Accelerated testing of the Wear Behavior of 3D-printed Spur Gears

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ABSTRACT

This paper presents the results of an in-depth investigation of 3D-printed plastic gears made of ABS, PLA, and annealed PLA. Wear tests performed on a specialized rig underscore the superior wear resistance of ABS gears, while the annealing process shows a modest improvement in PLA gear durability. The novelty of this study is a comprehensive evaluation of the wear behavior of different 3D printed materials under different loading conditions. This study introduces an innovative accelerated testing method, emphasizing efficiency in product development through reduced testing durations and adaptability to various scenarios.

Keywords-spur gears; accelerated testing; Acrylonitrile Butadiene Styrene (ABS); polylactic acid (PLA); annealing; wear

I. INTRODUCTION

Plastic gears are mainly used in the textile, food, and automotive industries due to their advantages of quiet operation, corrosion resistance, lightness, and low cost [1-3]. Plastic gears are generally manufactured employing injection molding or milling methods [4-11]. The additional costs of the molds deployed to produce injection parts and the waste issues that arise during milling production are driving companies to utilize additive manufacturing as an alternative application [6-7]. In the additive manufacturing method, the desired amount of product is produced without the waste problem [12-17]. In [1], the capabilities of three distinct thermoplastic materials commonly implemented in plastic gearing applications, ABS, PLA, and Nylon, were investigated. Gears were manufactured using 3D printing, and the results showed that ABS gears exhibited the highest specific wear rates while nylon gears demonstrated the lowest specific wear rates. In [2], a theoretical-experimental investigation was conducted on the impact of FDM parameters, specifically the height of the deposited layer at one pass and the percentage of filling, on the dimensions of PLA cylindrical spur gears. The findings revealed that the percentage of filling had a more significant impact on the dimensional accuracy of PLA cylindrical spur gears than the shaft diameter. Similarly, in [3], the influence of FDM parameters on the stiffness of PLA gears was examined. This study aimed to tune the FDM parameters to achieve maximum stiffness. On average, the stiffness of gears with identical parameters was found to be 8.18% higher than that of gears with the same layer height and variable filling percentages.

In [1, 18-27], specific test rigs were designed to assess the wear behavior of spur gears. In [18], initial tests involved acetal and nylon gears paired with similar materials, further exploring dissimilar polymer gear combinations. For acetal gears, the wear rate increased dramatically beyond a critical load and the surface temperature emerged as the dominant factor that influenced wear. Experimental investigations of nylon gears revealed distinct failure modes compared to those of acetal gears. In particular, when running acetal against nylon gears, especially with acetal as the driver gear, a significant difference in wear behavior was observed. In [23], a novel accelerated testing method was presented for plastic gears to address key product development criteria, such as reduced testing, shorter durations, and applicability to diverse scenarios. The method was applied to a polyacetal (POM) and polyamide 6 (PA6) gear pair, considering different speeds and loads. By monitoring gear temperature and cycles to failure, this study compared measured and calculated temperatures, and the results disclosed that polymer gears commonly fail due to fatigue or sudden melting, emphasizing the necessity of comprehensive testing for reliable gear design. In [24], the use of 3D printing for the manufacture of nylon polymer gears was investigated. Nylon spur gears, produced with Nylon 618, Nylon 645, alloy 910 filaments, and proprietary materials, such as Onyx and Markforged nylon, underwent wear rate tests on a custom-built gear wear test rig. The results displayed that Nylon 618 had the best wear performance among the 3D printing materials tested. Remarkably, 3D gears printed with Nylon 618 outperformed injection-molded nylon 66 gears under low-to-medium torque conditions.

This study designed a specialized experimental test rig specifically adapted to evaluate the wear behavior of spur gears. The unique test rig was particularly constructed to examine the performance and durability of plastic helical gears produced by the FDM method. The insights gained from this study can help optimize gear design and material selection in various applications, leading to more reliable and long-lasting gear systems in fields such as manufacturing, automotive, robotics, and other industries that rely on precision machinery. This knowledge can contribute to improvements in gear technologies, ultimately enhancing the overall efficiency and longevity of mechanical systems.

