Suitability of additive manufactured PEEK Gears as a means of gear sampling for Automotive High-Speed Gearboxes

Conference Proceedings

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Zusammenfassung

Die Nutzung von Hochdrehzahlantrieben bis 30.000 min^{-1} ermöglicht eine Steigerung der Leistungsdichte von Antriebssystemen. Durch die Reduzierung der Trägheit von schnell beschleunigten Komponenten kann der Verbrauch solcher Antriebsstränge weiter gesenkt werden. Besonders Hochleistungspolymere wie PEEK bieten aufgrund ihrer geringen Dichte die Möglichkeit, in einer Anwendung als Zahnrad die Dynamik des Systems sowie dessen akustischen Eigenschaften zu verbessern. Die Integration dieses Werkstoffs in den automobilen Hochgeschwindigkeits-Antriebsstrang ist jedoch mit vielen Herausforderungen verbunden. Aktuelle Auslegungsrichtlinien sind nicht in der Lage, die Leistungsfähigkeit einer Polymerverzahnung in diesem Drehzahlbereich zu beschreiben. Insbesondere geometrischer Konstruktionsparameter wie die Zahn- und Zahnradform müssen untersucht werden und den spezifischen Hochdrehzahlbedingungen angepasst werden, um zukünftige Ingenieure bei der Auslegung solcher Getriebe zu unterstützen.

Um verschiedene Geometrieparameter flexibel untersuchen zu können, wird die Eignung des Rapid-Prototyping-Fertigungsverfahren Fused Deposition Modeling (FDM) untersucht. Dieser ermöglicht den Druck von Prüflingen in geringer Stückzahl mit einer hohen Flexibilität, was eine ressourcenschonende Möglichkeit zur Untersuchung verschiedener Zahnradparameter darstellt. PEEK ist aufgrund seiner hohen Schmelztemperatur ein schwer zu druckender Werkstoff. Eine Untersuchung der Widerstandsfähigkeit von FDM-gedruckten Zahnrädern konnte zeigen, dass die Präzision des Verfahrens nicht ausreicht, um die für den störungsfreien Betrieb notwendigen Formtoleranzen einzuhalten. Ein Vergleich mit Zahnrädern aus dem Werkstoff Onyx, welcher strukturell schwächer, jedoch einfacher zu drucken ist, konnte den Einfluss des Fertigungsverfahrens bestätigen und die Widerstandsfähigkeit von PEEK als begrenzenden Faktor für das Versagen ausschließen.

Abstract

The use of high-speed drives up to 30,000 rpm makes it possible to increase the power density of drive systems. By reducing the inertia of rapidly accelerated components, the consumption of such drive trains can be further reduced. Due to their low density, high-performance polymers such as PEEK in particular offer the possibility of improving the dynamics of the system as well as its acoustic properties in a gear application. However, the integration of this material into the automotive high-speed powertrain is associated with many challenges. Current design guidelines are not able to describe the performance of a polymer gearing in this speed range. In particular, geometric design parameters such as tooth and gear shape need to be investigated and adapted to the specific high speed conditions in order to support future engineers in the design of such gears.

In order to be able to flexibly investigate different geometrical parameters, the use of the rapid prototyping manufacturing process Fused Deposition Modeling (FDM) is being investigated. This enables the printing of test specimens in small quantities with a high degree of flexibility, which represents a resource-saving option for investigating various gear parameters. PEEK is a difficult material to print due to its high melting temperature. An investigation of the resistance of FDM-printed gears was able to show that the precision of the process is not sufficient to maintain the shape tolerances necessary for correct operation. A comparison with gears made of the material onyx, which is structurally weaker but easier to print, was able to confirm the influence of the manufacturing process and rule out the mechanical durability of PEEK as a limiting factor for failure.

