



Enhancement of Mechanical and Wear Properties in 3D-printed PEEK Specimens using Eco-friendly Infill Patterns *via* Fused Filament Fabrication

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ABSTRACT

The increasing use of 3D-printed polyether ether ketone (PEEK) materials in load-bearing applications necessitates a comprehensive evaluation of their wear characteristics and hardness under dynamic loading conditions. This study investigates the wear loss, coefficient of friction (COF), and hardness values of PEEK materials with four distinct surface patterns, namely, Line, Grid, Cubic, and Hexagon patterns. Controlled experiments revealed that the Line and Hexagon patterns exhibited the lowest wear loss (0.004 g), indicating superior wear resistance, while the Cubic pattern showed the highest wear loss (0.009 g). In terms of friction, the Grid pattern demonstrated the lowest COF (0.21), suggesting it offers the least resistance to movement, while the Line and Hexagon patterns had moderate coefficients of friction (0.40 and 0.35, respectively). The Cubic pattern displayed the highest COF (0.45). Hardness testing revealed that the Hexagon pattern had the highest hardness value (30), followed by the Line pattern (28), the Grid pattern (25), and the Cubic pattern (20). These findings highlight a balance between wear resistance, friction, and hardness among the different surface patterns, providing valuable insights for applications where these properties are crucial. Scanning electron microscopic images were analyzed to investigate the wear characteristics of fused filament fabrication-printed PEEK samples with varying infill patterns. The results showed that the Hexagon pattern exhibited the least surface degradation, demonstrating superior wear resistance compared to the Line, Cubic, and Grid patterns. This study offers valuable guidance for selecting optimal surface patterns in engineering and industrial applications to enhance performance and durability.

Keywords: 3D-printed PEEK; Mechanical properties; Wear properties; Eco-friendly infill patterns; Fused filament fabrication; Surface morphology.

1. INTRODUCTION

Polyether ether ketone (PEEK) has emerged as a preferred material in advanced engineering applications due to its exceptional mechanical properties, thermal stability, and biocompatibility. With the increasing adoption of 3D printing techniques like Fused Filament Fabrication (FFF), optimizing infill patterns has become critical to enhancing the performance of material in load-bearing and wear-intensive environments. The 3D printing industry continues to experience significant growth and innovation, reaching a market value of over \$20 billion for the first time. This growth is driven by the transformative impact of 3D printing across various sectors, including aerospace, automotive, electronics, healthcare, and energy, where the technology offers enhanced efficiency, customizability, and cost-effectiveness compared to traditional manufacturing methods. The rise of 3D printing in ceramics, in particular, has opened new possibilities, allowing the

fabrication of complex structures and the use of diverse raw materials, overcoming the limitations of conventional fabrication methods (Subramani *et al.* 2024). Traditional 3D printing processes with thermoplastic elastomers face conversion difficulties and uniform extrusion issues, limiting their effectiveness. The 3D printing industry faces several challenges that limit its ability to scale production efficiently, including high material costs, inconsistent part quality, and the need for extensive post-processing (Ree *et al.* 2024). There are concerns about the environmental impact of certain materials and energy consumption (Zhang *et al.* 2024). Challenges around printing speed and quality control, particularly for large-scale 3D printing applications, make it difficult to scale production efficiently. Fused filament fabrication, also known as fused deposition modelling, is a widely used 3D printing technology. It works by extruding melted thermoplastic filament through a heated nozzle, building objects layer by layer (Mehtedi *et al.* 2024). Fused filament

