RESEARCH ARTICLE

Experimental and numerical analysis of laminated carbon fibre-reinforced polymer gears with implicit model for coefficient-of-friction evaluation

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Abstract
Laminated composites have so far received little attention as a potential material for gear drive applications. In the presented study, the thermomechanical performance of a newly developed type of epoxy impregnated, autoclave-cured carbon fibre-reinforced polymer gear—running in pair with a steel pinion—was analysed, using a combination of experimental and numerical approaches. The employed methods enabled the identification of the composite’s mechanical, thermal, and tribological characteristics, as related to the studied gear pair application. A newly proposed, finite-element-analysis-based iterative procedure enabled an implicit evaluation of the analysed material pair’s coefficient of friction (COF), which is a key parameter in determining the gear pair’s thermomechanical characteristics. For the considered material pair, a value of 0.34 was identified for the coefficient in the quasi-steady region. As the coefficient is strongly correlated with frictional heat generation and significantly affects the surface shear stress, it can consequently have a meaningful influence on the composite’s wear rate. The developed COF identification procedure was validated using a reciprocating cylinder-on-flat tribological test method. The composite gear’s service life was additionally tested at various running loads, resulting in pitch contact pressures ranging between 400 and 540 MPa. Lifetime gear test results showed a markedly superior performance compared to the high-temperature thermoplastic polyether ether ketone, which is typically employed in the most demanding polymer gear applications. Several methods are additionally proposed that could further improve the developed composite gears’ performance.

Keywords: carbon fibre; thermomechanical analysis; finite element method; mechanical testing; composites; autoclave

1 Introduction
Polymer gears have been widely used in the past decades for a variety of applications, typically involving lower load requirements, where metal gears would be too uneconomical to use. For this type of gear, the most common material choice is engineering grade and high-performance thermoplastics like polyoxymethylene (POM), polyamide 6/6, 6 (PA6/PA66), or polyether ether ketone (PEEK; Hoskins et al., 2014; Pogacnik & Tavčar, 2015; Tavčar et al., 2018). Along with polymer gears composed of homogeneous thermoplastics, a wide number of studies have been focused on the experimental and theoretical analysis of different kinds of composite gears. Wright and Kukureka (2001) conducted wear tests on six different types of fibre-reinforced PA66 composites using direct gear running tests and twin-disc tribotests. Three types of reinforcing agents were used for the composites, namely carbon fibre (CF), glass fibre (GF), and...
polytetrafluoroethylene (PTFE), in different ratios and combinations. The best wear performance was identified on a combination of PA66 with 30% GF and 15% PTFE. Mohan and Senthivelan (2014) carried out gear bending fatigue tests, using a custom-developed gear testing rig, on a homogeneous and a GF-reinforced type of polypropylene. The presented results indicated a substantially superior bending load carrying capacity of the GF composite polymer grade as compared to the homogeneous polypropylene. GF-reinforced polymer gears have additionally been experimentally tested by Senthivelan and Gnanamooorthy (2007). A thorough overview of various studied polymer gear material combinations in different lubrication regimes and their correlation with failure modes at different loads is presented by Tavcar et al. (2021). Bravo et al. (2018) produced and tested two types of bio-based composite gears, i.e., a semibio-based composite with a petroleum-based high-density polyethylene (HDPE) matrix and renewable yellow birch short fibres, and a fully bio-based version composed of a bio-based natural HDPE (NHDPE) matrix paired with the same type of birch fibres. While the fully bio-based gears exhibited bending fatigue performance that was comparable to that of unreinforced and reinforced PA6 gears, the performance of the semibio-based gears was found to be superior to the rest of the considered materials. Two additional types of semirenewable composite gears composed of a polyester resin matrix in conjunction with Madar plant and Bauhinia Racemosa fibres were analysed in the study by Sudhagar et al. (2019).

The vast majority of studies conducted so far have only considered composites where the reinforcing agents are added as short fillers inside a chosen thermoplastic matrix. In our study, we instead focused on the use of laminated composites with the aim of obtaining efficient load distribution across continuous fibres laid along the gear teeth. Specifically, a type of epoxy laminated carbon fibre-reinforced polymer (CFRP) produced in autoclave was considered, as described by Bergant et al. (2018) and Danila et al. (2019). The authors compared autoclave-cured CFRP samples to vacuum-bagged CFRP samples with different fibre orientation configurations by conducting mechanical tests in variable loading and thermal conditions. A generally improved performance of autoclave CFRP was confirmed from the tests. In relation to gear applications, CFRP has so far only been used as a metal gear web connector between the gearing rim and the internal hub. This solution has been shown to provide better noise damping and lower mass than a regular metal gear (Handschu et al., 2012, 2014; Catena et al., 2017, 2019; Contartese et al., 2019).

The thermal and mechanical characteristics of laminated CFRP composites are influenced by the properties of their base components, i.e., the polymer matrix and the reinforcing fibres, and to a very high degree also by the method of preparation and chosen orientation configuration of the laminate. Zhang et al. (2016) conducted quasi-static and dynamic tensile tests on unidirectionally woven CFRP samples. A characteristic influence of the strain rate on the tensile modulus and strength was observed in dynamic load tests, while in quasi-static tests this correlation was less pronounced. Abraham et al. (1998) tested the mechanical properties of epoxy laminated GF-reinforced composites (GFRP) produced through resin transfer moulding and with autoclave consolidation. The test results confirmed the superior performance of the autoclave samples, which is likely due to the higher fibre volume that can be attained with this technique. Similarly to Bergant et al. (2018), Goertzen and Kessler (2007) identified a characteristic influence of the dynamical load frequency imposed on CFRP on the glass transition temperature \(T_g\), but additionally found a substantial correlation between \(T_g\) and the curing method. The influence of the curing procedure on the void content in autoclave CFRP was studied by Agius et al. (2013). The authors showed that a suitable debulking method can lead to a substantially decreased void content that is independent of the heating rate during the curing procedure. Additionally, Brunbauer et al. (2015) and Qi et al. (2016) confirmed the influence of the fibre volume content in CFRP on the mechanical performance of the composite.

Related to the characterization of mechanical properties of CFRPs, Koch et al. (2016) and Gude et al. (2012) presented an experimental approach enabling pure bending loading conditions, which reduces the self-heating effect present in typical three- or four-point bending tests (refer also to Huang et al., 2020). The through-thickness compressive strength of CFRPs was studied by Kim et al. (2016), who proposed to use cubic test specimens with edge length at least twice the size of a plain or twill weave repeating unit. Additionally, Hoffmann et al. (2015) developed a new clamping method for CFRP test specimens in order to test the composite’s through-thickness tensile strength with a higher accuracy and repeatability than typically employed methods.

