Designing Quieter, More Energy-Efficient Gears with PEEK

Getting to the Heart of Wheels

High-performance plastics such as polyetheretherketone (PEEK) offer many interesting opportunities for improving gears. However, precise statements about the relevant characteristic values are crucial for their effective use. The plastics producer Evonik has carried out corresponding investigations for PEEK. The findings led, among other things, to the first use of PEEK gears in Mercedes-Benz transmissions.

The mass balancer gear made of Vestakeep 5000 G is the first plastic gear used in Mercedes-Benz transmissions. It replaces the metal gears previously used there.
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In many technical applications, gears made of plastic are replacing classic metal gears. They are lighter, quieter silent, have good dry-running properties, low friction and wear, and can be manufactured efficiently. Compared to gears made of engineering plastics, variants made of high-performance plastics, such as polyetheretherketone (PEEK), are generally more mechanically, thermally, and chemically stable and can therefore extend the load limits. A qualified assessment and the design of the components to suit the plastic are a crucial prerequisite here.

In 2018, Evonik set up a tribology competence center in Darmstadt, Germany, to specifically develop high-performance plastics such as PEEK, polyamide 12 (PA12) or polyimide (PI) for components subject to tribological stress. In addition to classic methods, such as pin-on-disc and ball-on-disc testing (via Mini Traction Machine), a new type of test rig has also been installed (**Fig. 1**).

Test Bench Enables Evaluation of Plastic Gears

The friction and wear behavior of a gear depends in a complex way on the specific, local stress in contact with a steel pinion and the ambient conditions in operation. Model tests such as pin-on-disk and the combination with classical static and dynamic mechanical tests on standardized test specimens have so far not allowed an adequate evaluation of the behavior of a plastic gear in operation due to the special meshing conditions [1]. In contrast, component-specific characteristic values for the design can be determined on plastic gears in the component test of the new gear test rig. Under defined torque load, speed, and temperature, a dynamic tribological and mechanical alternating load is applied to the plastic teeth with a driven metal pinion. A comparison of plastic gears lubricated with oil or grease, for example, and dry-running plastic gears is possible.

Tests are carried out in accordance with the German guideline VDI 2736–4 ("Thermoplastic gears: Determination of load capacity characteristics on gears") to determine results such as tooth load capacities and wear coefficients with different load collectives. These results are used as raw data in professional gear design simulation programs to assist customers with optimal design. Testing is usually carried out until the gear fails due to wear of the tooth flanks or tooth root fracture. The tooth root temperature influences the tolerable load changes, which can therefore be determined and controlled in the existing test rig via an infrared (IR) sensor.

PEEK Convinces with Mechanics and Chemical Resistance

When developing high-performance polymers for gears, different mechanical, thermal and tribological requirements must be reconciled as far as possible, depending on the stresses involved. Certain material modifications can have antagonistic effects on gear behavior. For example, in some cases additives for improved wear protection or reduced friction have negative effects on the dynamic-mechanical behavior of a gear, depending on the particle properties and bonding possibilities to the plastic matrix, if they act as imperfections or crack initiators.

Compared to engineering plastics such as polyoxymethylene (POM), PA6 or PA66, the high-performance plastic PEEK has many advantages as a material for gears. In particular, it can transfer high loads even at high temperatures [2]. Due to practically negligible water absorption and low shrinkage and post-shrinkage, molded parts are very dimensionally stable and, based on the molecular structure of the thermoplastic, exceptionally resistant to chemicals. This is even more important when gears are lubricated with engine or transmission oils, an aggressive environment for many plastics.

No Change for Oil Storage

Using the example of elongation after full-contact storage in gear oil (**Fig. 2**), it was possible to demonstrate that PEEK (grade: Vestakeep 4000 G from Evonik) is far more resistant than polyphthalamide (PPA, grade: Vestamid HTplus, formerly manufactured by Evonik), a partially aromatic PA with high temperature stability. While the elongation at yield does not change in the case of PEEK, the tested PPA already shows significant losses in elongation at break after 500 hours of storage. The embrittlement characteristic for PEEK is the elongation at yield, while for PPA it is the elongation at break due to the missing elongation at yield. Additional impact strength tests underlined the mechanical embrittlement behavior.

