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Lightweight gearwheel design using separate gear ring and wheel body Part II: Different manufacturing concepts for replacing a full body gearwheel

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Abstract

This paper presents two wheel body concepts for multi-component gearwheels, consisting of a gear ring and the already mentioned wheel body. Two process chains for manufacturing two wheel bodies are introduced. Additionally, both wheel bodies are investigated numerically. The torque between shaft and gearwheel a multi-component gearwheel is able to transfer is chosen as command variable to be maximized. Finally, both wheel body concepts are compared to each other.

1 Introduction

Funded by the Federal Ministry of Economic Affairs and Energy (BMWi) via the German Industrial Federation of Industrial Research Associations (AiF), the joint research project “Lightweight Forging” started in May 2015. In the context of this project, lightweight potentials of forged components are investigated in five work packages using different methods. In order to identify and to make use of lightweight potential of forged parts, networking of several stages of production becomes essential. The work package „Intelligent lightweight design through multi-component processes”, run by the Gear Research Centre (FZG) of the Technical University of Munich, investigates the potential of using assembled gearwheels. A common gearwheel is divided into three parts – gear ring, wheel body, and shaft – so in this paper the substitution of the wheel body will be investigated using three different manufacturing processes. In these investigations, special heat-treated gear rings provided by the Institute of Material Science (IWT, Bremen) are used. The Institute of Metal Forming and Casting (utg, Munich) of the Technical University of Munich deals with a wheel body made of stapled sheet metal and one made by deep-drawing. These two wheel bodies are joined with the gear ring at IWT using the gear ring’s shrinking after heat treatment. The Institute for Metal Forming Technology (IFU, Stuttgart) of the University of Stuttgart deals with wheel bodies manufactured by lateral extrusion (forging). Wheel body and gear ring are joined directly by one single forging stroke.

This paper focuses on the joining process and achieved properties for forged and stapled sheet metal wheel bodies. Manufacturing processes and numerical models to predict their load potential are introduced here. Furthermore, both wheel bodies are compared to each other.

2 Process routes for multi-component gearwheels

This chapter describes two processes to produce multi-component gearwheels. Gear ring and shaft provide geometrical boundaries for the different wheel bodies. The gear ring is 14 mm wide and has a maximum inner diameter of 77 mm. For forged wheel bodies the gear ring’s inner diameter is of complex shape. Stapled sheet metal wheel bodies use gear rings with the above values and cylindrical inner geometry. Both wheel bodies fit onto a DIN 5480-WAx30x1x28xh6x9e gear shaft

2.1 Stapled sheet metal wheel body

Figure 2.1 shows the process chain to manufacture a gearwheel with a stapled sheet metal wheel body. First, the wheel body's inner geometries are laser cut out of a large blank that is cut into smaller pieces in the same step. Inner geometries are the gear shaft geometry, four holes for aligning pins and specially designed holes to reduce the wheel body's weight. Since the sheet metal's outer circular geometry becomes a functional surface for the press fit between gear ring and wheel body, it is made by fine blanking. This special cutting technique allows generating nearly rectangular sheared edges with close to 100 % clean-shear share and very low surface roughness. One single sheet metal layer is 1.5 mm thick. Therefore, to achieve the wheel body's width, nine sheet metal layers are stapled. To join the wheel body and gear ring at IWT the wheel body's sheet metal layers have to be aligned and fixed. This is done by driving alignment pins through two of the laser cut round holes and two connectors through the other two holes. After tightening the connectors, retracting the alignment pins allows applying another two connectors to the wheel body. At IWT the two parts are joined directly after the gear rings heat treatment. With decreasing temperature, the gear ring shrinks onto the wheel body.

