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Wear Performance and Wear Monitoring of Nylon Gears Made Using Conventional and Additive Manufacturing Techniques

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Abstract: Polymer gears are increasingly replacing metal gears in applications with low to medium torque. Traditionally, polymer gears have been manufactured using injection molding, but additive manufacturing (AM) is becoming increasingly common. Among the different types of polymer gears, nylon gears are particularly popular. However, there is currently very limited understanding of the wear resistance of nylon gears and of the impact of the manufacturing method on gear wear performance. The aims of this work are (a) to study the wear process of nylon gears made using the conventional injection molding method and two popularly used AM methods, namely, fused deposition modeling and selective laser sintering, (b) to compare and understand the wear performance by monitoring the evolution of the gear surfaces of the teeth, and (c) to study the effect of wear on the gear dynamics by analyzing gearbox vibration signals. This article presents experimental work, data analysis of the wear processes using molding and image analysis techniques, as well as the vibration data collected during gear wear tests. It also provides key results and further insights into the wear performance of the tested nylon gears. The information gained in this study is useful for better understanding the degradation process of additively manufactured nylon gears.

Keywords: condition monitoring; gear surface evolution; vibration; wear of nylon gears

I. INTRODUCTION

Unlike metal gears, which are widely used in many applications and often require proper lubrication to reduce friction, minimize wear, and dissipate heat generated during operation, polymer gears are suitable for applications where light weight, low cost, quiet operation, corrosion resistance, and self-lubrication are required. Among existing polymer gears, nylon gears are popularly used in many applications including home appliances (e.g., washing machines), medical devices (e.g., infusion and blood pumps), office equipment (e.g., printers and scanners), automotive industry (e.g., power windows and seat adjusters), agricultural equipment (e.g., tractors and irrigation systems), and packing equipment.

Nylon gears are traditionally made using machining or injection molding techniques. With rapid development and application of additive manufacturing (AM) technologies, they are printed using fused deposition modeling (FDM) [1–4] and selective laser sintered (SLS) [5–9] methods in a lower cost and with a faster process. FDM heats and melts the filament of nylon that is fed from a large spool through a moving, heated printer extruder head and deposits it to form a product. Different to FDM, SLS belongs to the powder bed fusion group, which uses a laser as the energy source to fuse powdered nylon and to bind the material together to create a solid such as a gear. This is done by scanning cross sections on the surface of a powder bed and repeating the process on a new layer applied on top of the previous layer. It can be used to make complex geometries with various finishes. For making gears, both FDM and SLS are widely used. SLS printed gears often have a better surface finish with a higher cost. Both methods can suffer from quality issues including a large geometric deviation due to material shrinkage or uneven fusion during the manufacturing process, porous surfaces, which can affect the fatigue life of the gears [10].

In comparison to metal gears, whose wear mechanisms and failure modes have been well studied, there is much less existing work on the wear of polymer gears. It has been reported that, similar to metal gears, nylon gears often experience three wear stages including a short running-in, a steady (linear) progression and a final fracture phase [11]. Furthermore, it is reported that wear and surface fatigue are two common causes of plastic gear failure [12] along with tooth breakage and tooth deformation [13]. At a low load, abrasive wear predominates. An increase in load also increases temperature generated in the meshing area, which at the same time leads to a change in the mechanism of damage—plastic deformation of the teeth [10]. It is widely recognized that load-dependent thermal effects play an important role in the failure of plastic gears including nylon gears [11,14]. The final failure is often caused by a high temperature at the meshing area and/or a load that is higher than the allowable load (e.g., 10 Nm vs 9 Nm allowable load for the nylon gears reported in [11]). Further, a linear or close to linear relationship between the normal load and the temperature was established and reported [14]. Recently, there are a handful of publications on the wear performance of AM-made polymer gears and comparison to the gears made using a conventional method. Most existing works conducted fatigue life tests such as the tests and their results reported in [3]. The obtained test results show the Nylon 618 gears are the most durable among the three tested materials, including nylon 618, nylon 645, and alloy 910 filaments,

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and have a higher fatigue life than the gears produced by the injection method when low to medium torque was applied.

With the rapid growth of manufacturing technology and the wider use of AM-made polymer gears, it is imperative that the wear behaviors of these gears are better understood to improve their service life. Information on their wear and affected vibration characteristics is crucial for developing an effective wear monitoring technique for these gears. Furthermore, useful life prediction is an area that can significantly benefit the industry. As stated in reference [14], there is currently no well-accepted damage model for plastic spur gears. Further study of the wear and failure mechanisms of AM-made polymer gears will contribute to the development of such a damage model.

To fill in the above research gaps, the aims of this study are (a) to study the wear process of nylon gears made using the conventional injection molding method and two popularly used AM methods, namely, FDM and SLS, (b) to compare and understand the wear performance by monitoring the evolution of the gear surfaces and the wear depths of the teeth, and (c) to study their vibration characteristics in relation to the wear process. The rest of this paper is organized as follows. Section II presents the gear sample information, the gear test facility and data collection methods, and the analysis techniques to study the gear wear evolution and wear depths. Section III reports the main results of the gear wear analysis and the corresponding vibration features, followed by the discussions and future work in Section IV. Section V contains the main conclusions.

II. EXPERIMENTATION AND ANALYSIS TECHNIQUES

Three pairs of nylon gears with the same gear module (module 2) and the same tooth numbers (35/36) were purchased or manufactured for this study. Further information of these gears can be found in Section II.A. A spur gearbox rig was used to conduct extended degradation tests on these gears without lubrication. More information on the testing facility, gear test procedures, and data collection methods is presented in Section II.B. Section II.C outlines the data analysis techniques used in this study.

A. GEAR SAMPLES

Among the three pairs of nylon gears (Fig. 1), one pair made of MC nylon was manufactured using injection molding method and was purchased from KHK Gears. One pair of PA12 nylon gears was made using SLS and by PCBWay, and the third pair of nylon gears was made using Bambu carbon fiber-reinforced high-temperature nylon and the FDM method. Some main material properties of these gear materials can be found in Table I.

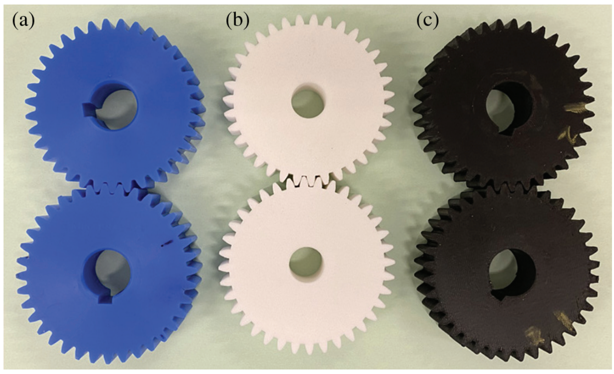


Fig. 1. Three pairs of new nylon gears: (a) MC nylon gears made using injection molding, (b) PA12 nylon gears manufactured using the SLS method, and (c) carbon fiber-reinforced nylon gears manufactured using the FDM method.