Introduction and state of the art

Power density increase in modern powertrain concepts

Improving the power density of electric drives is possible by augmenting the maximum speed of the motor while reducing its rotor diameter and therefore the maximum torque. The total power of the now smaller motor is kept equal by augmenting the turning rate, thus allowing a motor of the same power to be designed with much less space and weight. A gearbox is then needed in order to reach user torque and speed. By combining the high-revving drive with a multi-speed gearbox, the motor can be used more efficiently and be further reduced in power and weight while allowing the same dynamic behavior of the complete system [1]. Despite the added weight of the gearbox, a significant reduction of the total mass of the vehicle drivetrain of up to 34 % can be achieved by augmenting the turning rate of the prime mover from 10,000 rpm to 30,000 rpm [2, 3]. Additionally, 20 % of mass saving can be achieved in the powertrain with the use of multispeed gearboxes [4, 5]. In both cases, the first stage of the gearbox is subjected to high accelerations, while being simultaneously operated at a low torque. Further reduction of weight and power consumption can be achieved by optimization of the inertia of high-accelerating components of the drivetrain, like the gears in the first stage of the gearbox [5]. Due to the reduced torque at the motor output, the use of lightweight materials with a lower resilience than steel is possible [6] .

PEEK as gear material in high-speed gearboxes

Polymers, especially high-performance thermoplasts, offer a possibility to fill this gap. The high-performance semicrystalline thermoplastic polymer Polyether ether ketone (PEEK) has already been identified as a suitable gear material, combining high resilience and sliding properties with the additional benefits of an improved NVH behavior [7, 8]. The temperature resistance of PEEK is a major advantage of this material in regard to other polymers. In a typical gearbox, the maximum temperature is limited at around 130°C due to the heat resistance of the lubrication oil [9], which is below the glass transition temperature (T_g) of PEEK, at 143°C. Above this temperature, while retaining most of its mechanical properties, the material's Young's modulus drops significantly. Nonetheless, the material can still be used up to its continuous service temperature of 250°C, allowing for heat peaks to be absorbed. Still, there is a high importance on the cooling of future polymer gear systems [10, 11]. The high resilience and internal dampening capacity of Polymers allow for a quiet operation in several application domains [12]. In the case of high-speed gearboxes, PEEK gears are expected to have a high impact on the sound behavior of the highest-turning gear stage. High-frequency excitation of the gear mesh is a known challenge in the high-speed domain [13]. An improvement of 3 dB in comparison to cast iron steel could be observed in the testing of PEEK gears with speeds up to 14,500 rpm, which represents a 50 % reduction of the sound pressure level [14]. Manufacturing parts out of PEEK is challenging due to the high melting temperature of (T_m) 343°C. The material needs to be heated up to 370 - 390°C in order to be processed [15]. PEEK parts can be manufactured by injection molding or extrusion, but also by rapid prototyping techniques like fused deposition modeling (FDM) or selective laser sintering [7].

PEEK Polymer gears for high-performance applications have been studied thoroughly in the last years. RÖSLER studied the effect of graphite and aramid fiber reinforcement for polymer gearings made of PA, POM and PEEK and showed that gears made out of fiber-reinforced PEEK have a high potential to be used in high-performance applications with temperatures of up to 100°C. The gears have been investigated with power around 2 kW, with a maximum power of 5.8 kW and a circumferential speed of 7.5 m/s [8]. ZORKO ET AL. tested PEEK gears paired with a steel gear with a maximum power of 18 kW and circumferential speeds of 14.14 m/s. He shows the positive effect of grease lubrication and steel gear surface on the lifetime of the PEEK gear, and states that PEEK outperforms conventionally used polymers like Polyamide and Polyoxymethylene, even when those are reinforced with fibers [16].

WEIDIG ET AL. quantifies the inertial and mass savings of PEEK gears in comparison to cast iron. 68 % weight reduction and 78 % moment of inertia reduction can be achieved with operating points up to 14,500 rpm by replacing Iron gears with PEEK gears. This leads to a 9 % reduction in torque needed to obtain identical vehicle behavior [14]. The possible reduction of inertia in the first stage of a high-speed drivetrain up to 30,000 rpm is proposed by LAGIER ET AL. Here, an example gearbox is evaluated in which the first gear stage, designed with steel gears, is subjected to 20 Nm of torque and 30,000 rpm. The total transmissible power is therefore set at approx. 63 kW. By replacing the existing steel gears with similarly dimensioned gears made out of PEEK, a theoretical weight and inertia reduction of over 20 % in the first gear stage could be achieved [6].