II. MATERIALS AND METHODS

A. *Composition and Description of the Stand*

To determine the lifetime of the gears, wear tests were carried out in the closed circuit test device at the same load (1.2 Nm, rotation speed 178 rpm, motor power 180 W). Thermoplastic polymer materials PLA, ABS, and heat-treated PLA (at 75 degrees for 3 hours) were used in the production of gears with the geometric characteristics presented in Table I. The experimental wear test stand is a system mainly designed to evaluate the performance and durability of plastic gears in closed-loop applications. It is used to simulate real operating conditions and measure the degree of wear of these components in a controlled environment. Figure 1 depicts the schematic of the test rig that consists of a drive device that sets the gears running [28], simulating the motion and loads to which they are subjected in a real system. The plastic gears are mounted on a central shaft and driven by an electric motor. Through this movement, common operating conditions, such as rotational speed, load, and operating cycles, can be reproduced. The experimental stand is equipped with a tachometer that records the number of cycles performed by the gears, and the torque is applied precisely with a torque wrench.

TABLE I. GEOMETRICAL CHARACTERISTICS OF THE GEARS TESTED

Geometric Parameters	Values
Number of teeth	12
Module	4.5 mm
Pressure angle	20°
Type of gearing	External
Tip diameter	63 mm
Pitch diameter	54 mm
Root diameter	42.75 mm
Base diameter	50.7434 mm
Addendum	4.5 mm
Dedendum	5.625 mm
Width	8.5 mm
Shaft mounting diameter	10 mm

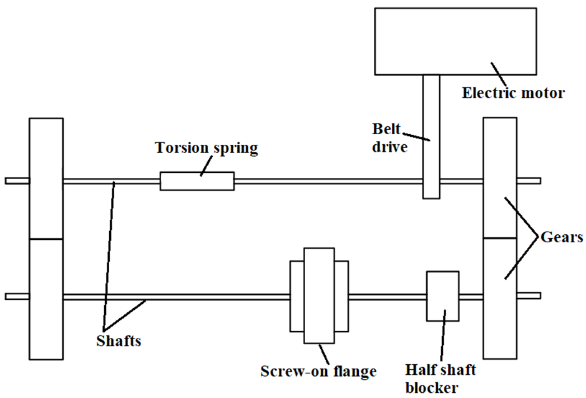


Fig. 1. Schematic representation of the wear testing equipment.

The experimental test rig allows the simulation of real operating conditions, having the ability to control parameters, such as load, rotation speed, and operating cycles, indicating a high level of flexibility and customization. A very important and distinctive characteristic is that the test rig is equipped with a tachometer to record the number of cycles performed by the gears and a torque wrench to control the applied torque. These measurement and control systems enable precise monitoring and adjustment of test parameters, ensuring accurate and repeatable testing. The tests on the experimental stand are carried out for certain durations, depending on the product specifications and the desired durability. Gear wear is evaluated using the gravimetric method, assessing the mass of the gears after different loading time intervals, with an accuracy of 10^{-4} grams, employing the analytical balance presented in Figure 2. The purpose of this test stand is to provide essential information about the performance of plastic gears and to validate their durability before they are implemented in a real system. Through bench testing, gear life, torque transmission capacity, and wear resistance can be determined.

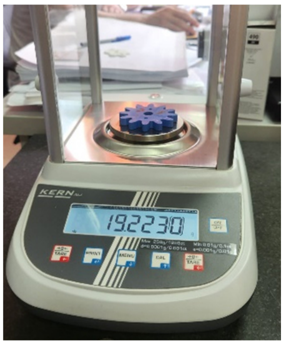


Fig. 2. Analytical balance used to determine the mass of spur gears.

B. Working Methodology

The main objective of the research and simulation of the operating conditions of the 3D-printed gears is to establish the durability and measure the wear resistance of the gears. The design of the experimental stand was adapted to the mechanical characteristics of the materials used throughout the other experimental tests, the biggest constraint being the maintenance of a small torsional moment in the system, adapted to the mechanical properties of the gears tested, as in the specialized literature [18]. The gears were manufactured on an ANYCUBIC 3D printer, seen in Figure 3, deploying 2 shell perimeters and 4 upper and lower solid layers each, based on the geometric model observed in Figure 4 and designed in Solid Edge2023.

Fig. 3. ANYCUBIC 3D printer.

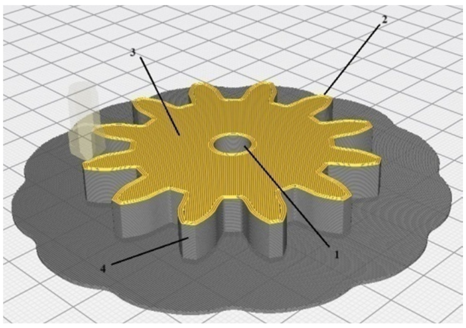


Fig. 4. Sliced gear model: 1-specimen; 2-shells; 3-infill pattern; 4-overlapping layers.

