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Research Article

Impact of geometries on performances and surface morphology of SLS 3D-printed thrust and roller bearings

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Abstract
Bearings are among the most prevalent elements in civil engineering buildings and mechanical machinery, with numerous applications. The global bearings market has experienced considerable growth in recent years, fuelled by rising demand in the automotive, aerospace, and manufacturing sectors. Bearings were used as early as 40 Before Christ (BC) and commonly have a solid geometrical design. Lately, there have been limited studies to predict the effects of different geometries on the behaviour of bearings. In this study, different geometrical models were designed using CatiaV5 software and manufactured using selective laser sintering (SLS) three-dimensional (3D) printing. The printed geometrical bearing samples were subjected to vibration analysis, performance testing, and surface validation using a scanning electron microscope (SEM) to evaluate their tribological behaviour. The findings indicated that the samples with a triangular geometry exhibited a remarkably smooth surface texture. This smoothness surpassed that of the samples with a square geometry, and this was attributed to the shorter spacing between the melted particles, extensive coverage of the particle area and reduced presence of independent particles. These findings highlight the intricate interplay between geometry and surface texture in bearing fabrication, offering valuable insights for further research and development.

Keywords
Bearings, Geometrical design, Selective laser sintering (SLS), Tribological behaviour, Vibration analysis, Surface texture.

1.Introduction
Bearings are critical components in mechanical systems, enabling smooth motion and reducing wear between moving parts. The global bearings market has seen considerable growth, driven by increasing demand across industries such as the automotive, aerospace, and manufacturing industries. Bearings play a key role in improving operational efficiency and reliability by minimising friction, which is a major source of energy loss in mechanical systems [1, 2].

Recent advancements in materials science and manufacturing techniques, particularly three-dimensional (3D) printing, have enabled the development of innovative bearing designs with enhanced performance characteristics [3, 4]. Additive manufacturing technologies, such as selective laser sintering (SLS), offer flexibility to produce intricate geometries, making them suitable for tailored solutions in diverse applications [5, 6].

Despite these advancements, friction-induced wear remains a persistent issue, leading to energy loss, material degradation, and premature failure in bearings [7]. Traditional materials and manufacturing methods often fail to meet the demands of harsh operating conditions such as exposure to extreme

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temperatures, chemicals, or abrasive environments [8]. The need for improved friction reduction and wear resistance has fuelled interest in exploring advanced surface texturing techniques and new material compositions [9, 10]. Existing designs often lack optimisation in geometric features such as grooves and dimples, which are essential for enhancing lubricant retention and tribological performance [11, 12].

This research was aimed at addressing these challenges by leveraging advanced materials, such as polyamide 12 (PA12) nylon, and cutting-edge manufacturing methods, such as SLS, to develop optimised bearing designs with superior performance. The study investigated the effects of surface texturing and geometric modifications on bearing stability, wear resistance, and friction torque [9, 13]. By integrating finite element analysis and experimental evaluations, this work advances bearing design methodologies and meets the evolving performance requirements of modern industries [14, 15].

This paper is structured as follows: the literature review is presented in Section 2, the methodology in Section 3, the results and discussion in Section 4, and the conclusion in Section 5.

2.Literature review

Recent advancements in surface texturing have demonstrated its significant potential in enhancing the performance of bearings by improving lubrication and reducing friction. Techniques such as laser ablation and etching are commonly used to create micro-scale geometric features such as dimples, grooves, and triangular shapes [16]. Studies show that dimples on the surfaces of thrust bearings form hydrodynamic pressure pockets that enhance load capacity and reduce wear [11]. Triangular grooves have proven to be effective in reducing the coefficient of friction under dry sliding conditions [17, 18]. While these methods improve lubricant retention and wear resistance, challenges such as high manufacturing costs and stress concentrations from excessive texturing still limit their widespread adoption [19].

Advancements in materials, particularly PA12 nylon and its composites, have further revolutionised bearing designs. These materials exhibit superior wear resistance, chemical stability, and thermal durability, making them suitable for high-speed and heavy-load applications [20]. Research has highlighted the effectiveness of nano-additives, such as zirconium dioxide (ZrO_2), in reinforcing PA12 nylon, resulting in an increase of up to 20% in load-carrying capacity and improved wear behaviour compared to unreinforced polymers [21]. The use of these materials is particularly beneficial for self-lubricating applications, where traditional bearing materials may degrade under harsh conditions [22]. However, their broader implementation is limited by the high cost of nano-additives and challenges in achieving a uniform dispersion [23].

PA12 powder presents numerous benefits for the fabrication of bearings, especially within additive manufacturing methodologies such as SLS. Its lightweight composition combined with its exceptional mechanical strength renders it ideal for rigorous applications in the aerospace and medical sectors [24]. The distinctive characteristics of PA12, including its capacity to preserve dimensional accuracy and mechanical stability across varying orientations during the printing process, significantly enhance its efficacy in bearing applications [25, 26].

SLS, a 3D printing technique, has emerged as a transformative approach to bearing manufacturing. It enables the creation of complex geometries and customised internal structures with minimal post-processing requirements [27]. Bearings manufactured using SLS have shown a 15% reduction in friction torque, particularly when optimised surface features such as rectangular grooves and spiral curves are incorporated [6]. This method is sustainable, allowing for powder reuse and minimal material wastage, and supports topological optimisation techniques to improve stiffness and reduce weight [28]. However, challenges such as high equipment costs and variability in the mechanical properties of the sintered parts due to inconsistencies in powder quality remain [23].

In addition to advancements in materials and manufacturing, groove geometry optimisation has been a key area of focus in bearing designs. Finite element analysis and experimental studies have revealed that triangular grooves distribute pressure more uniformly, thereby reducing contact stress and enhancing performance [29]. Furthermore, modifications to the groove geometry on rolling elements have been able to reduce contact pressure by up to 10%, highlighting their impact on tribological efficiency [14]. Despite these benefits, precise machining and computational resources are required to implement these optimised geometries, thus limiting their broader industrial application [30].

The reviewed studies highlight the significant strides made in bearing designs through surface texturing, advanced materials, and additive manufacturing. Surface texturing has proven to be an effective method for improving lubrication, while innovative materials like PA12 composites enhance durability under demanding conditions. The use of 3D printing technologies such as SLS has further enabled the development of intricate and optimised bearing geometries. However, challenges such as costs, material inconsistencies, and manufacturing complexities persist. These issues must be addressed through continued research, particularly in integrating advanced modelling techniques and improving material formulations to achieve further advancements in bearing technology.