However, those results were dimensioned with help of the VDI-guideline 2736, which only covers applications in the low-load and low-speed domain [17]. The guideline shows shortcomings for a use in high-speed applications, as several assumptions like wear behavior are under-estimated in comparison to real experiments [18, 19]. Also, the described power and speed domains aren’t representative of the high-speed operation conditions. The suitability of the VDI-guideline 2736 hasn’t been investigated for high-speed operating points yet, but is the aim of future studies. Especially the impact of high sliding speeds on the gear performance has to be investigated, as temperature elevation has a critical impact on the material’s performance in hindsight to resilience, wear behavior and possible melting [15]. In addition, the effect of centrifugal speed can cause the polymer to stretch, displacing the contact point in the gear mesh and possibly causing additional wear and stress onto the gear.

A validated evaluation of the achievable inertia savings of PEEK gears can only be done with reliable insights on the real resilience of those gears. Therefore, deepened investigations are necessary in order understand and to define the design parameters of polymer gears in the high-speed domain. To this end, several PEEK gears with different characteristics have to be manufactured and tested.

Manufacturing methods for gear sampling

The manufacturing of polymer test gears, as described above, can be done via injection molding. This method is highly accurate and repeatable, but not economic for small part numbers. A costly mold has to be manufactured for each single gear geometry. The required flexibility for the testing of several gear design parameters is not met. A method for highly flexible manufacturing is fused deposition modeling (FDM). Here, molten filament is layered in order to produce the desired product. FDM as a means of Rapid Prototyping is a possibility to increase efficiency in the development process of polymer parts. It enables material saving with near-zero-waste manufacturing and cuts production time. Rapid design iterations of components with high complexity and intricacy is possible without requiring specialized tools [20]. Especially the development of automotive products profits from those benefits [21].

MWEMA ET AL. describes the limiting factors in FDM as the adhesion forces between print layers, which can be the starting points of cracks. The surface roughness ranges in the micrometer scale. The high surface roughness can lead to a change in functionality when compared to other manufacturing methods like injection molding. Once the general mechanical resistance of FDM-printed parts has been proven, further understanding of the system behavior is necessary in order to validate its use as gear sampling material. An addition, penetration of fluids into the part can occur from this surface roughness. As the print is being processed from a volumetric computer file, its accuracy heavily depends on the used printer and the preprocessing and tessellation of the CAD model. Additionally, pores and cracks on the surface and within the material locally increases the stresses on the component, which cannot withstand the load for which it was dimensioned. Propagation of those defects reduces the mechanical stability of such components, rendering their use not suitable for certain high-load applications [20]. ZHANG ET AL. identifies the support structure as having the most influence on the performance of FDM-manufactured polymer gears [22]. In previous work of the authors, FDM printed PEEK gears have been operated up to 12,690 rpm and 1 kW for a short time before breaking. The failure has been identified as a breakage in the support structure of the 3D-printed gear. [6]

Research objective and test setup

The aim of this investigation is to determine the suitability of the gear samples manufactured with FDM for future research on high-speed PEEK gears. This manufacturing method shows high potential as sampling method in regard to the high design flexibility. This allows for a simple variation of design parameters in an explorative research. However, the manufacturing precision and the mechanical resilience of the final sample have to be quantified in order to use this method for testing in high-speed operating points.

Validation environment and validation objectives

Application-oriented investigation and development of tribological systems in machine elements requires a mixed physical-virtual test environment in order to verify simulations and model assumptions. A test environment allowing the operation of polymer gears while accurately representing the interplay with the residual system has been designed and commissioned at IPEK for in operating points up to 30,000 rpm [6]. The test bench is designed as a non-mechanically closed loop test rig according to VDI-guideline 2736 [17], allowing setting and variation of operating speed and load, as well as other parameters like the inertia and spring rate of the residual drivetrain..

The aim of future investigations is to evaluate the behavior of an example gearbox with a maximum operating point at the targeted power of 63 kW and a speed of 30,000 rpm and a PEEK gear in the first stage. For this, the behavior of the system under investigation needs to be analyzed under consideration of its interplay with the residual system and environment. The gearbox, starting from its second gear stage, as well as the residual drivetrain up to the contact of the wheel with the road, have to be modelized alongside the electric machine and the clutch by physical or virtual means [23]. Thus, in a first step, the aim of the investigation is to determine the maximum transmissible constant load and to evaluate the lifetime of the printed gear at this operating point. The targeted operating point is at the maximum speed of 30.000 rpm and 20 Nm of torque. A comparison of the calculated lifetime of injection-molded gears with the lifetime reached in the experiment with FDM-manufactured gears enables an evaluation of the suitability of the manufacturing method for future testing.

