

Article

Service Life and Failure Analysis of Nylon, Polycarbonate, and IGUS i180 Polymer Gears Made by Additive Manufacturing

Adis J. Muminović ¹, Sunita Bektašević ¹, Enis Muratović ¹, Nedim Pervan ^{1,*}, Jasmin Smajić ²,
Adil Muminović ¹, Isad Šarić ¹, Elmedin Mešić ¹, Mirsad Trobradović ³ and Muamer Delić ¹

- ¹ Department of Mechanical Design, Faculty of Mechanical Engineering, University of Sarajevo, 71000 Sarajevo, Bosnia and Herzegovina; adis.muminovic@mef.unsa.ba (A.J.M.); sunitabektasevic7@gmail.com (S.B.); muratovic@mef.unsa.ba (E.M.); muminovic@mef.unsa.ba (A.M.); saric@mef.unsa.ba (I.Š.); mesic@mef.unsa.ba (E.M.); delic@mef.unsa.ba (M.D.)
- ² Protoengs Sarajevo, 71000 Sarajevo, Bosnia and Herzegovina; jasmin@protoengs.com
- ³ Department of Vehicle Engineering, Faculty of Mechanical Engineering, University of Sarajevo, 71000 Sarajevo, Bosnia and Herzegovina; trobradovic@mef.unsa.ba
- * Correspondence: pervan@mef.unsa.ba

Abstract: An assessment of different materials for additive manufacturing (AM) of polymer gears is presented in this research. Experimental testing is carried out for three different materials. Two materials are selected as the most common materials used for gears made by additive manufacturing. These materials are nylon and polycarbonate (PC). The third material is IGUS i180, which is a tribological material specially developed for additive manufacturing of parts with demands for high resistance properties such as resistance to friction, wear, and high temperatures which are essential for the long service life of gears. Gears are experimentally tested to determine service life in the form of operating cycles until failure. In addition, the gear temperature is monitored during the experimental testing. Using the value of maximum temperature at the moment of total gear failure at a specific load level enables the categorization of failure type. Different types of gear failures are categorized and presented. Taking into consideration failure type and the service life in the form of operating cycles, the applicability of analyzed materials for specific applications concerning load, speed, and thermal conditions is presented and discussed at the end of the paper. The main goal of this research was to test IGUS i180 material and compare its mechanical and thermal properties with other commonly used materials for gears manufactured by AM, such as nylon (PA6/66) and polycarbonate (PC). IGUS i180 material showed inferior properties concerning gear design in the case of high loads. This research showed that PA6/66 material is still the best solution for polymer gears production using AM, but the applicability of this material, due to temperature constraints, is still quite limited.

Keywords: materials; additive manufacturing; polymer gears; service life; experimental testing



Academic Editor: Khalil Khanafer

Received: 24 November 2024

Revised: 19 December 2024

Accepted: 22 December 2024

Published: 25 December 2024

Citation: Muminović, A.J.; Bektašević, S.; Muratović, E.; Pervan, N.; Smajić, J.; Muminović, A.; Šarić, I.; Mešić, E.; Trobradović, M.; Delić, M. Service Life and Failure Analysis of Nylon, Polycarbonate, and IGUS i180 Polymer Gears Made by Additive Manufacturing. *Machines* **2025**, *13*, 5. <https://doi.org/10.3390/machines13010005>

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Additive manufacturing is one of the most exciting new technologies in the manufacturing world. It gained popularity in the last decade. Its rapid development over the years has brought this technology to almost every aspect of manufacturing, from toys and mechanical gears to airplane spacecraft parts [1]. Regardless of its benefits, the progress of additive manufacturing (AM) brings a lot of new questions and challenges that need to

be investigated. In the case of machine elements, AM enables the design of lightweight machine elements, but at the expense of the same (or similar) design and corresponding mechanical and thermal properties. For example, in the case of gears, AM enables gear production in the form of a shell with the infill inside. Today, most of the research about AM is focused on the research of so-called lattice structures [2]. Researchers mostly use predefined AM parameters for testing various mechanical properties. The preparation of AM parts can be performed with parameters predefined in default software settings or user-defined parameters [3,4].

Polymer gear production by AM requires a careful selection of materials that can be used for specific applications [5]. Even though heavy operational duty cycles in power transmission imply the usage of metal gears, such as steel, titanium, or aluminum, composite materials with carbon or glass fibers can offer a good combination of lightweight and high performance in low and moderate-load applications [6,7]. However, the applications of polymer gears are often limited as they come with lower mechanical and thermal properties [8]. The advantages of polymer gears, especially in the cases of AM, are reflected in easy and cost-effective production. AM also enables fast repair of gear mechanisms, i.e., gear replacement, as compared to other production methods, it offers prompt and low-cost manufacturing directly from a three-dimensional (3D) computer-aided design (CAD) model. Additionally, AM offers a wide scope of design possibilities and adjustments concerning various gear shapes, geometric parameters, and lightweight solutions with complex internal structures [9].

The first step in AM production is the selection of manufacturing technology. The most common technology for metal additive manufacturing (MAM) of gears is Direct Metal Laser Sintering (DMLS), while polymer gear manufacturing relies on a fused deposition modeling method, also known as the Material Extrusion (MEX) method [10]. In the second step, the material for manufacturing needs to be selected, which is the most challenging part as, taking into account the number of available polymer and polymer composite materials, designers are bound to make selections between different mechanical and thermal properties, cost-effectiveness and other manufacturing demands to satisfy the ultimate conditions of the gear application. MEX technology can be used for versatile materials, such as typical polymers like polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PET), polycarbonate (PC), polyamide (PA), etc., different polymer composite materials with carbon or glass fibers and mixtures of wood particles, and polymer composite materials with specially developed additives, i.e., filaments for high tribological requirements as is the case with the IGUS i180 material [11]. Typical polymers such as PLA, ABS, and PET are usually used for the development of educational models, as, due to lower and temperature-dependent mechanical properties, their application is not recommended for the manufacturing of gears and it is limited to certain products with low loads and negligible thermal influence. On the contrary, PC and PA materials, as well as polymer composite materials with carbon or glass fibers, proved to be suitable for gear applications. Additionally, filaments that enhance the tribological behavior of polymer materials, as is the case with the IGUS i180 material that will be experimentally investigated, are often a good choice for gear applications.

The novelty and the main objective of this research is to study the applicability of the IGUS i180 material in gear applications, concerning the AM technology, since no study on this topic has been conducted yet. The biggest contribution to this work is an attempt to remove the doubts that engineers have when choosing a polymer material for manufacturing polymer gears using AM. If someone looks at the literature or advice from engineering websites or material manufacturers, it is evident that there is a lot of disagreement about which material is most suitable for the production of polymer gears

using AM. The reason for such doubts lies primarily in the fact that there are no general for which materials should be chosen in each case. The choice of the material depends primarily on the mechanical and temperature demands of the application in which the gears are to be used, as we will discuss in the conclusion part of the paper.

2. Current State of the Art of AM Technology in Gear Design and Manufacturing

The rapid growth of industrialization can be attributed to the development of new technologies [12–14]. The expansion of AM, as one of the leading manufacturing technologies, in various industrial fields is more than justified especially in the cases of new product development and design as, compared to the conventional manufacturing methods, it enables various new design solutions or the lightweight redesign of existing products with an internal infill structure [15,16]. Additionally, AM technology enables the employment of numerous polymer materials which expands the field of design solutions even further, as these materials, due to their properties, are not typically used in conventional manufacturing processes [17]. Furthermore, AM technology allows for a combination of different polymer materials during the production process, which is of crucial importance for the new field of machine elements with targeted areas that require the specific properties of individual materials, such as better load-carrying capacity, thermal conductivity, etc.

As previously outlined, the benefits of AM can be applied to the fields of gear design and manufacturing, which are in full swing considering the amount of research provided by many different authors in recent years. When it comes to MAM technology, several papers, concerning gear design as well as some other rotating machinery components, can be highlighted. Tezel et al. [6] established a wear-testing methodology and compared the wear performance of AlSi10Mg and Ti6Al4V gears manufactured conventionally and using AM technology. Wear intensity was determined by analyzing the oil in the gearbox. Additionally, gear surfaces were inspected with scanning electron microscopy (SEM) and an energy-dispersive spectrometer before and after the wear tests, to perform a full comparative analysis of gears manufactured by different technologies. Senthilkumar et al. [18] investigated the repair method for damaged gears by using the wire arc AM technology. Sarzyński [19] provided a comprehensive review of MAM for the production of various vehicle parts and components. The significance of MAM techniques in the production of vehicle parts over the past several years was highlighted. This research indicated the specific industries and scientific sectors in which these production techniques have been applied successfully. The primary manufacturing methods, concerning both metallic and non-metallic materials, were presented. The authors put their primary focus on MAM techniques and categorized these methods into three main groups: laser-powder bed fusion (L-PBF), sheet lamination (SHL), and directed energy deposition (DED) techniques. Additionally, specific examples of vehicle components produced by MAM methods were provided.

Polymer-based AM, compared to MAM techniques, is much more common due to the availability of AM machines, primarily as there is a huge cost-per-unit difference. Accordingly, an individual field of research regarding polymer AM raises a question about AM techniques used for polymer gears and their potential to replace conventional manufacturing technologies. Yilmaz et al. [20] focused on the comparison of the wear and thermal properties of conventionally manufactured polyamide 6 (PA6) gears and polyetherimide (PEI) gears manufactured by AM. PA6 experienced better wear resistance at low and moderate rotational speeds, while PEI gears showed superior wear performance at higher rotational speeds. Furthermore, PEI gears displayed enhanced thermal properties, i.e., a lower increase in the bulk temperature compared to PA6 gears. This occurrence can

be explained by the inherent porous structure of the AM, which allows for better heat dissipation. The results suggest that PEI gears produced by AM could be used as an alternative in high-speed applications. Baciú et al. [10] outlined the fact that AM techniques are suitable for rapid prototyping of small batches of non-standard parts and the performance improvements of mechanisms by customizing certain dimensions to the specific needs of the system. Such an example, concerning gears, would be an adjustment to the sizes, shapes, and tooth profiles to obtain the necessary gear ratio. The article presents some of the techniques and technologies that can be employed to manufacture geared wheels and transmissions along with their respective pros and cons. Ciobanu et al. [21] proposed a series of experimental tests to establish the possibility of integrating the gears made by AM into mechanisms operating in dry-running conditions. The tests were conducted on several materials, such as PA, PLA, ABS, and photopolymer (PP), with the corresponding gear evaluation performed by the double flank test machine (Frenco ZWP 06) and 3D scanning with the ATOS CORE 135 3D scanner. The tests revealed that the PA and PP gears failed to meet the structural integrity limit after the tests, while the PLA gears exhibited superior resistance to the abrasive wear mechanism compared to the ABS gears, which were attributed to have higher structural integrity. Islam et al. [22] provided an in-depth overview of AM in the production of polymer components.