The selection of the printing parameters (infill percentage and layer thickness) of the gears for the tests was made according to the optimization results obtained from previous tribological tests [4]. For the PLA material, 4 gears with a layer thickness of 0.15 mm and an infill percentage of 50%, 4 gears with a layer thickness of 0.10 mm and 50% infill percentage for annealed PLA, and 4 gears with a layer thickness of 0.10 mm and 50% infill percentage for ABS were made. The mounting of the samples on the stand was performed using two M6 screws for each wheel. The torque applied with a torque wrench was calculated with the following calculation algorithm. The strength condition is:

$$\sigma_i = \frac{M_i}{W_i} \leq \sigma_{ai} \quad (1)$$

where σ_i is the bending stress, M_i is the bending moment, σ_{ai} is the allowable bending stress, and W_i is the section modulus calculated as:

$$W_i = \frac{b \cdot s_f^2}{6} = \frac{8 \cdot 7.77^2}{6} = 80.49 \text{ mm}^3 \quad (2)$$

where b is the gear width, and s_f is the thickness of the tooth on the root circle. Therefore, the maximum bending moment is obtained by:

$$M_{i,max} = W_i \times 0.2 \times \sigma_{ai} = 80.49 \times 0.2 \times 29.03 = 0.46\ Nm \quad (3)$$

$$M_{i,max} = F_t \times h_a' \Rightarrow F_t = \frac{M_{i,max}}{h_a'} = \frac{467.38}{9.69} = 48.23\ Nm \quad (4)$$

Torque is determined by:

$$M_t = F_t \cdot (h_a' + r_f) = 48.23 \cdot 31.09 = 1499 \text{ Nmm} = 1.49 \text{ Nm} \quad (5)$$

where h_a' is the height of the force application point, and r_f is the radius of the root circle. To determine the regression equations for each set of gears, 24 weight loss measurements were performed (6 measurements for each gear for the six periods of functioning time considered). So, for this study, a total of 216 measurements were conducted (24×3 resistive moments × 3 materials).

III. RESULTS AND DISCUSSION

Wear was evaluated using the gravimetric method. The measurements concerning mass loss were recorded at different time intervals, for different values of applied moment, but by maintaining some parameter, such as rotational speed and the power of the electrical motor, constant as can be noticed in Table II.

TABLE II. INPUT PARAMETERS FOR WEAR DETERMINATION

Resistive moment (torque) [Nm]				**Rotational speed**	**Power**	**Time [min]**
M_{max} [Nm]	70%×M_r	80%×M_r	90%×M_r	n [Rpm]	P_m (W)	0 15 45 105 120 135
1.499	1.05	1.2	1.35	178	180	

Surface plots and regression equations were obtained deploying Minitab 19. Figure 5 illustrates the Pareto charts of the effects implemented to compare the relative magnitude and statistical significance of the terms. The reference line on the graph indicates which terms are significant. In this analysis, a significance level of 0.05 was put into service to draw the reference line. In this case, the effects for 3 terms are statistically significant (α = 0.05). Significant effects are the resistive moment (A), the resistive moment squared (AA), and the resistive moment cubed (AAA). The effect for time (B) is not statistically significant because the bar does not extend past the red line.

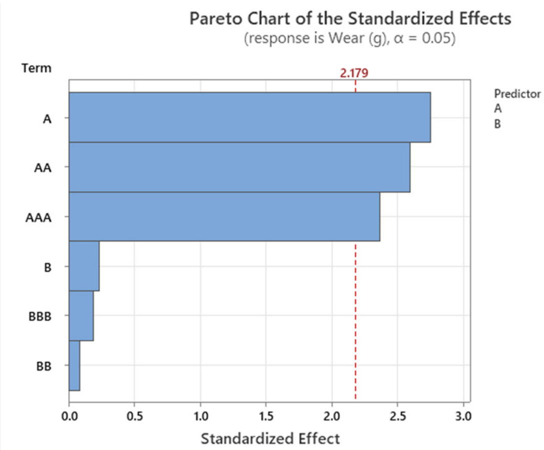


Fig. 5. Example of Pareto chart used to establish the significance of terms used for regression analysis (PLA annealed).