fabrication printers are user-friendly, offering a wide range of materials, each with unique properties. Fused filament fabrication, also known as fused deposition modelling, utilizes a variety of materials to cater to different printing needs and applications. One of the most popular materials is Polylactic Acid (PLA), which is biodegradable and easy to print, making it ideal for beginners and for educational purposes (Kharmanda *et al.* 2023). However, PLA has limited mechanical strength and heat resistance (Hou *et al.* 2023). Acrylonitrile Butadiene Styrene (ABS) is stronger and more heat-resistant than PLA but can be challenging to print due to its tendency to warp and emit odors during printing. It is commonly used in automotive parts, toys, and household items. Polyethylene Terephthalate Glycol (PETG) offers a balance by combining the ease of PLA printing with the strength and durability of ABS, making it suitable for functional parts and outdoor use (Durga *et al.* 2023). It is also transparent and can be used for food-safe applications (Sarker *et al.* 2023). Polymer materials are pivotal in modern industry due to their diverse properties and applications. These versatile substances can be tailored to exhibit a wide spectrum of characteristics, from flexibility and elasticity to rigidity and strength (Khan *et al.* 2023). Their lightweight nature contributes to fuel efficiency in aerospace and automotive sectors, while their durability ensures longevity in various applications, resisting wear and corrosion (Khan *et al.* 2024). Polymers are highly processable, enabling cost-effective manufacturing through techniques such as injection molding and 3D printing (Farrugia *et al.* 2024). They play important role as electrical insulators in electronics and offer biocompatibility for medical implants and drug delivery systems. Despite its benefits, FFF has notable drawbacks, including visible layer lines and a generally rough surface finish (Kantaros *et al.* 2023). Printing can be slow, especially for large or high-resolution objects, and support structures often increase print times.

Chithambaram *et al.* (2024) examined the hardness and wear behaviour of the polyether ether ketone specimens using a fused deposition modelling approach. The microhardness was measured using Vickers's microhardness tester, and wear behaviour was evaluated using the pin-on-disc method. They suggest that the test specimen created utilizing the parameters, including a printing speed of 20 mm/s and a layer thickness of 0.15 mm, had better wear and hardness properties than the other test specimens.

Dhakal *et al.* (2024) investigated the tribological properties of neat and carbon fiber-reinforced PEEK materials manufactured using the FFF technology. The reciprocating sliding behavior of printed polymers against stainless steel was investigated in both dry and water-lubricated circumstances. The findings of this study have important implications for improving the processing design of PEEK-based materials used in

extrusion-based 3D printing for tribological applications Haleem *et al.* (2019) examined the coefficient of friction (COF) and wear aspects of ABS polymer, with an emphasis on optimal 3D printing parameters. Layer height has a considerable impact on friction and wear rate, according to research using fused filament fabrication and response surface methods using a Box-Behnken design. The ideal settings include a layer height of 0.10 mm, a nozzle temperature of 234 °C, and a triangle print pattern. He *et al.* (2023) conducted orthogonal experiments to investigate the impact of annealing temperature and fused deposition modelling (FDM) parameters (nozzle temperature, platform temperature, layer thickness, and printing speed) on the mechanical properties of PEEK. With lower elongation at break and a peak in mechanical strength at 300 °C, annealing temperature was found to be positively correlated. The final strengths increased by 36%, 54%, and 21% in the tensile, flexural, and compressive domains. Examined in parallel, PEEK annealed at 200 °C showed the lowest wear rate ($1.37 \times 10^{-6} \text{ mm}^3/\text{Nm}$).

Massocchi *et al.* (2021) examined the friction and wear of PEEK in a dry sliding environment (without lubrication) and contrasted with those of Babbitt metal using a ball-on-disk tribometer. The PEEK polymers exhibit COFs of roughly 0.22 and 0.16 under the 1 and 5 N applied stress, respectively, according to the experimental activity's results. Results for COF and wear volume loss are presented and contrasted with the Babbitt coating used as a reference. The mechanical characteristics of specimens produced by 3D printing technology from poly-ether-ether-ketone material were ascertained, and the impact of print directionality on the mechanical properties was also examined (Mrówka *et al.* 2021). Two populations of specimens were studied; one had a crystal structure, while the other had an amorphous structure. Impact, three-point bending, and static tensile tests were performed. The outcomes show that compared to the unmodified specimens, the changed PEEK specimens have poorer thermoplastic characteristics. Lv *et al.* (2024) studied the new PEEK-based composites were made using multi-material FDM and consisted of silicon dioxide-filled and alternating short carbon fiber-reinforced PEEK layers. The combination effect of rolling nanoparticles and graphitized self-lubricating transfer films was discovered to be responsible for the minimal friction and wear that occurred at high contact pressure.

