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Improving Wear Resistance: Investigating Factors Affecting PLA Gear Wear Produced by FDM 3D Printing.

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Abstract:- Spur gears play a crucial role in engineering applications by enabling high gear ratios and promoting energy efficiency, especially in high-power and high-speed scenarios. A focus on optimizing additive manufacturing methods, such as fused deposition modeling (FDM), for gear production is key to improving competitiveness over traditional manufacturing techniques. This study examines the impact of key manufacturing parameters, namely infill density, infill pattern, layer thickness, and number of shells, on the wear behavior of PLA gears manufactured by FDM. Through systematic experimentation, different infill densities and patterns, layer thicknesses, and shell numbers were tested while keeping other printing parameters such as platform temperature and extruder temperature constant, along with print speed and orientation. Understanding how these parameters influence gear wear is critical for improving the reliability and performance of additively manufactured gears in real-world applications.

Keywords: *Spur Gear; wear; Fused Deposition Modeling; optimal parameters; Experimental plan (D-optimal).*

1. Introduction

Polymer gears, appreciated for their many advantages compared to their metallic equivalents, are increasingly popular in various applications. Their light weight, ability to absorb vibrations and affordable cost make them preferred choices, particularly in the automotive engineering sector. Today's technological advancements open promising horizons for various applications, ranging from precision movements to high power transmission, even in harsh environments such as automotive engineering and healthcare. ([1]; [2]). Analyzes in the field of automotive engineering have highlighted substantial benefits, including a marked reduction in mass, inertia and fuel consumption, highlighting the remarkable potential of polymer gears [3]. The production of polymer gears is frequently done by injection molding or machining, involving either the design of expensive molds or the use of advanced manufacturing machinery. However, additive manufacturing is emerging as an alternative to circumvent the disadvantages associated with these traditional methods [4]. The use of additive technologies presents an efficiency advantage over conventional manufacturing methods for the production of spur gears. In fact, the yield of material consumed during conventional machining is 31%, while with additive manufacturing it reaches 86% [5]. The FDM process, among the various additive manufacturing technologies, is characterized by its wide scope of application. It involves the extrusion of thermoplastic materials through nozzles onto a platform, providing high toughness and resistance to impact loads, surpassing some other plastics. However, their nominal resistance decreases by approximately half beyond a maximum temperature limit of approximately 120°C. Polymers commonly used in the additive manufacturing of mechanical parts include polyamide (PA or Nylon), polyoxymethylene (POM), acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) [6].

The study [1] examined the wear behavior of polymer gears made from five different materials using step loading tests. Significant differences in failure modes and performance were observed between the materials tested. The wear tests conducted on acetal gears reveal a slow wear rate below a critical torque, which can be determined by experimental testing [2]. An improved method for testing polymer gears has allowed for a more accurate prediction of their lifespan. These tests have shown the effect of load and temperature on the lifespan of polymer gears [7]. The mechanical properties of polymer gears have a drawback linked to their intrinsic degradation with increasing temperature [8]. By examining polymer gear flank wear, an analysis concluded that decreasing gear modulus and increasing face width are associated with increased power losses [9].

Tensile tests performed on PLA printed samples revealed that the most influential printing parameters are: reducing layer thickness increases tensile and flexural strength, while greater layer thickness strengthens Young's modulus and ductility. Additionally, infill density plays a crucial role, and high density has a positive impact on tensile strength and stiffness [10, 11]. Zhang et al. [12] compared 3D printed materials with injection molded nylon 66 gears. The nylon 618 printed gear stands out for its superior performance under low and medium torques, as well as its advantageous thermal behavior. Muminovic et al. [13] explored how infill percentage influences the longevity and failure modes of 3D printed nylon gears. Experiments were conducted using samples with different filling ratios while keeping other parameters constant, allowing gear life and failure characteristics to be evaluated. Evaluation of three types of polymer gears (Nylon, ABS and PLA) 3D printed, showed that the nylon gear is the most resistant to wear, while the PLA gear exhibited wear fast and fragile compared to ABS and nylon [14]. While the paper [6] examined the importance of printing parameters for involute gears produced by FDM. Experimental tests determined the optimal parameters in terms of operational characteristics of the gears. Spur gears made from PLA plastic by additive manufacturing, exhibit better operational performance in terms of temperature and vibration compared to their counterparts made from ABS plastic. This performance varies depending on time and rotation speed [15]. Wear is a frequent occurrence in polymer gears. According to Youssef et al. [16], gears under axial loads experience more significant wear. Helical, bevel, and worm gears exhibited increased wear rates of 56%, 60%, and 68%, respectively, compared to spur gears. Tests on polymer gears [17] identified three types of failures under various external loads: tooth root fracture, tooth deformation, and tooth melting.

In this study, we investigated the effect of several critical manufacturing parameters (including infill density, infill pattern, layer thickness, and number of shells) on the wear characteristics of additively manufactured PLA gears. Our experiments involved testing samples with different infill patterns ranging from 25% to 100% infill density, along with variations in layer thickness and number of shells. Other manufacturing parameters such as platform temperature, extruder temperature, printing speed, and orientation were kept constant for all samples.