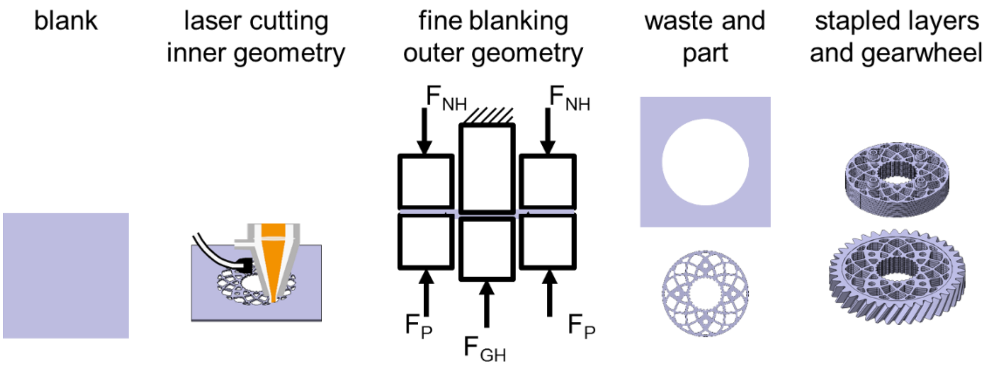

Figure 2.1: Process chain to manufacture gearwheel with stapled sheet metal wheel body

2.2 Lateral extruded (forged) wheel body

The forging process of an assembled gearwheel will be performed by laterally extruding a blank, placed between shaft and gear ring. Therefore, both the wheel body and the gear ring have to be prepared separately. Corresponding process route is shown in figure 2.2. First, the blank preparation starts with cutting slices of 9 mm height followed by piercing. Outer diameter and inner diameter have been chosen to be 72.0 mm and 27.8 mm while both do not have to be prepared with exact tolerances. Prior forming process, a conventional lubricant needs to be applied.

For the forming process, a completely finished gear ring is used. The gear hobbing and the hardening have to be therefore conducted before joining. Additionally, an out-of-round turning process is added in order to obtain an epitrochoid profile on in the inner side of the gear ring. This profile is combined with an extra cavity to enable a form and force fit in tangential and axial direction. Since this kind of undercut and non-circular shape cannot be manufactured on conventional turning or milling

machine, the test pieces were provided by J.G. Weisser Söhne GmbH & Co. KG in St. Georgen (Germany).
The actual joining process is performed with a one-stage hydraulic press. The gear ring is placed between six preloading die segments preventing impermissible tangential tension stress of the gear ring while and after forming. The blank is placed between two punches and is guided by the inner mandrel. The lateral extrusion process is initiated and conducted by the upper punch. In order to obtain a symmetric homogenized lateral extrusion process on a one-stage hydraulic press a hydraulic closing device, equipped with hydraulic chamber and nitrogen storages, is used.

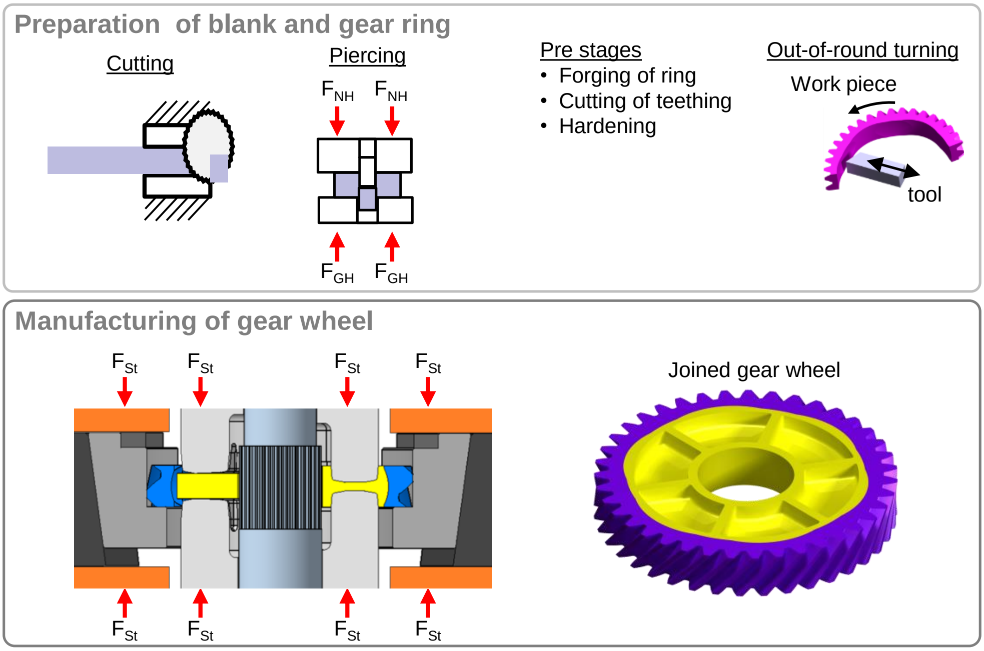

Figure 2.2: Preparation of blank and gear ring; manufacturing of joined gearwheel by lateral extrusion

