Multi-component lightweight gearwheels with deep-drawn wheel body for automotive applications

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Abstract. Multi-component gearwheels offer great lightweight opportunities for automotive applications. An assembly of a gear ring and a wheel body joined by press fit replaces the monolithic gearwheel. To save weight, the wheel body uses lightweight design. This lightweight design influences the assembled gearwheel’s mechanical properties like stiffness, weight and torque capacity. Further, the wheel body material influences the mentioned properties as well. In this paper, the effects of the lightweight wheel body manufactured by deep-drawing on the mechanical properties of the assembled gearwheel are investigated. Three different wheel body designs are examined regarding their stiffness and weight compared to a reference gearwheel. Using the best design, the influence of five materials with increasing yield strength on the maximum torque the gearwheel can transmit is studied. All research is done virtually using Abaqus 6.12-3.

1. Introduction
Due to increasing stringent restrictions concerning the exhaust emissions until the year 2020 [1], the automobile manufacturers aim at reducing their cars’ emissions. Lightweight design has become an important objective to fulfill the upcoming restrictions. While past efforts focused on the car body, recent investigations show high potential for weight reduction of the powertrain [2]. Gearwheels in the gearbox will serve as an example here. They are monolithic parts made from high strength steels due to high loads close to the tooth root. Apart from these small areas, the material’s capabilities stay unused [3,4]. The research project “Intelligent lightweight design through multi-component processes” focuses on the design and the manufacturing processes needed to produce multi-component gearwheels. Multi-component (differential) design allows to reduce the gearwheel’s weight while enhancing material use. The concept is shown in figure 1. A gear ring made from high strength steel supports the high local loads mentioned above and a lightweight wheel body transfers the torque from the gear ring to the shaft. Gear ring and wheel body are joined by a shaft-hub joint. Gear ring and shaft provide geometrical and mechanical boundary conditions that have to be considered while designing the wheel body and the corresponding manufacturing process. Geometry and mechanical properties of gear ring and shaft are derived from the reference gearing (table 1): the monolithic gears of the fourth gear of a light duty commercial vehicle. As manufacturing processes for the wheel body, forging, fine blanking [5,6] and deep-drawing are considered. This paper focuses on gearwheels with a deep-drawn wheel body. Three different wheel body designs and their effects on the gearwheel’s stiffness and weight are introduced. Based on these parameters, one wheel body design is chosen to investigate the effect of different
materials on the maximum transmittable torque. The general objective is choosing a wheel body design that reduces the gearwheel's weight by at least 25%.

Table 1: Characteristic values of the reference gearwheel

| Parameter                  | Normal module | Number of teeth | Helix angle | Distance between axles | Nominal torque | Force radial | Force tangential | Force axial |
|----------------------------|---------------|-----------------|-------------|------------------------|----------------|--------------|------------------|-------------|
| Value                      | 2 mm          | 38              | 30°         | 91.5 mm                | 400 Nm         | 4395 N       | 8858 N           | 5263 N     |

2. Wheel body design

Figure 1 depicts gearwheels with three different wheel body designs. Naming corresponds to the wheel bodies’ section form. S-shape describes a wheel body that consists of a single part. Double-S and double-U shaped wheel bodies consist of two parts. The wheel bodies are designed in two steps. Drafting the wheel body’s topology is the first one and dimensioning it the second one. During drafting the manufacturing process deep-drawing and its limits need to be considered already.

Figure 1: Multi-component gearwheels with three different deep-drawn wheel bodies, characteristic parameters of gear ring and shaft

Dimensioning the deep-drawn wheel body has to take geometrical and mechanical boundary conditions, applied by the gear ring and the shaft as well as the lightweight objective, into account. Geometrical boundaries are given in figure 1. Mechanical boundaries are the torque derived from the reference gearing and the press fit between gear ring and wheel body. The press fit (H6/u5) influences the mechanical properties of the whole gearwheel since it leads to pretensions in its parts. The light-
weight objective influences the sheet metal thickness (figure 2). To meet the lightweight objective, the sheet metal thickness for the double-U and the double-S shaped wheel bodies cannot be larger than 2.5 mm. Further investigations will use a sheet metal thickness of 1.5 mm as the lightweight objective is clearly met.