3.Methods

The methodology used in this study covered the bearing design through the application of Dassault Systèmes® CATIA® V5, SLS 3D printing for fabrication, the meticulous testing of bearing performance, and the surface analysis of the results. Vibration testing was essential to ensure the best performance of the bearing, and this study also explored its procedural features [31]. Scanning electron microscope (SEM) was also crucial for verifying the surface characteristics, thus enabling a close inspection of the surface texture, roughness, and wear [32]. This multi-faceted method was necessary for a thorough examination of the tribological behaviour of the bearing. A flowchart of the entire experimental procedure is given in *Figure 1*.

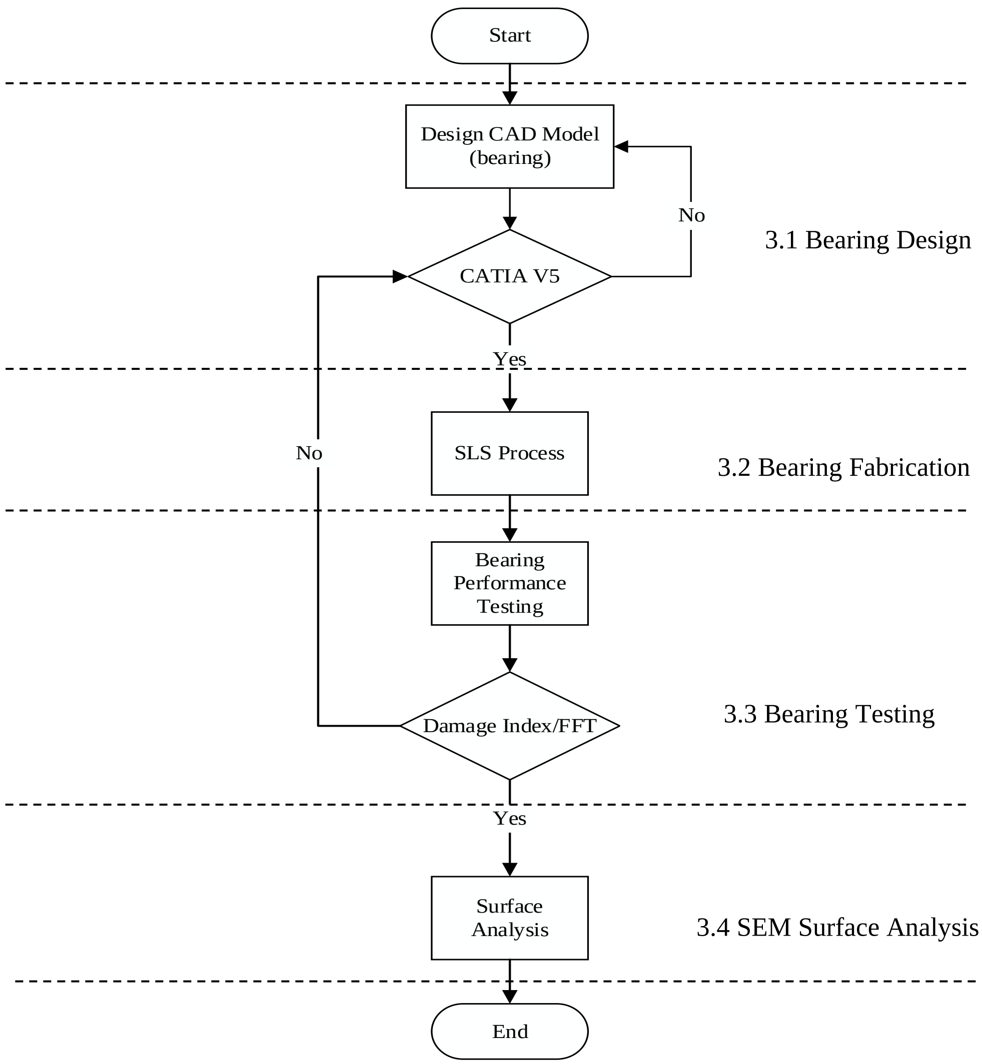


Figure 1 A flowchart of the entire experimental procedure

3.1Bearing design

First, 3D models were created using CATIA® V5. The cylindrical roller and thrust bearing were built separately in four parts: the roller/ball bearing, the bearing cage, and the outer and inner rings (*Figure 2*).

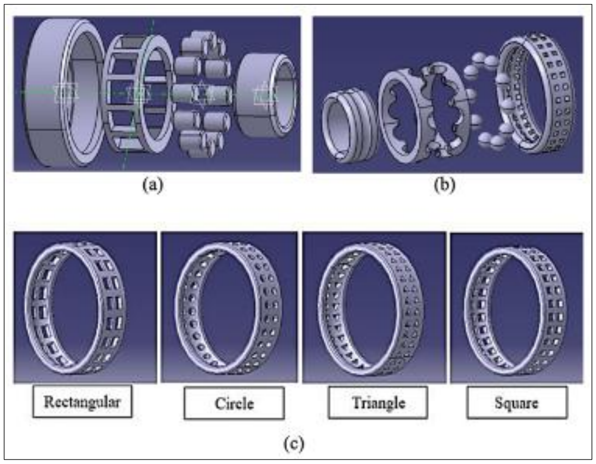


Figure 2 (a) Expanded view of the components in the roller bearing, (b) expanded view of the components in the thrust bearing, and (c) the geometries applied on both types of bearings

3.2Fabrication of bearings using SLS

The operational setup consisted of three main stages: (i) pre-processing, (ii) 3D printing, and (iii) post-processing. The SLS 3D printer was comprised of four main chambers: a feeder, building, collector, and powder overflow chamber with a roller for levelling. During the first stage, the volume and weight of the material were calculated using Materialise Magics 3D Print Suite, based on the quantity of the component that needed to be printed. In the 3D printing process stage, the primary constant parameters for the SLS 3D printer were set according to the configurations shown in *Table 1*. Next, the material block was removed from the building chamber of the SLS machine during the post-processing stage and transferred to the sieve machine. *Figure 3* shows the Farsoon® FS4092P SLS 3D printer that was used to produce all the specimens with a maximum usable area of 350×350×400 mm. The post-processing included removing the printed cake from the Farsoon® SS402P after the cooling process and placing it in the powder breakout station. Filter functions were used to break the printed cake, and the clean prototype was collected with a brush. The prototype in the media blasting cabinet was then blasted with highly compressed air to remove the small powder.