The mechanical properties of CFRPs can be further improved using various methods. Kim et al. (2011) proved that by integrating acid- or silane-treated multiwalled carbon nanotubes into the epoxy matrix, the flexural strength and wear resistance of the CFRP can be substantially improved. Additionally, other forms of carbon nanofibres could also be incorporated as reinforcing agent to further improve the composite’s properties and durability (Ramesh et al., 2021). A noticeable improvement in CFRP fatigue strength can also be achieved by implementing an inexpensive GF treatment, employing a combination of polyvinyl acetate adhesive and glass powder (Vedtrnma, 2019). Lee et al. (2017) studied the influence of CF hydrogen plasma treatment on the mechanical properties of CF-reinforced polyetherimide (PEI) and showed that a substantial improvement in the static tensile mechanical properties is achievable across a wide range of temperatures—i.e., between room and elevated temperatures up to 150°C—using this type of treatment. Chen and Feng (2014) demonstrated an improved thermo-mechanical performance of polyethyleneimine functionalized CFRP compared to a regular CFRP material. Additionally, Herr et al. (2018) presented a meticulous study of the temperature-dependent thermal properties of CFRP exposed to high thermal loads induced by a laser beam.

Apart from experimental studies, CFRP materials have also been meticulously analysed using numerical modelling approaches. Usui et al. (2014) carried out non-linear finite element analyses (FEAs) of a linear machining process using cohesive zone modelling and structured mesh splitting. Tabrizi et al. (2019) compared experimental results from GFRP and CFRP bending tests with numerical results obtained using a modified FEA procedure based on a so-called refined zigzag theory. Qi et al. (2019) used a multiscale FEA approach describing the composite using a so-called representative volume element to model the material’s behaviour at the microscale. By applying a machine learning algorithm, it was additionally possible to discern the mechanical properties of the fibre from that of the matrix material. Skinner et al. (2019) also presented the possibility to implement FEA for the optimization of CFRP fatigue test samples in order to achieve the required stress-strain response and reliable test results.

Gear performance is dependent, to a very high degree, on the tribological behaviour of the gear pair at the meshing contact interface. As noted by Bijwe and Sharma (2013), among
laminated composites, CFRPs are especially suitable for tribological applications. The authors studied the influence of the CF content ratio on the mechanical and tribological properties of CFRP with a PEI thermoplastic matrix. It was found that a 65% fibre content resulted in an optimal combination of mechanical and tribological properties. Additionally, Ramesh and Suresha (2014) studied the frictional and wear properties of epoxy impregnated CFRP and demonstrated a noticeable drop in surface wear if aluminium (Al2O3) and molybdenum disulphide (MoS2) fillers are integrated inside CFRP. A wide array of studies has been focused on the frictional and wear behaviour of CFRP during machining. Liang and Wu (2019) studied the wear of tungsten carbide tools used for drilling CFRPs. The frictional and wear behaviour was experimentally analysed using ball-on-disc (BOD) tests in dry running and actual drilling tests. A similar study was carried out by Wang et al. (2019) where a diamond-coated, tungsten carbide tool was considered (see also Kuo et al., 2018). Mondelin et al. (2010) presented an interesting experimental approach for measuring the coefficient of friction (COF) between a metal tool and CFRP in variable fibre orientation directions, using a so-called opened type of tribosystem.

In summary, CFRPs represent a class of highly durable lightweight materials that have been replacing metals in a variety of engineering applications. If a suitable processing technique is employed, they can provide high mechanical strength, good thermal stability, fairly high thermal conductivity, and favourable tribological properties. This makes them an ideal candidate for employment in complex engineering systems like gearings and other power transmission components. Currently, there is a substantial gap, in terms of performance, between high-durability metal gears and more economical (and lightweight) polymer gears. While injection moulded, short-fibre thermoplastic composites can in some cases provide improved gear durability, the improvements relative to homogeneous polymers are typically not remarkable, as they can exhibit higher rigidity, brittleness, and increased wear. Laminated composites can, in general, exceed their short-fibre counterparts in terms of engineering performance due to a more organized fibre configuration and a more favourable thermomechanical stress distribution between the matrix and reinforcing fibres. As noted above, many possibilities are additionally available to further enhance their thermomechanical and tribological properties and achieve highly competitive performance.

The goal of the presented study was to assess the possibilities of filling the noted gap between metal and regular polymer gears with the use of autoclave-cured, laminated CFRP gears. In the following pages, a thorough examination is presented of the influence of mechanical and thermal properties of a specific type of autoclave-cured CFRP on the performance of spur gears produced from this material, in combination with steel gears, in dry-running conditions. An assessment of the frictional properties of CFRP in combination with a 42CrMo4 type steel was also carried out based on a combination of gear-running experimental tests and thermomechanical numerical analyses. With the obtained results, additional insights could be drawn regarding the possibilities of using CFRP in high-performance gear applications, where regular thermoplastics do not fulfil the necessary performance requirements and metal gears are not a feasible alternative, which to the authors’ knowledge have not yet been thoroughly studied.

### 2 Material and Methods

#### 2.1 Analysed material pair

The autoclave-cured CFRP considered in the presented study was produced in accordance with the procedure presented by Bergant et al. (2018). The composite was prepared using plain-weave prepreg with designation CC202 ET445, which is composed of Torayca® T300 fibres (fibre diameter $d_{T} \approx 7 \mu m$) and ET445 epoxy resin. The composite was prepared as an 8-ply laminate using a specific stacking sequence with the following angular shift configuration: [45/0/45/0/0/45/0/45° or shortly [45/0])]. This configuration provides the composite with quasi-isotropic mechanical properties. Before processing, the eight layers of prepreg were covered with peel-ply and an absorber layer (Breatex) and put into vacuum bags where 30 kPa of internal pressure was established. The autoclave processing was carried out at an elevated pressure of 400 kPa and a temperature of 130°C for 100 min. The overall mean thickness of the composite plates produced in the described manner was $b = 2.05 \ mm$, while the fibre volume fraction was measured at $V_f = 44\%$.

In the gear tests presented in the following sections, the CFRP gears were paired with steel (S) gears composed of a 42CrMo4 grade steel (Table 1). The steel gear samples were plasma nitrided on the tooth surfaces (measured flank hardness of approximately 870 HV0.2) and superfinished (trovalised) in order to eliminate any residual burrs. Additionally, the data for the thermoplastic PEEK, which was used as a benchmark material in the study, are presented in Table 2.

### 2.2 Gear pair geometry and loading conditions

The CFRP gear study was carried out on a specific involute spur gear geometry, chosen in line with previous studies by the authors (Zorko et al., 2017, 2019; Cerne et al., 2019a, 2020b). The main gear parameters are presented in Table 3. All gear samples were cut/milled from semifinished products, i.e. the steel gears from cylindrical rods and the CFRP gears from plates. For the latter, only 2 mm thick plates were available, which
Table 3: Gear pair geometry parameters.