3 Numerical model setup

This chapter describes the numerical models used to predict the wheel bodies' load potential. To compare the different wheel bodies to each other, they are joined with the gear ring and thereafter the gear ring is loaded with torque. A comparable solid gearwheel is capable of transferring a torque of approximately 400 Nm. Material parameters used for the numerical simulation are shown in table 3.1, as well as the saved weight compared to a solid gearwheel.

3.1 Stapled sheet metal wheel body

3.1.1 Previous investigations

The wheel body is supposed to be at least 25 % lighter than its solid counterpart assuming comparable performance. Using the torque anchor design method by Mattheck [4], a lightweight design to support the load supplied by the gear ring onto the stapled sheet metal wheel body is developed. Figure 3.1 shows the steps of the wheel body's design process. In a first step, every teeth of the gear ring is con-

Table 3.1: Parameters of part, gear ring and simulation parameters

Properties	Unit	Forged	Stapled	Gear ring
Material	[-]	C15	DP-K 700Y980T	18CrNiMo7-6
E-Module	[N/mm²]	210,000	210,000	210,000
Tensile strength	[N/mm²]	400	980	835
Poisson ratio	[-]	0.3	0.3	0.3
Saved weight	[%]	31.5	36.8	

sidered within the design method. The resulting geometry is design one in figure 3.1. Since it is not producible, simplifying the geometry is the second step. Instead of making the number of teeth the main design parameter, a factor of 360 is now serving therefore. In this case, twelve turned out to be a suitable factor, see design two in figure 3.1. It has larger holes than the first one, which allows laser cutting at lower costs. Now that a design is chosen, dimensioning is the next step. Modifying geometry features of the second wheel body (e.g. radii and shape of holes) in several iterations leads to design three. A more homogenized load distribution within the wheel body is recognizable when comparing designs two and three. Design four indicates the design fur further investigations.

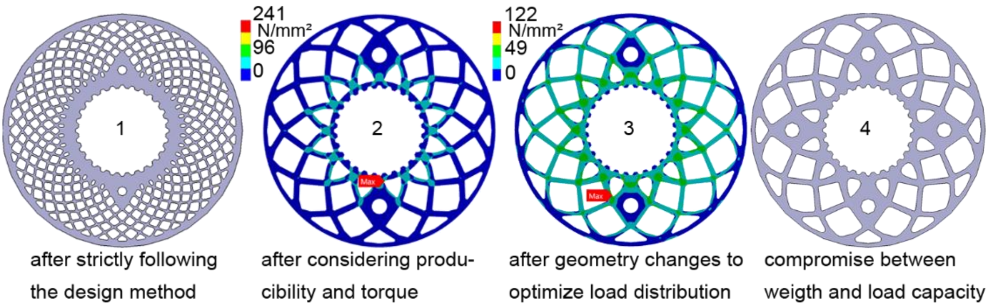

Figure. 3.1: Steps of design optimization of the stapled sheet metal wheel body

3.1.2 Numerical investigations to determine load potential

In Abaqus 6.12-3 an FEM two-stage model is built to investigate the wheel body's load potential. Both stages last one second and use the abaqus standard solver (implicit). To save computation time the gear ring is modelled with three teeth only. Structural meshing of the gear ring is difficult due to the teeth, so it is meshed with tetrahedron elements. The wheel body is meshed using hexahedron elements. (figure 4.1 left) Defining a reference point at the gearwheel's center helps determining the reaction moment later on. Its degrees of freedom are fixed by a boundary condition and the wheel body's gear shaft geometry coupled to it.