Wang *et al.* (2024) introduced a unique method that produces PEEK with different filling densities using 3D printing technology and then enhances PEEK's frictional performance by conducting in situ synthesis of zeolite imidazole framework nanomaterial on its surface. The results show that the composite material performs significantly better in terms of friction under low load, with a minimum wear rate of $4.68 \times 10^{-6} \text{ mm}^3/\text{Nm}$, which is approximately 1.3 times better than the wear rate of

$1.091 \times 10^{-5} \text{ mm}^3/\text{Nm}$ for the non-grafted PEEK material. This study addresses a significant research gap by examining the wear performance of PEEK manufactured through FFF.

Timoumi *et al.* (2022) investigated tensile properties using the Taguchi approach and identified optimal mechanical properties, including a tensile strength of 54.97 MPa and a modulus of 2.67 GPa, achieved with a honeycomb pattern having 40% infill. This configuration also resulted in a maximum stress of 7.186 MPa and a strain of 0.00627 mm, demonstrating potential for lightweight orbital implants. The authors concluded that wear properties could be minimized by optimizing tensile strength and Young's modulus. Similarly, Hassan *et al.* (2021) employed an experimental design to analyze infill patterns (rectilinear, grid, triangular, wiggle, fast honeycomb, and full honeycomb) and infill percentages (25%, 50%, 75%, and 100%). Energy consumption was found to be high for wiggle and triangular patterns and low for the rectilinear pattern during both the printing stage and the overall process. Pulipaka *et al.* (2023) measured mechanical properties and observed that roughness tests did not affect hardness and creep. Greco *et al.* (2024) studied the fatigue behavior of FFF-produced PEEK, considering variations in infill patterns (triangular and rectilinear). The fatigue behavior of PEEK made by FFF was examined in this work, with particular attention to the effects of changes in infill pattern (rectilinear or triangular) and layer height (0.15 mm or 0.25 mm). The results of the fatigue tests indicate that fatigue behaviour is significantly influenced by the infill design, with the rectilinear pattern outperforming the triangular one. When paired with the rectilinear infill pattern, layer height had minimal impact. Better fatigue performance was demonstrated by specimens with rectilinear patterns, which reached infinite fatigue life at about 70% of the ultimate tensile stress.

The current research investigated how different infill patterns, namely Hexagon, Grid, Circle, and Line, affect the wear behavior of the material. Wear tests were conducted under varying conditions to measure the performance of material. Understanding the interplay between infill patterns and wear performance enables not only the optimization of infill selection for enhanced durability but also the expansion of the practical uses of 3D printed PEEK components. By elucidating these relationships, the study aims to ensure the reliability and efficiency of 3D printed PEEK in diverse real-world applications, potentially transforming practices in industries where high-performance polymers are required.

2. MATERIALS AND METHODOLOGY

2.1 Fused Filament Fabrication Printing

This study employed FFF to print PEEK with several infill patterns, such as Line, Grid, Cubic, and Hexagon. The PEEK material (product code: PEEK K10) was obtained from Kexcelled3D in China. It had the following specifications: density: 1.23 g/cm^3 ; tensile strength range: 70–80 MPa elongation range: 4–6%. The filament measured 1.75 mm in diameter. India's Creatbot provided the FFF machine. Using Catia V5 software, the design model for 3D printing was produced and saved in STL format. The nozzle used by the FFF machine had a diameter of 0.4 mm. The printing process was carried out at 410 °C for the nozzle and 120 °C for the bed in order to improve adhesion and minimize warping. Throughout the printing process, a build orientation of 45°, an infill density of 100%, and a layer height of 0.2 mm were maintained. To guarantee correct adhesion to the build plate, the height of the initial layer was slightly increased to 0.3 mm. In light of the model's complexity, the printing speed was set at 30 mm/min in order to balance speed and print quality.

2.2 Experimental Procedure

The mechanical and tribological properties such as hardness and wear loss were calculated as per the ASTM standards.