Table 1 Constant configurations of the SLS 3D printer [33]

Properties	Value
Laser Beam Velocity	7.6 m/s
Layer Thickness (LT)	0.06 mm
Hatch Distance	0.30 mm
Chamber Temperature	169.5°C
Laser Power	70 Watts

3.3Bearing performance tests

The schematic diagram in *Figure 3* illustrates the experimental setup, while *Table 2* lists the details of each component used. Two types of vibration data were collected, namely, the fast fourier transform (FFT) spectrum (*Figure 4*) and envelope analysis (*Figure 5*) using the G.U.N.T. Hamburg® PT 500.04 computerised vibration analyser. The vibration data were gathered using two channels (horizontal and vertical) at five different speeds indicated as low speed (600 and 900 rpm), medium speed (1200 rpm) and high speed (1500 and 1800 rpm) using the G.U.N.T. Hamburg® PT 500.04 computerised vibration analyser. Both bearing prototypes were tested five times in dry conditions and the average results were plotted for analysis.

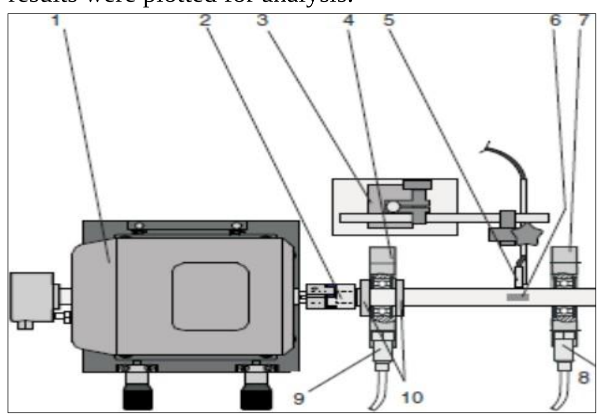


Figure 3 The vibration test equipment

Table 2 The components of the vibration test equipment

No.	Equipment
1	Drive unit
2	Elastic claw coupling
3	Magnetic clamp
4,7	Bearing housing
5	Speed sensor
6	Reflective mark
8,9	Accelerometer
10	Shaft collars

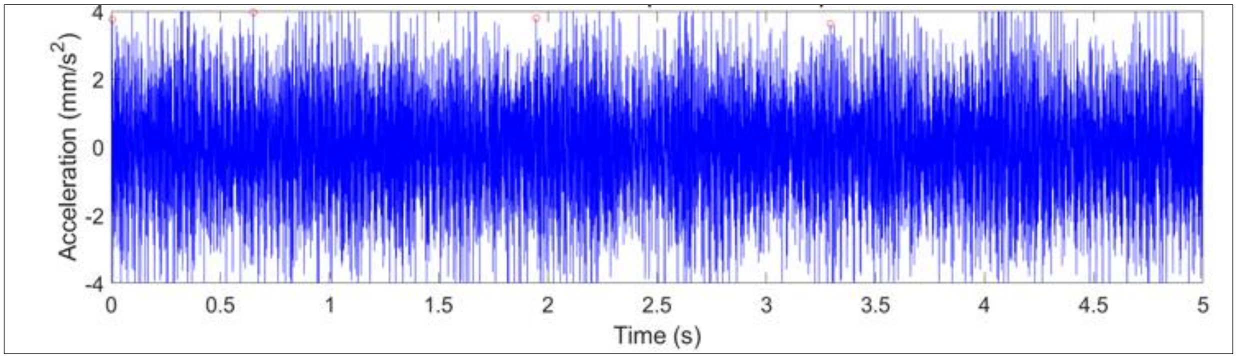


Figure 4 The spectral results of the FFT

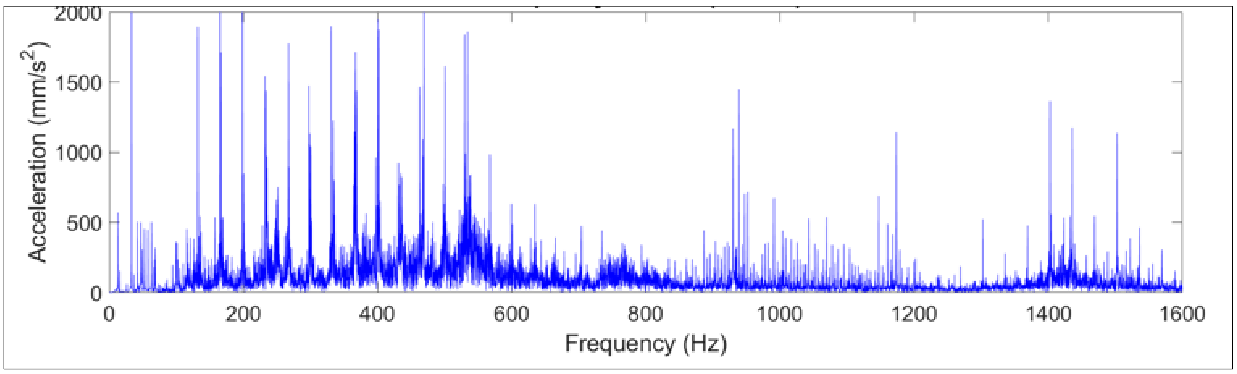


Figure 5 The results of the envelope analysis

3.4Bearing surface analysis

SEM uses electrons and X-rays to generate magnified images that reveal information concerning the chemical composition, crystalline structure, external morphology (texture) and orientation of materials. Two settings, namely low and high magnifications, were used to identify the wear surface results. *Figure 6* shows the SEM images taken at both these settings, where the low magnification (20x) was used to observe the wear on the surface of the material, while the high magnification (100x) was used to look at the texture, orientation and chemical composition of the material. The surface features observed included cracks and wear marks on the surface. The normal voltage was set at 15 kV and the working distance was set at 5-7 mm.

