Concerning the Structural Assessment of Metal/Polymer Gear Wheels Using the Finite Element Method

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Abstract: The development of technical polymers in recent years has led to a rapidly increasing number of industrial applications utilising these materials. Not only does the use of polymeric materials as an alternative to metals reduce weight, it also allows for highly complex designs to be realised in terms of both size and functionality. In fact, numerous contemporary product designs would either not be feasible or financially justifiable without the use of polymeric materials. The automotive industry has successfully been using polymers for over twenty years as a means of reducing cost and weight. The structural stiffness of machine elements such as bearings, bushings and gear wheels has often been contested, yet the versatility of polymeric material characteristics combined with resourceful design has proven most sceptics wrong. The beneficial damping characteristics along with high wear and chemical resistance makes a number of partially crystalline polymers suitable for the manufacturing of "small dimension" gears. These gears transmit power or speed to a large extent through the interaction of meshing grease-lubricated metal/polymer surfaces. The material pairing polymer/polymer is also utilized, lubricated as well as non-lubricated. Such gears are mainly deployed in the passenger compartment, although current investigations indicate a possible future expansion of their application area towards the engine bay. The load, size and temperature requirements have initiated the development of a methodology for realistic simulation of gears with components made of partially crystalline polymers. The methodology is verified through assessment of the structural behaviour of several gear assemblies now being produced by IMS Gear for the automotive industry. Further methodology development aims to incorporate detailed descriptions of the manufacturing influence on the mechanical properties of non-reinforced polymers. This paper considers the IMS Gear methodology as a joint-effort approach to modelling, analysing and evaluating gears of metal-polymer material pairing using the finite element method.

Keywords: Gear Design, Design Flexibility, Spur Gears, Worm Gears, Analysis Automation, Manufacturing-dependant material properties, technical polymers, joint-effort methodology

1. Mechanical properties of non-reinforced partially crystalline technical polymers

Rather than try to simply list properties and talk about them in general, the aim of this section is to focus on characteristics that can be directly used in the mechanical strength assessment of a gear wheel. More extensive introductions to polymeric materials are offered by [1] and [2].

The molecular chain structure of a polymer determines its properties in different directions "(Ainbinder, 1969)", "(Michaeli, 2000)", and hence non-reinforced, semi-crystalline polymers should be regarded as anisotropic and inhomogenous. For injection moulded polymeric gear wheels, process related considerations such as residual stress, shrinkage and short-time creep over solidification must be taken into account. Commercially available injection moulding software such as Moldex 3D or Moldflow offer some limited insights in this respect, however, there is still room for improvement in this area.

1.1 Elastic Moduli

Elastic moduli for partially crystalline polymers is a somewhat controversial subject, mostly due polymers exhibit elastic, plastic, viscoelastic and viscoplastic material behaviour (phases). In contrast to reinforced polymers (as illustrated in Fig. 1) it is more difficult to clearly define the elastic and plastic regions as there is a gradual change of the stress-strain curve gradient and no clearly defined yield point. A concise overview of the phases listed above in relation to a stress-strain diagram is offered in [12]. Characteristic schematic curves for brittle and ductile polymers are available in [13].

In linear design calculations for deflection and stress, elastic material moduli are used in combination with Hooke's law to determine quantitative values. It is paramount to bear in mind that the moduli for partially crystalline polymeric materials vary considerably depending on the applied load type. It is evident from Table 1, which gives the elastic moduli for a high-performance polymeric material used in gear manufacture, that polymers are stiffer in tension and bending than they are when subjected to shear.

Table 1. Measured elastic Moduli for VICTREX PEEK 450G

Modulus	Value (MPa)
Secant (tensile)	3400
Bending	4000
Shear	1300
Compression (initial)	1250
Compression (final)	2650