2. Methods and experiments:

Because of their critical importance, spur gears undergo thorough examination on specialized test rig, unlike certain other mechanical components whose load capacity is generally assessed based on sample mechanical characteristics. In this study, we developed a dedicated test bench for assessing wear and measuring temperature during gear meshing (Fig. 1).

The Polymer gear test rig operates in an open loop and comprises several key components. It features a three-phase Siemens electric motor rated at 0.37 kW with a nominal speed of 1385 rpm, controlled by a variable frequency speed controller (Telemecanique ATV31HU15M2). The motor shaft is connected to the input shaft via an elastic coupling, which in turn drives the driving gear. The driven gear is mounted on an output shaft. Both shafts are supported by four ball bearings to ensure smooth and accurate rotation.

To apply resistive torque to the output shaft, a lever braking system with suspended masses is utilized. Adjusting the weight position on the lever allows for different torque levels by varying the distance from the brake. The test bench's support structure is constructed from aluminum profiles, enabling easy assembly of bench equipment and precise adjustment of positions to accommodate different center distances required for testing gears of varying sizes.

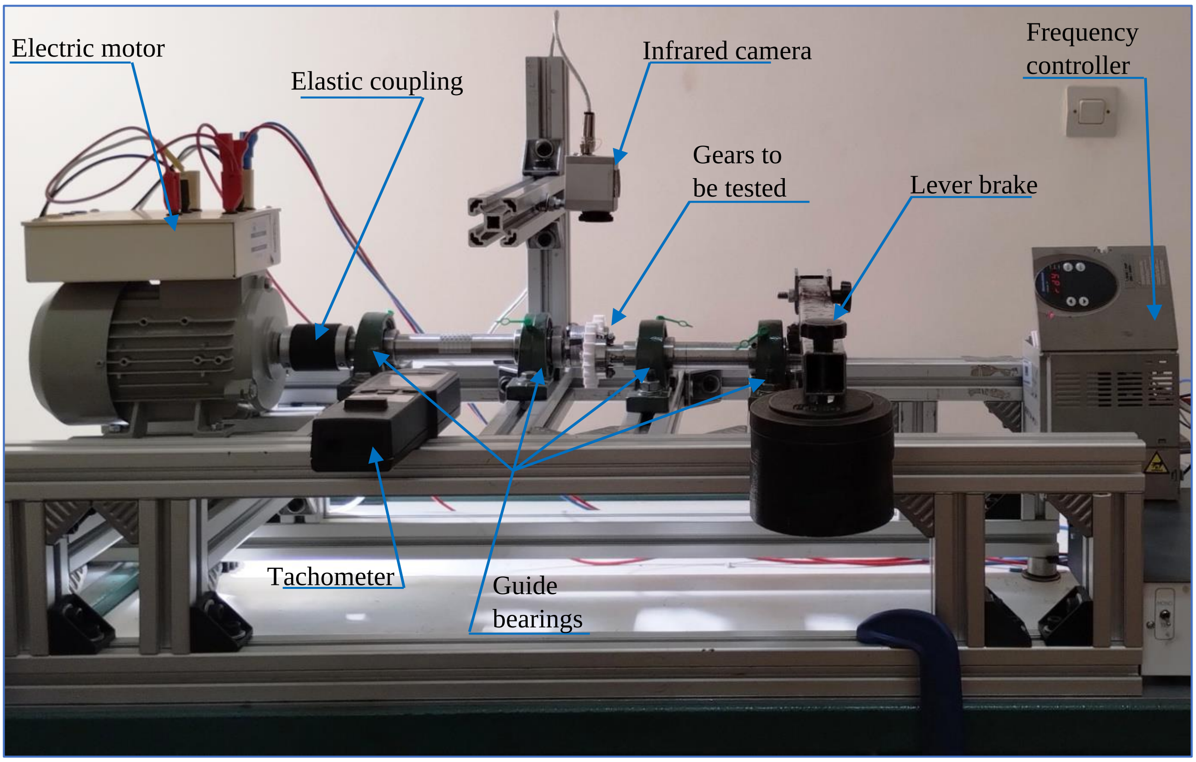

Fig. 1: The gear test rig designed and manufactured.

We measured the rotation frequency using a tachometer (CHAUVIN ARNOUX 1725), as depicted in Fig. 2a. To calculate the gear wear rate, we quantified the volume lost during meshing by weighing both the driving and driven gears initially after 3D printing and then after a specified number of rotations. Mass measurements were conducted using an Analytical Laboratory Balance (Mettler Toledo Newclassic MF), shown in Fig. 2b, with a precision of 0.1 mg. This method enabled precise quantification of gear mass changes over time, crucial for wear evaluation.

To begin 3D printing a polymer spur gear, we first designed the gear based on similar models used in a previous study [18]. The design took into account the bolted assembly of the test gears onto two shafts and ensured precise centering of the gears. Detailed specifications of the final gear are provided in Fig. 3, with specific dimensions and characteristics described in Table 1.

a **b**

Fig. 2: a: The tachometer; b: Analytical Laboratory Balance.