The residual system can therefore be simplified. The gears are operated at constant speed and torque by the electric drive. The residual gearbox and drivetrain of the final application aren’t yet considered in the test. Only the first stage, made with PEEK gears, is being physically operated on the test bench.

Polymer gear sample geometry

Table 1: Gear design

	Driving Gear	Driven Gear
Modulus m (mm)	1	
Normal pressure Angle (°)	20	
Helix Angle (°)	0	
Teeth Width b (mm)	45	
Center Distance in the Gearbox (mm)	84.29	
Transmission ratio	1.84	
Number of Teeth (i~1.84)	59	109
Load change number from dimensioning (in millions of revolutions)	4,500	2,435

The starting design for high-speed gear testing were involute polymer gears calculated from VDI-guideline 2736. The gear was dimensioned in accordance to the guideline, assuming that the material properties are those of molded or machined gears. When choosing the gear parameters, attention was put on minimizing the sliding speeds in the gear contact, which is realized by a small modulus. The VDI-guideline 2736 describes test gears with modulus of 1, 2 and 4.5 mm [17], therefore a modulus of 1 mm is chosen. Table 1 details the gear design resulting from the dimensioning. The print parameters for the PEEK gear as well as the Onyx gear used for comparison of performance are detailed shown in Table 2. The resulting printed gears are visible in Figure 1.

Table 2: Sample material data and print parameters

Material	PEEK CFR 450	Onyx
Tensile strength (MPa) at 23°C	190	40
Tensile elongation (%) at 23°C	1.7	25
Youngs modulus (MPa) at 23°C	17,500	3,000
Reinforcement	30% Short-Fiber Carbon filament	/
Melting temperature (°C)	343	197
Print parameters		
Nozzle temperature (°)	510	275
Bed temperature (°)	130	Not heated
Layer height (mm)	0.2	0.1
Print time for driven gear (h)	12	34
Infill pattern and density	Honeycomb 30%	Triangular fill 40%
Amount of wall layers / tooth material thickness	4	7
Amount of roof and floor layers	8 on top side, 5 on bottom side	4

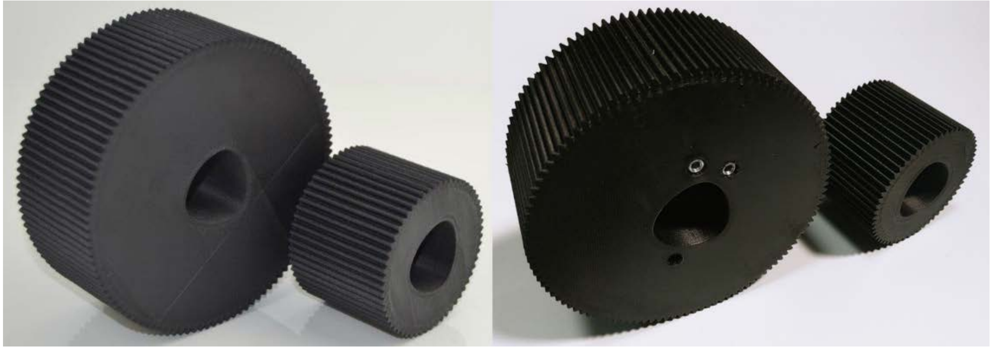

Figure 1: Test Samples. Polymer gears printed out of PEEK CFR 450 (left) and Onyx (right)

Test design

In order to investigate the performance of 3D printed polymer gears, first tests are conducted at low speeds. The goal is to evaluate if the dimensioning of the gear is accurate in regard to the real behavior of the gear under load. After a run-in at 400 rpm and low torque (< 2 Nm), the load is gradually increased until the targeted operating point is reached or the gears fail. Between each test run, the gears are analyzed and the damage of the gear evaluated. Failure of the gear is defined as a deformation of the teeth, by the appearance of pitting or excessive wear, melting, or breakage of the tooth and/or the support structure of the 3D print. The initial test design has been defined for operating points between 2.2 - 10 Nm and speeds ranging from 500 to 10,000 rpm, which is a third of the final targeted speed. Before each test run, a pre-run with 200 rpm and 0.2 Nm is run for approximatively 3,000 cycles in order to assure equal starting conditions, even oil distribution and even tooth temperature before starting the test. During operation, speed and torque are controlled and measured by the motors. Temperature information is collected from thermoelements placed at the oil input and output, as well as from accelerometers placed on the outside of the gearbox. The lubrication of the gears is done with a circulating oil lubrication. The sensor arrangement is shown in Figure 2.

