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ANALYSIS OF PRESSURE DISTRIBUTION IN 3D-PRINTED SLIDING BEARINGS USING HERTZIAN CONTACT THEORY

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Abstract: *The increasing use of additive manufacturing in tribological applications has led to an increasing interest in the performance of 3D-printed sliding bearings. This paper presents the pressure distribution in 3D-printed sliding bearings using Hertzian contact theory as a theoretical framework. This research compares the maximum contact pressures among the most commonly used 3D printing materials, including ABS, PLA, PLA reinforced with carbon fiber (PLA+CF), PETG, and PETG reinforced with carbon fiber (PETG+CF). We used mechanical properties such as Young's modulus and Poisson's ratio from published papers. Based on the calculations, it is clear that when materials are reinforced with fibers, the pressures are more closely aligned with Hertzian theory. Conversely, the deviation from Hertzian theory becomes more significant when materials lack fiber reinforcement. The results obtained in this work provide an initial reference for the selection of materials for 3D-printed bearings and serve as a basis for further numerical modeling and experimental validation.*

Keywords: *sliding bearings, 3D-printing, Hertzian contact theory, tribology, pressure distribution*

1. INTRODUCTION

Plain bearings are present in many technical applications, offering support and minimizing friction between moving parts. Nearly all modern devices use them to enable shaft rotation. The term plain bearing derives from the property that two surfaces move relative to each other without rolling contact [1]. Current trends toward the use of green energy, reduced carbon footprint, increased motion accuracy, and operating speeds in machines present clear challenges for bearing systems.

Additive manufacturing (AM) techniques have significant importance in science and engineering. Since 2013, the 3D printing technology has experienced rapid development and persists in providing new opportunities for the manufacturing of machine parts. The development of additive manufacturing technology has led to a wider range of materials utilized in this domain [2]. Additive manufacturing has found a significant place in the production of plain bearings, enabling design flexibility, rapid and economical prototyping, and the creation of complex geometries using different materials.

The distribution of contact pressure in sliding bearings is crucial for their operating life and functionality. Uneven pressure distribution can lead to excessive wear, fatigue, and potential failure, which can compromise the performance and reliability of the machines. The interaction between the shaft and the sliding bearing occurs at the contact line between the outer surface of one cylinder and the inner surface of another cylinder, which is one of the cases in Hertzian contact theory. In the absence of lubrication, Hertzian contact theory offers a fundamental method for approximating contact pressure.

In this paper, we use Hertzian contact theory as a starting point to compare the pressure distribution in sliding bearings made by additive technologies, mostly FDM. The aim is to create a starting point for material selection using mechanical property data from the published literature. Although Hertzian contact mechanics has been used in traditionally manufactured bearings, both sliding and rolling, there is a lack of studies on its application in additive manufacturing. The goal of this study is to fill in that gap by looking into the most common materials used in sliding bearings with uniform working conditions and comparing the highest pressure that can be reached using Hertzian contact theory. We will use the results as a starting point for more complex calculations using finite element analysis and advanced mathematical models. This will make it easier to choose materials and test them in the lab.

2. ADDITIVE MANUFACTURING AND MATERIAL SELECTION FOR 3D-PRINTED BEARING

Additive manufacturing technologies have progressed, transitioning from a specialized process to a widely used production method, which is nowadays used at home. 3D printing has been adopted in leading industries, such as automotive, aerospace, and medical, where it is used to produce parts with complicated geometry using an increasing range of materials, from polymers to metals.

Additive manufacturing offers numerous advantages over conventional production, encompassing cost, speed, quality, innovation, and impact [3]. Fused deposition modeling (FDM), direct printing, injection printing, selective laser sintering, and stereolithography are some of the most well-known and quickly spreading additive manufacturing methods [4]. FDM technology is significantly more economical than other additive manufacturing techniques due to its simplicity [5]. FDM offers significant benefits over traditional manufacturing approaches through rapid prototyping and on-demand manufacturing.

The fundamental idea of the FDM production process is to melt the raw material to enable the formation of new shapes. A temperature-regulated nozzle feeds the filament wound on a wheel, transforming it into a semi-liquid state. The nozzle precisely extrudes and directs the molten material to construct a structural part incrementally. The application software integrates the contours of a layer into the FDM operational system [4]. Figure 1 illustrates the fundamental working principle of a 3D printer that utilizes Fused Deposition Modeling (FDM).