The consistent printing parameters maintained include part orientation (horizontal), printing temperature (200°C), bed temperature (50°C), and printing speed (50 mm/s). The decision to use a horizontal orientation is based on previous studies [19, 20] showing that 3D-printed PLA specimens exhibit superior mechanical properties in this orientation (refer to Table 2 for detailed PLA material properties). Additionally, this orientation minimizes the need for support structures, reducing post-processing time required for support removal.

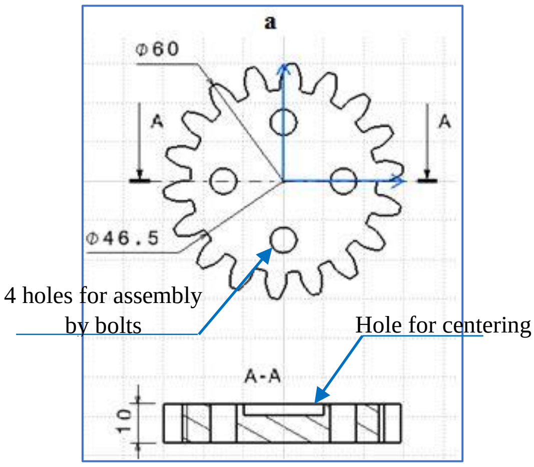

Fig. 3: definition drawing of the gear used for the tests.

Table 1. Specifications of gears.

Parameter	Value or type	Units
Type	Spur gear	--
Module	3	mm
Number of teeth	18	--
Pressure angle	20	degree
Tooth and gear width	10	mm
Root fillet	0.75	mm

The experimental study includes 20 trials selected according to an experimental design that involves four factors at four levels. We used a D-Optimal experimental design, as shown in the design matrix shown in Table 3. The tests were carried out at a constant rotation speed (***N* = 380 rpm**), adjusted by the frequency regulator. The load applied by the lever brake is constant (braking torque) with a value of 8.2 Nm. The duration of each test D_T was 60 minutes, with the exception of tests No. 6 and No. 17. These two tests were interrupted at 25 minutes due to the breakage of the gear teeth, leading to significant destruction (see Fig. 4). These tests were repeated a second time and were stopped at 24 minutes to avoid tooth breakage. The number of revolutions used to evaluate the specific wear rate was calculated from the rotation speed and the duration of the tests ($N_T = N * D_T$). Subsequently, the number of revolutions for all tests was 22800 revolutions, and for the two tests (No 6 and 17) 9120 revolutions. The wear volume was determined by measuring the mass loss ($M_l = m_0 - m_f$) of the printed gears, with m_0: representing the initial mass and m_f: the mass after wear, taking into account the density of the PLA material provided in Table 2. The wear volume was calculated according to the formula ($W_V = M_l * 1{,}25$). The specific wear rate (**Ws**) was calculated according to a standard formula [21]:

$$W_S = \frac{W_V}{2zmbN_T} \qquad (1)$$

With:

- z: Number of teeth;
- m: Module;

- b: Tooth and gear width.

Table 2 : propriété du PLA [22].

Property	Tensile Strength(MPa)	Flexural Strength(MPa)	Impact Strength(MPa)	Melting Temperature °c	Density (g/cm3)
value	62.63	65.02	4.28	190–220	1.25

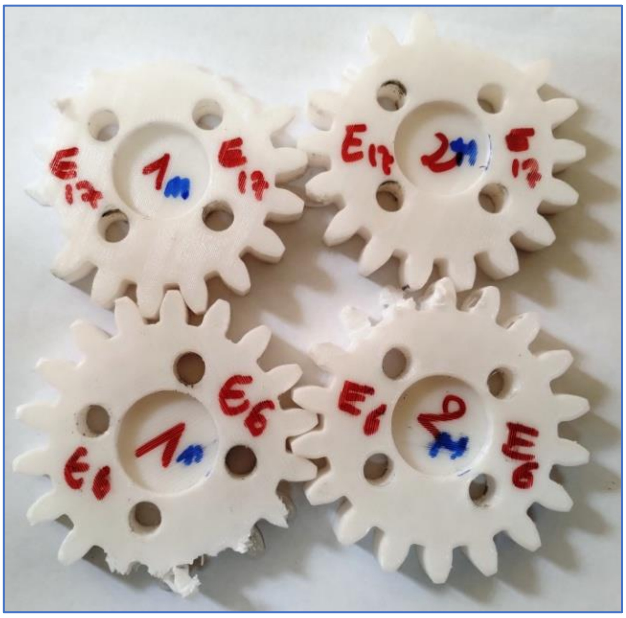

Fig. 4: The sample of test no. 6 and no. 17 (1: The drive gear and 2: The driven gear).

The response chosen to study the variation of the factors in the D-optimal matrix is the specific wear rate, measured in (µm / 100 rev). This rate is calculated according to equation (1), using the values of the initial masses (m0) measured for the 20 samples before the start of the tests, as well as the final masses (mf) obtained after each test. In our study, we noticed a noticeable difference in the wear rate between the drive gear and the driven gear.