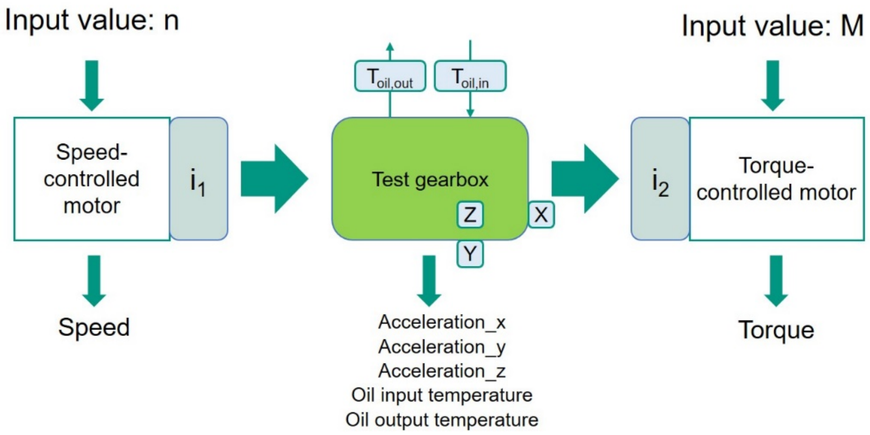

Figure 2: Schematic of the sensor arrangement on the test bench

The tests are run with the PEEK gears and are repeated with Onyx gears. As shown in Table 2, Onyx shows a smaller tensile strength than PEEK, and has a smaller temperature resistance. Both material parameters are known to have an influence on the lifetime of the gears. It is therefore expected that with identical gear geometries, failure will first occur in the Onyx gears.

Results

In this chapter the authors present the results of the test runs of FDM-manufactured gears made of PEEK, and the comparative tests with Onyx gears.

The PEEK gear failed during the run-in. After approx. 30,000 cycles at a speed of 400 rpm and a torque of 0.7 Nm, a thin rupture was visible on the edge of the of the top side of the gear. The crack is located between the 9th and 10th print layer of a total of 225. The rupture was extending on 1/4th of the gear perimeter. After running up to 60,000 cycles, the crack had extended and widened, and a tooth flank break could be observed. Additionally, oil was diffunding from the crack, as it has been absorbed into the gear structure during the test run.

The Onyx gear did not show any sign of failure during the run-in. It could be operated at higher speeds and load, up to a total load of 470 W at 2,000 rpm, cumulating around 85,000 cycles in total without failing.

Discussion of results

The Onyx gear, despite having worse mechanical properties than PEEK, was able to withstand more load. In the following chapter, the authors conduct a failure analysis and discuss which parameters could lead to the performance difference in the two test samples.

The location of the crack indicates where local stresses exceed the resilience of the gear. The crack occurred directly after the infill structure transitioned from the fully printed top layers to the 30% honeycomb infill structure. This supposedly correlates with a drop in the structure's mechanical properties coming from the hollowed-out part of the infill structure. The flank break is located only on one side of the print layer crack, as visible in Figure 3. As tooth flank breaks are due to excessive flank pressure, the side without tooth break has not been stressed in the same way. The break was thus caused by the local increase in flank pressure, provoked by the missing support from the detached print layers as described by MWEMA ET AL. [20].