2.2.1 Wear Test

Fig. 1 illustrates a test setup for evaluating the mechanical properties of materials. Panel (A) shows the overall apparatus, including the component used for sample positioning and feeding. Panel (B) zooms in on the specific section of the setup, where the material sample is being subjected to a test, as indicated by the red arrow. This setup likely involves mechanical testing methods such as wear or friction testing, which can provide insight into the performance of materials under dynamic conditions. During the wear test, the coefficient of friction and wear rate were determined for four samples of different patterns (Line, Grid, Cubic and Hexagon). The specimen weight is measured and recorded before and after the test. The difference in weight of the sample is the wear loss. The COF and wear rate was calculated using the standard formulae and procedure.

The following equations (1) and (2) are used for the calculation of both the coefficient of friction and wear rate.



Fig. 1: Pin-on-disc (a) machine setup and (b) enlarged view of sample position

$$\text{Coefficient of friction} = F_f/F \quad \dots (1), \quad \text{2.2.2 Hardness Test}$$

where F_f – frictional force in N and F is applied load in N.

$$\text{Wear loss in g} = W_1 - W_2 \quad \dots (2),$$

where W_1 - weight of the sample before test, W_2 - weight of the sample after test

Table 1 displays experimental settings for all wear test samples, shown in Fig. 2. The purpose of this wear analysis experiment was to assess a material's wear properties under particular operating conditions. The material was subjected to an applied force of 10 Newton, which replicated the stress it would encounter in practical situations. The relative speed between the material and the counter surface was determined by sliding the substance at a speed of one meter per second. With 500 m of sliding distance covered in the test, a thorough evaluation of wear across a sizable length was guaranteed. To ensure continuous sliding action, the material was allowed to slide along a 40 mm diameter circular route at a rotating speed of 478 revolutions per minute. 500 seconds were allotted to the test's execution. Throughout the test, data was recorded at intervals of 13 minutes and 32 seconds, giving precise insights into the wear behavior. This rigorous methodology contributes useful information regarding the prospective application of the material in many industries by enabling a complete investigation of the wear resistance of the material.

Table 1. Experimental settings for all wear test samples

Test Parameters	Machine Settings
Applied load (N)	101
Sliding velocity (m/s)	1
sliding distance (mm)	500
sliding dia (mm)	40
RPM	478
Time	13 minutes and 32 seconds

The average value of five samples was taken as hardness value of PEEK pattern. In the hardness test, the load was gradually applied on the specimen for penetration in five places, and after some time, the load was removed and an average of five indentations on the specimen was taken.

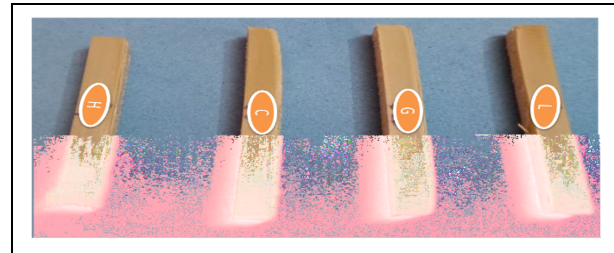


Fig. 2 Test samples used during the wear test

3. RESULTS AND DISCUSSION

3.1 Coefficient of Friction and Wear

Fig. 3(a) illustrates the coefficient of friction over time for four different surface textures (Line, Grid, Cubic, and Hexagon), which is crucial for understanding their wear behavior under dynamic conditions. The graph represents the time (m/s) in X-axis while the Y-axis shows the coefficient of friction. Each texture exhibits an initial transient phase where the COF changes rapidly before stabilizing after approximately 100 milliseconds. The hexagon texture shows the highest stabilized COF at around 0.45, followed by the line texture at 0.4, the cubic texture at 0.35, and the grid texture at 0.3. These results suggest that surface textures significantly influence wear behavior, with higher coefficients of friction typically indicate higher wear rates. Consequently, the hexagon texture, despite providing the highest friction, may experience more significant wear compared to the grid texture. This analysis highlights the importance of

selecting appropriate surface textures to balance friction and wear for various applications. This investigates how a cell's survival is impacted by the mechanical interaction with its surroundings, quantified by the COF.