3. Results and discussion

3.1. Effect of parameters on wear rate

The results obtained indicate that the drive gear has a higher wear rate than the driven gear, with a difference reaching on average up to 63% (Fig. 5). This significant difference highlights that the driving gear supports the resistive torque more than the driven gear. It should also be noted that tests 6 and 17, presenting the highest wear rate compared to the other tests, share in common the lowest filling rate (25%) as well as a minimal number of shells (one only shell).

The evolution of wear as a function of layer thickness is almost similar for the driving gear and the driven gear, as shown in Fig. 6. This observation suggests that as the layer thickness increases, the wear rate also increases, reaching its maximum at a layer thickness of 0.24 mm. This phenomenon can be explained by the fact that a lower layer thickness results in a greater number of layers, while a larger layer thickness reduces the number of layers, which may weaken the cohesion between horizontal layers. Interestingly, this trend has been observed in other studies involving 3D printing, where an increase in layer thickness has been associated with a decrease in the mechanical strength of printed parts [23].

Table 3: The optimal experimental design and the response Ws.

N° RUN	Factors			
	Layer thickness (mm)	Infill density (%)	Infill pattern	Number of shells
1	0.12	25	Tri-hexagon	3
2	0.16	50	Grid	1
3	0.12	50	Grid	1
4	0.2	25	Lines	3
5	0.16	100	Grid	4
6	0.24	25	Tri-hexagon	1
7	0.12	75	Tri-hexagon	3
8	0.24	50	Grid	3
9	0.12	75	Grid	2
10	0.2	100	Cubic	1
11	0.16	75	Cubic	4
12	0.2	75	Tri-hexagon	4
13	0.2	50	Tri-hexagon	3
14	0.12	100	Grid	1
15	0.24	25	Lines	3
16	0.24	75	Cubic	2
17	0.16	25	Grid	1
18	0.16	25	Tri-hexagon	2
19	0.2	50	Lines	4
20	0.16	75	Lines	2

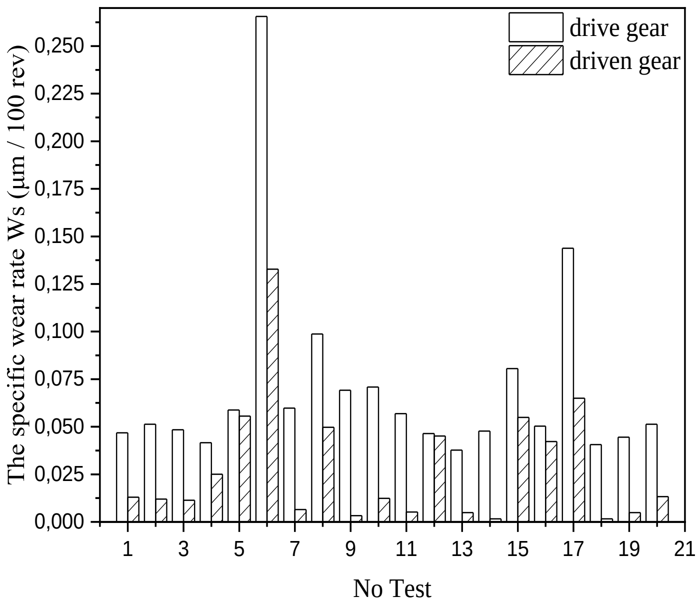

Fig. 5: Comparison of the wear rate between the drive gear and the driven gear.

The impact of infill density on gear wear is shown in Fig. 7. The results show that gears manufactured with a high Infill density exhibit less wear compared to those with a low infill density. This observation is consistent with existing literature, which suggests that the infill density has a positive effect on the strength of parts manufactured by additive manufacturing [24]. In addition, the variation in the wear rate for the drive gear and the driven gear is very small when the infill density exceeds 50%. The study [24] demonstrated that a part filled to 50% can increase its strength by an additional 25%, while a fill rate of 75% only increases the strength by 10%.