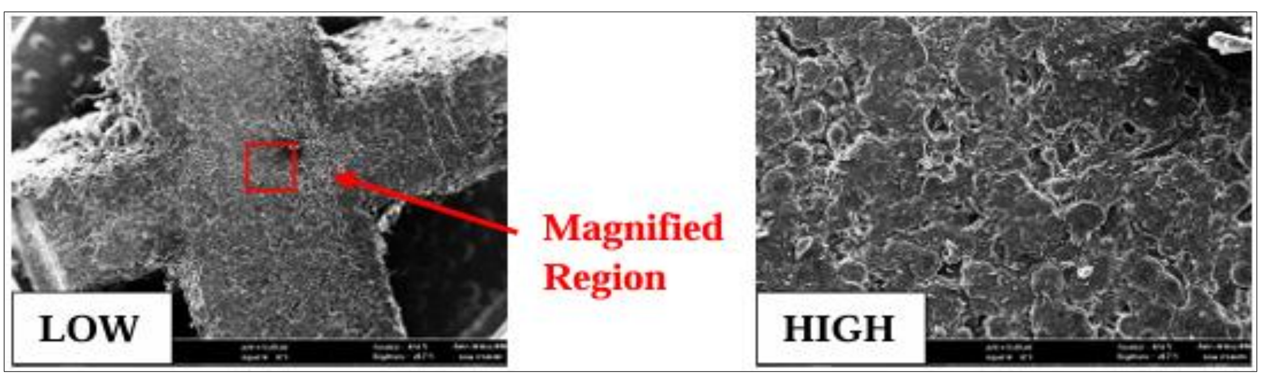


Figure 6 The results of the SEM imaging

4.Results and discussion

The vibration test and SEM imaging results were discussed. The vibration test findings were reorganised into a ranking system to simplify the assessment process. Consequently, the performances of the thrust and roller bearings were compared to determine which bearing design produced a superior performance.

4.1Experimental results

4.1.1Damage indices

Figures 7(a) and *7(b)* display the damage indices, while *Figures 8(a)* and *8(b)* display the overall rankings of the thrust and roller bearings, respectively. The experimental results showed that the square-shaped thrust bearings had the lowest damage index. However, the damage index of the triangle-shaped roller bearings was lower than that of their square counterparts. Compared to the other geometries, the triangular geometry was able to reduce friction and wear to significantly improve the vibration generated during the testing [33]. Furthermore, PA12 nylon is commonly used in SLS printing as it can withstand a higher force and pressure and has good sintering behaviour, which secures all the melted powder [34–36]. These advantages enabled the 3D-printed bearing to perform almost similarly to the actual bearing**.**

Table 3 presents the overall comparison between each thrust and roller bearing geometry. As can be seen, the thrust bearings performed better at low and high speeds, while the roller bearings dominated at medium speeds. According to Amontons' 2nd law, the friction force is independent of the apparent area of contact [37], and according to the 3rd law, the friction force is independent of the sliding velocity [38]. Therefore, the results were affected as the thrust bearings generated more friction than the roller bearings. However, both bearings encountered almost similar contact forces at high speeds.

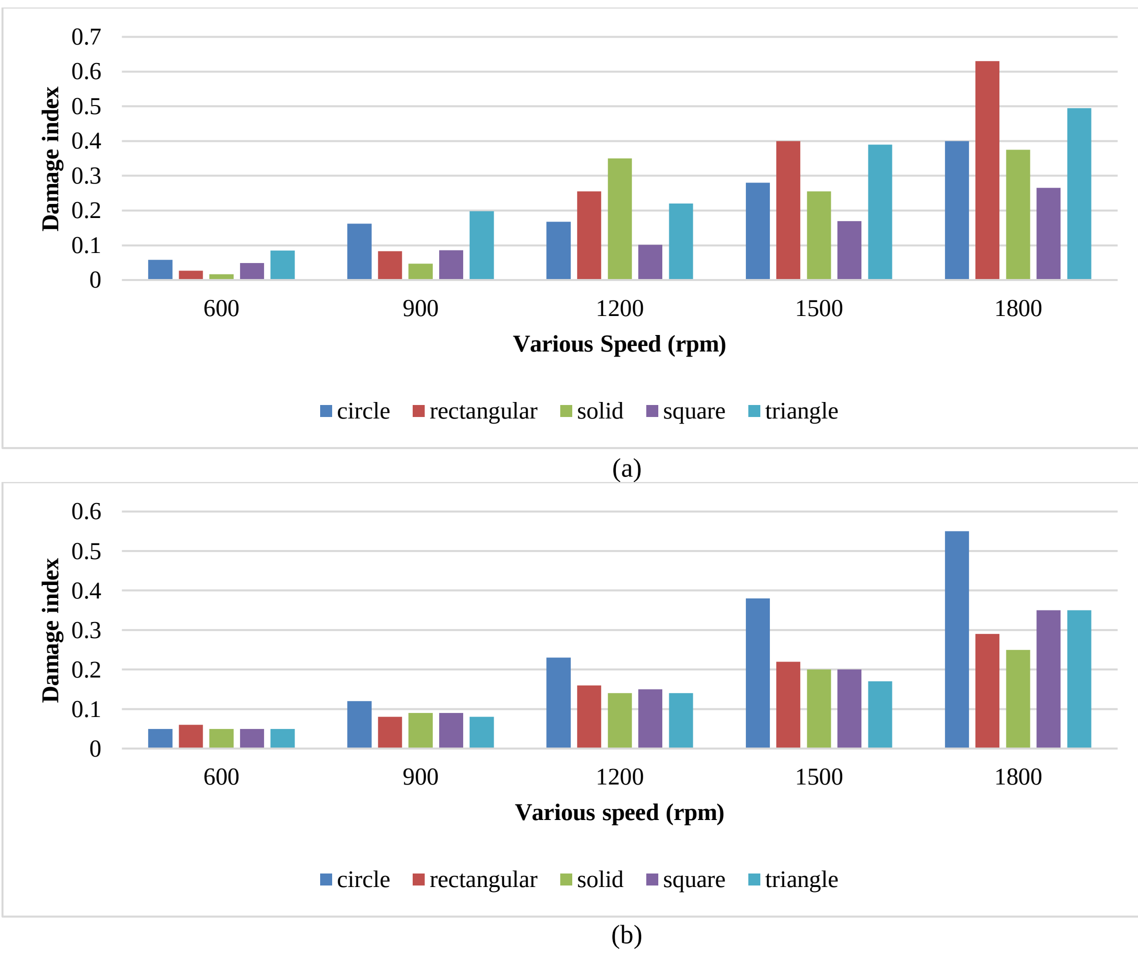
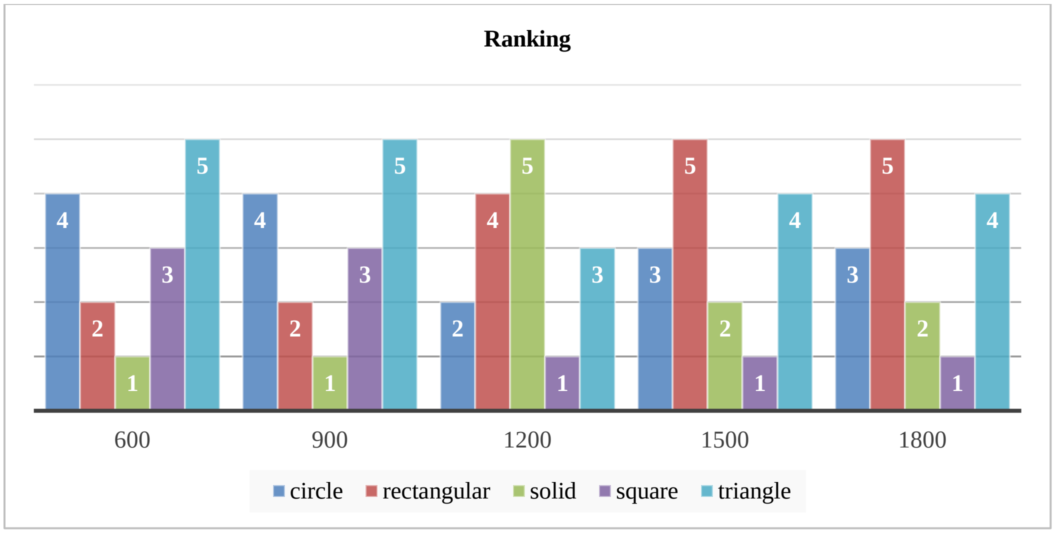
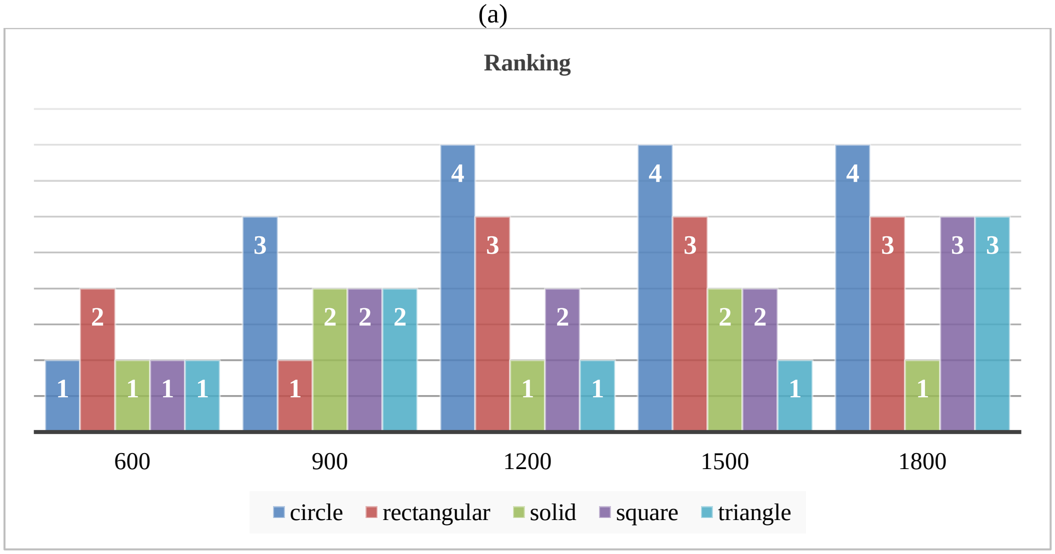