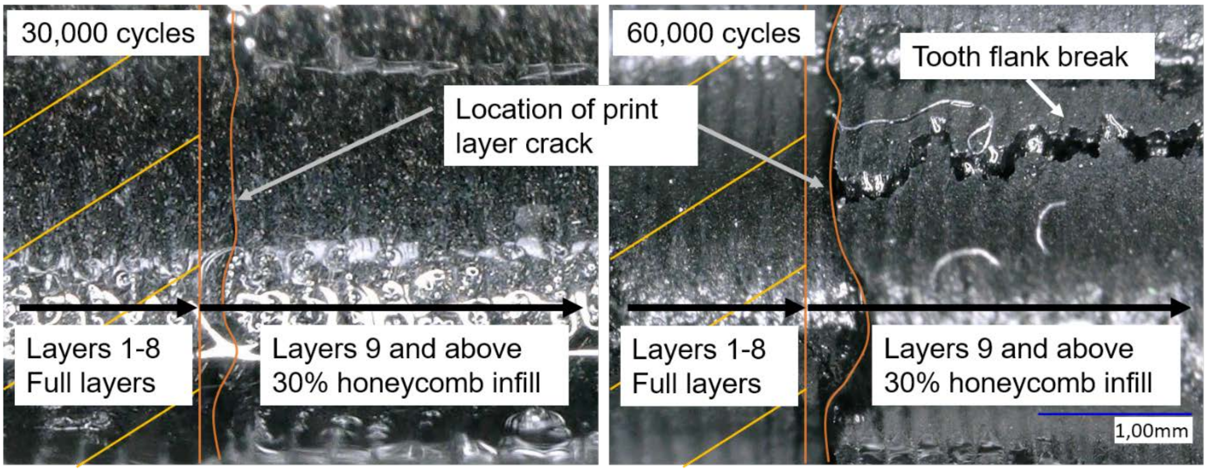

Figure 3: Print layer crack and tooth flank break in PEEK gear during run-in. The crack is located directly after the transition from fully printed infill layers to 30% honeycomb layers. The tooth flank break was caused by local increase of pressure due to missing support from the detached layers. On the left image, the oil diffusing from the crack is visible.

The used PEEK is reinforced with carbon fibers, with a diameter of 10-15 µm and a length of 100-150 µm. The Onyx gears are not reinforced. A major difference in the two gears is the print layer height. The Onyx print layers are 0.1 mm thick, whereas the PEEK print layers are 0.2 mm thick. The stress between each print layer for a given surface load on the gear flank is therefore doubled. Another difference between the prints is the infill structure and its density. The Onyx gears show a higher infill percentage, adding material which supports the stress coming from the operation of the gear. In accordance to the work of ZHANG ET AL., this can be considered as a major factor in the early failure of the PEEK gear.

The manufacturing precision also played a major role in the performance of the two samples. On the PEEK pinion gear, the runout, measured with a radial runout tester, was around 0.3 mm. An optical measure with a 3D coordinate measuring machine confirms this deviation, as it indicates an off-centering of the tip circle diameter to the hub center of 299.8 µm. On the driven PEEK gear, the optical measurement indicates an off-centering of 187.4 µm. This induces a periodical overlap of ±487.2 µm of the tip circles in the gear contact. In order to compensate for this overlap, the material must be deformed, which causes a stress elevation damaging the gears. The stress elevation also hinders the movement of the motor, which is observable in speed fluctuations while operating the gears.

