracy and sensitivity to high temperatures or loads. Anisotropy of additively manufactured bearings affects strength, wear and friction characteristics depending on the direction of load or rotation. This property is a consequence of layer-by-layer manufacturing, which weakens the bonds between the layers and leads to unstable wear and friction performance depending on the working conditions [22,25]. Surface roughness, as a consequence of the printing process, can lead to increased friction and wear, especially at high loads and rotation speeds [26]. 3D-printed bearings frequently exhibit dimensional inaccuracies resulting from printer resolution constraints, material shrinkage, and variations in post-processing [27]. Despite all the challenges, 3D printed bearings offer significant benefits, such as design flexibility that allows testing hypotheses about design improvement, lightweight construction, and the ability to produce bearings with different surface textures to improve tribological properties. Materials such as PA12 and its composites reinforced with carbon fibers, glass beads or dry lubricants ensure a low coefficient of friction and less wear, which makes them suitable for industries where traditional lubrication with lubricants cannot be used, such as the food and paper industries, as well as for maintenance-free bearings. The process of additive technologies enables faster development cycles and more economical production of small batches of bearings, which is especially useful in cases where it is necessary to quickly replace the bearing.

5. Conclusion and future work

Additive technologies provide significant improvements for the manufacturing of machine elements, especially sliding bearings, due to their ability to produce complicated structures, reduce material waste, and allow modification. However, the widespread application of 3D-printed bearings faces problems related to anisotropy of material, effects of layered structures, increased surface roughness, dimensional inaccuracies, and reduced thermal and mechanical stability compared to traditionally manufactured components. Tribological properties of printed parts are highly dependent on material selection, printing parameters, and post-processing treatments.

Recent studies have demonstrated that reinforcements such as carbon fibers, glass fibers, graphite, and MoS_2 can significantly improve wear resistance and reduce friction in SLS-produced polymer bearings. Nevertheless, careful optimization of sintering orientation and control of printing parameters remain crucial for achieving consistent tribological performance.

Future work will focus on experimental testing of 3D-printed sliding bearings under simulated real-world conditions, with an emphasis on long-term durability. Further research will also explore new composite formulations, improvements in surface finishing techniques, and the development of predictive models to better understand and optimize tribological behaviour.

REFERENCES

[1] Du, F., Li, D., Sa, X., Li, C, Yu, Y, Li, C, Wang, J, Wang, W. Overview of Friction and Wear Performance of Sliding Bearings. *Coatings,* 2022, *12*, 1303.

[2] Qin, J., Hu, F., Liu, Y., Witherell, P., Wang, C.C.L., Rosen, D.W., Simpson, T.W., Lu, Y., Tang, Q. Research and Application of Machine Learning for Additive Manufacturing. *Additive Manufacturing,* 2022, *52*, 102691.

[3] Hegab, H., Khanna, N., Monib, N., Salem, A. Design for Sustainable Additive Manufacturing: A Review. *Sustainable Materials and Technologies,* 2023, *35*, e00576.

[4] Tofail, S.A.M., Koumoulos, E.P., Bandyopadhyay, A., Bose, S., O'Donoghue, L., Charitidis, C. Additive Manufacturing: Scientific and Technological Challenges, Market Uptake and Opportunities. *Materials Today,* 2018, *21*, 22–37.

[5] Rajan, K., Samykano, M., Kadirgama, K., Harun, W.S.W., Rahman, Md.M.. Fused Deposition Modeling: Process, Materials, Parameters, Properties, and Applications. *Int J Adv Manuf Technol,* 2022, *120*, 1531–1570.

[6] Wong, K.V., Hernandez, A. A Review of Additive Manufacturing. *ISRN Mechanical Engineering,* 2012, *2012*, 1–10.

[7] Huang, J., Qin, Q., Wang, J. A Review of Stereolithography: Processes and Systems. *Processes,* 2020, *8*, 1138.

[8] Mohamed, O.A., Masood, S.H., Bhowmik, J.L., Somers, A.E. Investigation on the Tribological Behavior and Wear Mechanism of Parts Processed by Fused Deposition Additive Manufacturing Process. *Journal of Manufacturing Processes,* 2017, *29*, 149–159.

