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MANUFACTURING ISSUES WITH 3D-PRINTED GEARS MECHANICAL PROPERTIES – A LITERATURE SURVEY

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Abstract: Additive manufacturing, often known as 3D printing, is substantially revolutionizing the industrial environment by turning new ideas into tangible items. This technology promotes innovation in various industries, like healthcare, aerospace and automotive, by allowing for the development of sophisticated, one-of-a-kind designs while reducing waste and expenses. Prompting improvements in production, additive manufacturing demonstrates a great deal of design variation while also being very efficient. This technology reforms traditional production techniques and makes solutions that were previously impossible. This research delves into the mechanical properties and production challenges of additively manufactured 3D-printed gears. The evaluation of gear performance focuses on the influence of essential characteristics, including the analysis of printing orientation and infill patterns, among other factors. Mechanical properties such as tensile and bending strength rise in a horizontal direction; conversely, in a vertical structure, the reverse is true. Concentric, grid-like infill patterns improve materials like PLA and PLA+ in strength and surface quality. This study examines significant challenges, such as thermal expansion and air gaps that affect gear reliability. Effective solutions require refining gear designs, enhancing heat dissipation, and optimizing material properties. The research findings improve comprehension of how 3D-printing parameters affect gear performance, offering valuable insights for the design and manufacture of durable, high-performance 3D-printed gears in industrial applications.

Keywords: *printed gear, additive manufacturing, printing orientation, infill patterns*

1. INTRODUCTION

Additive manufacturing (AM), sometimes referred to as 3D printing, is a process used to construct three-dimensional solid items using 3D computer-aided design (CAD) model data, typically in a layer-by-layer manner, in contrast to conventional subtractive manufacturing techniques. This technology may replace several traditional manufacturing processes and enable the emergence of novel business models, goods, and supply networks (Markiz, Horváth, & Ficzere, 2020). The primary advantages of selecting additive manufacturing are design flexibility, cost-effective prototyping, material efficiency, customization, supply chain simplicity, and energy efficiency (Gupta, 2018), besides, AM is used in various applications in the medical-, defence-, aircraft-, and automobile industries, etc.

In mechanical power transmission systems, gears play a crucial role. They are suitable for both large rotating machines and small wristwatches because of their size variation. They are often composed of several metallic and non-metallic materials (Karupaiah, et al., 2024). Polymer gears have become favoured in moderate and heavy-duty tasks mainly to their cost-effectiveness and lower noise levels in comparison to metal gears. These polymer gears have several benefits, including cost-effectiveness, reduced weight, better efficiency, almost noiseless operation if the lubrication is in the right quantity, and in most cases the absence of a need for external lubrication, however, it is needed for specific cases. These characteristics make them especially appropriate for applications in automotive, aeronautical and medical engineering (Pujari, Manoj, Gaddikeri, Shetty, & Khot, 2024).

The mechanical properties of a 3D-printed gear can be negatively influenced by thermal expansion and material softening when the surface temperature of its teeth rises as a result of load and friction. This may result in excessive wear, deformation, and possible breaking of the gear teeth. Utilizing materials with great thermal stability, refining the gear design for increased heat dissipation, and ensuring considerable lubrications to lower friction are vital for reducing these defects. Additionally, any thermal issues can be quickly identified and addressed with thorough testing and careful observation of the operational conditions of the gear (Yilmaz, Yilmaz, & Gungor, 2024).

Among all parameters, those affecting the mechanical properties of the gear, printing orientation and infill pattern have their share of influencing the gear performance and need to be demonstrated properly.

Loads act on the gear tooth, and these loads create a bending moment somewhere on the tooth root, which can damage the tooth and break it somehow (rigid or fatigued). So, the aim is to investigate and know which printing direction is good since the helical gear starts horizontally and goes up at an angle, as shown below in Figure 1. Consequently, the best printing direction reduces the damage to the tooth.