2.1. Numerical model setup
To evaluate the effects that the different wheel body designs have on the gearwheel’s stiffness, a numerical model in Abaqus 6.12-3 is built (figure 3). The numerical model needs to consider the whole gearwheel as the press fit influences the mechanical behavior of wheel body and gear ring. Additionally, the load application is asymmetric. Therefore, a two-stage FEM model is used. Both stages use the Abaqus implicit solver. Within the first stage, the press fit between gear ring and wheel body is applied. In the second stage, the assembled gearwheel is loaded with the tooth forces derived from the reference gearing. A cylindrical coordinate system as shown in figure 3 is used.

Wheel body and gear ring are modeled and meshed using different techniques. The wheel body is modeled as its middle layer using shell elements (S8R). To save computation time, the gear shaft geometry is not part of the model. The gear ring is modeled as a volumetric body. Structurally meshing the whole gear ring is difficult due to the teeth’ geometry. Hence, the gear ring is divided into two cells by a cylinder with a diameter of 81 mm. The axis of the cylinder and the axial direction of the gearwheel are coincident. All areas outside this cylinder use tetrahedron elements (C3D10M) for meshing, while the areas inside that cylinder use hexahedron elements (C3D20R). Both mesh types are connected with an internal tie constraint. Element length for all meshes used is two millimeters.

Contact occurs between the inside of the gear ring and the outside of the wheel body. This contact is modeled by the surface-to-surface algorithm with finite sliding. The contact formulation defines normal and tangential interaction behavior. In normal direction, hard contact is set to omit overlapping in the press fit, since the interference between gear ring and wheel body is geometrically modelled. A penalty contact describes the tangential behavior using a friction value of 0.1.

There are three boundary conditions within the model. During the first stage (press fit), two displacement boundary conditions are active. One acts on the gear ring’s inside and the other one on the wheel body’s outside faces. Translations in axial and tangential direction are locked, allowing both parts to deform in radial direction. In the second stage (load), these two boundary conditions become inactive and RP center is clamped by a third boundary condition. This reference point and the inside of the wheel body are connected via a kinematic coupling that locks axial and tangential degrees of freedom. This holds the gearwheel in place in the second stage.

Load is applied during the second stage at RP load in the directions shown in figure 3. RP load and the white tooth surface (see figure 3) are connected via a kinematic coupling that locks all translational degrees of freedom. So, the load is distributed over one complete tooth flank.
2.2. *Wheel body design, stiffness and weight*

The gearwheel’s stiffness is determined using the numerical model described above. Gear ring material is 18CrNiMo7-6 and the wheel body’s material is CR700Y980T-DP. Table 2 shows the material properties. A tenth of the reference forces is applied during the second stage, as higher loads lead to non-linear deformation, while smaller loads produce negligible deviations only. Both is undesirable for determining stiffness. Using the deformation at RP load and Hooke’s law, the stiffness is calculated. Factorizing the overall deformation magnitude delivers the values needed to calculate the gearwheel’s stiffness in radial, tangential and axial direction. All stiffness values are set in relation to those of the monolithic reference gearwheel. Figure 4 shows the results.

| Table 2: Material data used in the numerical models |
|-----------------------------------------------|
| Unit | Deep-drawn wheel body | Gear ring |
| Material | DC04 | HC340 | CR440Y 780T-DP | CR590Y 980T-DP | CR700Y 980T-DP | 18CrNiMo7-6 |
| E-Module | 10³ N/mm² | 210 | 210 | 196 | 215 | 213 | 210 |
| Yield strength | N/mm² | 173 | 372 | 468 | 583 | 712 | 1020 |
| Tensile strength | N/mm² | 303 | 445 | 795 | 1004 | 993 | 1200 |
| Poisson ratio | - | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Density | g/cm³ | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 | 7.77 |

1Material data generated at the authors institute
2Material data provided by ThyssenKrupp Steel Europe
3Material Data provided by IWT Bremen

![Figure 4: Stiffness and weight of the three wheel body designs in relation to the reference gearwheel](image)

The double-U shaped wheel body shows the best stiffness results compared to the other designs. Obviously, the lightweight design leads to anisotropic stiffness. Loads in radial and axial direction yield to bending stresses in the wheel bodies. Due to the small wall thickness, bending stresses are not supported well by the deep-drawing designs. This leads to significantly lower stiffness in radial and axial direction. Further investigations will show, how the generally decreased and anisotropic stiffness influences gearwheels in mesh.