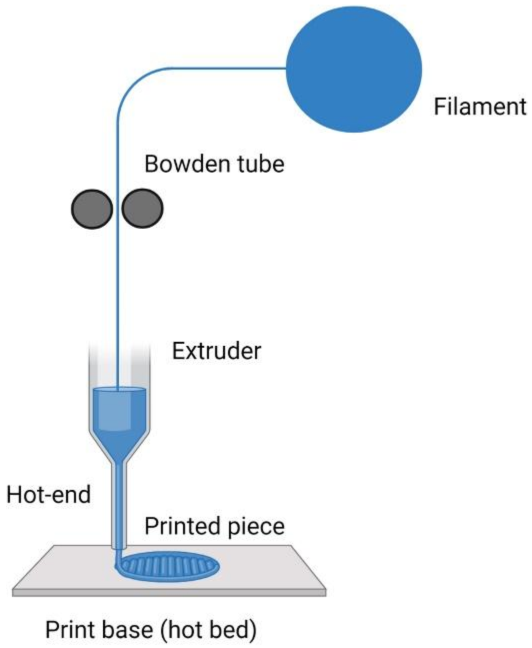

Figure 1. Representation of the Fused Deposition Modeling Process [4]

FDM has applied a variety of thermoplastic materials, each with unique properties that influence the performance of printed parts. Common and affordable printing materials are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). It is also possible to use Polyester Terephthalate Glycol (PETG), Nylon (a type of polyamide), Polyether Ether Ketone (PEEK), and Polyethylenimine (PEI) in Fused

Deposition Modeling (FDM). These polymers have good mechanical and thermal properties, so they can be used for more demanding tasks [6].

There are many factors that affect the mechanical properties of FDM-printed parts. These factors include the material, the structure (density of infill, direction of printing, and order of stacking), and the manufacturing process (printing speed, extrusion temperature, time between layers, nozzle speed, and bed temperature) [7]. When choosing materials for printing parts, these parameters must not be ignored, which, in addition to the material, directly affect strength, flexibility, wear, and impact resistance.

We selected five materials for this study because they are good at bearing loads and have good mechanical properties. These are ABS, PLA, Polyethylene Terephthalate Glycol (PETG), and Carbon Fiber-Reinforced PETG (PETG+CF) and PLA (PLA+CF). ABS is a high-strength, impact-resistant thermoplastic with excellent chemical and heat resistance, making it ideal for high-load and high-temperature applications. PLA is a biodegradable, stiff thermoplastic, but its lower heat and chemical resistance require reinforcement (e.g., carbon fiber) for improved durability. PETG is better at resisting water, chemicals, and heat, and it has strong mechanical properties. Adding carbon fiber can make it even better for better performance [8].

We obtained Young's modulus and Poisson's coefficient from published works that examined the mechanical properties of 3D printed test specimens. These properties play a key role in the operation of printed parts, since they describe stiffness and elasticity. The mechanical properties of the chosen FDM-printed materials are shown in Table 1. These properties include Young's modulus, Poisson's ratio, layer thickness, and testing standards. Knowing these properties is important for judging how well the materials work in sliding bearings.

ASTM 638-10 and ISO 527-2:2012 are complementary since both standards define procedures for tensile testing of plastics.