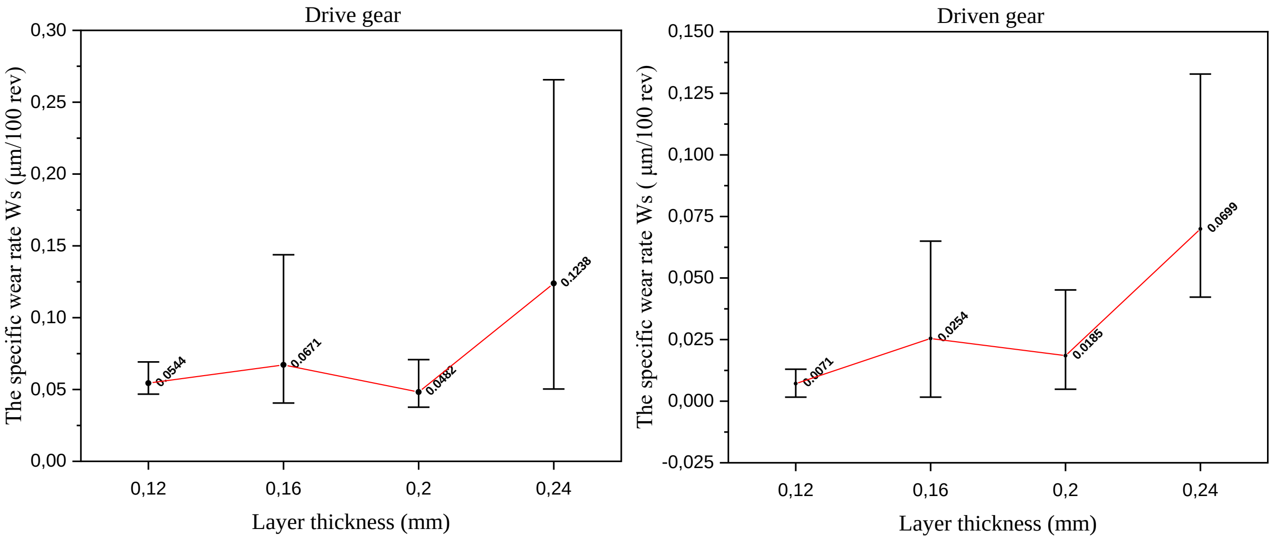

Fig. 6: Evolution of the wear rate as a function of layer thickness for the two gears.

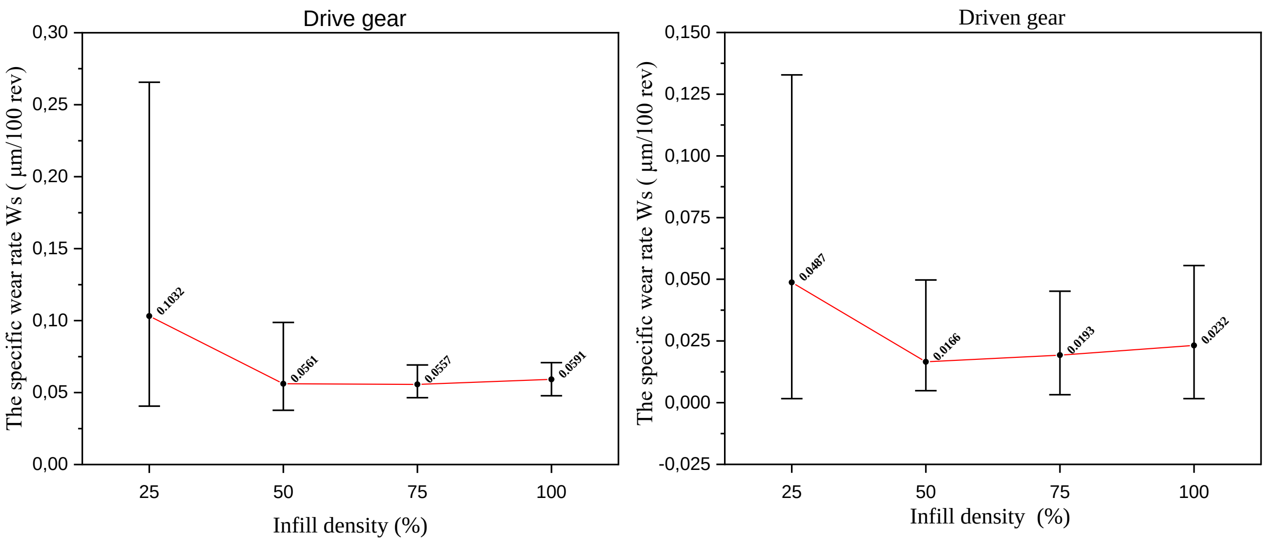

Fig. 7: Evolution of the wear rate as a function of infill density for the two gears.

The influence of the number of shells on gear wear is particularly significant for the driving gear, as shown in Fig. 8. The higher the number of shells, the less the gear shows signs of wear. Indeed, the rigidity of the teeth of a gear produced by the FDM technique depends on the number of external contours defined during the preparation of the print. The internal structure of the teeth is formed by parallel paths, which results in a non-uniform distribution of stiffness along the circumference of the circle [25]. Therefore, it is suggested that gears manufactured by FDM should consist of outer contours only, because the strength of a single fiber is greater than that of the bond between layers. This hypothesis is also supported by research by Kim et al. [26]. Figure 9 illustrates the difference between the two configurations, with three or eight contours.