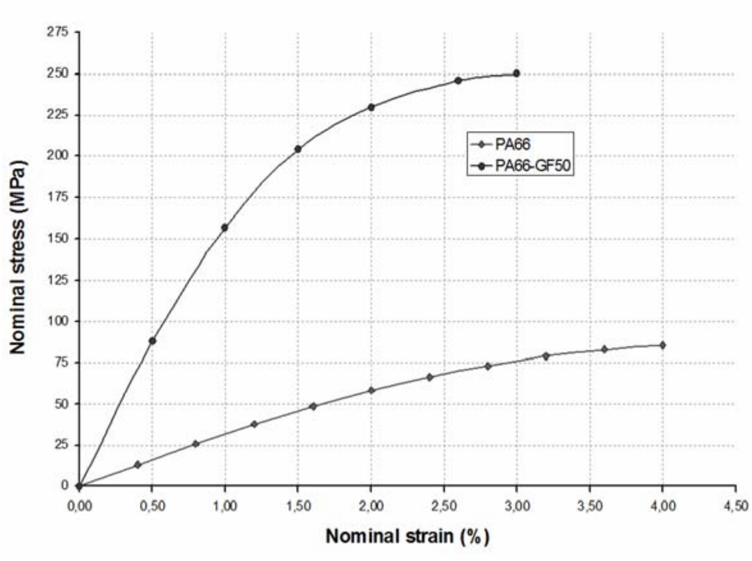


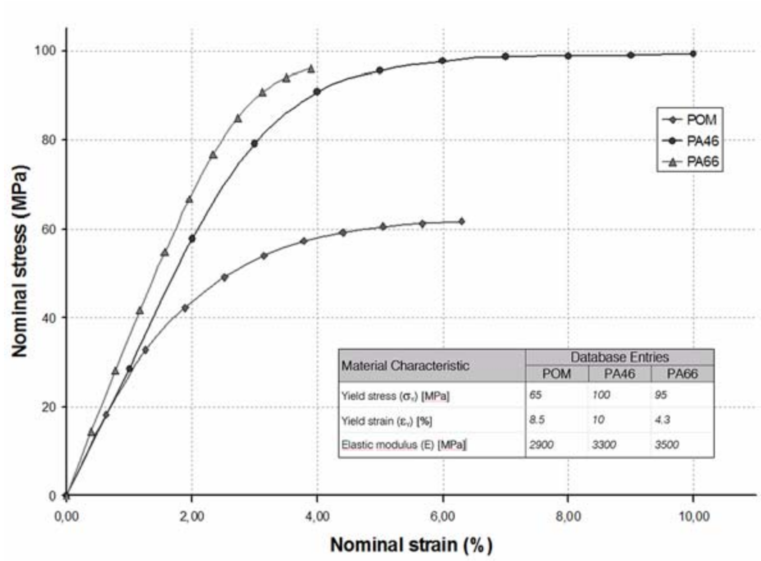
Figure 1. Stress-strain behaviour for a non-reinforced and a reinforced polymer

It is difficult to generally decide the strain range over which elastic moduli ought to be determined (illustrated in Fig. 2), as they can be influenced by processing conditions, material charge composition (additive ratios, impurities, residual pellets or resin), post-manufacturing heat treatment and load rates. Other influencing factors are molecular orientation and the degree of crystallinity. Base-line numerical values for different moduli are presented in “(Hellerich, 2004).”

Elastic Moduli can be considered as a customisable parameter, described as a function of strain:

$$E(\varepsilon) = E_0 + B \times \varepsilon^2 + C \times \varepsilon + D$$

Where E_0 is the initial tangent modulus, B and C and D are constants and ε is the strain for which the elastic modulus is being sought. The constants will vary between polymer families but the function will essentially remain the same. This behaviour is illustrated in Fig. 2. Dependency of temperature, load rate and water absorption (especially for polyamides) is schematically shown in Figs. 4 – 6.



Material Characteristic	Database Entries		
	POM	PA46	PA66
Yield stress (σ_y) [MPa]	65	100	95
Yield strain (ε_y) [%]	8.5	10	4.3
Elastic modulus (E) [MPa]	2900	3300	3500

Figure 2. Stress-strain behaviour for different, non-reinforced polymers

Having determined suiting elastic moduli, values can be extracted from any set of equations utilising elastic constants. Three examples of such equations are presented below.

1.1.1 Tooth tip deflection according to "(VDI 2545, 1992)."

$$\lambda = \frac{3F_t}{2b\cos\alpha_t}\,\varphi\left(\frac{\psi_1}{E_1}+\frac{\psi_2}{E_2}\right)$$

where:

λ is the tooth tip deflection
F_t is the tangential force
b is the tooth depth
α_t is the active pressure angle
φ is a dimensionless coefficient that considers the number of teeth on each wheel and their influence on the tooth shape and the position of the meshing point
$\Psi_{1,2}$ is a dimensionless coefficient that for each wheel considers the influence of the profile modification factor on the tooth shape
$E_{1,2}$ is the elastic modulus for each wheel

1.1.2 Tooth material factor according to “(VDI 2545, 1992).”

$$Z_E = \sqrt{0.72 \times \frac{(E_1 \times E_2)}{(E_1 + E_2)}}$$

where:

Z_M is the tooth material factor used for calculating the hertzian stress
$E_{1,2}$ is the elastic modulus for each wheel

1.1.3 Stress relaxation according to “(Birley, 1992).”

$$\sigma(t) = E \times \varepsilon_E = \sigma_0 \times e^{\left(\frac{-Et}{\mu}\right)}$$

where:

$\sigma(t)$ is the time dependant stress
E is the elastic modulus
ε_E is the elastic strain
σ_0 is the constant stress applied at zero time
t is the loading time
μ is the viscosity coefficient

For metals, it is generally believed that a high elastic modulus provides the highest safety against failure. This may not be the case for partially crystalline polymers. A high-modulus polymer usually means lower yield strain, lower strain energy capacity and brittle behaviour; whereas a low-modulus polymer generally has a higher yield strain, higher strain energy capacity and exhibits ductile behaviour under loading. In an impact situation such as one gear wheel being fixed and the other hitting it at full speed, it may more favourable to induce plastic deformation rather than brittle failure, mostly because of beneficial damping and subsequent safety reasons. In contrast, tooth deformation in a creep situation benefits from a high elastic modulus, resulting in less permanent deformation. The topic of creep in polymers is treated in detail by “(Findley, 1990).”

1.2 Yield

The yield limit (σ_Y, ε_Y) is the quantity against which results from analytical tooth root strength calculations should be compared. It is important from a design point of view not to exceed the yield point (excessive deformation) for two reasons: the first is that a tooth should not be subject to a plasticity-incurring load over one single meshing cycle. Also, any calculated stress value exceeding the yield point resulting from a linear equation must be regarded as erroneous. Polymer yield limits are widely available from databases (e.g. CAMPUS) and handbooks.

1.3 Ultimate Strength

The ultimate strength is useful in material selection when choosing between polymers of similar elasticity and strain energy capacity. Ultimate strength can be influenced and manipulated just like the elastic moduli and the yield limit. Brittle polymers usually break upon reaching the ultimate strength, whereas ductile polymers continue to yield plastically at a decreased stress level. An excellent example of this is shown in Fig. 3. Left is a Polyamide 66 strained to about 95% without rupturing. Right is a PEEK which strained to about 26% before rupturing. The direct use of ultimate strength on gear wheels (apart from assessing tooth strength) concerns the wheel body which must not break under any circumstances.

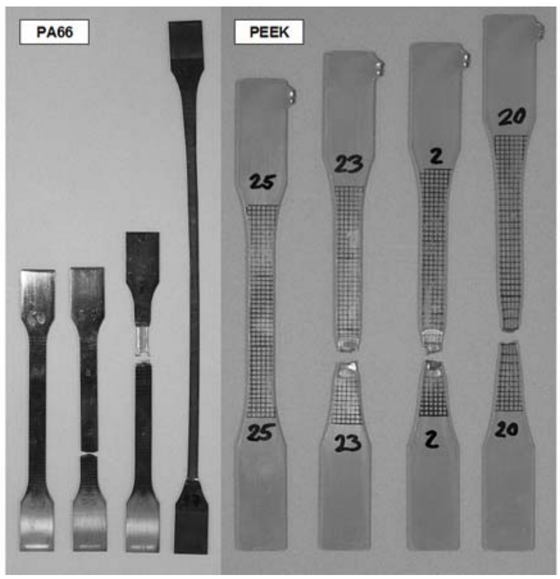


Figure 3. Deformed and undeformed polymer tensile bars

1.4 Hardness

The measurement of hardness (HB in MPa) according to "(DIN EN ISO 2039-1, 19xx)" differs from the procedure for metals in that the indentation is measured under load and after a specified time to account for initial viscoelastic effects. The hardness is therefore an indication of the resistance to short-time creep, which might occur e.g. in a seat position adjustment gear or an automotive window lift. Technically speaking, the hardness measurement procedure can be used to verify analytically calculated indentations resulting from static load cases between meshing tooth flanks. HB values for non-reinforced technical polymers range from about 80 to 180 MPa.

1.5 Fatigue

Life cycle curves for polymers can be obtained in a number of ways. This kind of data is not easy to come by and testing is under circumstances tedious and cost-intensive. Mostly, the fatigue data investigations are carried out using general test specimens and standardised procedures, as defined in "(DIN EN ISO 3167, 2003)" and "(DIN 50 100, 1978)". The values obtained from standardized testing is difficult to apply to manufactured parts because of the previously mentioned molecular orientation influence on the mechanical properties. Nevertheless, knowledge of fatigue is vital to the mechanical life cycle assessments, and one viable approach to producing useful diagrams is to run fatigue tests on parts of similar design from a specific product family.

Polymer gear wheels harden when subjected to cyclic loading. An increase in local flank strength with corresponding brittleness has been observed and will be quantified in the near future.

It should be noted that it is not possible to use every mechanical material characteristic in a finite element input file, yet the continuous study of properties feeds already established knowledge bases and increase engineering experience. As a result, the postprocessing of finite element analyses becomes more accurate and the confidence placed in simulation activities will also increase.