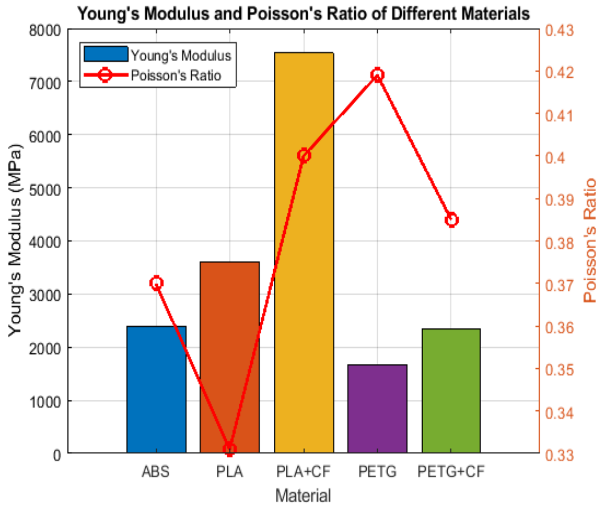

Figure 2. Mechanical properties of selected materials

Table 1. Material properties

Material	Young's Modulus	Poisson's ratio	Layer thickness	Testing standard	Reference
ABS	2400	0.37	0.254	ISO 527-2-2012	[9]
PLA	3376	0.331	0.3	ASTM D638-10	[6]
PLA+CF	7541	0.4	0.3	ASTM D638-10	[6]
PETG	1660	0.419	0.15 mm	ASTM D638-10	[10]
PETG+CF	2340	0.442	0.15 mm	ASTM D638-10	[10]

In Figure 2., the elasticity and stiffness of the materials chosen for the study are easily compared, where it can be seen that PLA+CF has the highest elasticity, while PETG has the lowest. PLA has the lowest stiffness, while PETG has the highest. It is important to note that the test specimens were made by 3D printing under identical conditions, so the values are closer to 3D-printed parts, in contrast to the data obtained by the classical testing of materials, where the test specimens are usually obtained by casting.

3. HERTZIAN CONTACT THEORY AND PRESSURE DISTRIBUTION

The Hertzian contact theory is a fundamental theory of contact mechanics and serves as an invaluable resource for engineers and scientists. Despite the complexity of deriving the theory, the ultimate solution includes a series of straightforward analytical equations that connect the system's attributes to the induced stress.

His research established mathematical correlations between distributed surface pressure and applied load for elastic, frictionless contact between bodies with quadratic surfaces and minimal contact areas, a methodology that remains popular in numerous contact problems today. Surfaces of entities that meet these criteria initially connect at a point (in the case of spherical contact) or along a line (in the case of cylindrical contact), and even when subjected to load, the size of the contact area remains minimal relative to the dimensions of the bodies themselves [11].

An equivalent module of elasticity is defined:

$$\frac{1}{E_e} = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \qquad (1)$$

Where E is Young' modulus and ν is Poisson's coefficient.
A relative diameter of curvature is defined using negative concave (bearing) and positive convex (shaft) part:

$$\frac{1}{d_e} = \frac{1}{d_1} + \frac{1}{d_2} \qquad (2)$$

According to the Hertz theory for the case of contact of cylinder on interior surface of other cylinder [12], maximum pressure is:

$$p_{max} = \sqrt{\frac{2FE_e}{\pi L E_e}} \qquad (3)$$

A width of contact surface is calculated with following procedure:

$$b = \sqrt{\frac{2Fd_e}{\pi L E_e}} \qquad (4)$$

Figure 3 illustrates the pressure distribution for sliding bearings using the Hertzian contact theory.

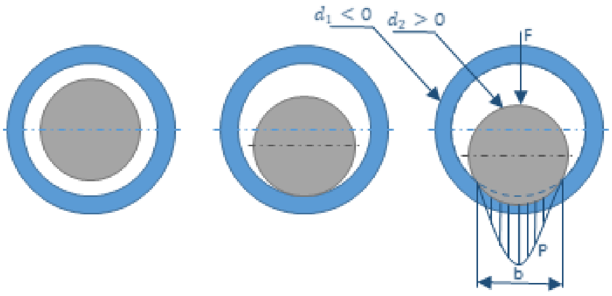

Figure 2. Pressure distribution on sliding bearing

Hertzian contact theory does not fully describe the pressure distribution in 3D-printed bearings since it does not take into account all the complexities that occur with 3D-printed parts, but it can be used as a first approximation when choosing printing materials, as well as for further, more sophisticated analyses that will take into account anisotropy, plasticity, and surface effects.

4. RESULTS

In this section, pressure distributions in sliding bearings will be presented using Hertzian contact theory. The goal is to compare the pressures of different materials and use those results to determine the appropriate materials for the specific applications of the manufactured bearing.