| Parameter                | Symbol | Unit | CFRP | Steel |
|--------------------------|--------|------|------|-------|
| Transmission             | i      | ()   | 1    | 1     |
| Module                   | m      | (mm) | 1    | 1     |
| Number of teeth (pinion/gear) | z₁/₂ | ()   | 20   | 20    |
| Pressure angle           | α      | (°)  | 20   | 20    |
| Gear width               | b      | (mm) | 2    | 6     |
| Shaft diameter           | dₖ    | (mm) | 6    |       |
| Tooth thick. tol. (DIN3967) | e₂⁵ | (μm) | −30/−60 | 25 (μm) |

constrained the CFRP gears’ face width to this value. For the milling, a Sodick MC 430L high-speed milling machine was used. An as-produced CFRP gear sample is presented in Fig. 1. The produced CFRP gears’ geometry was inspected using 3D scanning and evaluated in accordance with ISO 1328, following the procedure presented by Urbas et al. (2020). The achieved quality of the produced CFRP gears was of level Q10; however, most of the standardized inspection parameters were at a level Q9 or less. The single pitch deviation parameter \( f_{pt} \), which can result in substantial thermomechanical response deviations during gear meshing (Cerne et al., 2019b), was, for example, evaluated to be of the finer Q7 level. The used steel gears were additionally measured to be of quality grade Q8. Based on the identified geometric deviation levels, a substantial influence of these deviations on the gear performance is not expected. Additionally, the 3D scanning results showed an average gear tooth tip rounding of \( r_t = 0.12 \) mm. An inspection of the material’s roughness was also carried out using a TESA Rugosurf 90G measurement gauge. For the CFRP and steel gear samples, an average active flank surface roughness of \( Ra = 0.417 \) and \( 0.689 \) μm was measured, respectively. In the presented study, the gear pair’s performance was examined in four different sets of loading conditions (torque \( M \) and rotational speed \( n \)), which are listed in Table 4. The last column additionally presents the normal force \( F_n \) per unit length \( l \) at the CFRP gear’s pitch point for each applied torque. All tests were carried out at a running speed of approximately 1400 rpm.

![Figure 1: CFRP gear cut from 2 mm plate, with a schematic representation of the employed stacking layup (two mirrored 4-ply stacks as presented above were joined to obtain the [(45/0)/2]s configuration and an ∼2 mm thick plate).](image)

Table 4: Load cases considered for the flash-temperature evaluation.

| M (Nm) | \( F_n/l \) (N/mm) |
|--------|------------------|
| C1     | 0.4              | 21.3            |
| C2     | 0.5              | 26.6            |
| C3     | 0.6              | 31.9            |
| C4     | 0.7              | 37.3            |

2.3 Thermomechanical and tribological CFRP characterization

The mechanical performance of the considered CFRP was analysed both in monotonic and dynamic loading conditions by Bergant et al. (2018). Their results are briefly summarized in Fig. 2. As evident in Fig. 2a, the material exhibits a linearly elastic response to tensile, bending, and compressive monotonic loads almost till the yield point, which reflects the mechanical behaviour of the CFs in the stack (loading directions for each test are visible in the figure).

The Poisson’s ratio of laminated composites is highly dependent on the used ply configuration. In the case of a balanced, plain-weave, cross-ply \([0]_8 \) stack-up laminate configuration, the major and minor Poisson’s ratios were measured to be \( ν_{12} = 0.07 \) and \( ν_{13} = ν_{23} = 0.3 \). In the quasi-isotropic \([45/0]_2 \)s configuration, as used for the tested gear samples, however, due to the changing fibre orientation in the thickness direction, the major Poisson’s ratio again rises to a value of roughly 0.3. Compared to the employed steel, the CFRP exhibits a noticeably higher
specific modulus \( (E/\rho = 32.0 \times 10^6 \text{ m}^2/\text{s}^2 \) for CFRP v. 26.9 \( \times 10^6 \text{ m}^2/\text{s}^2 \) for 42CrMo4) and a substantially superior specific strength \( (R_m/\rho = 0.273 \times 10^6 \text{ m}^2/\text{s}^2 \) v. 0.122 \( \times 10^6 \text{ m}^2/\text{s}^2 \)). On the other hand, dynamic mechanical analysis (DMA) tests revealed a substantial influence of the viscoelastic properties of the epoxy matrix on the composite’s mechanical response to cyclic loading conditions (Fig. 2b). A noticeable correlation was observed between both temperature and loading frequency with the material’s mechanical response, where a glass transition temperature \( (T_g) \) in the range of 144–154°C—depending on the load frequency—was identified. The relative standard deviation of the measured storage and loss modulus values in the transition area ranged between 3.5% and 16%, while the relative standard deviation of the measured \( T_g \) was only 0.9%. Part of the presented study was focused on the evaluation of the main thermal properties of the CFRP composite. Quantifying these properties is a necessary step in conducting the thermal analysis of the gear running process presented in the following sections.

The CFRP gears’ temperature response was measured following the procedure described in Section 2.4 using a Flir T420 thermographic camera. The camera has a thermal sensitivity of 0.045°C (measured at 30°C) and an accuracy of ±2%. The device was set to an emissivity level of \( \varepsilon_t \approx 0.95 \), which, in order to acquire realistic temperature measurements, required an evaluation of the actual CFRP emissivity and a subsequent recalibration of the temperature measurements to comply with this emissivity. The emissivity was evaluated using a heating plate, onto which a CFRP sample was placed (Fig. 4a). An emissivity sticker with a known value of \( \varepsilon_t = 0.95 \) was layered onto the sample, facilitating comparison of the temperature measurements. During heating, a grid-like pattern emerged on the CFRP sample, which points to a non-homogeneous emissivity distribution. Since, during gear tests, the temperature is measured on a rotating body, an average emissivity was evaluated, as shown in Fig. 4b. The evaluation resulted in a temperature-dependent emissivity function, which, for subsequent temperature

### Table 5: Measured thermal properties and density of CFRP.

| Parameter                                 | Unit | Fibre dir. | Normal dir. |
|-------------------------------------------|------|------------|-------------|
| Environmental temperature                 | °C   | 23         | 23          |
| Thermal conductivity                      | W/(mK) | 2.416      | 1.446       |
| Thermal diffusivity                       | m²/s | \( 7.746 \times 10^{-7} \) | \( 2.410 \times 10^{-7} \) |
| Volumetric heat capacity                  | J/(m³ K) | 3.130 \( \times 10^6 \) | 6.012 \( \times 10^6 \) |
| Fibre density                             | kg/m³ | 1800       |
| Epoxy resin density                       | kg/m³ | 1200       |
| Fibre volume fraction                     | /    | 0.44       |
| Composite density                         | kg/m³ | 1464       |
| Specific heat capacity                    | J/(kg K) | 2138       | 4106        |

![Figure 3: Stack composition used for the CFRP thermal characterization on the Hot Disk TPS 1500 experimental device.](image)

![Figure 4: Evaluation of the average thermal emissivity of the analysed CFRP composite.](image)
measurement calibration, was approximated with a simple linear function, as noted in the diagram.

The tribological performance of CFRP against steel in dry sliding conditions has been studied by several researchers who present rather contrasting results in terms of evaluated COF. Suresha et al. (2018) (see also Suresha et al., 2006) carried out pin-on-disc (POD) tests using a CFRP pin and a hardened steel (EN-32) disc, and measured a COF of 0.18–0.41, depending on the used load and sliding speed (the higher the load and speed, the higher the COF). The BOD tests carried out by De Fazio et al. (2020) showed a time-dependent COF, where the peak recorded values ranged between 0.15 and 0.41 depending on the applied load (the highest value measured at lowest normal load and vice versa). Nak-Ho and Suh (1979) measured the COF of unidirectional CFRP in pair with 52100 steel in multiple directions relative to the fibre orientation and showed a variable COF ranging between 0.2 and approximately 0.55 depending on the orientation.