[9] Batista, M., Blanco, D., Del Sol, I., Piñero, D., Vazquez, J.M. Tribological Characterization of Fused Deposition Modelling Parts. *IOP Conf. Ser.: Mater. Sci. Eng.,* 2021, *1193*, 012068.

[10] Kruth, J.P. Material Incress Manufacturing by Rapid Prototyping Techniques. *CIRP Annals,* 1991, *40*, 603–614.

[11] Han, W., Kong, L., Xu, M. Advances in Selective Laser Sintering of Polymers. *Int. J. Extrem. Manuf.,* 2022, *4*, 042002.

[12] Kruth, J., Mercelis, P., Van Vaerenbergh, J., Froyen, L., Rombouts, M. Binding Mechanisms in Selective Laser Sintering and Selective Laser Melting. *Rapid Prototyping Journal,* 2005, *11*, 26–36.

[13] Schmidleithner, C., Kalaskar, D.M. Stereolithography. In *3D Printing*; Cvetković, D., Ed, InTech, 2018

[14] Bhatia, A., Sehgal, A.K. Additive Manufacturing Materials, Methods and Applications: A Review. *Materials Today: Proceedings,* 2023, *81*, 1060–1067.

[15] Otieno, D.B, Bosire, G.O, Onyari, J.M, Mwabora, J.M. Comparative Analysis of 3D-Printed Polylactic Acid and Acrylonitrile Butadiene Styrene: Experimental and Materials-Studio-Based Theoretical Studies. *J Polym Res,* 2022, *29*, 291.

[16] Roy, R., Mukhopadhyay, A. Tribological Studies of 3D Printed ABS and PLA Plastic Parts. *Materials Today: Proceedings,* 2021, *41*, 856–862.

[17] Wörz, A., Drummer, D. Tribological Anisotropy of Selective Laser Sintered PA12 Parts. *Polymer Testing*, 2018, *70*, 117–126.

[18] Gadelmoula, A., Aldahash, S.A. Tribological Properties of Glass Bead-Filled Polyamide 12 Composite Manufactured by Selective Laser Sintering. *Polymers,* 2023, *15*, 1268.

[19] Gadelmoula, A, Aldahash, S.A. Dry Friction and Wear Behavior of Laser-Sintered Graphite/Carbon Fiber/Polyamide 12 Composite. *Polymers* 2023, *15*, 3916.

[20] Nar, K., Majewski, C., Lewis, R. Evaluating the Effect of Solid Lubricant Inclusion on the Friction and Wear Properties of Laser Sintered Polyamide-12 Components. *Wear,* 2023, *522*, 204873.

[21] Yu, G., Ma, J., Li, J., Wu, J., Yu, J., Wang, X. Mechanical and Tribological Properties of 3D Printed Polyamide 12 and SiC/PA12 Composite by Selective Laser Sintering. *Polymers,* 2022, *14*, 2167.

[22] Mourya, V., Bhore, S.P. Experimental Investigation of Tribological Performance of 3D Printed Textured Journal Bearings for Various Polymers. *Journal of Thermoplastic Composite Materials,* 2024, *37*, 1586–1618.

[23] Lee, Y.-J, Lee, K.-H, Lee, C.-H. Self-Lubricating and Friction Performance of a Three-Dimensional-Printed Journal Bearing. *Journal of Tribology,* 2018, *140*, 054501.

[24] Andrearczyk, A., Bagiński, P. THE USE OF ADDITIVE MANUFACTURING TECHNOLOGYTO MANUFACTURE SLIDE BEARING SLEEVES – A PRELIMINARYSTUDY. *Tribologia,* 2020, *291*, 7–14.

[25] Silvestri, A.T., Papa, I., Rubino, F., Squillace, A. On the Critical Technological Issues of CFF: Enhancing the Bearing Strength. *Materials and Manufacturing Processes,* 2022, *37*, 123–135.

[26] Lee, Y.-J, Lee, K.-H, Lee, C.-H. Friction Performance of 3D Printed Ball Bearing: Feasibility Study. *Results in Physics,* 2018, *10*, 721–726.

[27] Uzcategui, A.C., Muralidharan, A., Ferguson, V.L., Bryant, S.J., McLeod, R.R. Understanding and Improving Mechanical Properties in 3D Printed Parts Using a Dual-Cure Acrylate-Based Resin for Stereolithography. *Adv Eng Mater,* 2018, *20*, 1800876.