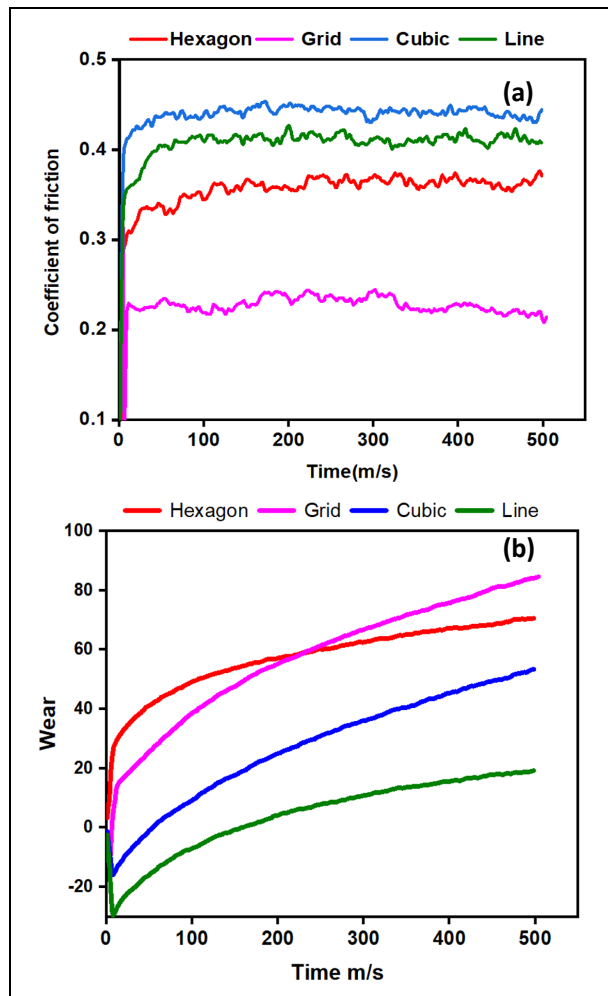


Fig. 3: (a) Coefficient of friction and time and (b) Wear and time

The graphs represent the cell tolerance to these interactions, with the x-axis depicting the COF (measured in milliseconds) and the y-axis representing a measure of cell health or survival time. The grid type and line styles differentiate the specific mechanical environments. The top left graph, visualized on a linear grid with a straight line, suggests that a cell on a smooth surface (linear grid) experiences optimal survival (around 500 milliseconds) under low friction (around 0.15). This implies that minimal friction allows the cell to move freely, potentially facilitating essential mechanical processes like nutrient uptake and waste removal, ultimately extending its lifespan. In contrast, the bottom left graph, plotted on a cubic grid with a curved line, indicates that a cell in a more confined environment (cubic grid) survives longest (around 400 milliseconds) under high friction (around 0.40). The increased friction in this scenario might provide crucial mechanical

support, preventing excessive movement and potential damage to the cell in a structurally complex environment. Fig. 3(b) presents the wear *versus* time graph. Here, the Y-axis represents the amount of wear the cell experiences. This graph suggests that on a honeycomb-like structure (hexagonal grid), the cell experiences the least wear (around 0.20) when the COF is high (around 0.40). This implies that high friction in this context reduces the mechanical stress and wear on the cell by providing stability. Understanding the interplay between mechanical properties and cell biology is crucial in areas like bioengineering and tissue regeneration, where designing surfaces that optimize cell function and lifespan requires careful consideration of the mechanical cues.

Table 2 summarizes the results of wear analysis experiment on different 3D printed patterns. The experiment evaluated the wear resistance of the patterns by measuring their weight loss before and after a simulated wear test.

Table 2. Experimental readings of wear analysis

Patterns	Initial Weight (g)	Final Weight (g)	Wear Loss (g)
Line	1.551	1.547	0.004
Grid	1.437	1.43	0.007
Cubic	1.488	1.479	0.009
Hexagon	1.451	1.447	0.004

As observed, all patterns exhibited some degree of wear loss during the experiment. The cubic pattern showed the highest wear loss (0.009 g), followed by the grid (0.007 g) and the Line and Hexagon patterns (0.004 g each). These initial findings suggest that the geometry of the 3D printed pattern may influence its wear resistance. Further analysis is required to determine the specific mechanisms contributing to wear in each pattern.