For comparison purpose, each gear pair consisted of a driving gear (pinion) with 35 teeth and a driven gear (DG) with 36 teeth. All teeth have the same face width of 20 mm, and all gears have a module of 2 mm. Their initial surface roughness was measured using a laser scanning microscope with a 20x objective lens and a Z-step size of 0.2 μm. They are presented in Table II.

B. TESTING FACILITY AND EXPERIMENTS

A spur gearbox rig located in the School of Mechanical & Manufacturing Engineering, UNSW Sydney, was used to conduct gear tests. This rig, shown in Fig. 2, has the following four main components: a spur gearbox, a 4 kW 3-phase induction motor connected to the input shaft, a magnetic particle brake to apply load to the output shaft, and a variable frequency drive to control the speed of the input shaft. Detailed information on the rig can be found in [15]. Multiple sensors were installed on the rig. They include three accelerators installed on the gearbox casing to collect vibration data in the x, y, and z directions.

No lubricant was used in the tests. During the tests, the rig was run at different constant speeds—2, 5, and 10 Hz for the input shaft—and with torque loads in the range of 0 to 20 Nm. These varied operational parameters provided vibration data at different running conditions. Table II shows the total running hours, cycles, maximum temperature during the tests, and their final operating conditions. This implemented strategy for running schedule aims to collect efficient data for studying wear characteristics and lifespan of each gear material.

During the tests, a molding technique [16] was used to collect gear molds for studying the surface evolution of the gears. It involves making replicas of the gear surface to allow detailed examinations without disassembling the gear

Table I. Main material properties of the nylon materials

Materials	Tensile strength (MPa)	Elongation (%)	Compression yield point (MPa)	Vickers hardness	Thermal conductivity (W/(m.k))	Heat deformation temperature (°C)
MC901 Nylon	96	30	103	8.2	0.23	200
PA12 Nylon	47	8	75	4.72	–	150
Carbon fibre-reinforced high-temperature Nylon	92	8.4	–	7.66	–	194

Table II. Initial surface finishes, total running hours, cycles, maximum temperature measured on the tested gears near the meshing area, and final operating conditions of the three tests

Gear Types	Initial surface finish (Sa, μm)	Total running time (hours)	Number of cycles ($\times 10^3$)	Max. temperature throughout test (°C)	Operating conditions (at input)
Injection-molded Nylon	2.35 (Pinion) 1.76 (DG)	8.42	192.54	42.5	2 – 10 Hz 0 – 20 Nm
SLS Nylon	20.85 (Pinion) 17.42 (DG)	7.03	188.76	40.0	2 – 10 Hz 0 – 20 Nm
FDM Nylon	14.68 (Pinion) 13.46 (DG)	4.83	109.92	87.6	2 – 10 Hz 0 – 20 Nm

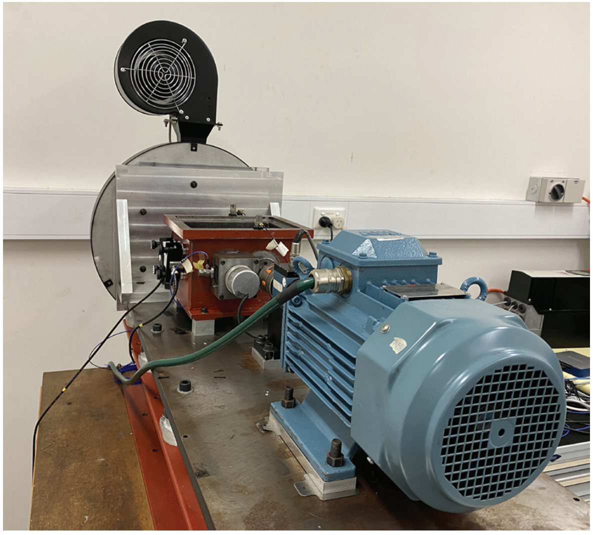


Fig. 2. The spur gearbox rig.

test rig. Two or three molds were collected from each gear when the rig was stopped for mold collection. There were 88, 66, and 88 molds collected during the tests on the injection-molded, SLS manufactured nylon, and FDM-made nylon, respectively.

In addition to the gear molds, the surface temperature of the teeth in contact was measured using a noncontact temperature sensor as soon as the rig was stopped on each occasion.

The vibration measurements were taken mostly at 10 Hz with different nominal loads (although the gears were also run at lower speeds) at 3×10^3 cycle intervals.

For the first test, with commercial MC nylon gears, vibration data were measured at 10 Hz and 10 Nm every 3×10^3 cycles from 9.72×10^3 cycles to 125.52×10^3 cycles. Then, the load was increased to 15 Nm at 128.52×10^3 cycles. Vibration measurements at 10 Hz and 15 Nm were taken from 128.52×10^3 cycles to 188.34×10^3 cycles with the same intervals. The last measurement was 10 Hz and 20 Nm at the end of the test.

For the second test (SLS printed PA12 nylon gears), the vibration data were taken at 10 Hz and 10 Nm from 9.84×10^3 cycles to 55.68×10^3 cycles and at 172×10^3 cycles, a few cycles before the gears failed. The gears were first run at 10 Nm to observe the bending strength and surface strength of the gears. After observation of the mold at 55.68×10^3 cycles, the load was reduced to 5 Nm until 118.32×10^3 cycles, and the vibration measurements were taken.

For the third test, the FDM-made nylon gears were run at 10 Hz and 5 Nm from 2.7×10^3 cycles to 89×10^3 cycles, and the vibration data were collected with intervals of 3×10^3 cycles. Vibration signals at 10 Hz and 10 Nm were recorded at 78.3×10^3 cycles and 93.4×10^3 cycles.

The analysis in Section III.D uses the vibration data collected at 10 Hz and 10 Nm for the commercial MC nylon and SLS nylon gears and 10 Hz and 5 Nm for the FDM nylon gears.

