FEM STUDY ON THE EFFICIENCY OF 3D PRINTED GEARS

Valentin MEREUŢĂ [1], Andreea SANDU[2], Elena-Felicia BEZNEA[1]
Nicuşor BAROIU[3],

[1] "Dunarea de Jos" University of Galați, Faculty of Engineering, Department of Mechanical Engineering, 47 Domneasca Str., 800008, Galati, Romania,
[2] "Dunarea de Jos" University of Galați, Faculty of Engineering, master student at the Mechanical Engineering Departament, 47 Domneasca Str., 800008, Galati, Romania
[3] "Dunarea de Jos" University of Galați, Faculty of Engineering, Department of Industrial Engineering, 47 Domneasca Str., 800008, Galati, Romania
email: elena.beznea@ugal.ro

ABSTRACT

This paper presents the 3D modeling and static structural analysis in ANSYS of a spur gear set manufactured from four different materials: two conventional steels, 36Mn5 and 18CrNiMo7, and two 3D printable Ultrafuse 17-4PH and 316L. The study aimed to compare maximum elastic deformations, Von Mises stresses, and material-specific mechanical properties in order to evaluate their suitability for gear applications. Significant differences were observed in hardness, yield strength, and wear resistance. The carburized steel 18CrNiMo7 exhibited superior strength and hardness, confirming its suitability for heavy-duty industrial transmissions, while 36Mn5 proved adequate for moderate-load applications. Among the Ultrafuse materials, 17-4PH demonstrated a favorable compromise, with acceptable ductility and the potential for post-printing heat treatment, making it suitable for functional prototypes and gears with moderate loads. The analysis concludes that while Ultrafuse materials can be effectively employed in prototyping and testing, carburized steel 18CrNiMo7 remains the recommended choice for industrial series production of gears subjected to high loads and wear.

KEYWORDS: 3D modeling, FEM Study, conventional steels and 3D printable.

1. INTRODUCTION

The use of 3D printing for model fabrication is increasingly prevalent in the fields of electromechanics and reconstructive engineering [1]. This trend is primarily driven by advancements in additive manufacturing processes and the continual development of high-performance materials. The technology enables the production of non-standard components with intricate geometries that are often unfeasible to manufacture using conventional subtractive methods. Moreover, it offers cost-effective production without the necessity for specialized tooling or equipment. Despite these advantages, additive manufacturing poses certain limitations in mechanical engineering applications, particularly in the fabrication of micro-scale components. Additionally, there is a notable lack of standardized data regarding the mechanical and thermal performance of printed parts, which can impede their use in load-bearing or high-temperature environments.

Gears represent fundamental mechanical components, traditionally manufactured from metallic alloys through conventional machining processes. Nevertheless, recent advancements in materials science have shifted the research focus towards composite gears, primarily due to their enhanced mechanical performance. These include superior wear and corrosion resistance, the ability to operate without lubrication, reduced noise generation, and an improved strength-to-weight ratio, all of which make them increasingly viable for high-performance and lightweight mechanical systems [2].

Authors of such publications primarily report results concerning spur gears. The studies mainly

address various aspects of gear modeling, with particular emphasis on evaluating the stiffness of polymer-based gears through the application of analytical methods and finite element analysis (FEM) [3].

Düzcükoglu H. [4] provides insights into the design of polymer gears aimed at enhancing gear performance and durability. The authors also focus on testing the load-bearing capacity of spur gears made from polymers, with particular attention to their tribological behavior under dry operating conditions. In contrast, the literature contains significantly less data regarding the performance of lubricated polymer gear systems [5].

The specialized literature provides limited information on the wear resistance analysis of additively manufactured gears, with most studies focusing primarily on the evaluation of their geometric accuracy [6].

Numerous studies have reported the outcomes of strength analyses performed on material samples used in additive manufacturing. These works primarily focus on the selection of suitable technological parameters for the additive process and on the optimization of the source model's geometry in order to ensure maximum mechanical strength and the geometric accuracy required by the final product. Special attention must be given to the manufacturing process itself, particularly with respect to the condition of the surface geometry, most notably surface roughness, which plays a crucial role in the performance and reliability of the resulting components [7].