3. Experimental Research Preparation and Design of Experiment

The research carried out in this paper is completely experimental. In the first step, the design of the experiment is carried out, which includes the preparation of all steps: the selection of dimensional characteristics of gear specimens, the selection of materials, the selection of the AM technology and its parameters, the selection of testing conditions (load and speed), the selection of measuring equipment, and adjustment of the testing rig. The steps of the experimental research are shown in Figure 1.

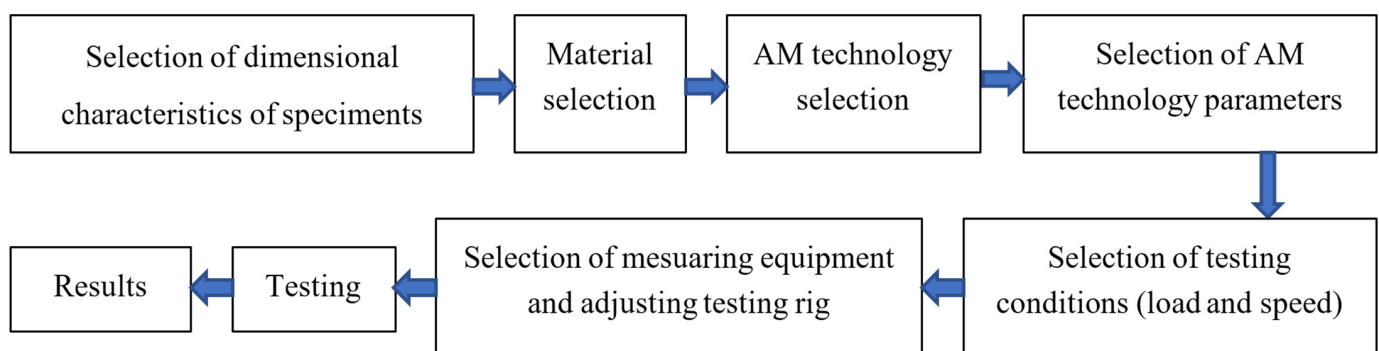


Figure 1. Design of experiment.

In this research, more advanced design of experiment (DOE) methods were not used because the main goal of the experiment was not to compare and investigate a large number of parameters, but to compare only three types of materials while selecting standard production parameters that engineers would most often use in practical applications.

3.1. Manufacturing of Gears

3.1.1. Dimensional Properties

For more details on the selected dimensional characteristics of gears, the readers will be redirected to our previous research [8,23]. The same dimensional characteristics were used in all of our previous research papers, with the goal being to be able to compare results for different manufacturing technologies, materials, parameters, loads, speeds, etc.

Accordingly, the present study is focused on the comparison of the experimental results concerning gears produced by hobbing, as was the case in our previous research, and gears produced by AM. Table 1 presents the dimensional characteristics of gears.

Table 1. Dimensional characteristics of gears.

Property	Label	Value
Profile	-	Involute
Module	m	3 mm
Number of teeth	z	17
Pressure angle	α_n	20°
Face width	b	20 mm
Pitch diameter	d	51 mm
Root diameter	d_f	44.4 mm
Tip diameter	d_a	57 mm
Base diameter	d_b	47.924 mm
Profile shift coefficient	x	0
Radial contact ratio	ε_a	1.516

3.1.2. Selection of Materials

Following the recommendations by other authors, Ultimaker PA6/66 and PC, as the two most common materials for MEX AM of gears, were selected for experimental testing [5–7,20,21]. Other commonly used materials for MEX additive manufacturing, like PLA, ABS, and PET, were not selected because these have already been investigated, and it has been proven by other authors that these materials are not suitable for AM of gears, especially in the case of high load [24,25]. Additionally, gears made out of IGUS i180 material with specially developed filaments were tested. Even though the tribological properties of IGUS i80 materials have been investigated by other researchers in the field, the applicability of the IGUS i80 in gear applications, especially referring to the study of life-cycle properties, has not been established yet [26–29]. The goal was to compare this new material (IGUS i180) with commonly used materials for polymer gear AM.

PA6/66 material is usually used for the manufacturing of parts that require higher mechanical properties and long service life, as the semi-crystalline structure of the material is attributed to its high impact and wear resistance and small shrinkage percentage after cooling. A small shrinkage percentage results in good dimensional accuracy of manufactured parts, which is very important in the case of gears. Additionally, the material has self-lubricating properties which offer a great advantage in the reduction of friction, which is of crucial importance for the sliding surfaces in engagement. However, the same material exhibits some disadvantages due to high moisture sensitivity, and needs to undergo a drying process before being used for AM. The mechanical properties of the PA6 material are presented in Table 2. The thermal properties of the PA6 material are presented in Table 3.

As emphasized previously, the second material selected for gear AM was PC. The material has good mechanical properties and, compared to PA6/66, better thermal resistance with slightly lower properties concerning elasticity and wear resistance. The basic mechanical and thermal properties of the PC material are presented in Tables 4 and 5, respectively.

The xy (Flat), yz (Side), and Z (Up) columns in Tables 2 and 4 represent the printing direction of 3D printed parts before testing. These directions are given as in Figure 2. It is known that 3D printing direction determines different mechanical properties of parts produced using AM, i.e., parts will have different mechanical properties according to the orientation on the build plate.

Table 2. Mechanical properties of Ultimaker PA6/66 material.

Property	Value			Test Method
	xy (Flat)	yz (Side)	Z (Up)	
Young's modulus ¹	2331 ± 55 MPa	2336 ± 75 MPa	2300 ± 64 MPa	[30]
Tensile stress at yield ²	63.1 ± 1.1 Mpa	65.3 ± 0.5 MPa	No yield	[30]
Tensile stress at break	40.4 ± 2.2 MPa	42.3 ± 1.3 MPa	23.0 ± 2.3 MPa	[30]
Elongation at yield	6.1 ± 0.2%	6.5 ± 0.1%	No yield	[30]
Elongation at break	>120%	>130%	1.7 ± 0.2%	[30]
Flexural modulus ³	1872 ± 90 MPa	1052 ± 56 MPa	1060 ± 58 MPa	[31]
Flexural strength ⁴	82.9 ± 3.1 MPa *	63.4 ± 2.8 MPa +	36.6 ± 3.0 MPa ‡	[31]
Flexural strain at break	No break (>10%)	No break (>10%)	4.0 ± 0.3%	[31]
Charpy impact strength ⁵	13.7 ± 1.2 kJ/m ²	-	-	[32]
Hardness ⁶	81 MPa	-	-	[33]

^{1,3} v = 1 mm/min; ^{2,4} v = 5 mm/min; ⁵ notched, at 23 °C; ⁶ Durometer, Shore D; * at 6.6% strain; + at 7.5 strain; ‡ at 4.0% strain. (Data provided in this table are given according to the Ultimaker manufacturer data sheet from Ultimaker company (Geldermalsen, The Netherlands, EU)).

Table 3. Thermal properties of Ultimaker nylon material.

Property	Value	Test method
Melt mass-flow rate (MFR)	6.2 g/10 min	[34] (300 °C, 1.2 kg)
Heat deflection (HDT)	89.2 ± 5.6 °C	[35]
Vicat softening temperature	169.6 ± 0.8 °C	[36]
Glass transition temperature	55.1 °C	[37] (DSC, 10 °C/min)
Melting temperature ²	188.4 °C	[37] (DSC, 10 °C/min)

(Data provided in this table are given according to the Ultimaker manufacturer data sheet).

Table 4. Mechanical properties of Ultimaker PC material.

Property	Value			Test Method
	xy (Flat)	yz (Side)	Z (Up)	
Young's modulus ¹	2394 ± 98 MPa	2352 ± 77 MPa	2255 ± 77 MPa	[32]
Tensile stress at yield ²	53.3 ± 1.2 MPa	58.5 ± 0.9 MPa	No yield	[32]
Tensile stress at break	43.2 ± 1.5 MPa	54.8 ± 1.0 MPa	25.2 ± 2.1 MPa	[32]
Elongation at yield	6.1 ± 0.3%	5.9 ± 0.2%	No yield	[32]
Elongation at break	9.2 ± 0.9%	6.7 ± 0.3%	2.0 ± 0.1%	[32]
Flexural modulus ³	1619 ± 81 MPa	2052 ± 95 MPa	2032 ± 43 MPa	[33]
Flexural strength ⁴	89.4 ± 2.3 MPa *	98.4 ± 3.5 MPa +	32.3 ± 3.7 MPa at ‡	[33]
Flexural strain at break	No break (>10%)	No break (>10%)	1.5 ± 0.2%	[33]
Charpy impact strength ⁵	11.6 ± 1.4 kJ/m ²	-	-	[34]
Hardness ⁶	81 MPa	-	-	[35]

^{1,3} v = 1 mm/min; ^{2,4} v = 5 mm/min; ⁵ notched, at 23 °C; ⁶ Durometer, Shore D; * at 6.9% strain; + at 6.1 strain; ‡ at 1.5% strain. Data provided in this table are given according to the Ultimaker manufacturer data sheet from Ultimaker company (Geldermalsen, The Netherlands, EU).

Table 5. Thermal properties of Ultimaker PC material.

Property	Value	Test Method
Melt mass-flow rate (MFR)	23–26 g/10 min	[34] (300 °C, 1.2 kg)
Heat deflection (HDT)	104.5 ± 0.7 °C	[35]
Vicat softening temperature	114.7 ± 0.4 °C	[36]
Glass transition temperature	107.7 °C	[37] (DSC, 10 °C/min)
Melting temperature	(amorphous)	[37] (DSC, 10 °C/min)

Data provided in this table are given according to the Ultimaker manufacturer data sheet from Ultimaker company (Geldermalsen, The Netherlands, EU).

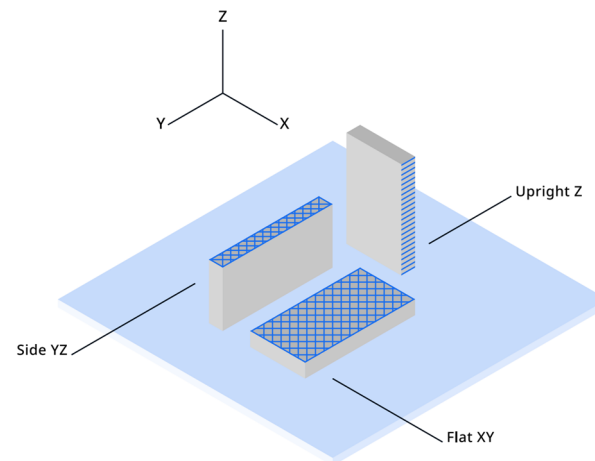


Figure 2. Orientation of the testing samples during additive manufacturing (Ultimaker materials).