Fig. 4 (a) and (b) present a technical analysis of the coefficients and wear loss for four different samples (Line, Grid, Cubic, and Hexagon), with associated error bars indicating variability in the measurements. The wear coefficient values were- Line (0.41), Grid (0.22), Cubic (0.42), and Hexagon (0.35). The wear coefficient indicates the rate at which material is worn away under specified conditions. The relatively high wear coefficient for the Line sample (0.41) suggests moderate resistance to wear, likely due to its uniform but less interlocked microstructure. The Grid sample (0.22) exhibits significantly lower wear, indicating enhanced wear resistance, likely due to better stress distribution and reduced localized deformation.

The Cubic sample (0.42) has a wear coefficient similar to the Line sample, suggesting that the cubic geometry does not significantly enhance wear resistance, possibly due to internal stress concentrations or less

effective load distribution. The Hexagon sample (0.35) shows good wear resistance, attributed to its efficient packing and structural stability, which help minimize deformation and even distribution of stress. The error bars indicate the variability in these measurements, highlighting the consistency and reliability of the data. Overall, the Grid structure demonstrates the best wear resistance, while the Line and Cubic structures show higher wear coefficients and the hexagonal structure provides balanced performance with good wear resistance.

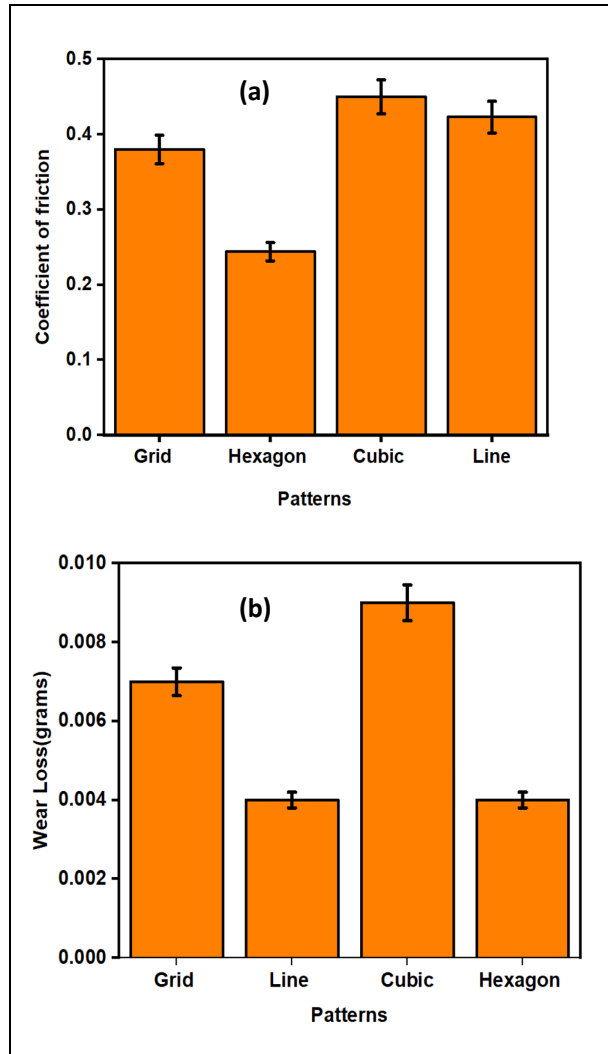


Fig. 4: (a) Coefficient of friction for various infill patterns and (b) Wear loss of various infill patterns

3.2 Hardness Test

Fig. 5 shows the microhardness value of the four different patterns of the PEEK specimens. The hardness values of the specimens were recorded after conducting tests as 28 HV, 25 HV, 20 HV, and 30 HV for Line, Grid, Cubic, and Hexagon patterns respectively. The hardness values of Line and Hexagon pattern were greatly increased by 34% compared to the sample with the cubic

pattern. It was noted that the specimens with line and hexagon patterns improved the hardness maximum due to the geometrical shape of these patterns.