From these results, it is evident that the steel/CFRP (S/CFRP) COF is highly dependent on the chosen test set-up, the loading conditions, the chosen metal counterpart, the composite’s preparation, and the sliding direction. In our study, an implicit COF identification procedure was developed based on a numerical and experimental analysis of the CFRP gear’s thermal response during running. The method was subsequently validated using a reciprocating cylinder-on-flat (RCF) tribological test method, which can faithfully reproduce the sliding pattern present during gear meshing. The details of this approach are discussed further in Section 3.2.

2.4 CFRP gear testing

For the gear running tests, two types of custom-built testing devices, previously described by Cerne et al. (2020b) and Zorko et al. (2017), were used. The first one enables the active measurement and regulation of the torque and running speed, using a set of integrated sensors as depicted in Fig. 5. The second uses a passive running load regulation through pre-calibrated frequency converters. At a given running load, multiple tests were carried out, employing both testing rig types interchangeably. The rigs were located inside a thermal chamber with air-conditioning (AC) temperature regulation. This enabled us to keep the average environmental temperature during the tests within a range of 22 ± 2°C.

All gear tests were carried out in dry-running conditions. For each load level, a new set of samples was used, with multiple \( N = 2 \times 10^6 \) cycle test runs being carried out for each sample. During each test, the temperature increase was measured using the Flir T420 camera with an emissivity set-up as described in Section 2.3. Exemplary measurement results are presented in Fig. 6. The point P1 marks the area just below the root diameter, which can be considered as a marker of the gear’s nominal temperature increase and was in this case used as reference for subsequent model result comparison. The temperature field measured on the steel gear typically shows a lower average temperature than the polymer gear. As will be visible from the numerical simulation results, the steel gear actually exhibits a higher temperature increase than its polymer counterpart. This misleading temperature measurement is a consequence of a much lower emissivity of steel than the set value of \( \varepsilon = 0.95 \).

The resulting temperature changes measured during multiple test repetitions are presented for the lowest and highest considered running loads C1 and C4 in Fig. 7a and b, respectively. In several instances, there was a periodic fluctuation in the measured gear’s nominal temperature, which was caused by ambient temperature fluctuations produced by the AC system.

3 Numerical Modelling

3.1 Thermomechanical gear running analysis

Several models have emerged in the last years, which enable the prediction of the thermomechanical behaviour of non-metal gears during running, e.g. those developed by Fernandes et al. (2018), Roda-Casanova and Sanchez-Marin (2019), and Doll (2015). The CFRP gear analyses presented on the following pages are based on a modelling approach developed by Cerne et al. (2020b) (see also Cerne et al., 2020a). In it, a sequential procedure is implemented, where a 2D plane-stress finite element method (FEM) is used to evaluate the mechanical contact response of the gear pair during a gear meshing cycle. The used finite element (FE) mesh, applied loads, and boundary conditions (BCs) are shown in Fig. 8, while the main mesh parameters are noted in Table 6. This type of model can generally be used to study the mechanical behaviour of involute as well as other types of gearing geometries (e.g. S-gears; see Zorko et al., 2021).
Implicit COF characterization of CFRP gears

Figure 7: Nominal temperature results at reference point P1, measured at running conditions C1 and C4 (see Table 4). AAT and GT denote the average ambient temperatures and nominal gear temperatures—as measured at the P1 point (Fig. 6)—respectively.

Figure 8: FEM model used for the mechanical CFRP gear meshing analysis.

Subsequently, a semi-analytical and FEM thermal analysis method is implemented that enables the evaluation of both the nominal and flash temperature components, which define the overall gear temperature increase during running. Due to the fact that, for the subsequent thermal analysis, we were interested solely in the contact response of the gear pair, the CFRP was modelled as a homogenized material with linear elastic behaviour, defined by the tensile modulus $E_t = 46.9$ GPa and a Poisson’s ratio of 0.3. Nevertheless, the validity of the presumption of (quasi-)isotropic linear elasticity has been thoroughly verified both on 2D and 3D gear pair FEM models, where it was confirmed that the orthotropic properties and local ply orientations of the CFRP play a minor role in the overall contact response of the composite gear. The orthotropic properties, even when considering a variable Poisson ratio of $v_{12} = 0.07$ and $v_{13} = v_{23} = 0.3$, which was only identified in the case of [0]s CFRP configuration (the quasi-isotropic [(45/0)_2]_s configuration used in gear samples did not exhibit such value reduction), only accounted for a change in the contact pressure between 0.45% and 1.1% relative to the isotropic model with the same in-plane mechanical properties. For the [(45/0)_2]_s composite, these deviations are even lower. It should also be recognized that a drop in contact pressure due to e.g. reduced stiffness is offset by an inversely proportional rise in the contact area, which, in terms of frictional heat generation, phases out any major changes in the generated heat losses. Additionally, the influence of variable local ply configurations at each gear tooth on the local strain levels has been tested. The results pointed to deviations of up to 0.5% in the local strain distribution between various teeth on the gear. These deviations result in a negligible influence on the evaluated thermal response of the system and identified COF. It is nonetheless always advisable to verify the influence of the material’s orthotropic behaviour on the mechanical response for each specific case.

The mechanical analysis applied to the S/CFRP gear pair at the considered running conditions enables an evaluation of the contact pressure (Fig. 9a), contact area, and sliding speed (Fig. 9b) during the meshing phase. Based on the obtained mechanical contact analysis results, the thermal part of the analysis further provides a method for the evaluation of the flash temperature increase during gear meshing (Fig. 10a) as well as the time-averaged heat flux distribution across the active part of the tooth flank (Fig. 10b). The results were obtained by considering $\mu = 0.34$, which is the COF identified using the implicit procedure presented in Section 3.2. The so-called partitioning coefficient marked by the grey line in Fig. 10a defines the time-dependent partitioning ratio of the heat flux among both gear teeth in meshing contact, so that the precondition of equal temperature on both contact surfaces is retained (see e.g. Kennedy et al., 2015).

The heat flux distribution curves presented in Fig. 10b can be applied to the active tooth flank surface of the CFRP gear inside the FEM model depicted in Fig. 11. It provides a cyclic periodicity BC on the inner surfaces of the fastened CFRP gear section, while on the outer surfaces of all included bodies a suitable convective heat transfer coefficient has to be applied as defined in

| Model parameter | Type/value |
|-----------------|------------|
| Structural FE   | PLANE183   |
| Contact FE      | CONTA172/TARGE169 |
| FE size         | 0.2–0.00075 mm |
| Number of DOFs  | $>1.41 \times 10^6$ |
| Shape fun. approx. order | Quadratic |
| FE asp. ratio (mean) | 1.14 |
| Number of time steps | $>280$ |
| Contact type    | Frictional contact |
| Contact formulation | Augmented Lagrange |

Table 6: Parameters of the FE mesh used for the mechanical analysis.
Figure 9: Mechanical contact response during a gear meshing cycle evaluated using the developed mechanical FEM model for all four considered running conditions (Table 4).