The third selected material, IGUS i180, has good processing abilities, wear resistance, strength, and temperature properties. The basic mechanical and thermal properties, along with currently available data on test methods, according to IGUS, are presented in Tables 6 and 7, respectively.

Table 6. Mechanical properties of IGUS i180 material.

Property	Value	Test Method
Young's modulus	1000 MPa	[38]
Coefficient of sliding friction ¹	0.24	-
Coefficient of sliding friction ²	0.17	-
Flexural strength	46/33 MPa	-
Density ³	1.21 g/cm ³	-
Pressure load	59 MPa	-
Surface pressure ³	30 MPa	-
Hardness ⁴	66 MPa	[39]

¹ dynamic, against Cf53 steel; ² dynamic, against 304 stainless steel; ³ at 20 °C; ⁴ Shore D. Data provided in this table are given according to the Igus manufacturer data sheet from Igus ltd. Caswell Rd, Northampton NN4 7PW, UK.

Table 7. Thermal properties of IGUS i180 material.

Property	Value	Test Method
Long-term application temperature	100 °C	-
Short-term application temperature	120 °C	-
Lower application temperature	−40 °C	-
Thermal expansion coefficient	$9 \times 10^{-5} \text{ K}^{-1}$	[40]
Thermal conductivity	0.23 W/(K·m)	[41]

Data provided in this table are given according to the Igus manufacturer data sheet from Igus ltd. Caswell Rd, Northampton NN4 7PW, UK.

3.1.3. Selection of AM Technology

The MEX AM process begins with the creation of a CAD model, which is converted into a standard triangle language (STL) file for more detailed information on the layer creation. The materials used in this manufacturing method are in the form of a long wire, which can be located inside or outside the 3D printer. The driving wheels serve to

feed and regulate the speed of the wire entering the nozzle, which has in-built heaters. The heaters maintain a temperature higher than the melting temperature of the plastic material so the continuous flow of material is enabled. When the wire melts, it passes through the nozzle in a liquid state and deposits a plane layer of material. After making the initial layer, the platform moves along the z-axis for the height adjustment of the next layer, and the procedure is repeated until the creation of the final 3D shape, i.e., product. Between these layering steps, a cooling of deposited material occurs. With the constant feed of the material and the usually small nozzle diameters, AM technology, compared to conventional manufacturing technologies, offers great convenience as it results in a small amount of unused material [26–28]. When it comes to the presented research, two types of AM machines, i.e., 3D printers are used, namely, Ultimaker 3 (Ultimaker company (Geldermalsen, The Netherlands, EU) and BambuLab X1 Carbon (BambuLab Company, Shenzhen, China).

3.1.4. Selection of AM Parameters

In the case of MEX AM, it is very important to properly select manufacturing parameters for the best mechanical and thermal properties of manufactured parts, i.e., gears. The basic and most important parameter is gear orientation during manufacturing [29]. Parts produced by MEX additive manufacturing technology are built up from layers of melted material, and the connections between these layers are usually the weak points of manufactured parts. The gears were placed on the build plate, as shown in Figure 3.

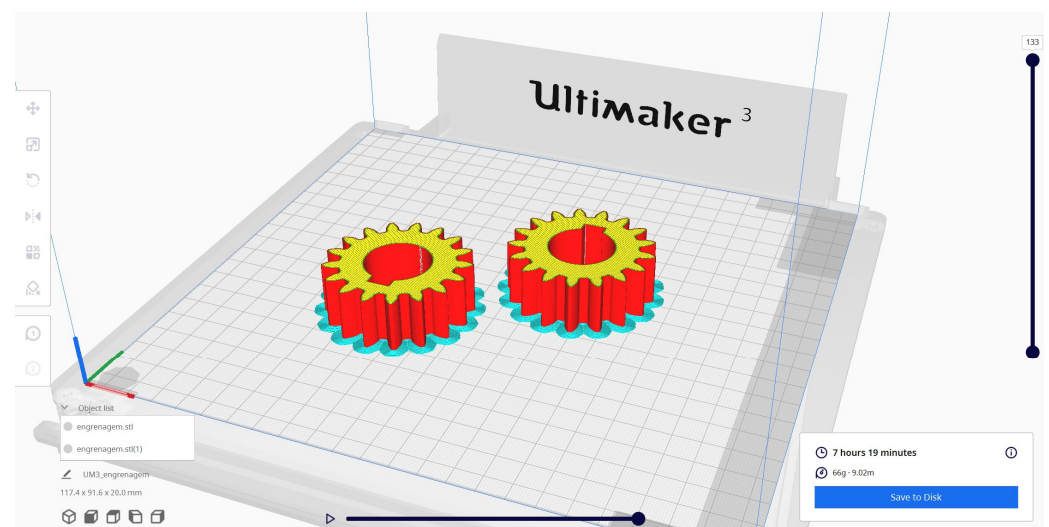


Figure 3. Orientation of gears during manufacturing.

Parameters for the AM of PA6/66 and PC gears were established with the Ultimaker Cura v5.8 software, while the BambuLab Studio v1.9.7 was used for the IGUS i180 gears. A normal quality profile, due to a good combination of speed and quality of 3D printing, was established for all of the gears. This standard profile selection refers to 0.15 mm layer height and a 0.4 mm nozzle. Three gear samples were manufactured for each material with an infill density of 100%, as the durability criteria of AM products is a function of the infill structure [42,43]. Figure 4 presents the flowchart of the AM parameter setup.

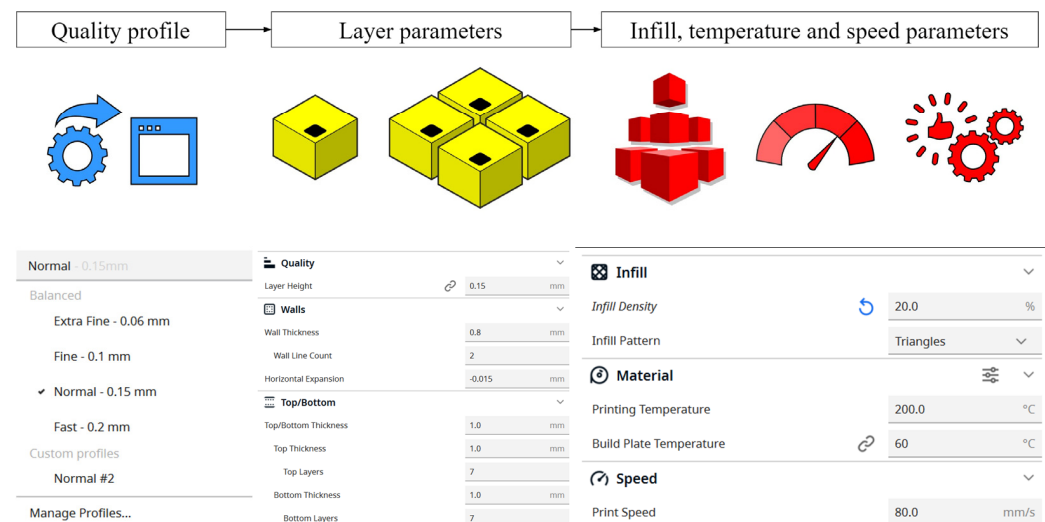


Figure 4. Flowchart of the AM parameter setup.

4. Experimental Testing

As one of the goals of the presented research was to compare the performance of the gears produced by conventional means and AM, the samples were tested in the standard engagement of steel pinion and plastic gears. The same engagement, i.e., testing conditions, were used in our previous research, which will be discussed later on [8,23].

4.1. Experimental Test Rig

Experimental testing was performed on an open-loop test rig shown in Figure 5. The power was supplied through an electric motor (EM1) (Marathon Electric HJA-IE2 132 M, Regal Rexnord Corporation, Wausau, WI, USA), which was controlled by a frequency regulator (EN600-4 T 0075G/110P, Shenzhen Encom Electric Technologies CO, Shenzhen, China). The torque transducer (HBM T20WN T153040, Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany), which was used for the measurement of torque and angular velocity, was connected to the HBM Quantum X data acquisition system. The electric motor was connected, via couplings and bearing units, to the first shaft. The first shaft was supported by two roller radial bearings. At the end of the first shaft, steel gear, as a driving unit, was mounted. The gears produced by the AM were mounted on the second parallel shaft, which was connected, via bearing units, to the second electric motor (EM2) with the gear reducer. The horizontal displacement of the second shaft could be adjusted, therefore enabling the assembly and testing of gears of different sizes. EM2 with a gear reducer was used to control the torque level, i.e., the simulated load. The initial torque of the open-loop system was neglected, i.e., zeroed with the catmanEasy 5.3.1 software of the Quantum X data acquisition system. The temperature of the tested gears was monitored with a thermal camera (Testo 865, Testo SE, Titisee-Neustadt, Germany).

4.2. Testing Conditions

Full-time testing can determine gear life under specific test parameters, such as torque load and angular velocity. When it comes to polymer gears, the lifetime can refer to various aspects, such as the number of operating cycles until fatigue occurs, or operating time at a certain load, temperature, etc. Usually, the lifetime of a plastic gear is defined according to the basic failure parameters, such as tooth root fracture or temperature-induced deformation. However, since polymer gears are prone to fail due to a combination of several factors, it is not always possible to determine the most adequate parameter to determine their lifetime. In addition, reliable lifetime predictions require the collection of large data

sets, which is often not an easy task to achieve, as gears and other machine elements, such as bearings, require complex and time-consuming tests with different experimental conditions that vary concerning the materials, geometry, test conditions, and other gear application requirements. Full-time testing was carried out for the torque level of 6 Nm and constant rotational speed of 1000 rpm. It is important to note that the torque level was set at a constant of 6 Nm, but it varied a little in testing due to the changes in friction values, increased temperature, wear, etc. Torque load varies in real application scenarios also, so in this way, real conditions were simulated better. This testing rig did not have active control of the torque; we plan to implement this in future research. This small variation in the torque was considered acceptable, because the variations were small, and as mentioned above, better simulation of real applications was achieved in this way. These testing parameters were selected according to previous research, so comparison between the two manufacturing techniques could be performed. The gears were subjected to load until failure occurred. In total, according to the number of manufactured gears, nine tests were carried out. The temperature of gears was monitored during the test, so the type of failure could be classified more easily. Due to the many possible failure mechanisms of plastic gears, it was important to classify the type of failure (thermal or load-induced failure), as will be discussed in the next section.

