EFFICIENT DEVELOPMENT OF HIGH PERFORMANCE POLYMER PARTS USING ADVANCED SIMULATION METHODS

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Abstract: The optimization of part development process should lead to an improved time to market performance, raise cost and resource efficiency and at the same time it has to ensure product quality and reliability. The quality and performance of polymer parts, in contrast to metal parts, depend not only on selected material but additionally they are determined by processing conditions during manufacturing e.g. injection moulding process. Thus, the optimization of development process of polymer parts is of high importance.

The nowadays available simulation techniques are necessary tools in the virtually based development process and by the creation of a reliable simulation results the development process can be considerably accelerate and the competitive quality parts can be in short time realized.

This article shows the advantages of application and combination of the current available simulation techniques in the development of single stage gear made of plastic. The evaluation and verification of the simulation results will be presented and discussed.

Keywords: CAE, FEM, Structure Optimization, Filling Simulations, Rapid Prototyping, Virtual Development

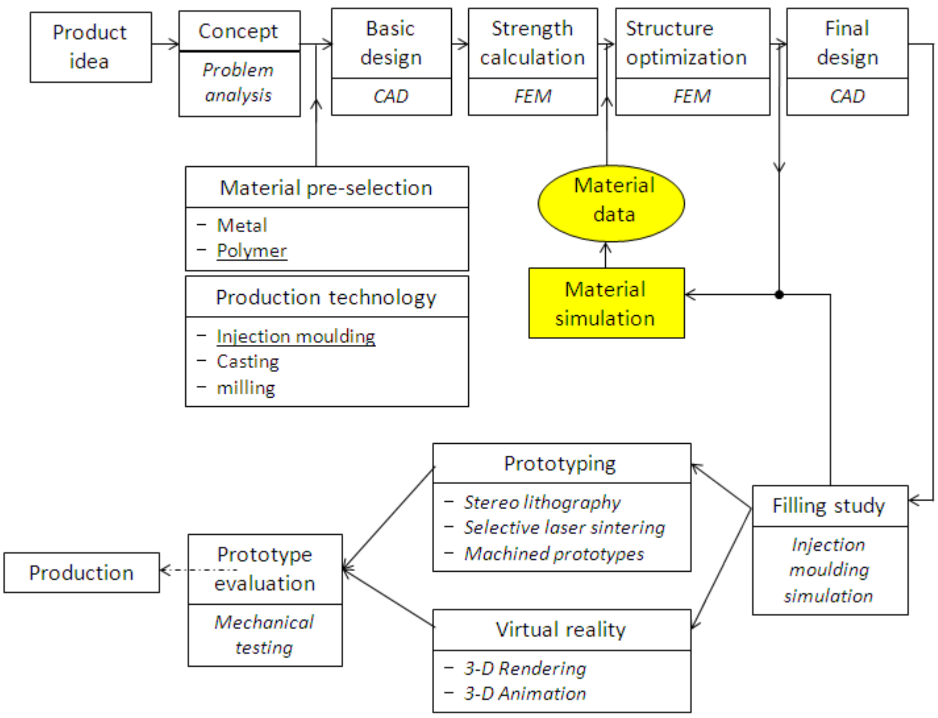

Figure 1: *Flow chart of the virtual development process of polymer products*

1. Introduction

For the development of highly loaded parts, the selection of a suitable material is of the first importance while it determines the final product properties and the whole development process. The development process depends on the chosen material class, namely for polymer, in comparison to metal, it needs special polymer adapted methods (e.g. polymer design, filling simulations). Thus, the complexity of development process of plastic parts is much higher than steel parts. Nevertheless, polymer materials, due to their lower density in comparison with metals, show a special potential in the field of lightweight construction. They offer also flexibility in the processing and design. Additionally, polymers offer the chance to combine different properties (multi-functionality, multi-component parts, "tailor made" polymers e.g. fibre reinforcement), which can lead to some advantages in comparison to steel.

For a complete use of the potential of polymeric materials, the virtual material development and simulation have to be involved in the polymer part development. The flowchart [Figure 1] shows the necessary steps in the development process of polymer parts and the necessary interfaces to simulation and development of the material.

Consecutively the steps in the flow chart will be shown in details on the example of a gear wheel made of engineering thermoplastic - polyoxymethylene (POM). Additionally, the aim is to replace the steps "prototyping" and "prototype evaluation", which include the cost expensive and time consuming manufacturing and testing of hardware prototypes, by virtual assessment methods.

2. Development of a highly loaded polymer part

According to the flow chart [Figure 1] the first step in the development process is the creation of the product idea. Principally in the creation of product idea following aspects have to be taken into consideration: function, economy and ecology.