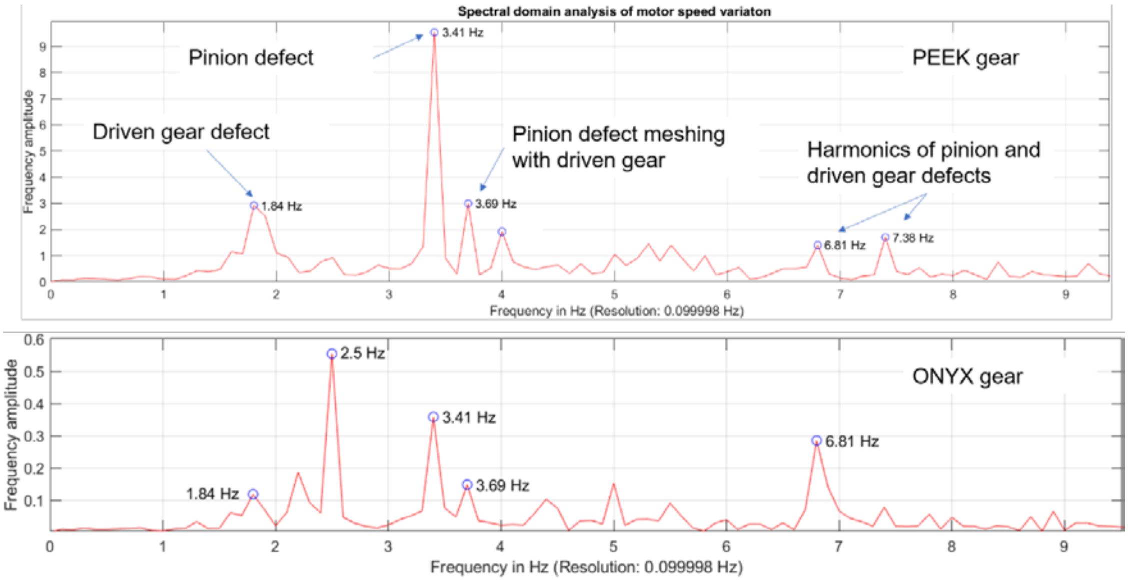

Figure 4: Spectral domain analysis of motor speed when operating with PEEK samples. The gear geometry defects cause fluctuations in the motor turning rate. On the more accurate Onyx gear, the speed fluctuations are of much smaller amplitude.

The irregular speed of the motor can be correlated to the movement of the gears. On the motor speed spectrum analysis (see Figure 4), the frequency with the highest amplitude corresponds to the first order of the rotation of the pinion gear at 3.41 Hz. This is also the gear with the most significant runout deviation. The next notable peaks are perceptible at the first and second order of the driven gear rotation, at 1.84 Hz and 3.69 Hz. The first order of driven gear rotation is representative of the runout variation of the driven gear. The second order represents the defect of the driving gear meshing with the driven gear. The second order Secondary peaks at multiples of those frequencies (6.81 Hz and 7.38 Hz) are also visible, although far less dominant.

The comparative Onyx print lead to a better sample. In an identical run, the motor speed variations were less big, with a maximum frequency amplitude of the motor speed irregularities peaking at 0.5, compared to over 9.0 with the PEEK gear. The geometric deviations are also visible at a smaller scale. When observing the gear profile, the PEEK gear shows a much higher deviation from the involute profile that was programmed into the printer, as it is shown in Figure 5.

When evaluating the surface quality of the gears, as they were not post-processed, a rough surface can be seen in which the individual print layers are distinguishable (see Figure 6) Warping along the tooth width could also be observed. The tooth flanks smoothed out with ongoing operation of the gears. As failure was observed from print layers before tooth flanks were damaged, no conclusion is drawn from the initial surface quality of the tooth flank on the gear performance. In total, the PEEK gears reached less than 0.01 % of the planned load change number when failing.

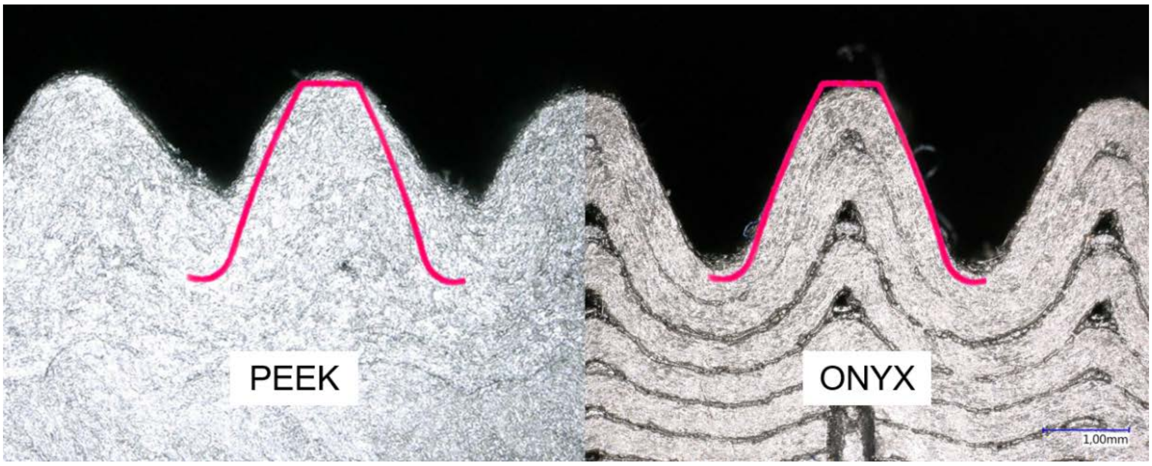

Figure 5: PEEK and Onyx tooth profile comparison with expected profile at 50x magnification. PEEK gear has a much coarser print and deviates more from the expected profile.