The surface geometric structure of gears manufactured using 3D printing techniques is influenced by multiple factors, including the specific printing method employed [8], the orientation of the part within the printer's build space [9], as well as the post-processing procedures applied [10].

Prior to evaluating the surface layer condition of models produced through 3D printing techniques, it is essential to develop a methodology that enables the selection of an appropriate measurement method and the analysis of the resulting data [11]. This may involve contact or non-contact surface scanning, performed either horizontally or vertically. The most commonly employed techniques include confocal microscopy [12], structured light projection [13], and focus variation microscopy [14].

Senthilvelan and Gnanamoorthy [15] investigated the effect of fillet radius on nylon 6/6 gears under various loading conditions and concluded that gears with a larger fillet radius exhibit greater durability, while those with a smaller radius tend to experience higher levels of deformation.

Senthilvelan and Gnanamoorthy [16] also investigated the performance of unreinforced nylon 6 and nylon 6 reinforced with 20% short glass fibers under varying rotational speeds. The results indicated that rotational speed significantly affects the performance of both gear types under high-speed and high-load conditions. It was concluded that, across all speed conditions, glass fiber-reinforced nylon gears exhibit superior performance compared to their unreinforced nylon counterparts.

Yong-jun and colleagues [17] conducted dynamic contact simulations on helical gears, both with and without tooth profile modification. The simulations were compared with experimental results under various loading conditions. The study concluded that modifying the tooth profile of helical gears proved effective in reducing vibration during operation under load.

The present comparison of steels and 3D-printable materials aligns with previous studies on the flexural behavior of sandwich composite structures [18], emphasizing the importance of integrating both experimental and numerical approaches to evaluate material performance under real loading conditions.

Bharat and colleagues [19] investigated the contact stress analysis of spur gears modeled in Pro-E software using the finite element method in Ansys. The study concluded that contact stress decreases with an increase in the gear module.

Mahebub et al. [20] conducted a comparative finite element analysis on metallic and non-metallic materials. A 3D model of a spur gear was created using Proengineer modeling software and simulated in Ansys. The study concluded that non-metallic gears provide additional advantages only in applications with limited strength requirements, as compared to metallic gears.

2. GEAR MODELING

A pair of helical cylindrical gears was designed for finite element analysis by inputting the geometric parameters into the dedicated gear design module within Autodesk Inventor 2025, in accordance with the ISO 6336:1996 standard. This approach ensured the generation of a precise and standardized gear geometry suitable for both analytical and numerical evaluations. The geometric parameter values for the two helical cylindrical gears are presented in Table 1. The common technical parameters of the gears are summarized in Table 2.

Fig. 1. *Helical cylindrical gear assembly*

Table 1. *Geometric dimensions of the two gears*

		Gear 1	Gear 2
Type of model		Component	Component
Number of Teeth	z	18 ul	54 ul
Pitch Diameter	d	28.000 mm	84.000 mm
Outside Diameter	d_a	31.000 mm	87.000 mm
Root Diameter	d_f	24.250 mm	80.250 mm
Base Circle Diameter	d_b	26.196 mm	78.587 mm
Work Pitch Diameter	d_w	28.000 mm	84.000 mm
Facewidth	b	18.000 mm	16.000 mm
Facewidth Ratio	b_r	0.5714 ul	0.1905 ul
Root Fillet	r_f	0.3500 ul	0.3500 ul

Table 2. *Common parameters*

Gear Ratio	i	3.0000 ul
Module	m	1.500 mm
Helix Angle	β	15.3553 deg
Pressure Angle	α	20.0000 deg
Center Distance	a_w	56.000 mm
Product Center Distance	a	55.999 mm
Circular Pitch	p	4.712 mm
Base Circular Pitch	p_{tb}	4.572 mm

To determine the meshing forces and output data for the driven gear, it was necessary to define the input power and rotational speed at the reducer's input. Both the input data and the results obtained from the calculation are presented in Table 3.