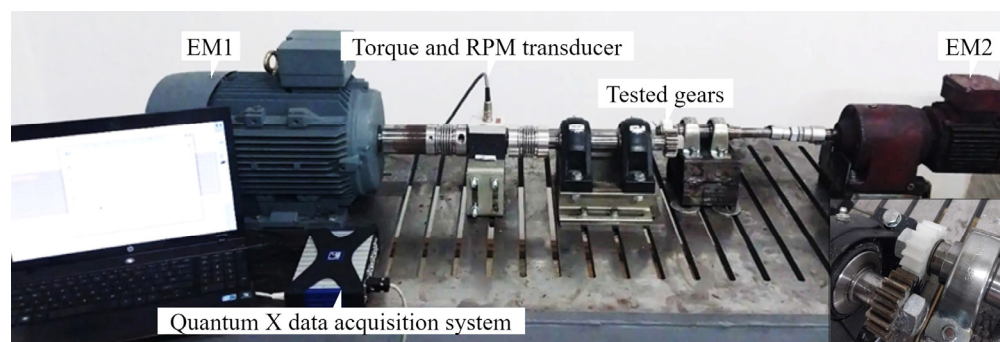


Figure 5. Test rig configuration.

5. Results

Results in the form of full-time testing diagrams, maximal measured temperature, and classification of failure types are presented in this section. Additionally, a comparative chart for different materials is introduced.

5.1. Results of Service Life

5.1.1. PA6/66 Material

The diagrams presented in Figures 6–8 show the life-cycle testing results of three PA6/66 gear samples. The 0 Nm torque drops observable in some diagrams correspond to the random stoppages of an open-loop system for the visual inspection of gear samples.

As emphasized previously, experimental testing was conducted on steel/plastic engagements. Diagrams presented in Figures 6–8 show an approximately constant load of 6 Nm, with small variations resulting from wear on the gear tooth surfaces. Table 8 presents the lifetime results. From the results, it can be noted that the PA6/66 gears manufactured by AM technology have an excellent service life, as one of the samples withstood almost 2×10^6 load cycles. Additionally, it can be noticed that the results of the tested gear samples differed a lot. Such a significant difference can be explained by the errors during experimental testing or assembly, i.e., positioning errors. Data discrepancy indicates that a larger amount of gear samples need to be tested in future research.

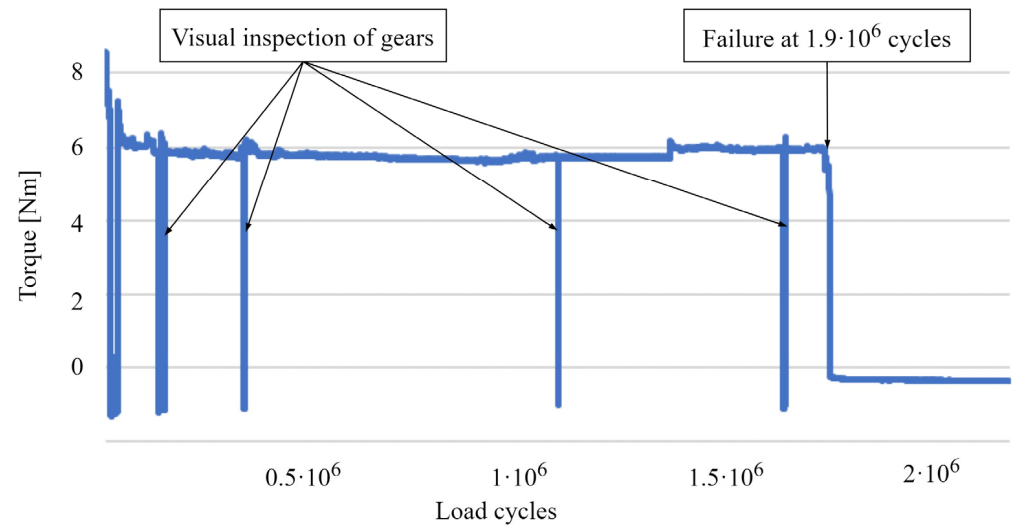


Figure 6. Number of life cycles for the first PA6/66 sample.

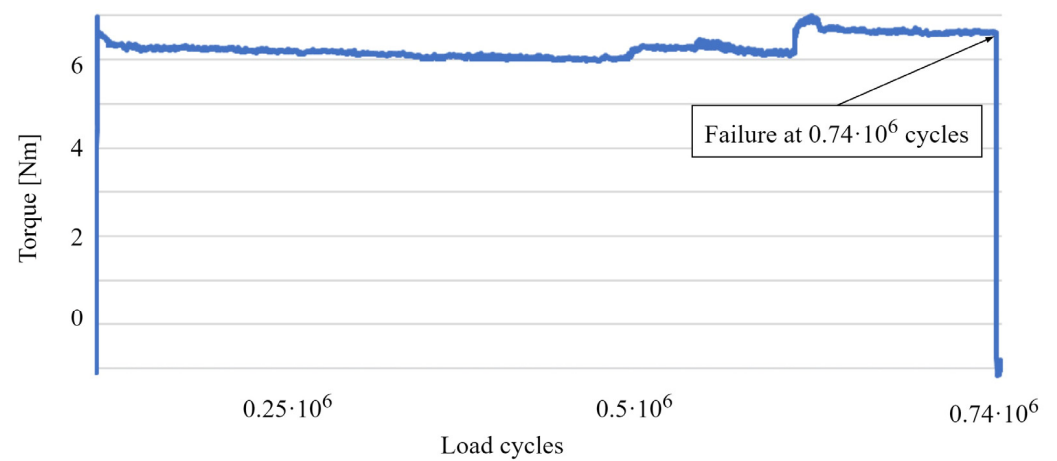


Figure 7. Number of life cycles for the second PA6/66 sample.

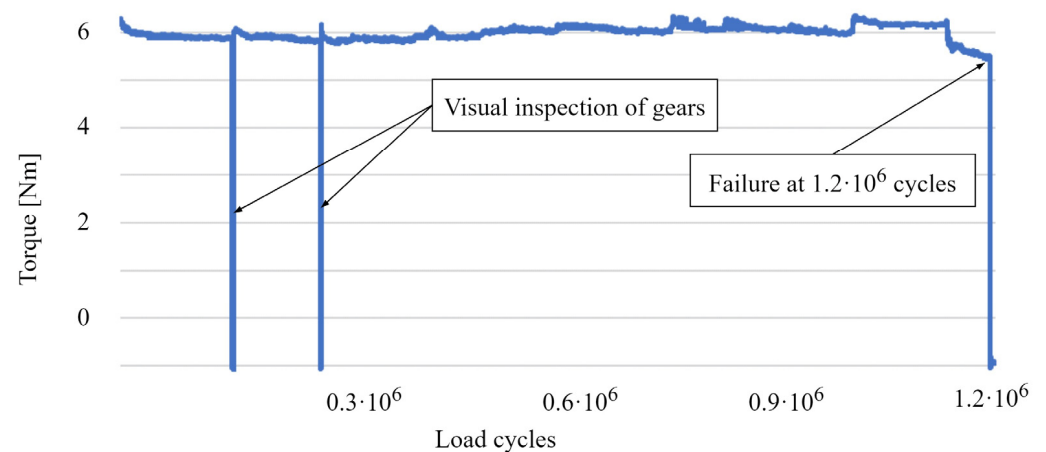


Figure 8. Number of life cycles for the third PA6/66 sample.

During the experimental testing, the maximum developed temperature at the engagement zone was monitored, as shown in Figure 9. The temperature of 76°C , presented in Figure 8, resulted from a heat accumulation over a large number of operating cycles. This monitored temperature value is important, as it can be used to classify the type of gear failure, i.e., to determine the mechanism-induced failure that can correspond to thermal

changes in the plastic material, resulting in melting or deformation, and to load-induced changes, resulting in fatigue, wear, and accompanying fractures.

Table 8. Lifetime results for PA6/66 material.

Gear	Time, t (s)	Time, t (h)	Number of Load Cycles
First sample	117,567	32.65	1,959,450
Second sample	44,403	12.33	740,050
Third sample	76,093	21.13	1,268,216



Figure 9. The monitored temperature at the engagement zone of the PA6/66 gears.

5.1.2. PC Material

Diagrams presented in Figures 10–12 show the life-cycle testing results of three PC gear samples.

Table 9 shows the test results for PC gears. From the results, it can be concluded that gears made of PC material experienced a significantly shorter lifetime, i.e., a reduced number of load cycles compared to PA6/66 gears. In this case, the difference in the lifetime results between the tested PC gear samples was not large, but still considerable. As emphasized previously for PA6/66 gears, for more complete results, a larger number of gear samples needs to be tested. Analysis of these results, with the classification of the failure modes and result comparison, will be discussed later on.

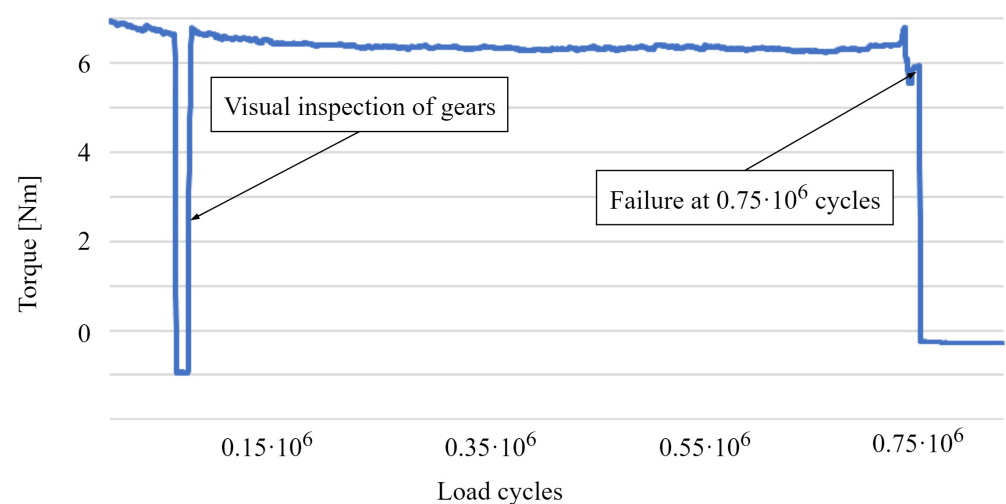


Figure 10. Number of life cycles for the first PC sample.