Fig. 12 and Table 7 (see Cerne et al., 2020b). The main FE mesh parameters are additionally noted in Table 8. For the tooth flank surfaces \( f_G \) (see Fig. 12), the coefficient was approximated using the equation (Holman, 2010)

\[
\text{Nu} = \frac{2h_c \cdot r_k}{k_{\text{air}}} = C_h \left( \frac{2\nu_0}{\lambda_{\text{air}}} \right)^{n_h} Pr^{1/3},
\]

where Nu, Pr, \( h_c \), \( r_k \), \( k_{\text{air}} \), \( \nu_0 \), and \( \lambda_{\text{air}} \) are the Nusselt number, Prandtl number, heat transfer coefficient, tooth height, air’s conductivity, velocity at the pitch point, and kinematic viscosity, respectively, with \( C_h = 3.8 \) and \( n_h = 0.27 \). Here, the tooth height should be viewed as a radial measure of a semicylindroid body representing the shape of the gear tooth, being positioned in air cross-flow at the identified pitch-point velocity.

An approximative rolling friction model, developed by Wannop and Archard (1973), which provides an assessment of the heat losses due to the material deformation below the contact interface, was also considered in the analysis. Between both gear teeth, an additional virtual connection body was added that holds very high (approaching infinity) thermal conductivity in the vertical \( Y \) direction and infinitesimal (approaching zero) conductivity in the other two perpendicular directions. This virtual body provides a direct connection between both active tooth flanks and models the time-dependent partitioning of the generated heat flux between both contact bodies. The body should be understood as a non-physical entity that serves the sole purpose of enabling an active distribution of the generated heat between both bodies in contact. Ideally, if the used software or FEM code enables it, the body could be substituted with a node-to-node interface, connecting both active tooth flanks. While this method results in a slight loss of accuracy in the flash temperature distribution on both flanks, it provides a reliable method for nominal bulk temperature evaluation. Figure 13 depicts the...
resulting temperature field on the CFRP gear, as evaluated using the developed model. The average temperature, calculated on the reference line marked just below the tooth root, was used for a comparison of the numerical results with the experimental measurements obtained at point P1 in Fig. 6.

3.2 Influence of the COF on the temperature rise

The thermal response of a gear pair is directly correlated with the generated heat losses due to the sliding friction and, to a much lower extent, to deformation hysteresis. The sliding friction losses are proportional to the COF, which, as noted in Section 2.3, can be related to a number of different test parameters. For this reason, selecting a correct COF for the gear pair considered in this study was problematic and required specific attention. The COF influences both the mechanical and thermal responses of a gear pair. Its influence on the contact shear stresses is especially apparent. Figure 14 shows the shear stresses present on both gears around the contact interface for load conditions C4 and two substantially different COF values. A COF rise results in a substantial increase of the shear stress at the contact interface that can even surpass the stress concentrations just below the interface, where the peak stresses are typically expected. For the considered COF range, the peak contact interface shear stresses evaluated in the positive direction throughout the meshing cycle are plotted in Fig. 15a, while the peak contact pressures are shown in Fig. 15b. Evidently, while the surface shear stress is highly dependent on the chosen COF, the contact pressure is affected to a very limited degree.

Table 7: Evaluation of the convective heat-transfer coefficient for different surface types at different Reynolds numbers (refer to Millsaps & Pohlhausen, 1952; Kendoush, 1996; Cardone et al., 1997; Holman, 2010).

| Parameter | Cylindrical surfaces ($\text{S}_1$) | Side surface ($\text{S}_2$) | Tooth side ($\text{S}_3$) |
|-----------|----------------------------------|-------------------------|-------------------------|
| Re        | $\text{Re}_{\omega} < 1000$     | $\text{Re}_{\omega} \geq 1000$ | $4 \leq \text{Re}_{\omega} \leq 2 \times 10^6$ | $< 5 \times 10^5$ |
| Nu        | Free convection                  | $0.533 \cdot \text{Re}_{\omega}^{1/2}$ | $0.326 \cdot \text{Re}_{\omega}^{1/2}$ | $0.664 \cdot \text{Re}_{\omega}^{1/2} \cdot Pr^{1/3}$ |
| h         | $\approx 10 \text{ W/(m}^2\text{K)}$ | $\text{Nu} \cdot k_{air} / d$ | $\text{Nu} \cdot k_{air} / r$ | $\text{Nu} \cdot k_{air} / L$ |
The proposed model involves a fairly straightforward iterative optimization procedure, where the thermomechanical model described in the previous section is first applied using a rough initial COF estimation. The analysis should be carried out for at least three load levels, preferably more. The obtained numerical nominal temperature results—at the time length where steady-state conditions are reached—are compared to the mean experimental (quasi-)steady-state temperature value evaluated at the same time length. Based on the identified divergence between numerical and experimental data, a recalibration of the COF is carried out, and the procedure is repeated in multiple iterations till a tolerable divergence between numerical and experimental temperature data is reached. The developed procedure is presented in a flowchart format in Fig. 18. As a correlation criterion, an average relative residual error type function can be employed:

$$e_r = \frac{1}{N} \sum_{i=1}^{N} \frac{\Delta T_{\text{m},i} - \Delta T_{\text{e},i}}{\Delta T_{\text{e},i}}$$

where $N$ denotes the number of tested load levels, $\Delta T_{\text{m},i}$ is the numerically evaluated steady-state temperature rise at $i$-th load, and $\Delta T_{\text{e},i}$ is the average experimental steady-state temperature, measured in the range where the numerical model shows steady-state conditions. The value of $e_r$ should iteratively be
optimized to fulfill $e_r < \text{tol}$, where, as a rule of thumb, tol should in all cases be set at or below 0.05. This can be achieved by performing the analysis at two COF values lying in the expected range (ideally a pair of lowest and highest marginal COF values is chosen) and linearly interpolating the obtained nominal steady-state temperatures as a function of the COF. Due to an almost linear correlation between the COF and the temperature rise, the actual COF can be evaluated using the obtained interpolation function and the experimentally measured nominal temperature rise. By employing this approach, the solution can in general be found in three or at most four analysis iterations. The COF providing suitable correlation can be considered a realistic value for describing the frictional characteristics of the analysed gearing’s material pair.

4 Results and Discussion

4.1 COF identification and validation

Using the described model for the considered S/CFRP case, a COF of $\mu = 0.34$ was identified as the coefficient showing the highest correlation with the experimental tests ($e_r = 0.021$). The comparison of measured and evaluated nominal temperature rise at the reference point just below the root diameter of the CFRP gear is presented in Fig. 19. By considering all the previously mentioned parameters and assumptions, the model shows good agreement with the measured temperature response of the gear pair.

The implicitly derived COF value was subsequently validated by employing an RCF tribological testing method (Fig. 20a). The steel cylinder (42CrMo4) was produced by turning, while the CFRP plate was manufactured using the method described in Section 2.1. The applied average radial contact force during the tests was $F_r = 56$ N, which corresponds to a peak contact pressure of $p_c = 195$ MPa. During each reciprocating slide, a sliding speed of $v_s = 0.4$ m/s is reached at the middle of the plate, which correlates well with sliding speeds exhibited on the gears during meshing. The tests were carried out on multiple sample pairs, with each sample being tested in two test runs lasting 180 s. In all cases, the tests showed a gradual increase of the COF during the first run, with a steady state not yet being fully achieved. During the second run, a steadier behaviour was observed with a plateau COF of $0.33 \pm 0.005$ (Fig. 20b). This behaviour is attributed to a gradual deposition of CF on the steel cylinder, which causes an increase in the COF until a stable CF layer is formed. As visible in the bottom right image, a similar behaviour is also observed during gear running. The implicitly evaluated COF, hence, agrees well with experimental findings and the presented COF evaluation method shows high potential for use in general polymer gear running cases, where the COF is unknown. The described approach can therefore reduce the necessity for specialized tribological testing procedures, as was applied in this case for validation purposes.