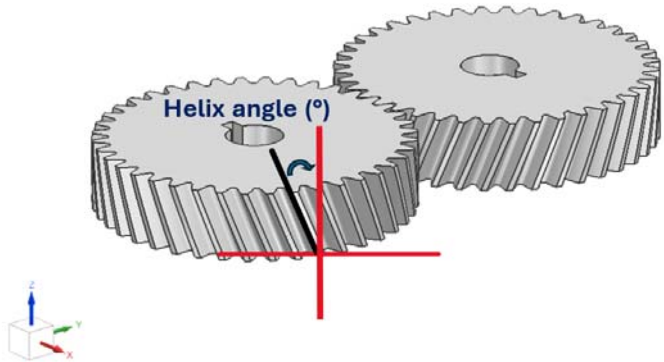

Figure 1. *Helix Angle direction of two meshed gears*

And need to experience which type of infill pattern can endure and withstand the loads (pressure and bending moment), as explained in Figure 2. The line of action is signed with blue line in the figure, for the two meshed gears. The normal tooth force is (red) acting on the centre point of the flank, in the direction of the line of action, the letter "n" indicates the direction of the rotation speed (black), while the bending moment loads the cross-section of the root of the tooth (green), with the possibility of using different types of patterns simultaneously.

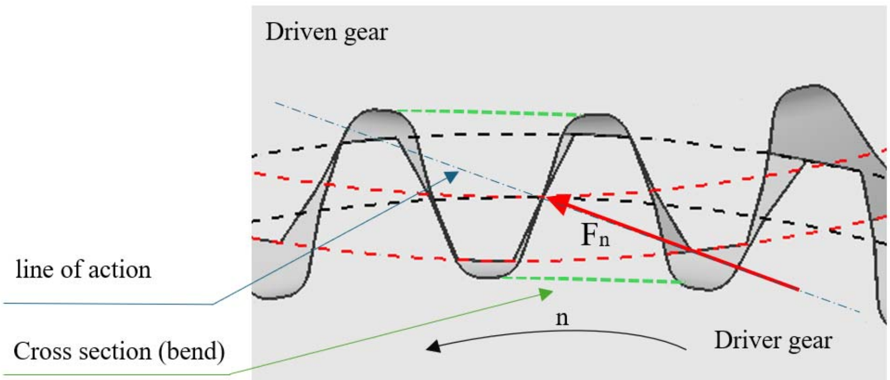

Figure 2. *A simple schematic diagram showing the (force and the bending moment) acting on the teeth*

2. THE INFLUENCE OF PRINTING ORIENTATION ON THE STRENGTH OF THE COMPONENTS

As mentioned earlier, many factors can influence the strength of the printed part. Among these factors -as an additive manufacturing technology- printing orientation shows up with a pivotal effect, as it significantly impacts the behaviour of the printed part by determining how much the printed part can endure for a long time of working cycles without a breakage.

Horizontal orientations along the XY (flat) and YZ (on-edge) offer the best tensile and impact strength in comparison to vertical orientations along the ZX (which are often poorer in terms of strength and stiffness) (Mohd Khairul Nizam, Ismail, & Yap, 2022), as illustrated in Figure 3. Moreover, to investigate the impact of printing orientation (horizontal/vertical) and printing continuity on the strength of the printed components, printing with a pause for a specified duration and resuming afterwards does not considerably affect ultimate tensile strength for the horizontal direction, in contrast, the vertical direction resulted in reduced ultimate tensile strength (Alzyod & Ficzere, 2022). Optimal orientation selection, such as horizontal alignment, is best for gears used in load-bearing applications.

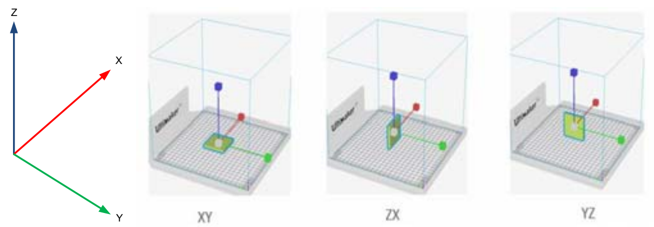

Figure 3. *Printing Orientation*
(Mohd Khairul Nizam, Ismail, & Yap, 2022)

For all orientations (upright, on-edge, and flat), increased feed rates resulted in reduced strength and stiffness properties, contributing to more brittle behaviour. Conversely, increased layer thickness in various printing orientations enhanced tensile and bending strengths; however, this also resulted in a heavier specimen, extended printing duration, and lowered ductility (Chacón, Caminero, García-Plaza, & Núñez, 2017). Three orientations (X, Y, Z) and three cooling settings (cooling within the printer, in an oven, and at room temperature) were examined to assess the impact of printing direction and post-printing cooling conditions on the fatigue bending properties. The results indicated that specimens in the X and Y directions showed similar mechanical performance when cooled in the printer or oven;

conversely, samples cooled at room temperature exhibited weaker performance, with Z-direction samples demonstrating the poorest bending ability. For industrial applications, oven cooling may be superior to in-printer cooling (Glaskova-Kuzmina, et al., 2023).