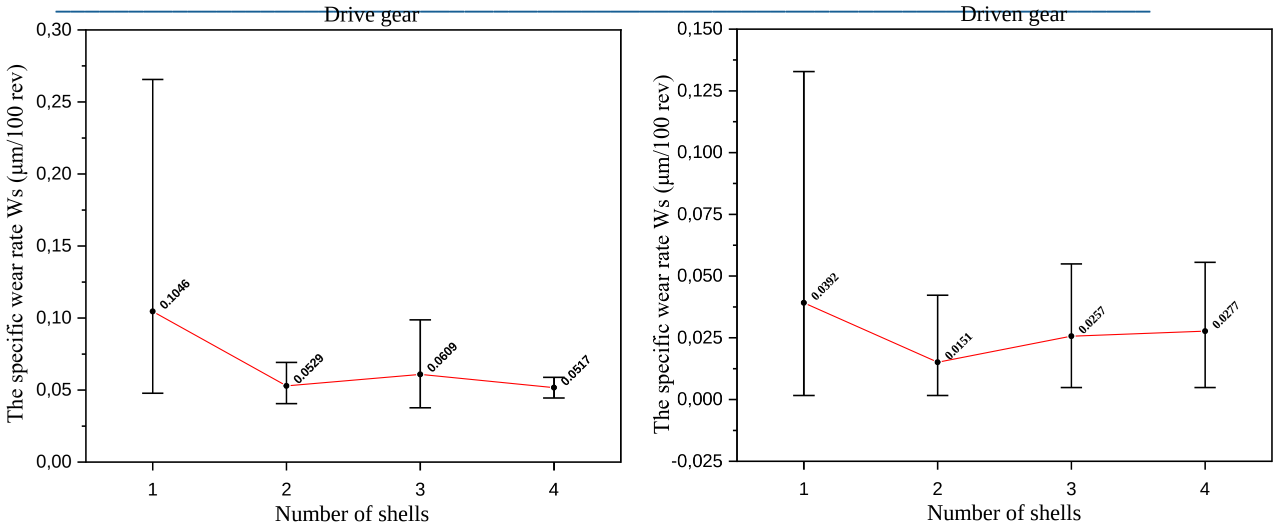

Fig. 8: Evolution of the wear rate as a function of number of shells for the two gears.

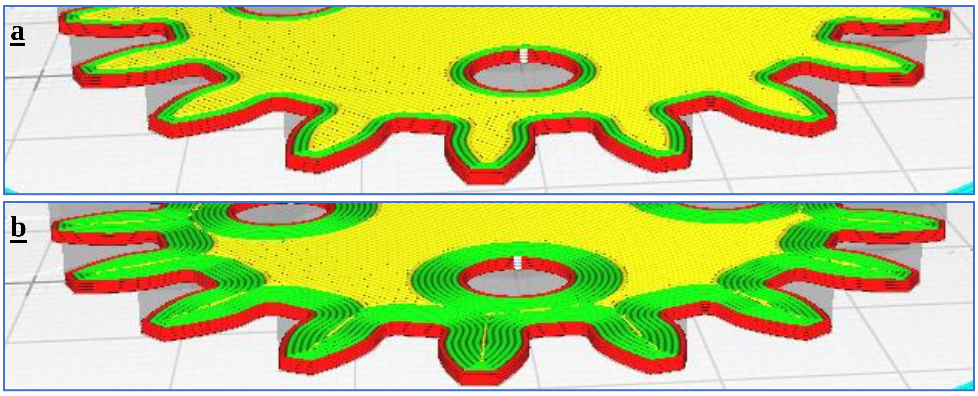

Fig. 9: The way of arranging the paths of a gear according to the number of shells. a) 3 shells; b) 8 shells.

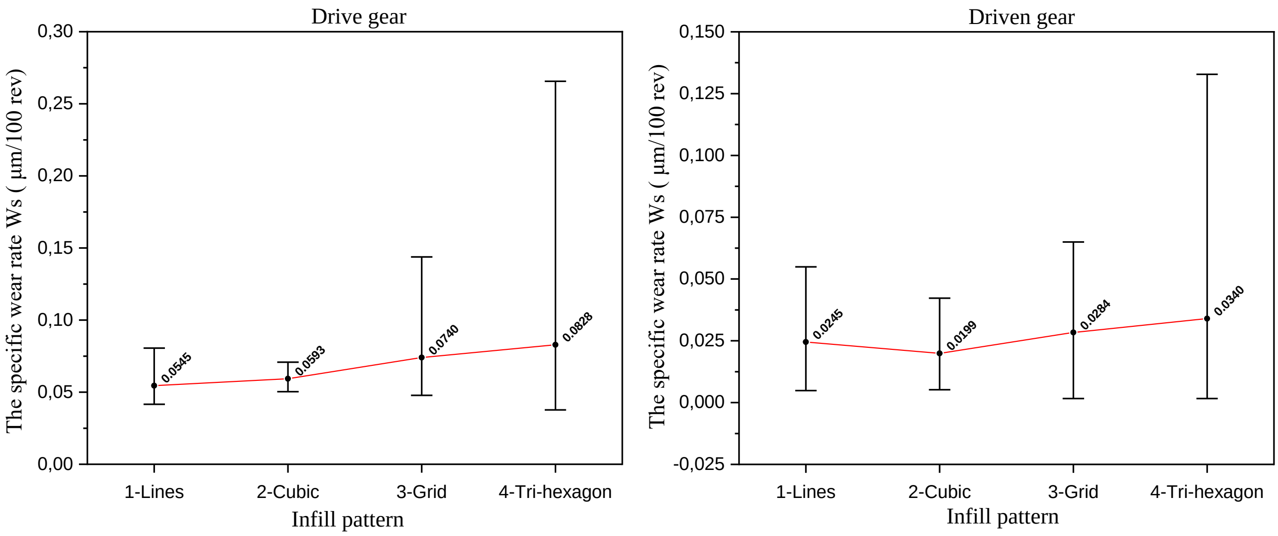

Fig. 10: Evolution of the wear rate as a function of infill pattern for the two gears.