The very high mechanical and thermal stability of PEEK compared to many other engineering plastics pays off in gear applications. This is illustrated by the tests on gears made of high-molecular-weight ductile PEEK with the described test rig in a dry pairing and in the engine oil-lubricated condition at 80 °C and 130 °C (**Fig. 3**). The plastic gear was driven at a speed of 650 rpm by a steel pinion of defined surface hardness and roughness. The result: oil-lubricated PEEK can transmit a very high load over a long service life. In the dry running condition, wear is the predominant mode of failure, while in the oil-lubricated condition, tooth root fracture dominates due to fatigue.

Lower Friction with PEEK

Further advantages of PEEK include the very good tribological properties, in particular the low wear and friction coefficients [3]. The latter ensures energy savings in the application both in dry running and in lubricated condition. This was demonstrated in another experiment (**Fig. 4**). In the ball-disc experiment in engine oil at 23 °C and 130 °C, the coefficient of friction of steel to steel and PEEK to steel was investigated using »

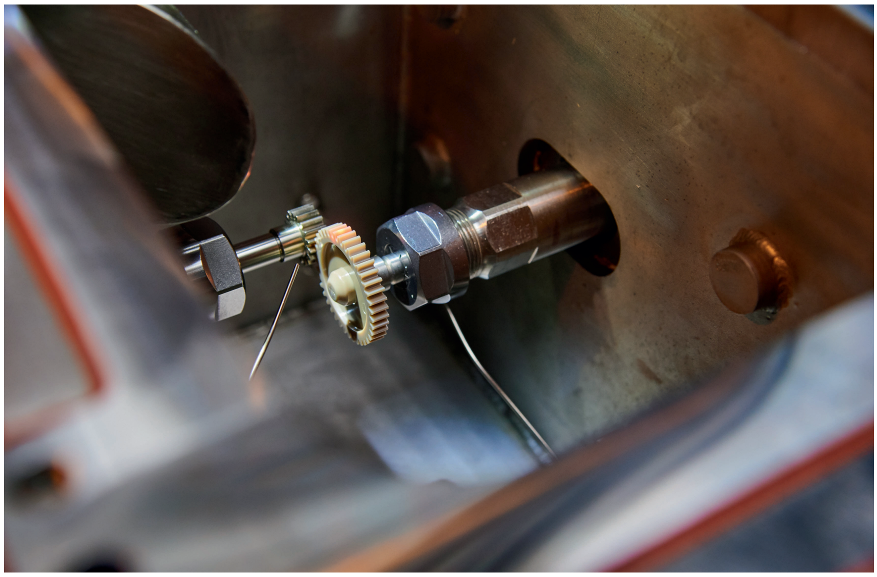

Fig. 1. Gear test rig for plastic gears at Evonik's Tribology Competence Center in Darmstadt: it can be used to determine component-specific characteristic values for the design of gears. © Evonik

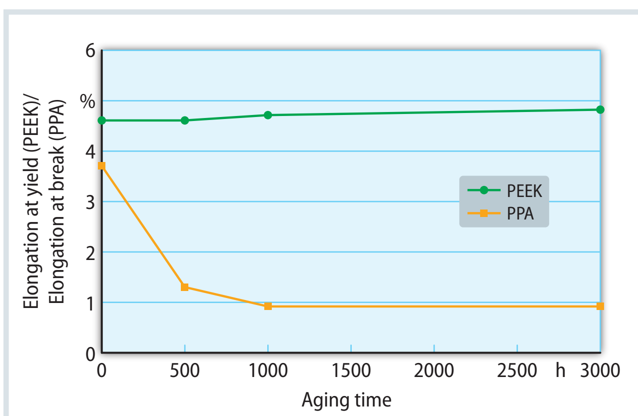

Fig. 2. Elongation at yield of PEEK and elongation at break of PPA after full-contact storage in gear oil at 150 °C: PPA shows greatly reduced values after only a short time. In contrast, the elongation of PEEK remains constant. Source: Evonik; graphic: © Hanser