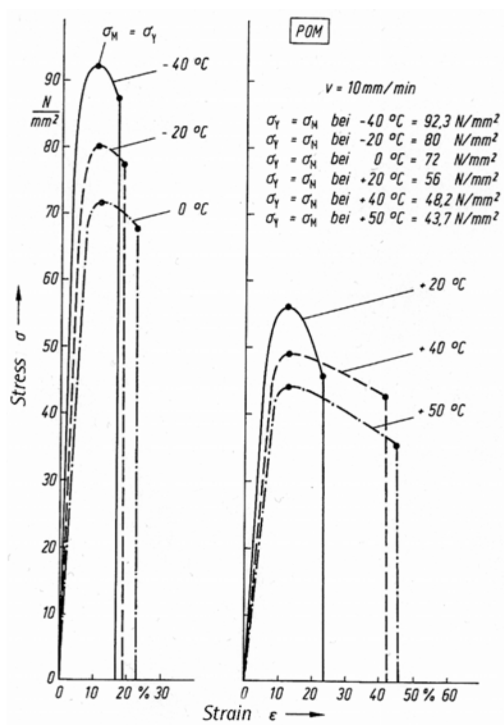


Figure 4. Temperature-dependant polymer behaviour "(Hellerich, 2004)"

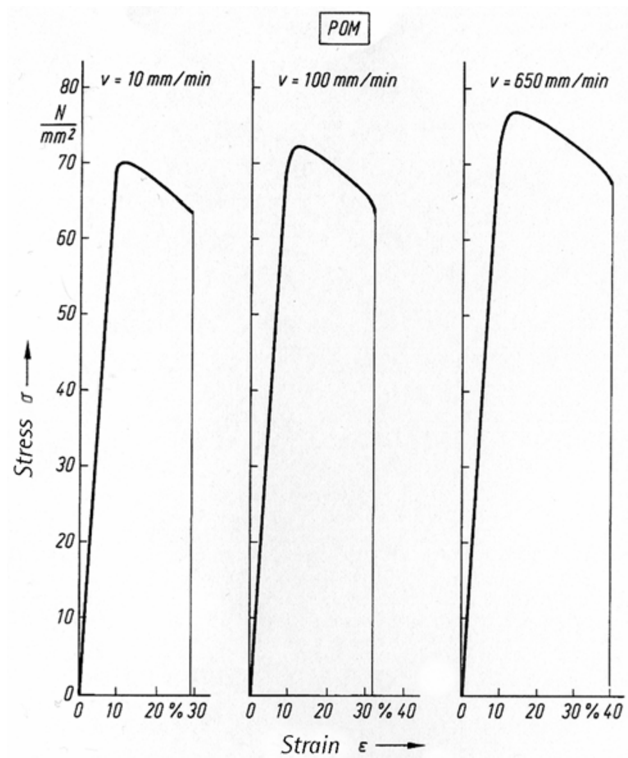


Figure 5. Loadrate-dependant polymer behaviour "(Hellerich, 2004)"

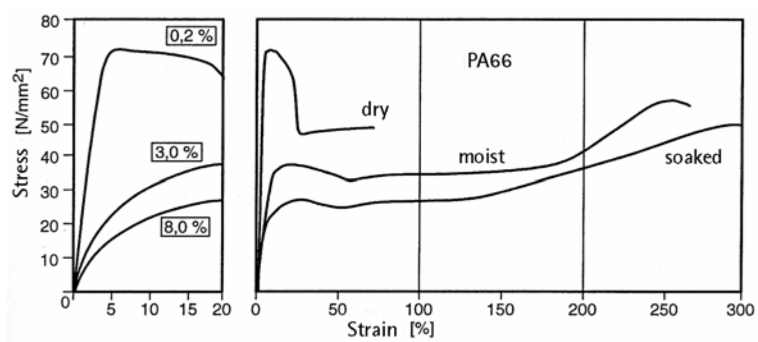


Figure 6. Water-absorption dependant polyamide behaviour "(Ehrenstein, 2002)"

2. The IMS joint-effort approach

When performing concept-level viability assessments of gears, IMS uses analytical approaches as outlined using e.g. ("DIN 3990, 19xx") and ("VDI 2545, 1992"). These are implemented in in-house software, which also generates the tooth profiles considered for a particular design proposal. In cases where either a limit load is expected to occur, or tooth profiles need to be investigated in explicit detail (tooth root stress distribution), ABAQUS (Standard and Explicit) serves as the dedicated tool. Other ABAQUS-designated analyses include thermal, dynamic impact and tooth meshing analyses.