Table 3. *Input data*

		Gear 1	Gear 2
Power	P	0.414 kW	0.406 kW
Speed	n	705.00 rpm	235.00 rpm
Torque	T	5.608 N m	16.487 N m
Efficiency	η	0.980 ul	0.980 ul
Radial Force	F_r	151.205 N	151.205 N
Tangential Force	F_t	400.548 N	400.548 N
Axial Force	F_a	109.993 N	109.993 N
Normal Force	F_n	442.042 N	442.042 N
Circumferential Speed	v	1.034 mps	1.034 mps
Resonance Speed	n_{E1}	47714.576 rpm	47714.576 rpm

3. 3D PRINTING

The 3D printing of the helical cylindrical gear pair was carried out using the AnkerMake M5 3D printer [21], whose technical specifications are presented in Table 4.

Table 4. *Technical specifications of the AnkerMake M5 3D printer*

Print Volume (L×W×H)	235×235×250 mm³
Fast Mode Speed	500 mm/s
Fast Mode Acceleration	5,000 mm/s²
Normal Mode Speed	250 mm/s
Normal Mode Acceleration	2,500 mm/s²
Max Extruder Speed	100mm/s
Print Precision	±0.1 mm
Nozzle Diameter	0.2, 0.4, 0.6, 0.8
Filament Diameter	1.75 mm
Extruder Temperature	Maximum 260°C
Heating Plate Temperature	Maximum 100°C

The 3D model of the gears was created in Autodesk Inventor 2025 and then exported in STL format, compatible with the applications used to configure the printing process. This format allows for the definition of printing parameters, part positioning on the build platform, extrusion temperature settings, and other working conditions. The printing preparation was carried out using AnkerMake Studio [22], the dedicated software for the AnkerMake M5 3D printer.
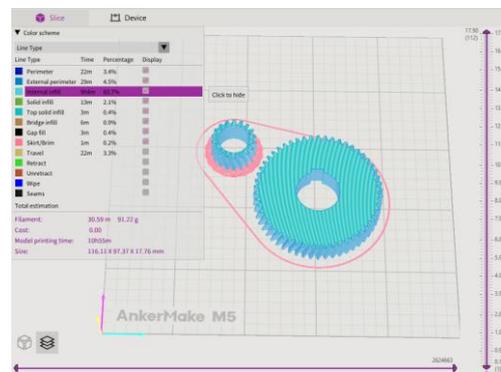

Fig. 2. *AnkerMake M5 printer slicer*

The printing settings were established according to the recommendations provided by the manufacturer of the Ultrafuse® 17-4 PH filament [22], as specified

in the material's technical datasheet. The relevant values used in the process are presented in Table 5.

Fig. 3. *3D-printed helical gears*

Table 5. *Printing settings*

Filament Diameter	1.75 mm
Nozzle Temperature	230 – 250 °C
Bed Temperature	100 °C
Nozzle Diameter	0.4 mm
Print Speed	15 - 50 mm/s

4. ANALYZED MATERIALS

The materials for the gears are selected to meet the strength requirements imposed by operational loads. This study presents a comparative analysis of four materials that can be used for gear manufacturing. In the first case, 36Mn5 steel and 18CrNiMo7 steel were selected, and their properties are presented in Table 6.

Table 6. *Mechanical properties of 36Mn5 steel and 18CrNiMo7 steel*

Mechanical properties		36Mn5 steel	18CrNiMo7 steel
Ultimate Tensile Strength	S_u	700 MPa	1100 MPa
Yield Strength	S_y	340 MPa	900 MPa
Modulus of Elasticity	E	206000 MPa	210000 MPa
Poisson's Ratio	μ	0.300 ul	0.300 ul
Bending Fatigue Limit	σ_{Flim}	352.0 MPa	500 MPa
Contact Fatigue Limit	σ_{Hlim}	1140.0 MPa	1.3 GPa
Hardness in Tooth Core	JHV	30 – 40 HRC	30–45 HRC
Hardness in Tooth Side	VHV	56 – 60 HRC	58–62 HRC

In the second case, a gear assembly was 3D-printed using Ultrafuse® 17-4 PH filament and Ultrafuse® 316L [23]. The mechanical properties of the Ultrafuse® 17-4 PH filament and Ultrafuse® 316L are presented in Table 7.