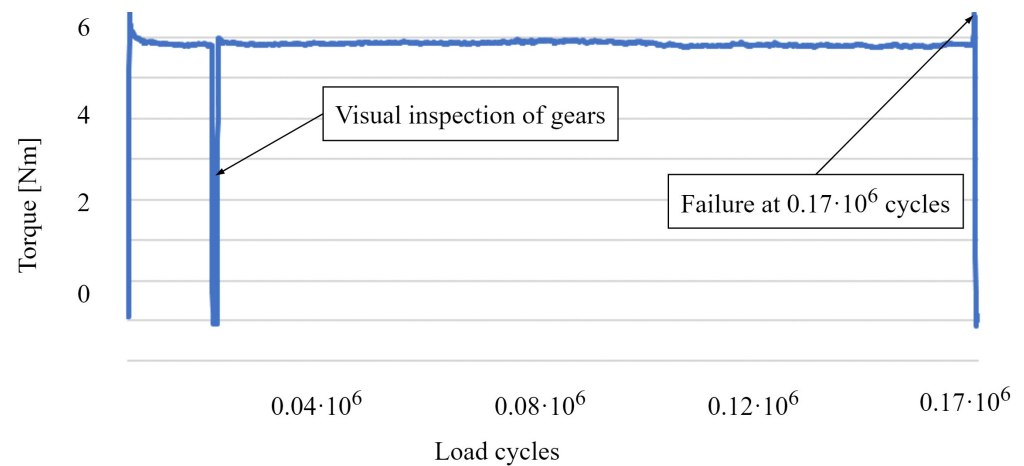


Figure 11. Number of life cycles for the second PC sample.

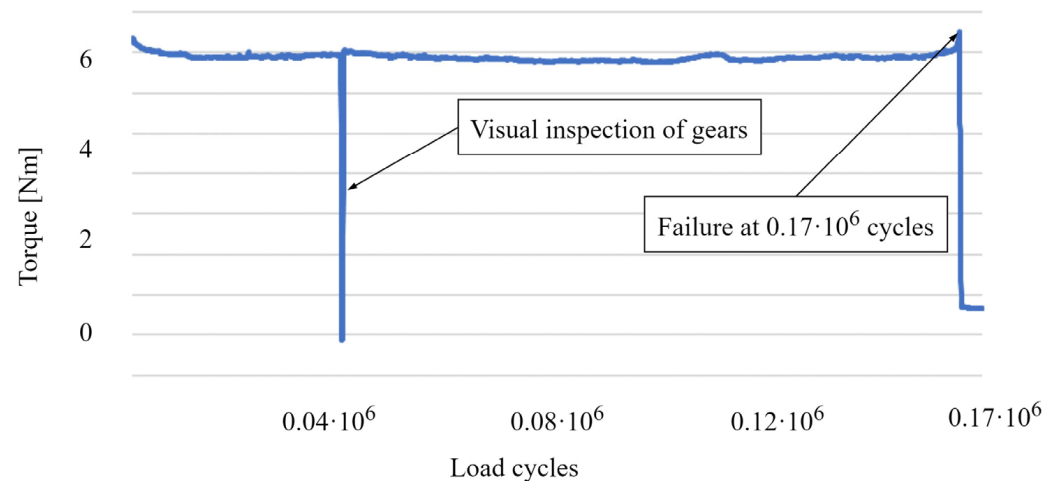


Figure 12. Number of life cycles for the third PC sample.

Table 9. Lifetime results for PC material.

Gear	Time, t (s)	Time, t (h)	Number of Revolutions
First sample	4527	1.25	75,450
Second sample	10,079	2.79	167,983
Third sample	13,974	3.88	232,900

The temperature of PC gear samples was also measured using a thermal camera. The maximal measured temperature was 56 °C, as shown in Figure 12. For the PC gear samples, unlike the PA6/66 gears, the monitored temperature presented in Figure 13 is not necessarily the maximum developed temperature at the engagement tone, as the gears experienced a smaller number of operating cycles. Correspondingly, the temperature of 56 °C is far below the temperature at which the mechanical properties of PC material start to change, so the preliminary failure mode can be classified as a load-induced failure.

5.1.3. Results for IGUS i180 Material

Diagrams presented in Figures 14–16 show the life-cycle testing results of three IGUS i180 gear samples.

Table 10 shows the test results for IGUS i180 gear samples. As presented in Table 10, the gears made out of IGUS i180 material had approximately the same lifespan properties compared to PC gears, but a significantly shorter lifetime compared to PA6/66 gears.

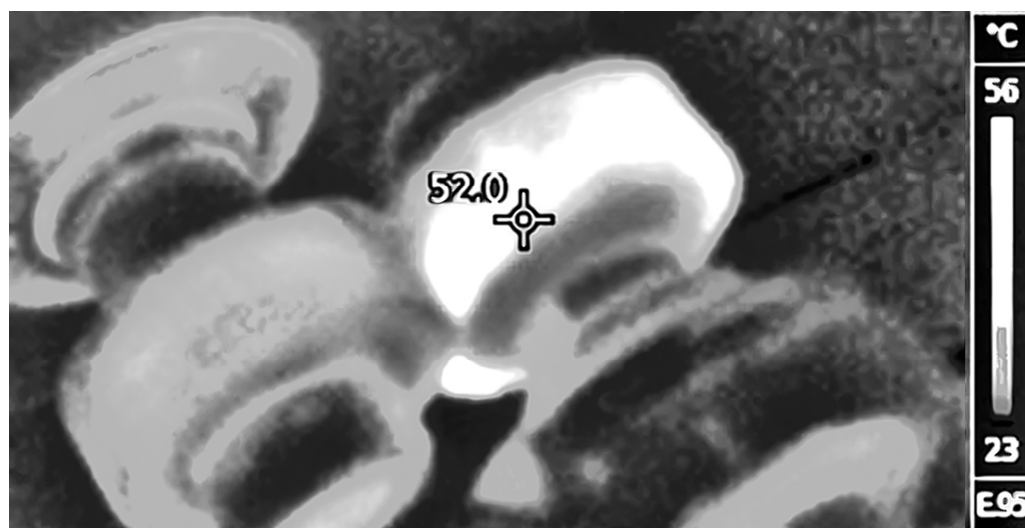


Figure 13. The monitored temperature at the engagement zone of the PC gears.

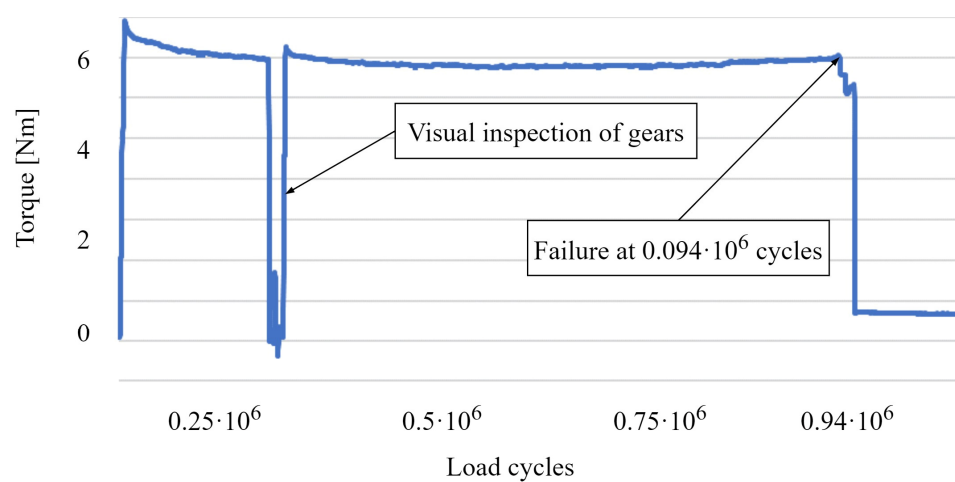


Figure 14. Number of life cycles for the first IGUS i180 sample.

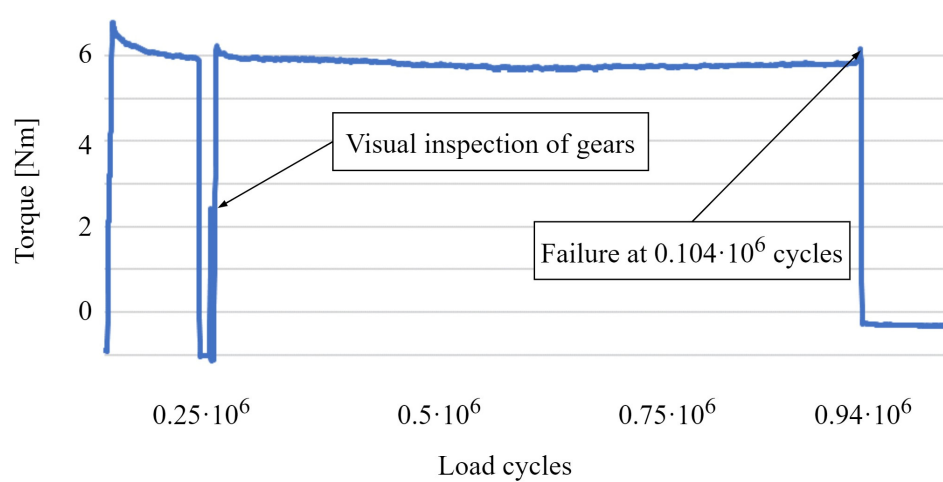


Figure 15. Number of life cycles for the second IGUS i180 sample.

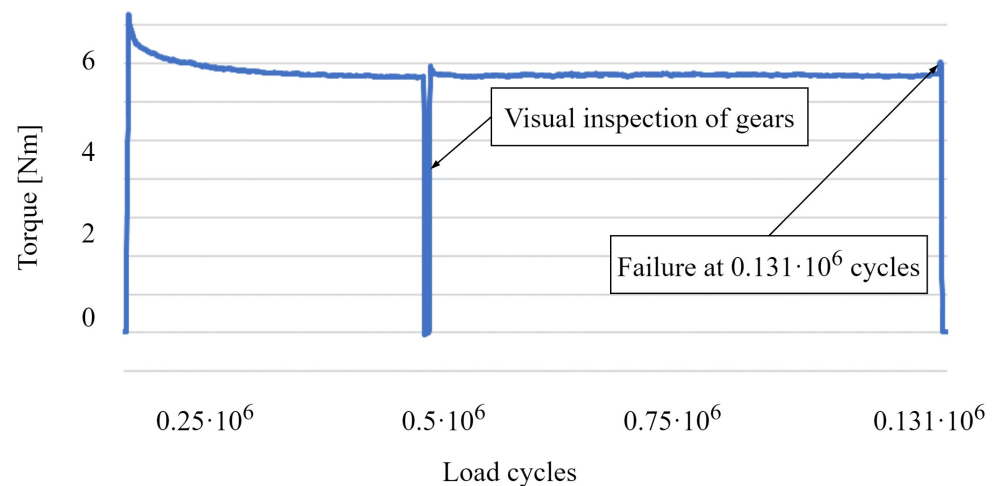


Figure 16. Number of life cycles for the third IGUS i180 sample.