All three wheel body designs reach the objective of reducing the gearwheel’s weight by at least 25 %. The S shaped wheel body leads to the lightest gearwheel, but taking weight and stiffness into account, the double-U shaped wheel body is the best design. Therefore it is chosen for further investigations.
3. Improving the double-U shaped wheel body

Figure 5 shows the geometry parameters used to describe the double-U shaped wheel body. To improve its mechanical properties regarding torque, axial and radial loads, the geometry parameters are varied. The chosen values for the geometry parameters shows table 3. Fixed parameters are indexed. Both radii have little influence on the objectives but lead to higher weight if increased. Therefore, they are set to small values which still are suitable for deep-drawing. Further investigations will check, if decreasing the radii further is possible. Angle $\alpha$ of the outside flange has significant influence on the objectives. On the one hand, an increase of $\alpha$ leads to a better pressure distribution within the press fit and to a higher torque the gearwheel can transmit. On the other hand, setting $\alpha$ to higher values than one degree makes joining of gear ring and wheel body difficult. Thus, $\alpha$ is set to one degree.

![Figure 5: Geometry parameters used to describe the double-U shaped wheel body](image)

**Table 3: Geometry values for double-U shaped wheel body**

| Parameter | $d_a$ | $d_i$ | $r_a$ | $r_i$ | $\alpha$ | $h$ |
|-----------|-------|-------|-------|-------|----------|-----|
| Value     | 77 mm | 28-30 mm | 3 mm | 3 mm | 1° | 7 mm |

$^1$Fixed by boundary condition

4. Wheel body material

To investigate the wheel body material’s influence on the assembled gearwheel, the numerical model described above is used. Five different materials with increasing yield strength are taken into account. Figure 6 shows the results. The maximum torque (black line) the gearwheel can transmit and the maximum von Mises stress value (grey line) in the wheel body are taken from the first time step after sliding between gear ring and wheel body occurs. Torque values are related to the reference gearwheel. Markers indicate the material’s yield and tensile strength.

![Figure 6: Torque in relation to reference gearwheel and mechanical properties of investigated wheel body materials](image)
Torque and von Mises stress correlate well with the wheel body material’s yield strength. To maximize torque, a wheel body material with high yield strength is desirable. This influences the wheel body’s design, as with higher yield strength formability decreases [7]. Especially the gear shaft’s geometry is challenging to manufacture. Furthermore, springback needs to be considered carefully.

5. Conclusions
Multi-component gearwheels offer great lightweight opportunities. The material choice and the manufacturing process influence the mechanical properties of the assembled gearwheel a lot and need to be considered early in the design phase. The three presented wheel body designs manufactured by deep-drawing do not differ largely in regard to the assembled gearwheel’s weight, but in regard to the gearwheels stiffness. Stiffness is critical for the maximum torque the gearwheel can transmit. The same counts for the material choice. Materials with high yield strengths lead to maximum torque values. This results in a conflict of objectives, as materials with increasing yield strength show decreasing formability. Therefore, an optimal wheel body design would allow to use high strength steels. As this influences not only the wheel body design itself but the design of the shaft-hub joint between gearwheel and shaft as well, impacts on the whole gear box arise. Therefore, to maximize the benefits of multi-component gearwheels, including their environment in the design process is necessary. Especially, as multi-component gearwheels made by deep-drawing show decreased torque capacities related to the reference, this becomes important.

In the end, it will be the end user’s choice, what gearwheel design, what manufacturing process and what material fulfils the requirements best. If this decision is taken well, multi-component gearwheels could be another step to fulfill the upcoming emission restrictions.

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