Within the first stage the press fit is applied. Interference between gear ring and wheel body is modelled geometrically. Meshing is critical especially in press fit area, as contact behavior tends to become unstable if mesh sizes of contact partners differ largely. Local mesh controls regarding element size ensure the same surface meshes in the contact area on both contact partners. Contact behavior in tangential direction is set to penalty with friction coefficient 0.1. The contact's normal behavior is set to a hard contact. Between the single sheet metal layers, contact behavior is defined using the above settings. Within the simulation model's second stage, a defined displacement in tangential direction is applied as a boundary condition on the gear ring's outer surface. Displacement increases linearly with time until it reaches 0.05 mm by the end of the second stage, which leads to sliding between gear ring and wheel body. Figure 4.1 (left) depicts the gear wheel's displacement in tangential direction. When the press fit fails, the maximum torque the gear wheel is able to transmit is reached.

3.2 Lateral extruded wheel body

3.2.1 Previous investigations

Previous investigations were related to fundamental process influences and process characteristics. First, the influence of several geometric parameters on the punch force and material are investigated [1]. The investigations are conducted using the materials steel C15 and aluminium Al 1070A. The highest influence is determined to be the wall thickness - the thinner the walls and bridges the higher will be the punch force. Since the lightweight potential is directly dependent on the wall thickness a compromise needs to be figured out. Therefore, the material volume, the punch force as well as the part strength while use need to be targeted at the same time. Regarding the punch force and material flow, the inner gear ring profile, punch segmentation, punch positioning as well as friction show minor influences.

During and after forming high tangential tension stresses will occur at the outer gear ring. In order to prevent failure, a tool is designed to preload the gear ring before the joining process. The preloading is conducted by six segments placed on a slope of the die. The upper tool moves these segments in press direction before the forming process starts. An optimal slope of 8° is figured out to adjust the preloading as precise as possible while preventing self-retention of the segments during the process [2].

Having an epitrochoid profile on the inner side of the gear ring will show high radial displacement differences since the material elasticity mirrors the inner profile under compression. Depending on the profile eccentricity, the gear ring preloading is capable of lowering the radial displacements in total up to 60 %, subsequent grinding will be faster or may be totally prevented [3].

3.2.2 Numerical simulations with different inner gear ring profile designs

In this paper a numerical comparison between two different multi-component gearwheel designs is presented. Regarding the forged gearwheel, two fundamental simulations were conducted – the forming process and a subsequent structural analysis. For the forming process the standard geometric parameters, as depicted in table 3.2, are used. The inner gear ring's epitrochoid profile is between a minimum inner diameter of 73 mm and the outer diameter of 77 mm in order to compare different multi-component gearwheel solutions more accurate by having same dimensions. For this investigation three inner gear ring profiles are used (table 3.2). Both, the blank and the gear ring are regarded elastic-plastic during forming. During the forming process, a constant punch velocity of 100 mm/s is used. After the forming process, each part is separated in order to calculate the geometrical change after spring back. In order to save computing time, the smallest geometry model possible is used considering axial and rotational symmetries. The forming process is simulated using DEFORM 3D™.

Table 3.2: geometrical parameters of gear ring for forged wheel body

Parameter	dimension
Outer gear ring diameter	94.38 mm
Inner gear ring diameter	73.0 – 77.0 mm
Friction	0.12
Extensions in inner gear ring profile	6
Punch segmentation	6
Wall thickness	3 mm
Eccentricity	V1: 0.7 mm; V2: 2.0 mm; V3: 2.0 mm
Cavity depth	V1: 0.7 mm; V2: 0.7 mm; V3: 2.0 mm

In order to analyse the structural strength, gear ring and wheel body need to be mirrored on the symmetry planes to obtain full bodies. In figure 3.2 the procedure before the structural analysis is depicted.