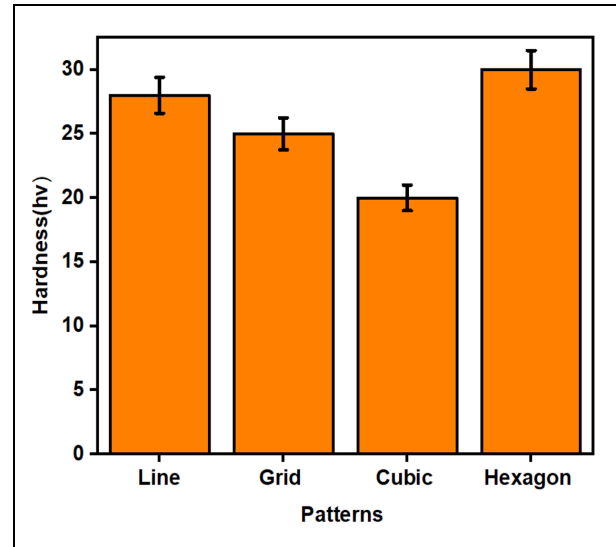


Fig. 5: Variation of hardness against the different patterns of PEEK specimen

3.3 SEM Analysis

The scanning electron microscopic images were taken at the wear surfaces of the four different sample patterns - (a) Line, (b) Grid, (c) Cubic and (d) Hexagon, respectively as shown in Fig. 6.

The SEM pictures of the PEEK material show a number of surface characteristics that could shed light on its properties and possible functionality. The smooth surface with few pores and a possible break is shown in Fig. 6(a), indicating that although the material is largely undamaged, it may be subjected to localized stress or impact, and little cracks could eventually cause the material to deteriorate. A more textured surface with deeper pores and fissures is seen in Fig. 6(b), suggesting more stress or degradation of the material, maybe as a result of wear, fatigue, or exposure to the environment, making it more prone to failure. The ridge-like structure shown in Fig. 6(c) may have developed as a result of material deformation under stress. The presence of cracks or discontinuities within the ridge indicates weak areas that could reduce the overall strength of the material, particularly if the ridge plays an essential role in structural integrity.

The uneven material properties, which are probably the result of inconsistent processing or different environmental conditions, are shown in Fig. 6(d), which shows a mix of smooth and rough regions with a higher concentration of pores in some areas. This could lead to localized weakness and increase the likelihood of failure in those regions. Collectively, these pictures show different levels of material deterioration, from little

imperfections to more serious structural deficiencies, emphasizing how crucial it is to find and fix flaws in order to stop additional harm. Numerous factors, like the production process, material deterioration, or mechanical stress during service, may have an impact on these

characteristics. For example, residual stresses or surface roughness may be left behind by the processing methods such as injection molding or milling, used to make the PEEK material.