Upon investigating the influence of angle on mechanical properties, a sample printed along the x-axis at various angles (0°, 30°, 60°, 90°), as illustrated in Figure 4, revealed no correlation between the orientation of the specimen on the printing bed and the direction of the fracture surface, which is perpendicular to the applied testing force (Cojocaru, Frunzaverde, Nedelcu, Miclosina, & Marginean, 2021).

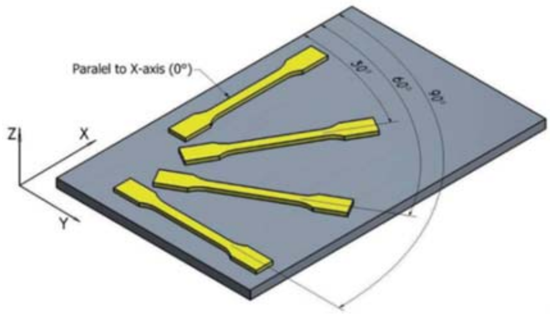

Figure 4. *Printing orientation angle (Cojocaru, Frunzaverde, Nedelcu, Miclosina, & Marginean, 2021)*

Oppositely, ultimate tensile strength is at its highest at a 90° printing angle and reduces as the angle lowers when the samples are printed vertically, as the layers are aligned with the direction of the applied force (Yao, Deng, Zhang, & Li, 2019), as briefly shown below in Figure 5.

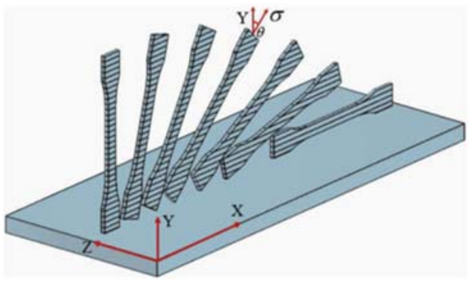

Figure 5. *The printing positions and angles of 3D printing specimens (Yao, Deng, Zhang, & Li, 2019)*

3. THE INFLUENCE OF THE INFILL PATTERNS ON THE MECHANICAL PROPERTIES OF THE COMPONENTS

As a part made by additive manufacturing, so-called 3D printing, which totally differs from the conventional manufacturing methods (i.e. injection moulding, CNC, hobbing, etc.), the infill pattern plays a crucial role in defining and determining the mechanical properties and lifetime of a product.

The selection of various materials and infill patterns significantly affects the mechanical properties of the printed component. Various densities (20% - 100%) for diverse filling patterns, as seen in Figure 6, indicate that the concentric and grid patterns yield superior surface quality and tensile strength for Polylactic Acid (PLA). Conversely, triangle and zigzag designs have the least desirable properties (Lalegani Dezaki, et al., 2021). Moreover, increasing the infill density enhances strength but increases weight.

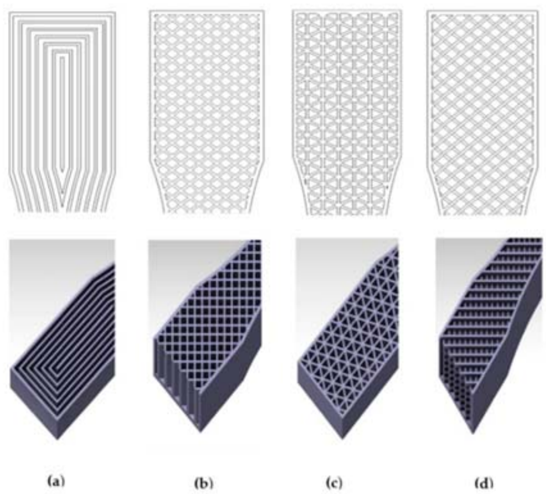

Figure 6. *(a) concentric pattern, (b) grid pattern, (c) triangle pattern and (d) zigzag pattern (Lalegani Dezaki, et al., 2021)*

For enhanced PLA (PLA+/tough PLA), which offers greater resistance against damage than the normal PLA, the concentric pattern offers optimal strength and surface quality, whereas the gyroid and quarter-cubic, Figure 7, patterns for Polyethylene Terephthalate Glycol (PETG) provide superior smoothness and high tensile strength (Kadhum, Al-Zubaidi, & Abdulkareem, 2023).