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**Figure 17:** COF influence on the resulting nominal temperature rise (load cond. C4).

**Figure 18:** Flowchart describing the developed COF evaluation method.

**Figure 19:** Comparison of the experimental temperature measurements at reference point P1 with the calculated nominal temperature values considering the identified S/CFRP COF value.

**Figure 20a:** Steel cylinder (42CrMo4) produced by turning.

**Figure 20b:** CF deposition on the steel cylinder during tribological testing.
Additionally, a comparison of the obtained results with other related studies reveals that, while no S/CFRP tribological test results have been found for exactly the same loading conditions and test configuration, several works can be considered for an approximate assessment of the validity of the presented results. The POD tests by Suresha et al. (2018) were carried out at a similar load ($F = 60$ N) and sliding speed ($v_s = 0.75$ m/s) to our case, with the samples being pressed on the lateral composite surface (normal direction in Fig. 3). A comparable COF was measured in this case, i.e. $\mu = 0.32$. Ruggiero et al. (2015) measured the COF of a plain-weave CFRP using a ball-on-flat test set-up, where an AISI E52100 steel ball was pressed against the composite’s flat lateral surface. By using this set-up, an average COF of 0.44 was recorded. Interestingly, the quasi-steady-state COF dropped to 0.34 if the tests were performed on a unidirectional sample with fibres positioned perpendicularly to the sliding direction. In general, the noted results should not be considered as fully representative of the gear case presented in this study, since the fibre orientations relative to the contact are rather different. Nak-Ho and Suh (1979) showed that the COF varies with the angle of fibre orientation relative to the contact surface. For angles between $0^\circ$ (i.e. fibres normal to contact) and $45^\circ$, the COF ranged between 0.27 and 0.35, respectively. Given that, in the developed gears, most of the fibres diverge from perpendicular alignment with the contact surface, we could assume that the values measured at around $45^\circ$ fibre configuration are more representative in this case than the one at $0^\circ$.

At all applied running conditions, however, the experimental measurements showed an accelerated initial temperature rise till a peak temperature was achieved, followed by a gradual decrease to a quasi-steady temperature level, which can be described as a running-in phase. Two hypotheses can be proposed to explain this phenomenon. The first one relates to the geometric deviations of the gear pair and non-elastic mechanical properties of the composite. On the one hand, the geometric deviations could cause high initial contact pressure overloads that would result in increased heat generation, which could, on the other hand, decrease to some extent due to viscous creep compliance and a running-in ‘adaptation’ of the CFRP gear teeth, which could decrease the contact loads during meshing. Based on the previously carried out DMA bending tests, a master curve of the material’s storage modulus was assembled, representing the stiffness variation of CFRP at a chosen reference temperature ($T_{\text{ref}}$) of 45°C. Based on the evaluated storage modulus function, the material’s creep compliance was evaluated by following the procedure described by Yin et al. (2010) and Schapery and Park (1999). The results are presented in Fig. 21b. The evaluated measurement uncertainty was in the range of $\pm0.0026$ MPa. Evidently, the creep compliance plays a very limited role in the composite’s dynamic response. Even though the material is exposed to comparably higher dynamic loads during gear running than during the DMA tests, we could conclude that the first hypothesis does not explain satisfactorily the running-in behaviour observed during the gear tests.

The second hypothesis that could explain the described behaviour is the variation of the COF during the gear running
process. As noted in Section 2.3, the COF of an S/CFRP pair can be highly variable and dependent on several parameters like contact load, and sliding speed, but also on time. Several authors indeed reported increased initial COF levels during their tribological tests (Ruggiero et al., 2015; Sahin & Baets, 2017; Liang & Wu, 2019; Wang et al., 2019), which could also explain the running-in phase observed during gear tests. It is presumed that the steel body's surface morphology can play a key role in this regard. In our tests, the roughnesses of the steel gear and steel cylinder (in the tribological tests) were comparable. However, due to the used production methods, the lay directions were longitudinal relative to the sliding movement for the steel cylinder and perpendicular for the steel gear (even though the employed superfinish reduced this orientation to a certain degree). This would explain the initial divergences in evaluated COF between both methods, which were, however, quickly eliminated due to the CF deposition between the steel asperities.

The time-dependent changes in surface morphology—due to effects like wear or thermal degradation—could additionally influence the material pair’s COF after longer running periods. Figure 22 shows scanning electron microscope images of a CFRP gear sample after being run at C2 load conditions for 120 h, where the effects of abrasive wear are clearly visible. Apart from fibre tearing noticeable at the outer edge of the tooth (Region 1), increased wear of the epoxy matrix and CF exposure can clearly be seen in Region 2, while increased epoxy degradation is additionally visible in Region 3. These degradations could play a key role in long-term changes of the COF, which could result in increased surface shear stresses and consequently further increased wear. The described effects could be reduced by introducing extra thin-ply laminates and nano-toughened resin formulations and which would likely decrease the S/CFRP pair’s COF and influence beneficially the gear pair’s service life.

### 4.2 CFRP lifetime testing and performance evaluation

In order to fully assess the performance of the analysed S/CFRP gear pair, lifetime gear tests were carried out at all four considered load levels. The test results are presented in Table 9. During the tests, a noticeable amount of wear has been identified after extended running times; however, the final mode of failure has almost exclusively been due to delamination at the interface between plies.

One of the main goals of the presented study was to establish whether CFRP gears can be used as a viable alternative to the more commonly used high-performance thermoplastics. In this segment, PEEK established itself as the best performing polymer for gear applications. Zorko et al. (2019) carried out an in-depth experimental and numerical investigation into the material’s (specifically, Victrex 650G was considered) performance in pair with the same steel as used in this study. By
applying the implicit COF evaluation method described in Section 3.3, a value of $\mu = 0.14$ was evaluated for the S/PEEK pair in dry-running conditions. Even though the COF is much lower than the S/CFRP pair, the service life of PEEK was found to be substantially lower than that of CFRP gears. For the C1 load case, the average number of load cycles achieved by PEEK gears was, e.g., $1.256 \times 10^7$ — a 5.54 times shorter service life compared to CFRP gears. These results point to a great potential for use of CFRP gears in demanding applications, where regular thermoplastic gears fail to reach the required capabilities. Further research could be focused on a comparison between the developed gears and other high-performance thermoplastics like CF-reinforced PEEK (Davim et al., 2001; Davim & Cardoso, 2006), nanometre Al$_2$O$_3$-reinforced PEEK (Qiang & Guoliang, 2010), which could provide superior performance to homogeneous PEEK in a gear application.