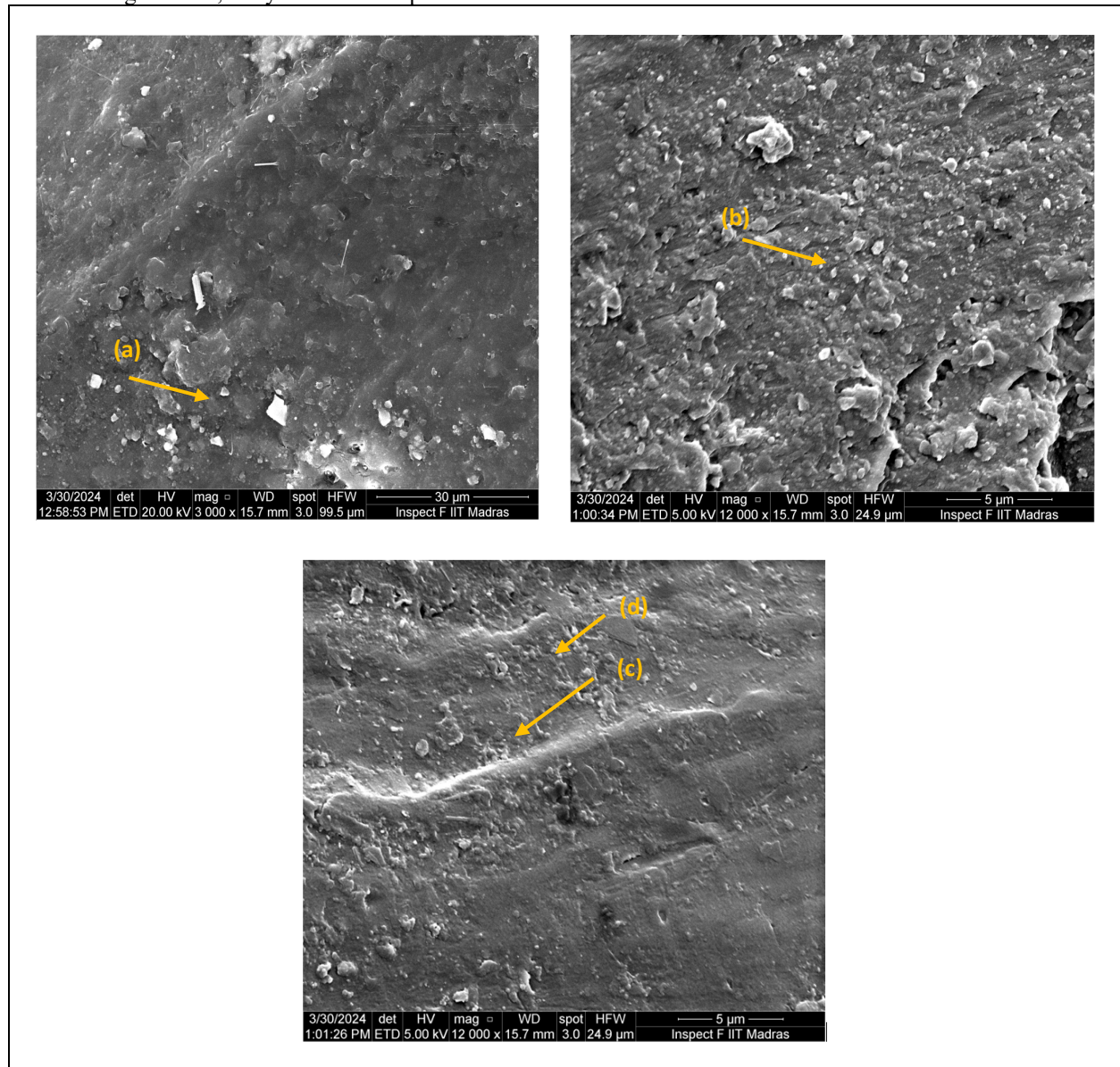


Fig. 6: SEM images of all four patterns of wear test specimens (a) Line (b) Grid (c) Cubic and (d) Hexagon

4. CONCLUSION

This research highlights the significant impact of surface patterns on the wear characteristics, coefficient of friction, and hardness of 3D-printed PEEK materials under dynamic loading conditions. The Hexagon pattern demonstrated the highest hardness value and the least wear loss, indicating superior resistance to wear and surface degradation. The superior wear resistance of hexagon pattern and hardness can be attributed to its geometric design, which provides isotropic load distribution and enhanced stress dissipation during wear

tests. The interconnected structure of hexagons offers inherent stability and minimizes localized deformation. The Line pattern also showed low wear loss and high hardness, making it an excellent choice for applications requiring durability. The Grid pattern exhibited the lowest COF, suggesting it is ideal for applications where low resistance to movement is crucial. Conversely, the Cubic pattern, despite its highest wear loss and COF, provides valuable insights into the balance between wear resistance and friction. The SEM images further confirmed the superior wear resistance of the hexagon pattern, revealing minimal surface degradation compared

to the other patterns. These findings offer valuable guidance for optimizing surface patterns in engineering and industrial applications, enabling the selection of the most suitable pattern to enhance performance and durability. Future research could extend these findings by exploring additional surface patterns and varying dynamic conditions to further refine the application of 3D-printed PEEK materials in load-bearing environments.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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