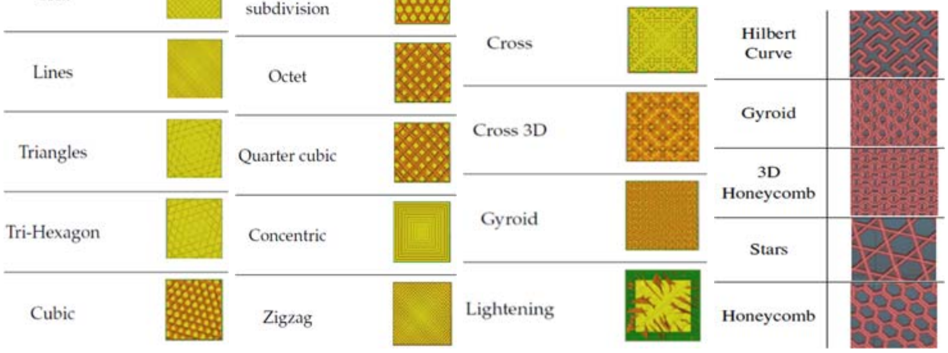

Figure 7. *Different infill patterns*
(Kadhum, Al-Zubaidi, & Abdulkareem, 2023)

Whereas the influence of raster angle greatly enhances the strength for specific raster angles (0° - 90°). The 0°, 90° raster angle exhibits greater resistance to deformation, whereas -45°, +45° enhances elongation and toughness (taking into consideration the part design and shape). Taking care of the air gaps -space between two tool paths- is also important to ensure better properties; however, as the air gaps decrease, as shown in Figure 8, tensile strength increases (Akhouri, Karmakar, Banerjee, & Mishra, 2021). The best pattern in this concern is the honeycomb and the hexagonal, which leave small air gaps, while The Hilbert tends to have the weakest properties because of the large air gaps (Eryildiz, 2021).

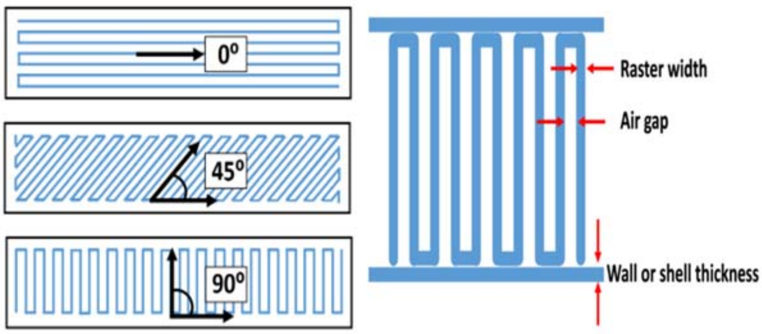

Figure 8. *Air gap and raster properties (angle, width)*
(Gordelier, Thies, Turner, & Johanning, 2019)

4. CONCLUSION

The examination of manufacturing challenges in 3D-printed gears underscores the considerable impact of printing orientation, infill patterns, and material characteristics on their mechanical performance. The best printing orientation, especially when aligned horizontally (in the XY and YZ planes), significantly improves tensile and bending strength, which is perfect for applications that bear loads. On the other hand, vertical orientations typically demonstrate weakened strength and stiffness.

Infill patterns are crucial, with designs like concentric and grid patterns providing enhanced strength and surface quality for materials such as PLA and PLA+ (tough). Increasing infill density improves mechanical properties; however, this comes with the cost of added weight and longer printing durations. Furthermore, the impact of raster angles and air gaps highlights the necessity for careful design to enhance strength and elongation characteristics. Dealing with issues like thermal expansion, wear, and deformation demands meticulous material selection and operational modifications, including enhanced heat dissipation and lubrication methods. The findings establish a basis for enhancing the durability and efficiency of 3D-printed gears, facilitating their wider use in mechanical systems across multiple industries.

Future research should focus on advanced materials selection and hybrid infill patterns to further enhance the performance of these components. It should also address the possible damages that could happen to 3D-printed gears and distinguish them from other traditional gear manufacturing technologies.

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