Table 7a. *Mechanical properties of Ultrafuse® 17-4 PH*

Standard ISO 6892-1	Ultrafuse® 17-4 PH	
	Flat Position	Upright Position
Tensile strength	990 MPa	1276 MPa
Young´s Modulus	191000 MPa	198000 MPa
Elongation at Break	4 %	6 %
Yield Strength, Rp 0.2	756 MPa	1109 MPa
Vickers Hardness HV10	291	4003

Table 7b. *Mechanical properties of Ultrafuse® 316L*

Standard ISO 6892-1	Ultrafuse® 316L	
	Flat Position	Upright Position
Tensile strength	561 MPa	521 MPa
Young´s Modulus	191000 MPa	191000 MPa
Elongation at Break	53 %	36 %
Yield Strength, Rp 0.2	251 MPa	234 MPa
Vickers Hardness HV10	128	128

After printing, the gear assembly undergoes a debinding process to remove the polymer binder, followed by a sintering process to significantly enhance its mechanical properties.

In the first stage, the polymer that binds the metal particles together is gradually removed. This process can be performed thermally by slowly heating up to a maximum of 600°C in an inert atmosphere (argon or nitrogen) to eliminate the remaining binder. At this stage, the gear becomes fragile, which is why it is followed by the second process sintering, during which the gear is heated to temperatures close to the melting point of 17-4 PH stainless steel (1300–1400°C). In this stage, the gear undergoes a volume reduction of approximately 20%, which requires compensation during the modeling phase.

After sintering, the metal particles fuse, increasing density and providing mechanical properties comparable to those of 36Mn5 steel. The mechanical properties of the printed gear after sintering are presented in Table 8.

Table 8. *Mechanical properties of Ultrafuse® 17-4 PH after sintering*

Tensile strength	900 - 1100 MPa
Ultimate strength	1000 - 1200 MPa
Young´s Modulus	190 - 210 GPa
Poisson's Ratio	0.27 - 0.30
Elongation at Break	6 - 10%
Density	7.7 - 7.8 g/cm³

5. FEM ANALYSIS OF THE GEAR

The finite element analysis was carried out using the dedicated software Ansys Workbench by importing the previously modeled gear assembly. The first step involved defining the two materials by inputting their specific parameters, followed by the application of boundary conditions based on the results obtained from the Autodesk Inventor model, as shown in Figure 4.

To obtain more accurate results, a finer mesh was applied to the gear assembly, which was discretized into 70.786 nodes and 18.763 elements, as shown in Figure 5.
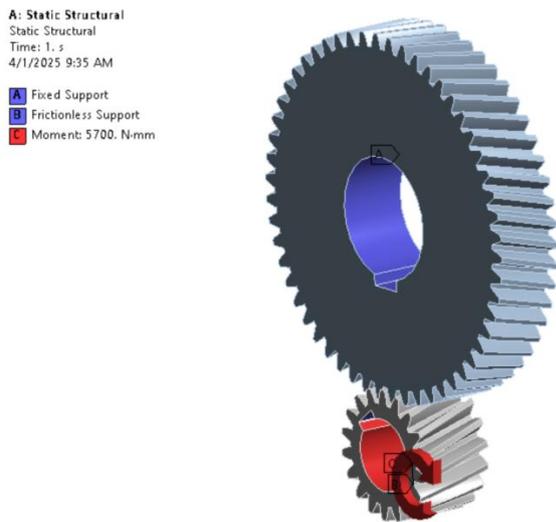
Fig. 4. *Application of boundary conditions*
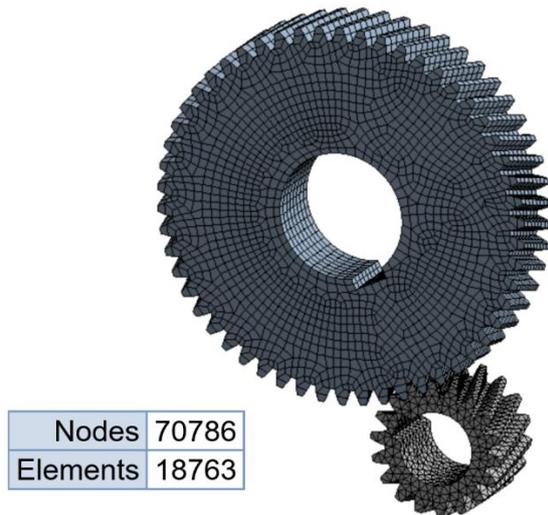
Fig. 5. *Gear mesh discretization*