C. DATA ANALYSIS TECHNIQUES

To study the gear surface evolution, the mold samples were imaged using laser scanning confocal microscopy (LSCM) for both qualitative and quantitative analysis. LSCM was employed to capture images of selected molds so that distinctive surface features, such as wear marks due to abrasive wear or surface pitting caused by fatigue, can be observed. A 10x objective lens with a z-step size of 0.5 μm was first implemented to capture the images of the entire mold surface. These images were used to qualitatively study the wear processes including the wear mechanisms. In order to quantify changes in the surface roughness and the wear depths of the gears, a 20x objective lens with a z-step size of 0.2 μm was used to capture mold images from the tip to the root in the direction of gear sliding. These three-dimensional (3D) images contain the height information for surface roughness and wear depth measurements. The most commonly used surface roughness parameter, Sa, was used to quantify the surface roughness of the molds.

To study the dynamic responses of the gear wear progression, vibration analysis was performed. First, the raw vibration signals were order-tracked and synchronously averaged (SA) with respect to the input shaft. These methods minimize the speed fluctuation effect and reduce the unrelated noise, respectively. It is known that wear information can usually be observed from the first few gear mesh harmonics [17], so the signal was then low pass filtered to include only the five gear mesh harmonics. The RMS value of this filtered signal was then calculated and trended for each of the tests. Second, a residual signal was obtained by subtracting the input shaft SA signal and the output shaft SA signal from the order tracked signal, leaving only random signal content. The RMS of the residual signal was then obtained and trended for each of the tests, as with the previous SA signals. Lastly, an indicator of second-order cyclostationary (ICS2) [18], was calculated (from the residual signal) and trended. ICS2 is intended to capture the level of random vibrations that are modulated at gearmesh frequency. The motivation for the three approaches was to investigate how the changes due to wear in nylon gears manifest themselves in various parts of the signal: the deterministic components (shaft/gearmesh harmonics), stationary random part, and second-order cyclostationary part, respectively.

III. RESULTS AND DISCUSSION

This section presents the acquired images and quantitative data of the surface evolutions of the three pairs of tested gears. Sections III.A–III.C contain the key results of the commercial, SLS-made, and FDM-made nylon gears, respectively. Differences in their vibration signals are presented in Section III.D. Temperature changes of each gear are presented in Section III.E.

A. COMMERCIAL MC NYLON GEARS MADE USING THE CONVENTIONAL MACHINING METHOD

The microscopic surface of the injection-molded nylon gear teeth initially appeared quite smooth, with manufacturing marks running along the tooth face width (Fig. 3(a)). The first signs of abrasive wear appeared at 4.80×10^3 cycles in localized areas of the pinion (see an example in the yellow highlighted area in Fig. 3(b)). The scratch marks, which follow the sliding direction of the two gear surfaces when in mesh, then expanded to other areas. Those scratch marks could be viewed with the naked eye (Fig. 4). Surface pitting was observed at 45.8×10^3 cycles (see the red circled small pits in Fig. 3(c)) and continued until the end of the test (Fig. 3(d)). Similar wear marks were observed on the DG.

The Sa values of the contact surfaces of both the pinion and DG were measured and are presented in Fig. 5.

The Sa data in Fig. 5 show that the pinion's surface roughness decreased during the wear process, while the DG's surface roughness remained steady overall, likely due to the initial surface roughness of the pinion being higher than that of the DG. Both reached similar values by the end of the test.

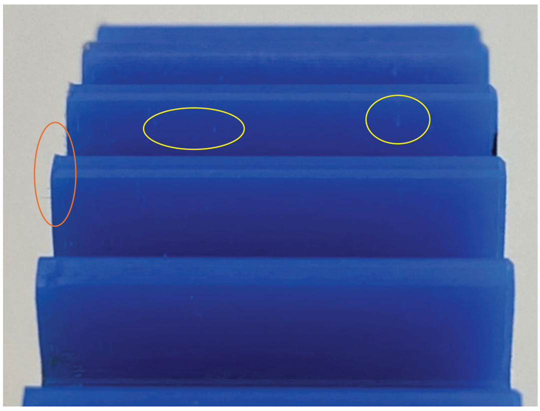


Fig. 4. Scratch marks (circled in yellow) on the pinion and temperature-related plastic deformation at the edge.

Overall, it was found that the injection-molded nylon gears performed well under a self-lubricated condition and when the applied load was 10 Nm or below. Once the torque was increased to 15 Nm at 129×10^3 cycles more surface pitting (Fig. 3(d)), along with deep scratch marks and plastic deformation at the end (Fig. 4), were observed. This indicates that the critical torque of these injection-molded nylon gears is around 10 Nm, as reported in [11]. The two wear mechanisms observed under the critical torque, namely, abrasive wear and surface pitting, are to be expected and were reported by other researchers [12].

B. SLS PRINTED PA12 NYLON GEARS

The surfaces of SLS printed nylon gear teeth ware initially significantly rougher (Sa = 20.85 μm) than those of the