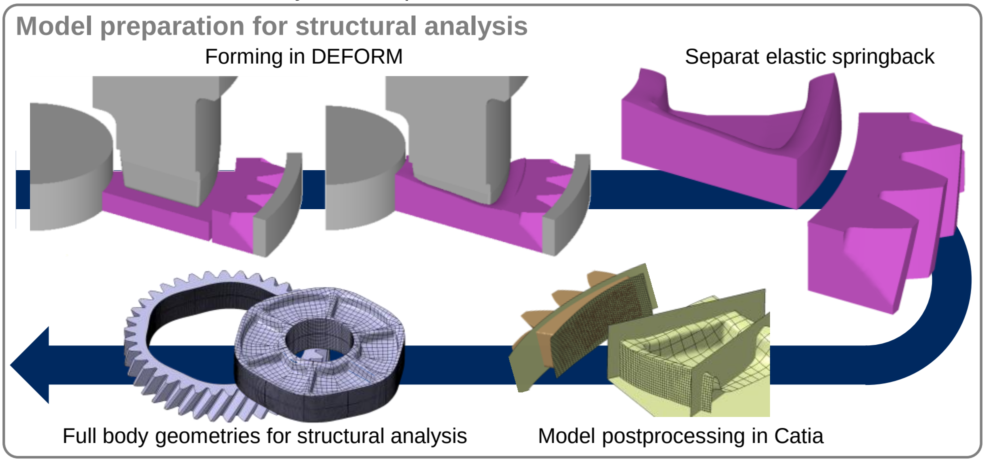

Figure. 3.2: Preparation of formed geometries for structural analysis

3.2.3 Numerical model for structural analysis in Ansys

The structural analysis of the lateral extruded wheel body is processed using ANSYS. After elastic spring back, the geometries of gear ring and wheel body show interferences at the contacting surfaces. Therefore, an interference adjustment using the elasticity needs to be conducted first. In figure 3.3 the comparison of the contact pressure distribution is depicted after the forming process in DEFORM 3D^{TM} (left) and after the interference adjustment in ANSYS (right) for an inner gear ring profile having an eccentricity of e = 2.0 mm and a cavity of c = 2.0 mm. The distribution along the inner surface as well as the absolute contact pressure shows high correlation.

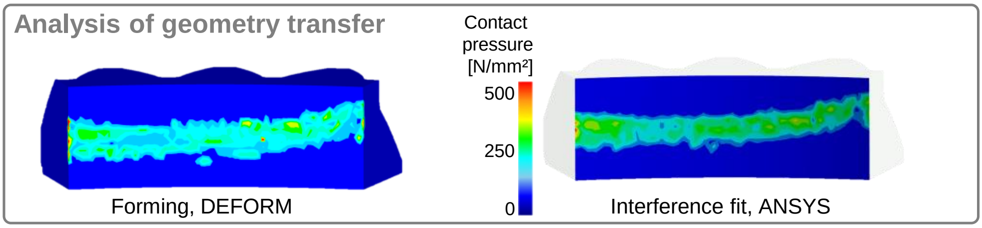

Figure. 3.3: Display of contact pressure between gear ring and wheel body after forming (DEFORM) and after interference fit (ANSYS)

In order to investigate the effect of torque a fixed bearing is applied on the inside of the gearwheel. Since a torque of 400 Nm is targeted a constant force of 8,858.2 kN is applied at the diameter of 90.31 mm.

4 Results

4.1 Structural analysis of stapled sheet metal wheel body

Figure 4.1 (three pictograms on the right) shows the wheel body's contact pressure and status as well as von Mises stresses right before the press fit fails. As the outer ring of the wheel body is supported at twelve points only, the pressure distribution in the press fit is inhomogeneous. This is due to the changing radial stiffness. Contact status shows that areas with higher contact pressure start to slip later than the ones with lower contact pressure. Therefore, areas in between supporting structures hardly contribute to the press fit. Von Mises stresses are within a range, where the material's possibilities are not yet used completely.