As a result of the static analysis, similar Von Mises stress values were obtained, remaining below the yield strength for all the 36Mn5 steel, 18CrNiMo7 steel gear (as shown in Figure 6 and Figure 7), and the 3D-printed gear made from Ultrafuse® 17-4 PH filament and Ultrafuse® 316L (as shown in Figure 8 and Figure 9).
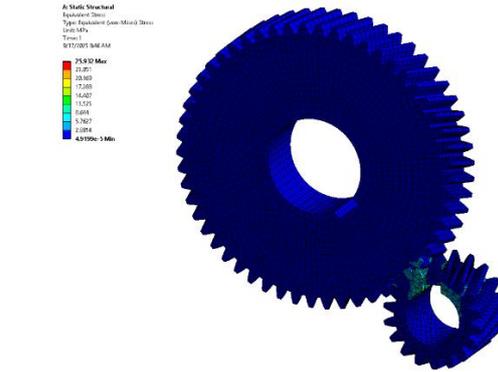
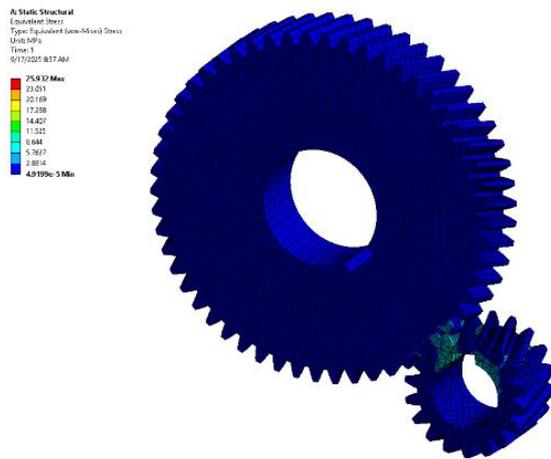
Fig. 6. *Von Mises stresses 36Mn5 steel*
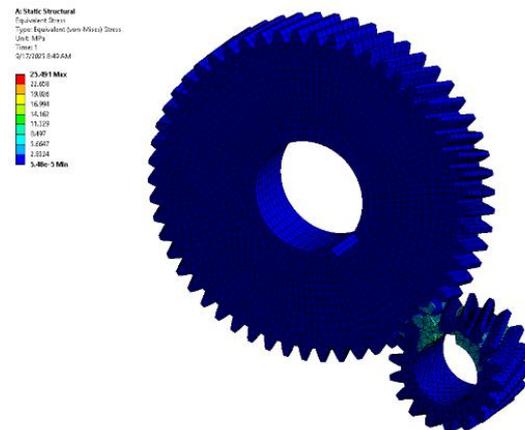

Fig. 7. *Von Mises stresses 18CrNiMo7 steel*

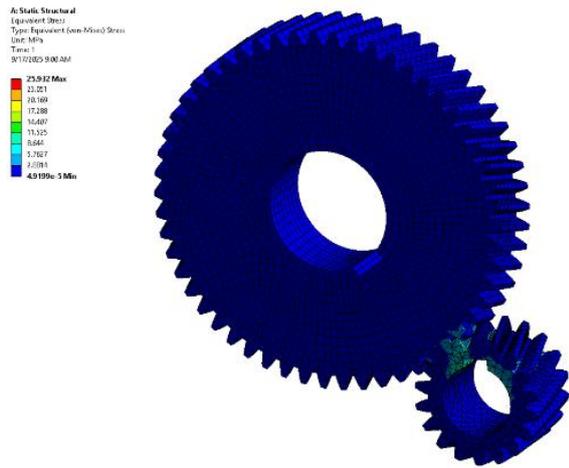**Fig. 8**. *Von Mises stresses Ultrafuse® 17-4 PH*
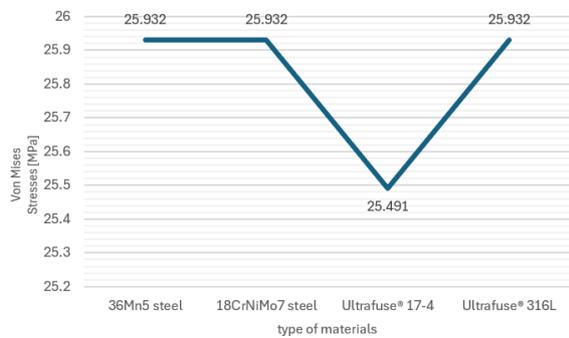
Fig. 9. *Von Mises stresses Ultrafuse® 316L*