The sliding bearing under investigation has dimensions of $\emptyset 20 \times \emptyset 25 \times 20\, mm$ and is analyzed as a short-bearing with corresponding approximation. The test is meant to be done in future research under identical working conditions on the USL 5-30 testing instrument, created in partnership with a bearing manufacturer. A radial load was exerted by a lever arm mechanism with a 10:1 ratio, whereby a 1 kg mass produced a force:

$$F = 10\,m\,g = 98.1\,N \quad (5)$$

Under the influence of the radial force, pressure occurs between the bearing and the shaft, and this force defines the contact pressure. The real measurements of bearings diameter and diameter of the shaft are presented in Table 2.

Table 2. Measurements of bearings and shafts

Measure	d1	d2
1	20.12	19.93
2	20.19	19.95
3	20.17	19.96
4	20.22	19.94
5	20.20	19.92
Mean value	20.18	19.94

The assumptions applied in this calculation are:

- The profile of contact pressure distribution is parabolic.
- The contact surfaces are treated as semi-infinite bodies.
- Classical elasticity theory assumptions are fully applied.
- The material is assumed to be homogeneous within the contact region.
- Surface roughness is either minimal or incorporated into the model

The MATLAB software package was used to calculate the maximum pressure, and the maximum pressure is in the middle of the contact region. A comparative presentation of the results is given in Figure 4.

The results indicate that the highest contact pressure was obtained using PLA+CF, whereas the lowest pressure was observed with PETG. The results for ABS and PETG+CF were nearly identical.

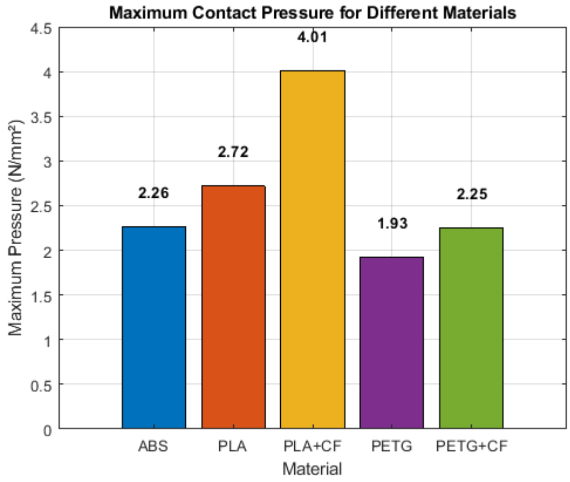

Figure 3. Maximum contact pressures of the bearings

Figure 5. shows a comparison of pressure distributions, and it can be seen that PLA+CF and PETG+CF are closest to the theoretical Hertz distribution, which shows that CF-reinforced materials are closest to the theoretical one, while ABS, PLA, and PETG have significant discrepancies.

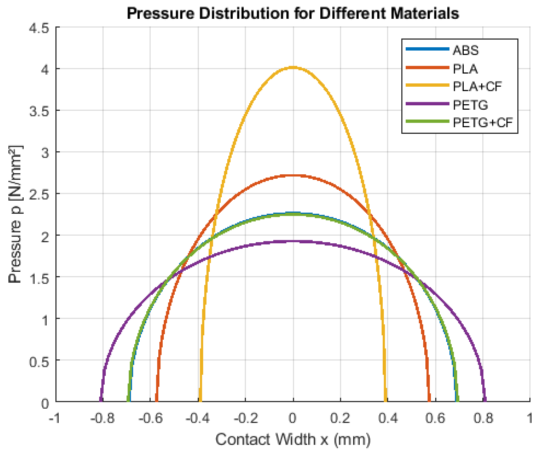

Figure 4. Pressure distribution of selected bearing materials

5. CONCLUSION

This study illustrates that fiber-reinforced 3D printing materials yield a more accurate estimation of Hertzian contact pressure predictions. In the design of sliding bearings, reinforced composites should be favored for high-load applications, whilst non-reinforced materials may suffice for low-load conditions.

- Reinforced materials (PLA+CF, PETG+CF) demonstrate increased stiffness,

making them more appropriate for high-load applications.
- Non-reinforced materials (ABS, PLA, PETG) exhibit greater pressure deviations, suggesting poor performance under heavy loads.

The findings may act as a preliminary reference for choosing materials for 3D-printed sliding bearings according to anticipated load circumstances.

Future investigation includes tribological testing for validation, the integration of nonlinear deformation for enhanced precision, and the examination of surface roughness impacts on pressure distribution aimed to improve bearing performances in exploitation.

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