Figure 7 A comparison of the damage indices of the (a) thrust and (b) roller bearings



(a)



(b)

Figure 8 A comparison of the rankings of (a) thrust and (b) roller bearings, where a lower value indicates a better geometry

Table 3 The most significant damage indices of the different geometries for the thrust and roller bearings

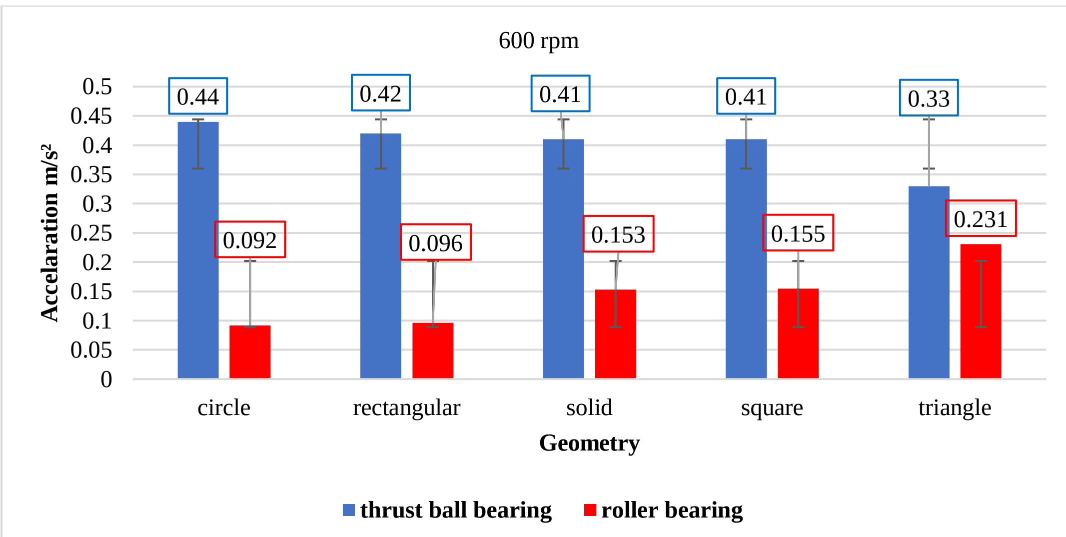
Speed	Geometry					Result
	Circle	Rectangular	Solid	Square	Triangle	
600						
900						
1200						
1500						
1800						

4.1.2Fast fourier transform (FFT)