Fig. 10. *Von Mises stress variation for each material*

In the case of deformations, the values were similar, with the lowest deformation recorded for the gear made of 36Mn5 steel, 18CrNiMo7 steel gear (as shown in Figure 11 and Figure 12), and the 3D-printed gear made from Ultrafuse® 17-4 PH filament and Ultrafuse® 316L (as shown in Figure 13 and Figure 14).
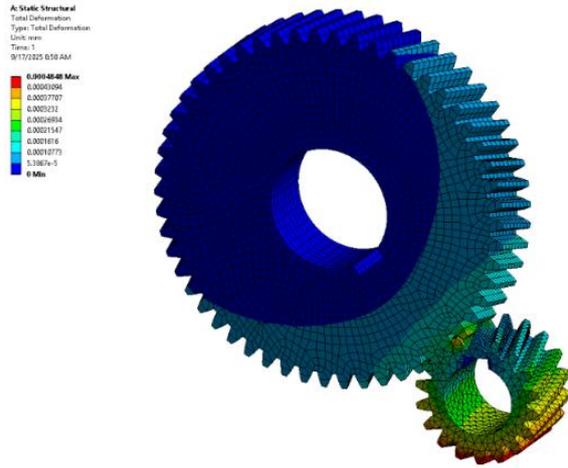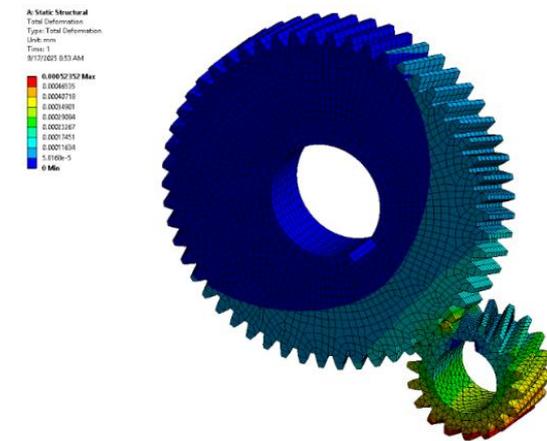

Fig. 11. *Total deformations 36Mn5 steel*

Fig. 12. *Total deformations 18CrNiMo7 steel*

Fig. 13. *Total deformations Ultrafuse® 17-4 PH*
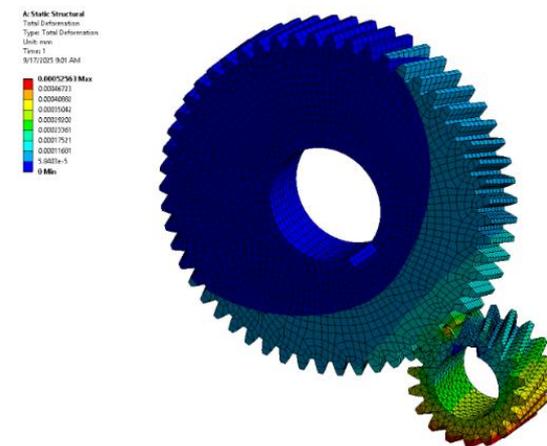

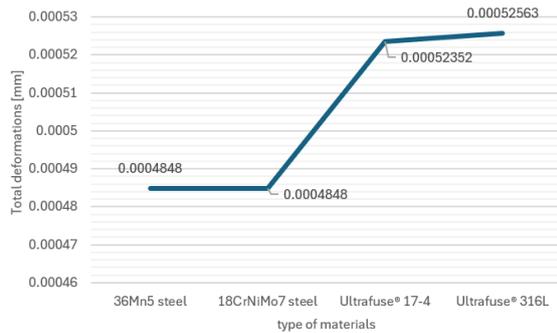**Fig. 14.** *Total deformations Ultrafuse® 316L*

Fig. 15. *Total deformation for each material*

Based on the obtained results, it can be observed that:

The maximum deformations are very close, ranging between 0.000484 and 0.000525 mm, with an approximate maximum difference of 8%.