Figure 6(a) portrays the surface plot for the PLA gears, indicating that as both the time and resistive moment increase, the wear also increases, which is typical of mechanical components. Wear increases more significantly with time than with resistive moment, indicating that time has a greater wear impact on this material (Figure 7). For annealed PLA gears, the general shape of the surface is similar to PLA gears, disclosing a consistent relationship between time, resistive moment, and wear, as observed in Figure 6(b). However, the wear scale seems to be slightly lower, suggesting that the annealing process may have improved the wear resistance of the PLA gears to some extent. Figure 6(c) corresponds to ABS gears, showing that wear levels are notably lower than those for PLA, both before and after annealing, in most test conditions. This suggests that ABS gears have a higher wear resistance than PLA gears. The shape of the surface is more curved towards the higher resistive moment axis, indicating that the increase in wear rate is more sensitive to an increase in the resistive moment than to the time when compared to PLA. The experimental study in [1] reveals a correlation in which wear increases with increasing loads that impact the gear, while wear decreases with increased rotational speed. In [2], the wear depths of ABS and PLA materials exhibited a close similarity. In summary, ABS gears exhibit the best wear resistance, with wear increasing more gradually than PLA gears. The annealed PLA gears show improved wear resistance over the as-built PLA gears but still do not perform as well as the ABS gears under the same conditions. This comparative interpretation is consistent with the regression equations and R^2 values from Table III, where the ABS gears had the lowest predictive accuracy for wear, potentially due to their better overall wear resistance, resulting in less overall wear and thus less data variation to fit the model.

(a)
(b)
(c)

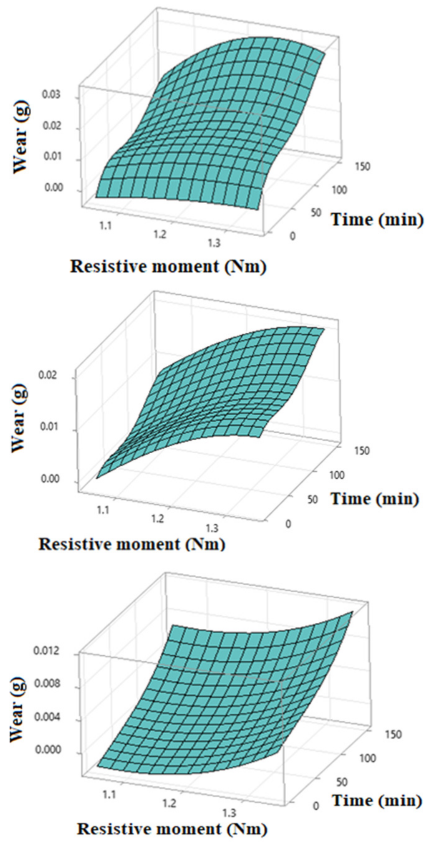
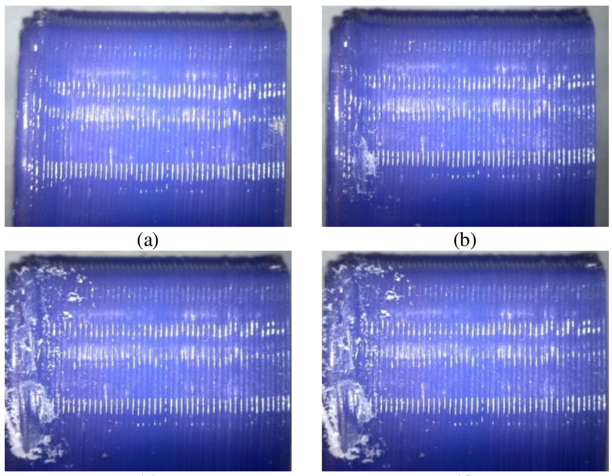


Fig. 6. Wear variation against torque and time: (a) PLA gears, (b) annealed PLA gears, (c) ABS gears.

TABLE III. REGRESSION EQUATIONS FOR MASS LOSS (*Z*), AS FUNCTION OF TIME (*X*) AND RESISTIVE MOMENT (*Y*)

Material	R^2	Regression equation
PLA	97.51%	$z = 0.000012x^2 + 0.002093y^2x - 0.00526xy + 0.0611y^2 + 0.00271x - 0.162y - 0.106$
PLA annealed	96.54 %	$z = -0.1341x^3 + 0.356x^2 - 0.000007y^2 - 0.2301x + 0.000307y$
ABS	88.50 %	$z = 0.0543y^3 - 0.117y^2 + 0.000041x + 0.0612y$



(a) (b)
(c) (d)

Fig. 7. Wear images of the flank of the teeth: (a) at the beginning, (b) after 30 min, (c) after 60 min, (d) after 120 min.