5 Conclusion

In summary, the study presents so-far obtained insights regarding the implementation of autoclave-cured CFRP for gear applications. Based on the presented results, the material shows a very high potential for this type of application due to its high dynamic strength, which is a consequence of a favourable load distribution across continuously oriented CFs, positioned in a quasi-isotropic layout along the gear’s teeth. The study’s key findings can be summarized as follows:

(i) The thermal properties of the developed composite have been characterized using a suitable thermal constant analyser.

(ii) An iterative procedure is proposed, based on a developed thermomechanical polymer gear model, for an implicit COF evaluation. The procedure is based on a correlation between the numerically evaluated nominal temperature rise and the experimentally measured temperature rise at the same location on the gear.

(iii) The (average) COF of the analysed S/CFRP gear pair in dry-sliding conditions was identified to be $\mu = 0.34$, which is somewhat higher than typical steel-thermoplastic material combinations in this type of conditions.

(iv) Experimental tests performed on the S/CFRP gear pair showed a consistently occurring running-in phase at the beginning of each test, with the nominal temperature reaching an initial peak followed by a gradual decrease till a quasi-steady state is reached. Based on the gathered data, the phenomenon is attributed to an unsteady time- and/or temperature-dependent COF.

(v) A performance comparison of the S/CFRP gear pair with an S-PEEK pair points to a substantially superior performance of CFRP compared to PEEK in terms of service life—a more than five times longer service life was measured using the developed CFRP gears as compared to benchmark PEEK variants.

The presented results lay the foundations for further research and development on CFRPs for high-performance, lightweight gear applications. This type of gear could serve as a middle ground between steel and polymer gears, providing improved strength and service life over polymer gears, while retaining other positive properties of polymer gears like noise reduction, lower weight, and, possibly, lower production costs than steel gears. Furthermore, an improved version of the developed CFRP gears could be obtained in terms of their tribological and fatigue properties, by use of nano-toughened resin formulations and extra thin-ply laminate configurations. Such modifications could substantially increase the composite’s strength, decrease the S/CFRP pair’s COF, and further increase its service life. Likewise, a substitution of the epoxy matrix with a thermoplastic like PEI could presumably further improve the tribological properties of the composite, as it can provide a lower COF and higher thermal stability compared to the epoxy resin. Additionally, the employment of CF hydrogen plasma treatment has been shown to increase the fibre roughness and substantially improve the adhesion between CFs and polymer matrices. This effect generally results in considerably higher material strength, which could also translate into improved gear durability.

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Conflict of interest statement

The authors declare that they have no known competing financial interests that could have influenced the work reported in this paper.

References

Abraham, D., Matthews, S., & McIlhagger, R. (1998). A comparison of physical properties of glass fibre epoxy composites produced by wet lay-up with autoclave consolidation and resin transfer moulding. Composites Part A: Applied Science and Manufacturing, 29(7), 795–801. https://doi.org/10.1016/S1359-835X(98)00055-4.

Agius, S., Magniez, K., & Fox, B. (2013). Cure behaviour and void development within rapidly cured out-of-autoclave composites. Composites Part B: Engineering, 47, 230–237. https://doi.org/10.1016/j.compositesb.2012.11.020.

Bergant, Z., Savin, A., & Grum, J. (2018). Effects of manufacturing technology on static, multi-frequency dynamic mechanical analysis and fracture energy of cross-ply and quasi-isotropic carbon/epoxy laminates. Polymers and Polymer Composites, 26(5–6), 358–370. https://doi.org/10.1007/s11166-018-0798-266.

Bijwe, J., & Sharma, M. (2013). Carbon fabric-reinforced polymer composites and parameters controlling tribological performance. In J. P. Davim (Ed.), Wear of Advanced Materials (Chap. 1, pp. 1–60). John Wiley & Sons, Ltd.

Bravo, A., Toubal, L., Koffi, D., & Erchiqui, F. (2018). Gear fatigue life and thermomechanical behavior of novel green and biocomposite materials vs. high-performance thermoplastics. Polymer Testing, 66, 403–414. https://doi.org/10.1016/j.polymertesting.2016.12.031.
Brunbauer, J., Stadler, H., & Pinter, G. (2015). Mechanical properties, fatigue damage and microstructure of carbon/epoxy laminates depending on fibre volume content. *International Journal of Fatigue*, 70, 85–92. https://doi.org/10.1016/j.ijfatigue.2014.08.007.

Cardone, G., Astarita, T., & Carlomagno, G. M. (1997). Heat transfer measurements on a rotating disk. *International Journal of Rotating Machinery*, 3(1), 1–9. https://doi.org/10.1155/S1023621X97000018.

Catera, P. G., Gagliardi, F., Mundo, D., Napoli, L. D., Matveeva, A., & Farkas, L. (2017). Multi-scale modeling of triaxial braided composites for FE-based modal analysis of hybrid metal-composite gears. *Composite Structures*, 182, 116–123. https://doi.org/10.1016/j.compstruct.2017.09.017.

Catera, P. G., Mundo, D., Treviso, A., Gagliardi, F., & Viselioia, A. (2019). On the design and simulation of hybrid metal-composite gears. *Applied Composite Materials*, 26(3), 817–833. https://doi.org/10.1007/s10443-018-9753-6.

Cerne, B., Duhoznik, J., & Tavcar, J. (2019a). Semi-analytical flash temperature model for thermoplastic polymer spur gears with consideration of linear thermo-mechanical material characteristics. *Journal of Computational Design and Engineering*, 6(4), 617–628. https://doi.org/10.1007/j. jcode.2019.03.001.

Cerne, B., Zorko, D., Duhoznik, J., Tavcar, J., & Žavbi, R. (2019b). Flash temperature analysis method for polymer gears with consideration of deviations in meshing kinematics. In *ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (Vol. 10). https://doi.org/10.1115/ DETC2019-97824.

Cerne, B., Lorber, R., Duhoznik, J., & Tavcar, J. (2020a). Influence of temperature- and strain rate-dependent viscoplastic properties of polyoxymethylene on the thermo-mechanical response of a steel-polyoxymethylene spur gear pair. *Materials Today Communications*, 25, 101078. https://doi.org/10.1016/j.mtcomm.2020.101078.

Cerne, B., Petkovšek, M., Duhoznik, J., & Tavcar, J. (2020b). Thermo-mechanical modeling of polymer spur gears with experimental validation using high-speed infrared thermography. *Mechanism and Machine Theory*, 146, 103734. https://doi.org/10.1016/j. mechmachtheory.2019.103734.

Chen, S., & Feng, J. (2014). Epoxy laminated composites reinforced with polyethyleneimine functionalized carbon fiber fabric: Mechanical and thermal properties. *Composites Science and Technology*, 101, 145–151. https://doi.org/10.1016/j.compscitech.2014.07.003.

Contartese, N., Catera, P. G., & Mundo, D. (2019). Static mesh stiffness decomposition in hybrid metal-composite spur gears. In *Advances in mechanism and machine science* (pp. 977–985). Springer International Publishing.

Danila, A. N., Steigmann, R., Savin, A., Blanari, I., & Barsanescu, P. D. (2019). Arcan device employed in CFRP testing. In 10th International Workshop NDT in Progress, NDT.net.

