

Forschung im Ingenieurwesen

Manufacturing Processes for Multi-component Gearwheels

--Manuscript Draft--

Manuscript Number:	FIIN-D-17-00059R2	
Full Title:	Manufacturing Processes for Multi-component Gearwheels	
Article Type:	S.I. : VDI International Conference on Gears 2017	
Funding Information:	Research Association for Steel Application (FOSTA) supported by the Federal Ministry of Economic Affairs and Energy (IGF-Nr. 18189 N)	Not applicable
Abstract:	<p>Gearwheels in automotive applications are usually designed as monolithic parts. Adapting the concept of multi-component design to those applications allows to reduce the car's weight. The presented multi-component gearwheels consist of three pieces: a gear ring including teeth, a shaft and a wheel body that connects shaft and gear ring. Two gearwheel concepts as well as the corresponding joining strategy of gear ring and wheel body are introduced in this paper. First manufacturing concept is about the wheel body stapled by fine blanked sheet metal layers. Gear ring and wheel body are joined by a press fit. The second concept focuses on manufacturing the wheel body by lateral extrusion of a metal disk. Using the gear ring as the die in the forging tool allows manufacturing the wheel body as well as joining wheel body and gear ring simultaneously. The authors investigate both production processes virtually and compare both gearwheels designs regarding load and lightweight potential.</p>	
Corresponding Author:	Robert Meißner Institute for Metal Forming Technology Stuttgart, GERMANY	
Corresponding Author Secondary Information:		
Corresponding Author's Institution:	Institute for Metal Forming Technology	
Corresponding Author's Secondary Institution:		
First Author:	Robert Meißner	
First Author Secondary Information:		
Order of Authors:	Robert Meißner	
	Tim Benkert, Dipl.-Ing.	
	Maria Hiller, Dipl.-Ing.	
	Mathias Liewald, Prof. Dr.-Ing.	
	Wolfram Volk, Prof. Dr.-Ing.	
Order of Authors Secondary Information:		
Author Comments:		
Response to Reviewers:	<p>Reviewer #2: Please think of a better solution for the right diagram in figure 4. The caption of the X-axis is not clear.</p> <p>The caption in figure 4 itself as well as the caption of the diagram have been adapted. I hope, they are easy to understand now.</p>	

Manufacturing Processes of Multi-Component Gearwheels

Authors:

R. Meissner, M. Liewald

University of Stuttgart, Institute for Metal Forming Technology (IFU)/
Germany

T. Benkert, M. Hiller, W. Volk

Technical University of Munich, Institute of Metal Forming and Casting (utg)/
Germany

Corresponding author:

R. Meissner,

University of Stuttgart

Institute for Metal Forming Technology (IFU)

Holzgartenstraße 17

70174 Stuttgart

Germany

1 Introduction

Due to increasing stringent restrictions concerning the CO₂ emissions until the year 2020, the automobile manufacturers aim at reducing their cars' emissions. Lightweight design is 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 [1]. Gearwheels in the gearbox will serve as an example here. They are made from high strength steels due to high loads close to the tooth root [2]. Apart from these small areas, the material's capabilities stay unused. Multi-component (differential) design (figure 1) allows to reduce the gearwheel's weight while enhancing material use. 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. In this paper, it is investigated how the additional shaft-hub joint and a lightweight wheel body affect the transferable torque of the gearwheel. Two different wheel body concepts that are based on the manufacturing processes forging and stapling fine blanked sheet metal are introduced. Gear ring and shaft provide geometrical and mechanical boundary conditions that have to be considered while designing the wheel bodies and the corresponding manufacturing processes. Geometry and mechanical properties of gear ring and shaft are derived from the gearing of the fourth gear of a commercial vehicle. This reference gearing leads to a gear ring with characteristic values shown in figure 1. The gearing's module is 2.00 mm with a helix angle of 30° and the shaft corresponds to DIN 5480 WA 30 x 1 x 28 x h6 x 9e. The inner side of the forged wheel body is machined after forging to use the same shaft geometry for testing. Stapled sheet metal wheel bodies use gear rings with cylindrical inner geometry. For forged wheel bodies the gear ring's inner geometry is of a more complex shape. A general objective is to choose a wheel body design that reduces the gearwheel's weight by at least 25 %.