ABAQUS/CAE is used to generate the finite element models. Creating three-dimensional models of gears for subsequent ABAQUS analyses is a tedious task which can favourably be streamlined through the use of automation scripts written in the python language ("Goetz, 2005"). The IMS software has been extended to provide the export of tooth profiles in a script-usable format. As a result of successfully implementing the automation script, the model generation time for spur gears and screw gears has so far reduced from about three hours down to approximately five minutes.

The polymers used in IMS application (and thus the ones used in finite element analyses) are technical polymers (such as PA46, PA66, POM) and high performance polymers (such as PEEK and PPS). In order to feed the material models available in ABAQUS, extensive testing is carried out in the IMS laboratory on injection moulded material specimens as well as manufactured parts. Tests include tension, compression, hardening, fatigue, climate change influences and impact tests. Several comparisons between finite element analyses and laboratory tests have shown the importance of modeling the polymeric materials to as detailed an extent as is physically possible ("Winkler, 2006"). The IMS material data base is thus continually being updated and efforts are focused on increasing the understanding of non-reinforced technical polymer behaviour under varying loading conditions.

The evaluation of analyses can only be considered credible if sufficient experience regarding gear behaviour is available. ABAQUS/CAE offers a large amount of ways to display quantities relevant to the mechanical strength assessment of gears such as root stress, hertzian pressure, temperature-induced dimensional change and tolerance errors. It is also possible to observe them over the meshing distance. With the necessary results extracted, these need to be put into perspective by carefully allocating them to their corresponding physical behaviour as observed in similar-condition tests in the past.

The activities described above result in a workflow (or methodology), which has been given the name "practice-oriented-simulation". Practice-oriented simulation encompasses the efforts of combining the knowledge in programming, structural mechanics and laboratory testing experience. Its goal is to have simulation reflect reality to such an extent, that the majority of standard issue testing can be avoided.

The advantages of practice-oriented simulation are of course many, yet a few deserve special attention:

i. increased model generation productivity
ii. improved material definitions for structural simulations
iii. increased model reliability
iv. realistic model deformation behaviour (global and local)

With constantly growing practice-oriented simulation knowledge, it has become significantly easier to determine rights and wrongs in a model, i.e. if there is an error within the model definition or if a structure would actually fail under a defined load. As a result, the ETA for finding errors and debugging a running analysis has drastically reduced.

3. IMS Gear Design Case Study Examples

Figures 7 to 12 show results from different analyses of gears manufactured at IMS using practice-oriented simulation.

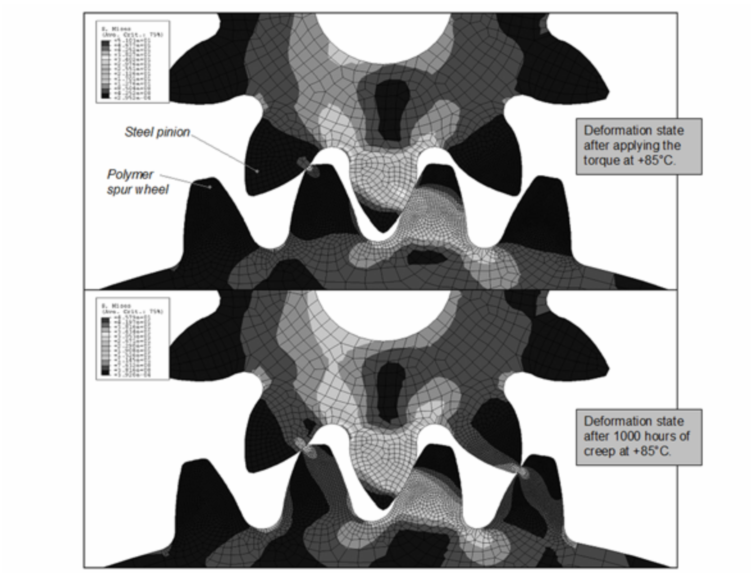


Figure 7. Spur gear creep analysis

The gear assembly in Figure 7 was analysed for possible failure of the polymer spur wheel at a temperature of +85°C. A torque was applied through the steel pinion and continuously held for 1000 hours, while the spur wheel was fixed (blocking situation). The image shows the assembly deformation states as specified. Data from laboratory tests were used to describe the plasticity curve, and isochronous stress-strain diagrams provided by the polymer manufacturer for the calibration of creep law parameters. The analysis was performed with ABAQUS/Standard, and showed that the spur wheel would not fail. This was later verified by laboratory tests and through customer feedback.