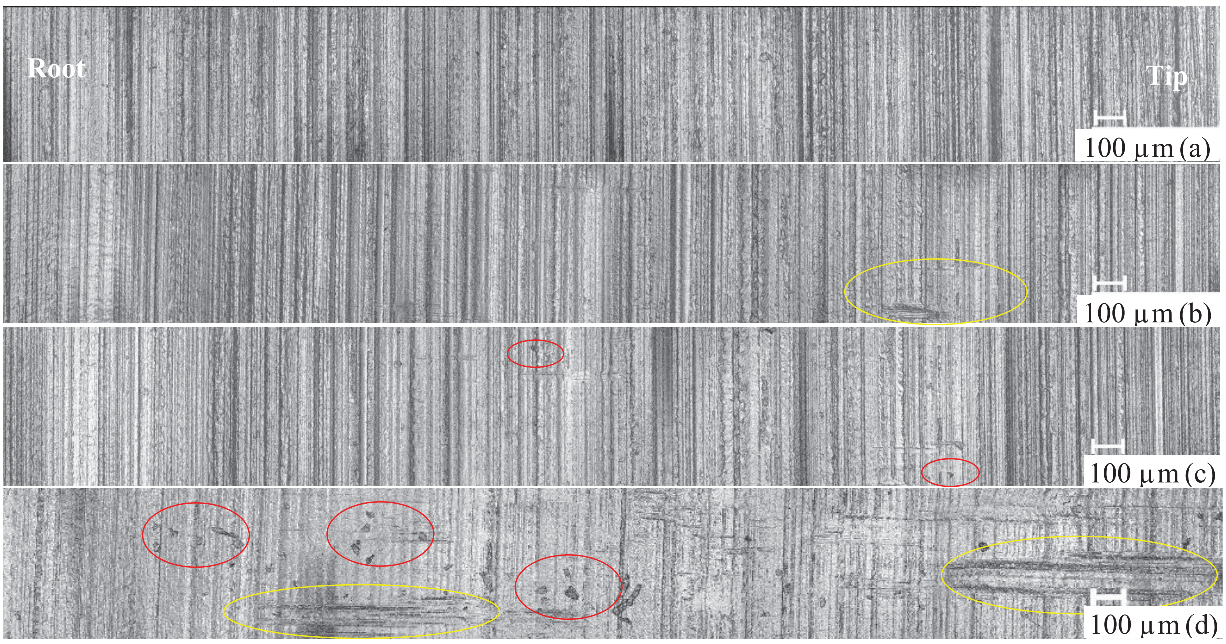


Fig. 3. Images of the commercial nylon pinion at different running cycles: (a) 0 cycle, (b) 4.8×10^3 cycles, (c) 45.8×10^3 cycles, (d) 193×10^3 cycles. Examples of scratch marks caused by the sliding motion are highlighted in yellow, while pits on the tooth surface are highlighted in red. (Note: sliding due to meshing is in the horizontal direction.)

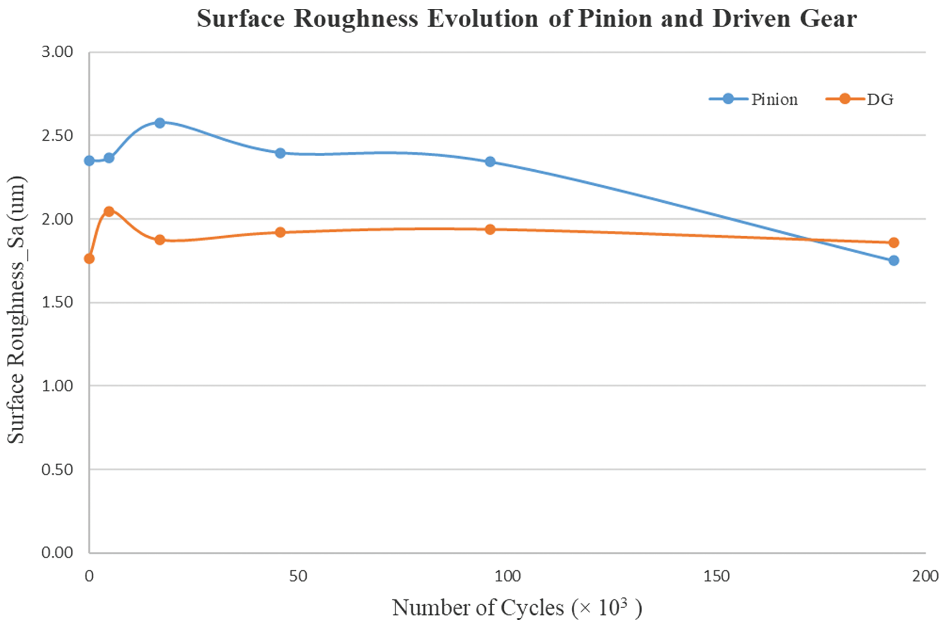


Fig. 5. The surface roughness (Sa) values vs running cycles of the pinion and DG made using the injection-molding method.

injection-molded gears. Figure 6(a) shows an image of the gear surface of the SLS printed pinion, revealing its rough surface finish resulting from the manufacturing process. The surface became relatively smoother during the wear process (Fig. 6(b)–(c)). At 183×10^3 cycles (Fig. 6(d)), there was a significant number of large pits on tooth surface, which led to an increase in the surface roughness (Sa = 21.33 μm).

During the wear process, the surface roughness of the DG teeth showed an overall decreasing trend. For the DG, some pits formed into larger ones before 57.1×10^3 cycles. And then, the number of pits as slightly decreasing until 144×10^3 cycles. At 183×10^3 cycles, the surface became smoother (Sa = 11.91μm) although few more larger pits were observed.

The pinion consistently had a higher surface roughness than the DG. The Sa values of the contact surfaces of both the pinion and DG were measured and are presented in Fig. 7.

After 168×10^3 cycles, the torque applied on the gears was increased to more than 10 Nm, while speed remained at 10 Hz to test the critical load. Between

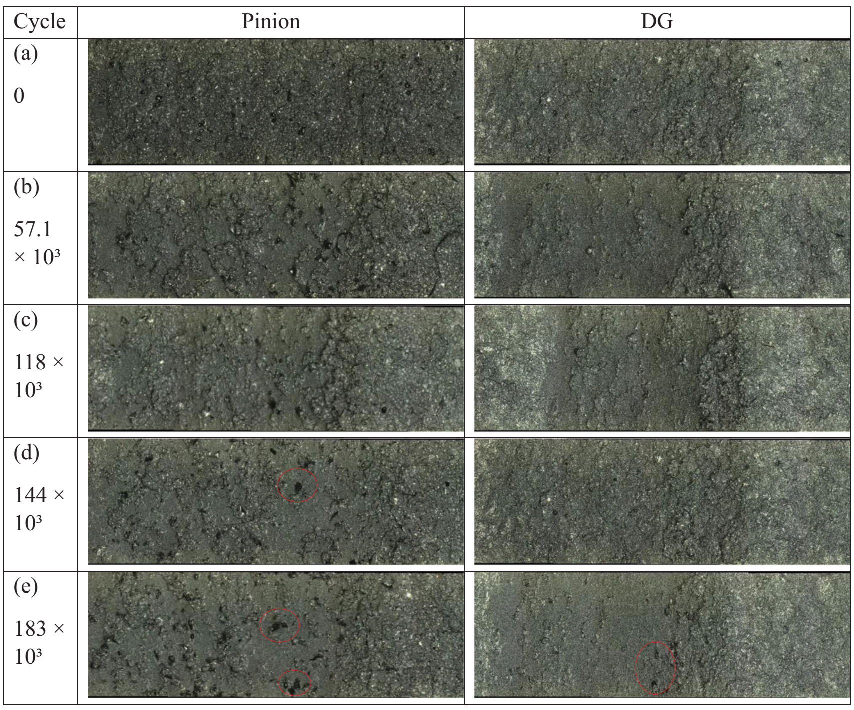


Fig. 6. Images of the SLS nylon pinion and DG at different running cycles: (a) 0 cycles, (b) 57.1×10^3 cycles, (c) 118×10^3 cycles, (d) 144×10^3 cycles, (e) 183×10^3 cycles. Examples of pits on the tooth surfaces are highlighted in red.