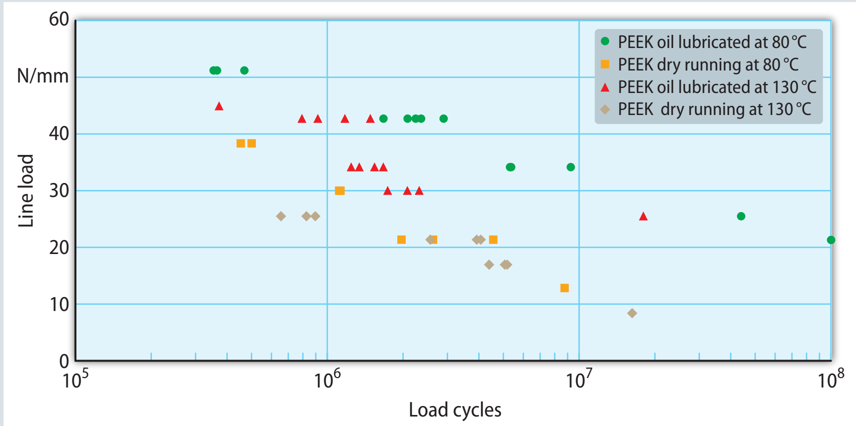

Fig. 3. Mechanical testing of a gear made of Vestakeep 5000 G: especially oil-lubricated PEEK gears can transfer higher loads over many cycles. Source: Evonik; graphic: © Hanser

a steel ball with a radius of 9.5 mm and one steel and one PEEK disc each. In this experiment, the ball was loaded with 30 N and operated with a sliding roll ratio of 25 %, which allowed the testing of sliding and rolling movements of the two contact partners.

The so-called Stribeck curves demonstrate that very energy-efficient solutions can be realized with a PEEK-steel pairing in the oil-lubricated system. Both in the boundary friction, the condition at low speed with hardly any lubricating film between the contact surfaces, and in the hydrodynamic range, the condition at high speed with complete lubricating film between the contact surfaces, the coefficient of friction is higher by a factor of four to seven for steel on steel. This can be explained, among other things, by the viscoelastic behavior of PEEK and the resulting lower Hertzian pressure in the contact [4].

The viscoelastic behavior and the associated good damping effect of PEEK are also the reason for the very pleasant noise behavior. Silent transmissions are becoming increasingly relevant, especially in electric vehicles, as the noise of the combustion engine is eliminated. In a grease-lubricated helical gear unit, a PEEK steel contact reduces the airborne noise drastically by more than 10 dB in some cases (**Fig. 5**). The measurement was carried out at the Chair of Industrial and Automotive Driveline Technology (IFA) of the Faculty of Mechanical Engineering at Ruhr University Bochum, Germany.

Mercedes-Benz: Plastic instead of Metal

The advantages demonstrated led to the series application of PEEK gears in a mass balancer gearbox manufactured for

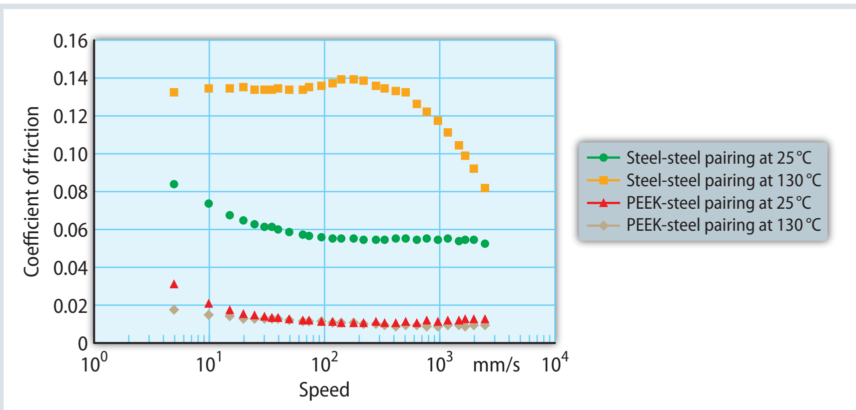

Fig. 4. Coefficient of friction of steel-steel and PEEK-steel pairings in engine oil: the coefficient is significantly lower when the high-performance plastic Vestakeep 5000 G is used.
Source: Evonik; graphic: © Hanser

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References & Digital Version