IV. CONCLUSIONS

The study presents compelling findings derived from extensive research into the wear behavior of 3D-printed plastic gears, focusing particularly on ABS, PLA, and annealed PLA materials. This study not only contributes valuable insights to the field, but also introduces novel perspectives in terms of material selection, manufacturing processes, and testing methodologies for plastic gears. The results of wear tests conducted on the specialized experimental test rig highlight the superior wear resistance of ABS gears compared to PLA gears. Furthermore, the annealing process demonstrated a modest improvement in the wear resistance of the PLA gears. These results offer a detailed understanding of how different thermoplastic materials and post-processing treatments influence the durability and performance of plastic gears. Regression equations derived from Minitab were used to draw surface plots and depict the relationship between the mass loss of spur gears, resistive moment, and time to predict mass loss values for a range of resistive moment and time combinations. By examining the surface plot, insights are gained into the relationship between mass loss and independent variables, identifying regions of the plot where mass loss is particularly sensitive to changes in resistive moment or time. The introduced accelerated testing method for plastic gears provides an innovative approach, emphasizing efficiency in product development criteria, such as reduced testing durations and applicability to diverse scenarios. Practically, the insights gained from this study have significant implications for optimizing gear design and material selection in real-world applications. Industries, such as manufacturing, automotive, robotics, and precision machinery, can benefit from the improved reliability of plastic gears achieved through informed decision-making.

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REFERENCES

[1] K. M. Harsha, Y. S. Rao, and D. J. Rao, "Comparison of wear behaviour of polymer spur gears using FDM process," *IOP Conference Series: Materials Science and Engineering*, vol. 1168, no. 1, Apr. 2021, Art. no. 012028, https://doi.org/10.1088/1757-899X/1168/1/012028.

[2] D. G. Zisopol, M. Minescu, and D. V. Iacob, "A Theoretical-Experimental Study on the Influence of FDM Parameters on the Dimensions of Cylindrical Spur Gears Made of PLA," *Engineering, Technology & Applied Science Research*, vol. 13, no. 2, pp. 10471–10477, Apr. 2023, https://doi.org/10.48084/etasr.5733.

[3] D. G. Zisopol, D. V. Iacob, and A. I. Portoaca, "A Theoretical-Experimental Study of the Influence of FDM Parameters on PLA Spur Gear Stiffness," *Engineering, Technology & Applied Science Research*, vol. 12, no. 5, pp. 9329–9335, Oct. 2022, https://doi.org/10.48084/etasr.5183.

[4] A. I. Portoacă, R. G. Ripeanu, A. Diniță, and M. Tănase, "Optimization of 3D Printing Parameters for Enhanced Surface Quality and Wear Resistance," *Polymers*, vol. 15, no. 16, Jan. 2023, Art. no. 3419, https://doi.org/10.3390/polym15163419.

[5] D. G. Zisopol and A. Dumitrescu, *Materiale şi tehnologii primare. Aplicații practice şi studii de caz.* Ploiesti, Romania: Universității Petrol-Gaze din Ploiești, 2005.

[6] D. G. Zisopol and A. Dumitrescu, *Ecotehnologie. Studii de caz.* Romania: Editura Universității Petrol-Gaze din Ploiești, 2021.

[7] D. G. Zisopol, A. Dumitrescu, and C. N. Trifan, *Ecotehnologie: Noţiuniteoretice, aplicaţiişi studii de caz.* Romania: Editura Universității Petrol-Gaze din Ploieşti, 2010.

[8] D. G. Zisopol and M. J. Săvulescu, *Bazele tehnologiei*. Ploieşti, Romania: Editura Universității din Ploieşti, 2003.

[9] M. J. Săvulescu and D. G. Zisopol, *Tehnologii industriale şi de construcții*. Ploiesti, Romania: Editura Universității Petrol-Gaze din Ploiești, 2002.

[10] D. Zisopol, *Tehnologii industriale și de construcții. Aplicații practice și studii de caz.* Ploiesti, Romania: Publisher: Editura Universității din Ploiești, 2003.

[11] M. J. Săvulescu, D. G. Zisopol, and I. Nae, *Bazele tehnologiei materialelor: Îndrumar de lucrări practice*. Ploiești, Romania: Editura Premier Ploiești, 1997.

[12] D. G. Zisopol, I. Nae, A. I. Portoaca, and I. Ramadan, "A Statistical Approach of the Flexural Strength of PLA and ABS 3D Printed Parts," *Engineering, Technology & Applied Science Research*, vol. 12, no. 2, pp. 8248–8252, Apr. 2022, https://doi.org/10.48084/etasr.4739.