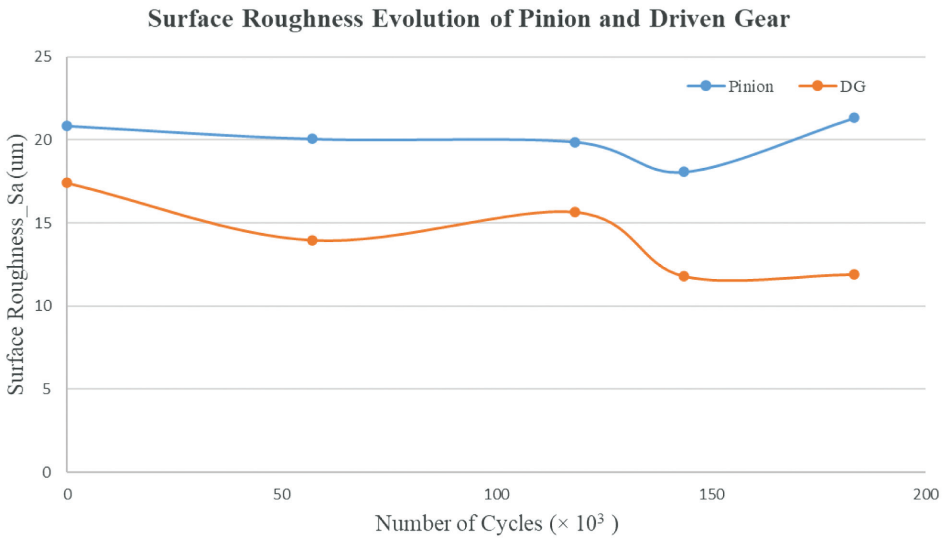


Fig. 7. The surface roughness (Sa) values vs running cycles of the pinion and DG made using the SLS printing method.

Fig. 8. Failed pinion made of nylon using the SLS method.

168×10^3 and 183×10^3 cycles, loads of 12 and 15 Nm were applied for 8 minutes, respectively, which is likely the reason for the increasing number of pits for both pinion and DG at 183×10^3 cycles. After 183×10^3 cycles, a load of 17 Nm was applied for 8 minutes, after which a 20 Nm load was applied. Soon after the increase to 20 Nm, most of the gear teeth broke off at the root, as shown in Fig. 8.

C. FDM PRINTED GEARS REINFORCED WITH CARBON FIBRES

In comparison to the injection-molded nylon gears, the initial surface roughness of the FDM nylon gears was high. Figure 9 shows that the pinion underwent varying degrees of polishing throughout the test. Specifically, the pinion experienced a rapid polishing phase before 76.6×10^3 cycles (Fig. 9(c)), followed by a rapid growth phase of large pits between 76.6×10^3 and 94.1×10^3 cycles (highlighted in red in Fig. 9(d)). During these two stages, pitting gradually formed and condensed into larger pits by 94.1×10^3 cycles. The largest pit reached approximately 300 μm. Additionally, the contact pressure at these surface irregularities increased with increasing applied torque (from 8 Nm to 10 Nm), which resulted in abrasive wear between the meshing surfaces. By 110×10^3 cycles (Fig. 9(e)), the pits on the tooth surface had almost disappeared and resulted in a very smooth surface, which left primarily mild abrasive wear. This mild abrasive wear was likely due to the high load and speed operating conditions between 94.1×10^3 and 110×10^3 cycles, specifically at 10 Hz and load of 12 Nm, 14 Nm, 15 Nm, 17 Nm, and 20 Nm. The decreasing trend of the Sa values shown in Fig. 10 also confirms the surface evolution observed using the images of the mold samples.

For the DG, the polishing process occurred from the beginning of the test until 94.1×10^3 cycles, as shown in

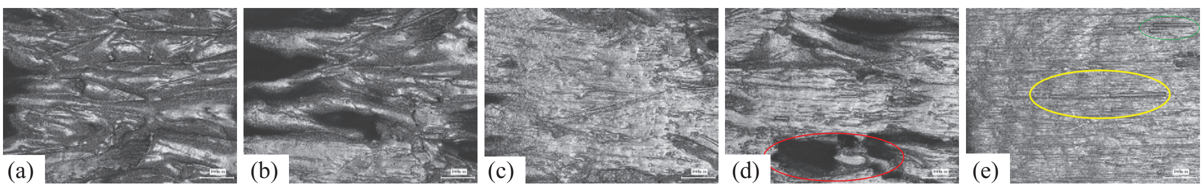


Fig. 9. Images of the pinion of the FDM nylon gears at different running cycles: (a) 0 cycles, (b) 32.1×10^3 cycles, (c) 76.6×10^3 cycles, (d) 94.1×10^3 cycles, (e) 110×10^3 cycles. Examples of scratch marks caused by the sliding motion are highlighted in yellow, while pits on the tooth surface are highlighted in red. The size of each image is about 600 μm by 500 μm.

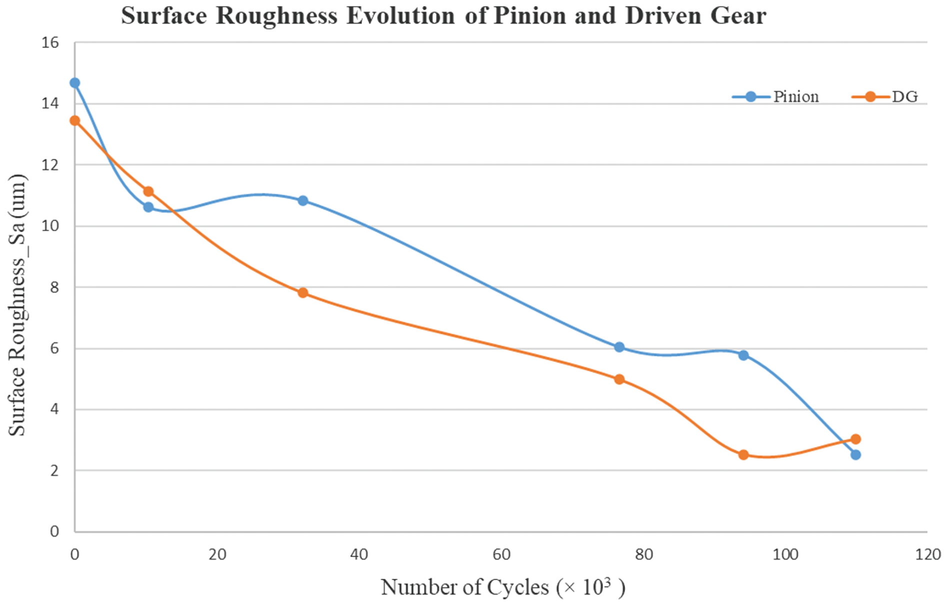
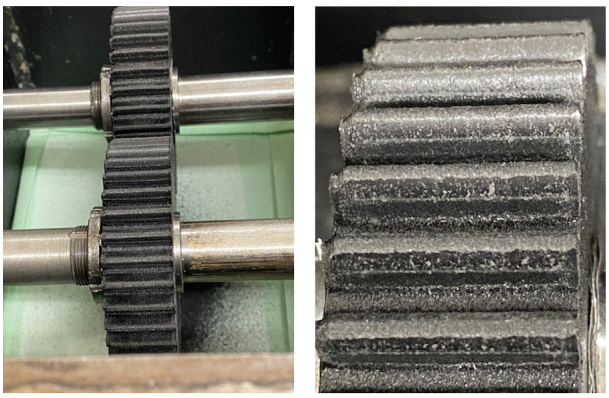


Fig. 10. The surface roughness (Sa) values vs running cycles of the pinion and DG made using the FDM printing method.