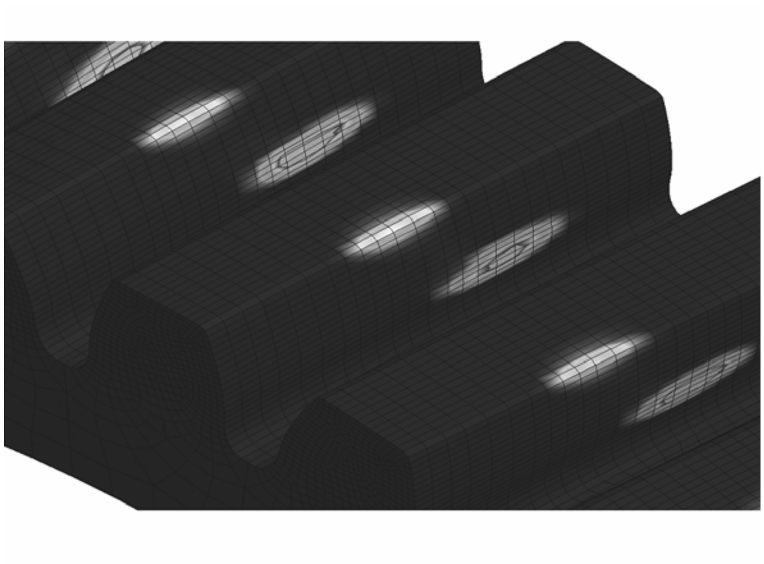


Figure 8. Screw gear nominal load analysis

The aim of the analysis shown in Figure 8 was to assess whether or not a screw gear would suffer severe plastic deformation when subjected to a nominal torque. One problem resulting from excessive plastic deformation is an error in pitch, which in turn can lead to torque deviations or self-locking. The analysis was performed in ABAQUS/Explicit, during which the torque was continuously applied, and the worm rotated causing 180° of the screw wheel. The analysis indicated strains high enough to pose pitting problems, should the load be applied over a longer period of time. As this was not the case, and the strains small enough not to cause pitch errors, the design was carried on for further development. Figure 9 shows the results of a durability test using a design prototype. The test lasted considerably longer than initially required, and the physical pittings show good agreement with the analysis in figure 8.

Figure 9. Pittings on screw gear flanks

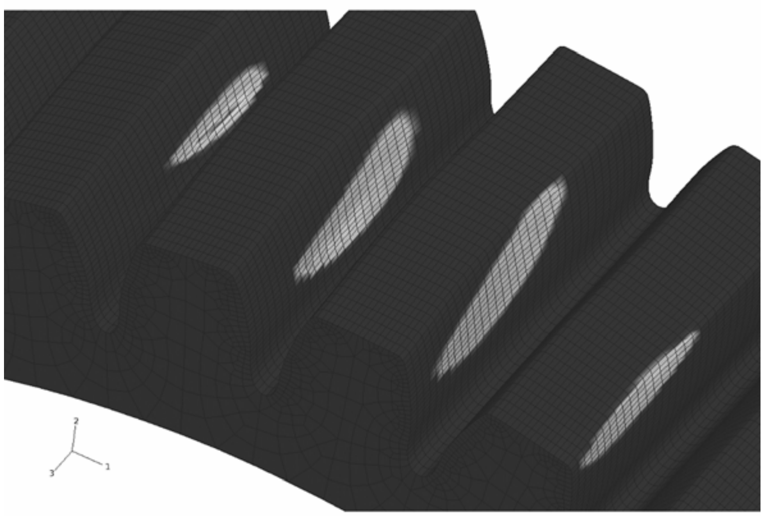


Figure 10. Screw Gear Contact pattern analysis

Figure 10 shows the result of a contact pattern analysis performed in ABAQUS/Explicit on a screw gear in order to assess the load distribution and contact path. A torque was applied at +85°C and the worm was rotated corresponding to 90° rotation of the screw wheel. The increased temperature increased the overlap ratio, and decreased the global stresses. The contact path prediction agreed well with results from bed-in tests carried out on test gears with inked flanks. It is interesting to note the excellent agreement of the maximum contact pressure with the position and size of pittings occurring after a large number of load cycles. This is illustrated in figure 11.