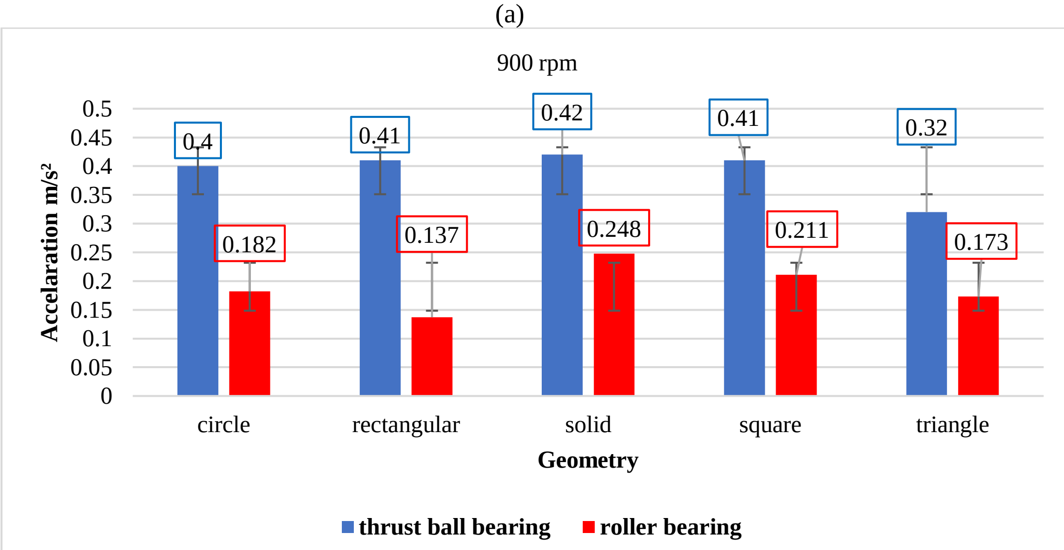
Figure 9 shows that there were considerable differences in the performances of the thrust and roller bearings at various speeds. The thrust bearings accelerated more at 600 rpm (*Figure 9(a)*), 900 rpm (*Figure 9(b)*), 1200 rpm (*Figure 9(c)*), and 1500 rpm (*Figure 9(d)*), while the roller bearings consistently outperformed them, showing a lower acceleration regardless of the geometry. This phenomenon could be explained by the narrower error bars and consistent acceleration of the thrust bearings, which suggested that they were less stable. However, the accelerations of both bearings converged at 1800 rpm *(Figure 9(e))*, although the thrust bearings, particularly the square- or triangular-shaped ones, performed somewhat worse. The error bars of the roller bearings always showed a higher value, indicating external susceptibility. Hence, this data supports the notion that vibrations are affected by structural loosening.

4.2Surface analyses

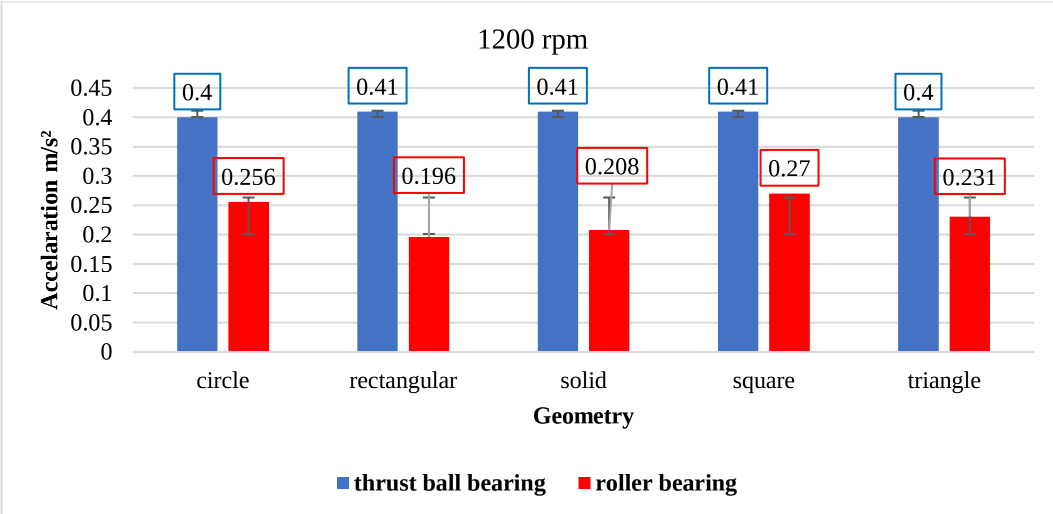
During the testing phase, a thorough examination of the samples revealed interesting findings regarding the behaviour of the contact friction surfaces. The majority of the samples displayed plastic deformation, a characteristic that is consistent with the properties of the PA12 nylon used in crafting the bearings. This material, known for its plasticity, underwent deformation when subjected to loads approaching its yield point [39, 40].



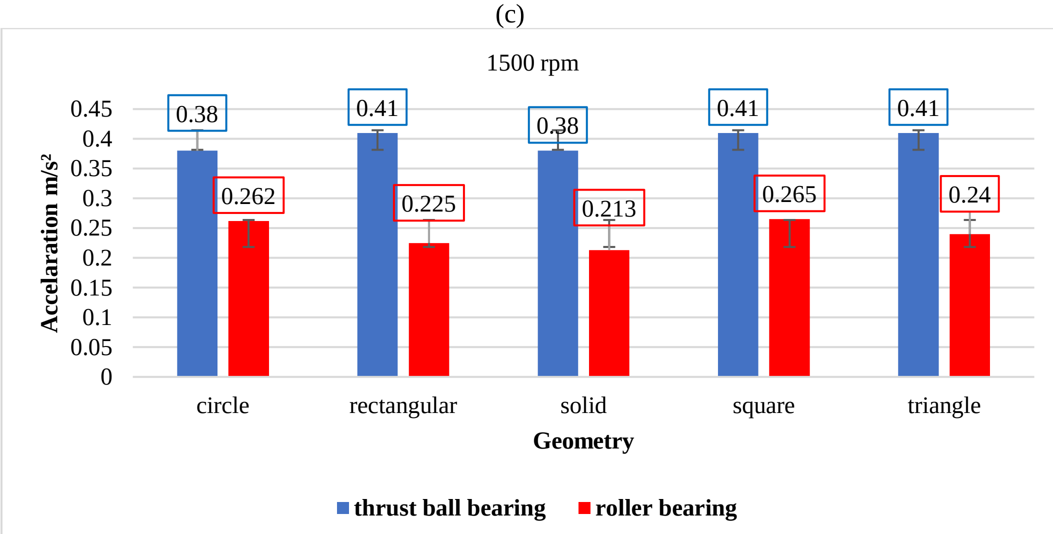
(a)