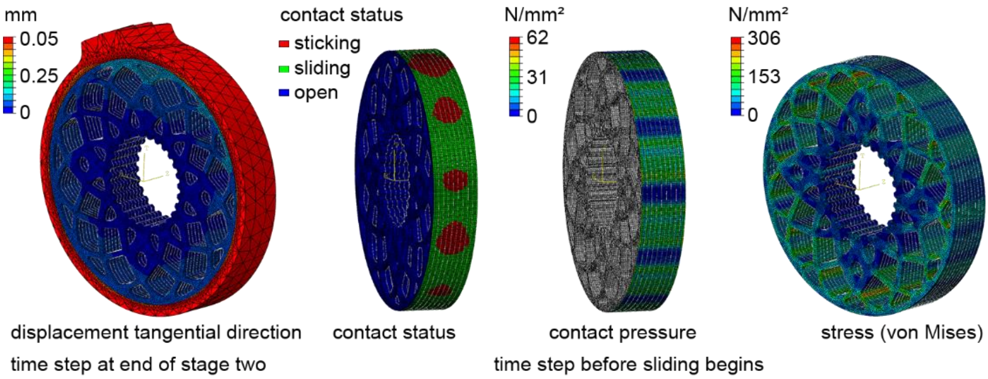

Figure. 4.1: Illustration of the numerical model in Abaqus, contact and stress results

Figure 4.2 shows the numerically determined torque a gearwheel with a stapled sheet metal wheel body can transfer. At the beginning, torque increases linearly with time. Once sliding begins, torque increasing slows down until it reaches a limiting value. This limiting value is 250 Nm. It will be increased by adapting the wheel body's lightweight design, to achieve a homogeneous pressure distribution in the press fit.

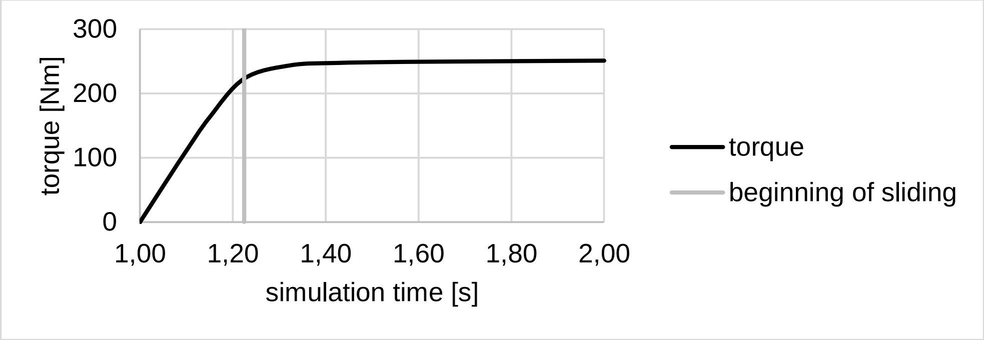

Figure. 4.2: Numerically determined torque the press fit can support

4.2 Structural analysis of lateral extruded (forged) gearwheel body

First, the torque will be examined. In order to proof that the initial torque was transmitted to the shaft the moment reaction and the change of friction needs to be investigated. In order to proof that the torque is transmitted from teething to inner shaft the moment reaction on the inside and the change of friction will be displayed. In figure 4.3 left, the diagram depicts the torque on the teething and the received torque on the shaft. For all three variants, the targeted torque was achieved without any noticeable difference. On the right of figure 4.3 the change of contact status is displayed for version three (eccentricity e = 2.0 mm, cavity of c = 2.0 mm). First, the interference fit will be calculated. During torque application no significant change in contact was detected.

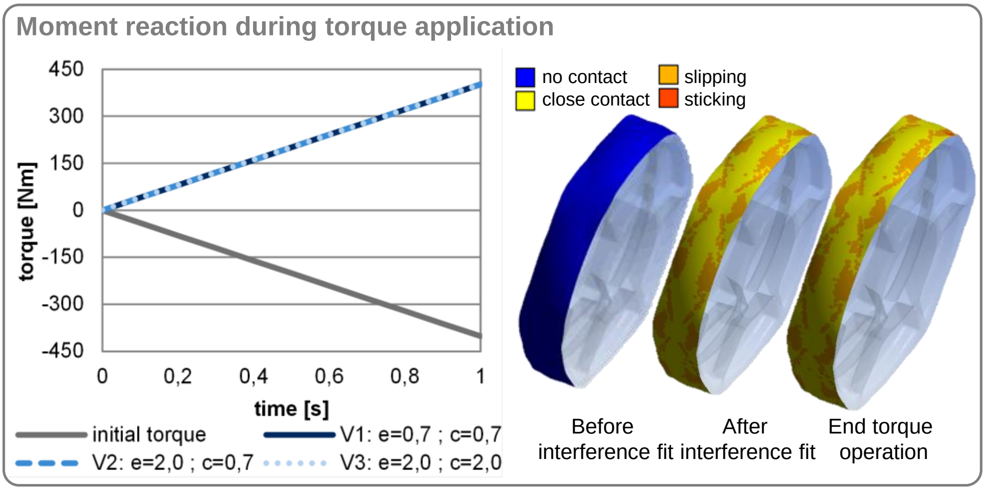

Figure. 4.3: Moment reaction during torque application for three different inner gear ring profiles and corresponding contact status