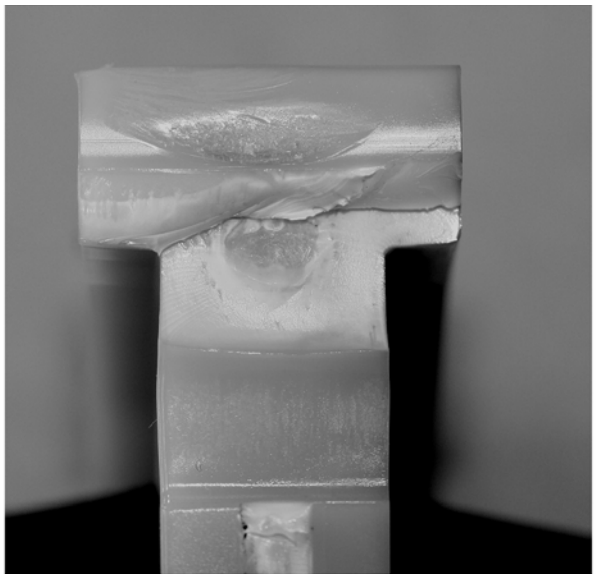


Figure 11. Pittings on a screw gear flank

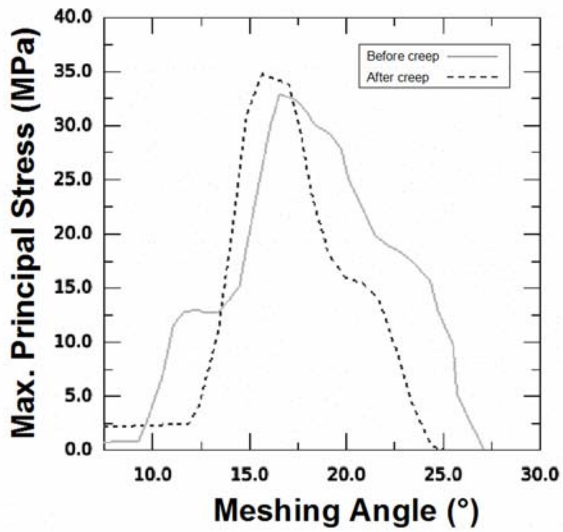


Figure 12(a). Helical gear creep analysis – max. principal stress

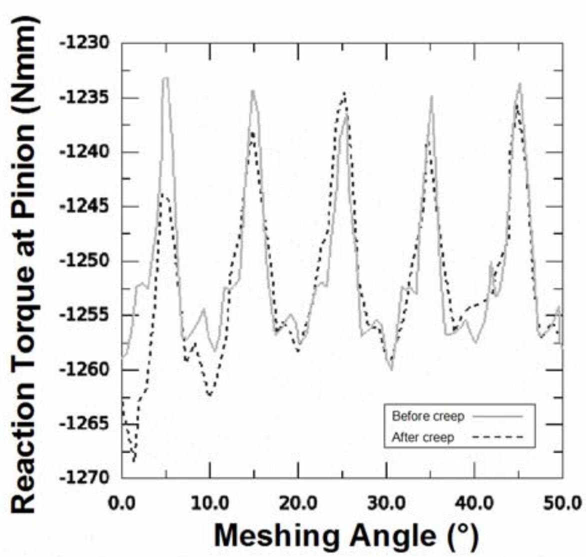


Figure 12(b). Helical gear creep analysis – reaction torque

Figures 12(a) and 12(b) show the maximum principal stress and the reaction torque in a helical gear before and after 10000 hours of creep at ambient temperature. The solid line represents the geometrical state before creep and the dashed line the state after creep. The effects on the contact ratio were clearly visible with the maximum principal stress in the tooth root ranging over a significantly lower meshing angle, whereas the reaction torque was only negligibly influenced. The analysis was performed in ABAQUS/Standard and the creep time law calibrated with data supplied by the polymer manufacturer.

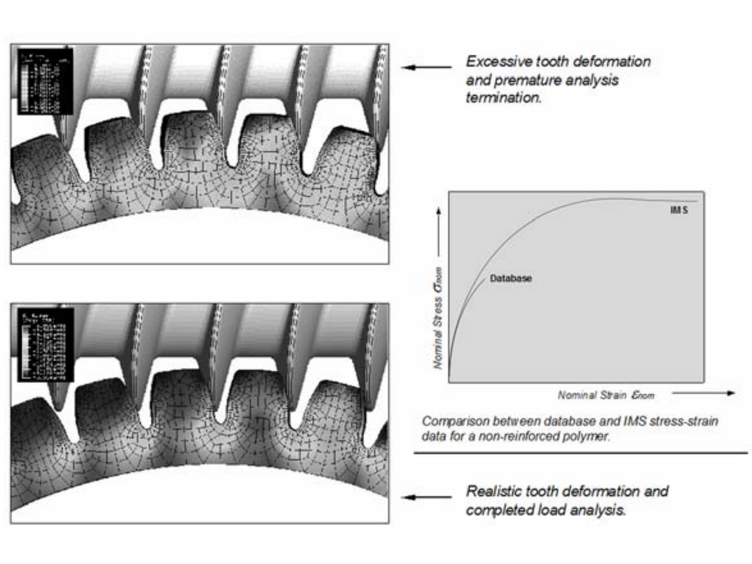


Figure 13. Material modeling issue in a screw gear analysis

A screw gear was analysed for the its capacity to transfer an estimated torque. The analysis was performed with ABAQUS/Explicit and terminated after reaching 30% of the expected load. Careful model debugging found no obvious reason for a terminating error. Examining the strain results in detail indicated an inadequate description of the material data. Basic database values had been used to describe the plasticity curve, and the decision was made to extend this data by carrying out in-house material testing. The new data allowed the finite element model to reach the full expected load and provide satisfactory deformation behaviour.