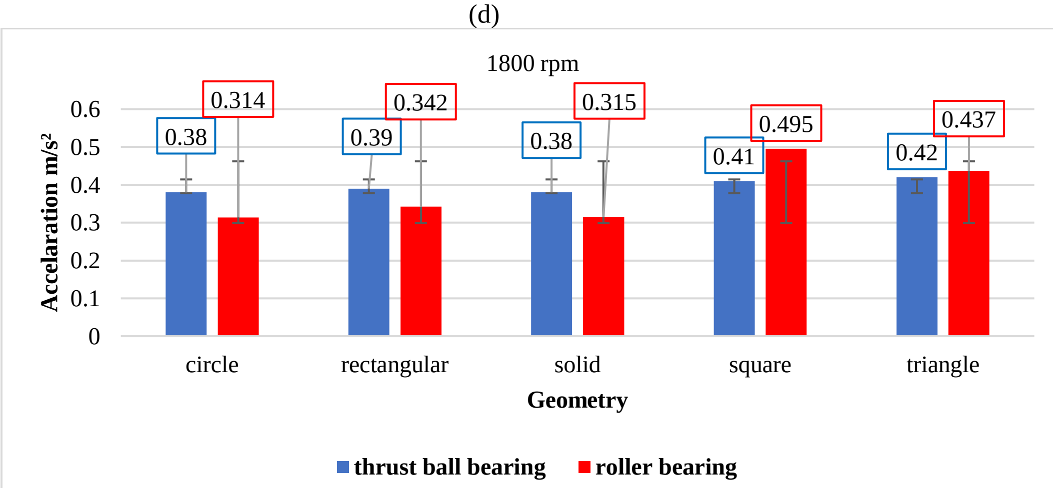
(b)



(c)



(d)



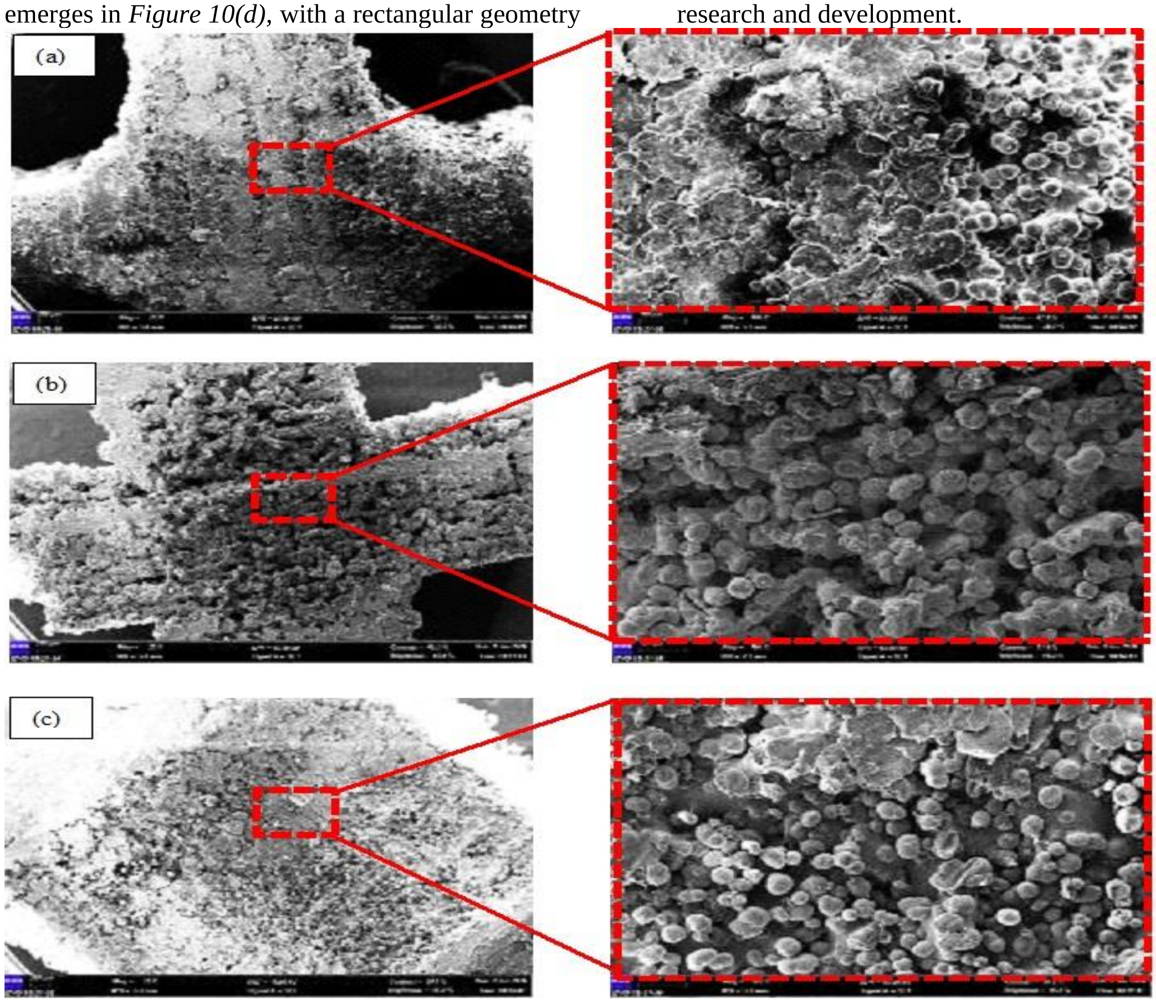
(e)

Figure 9 A comparison of the frequency spectra at (a) 600rpm, (b) 900rpm, (c) 1200rpm, (d) 1500rpm, and (e) 1800rpm

However, the analysis uncovered variations in the surface deformities, which were attributed to the different geometries. In *Figure 10(a)*, which depicts a circular geometry, the surface exhibited considerable roughness across an exceedingly small area due to widely spaced melted particles, some of which appeared disjointed. Conversely, *Figure 10(b)* showcases a smoother surface associated with a square geometry, albeit with numerous independent particles of irregular shapes.

Figure 10(c) depicts a solid geometry, where the surface texture retained a degree of roughness despite having a moderate surface area due to multiple independent particles. A contrasting scenario emerges in *Figure 10(d)*, with a rectangular geometry displaying a notably rough surface texture across an extremely minuscule area, characterised by significant distances between the melted particles and the presence of independent particles.

Transitioning to *Figure 10(e)*, a distinct observation unfolds as the triangular geometry exhibits a remarkably smooth surface texture. This smoothness surpassed the square geometry, and it was attributed to the shorter spacing between the melted particles, extensive coverage of the particle area, and the reduced presence of independent particles. These findings underscored the intricate interplay between the geometry and surface texture in the fabrication of bearings, offering valuable insights for further research and development.