Davim, J. F., & Cardoso, R. (2006). Tribological behaviour of the composite PEKK-CF30 at dry sliding against steel using statistical techniques. *Materials & Design*, 27(4), 338–342. https://doi.org/10.1016/j.matdes.2004.11.006.

Davim, J. F., Marques, N., & Baptista, A. M. (2001). Effect of carbon fibre reinforcement in the frictional behaviour of peek in a water lubricated environment. *Wear*, 251(1), 1100–1104. https://doi.org/10.1016/S0043-1648(01)00741-4.

De Fazio, D., Boccarusso, L., & Durante, M. (2020). Tribological behaviour of hemp, glass and carbon fibre composites. *Biotribology*, 21, 100113. https://doi.org/10.1016/j.biotrib.2019.100113.

Doll, N. P. (2015). Modeling thermomechanical behavior of polymer gears (thesis). University of Wisconsin-Madison.

Fernandes, C. M. C. C., Rocha, D. M. P., Martins, R. C., Magalhães, L., & Seabra, J. H. O. (2018). Finite element method model to predict bulk and flash temperatures on polymer gears. *Tribology International*, 120, 255–268. https://doi.org/10.1016/j.triboint.2017.12.027.

Goertzen, W., & Kessler, M. (2007). Dynamic mechanical analysis of carbon/epoxy composites for structural pipeline repair. *Composites Part B: Engineering*, 39(1), 1–9. https://doi.org/10.1016/j.compositesb.2006.06.002.

Gude, M., Hufenbach, W., Koch, I., & Koschichow, R. (2012). Fatigue testing of carbon fibre-reinforced polymers under hvcf loading. *Materialprüfung/Materials Testing*, 54(11-12), 756–761. https://doi.org/10.3139/120.110396.

Handschr, R. F., Roberts, G. D., Sinnamon, R. R., Stringer, D. B., Dykas, B. D., & Kohlman, L. W. (2012). Hybrid gear preliminary results – Application of composites to dynamic mechanical components. In 68th American Helicopter Society (AHS) Annual Forum and Technology Display, NASA STI Program, NASA/TM—2012-217630 (pp. 1–10).

Handschr, R. F., LaBerge, K. E., Deluca, S., & Pelagalli, R. (2014). Vibration and operational characteristics of a composite-steel (hybrid) gear. In NASA/TM-2014-216646, NASA Glenn Research Center, Fundamental Aeronautics Program (pp. 1–13).

Herr, N. C., Gonzales, A. E., & Perram, G. P. (2018). Kinetics, evolving thermal properties, and surface ignition of carbon fiber reinforced epoxy composite during laser-induced decomposition. *Polymer Degradation and Stability*, 152, 147–161. https://doi.org/10.1016/j.polydegradstab.2018.04.007.

Hoffmann, M., Zimmermann, K., Bautz, B., & Midendorf, P. (2015). A new specimen geometry to determine the through-thickness tensile strength of composite laminates. *Composites Part B: Engineering*, 77, 145–152. https://doi.org/10.1016/j.compositesb.2015.03.020.

Holman, J. P. (2010). Heat transfer (10ed.). McGraw-Hill.

Hoskins, T. J., Dearn, K. D., Chen, Y. K., & Kukureka, S. N. (2014). The wear of PEKK in rolling-sliding contact – Simulation of polymer gear applications. *Wear*, 309, 35–42. https://doi.org/10.1016/j.wear.2013.09.014.

Huang, J., Garnier, C., Pastor, M.-L., & Gong, X. (2020). Investigation of self-heating and life prediction in CFRP laminates under cyclic shear loading condition based on the infrared thermographic data. *Engineering Fracture Mechanics*, 229, 106971. https://doi.org/10.1016/j.engfracmech.2020.106971.

Kendoush, A. A. (1996). An approximate solution of the convective heat transfer from an isothermal rotating cylinder. *International Journal of Heat and Fluid Flow*, 17(4), 439–441. https://doi.org/10.1016/0142-727X(95)00002-8.

Kennedy, F. E., Lu, Y., & Baker, I. (2015). Contact temperatures and their influence on wear during pin-on-disk tribotesting. *Tribology International*, 82, 534–542. https://doi.org/10.1016/j.triboint.2013.10.022.

Kim, B. C., Park, D. C., Kim, B. J., & Lee, D. G. (2010). Through-thickness compressive strength of a carbon/epoxy composite laminate. *Composite Structures*, 92(2), 480–487. https://doi.org/10.1016/j.compstruct.2009.08.032.

Kim, M. T., Rhee, K. Y., Lee, J. H., Hui, D., & Lau, A. K. T. (2011). Property enhancement of a carbon fiber/epoxy composite by using carbon nanotubes. *Composites Part B: Engineering*, 42(5), 1257–1261. https://doi.org/10.1016/j.compositesb.2011.02.005.

Koch, I., Just, G., Koschichow, R., Hanke, U., & Gude, M. (2016). Guided bending experiment for the characterisation of CFRP
Wang, X., Wang, C., Shen, X., & Sun, F. (2019). Tribological behaviors of the diamond films sliding against the T800/X850 CFRP laminates. Wear, 418–419, 191–200. https://doi.org/10.1016/j.wear.2018.12.007.

Wannop, G. L., & Archard, J. R. (1973). Elastic hysteresis and a catastrophic wear mechanism for polymers. Proceedings of the Institution of Mechanical Engineers, 187(1), 615–623. https://doi.org/10.1243/PIME_PROC.1973.187.147.02.

Wright, N., & Kukureka, S. (2001). Wear testing and measurement techniques for polymer composite gears. Wear, 251(1), 1567–1578. https://doi.org/10.1016/S0043-1648(01)00793-1.

Yin, H., Chehab, G. R., Stoffels, S. M., Kumar, T., & Premkumar, L. (2010). Use of creep compliance interconverted from complex modulus for thermal cracking prediction using the m–e pavement design guide. International Journal of Pavement Engineering, 11(2), 95–105. https://doi.org/10.1080/10298430802621531.

Zhang, X., Hao, H., Shi, Y., Cui, J., & Zhang, X. (2016). Static and dynamic material properties of CFRP/epoxy laminates. Construction and Building Materials, 114, 638–649. https://doi.org/10.1016/j.conbuildmat.2016.04.003.

Zorko, D., Kulovec, S., Tavcar, J., & Duhovnik, J. (2017). Different teeth profile shapes of polymer gears and comparison of their performance. Journal of Advanced Mechanical Design, Systems and Manufacturing, 11(6), JAMDSM0083. https://doi.org/10.1299/jamdsm.2017jamdsm0083.

Zorko, D., Kulovec, S., Duhovnik, J., & Tavcar, J. (2019). Durability and design parameters of a steel/peek gear pair. Mechanism and Machine Theory, 140, 825–846. https://doi.org/10.1016/j.mechmachtheory.2019.07.001.

Zorko, D., Duhovnik, J., & Tavcar, J. (2021). Tooth bending strength of gears with a progressive curved path of contact. Journal of Computational Design and Engineering, 8(4), 1037–1058. https://doi.org/10.1093/jcde/qwab031.