Fig. 10. Surface pitting was observed during this process, and most of pits were less than 100 μm in size. At 94.1×10^3 cycles, the surface roughness (Sa = 5.75 μm) of the pinion was higher than that of the DG, which is 2.53 μm. Due to the difference in the surface roughness values of the two contact surfaces, it is reasonable to see that the surface of the pinion experienced a further smoothening process, while the surface of the DG became rougher at the end of the test.

Similar to the test on the SLS gears, different loads were applied toward the end of the wear test on the FDM-made nylon gears. More specifically, before 76.6×10^3 cycles, applied torques were below 10 Nm (between 0 and 8 Nm). Between 76.6×10^3 and 94.1×10^3 cycles, a torque of 10 Nm was applied for more than 20 minutes, which resulted in a rapid growth phase of large pits on the pinion, indicating that the critical load of FDM nylon gear is approximately 8 Nm. Figure 11 shows wear particles and the gear surface at the end of the test.



(a) (b)

Fig. 11. (a) A large number of wear particles generated during the FDM nylon gear test, (b) the worn gear surface at the end of the test.

D. VIBRATION ANALYSIS RESULTS

The comparison of the RMS vibration and ICS2 results for commercial nylon, SLS nylon, and FDM nylon can be seen in Fig. 12. The vibration results for commercial nylon were taken at 10 Hz and 10 Nm, while the FDM nylon result was taken at 10 Hz and 5 Nm. Those measurements were chosen because they were taken in the early stages and near the end of each test. Therefore, the vibration results at the beginning and the end of the test can be compared. Meanwhile, due to data (un)availability, three different load conditions for the SLS nylon gears are presented, namely, 10 Nm, 8 Nm, and 5 Nm.

The RMS of the input shaft SA signal is shown in Fig. 12(a). At the same operating conditions (10 Hz and 10 Nm), SLS nylon's result is higher than the commercial nylon result. Meanwhile, even though FDM nylon was run at a lower load (5 Nm), the RMS of the SA signals was higher than that of the commercial gears and similar to that of the SLS nylon gears. The decrease in the value of the SLS nylon RMS around 60×10^3 cycles was caused by the reduction in load to 5 Nm. However, it increases just after 120×10^3 cycles when the load increases to 8 Nm. Commercial nylon has the most stable RMS value of the three gears, with SLS nylon close behind, and a greater fluctuation in the FDM nylon gears. However, it is interesting to note that the result for all gears is quite stable (within ~2:1, or 6 dB, variation), and there is no discernible trend with wear progression.

As for the residual signal results (Fig. 12(b)), which present only the random components, the FDM nylon becomes more stable. The results from the SLS and commercial gears are also quite stable (allowing for the different loads in the SLS gears), but with a slightly decreasing trend for the commercial gears.

The ICS2 results can be seen in Fig. 12(c). It is shown that the result from the commercial gears shows a marked downward trend with wear, while the FDM nylon's results are quite flat, albeit with some noise. Meanwhile, the SLS nylon gears display an increase throughout the 10 Nm