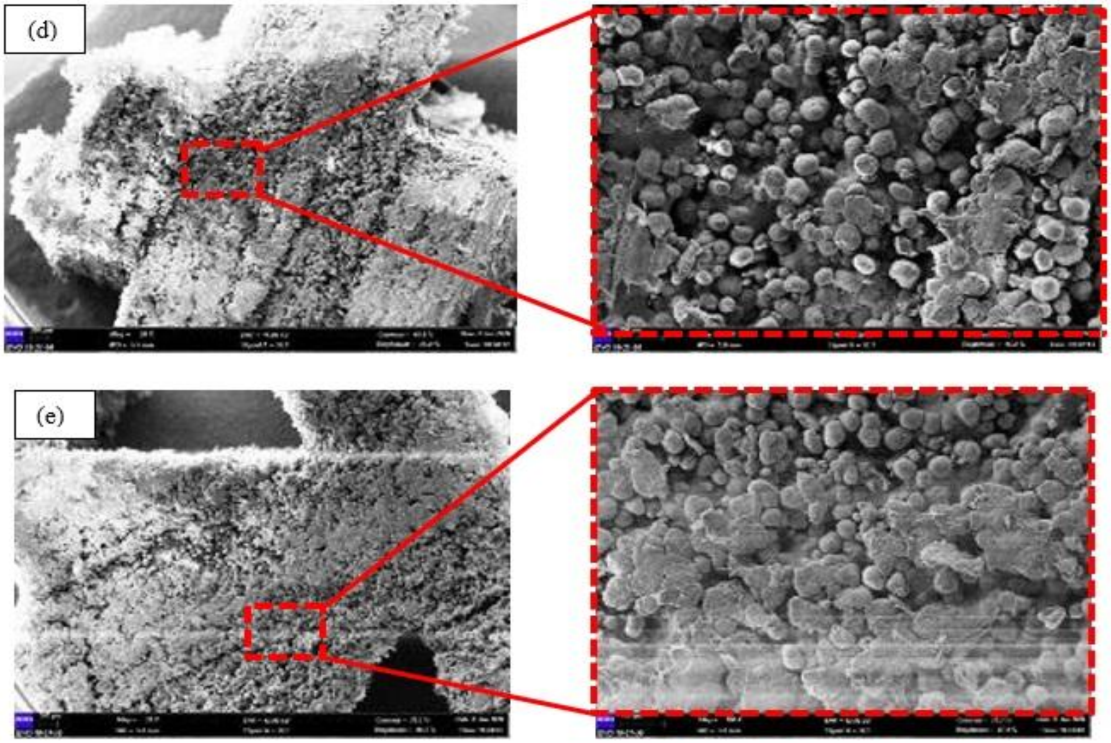


Figure 10 (a) Circle, (b) Square, (c) Solid, (d) Rectangular and (e) Triangular geometry

4.3Limitations

The results presented are based exclusively on bearings fabricated using SLS technology and do not directly apply to those produced through fused deposition modelling (FDM). This distinction is critical because SLS and FDM employ fundamentally different manufacturing techniques that lead to variations in structural, mechanical, and surface properties [41]. SLS is a powder-based additive manufacturing process where a high-powered laser selectively fuses powdered material layer by layer to create a part. This technique offers high precision, complex geometry capabilities and produces parts with superior mechanical strength and uniformity due to the dense material structure formed during sintering [42]. The inherent porosity and material bonding properties in SLS parts are generally minimal, contributing to more excellent durability and load-bearing capabilities. In contrast, FDM builds parts by extruding thermoplastic filaments layer by layer through a heated nozzle. Although FDM is more accessible and cost-effective than SLS, it often results in parts with noticeable layer lines and anisotropic mechanical properties. These limitations stem from weaker inter-layer bonding and possible voids between extruded lines, which can affect the load-bearing capacity and surface finish [43]. The lack of comprehensive studies on bearings fabricated using different internal geometrical structures and manufacturing techniques adds complexity to comparative analyses. For instance, while SLS parts may exhibit higher strength and wear resistance, FDM parts can be optimized for different applications through strategic design and infill geometry adjustments [44, 45]. These distinctions are essential for understanding the tribological performance and wear mechanisms in bearings produced through different 3D printing methods. Further research is necessary to evaluate the performance of FDM-printed bearings under similar test conditions and geometries, enabling a more comprehensive understanding of how manufacturing techniques influence bearing performance and mechanical durability.

A complete list of abbreviations is listed in *Appendix I*.

5.Conclusion and future work

The geometry applied in bearing designs offers the potential for innovative discoveries that could reduce raw material usage without compromising performance. In summary, the triangle-shaped thrust bearings had better damage indices than bearings with a square geometry, especially roller bearings.

The roller bearings consistently outperformed the thrust bearings with a lower acceleration across different geometries. The thrust bearings displayed narrower error bars and consistent acceleration, potentially indicating lower stability. The triangular geometry showcased a smooth surface texture that surpassed that of the square geometry.

Future studies could explore alternative geometries, such as hexagonal shapes, to optimise performance and the use of materials. Advanced simulations and experiments can assess the load distribution, wear, and stability. Investigating material-coating combinations and dynamic conditions would further enhance durability and efficiency.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

None.

Author's contribution statement

Fawzan Hanafi Mohamad Fazdhli: Investigation, Data collection, Analysis, Writing original draft manuscript. **Muhammad Ilman Hakimi Chua Abdullah:** Supervision, Challenges investigation, and Writing draft manuscript. **Ignatius Wong Loke Wei:** Data collection, Analysis, and Writing draft manuscript. **Alif Iqmal Abdul Khalid:** Data collection, Analysis, and Writing draft manuscript. **Mohd Rizal Alkahari:** Challenges investigation and Writing draft manuscript. **Rohana Abdullah:** Writing draft manuscript. **Mohd Fadzli Abdollah:** Challenges investigation and Writing draft manuscript. **Amir Abdullah Muhamad Damanhuri:** Writing draft manuscript. **Effendi Mohamad:** Writing draft manuscript. **Poppy Puspitasari:** Writing draft manuscript.

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Appendix I

S. No.	Abbreviation	Description
1	3D	Three-Dimensional
2	BC	Before Christ
3	FDM	Fused Deposition Modelling
4	LT	Layer Thickness
5	PA-12	Polyamide 12/nylon
6	rpm	Rotation Per Minutes
7	SEM	Scanning Electron Microscope
8	SLS	Selective Laser Sintering
9	FFT	Fast Fourier Transform
10	ZrO_2	Zirconium Dioxide