2.1 Product idea

A single-stage spur wheel gear made of polymeric material is intended for application in electrically driven vehicles. A single stage gear needs a high gear transmission ratio between the pinion and the gear wheel, and therefore the gear wheel is big-sized. The application of polymeric materials enables the lightweight constructions what results in the reduction of both, the rotating masses and the mass of the car. The lightweight leads to a higher acceleration, energy saving and thus less CO^2 emission. Another important aspect for using a polymer material is that for the large scale production injection moulding is competitive method due to the short cycle time and the ready mould part "without post handling". Hence, a significant cost reduction can be achieved in comparison to a gear wheel made of steel.

The material of choice for the gear wheel construction is polyoxymethylene (POM). A gear wheel made of POM can provide low friction and low noise emission as well as the damping behaviour. In order to reduce the mass of vehicle, the polymer gear wheel shall substitute the safety clutch between the electrical engine and the gear. Due to sufficient impact toughness, POM is the suitable material for this application.

2.2 Concept

To concept the product it is necessary to analyze the problem and clearly define the requirements. Thus, all boundary conditions of the electrical vehicle and the polymer gear are specified:

- Rear wheel drive
- Max. velocity = 120 km/h
- Worst load case: Blocking of the electrical engine
- Consequence of the blocking: Blocking of the rear wheels which leads to deceleration of the car
- Dynamic axle load during the deceleration: 300 kg on the rear axis
- Friction between the tires and the street: $\mu = 0.8$
- Diameter of the wheel: 0.62 m
- Rotational speed of the electrical engine: 3000 rpm
- Material pre-selection: Polyoxymethylene (POM)
- Manufacturing process: Injection moulding

Based on the basic information, the transmission and the worst case loading with respect to torque as well as the required gear wheel dimensions can be calculated as follows.

2.2.1 Calculation of the transmission [1]

Circumference of the tire in [m]:
$2\pi r = 0.6 \times \pi = 1.884\, m$

Velocity in [$\frac{m}{s}$]:
$v = 120 \frac{km}{h} \div 3.6 = 33.33 \frac{m}{s}$

Rotations per second:
$33.33 \div 1.884 = 17.69\, r/s$

Rotations per minute:
$17.69 \times 60 = 1061.46\, rpm$

Max. rpm engine: 3000rpm

Selected transmission: i = 3:1

2.2.2 Calculation of the maximum torque

Max. friction force:
$F_{fr} = \mu \times F_n = 0.8 \times 300kg \times 9.81 \frac{m}{s^2} = 2354\, N$

Max. torque:
$T_{max} = F_{fr} \times r_{dyn} = 2354 \times 0.3 = 706\, Nm$

Max. torque, gear wheel:
$T_{max} = 706\, Nm$

Max. torque, pinion:
$T_{max} = 706 \div 3 = 235.33\, Nm$

2.2.3 Conception of the gear

The basic concept of the gear is shown in Figure 2.

Data of the gear:

Transmission: i = 3
Pressure angle: $\alpha = 20°$
Module: m = 12
Pinion: 10 teeth
Gear wheel: 30 teeth
Pitch circle pinion: $p_c = 12 \times 30 = 360$
Pitch circle gear wheel: $p_c = 12 \times 10 = 120$
Centre distance: C = 245 mm

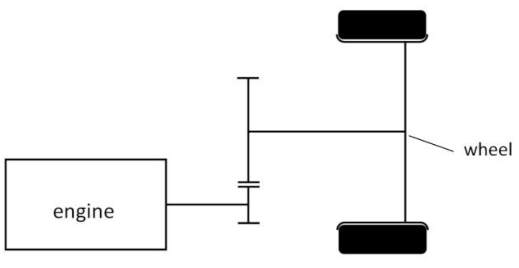

Figure 2: *Basic concept of the single stage gear*

2.2.4 Calculation of tooth root stress

Parameters:

E-Modulus of POM: E = 2700 MPa ***[2]***
Temperature: 40°C
Load cycles: 10^5
Safety factor: s = 1.4

Dynamic strength of the root ***[3]***:
$\rightarrow \sigma_{max} = \frac{\sigma_{fN}}{s} = 46.4\, MPa$

Circumference force ***[2]***:
$F_u = \frac{2 \times T}{d} = 3922.22\, N$

Tooth root stress ***[2]***:
$\sigma_F = \frac{F_u}{b \times m} \times K_A \times Y_F \times Y_\varepsilon \le \frac{\sigma_{fN}}{s} = 46.4\, MPa$

→ width of the tooth: w = 40 mm

2.2.5 Calculation of surface pressure [2]

Max. surface pressure: $\sigma_{HN} = 100\, MPa$
Temperature: 40°C, in oil
Load cycles: 10^5
Safety factor: s = 1.4