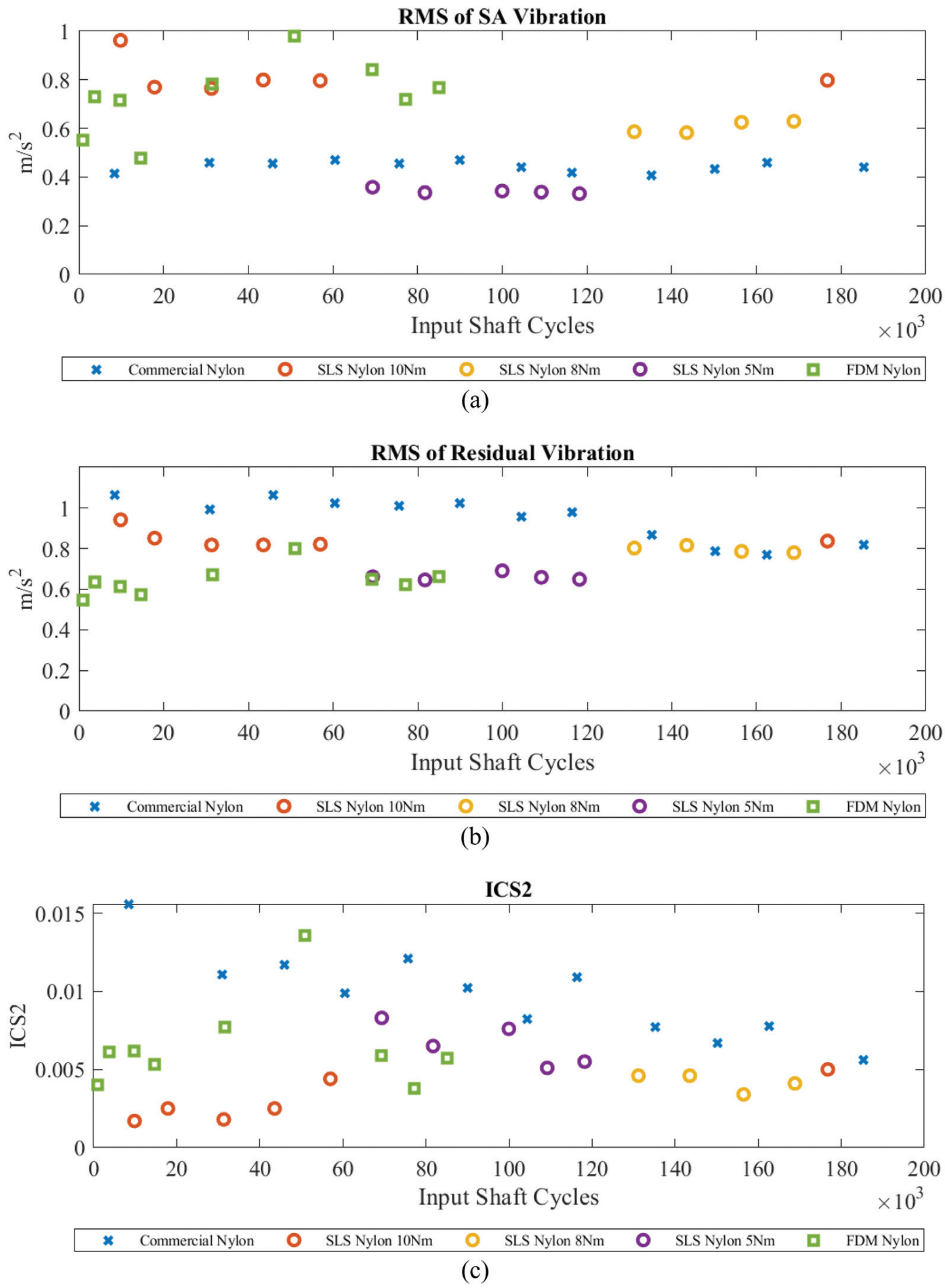


Fig. 12. Vibration signal comparison and trends: (a) RMS of SA with respect to input shaft, (b) RMS of residual signal, and (c) ICS2 for three different nylon gears.

measurements. The increasing value in the middle of the cycles is probably due to the influence of load change, noting that the ICS2 metric is normalized by signal power, so a reduction in RMS associated with lower load may lead to a higher level of cyclostationarity. Of the three vibration metrics, ICS2 displays the greatest sensitivity to wear progression, yet with different trends for the three gears.

By examining the initial surface roughness data presented in Table II, there appears to be a relationship between the surface roughness and the RMS values of the vibration signals at the beginning of the tests. The SLS gears had the highest initial surface roughness and the highest RMS value, while the commercial gears had both the lowest initial surface roughness and RMS value. The RMS values of these gears did not change significantly at the end of the tests for all the gears. This may be expected for the commercial and SLS gears, as their surface roughness values at the end of their tests were similar to those at the start. Conversely, the surface roughness of the FDM gears decreased considerably throughout the test, while the RMS value toward the end was slightly higher than that at the beginning. The gear wear process generally involves changes to both the tooth surface roughness and macro profile. It was previously thought that profile changes would be reflected in the SA signal and that roughness would be loosely proportional to both the strength of the residual signal and the ICS2 metric, the latter essentially a more targeted measure specific to this particular gearmesh frequency. Indeed, such relationships have been found in steel gears [19–21]. However, the results in Fig. 12 do not show such trends. Further research is therefore required to better understand the relationship between vibration characteristics and wear processes in nylon gears.

E. TEMPERATURE ANALYSIS RESULTS

The surface temperature changes of commercial nylon, SLS nylon, and FDM nylon gears are shown in Fig. 13.

It can be seen that the surface temperature of commercial nylon gears remained at a low level. It gradually increased from 30.8°C at the first measurement to 42.5°C at the end of the test. No obvious thermal failure was observed even though a high torque of 20 Nm was applied on the gears for 10 minutes at the end of the test, which demonstrates the outstanding thermal performance of the commercial nylon gears.

The surface temperature of FDM gears grew more rapidly than that of the commercial gears, rising from 24.7°C to 87.6°C. At the end of the test, when a torque of 20 Nm was applied for 2 minutes, the gear temperature increased most rapidly. Slight deformation and surface melting were observed on the teeth. Thermal deformation is the main cause of the failure.

On the other hand, the surface temperature of SLS gears showed a decreasing trend in the period that the applied torque was between 0 and 10 Nm. However, most of the teeth fractured at the root, indicating that the gears failed due to the teeth shearing at 20 Nm. The surface temperature could not be measured since most of teeth already fractured at the end, but it is believed that material softening was not the main cause of the failure as no obvious plastic deformation such as melting was observed at the fractured surface under the laser scanning microscope.

IV. CONCLUSIONS

This study has found that the commercial nylon gears made using the injection-molding method had the smoothest surface finishes, the highest hardness, and the longest service life. Their wear mechanisms are mild abrasive wear and surface pitting when operating under dry conditions and when the applied load is below 10 Nm. Once the applied load exceeds around 10 Nm, plastic deformation begins to occur on the edges of the teeth.

Different to the injection-molded gears, the AM-made nylon gears had a rougher surface finish resulting from the manufacturing process. Due to their initial high surface roughness, most of the wear was dominated by abrasion. Their eventual failure was caused by high torque load. Although the hardness of the reinforced gears increased by adding carbon fibers and the surface finish was slightly smoother than those made of nylon using the SLS method, under the same operating conditions, the carbon fiber-reinforced nylon gears generated a large number of wear particles and had the shortest life. This resulted in the reinforced gears experiencing a dramatic reduction in surface roughness (polishing) throughout the test, while the roughness of the other gears did not change markedly.

This investigation observed that the tribological performance of the AM-made gears is not as good as the conventional ones with the following three main reasons affecting their performance. First, the current AM methods introduce defects in AM-made gears, resulting in weakened mechanical properties, especially the strength and hardness, which are important for anti-wear. To address this issue, processing parameters need to be optimized to reduce or eliminate manufacturing defects. Additionally, reinforcing materials, such as carbon fiber and nanoparticles, can be used to improve mechanical properties. Second, the surface finish plays an important role in determining the wear process in terms of the wear mechanism and wear rate. Post surface treatment or a combination of an AM process followed by a gear machining process can be used to produce gear teeth with a smooth finish. Third, elevated temperature during gear operation due to friction and wear makes the material softer, leading to plastic deformation and temperature-related failure. Further work on enhancing the mechanical properties