Gears with line or cubic infill pattern have very low wear rates. In contrast, those with grid or tri-hexagonal patterns show a slight increase in wear rate (see Fig. 10). The variation in the specific wear rate remains low compared to the other parameters.

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For the rest of the study, we will focus specifically on analyzing the wear of the drive gear, as it tends to experience more wear compared to the driven gear. Additionally, we will only consider the following print parameters: layer thickness, infill density, and number of shells.

3.2. Interaction effect between parameters on wear rate

Our initial analysis focuses on examining the interaction between two printing parameters: the number of shells and the infill density. It's important to highlight that the influence of the number of shells on the wear rate is particularly pronounced at lower infill densities, specifically between 25% and 50%, as depicted in Fig. 11. It is evident that at 100% infill density, the wear rate remains relatively constant regardless of whether there is one shell or four shells. This observation is logical because at maximum infill density, the number of perimeter layers does not significantly affect the strength of the printed part. However, changes in infill density have a noticeable impact only when there are fewer shells present.

The primary goal of any design is to optimize manufacturing parameters to create gears that are highly resistant to wear and have a longer service life. In this context, our aim is to minimize the rate of wear. The initial approach, involving the use of maximum infill density with an average of three shells, appears to yield the lowest wear rate. Alternatively, the second approach, which utilizes a maximum number of shells to fill the tooth thickness at a 50% infill density, is also worth considering. Another important economic factor to consider is manufacturing time, which may favor the second approach due to its feasibility within a shorter timeframe [18].

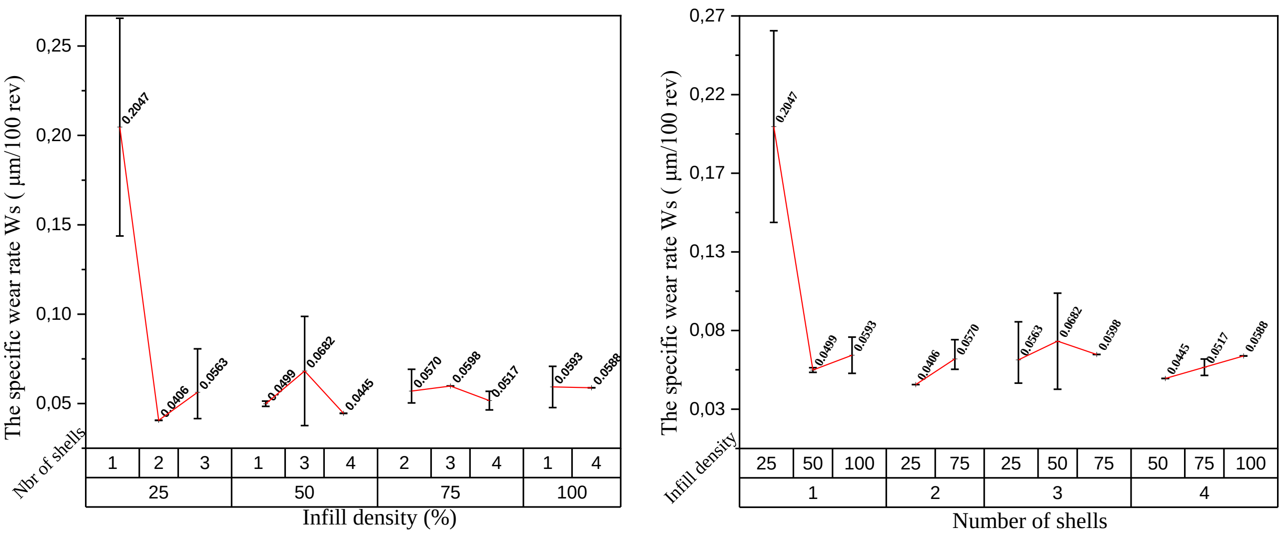

Fig. 11: Interaction between the number of shells, the infill density and the wear rate of the drive gear.

The second analysis examines how infill density and layer thickness interact. We observed that the impact on wear rate is minimal with low layer thicknesses, similar to how layer thickness significantly affects wear rate with low infill density. Building on the findings of our initial analysis, our goal is to identify the optimal layer thickness that minimizes wear rate at an infill density of 50%. The results depicted in Figure 12 indicate that a layer thickness of 0.2 mm is most effective under these conditions.

The ultimate analysis investigates how the number of shells and layer thickness are related. Our results demonstrate that the wear rate is minimized when using a layer thickness of 0.2 mm with three shells. This conclusion is well supported by the data in Figure 13, which shows a wear rate of 0.0396 µm/100 rev.