Figure 4.4 shows the wheel body's displacement, contact pressure and status as well as von Mises stresses at a torque load of 400 Nm. The contact pressure displays a non-uniform distribution along the surface between gear ring and wheel body resulting from the epitrochoid inner profile.

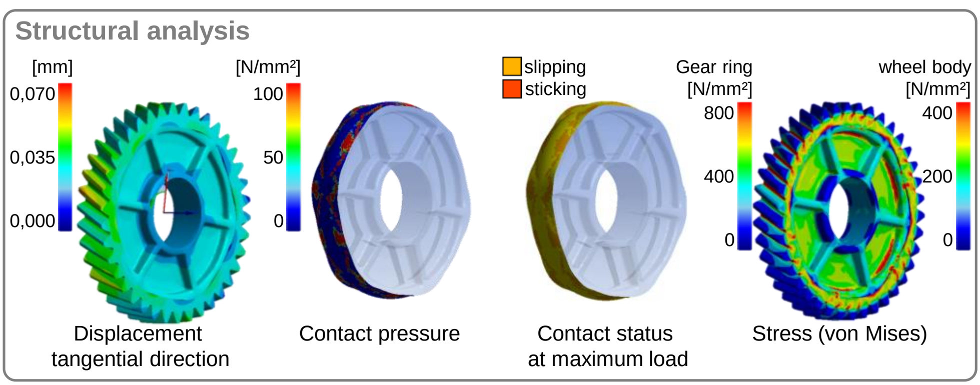

Figure. 4.4: Illustration of the numerical model in Ansys, contact and stress results at 400 Nm torque

The contact status at maximum load displays larger slipping than sticking regions. Sticking regions with high contact pressure occur in areas where the inner gear ring profile has extensions providing an additional form fit. Von Mises stresses are within an acceptable range. The stresses are displayed for the gear ring material 18CrNiMo7-6 and the wheel body material C15 respectively.

5 Conclusion

The two wheel bodies presented in this paper show different torque capacities. While the forged wheel body is supporting the design load completely, the stapled sheet metal alternative fails at 250 Nm due to the press fit. This value might be increased, but simulations with a stapled sheet metal wheel body without a light-weight structure show, that the maximum torque to reach is 325 Nm. So, the forged wheel body is the first choice for high torque. Manufacturing of the stapled sheet metal wheel body will be possible at lower cost though, since there is no need to apply a complex shaped inner surface to the gear ring. Furthermore, blanking tools usually generate more output per time while having a higher lifetime than forging tools. In the end, it will be the end users choice, which wheel body fulfils the requirements best.

6 Acknowledgement

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7 References

[1] Meissner, R., Liewald, M., 4.-7. Juli 2016: Numerical investigations of multicomponent lightweigth design for joining gearwheels by lateral extrusion; NUMIFORM 2016, Troyes, Frankreich

[2] Meißner, R., Liewald, M., 2016: Verfahrenskonzept zur umformtechnischen Herstellung von gebauten Zahnrädern im Mehrkomponentenverfahren mittels Quer-Fließpressen, 7. VDI-Fachtagung Welle-Nabe-Verbindungen; Paper reviewed und angenommen

[3] Meißner, R.; Liewald, M.; Weiß, A.: 2016: Numerische Untersuchungen zum Einfluss der Vorspannung auf gefügte Zahnräder; 23. Sächsische Fachtagung Umformtechnik, Dresden

[4] Mattheck, C.; Schäfer, J.: 2010; Denkwerkzeuge nach der Natur; 1. Auflage, Karlsruher Institut für Technologie –Campus Nord