[13] D. G. Zisopol, I. Nae, and A. I. Portoaca, "Compression Behavior of FFF Printed Parts Obtained by Varying Layer Height and Infill Percentage," *Engineering, Technology & Applied Science Research*, vol. 12, no. 6, pp. 9747–9751, Dec. 2022, https://doi.org/10.48084/etasr.5488.

[14] A. Portoaca, I. Nae, D. G. Zisopol, and I. Ramadan, "Studies on the influence of FFF parameters on the tensile properties of samples made of ABS," *IOP Conference Series: Materials Science and Engineering*, vol. 1235, no. 1, Nov. 2022, Art. no. 012008, https://doi.org/10.1088/1757-899X/1235/1/012008.

[15] D. G. Zisopol, A. I. Portoaca, I. Nae, and I. Ramadan, "A Comparative Analysis of the Mechanical Properties of Annealed PLA," *Engineering, Technology & Applied Science Research*, vol. 12, no. 4, pp. 8978–8981, Aug. 2022, https://doi.org/10.48084/etasr.5123.

[16] D. G. Zisopol and A. Dumitresku, *Materiale si Tehnologii Primare*. Ploiesti, Romania: Editura Universității din Ploiești, 2005.

[17] A. Portoaca, I. Nae, D. G. Zisopol, and I. Ramadan, "Studies on the influence of FFF parameters on the tensile properties of samples made of ABS," *IOP Conference Series: Materials Science and Engineering*, vol. 1235, no. 1, Nov. 2022, Art. no. 012008, https://doi.org/10.1088/1757-899X/1235/1/012008.

[18] K. Mao, W. Li, C. J. Hooke, and D. Walton, "Friction and wear behaviour of acetal and nylon gears," *Wear*, vol. 267, no. 1, pp. 639–645, Jun. 2009, https://doi.org/10.1016/j.wear.2008.10.005.

[19] M. S. Tunalioglu and T. Torun, "The investigation of wear on three-dimensional printed spur gears," *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 235, no. 6, pp. 2027–2034, Dec. 2021, https://doi.org/10.1177/09544089211027732.

[20] K. Mao *et al.*, "The wear resistance improvement of fibre reinforced polymer composite gears," *Wear*, vol. 426–427, pp. 1033–1039, Apr. 2019, https://doi.org/10.1016/j.wear.2018.12.043.

[21] S. M. Evans and P. S. Keogh, "Wear mechanisms in polyoxymethylene spur gears," *Wear*, vol. 428–429, pp. 356–365, Jun. 2019, https://doi.org/10.1016/j.wear.2019.03.027.

[22] H.-J. Dennig, L. Zumofen, and A. Kirchheim, "Feasibility Investigation of Gears Manufactured by Fused Filament Fabrication," in *Industrializing Additive Manufacturing*, 2021, pp. 304–320, https://doi.org/10.1007/978-3-030-54334-1_22.

[23] A. Pogačnik and J. Tavčar, "An accelerated multilevel test and design procedure for polymer gears," *Materials & Design (1980-2015)*, vol. 65, pp. 961–973, Jan. 2015, https://doi.org/10.1016/j.matdes.2014.10.016.

[24] Y. Zhang, C. Purssell, K. Mao, and S. Leigh, "A physical investigation of wear and thermal characteristics of 3D printed nylon spur gears," *Tribology International*, vol. 141, Jan. 2020, Art. no. 105953, https://doi.org/10.1016/j.triboint.2019.105953.

[25] H. İmrek, "Performance improvement method for Nylon 6 spur gears," *Tribology International*, vol. 42, no. 3, pp. 503–510, Mar. 2009, https://doi.org/10.1016/j.triboint.2008.08.011.

[26] P. K. Singh, Siddhartha, and A. K. Singh, "An investigation on the thermal and wear behavior of polymer based spur gears," *Tribology International*, vol. 118, pp. 264–272, Feb. 2018, https://doi.org/10.1016/j.triboint.2017.10.007.

[27] M. S. Tunalioglu and B. V. Agca, "Wear and Service Life of 3-D Printed Polymeric Gears," *Polymers*, vol. 14, no. 10, Jan. 2022, Art. no 2064, https://doi.org/10.3390/polym14102064.

[28] B. Roth *et al.*, "Stand for fatigue testing of gears made of plastic materials with automatic reading of the moment value and the teeth wear value," A/00877/2023, Dec. 01, 2023.