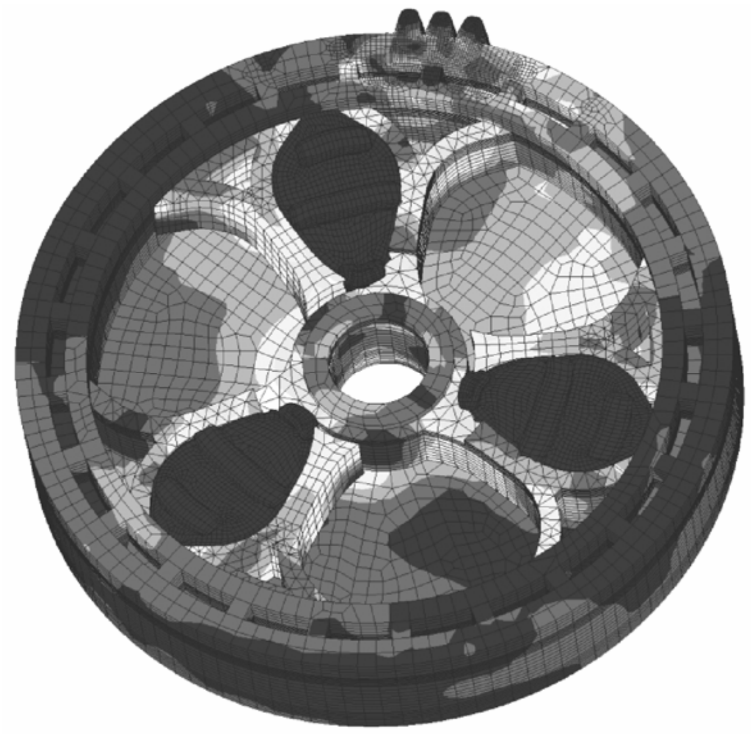


Figure 14. Design improvement potential analysis of an automotive window lift

Depicted in Figure 14 is an automotive window lift in a through-depth cut. A load analysis was performed using ABAQUS/Explicit in order to find areas of potential design improvement and cost cutting. As the assembly included large rubber dampers, laboratory tests were performed in order to assess the torque-displacement behaviour. Diagrams based on test data were compared to values extracted from the finite element analysis and found to be in acceptable agreement. Extensive material data was produced for the finite element model, which in a subsequent analysis produced results that correlated well with the laboratory test data. Having established a satisfactory level of confidence in the finite element model, the assessment of potential improvements could be successfully carried out.

4. Discussion and Conlusions

The finite element method is an important tool in the concept phase of gear design, especially when considering a metal/polymer material pairing. FEM not only offers the possibility to assess the gear load capacity, but also the opportunity to analyse the structural behaviour of a complete gear assembly under load. In order to be able to extract sensible information from such analyses, precise material modelling and a solid understanding of how a polymer application reacts to interference factors is crucial. As an example one might consider flank surface disruptions or tribochemical reactions between the gear wheel material and an applied lubricant.

The complexity of interference factors is at present generally not possible to numerically consider, and if at all possible, the task becomes extremely tedious. Hence, the interference factors must currently remain partially regarded at best. This is the point at which application-specific knowledge becomes utterly important.

The need for comprehensive analyses (gear assemblies, overall load configuration and complete process chains) continues to grow steadily with the development of contemporary FEM software and powerful computer hardware. In addition, the demands for agreement between simulation and reality are higher than ever. A nicely coloured picture is no longer considered an adequate result. An accurate correlation between structural analyses and tests performed on manufactured parts is indispensable in order to be able to cut the costs in testing and the development as a whole.

Looking to the future, our aim is to numerically integrate the individual development processes (CAD, injection moulding simulation, FEM, fatigue testing) to a widest possible extent. This aim calls for much more detailed consideration of real-life situations such as:

- manufacturing-based material properties
- manufacturing-based part and assembly conditions
- dynamically loaded gear assemblies
- friction and wear
- durability

The aim stated above has initiated an in-house development of a structural simulation methodology referred to as “Practice-Oriented Simulation”. The use of practice-oriented simulation has allowed us to streamline simulation activities, increase confidence in the analysis results and reduce the number of laboratory tests. The IMS methodology is no way a completed method. It is an organic process, which will continue to grow along with the ever-changing needs of the industry and its increasing demand for more sophistication in structural analyses. Our target is to drive the further development of our methodology so as to always deliver best practice simulations and state-of-the-art end products.

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