Table 10. Results for IGUS i180 material.

Gear	Time, t (s)	Time, t (h)	Number of Revolutions
First sample	5643	1.56	94,050
Second sample	6241	1.73	104,000
Third sample	7917	2.1	131,000

The maximum measured temperature, which amounted to 46 °C, is shown in Figure 17. As the gears exhibited a shorter lifespan, similar to the PC gear samples, the maximum monitored temperature of 46 °C was well below the temperature that would lead to changes in the mechanical properties of IGUS i180 material. Therefore, the preliminary failure mechanism can be classified as load-induced.

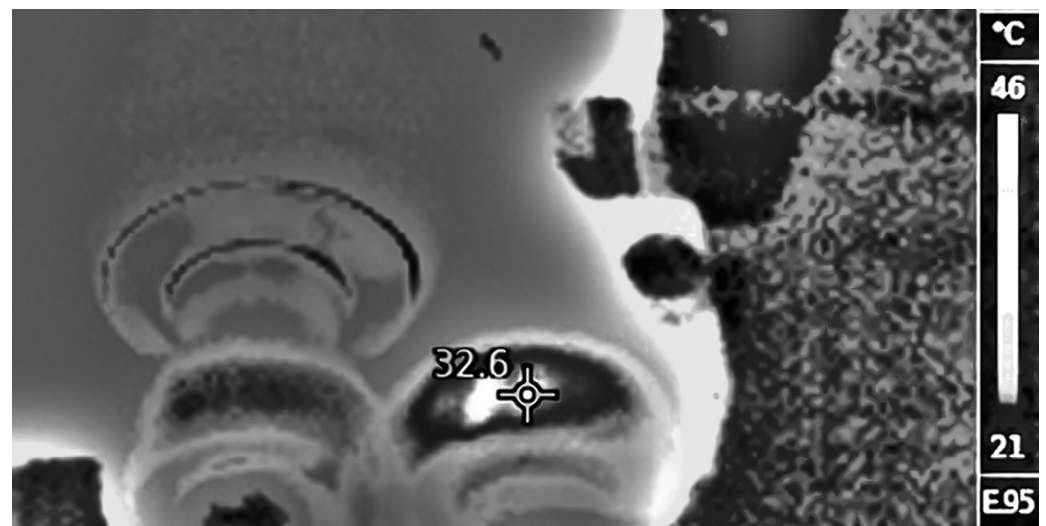


Figure 17. The monitored temperature at the engagement zone of the IGUS i180 gears.

5.2. Results for Failure Mode Categorization

A classification of failure modes of gears produced by AM is presented in this chapter. To further improve, analyze, and recommend the potential applications of gears produced by AM, it is very important to categorize the induced failures and the corresponding reasons from an engineering point of view. Figures 18 and 19 present the PA6/66 gears after the failure.

As shown in Figures 18 and 19, the simultaneous effects of temperature increase and load level caused the deformation of the teeth and tooth root fracture, respectively. A temperature of 70 °C, according to the datasheet, represents the threshold temperature at which thermally induced changes occur in the PA6/66 material.

As presented in Figure 18a, thermally induced deformations led to a functional failure of the PA6/66 gear. The preserved tooth, presented in Figure 18b, indicates the absence of the wear mechanism, with the fatigue-induced fracture at the tooth root area.

The gear temperature should not exceed 70 °C in the case of higher loads. When analyzing polymer machine elements that are heated, it is very important to distinguish the melting temperature, which is normally given in the description of the material and at which the material changes to a liquid state, from the temperature at which mechanical properties change due to thermal effects. Changes in mechanical properties occur when temperatures are much lower than the melting temperature, especially in cases of higher loads. In this case, it can be seen that the deformation of the teeth occurred at a temperature of 76 °C.

Figures 18 and 19 also show the characteristic appearance and crack propagation at the tooth root area. PA6/66 material also has self-lubrication properties, as the sliding action of the tooth flank is followed by micro-melting of the material, which forms a transfer, i.e., lubrication layer that has a positive effect on the friction properties at the engagement zone. Figure 20 presents the excessive wear of the PC gears after 30 min of testing. Due to reduced tooth cross-section, the gears eventually experience tooth root fractures, as shown in Figure 21.

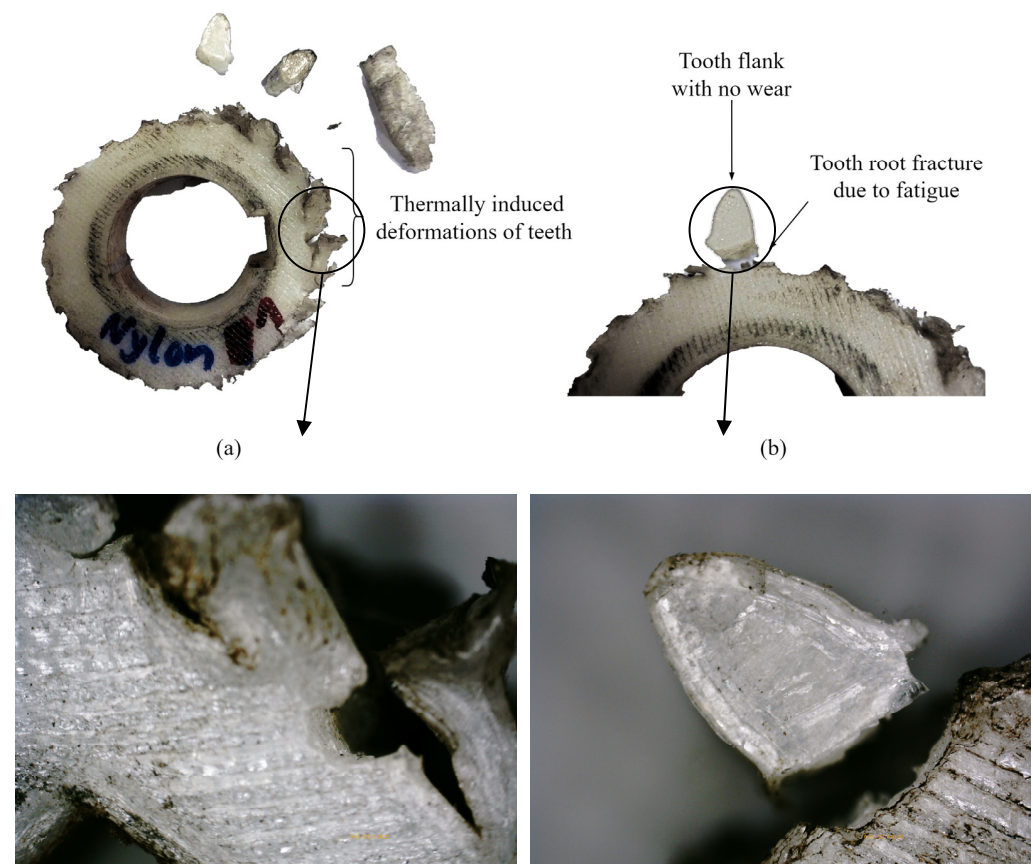


Figure 18. The failure mechanism of the first PA6/66 gear sample: (a) thermally induced deformations of teeth; (b) fatigue-induced tooth root fracture.

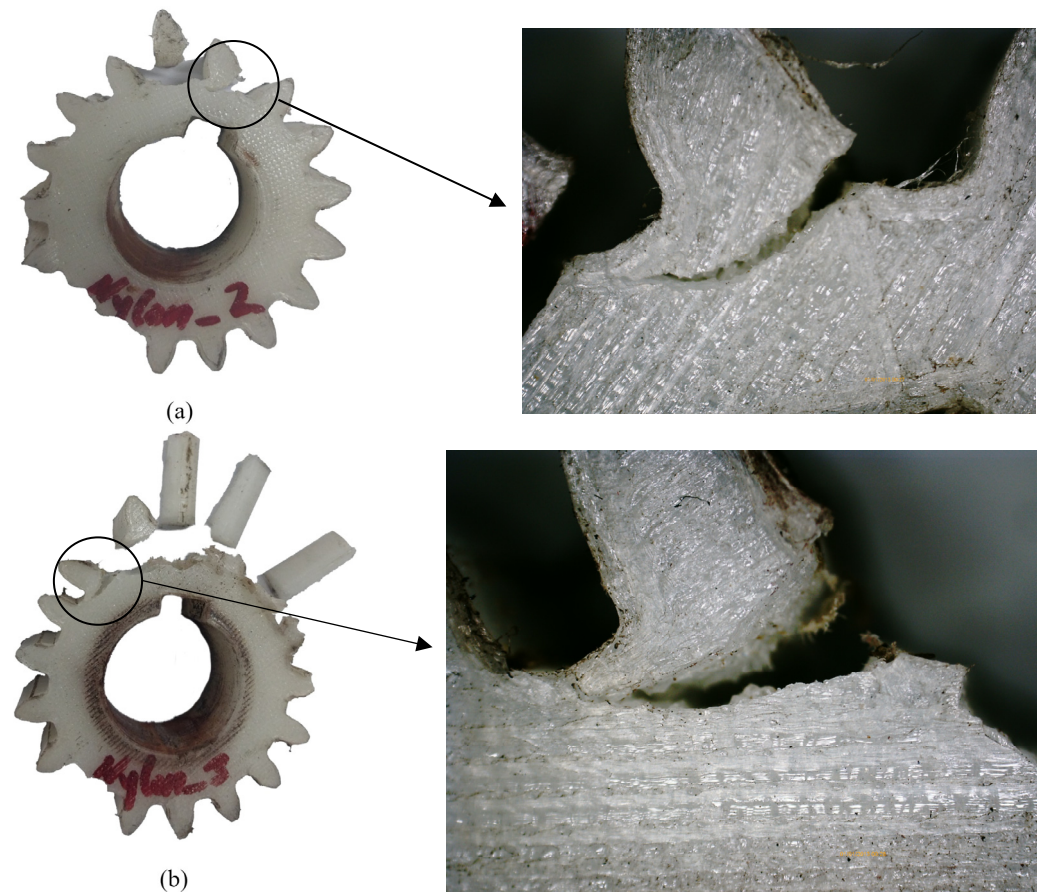


Figure 19. PA6/66 gears: (a) second sample; (b) third sample.



Figure 20. Excessive wear of the PC gear sample after 30 min of testing.