$\rightarrow \sigma_{HNmax} = \frac{\sigma_{HN}}{s} = 71.4\, MPa$

Surface pressure:

$$\sigma_H = Z_H \times Z_E \times Z_\varepsilon \times \sqrt{K_A \times \frac{z_1 + z_2}{z_2} \times \frac{F_u}{d_o \times b}} \le \frac{\sigma_{HN}}{S} = 71.4\, MPa$$

$\rightarrow \sigma_H = 64.26 \le 71.4\, MPa$

2.3 Basic Design

On the basis of the calculated, required dimensions of the gear wheel, the construction of the basic design can be done. With the 3D-CAD-program ProEngineer, 3-D models of the gear wheel [Figure 3] and the pinion [Figure 4] are constructed. In addition, the design of the gear shaft hub is realized. By assembling the single parts, the fitting of the parts can be proven.
The models will be used in the dynamic impact calculation with LS-Dyna. For this purpose only the gear teeth are important and that is why the first draft of the wheel and the pinion contains no ribs.

Advantages of 3-D-CAD systems:

With virtual assemblies, the functionality of the system can be ensured.

Iterative course of action:

Depending on the results of the dynamic strength calculation, the basic design can be improved until the necessary strength is achieved.

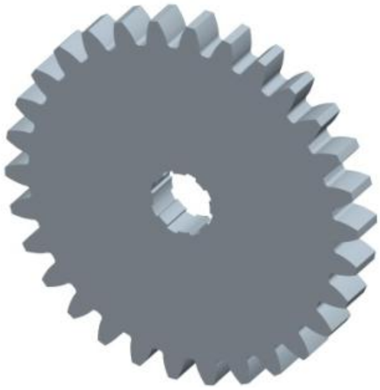

Figure 3: *Basic design of the gear wheel*

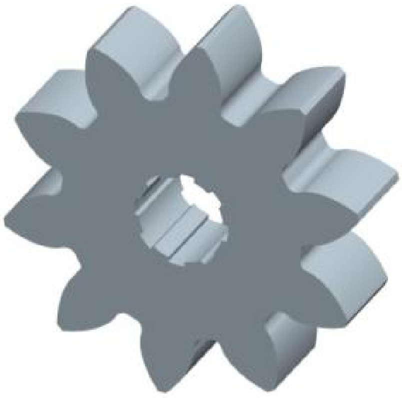

Figure 4: *Basic design of the pinion*

2.4 Dynamic strength calculation

The FEM-calculation of the gear wheel impacting the pinion is executed with the explicit FEM-solver LS-Dyna. For the simulation of an abruptly stopping engine, the pinion is stopped after a rotation of 180°. Like in the reality, the gear wheel is loaded with the momentum from the sliding wheel of 607 Nm. In consequence of the abrupt stopping, the teeth of the gear are impacting each other. But also the hub-rim-connections are highly loaded [Figure 5].

Advantages of dynamic simulations:

Load peaks which results from dynamic loads can be calculated. In addition, the functionality is proven by examination of the sliding behaviour of the teeth.

Iterative course of action:

If necessary, the results of the dynamic FEM-calculation must be taken into consideration for the improvement of the basic design. On the example of the gear, the teeth are strong enough, only the rim-hub-connection of the pinion requires improvement [Figure 5].

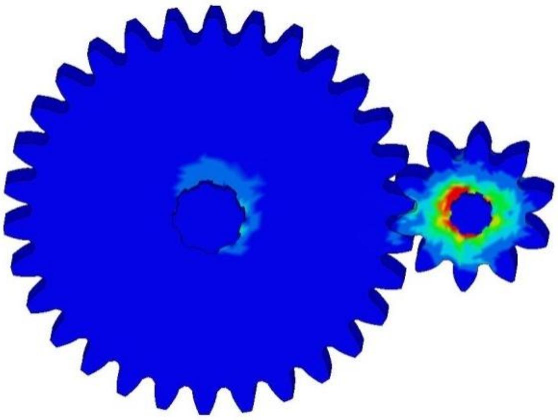

Figure 5: *Dynamic simulation of the gear wheel impacting the pinion (Ls-Dyna)*

2.5 Structure Optimization

The aim of a structure optimization is the improvement of the properties. These properties could be e.g. the eigenfrequencies, the stiffness of the part and its weight.

On the example of the gear, the aim is to reach the lowest possible weight, under the condition, that the gear wheel will still resist the worst case load. The optimization is realized with the optimization program "Optistruct" from the Altair Company. It is an implicit solver and the optimization works with a static FEM-calculation. The course of action is that the FE-meshed gear wheel is loaded with the circumference force on the teeth. During the calculation, the program identifies elements with low stresses and deformations. These elements will be deleted and the calculation runs again. After some steps of iteration, the program offers a proposition of an improved shape of the part. In addition, there are some tools for defining boundary conditions. For plastic parts, the opportunity to propose shape without undercut which guarantees good release properties is really important tool. Another important tool is the pre-setting of a constant wall thickness. This new shape can be converted back into a CAD-part, in this case a ProEngineer file. In case, that the result, e.g. the weight reduction, is not satisfying, there is the possibility to switch back to the material simulation and try to get e.g a material with a higher stiffness.