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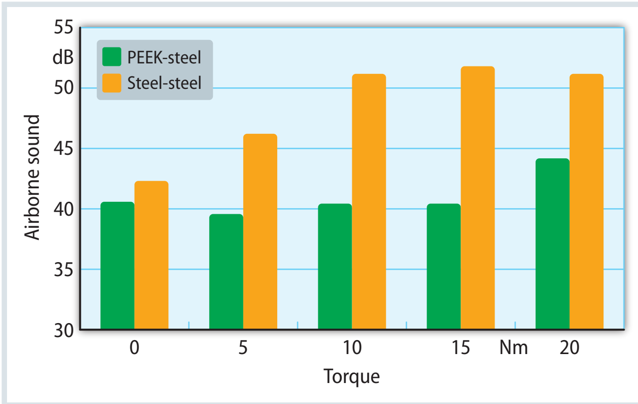

Fig. 5. Airborne noise measurement in a helical gear unit on a grease-lubricated PEEK-steel and a steel-steel pairing at 3000 rpm: the noise level is in some cases more than 10 dB lower with PEEK.
Source: Evonik; graphic: © Hanser

Mercedes-Benz (**Title figure**). This is the first PEEK plastic gear in this very challenging engine application, which was previously reserved exclusively for metal gears. Extensive testing and evaluations of competent manufacturing partners enabled the use of PEEK in this harsh environment. The gears are manufactured cost-effectively and precisely using injection molding. This eliminates the need for the extensive post-processing that was previously required when using metals. In addition, the lower mass moment of inertia during driving saves energy and enables very smooth running and low noise behavior [5].

Summary and Outlook

From use in classic automotive engineering to robots or drones – the possible applications of plastic gears are diverse. High-performance plastics such as PEEK expand the range of applications for plastic gears in transmissions to higher torques, speeds and temperatures. To achieve this, they must be designed with plastics in mind so that they can ultimately be used in smaller, lighter and more energy-efficient units. These advantageous properties will drive the use of PEEK gears in electromobility and increase metal substitution. 3D printing will prove advantageous in this context. This will make further applications possible. Increased use of hybrid solutions and the integration of additional functions such as cooling, or lubrication channels also offer more options.

Above all, sophisticated multicomponent injection molding technology opens a great design freedom in gear design. This makes it possible, for example, to realize variants made of wear-optimized plastics in the tooth flank area, with tough plastic modification in the tooth root area and metallic or highly stressable, fiber-reinforced plastics around load peaks. They can be produced very economically and precisely, for example in rotary molds. In addition, intelligent material developments based on PEEK enable – with reinforcement and additivation – tribological systems to be designed without external lubricants in an energy- and material-efficient way. ■

TPE with PIR

Recycling Content for Automotive Interiors

Kraiburg TPE is expanding its portfolio of thermoplastic elastomers (TPE) for automotive interiors with grades with a recycling content of up to 38 %. The post-industrial recycled raw material used is waste material derived from other companies' manufacturing process for plastic products. Possible applications of the TPEs include anti-slip mats, floor mats, soft components in cup holders, as well as fixation elements. The series is also suitable for other applications requiring a hardness range between 60 and 90 Shore A.

Strict OEM requirements for emission and odor are fulfilled and the material can be either combined with polypropylene in co-injection molding applications or used as single soft component solution. In addition, Interior PIR TPE provides good abrasion resistance and excellent flowability combined with low density to keep the part weight at a minimum. "We're expanding our product range to include Interior PIR TPE in response to the sustainability issues raised by OEMs. We're sure our customers will benefit substantially from the option of using TPEs based on recycled raw materials for automotive interiors," says Matthias Michl, Head of Automotive Application Development at Kraiburg TPE.

The company is now able to provide the product carbon footprint (PCF) of compounds for many products. The PCF quantifies the CO_2e-footprint – in this case within the system boundaries cradle-to-gate. The global warming potential (GWP) of a product is calculated, indicating how much the product contributes to global warming from raw material extraction to the product manufacture's gate. Producers require this value to assess the carbon footprint of their components, and ultimately of the whole vehicle. As stated in a press release, Kraiburg TPE claims full transparency in assessing the PCF and calculates the values according to DIN EN ISO 14067 and DIN EN ISO 14044, following the GHG Protocol.

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The post-industrial recycled raw material used is waste material derived from the manufacturing process for plastic products. © Kraiburg TPE