The failure mechanism of the PC gears produced by the AM is related to tribological properties, as the temperature increase had no direct effect on the failure of gear samples. Due to an excessive wear mechanism, presented in Figure 21a,b, the teeth cross-section reached a stiffness critical state, resulting in tooth root fractures, presented in Figure 21c. Although there are notable teeth deformations in Figure 21a,b, they are, as previously emphasized, not directly related to temperature increase, but to the reduced bending stiffness of the worn-out teeth.



Figure 21. The failure mechanism of PC gear samples: (a) first gear sample; (b) second gear sample; (c) third gear sample.

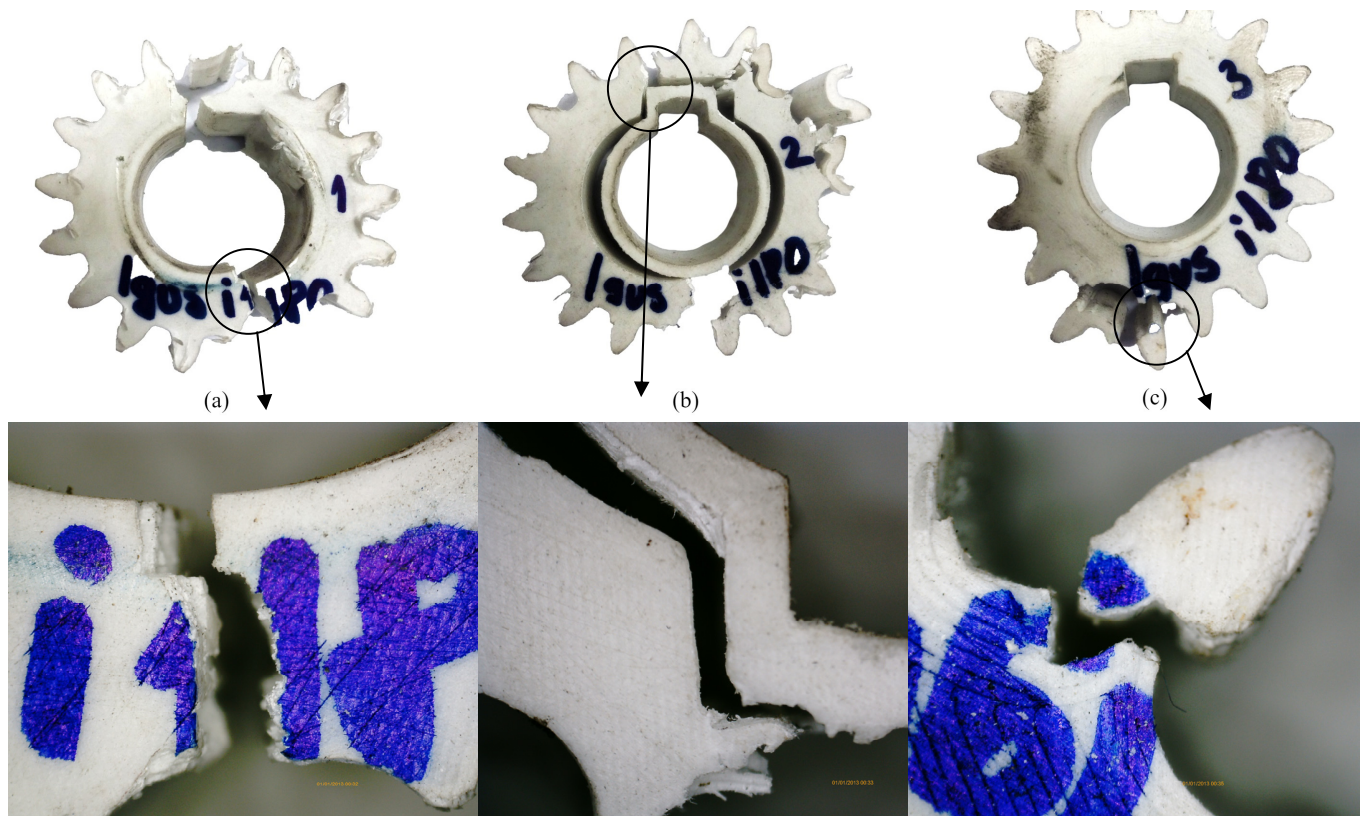


Figure 22. The failure mechanism of IGUS i180 gear samples: (a) first gear sample; (b) second gear sample; (c) third gear sample.

The IGUS i180 material, specially developed for various tribological applications, proved to be wear-resistant. However, due to the extremely brittle structure of the material gear teeth as well as the gear body, the gears experienced fractures, as shown in Figure 22a–c. The characteristic crack between the 3D printed layers, notable in Figure 22b, indicates weak adhesion between the layers.

The results indicate that gears made out of IGUS i180 material are excellent in applications where low wear and long-term operation are required, but only in the cases of small static loads. The IGUS i180 material, initially developed for use in sliding bearings and other limited sliding applications, proved to be insufficient for use in rotating machinery that includes power and torque transmission.

5.3. Comparison of the Results

The diagram shown in Figure 23 presents the difference between the number of cycles endured by the different gear samples before failure. As shown in Figure 23, PA6/66 gears exhibited a significantly longer lifespan compared to PC and IGUS i180 samples, which showed similar lifespan properties. Based on the presented experimental results, Table 11, with applicability recommendations, was created. Additionally, recommendations for future research directions are provided.

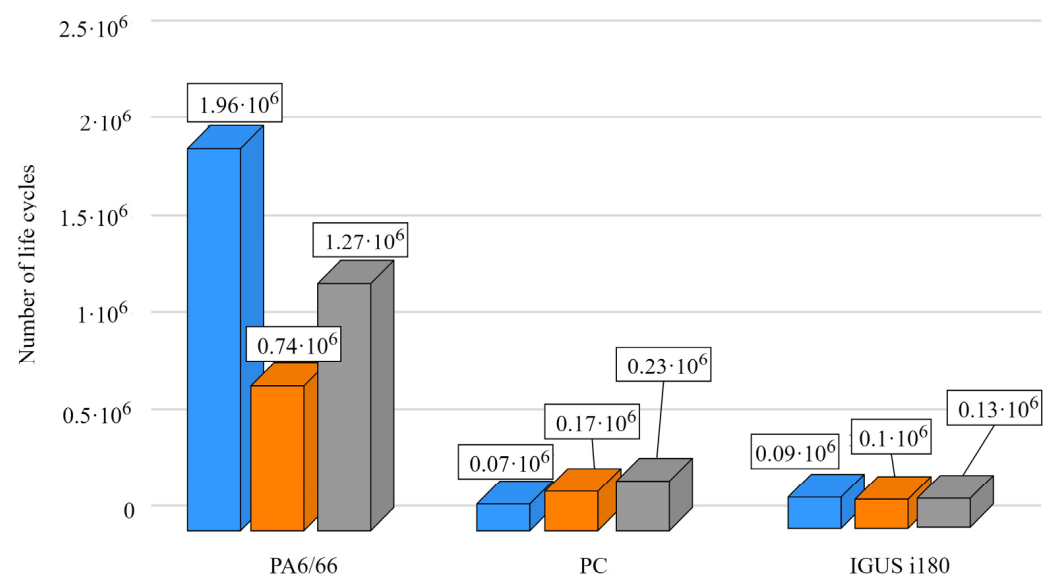


Figure 23. Result comparison.

Table 11. Recommendations for material use.

Material	Wear	Properties	Recommendation for Applications
PA6/66	Low	Rigid	Use in applications with a high number of revolutions and a higher load. There must be no heat source near the gears. The shaft on which the gear is located must not be heated by other elements.
PC	High	Brittle	Use in the case of low-load and low-speed applications. Intense gear wear can have an impact on other systems located near the gear. Use in applications where gears are heated up to 150 °C. The gear load must be static.
IGUS i180	Low	Brittle	Use in low-load and low-speed applications. Use in applications where gears are heated up to 150 °C. The gear load must be static.

Although the material IGUS i180 is categorized as a tribological material recommended for use in applications that require good friction and wear properties, in the case of plastic gears with high load and high speed, this material cannot meet the required requirements. The reason lies in the fact that these are brittle materials that are very sensitive to high dynamic loads.

6. Conclusions

Additive manufacturing technology advances every day. New materials for different applications are introduced constantly. All these new materials need to be experimentally tested and compared to each other. One of the latest tribology materials is IGUS i180 material, developed especially for applications with high tribological demands. Considering this case study, this material showed inferior properties concerning the gear design for AM in the case of high loads. This leads to the conclusion that it is not only necessary for the material to have wear and thermal resistance to be suitable for gear manufacturing, but it needs to have good mechanical properties also, especially high toughness. This research showed that PA6/66 material is still the best solution for polymer gears production using AM, in comparison to other commonly used materials for AM, but the applicability of this material, due to temperature constraints, is still quite limited.

Comparing results from this paper and results from our previous research [8,23], it can be seen that MEX AM polymer gears still cannot replace polymer gears produced using conventional technologies from materials like polyoxymethylene (POM) or polyvinylidene fluoride (PVDF) across the full life cycle. MEX AM polymer gears can be used for temporary replacement, but they do not have the same life cycle as polymer gears produced using conventional manufacturing technologies.

Future research should include new materials for AM and gear applications. Additionally, materials such as POM or PVDF that are used in conventional gear manufacturing need to be tested for AM cases, as these materials are not so common in AM, but have demonstrated great results in the case of conventional gear manufacturing, as established in our previous research [8,23].

Additionally, different AM technologies for gear manufacturing should be compared in future research. There are a lot of different AM technologies that can be used for polymer gear manufacturing. All of these technologies, with their specific properties and parameters, produce parts with different mechanical, tribological, and thermal characteristics, which need to be tested. The big question is, can we use AM to replace conventionally manufactured gears?

Author Contributions: Conceptualization, A.J.M. and S.B.; methodology, E.M. (Enis Muratović); validation, N.P., I.Š., M.T., A.M. and E.M. (Elmedin Mešić), resources, J.S. and M.D.; writing—original draft preparation, A.J.M.; writing—review and editing, E.M. (Enis Muratović), M.T.; visualization, A.J.M. and E.M. (Enis Muratović); funding acquisition, A.J.M. and J.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry for Science, Higher Education, and Youth of Canton Sarajevo, 71000 Sarajevo, Bosnia and Herzegovina; grant numbers (45/1235; 27-02-35-37082-45/23; 27-02-35-33087-28/24; 27-02-35-33086-12/24).