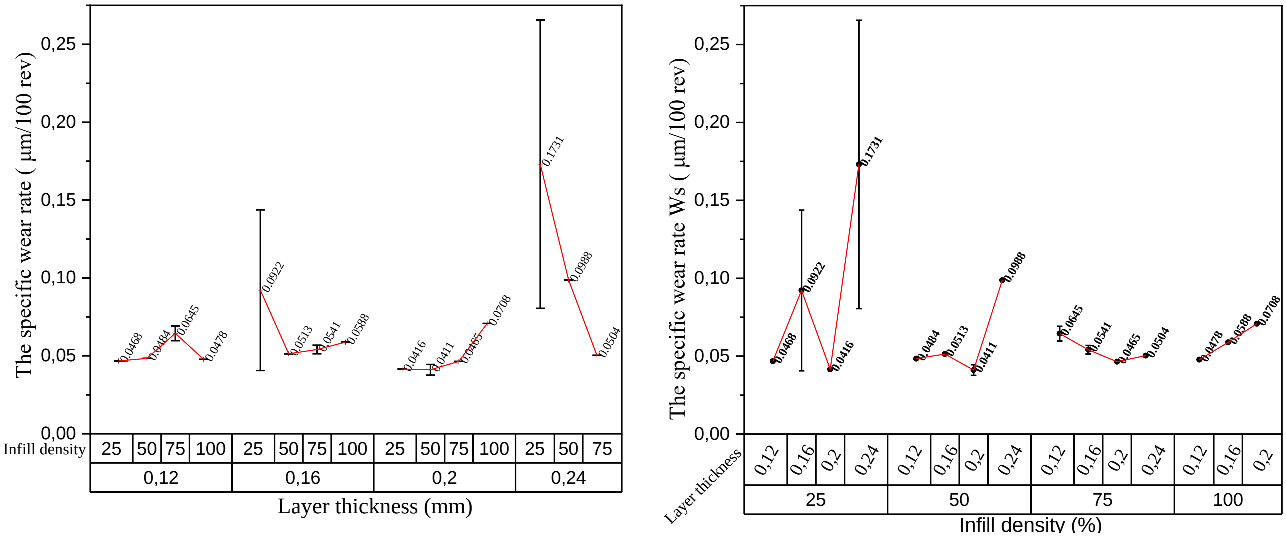

Fig.12: Interaction between the infill density, the layer thickness and the wear rate of the drive gear.

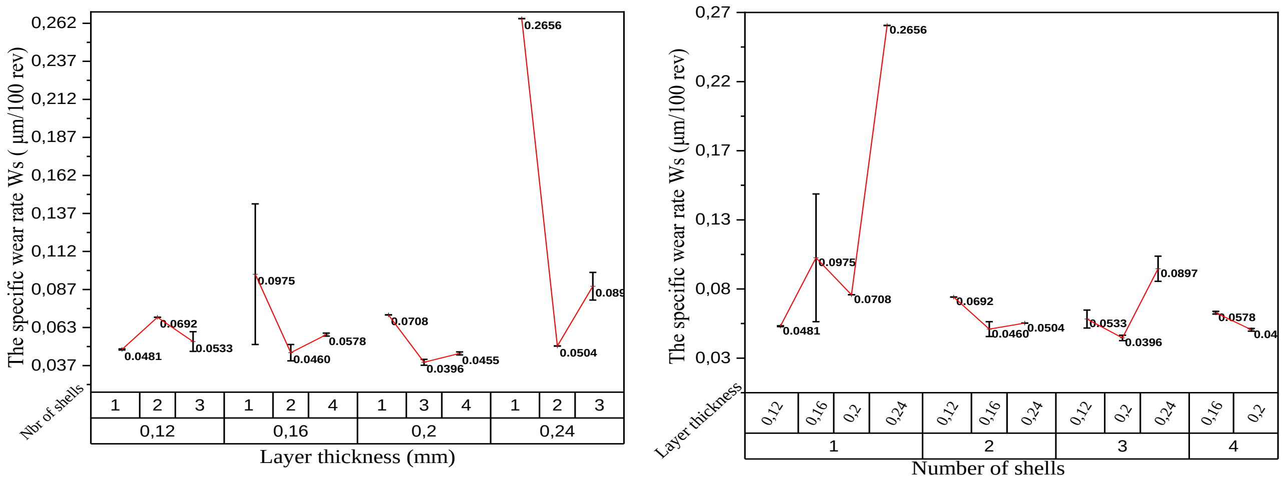

Fig.13: Interaction between the number of shells, the layer thickness and the wear rate of the drive gear.

4. Conclusion

In conclusion, our experimental analysis of wear rate based on printing parameters yielded the following findings:

- The driving gear experiences significantly higher wear compared to the driven gear, with an average difference of up to 63%. Tests with the highest wear rates commonly share characteristics such as low infill density (25%) and a single shell.
- Layer thickness also influences gear wear, with wear tending to increase for a layer thickness of 0.24 mm.
- Gears manufactured with higher infill density exhibit less wear, consistent with other studies on additive manufacturing.
- The number of outer shells is crucial, as a higher number of shells helps reduce gear wear.

To optimize FDM gear wear resistance, it is recommended to use high infill density along with an adequate number of outer shells and a layer thickness of 0.2 mm. These parameters minimize wear rate and enhance gear lifespan.

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