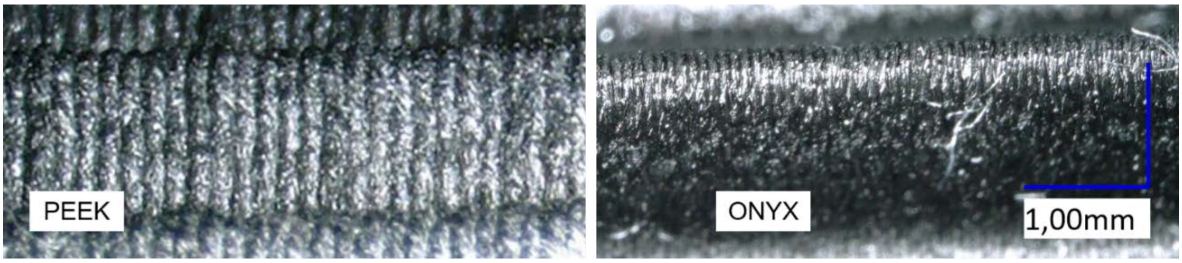

Figure 6: PEEK and ONYX tooth flank surface before test runs at 50X magnification. The print layers are easily distinguishable. The smaller layer height on Onyx gear causes a smoother surface.

Conclusion and outlook

In this contribution, the authors examine the possible use of fused deposition modeling (FDM) as a means of quick and flexible sample manufacturing for high-speed gears with speeds up to 30,000 rpm. FDM-manufactured PEEK gears are compared to gears made from Onyx. Although having less material resilience, the gear sample made out of Onyx performed better. Geometrical deviations on the PEEK sample caused additional stress in operation, leading to a crack in the print layers which lead to a tooth break. Therefore, the print quality could be identified as a limiting factor for the used FDM gear manufacturing method. PEEK has already been identified as a challenging material to manufacture with FDM due to its high melting temperature. Several print parameters can be optimized in order to achieve higher resilience and better performance as a gear. For example, the layer height can be reduced, allowing for a better distribution of load and reduced stress in each layer contact surface. A higher infill density can also lead to a better performance. Reinforcing the material with continuous fibers instead of short fibers would also lead to a better performance.

On order to be used as a gear manufacturing process, the general print accuracy of PEEK has to be improved. A possibility to achieve higher precision in the tooth geometry is postprocessing of the gear is by hobbing or machining of the gear. This would be counterproductive, as the use of tools nullifies the benefit of FDM tool-free manufacturing. Another way to reduce inaccuracy in the tooth form is to reduce the nozzle size or to increase the tooth modulus, limiting the use of this manufacturing method to bigger teeth forms.

Using rapid prototyping methods bears the advantage of quick and flexible manufacturing, which is especially useful when investigating gear tooth geometries. However, the manufactured PEEK gears with the chosen geometry produced a sample which failed prematurely. The use of a second gear sample from another material helped identifying the print quality as a bottleneck in the performance of the gear. As the focus of future investigations is to understand the interactions of the gear geometry with the residual system, the manufacturing precision is a highly relevant topic. Also, as there are several unknown manufacturing parameters that could interplay with the final performance of the gear, a deepened study of those parameters has to be conducted first. Therefore, the general mechanical resistance of FDM-printed parts has first to be proven adequate for experimentation in the aimed operating points. The next step is to then validate the use of FDM-manufactured parts for experimentations on gears that will ultimately be manufactured with injection molding. For that, comparative studies between the effect of design parameters and the gear performance with different manufacturing methods are needed.

The investigation of geometry parameters for PEEK gears in high-speed automotive drivetrains therefore isn’t yet possible with samples made out of the described FDM method. Further testing of PEEK high-speed gears will be conducted with machined or injection-molded gears, trading the reduced flexibility for higher precision in the manufacturing and higher material resilience.

Acknowledgements

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