Advantages of structure optimization:

The structure optimization enables great progresses in the shape of a part, because it identifies the unloaded sections and carries out much iteration. This is much more efficient than a manual improvement of the shape.

Iterative course of action:

On the one hand, the results from the optimization can require improvement of the materials, but on the other hand, the results of the filling study can require changes of the design, so that the optimization has to be processed again.

2.6 Final Design

Based on the optimized CAD-part, the final design is reached by adding the necessary details to the construction. These details are e.g. radiuses, chamfers and relief grooves. In the example, this step is realized with ProEngineer. For the next step in the development process, the simulation of the injection moulding process, some versions of the gear wheel with different sprues should be designed. For the gear wheel, the best location for injection is from the hub, maybe with single sprues or with a film gate.

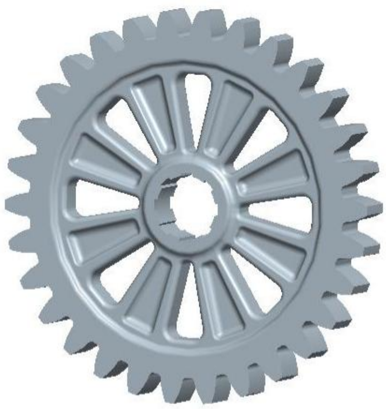

Figure 6: *Final design of the gear wheel*

2.7 Filling study

The injection moulding simulation is used for the assessment of the draft design concerning the ability to reach good material and morphological properties. The program which is used is "Moldflow", a product of the Autodesk Company. The purpose of Moldflow is a complete virtual testing of the production process (injection moulding). It is possible to edit all necessary parameters for the simulation.

- Selection of the material with all relevant properties:
  - Matrix material
  - Filling material (fibres, spheres)
  - Viscosity of the material
  - Thermal properties of the material
- Adjustment of the tool temperature
- Setting of injection and holding pressure
- Setting of switchover point
- Setting of holding time

The results of the Moldflow simulation are information about the following parameters:

- Cooling rate of the part
- Building of the morphology (amorph, semi-crystalline etc.)
- Process time
- Fibre orientations
- Appearance of voids [Figure 7]
- Weld lines [Figure 8]
- Mould shrinkage
- Deformation of the part triggered by different cooling rates and the resulting differences in morphology

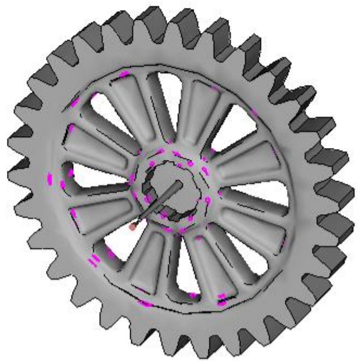

Figure 7: *Voids in the gear wheel*

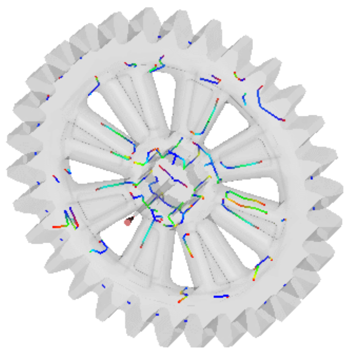

Figure 8: *Weld lines in the gear wheel*

Interpretation of the filling study:

The voids signify a weakening of the material. With the knowledge about their appearance in the part, it can be assessed, if they are critical or not.

The weld lines [Figure 8] mean considerable weakening of the part, particularly in combination with fibre reinforced materials, because the orientation of the fibres at the weld lines are disadvantageous. Furthermore, the weld lines in the gear wheel are localized in the critical area around the highly loaded hub.

Advantages of filling study:

The filling study enables the optimization of the shape, the mould, the material and the process parameters in a way, which cannot be achieved easily with normal methods. It means an enormous cost reduction compared with the manufacturing of testing-moulds. Moreover, it allows assessing of the morphological properties of the manufactured part. Normally, the analysis of the morphological properties would require the expensive analysis of hardware prototypes with a computer tomography.

Iterative course of action:

According to the flow chart [Figure 1], the results of the filling study can require an iterative back step to the material simulation and the final design of the part.

4. Outlook

The subject of prospective researches will be the analysis of the influence of the voids on the mechanical strength of polymer parts. Therefore, the real parts with voids will be scanned in the computer tomography. Using the methods of reverse engineering, a CAD-model of the part with the voids will be created. Based on this virtual part, all the necessary FEM-calculations will be executed. For the purpose of evaluation and verification, the simulation result will be compared with the results of mechanical tests on the physical parts.

5. References

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