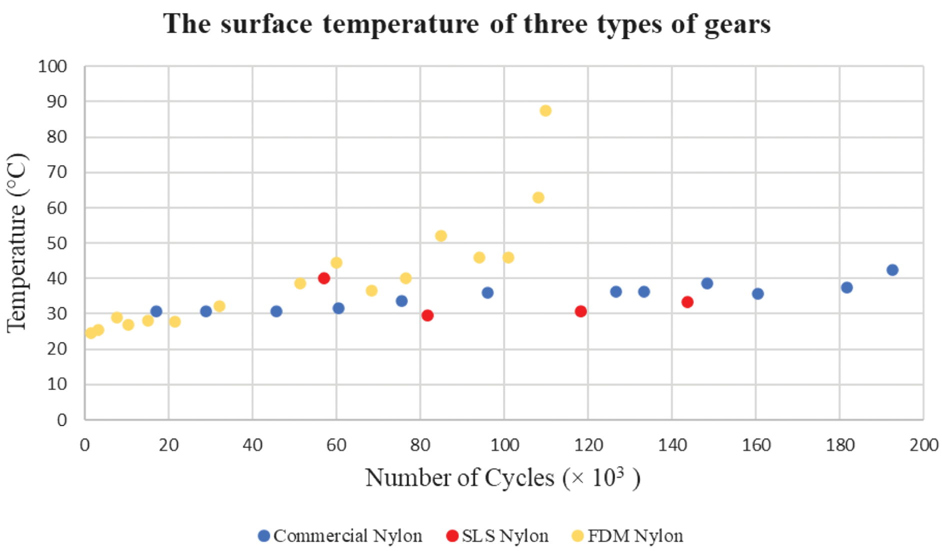


Fig. 13. The surface temperature of teeth in contact for three types of nylon gears.

and thermal stability, as well as achieving a good surface finish, will be conducted to improve the tribological performance of AM-made nylon gears.

Lastly, the study analyzed three established vibration metrics and their capability in trending the wear process of the three gears. It was found that none of the metrics trended consistently with wear severity across all three gear types, suggesting that more work is required in developing reliable vibration-based tools for tracking the degradation of nylon gears.

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CONFLICT OF INTEREST STATEMENT

Wade Smith is an Associate Editor for the *Journal of Dynamics, Monitoring and Diagnostics* and was not involved in the editorial review or the decision to publish this article. The authors declare that they have no conflict of interest.

REFERENCES

[1] M. Montez, K. Willis, H. Rendler, C. Marshall, E. Rubio, D. K. Rajak, M. H. Rahman, and P. L. Menezes, "Fused deposition modeling (FDM): processes, material properties, and applications," In *Tribology of Additively Manufactured Materials Fundamentals, Modeling, and Applications*. Amsterdam: Elsevier, 2022, pp. 137–163.
[2] P. Skawiński, P. Siemiński, and P. Błazucki, "Applications of additive manufacturing (FDM method) in the manufacturing of gear," *Mech.*, vol. 12, pp. 976/173–976/179, 2015.
[3] Y. Zhang, C. Purssell, K. Mao, and S. Leigh, "A physical investigation of wear and thermal characteristics of 3D printed nylon spur gears," *Tribol. Int.*, vol. 141, p. 105953, 2020.
[4] A. J. Muminovic, N. Pervan, M. Delic, E. Muratovic, E. Mesic, and S. Braut, "Failure analysis of nylon gears made by additive manufacturing," *Eng. Fail. Anal.*, vol. 137, p. 106272, 2022.
[5] C. R. Deckard, "Method and apparatus for producing parts by selective sintering," United States Patent 4863538A, Sep. 05, 1989.
[6] A. K. Pandian, S. S. Gautam, and S Senthilvelan, "Comparison of the bending fatigue performances of selective laser sintered and injection moulded nylon spur gears," *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.*, vol. 236, no. 3, p. 146442072110473, 2021.
[7] M. Jain and S. Patil, "Comparative analysis of surface characteristics of Nylon based polymer gears manufactured by different techniques," *Mater. Today:. Proc.*, vol. 63, pp. 40–45, 2022.
[8] A. Kalani, J. Vadher, S. Sharma, and R. Jani, "Investigation of thermal and wear behaviour of 3D printed PA-12 nylon polymer spur gears," *El-Cezeri Fen ve Mühendislik Derg.*, vol. 9, no. 3, pp. 1121–1135, 2022.
[9] S. Bharti and S. Selvaraj, "Performance of selective laser sintered polyamide spur gear under dry and lubricated conditions," *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol*, vol. 237, no. 2, pp. 404–414, 2022.
[10] J. Łuszczek, "Review of methods of designing and additive manufacturing of gears," *Biul. WAT*, vol. 70, no. 2, 2021.
[11] K. Mao, W. Li, C. J. Hooke, and D. Walton, "Friction and wear behaviour of acetal and nylon gears," *Wear*, vol. 267, no. 1–4, pp. 639–645, 2009.
[12] W. M. Ghazali, D. Mohamad, A. H. Sofian, J. P. Siregar, and A. Abdul, "A review on failure characteristics of polymer gear," *MATEC Web Conferences*, vol. 90, pp. 01029–01029, 2016.
[13] S. P. Kumar, K. N. S. Suman, and S. Ramanjaneyulu, "A review on tribological performance characteristics of plastic gears," *Int. J. Mech. Engineering Technol.*, vol. 10, no. 01, pp.516–526, 2019.
[14] A. Bravo, D. Koffi, L. Toubal, and F. Erchiqui, "Life and damage mode modeling applied to plastic gears," *Eng. Fail. Anal.*, vol. 58, pp. 113–133, 2015.
[15] Y. Zhang, A. A. A. Daman, P. He, X. Li, P. Borghesani, and Z. Peng, "Wear study of additively manufactured 316L stainless steel gears," *Wear*, p. 205796, 2025. DOI: 10.1016/j.wear.2025.205796.
[16] H. Chang, P. Borghesani, W. A. Smith, and Z. Peng, "Application of surface replication combined with image analysis to investigate wear evolution on gear teeth – a case study," *Wear*, vol. 430–431, pp. 355–368, 2019.
[17] R. Randall, *Vibration–based Condition Monitoring: Industrial, Automotive and Aerospace Applications*, 2nd ed. Hoboken, NJ: Wiley, 2021.
[18] A. Raad, J. Antoni, and M. Sidahmed, "Indicators of cyclostationarity: theory and application to gear fault monitoring," *Mech. Syst. Sig. Process.*, vol. 22, no. 3, pp. 574–587, 2008.
[19] R. B. Randall, "A new method of modeling gear faults," *J Mech N Y*, vol. 104, no. 2, pp. 259–267, 1982.
[20] Y. Yang, W. A. Smith, P. Borghesani, Z. Peng, and R. B. Randall, "Detecting changes in gear surface roughness using vibration signals," In *Proceedings of the Acoustics Conference*, Hunter Valley, NSW, Australia, November 2015, pp. 15–18.
[21] X. Zhang, W. A. Smith, P. Borghesani, Z. Peng, and R. B. Randall, "Use of cyclostationarity to detect changes in gear surface roughness using vibration measurements," In *Asset Intelligence through Integration and Interoperability and Contemporary Vibration Engineering Technologies*. Cham: Springer, 2019, pp. 763–771.