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Author Jasmin Smajić was employed by the company Protoengs Sarajevo. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Gibson, I.; Rosen, D.; Stucker, B.; Khorasani, M. *Additive Manufacturing Techniques*; Springer: Cham, Switzerland, 2021.
- Monkova, K.; Monka, P.P.; Vanca, J.; Hricova, R.; Knapcikova, L.; Kozak, D.; Beno, P. Natural Frequencies of a Simple 3D Printed Lattice Structure. In Proceedings of the 2021 12th International Conference on Mechanical and Aerospace Engineering, ICMAE 2021, Athens, Greece, 16–19 July 2021.
- Hodžić, D.; Pandžić, A. Influence of Printhead Nozzle Diameter on Mechanical Properties of FDM Printed PLA Material and Printing Time. In Proceedings of the 33rd DAAAM International Symposium, Vienna, Austria, 27–28 October 2022; Volume 33.
- Pandzic, A.; Hodzic, D. Mechanical Properties Comparison of PLA, Tough PLA and PC 3D Printed Materials with Infill Structure—Influence of Infill Pattern on Tensile Mechanical Properties. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1208*, 012019. [\[CrossRef\]](#)
- Pujari, L.; Manoj, S.; Gaddikeri, O.K.; Shetty, P.; Khot, M.B. Recent advancements in 3D printing for gear design and analysis: A comprehensive review. *Multiscale Multidiscip. Model. Exp. Des.* **2024**, *6*, 4979–5003. [\[CrossRef\]](#)
- Tezel, T.; Schultheiss, U.; Hornberger, H.; Kovan, V. Operational wear behaviour of 3D-printed lightweight metal gears: EDS and oil analysis comparison. *Mater. Test.* **2024**, *66*, 830–834. [\[CrossRef\]](#)
- Hriberšek, M.; Kulovec, S.; Ikram, A.; Kern, M.; Kastelic, L.; Pušavec, F. Technological optimization and fatigue evaluation of carbon reinforced polyamide 3D printed gears. *Heliyon* **2024**, *10*, e34037. [\[CrossRef\]](#) [\[PubMed\]](#)
- Muratović, E.; Muminović, A.; Delić, M.; Pervan, N.; Muminović, A.J.; Šarić, I. Potential and Design Parameters of Polyvinylidene Fluoride in Gear Applications. *Polymers* **2023**, *15*, 4275. [\[CrossRef\]](#)
- Muminovic, A.J.; Colic, M.; Mesic, E.; Saric, I. Innovative design of spur gear tooth with infill structure. *Bull. Pol. Acad. Sci. Tech. Sci.* **2020**, *68*, 477–483. [\[CrossRef\]](#)
- Grănescu, B.; Constantin, V.; Moraru, E. Check for updates A Review of Additive Technologies Applied to Gear Transmission. In Proceedings of the Innovations in Mechanical Engineering III 2024, Povoação, Portugal, 26–28 June 2024; p. 44.
- Subramani, R.; Mustafa, M.A.; Ghadir, G.K.; Al-Tmimi, H.M.; Alani, Z.K.; Rusho, M.A.; Rajeswari, N.; Haridas, D.; Rajan, A.J.; Kumar, A.P. Advancements in 3D printing materials: A comparative analysis of performance and applications. *Appl. Chem. Eng.* **2024**, *7*, 3867. [\[CrossRef\]](#)
- Khan, N.; Riccio, A. A systematic review of design for additive manufacturing of aerospace lattice structures: Current trends and future directions. *Prog. Aerosp. Sci.* **2024**, *149*, 101021. [\[CrossRef\]](#)
- Jin, L.; Zhai, X.; Wang, K.; Zhang, K.; Wu, D.; Nazir, A.; Jiang, J.; Liao, W.H. Big data, machine learning, and digital twin assisted additive manufacturing: A review. *Mater. Des.* **2024**, *244*, 113086. [\[CrossRef\]](#)
- Zhou, L.; Miller, J.; Vezza, J.; Mayster, M.; Raffay, M.; Justice, Q.; Al Tamimi, Z.; Hansotte, G.; Sunkara, L.D.; Bernat, J. Additive Manufacturing: A Comprehensive Review. *Sensors* **2024**, *24*, 2668. [\[CrossRef\]](#) [\[PubMed\]](#)
- Hussain, N. The Impact of Additive Manufacturing on Engineering Design and Production. *Res. Corridor J. Eng. Sci.* **2024**, *1*, 33–43.
- Muminović, A.J.; Gierz, Ł.; Rebihić, H.; Smajić, J.; Pervan, N.; Hadžiabdić, V.; Trobradović, M.; Warguła, Ł.; Wiecek, B.; Łykowski, W.; et al. Enhancing Furniture Manufacturing with 3D Scanning. *Appl. Sci.* **2024**, *14*, 4112. [\[CrossRef\]](#)
- Zhu, C.; Gameda, H.B.; Duoss, E.B.; Spadaccini, C.M. Toward Multiscale, Multimaterial 3D Printing. *Adv. Mater.* **2024**, *36*, 2314204. [\[CrossRef\]](#) [\[PubMed\]](#)
- Senthilkumar, M.; Logesswaran, T.S.; Suhail, M.; Buddhathirani, P.; Siddharth, S. Repair and Validation of Gear by using Wire Arc Additive Manufacturing. In Proceedings of the International Conference on Advancements in Materials, Design and Manufacturing for Sustainable Development, ICAMDMS 2024, Coimbatore, Tamil Nadu, India, 23–24 February 2024.
- Sarzyński, B.; Śnieżek, L.; Grzelak, K. Metal Additive Manufacturing (MAM) Applications in Production of Vehicle Parts and Components—A Review. *Metals* **2024**, *14*, 195. [\[CrossRef\]](#)
- Yilmaz, M.; Yilmaz, N.F.; Gungor, A. Wear and thermal coupled comparative analysis of additively manufactured and machined polymer gears. *Wear* **2024**, *556*, 205525. [\[CrossRef\]](#)
- Ciobanu, R.; Rizescu, C.I.; Rizescu, D.; Gramescu, B. Surface Durability of 3D-Printed Polymer Gears. *Appl. Sci.* **2024**, *14*, 2531. [\[CrossRef\]](#)
- Islam, M.A.; Mobarak, M.H.; Rimon, M.I.H.; Al Mahmud, M.Z.; Ghosh, J.; Ahmed, M.M.S.; Hossain, N. Additive manufacturing in polymer research: Advances, synthesis, and applications. *Polym. Test.* **2024**, *132*, 108364. [\[CrossRef\]](#)
- Muratovic, E.; Muminovic, A.; Pervan, N.; Delic, M.; Muminovic, A.; Saric, I. Assessing Wear Coefficient and Predicting Surface Wear of Polymer Gears: A Practical Approach. *Eng. Technol. Appl. Sci. Res.* **2024**, *14*, 15923–15930. [\[CrossRef\]](#)
- Pawlak, W.; Wieleba, W.; Kluczyński, J.; Śnieżek, L. The influence of the addition of graphite on the tribological properties of polylactic (PLA) applied in 3D printing technology. *Q. Tribol.* **2018**, *277*, 89–93. [\[CrossRef\]](#)
- Gooneratne, S. Digitally Fabricated Reduction Drive for Low-Cost Robotics Applications. 2021. Available online: <https://sear.unisq.edu.au/id/eprint/51812> (accessed on 1 September 2024).

26. Gordelier, T.J.; Thies, P.R.; Turner, L.; Johanning, L. Optimising the FDM additive manufacturing process to achieve maximum tensile strength: A state-of-the-art review. *Rapid Prototyp. J.* **2019**, *25*, 953–971. [[CrossRef](#)]
27. Mazurchevici, A.D.; Nedelcu, D.; Popa, R. Additive manufacturing of composite materials by FDM technology: A review. *Indian J. Eng. Mater. Sci. (IJEMS)* **2021**, *27*, 179–192.
28. Chaudhari, M.; Jogi, B.F.; Pawade, R.S. Comparative study of part characteristics built using additive manufacturing (FDM). *Procedia Manuf.* **2018**, *20*, 73–78. [[CrossRef](#)]
29. Al-Tamimi, A.A.; Pandžić, A.; Kadrić, E. Investigation and Prediction of Tensile, Flexural, and Compressive Properties of Tough PLA Material Using Definitive Screening Design. *Polymers* **2023**, *15*, 4169. [[CrossRef](#)]
30. *Standard ASTM D3039*; Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. ASTM International: West Conshohocken, PA, USA, 2017.
31. *Standard ISO 178*; Plastics—Determination of Flexural Properties. ISO: Geneva, Switzerland, 2019.
32. *Standard ISO 179-1/1eB*; Plastics—Determination of Charpy Impact Properties—Part 1: Non-Instrumented Impact Test. ISO: Geneva, Switzerland, 2023.
33. *Standard ISO 7619-1*; Rubber, Vulcanized or Thermoplastic—Determination of Indentation Hardness. ISO: Geneva, Switzerland, 2010.
34. *Standard ISO 1133*; Plastics—Determination of the Melt Mass-Flow Rate (MFR) and Melt Volume-Flow Rate (MVR) of Thermoplastics. ISO: Geneva, Switzerland, 2022.
35. *Standard ISO 75-2/B*; Plastics—Determination of Temperature of Deflection Under Load. ISO: Geneva, Switzerland, 2013.
36. *Standard ISO 306/A120*; Plastics—Thermoplastic Materials—Determination of Vicat Softening Temperature (VST). ISO: Geneva, Switzerland, 2022.
37. *Standard ISO 11357*; Plastics—Differential scanning calorimetry (DSC). ISO: Geneva, Switzerland, 2016.
38. *Standard DIN 53457*; Testing of Plastics; Determination of the Modulus of Elasticity by Tensile, Compression and Flexural Test. Deutsches Institut für Normung: Berlin, Germany, 1968.
39. *Standard DIN 53505*; Shore A and Shore D Hardness Testing of Rubber. Deutsches Institut für Normung: Berlin, Germany, 2000.
40. *Standard DIN 53752*; Testing of Plastics; Determination of the Coefficient of Linear Thermal Expansion. Deutsches Institut für Normung: Berlin, Germany, 1980.
41. *Standard ASTM C 177*; Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus. ASTM International: West Conshohocken, PA, USA, 2023.
42. Muminovic, A.J.; Pervan, N.; Delic, M.; Muratovic, E.; Mesic, E.; Braut, S. Failure analysis of nylon gears made by additive manufacturing. *Eng. Fail. Anal.* **2022**, *137*, 106272. [[CrossRef](#)]
43. Kallel, A.C.; Koutiri, I.; Babaeitorkamani, E.; Khavandi, A.; Tamizifar, M.; Shirinbayan, M.; Tcharkhtchi, A. Study of Bonding Formation between the Filaments of PLA in FFF Process. *Int. Polym. Process.* **2019**, *34*, 434–444. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.