The 3D Ultrafuse materials show a slight advantage in deformability, meaning they are somewhat more ductile compared to conventional steels.

When comparing the two types of materials, it can be observed that for the analyzed steels 36Mn5 and 18CrNiMo7, the major difference appears in yield strength and hardness:

- 36Mn5 lower FOS, modest hardness, suitable for gearboxes with moderate loads.

-18CrNiMo7 superior strength after carburizing, high hardness, which indicates suitability for high-power transmissions and heavy contact loads.

Analyzing the two materials used for 3D printing, it can be observed that:

- Ultrafuse 17-4PH has a lower elastic modulus than traditional steels, which is reflected in a slightly higher maximum deformation of approx. 0.000523 mm and a lower maximum Von Mises stress of 25.491 MPa, showing a more ductile behavior. It has the advantage of being 3D printable and can be further heat-treated for higher strength. However, it has lower hardness and strength compared to premium carburized steels, making it more suitable for prototypes or gears with moderate loads.

- Ultrafuse 316L has a lower elastic modulus and shows a slightly higher maximum deformation of 0.000525 mm. The maximum Von Mises stress is similar to 36Mn5, being a very ductile material, but not very resistant to wear or heavy contact loads. Ultrafuse 316L has the advantage of excellent corrosion resistance and easy 3D printability. However, it is not recommended for high-power gears, being more suitable for prototypes, corrosive environments, or in low-load applications.

From the comparison of the results obtained for the analyzed materials, the following conclusions can be drawn:

- 18CrNiMo7 is recommended for conventional industrial production, showing high hardness, low wear, high FOS, excellent FEM results, and performance similar to 36Mn5.

- Ultrafuse 17-4PH offers a good compromise for lighter applications, functional 3D prototypes, with reasonable 3D printability and strength, slightly higher but acceptable deformations.

- Ultrafuse 316L is suitable for rapid prototypes, used in corrosive environments and under low loads. Deformations and stresses remain small, but hardness and strength are limited; it is not recommended for heavy loads or wear durability.

- 36Mn5 is good for moderate-load applications, commonly used because it is easy to machine.

6. CONCLUSIONS

The FEM analysis showed that structurally, all materials can withstand the simulated loads. The decisive factor remains contact and wear resistance, not only elastic deformation. Therefore, if prototypes or tests are intended, Ultrafuse 17-4PH and Ultrafuse 316L can be used, while for series production of industrial gears, 18CrNiMo7 steel is recommended.

In comparing the two steels, 36Mn5 shows lower yield strength and modest hardness, which limits its application to moderate gearbox loads. By contrast, 18CrNiMo7, once carburized, develops superior strength and high hardness, making it the preferred choice for heavy-duty transmissions and high contact stresses.

Ultrafuse 17-4PH and 316L offer good 3D printability and ductility, with 17-4PH allowing higher strength after heat treatment, while 316L provides superior corrosion resistance, but both are more suitable for prototypes or moderate/low-load gears than for high-power applications.

The comparison shows that 18CrNiMo7 remains the best choice for conventional production, offering high hardness, wear resistance, and excellent performance. Ultrafuse 17-4PH provides a practical balance for lighter applications and functional 3D prototypes, while Ultrafuse 316L is more suited to rapid prototyping in corrosive environments under low loads. Meanwhile, 36Mn5 is a reliable option for moderate-load applications thanks to its good machinability.

A disadvantage of the 3D-printed gear is that its mechanical properties can be influenced by the manufacturing process parameters, including porosity, layer orientation, and, importantly, the required post-processing treatment factors that must be carefully considered in practical applications.

To improve the performance of 3D-printed gears made from Ultrafuse® 17-4 PH, the application of heat treatments after sintering could be considered, with the aim of reducing deformations and increasing durability.

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