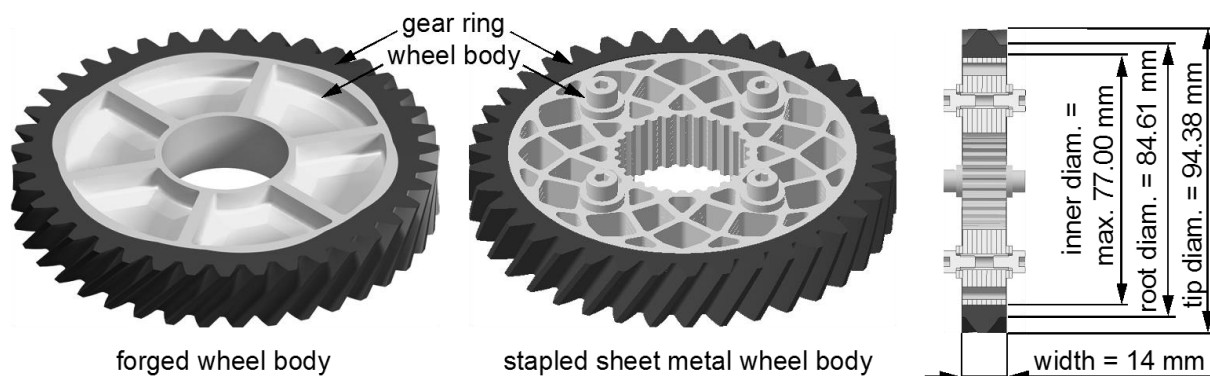


Figure 1: Multi-component gearwheels made by different manufacturing processes

2 Stapled sheet metal wheel body

Figure 2 (left) shows the CAD model of a stapled sheet metal wheel body. Each sheet metal layer is manufactured separately. In the experimental setup used here, the wheel body's inner geometries (gear shaft pocket, four holes for connectors, lightweight geometry) are laser cut. Subsequently, the outer circular geometry is fine blanked. Considering an industrial

process with high lot sizes, fine blanking of all geometries would be reasonable. Finally, the wheel body's height is achieved by stapling nine sheet metal layers. To join wheel body and gear ring the wheel body's sheet metal layers have to be aligned and fixed, which is ensured by connector elements here. This could be done with stacking after stamping in an industrial process. Wheel body and gear ring are joined directly after heat treatment of the gear ring. While the gear ring is still hot, it is aligned with the wheel body. With decreasing temperature, the gear ring shrinks onto the wheel body. Afterwards, the connectors are removed.

Fine blanking is a special cutting technique that generates functional surfaces without subsequent machining. In this case, the process parameters shown in table 1 are used for fine blanking. Figure 2 right shows the 2D contour of a sheared edge of a fine blanked sheet metal used to build wheel bodies. Clean shear height h_S is close to sheet metal thickness s leading to a clean shear share of 95 %. With $\alpha = 87^\circ$ the clean shear angle is lower than the target angle of 90° . A correction of cutting clearance towards positive values would increase it [3]. Further investigations on the influence of clean shear angle on the gearwheel's mechanical properties will show, if a correction of cutting clearance is necessary. The lightweight geometry is designed using Mattheck's torque anchor method [4, 5].

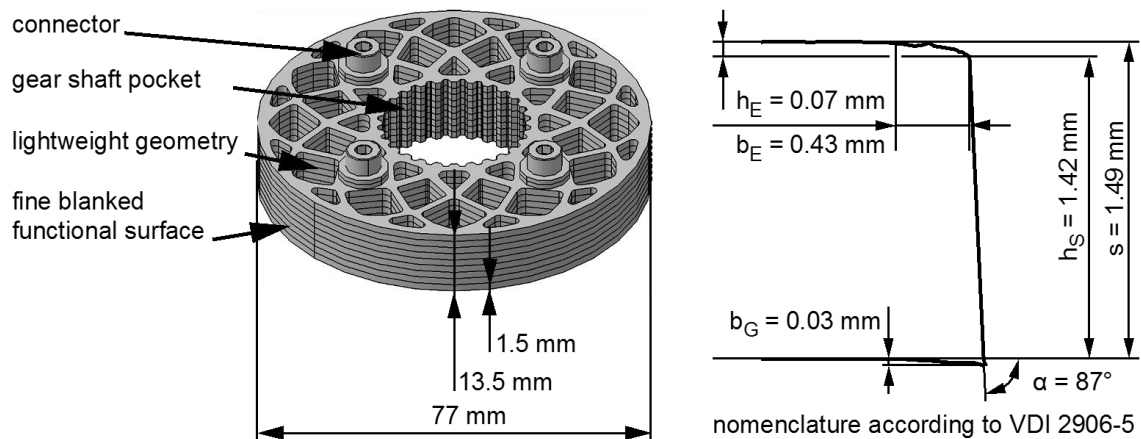


Figure 2: Stapled sheet metal wheel body (left) and 2D contour of a sheared edge of a fine blanked sheet metal (right)

Table 1: Process parameters used for fine blanking of sheet metal

Parameter	Punch corner radius	Die chamfer	V-ring	Cutting clearance
Value	0.05 mm	30° x 0.15 mm	none	-10 μ m
Parameter	Counter punchforce	V-ring force	Material	Material thickness
Value	100 kN	500 kN	CR700Y980TDP	1.5 mm

3 Numerical model setup for the gearwheel with stapled sheet metal wheel body

A two-stage FEM model is built in Abaqus 6.12-3 to investigate the wheel body's mechanical properties. Both stages use the Abaqus implicit solver. The first stage applies the press fit between gear ring and wheel. The interference needed therefore is geometrically modelled. The second stage rotates the gear ring around the wheel body. Structurally meshing the gear ring with hexahedron elements is difficult due to the teeth, so it is meshed using tetrahedron elements (C3D10M). The wheel body is structurally meshed using hexahedron elements (C3D8R). Meshing is critical especially in the 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 similar surface meshes in the contact area on both contact partners and that there are at least three elements covering the thickness of one sheet metal layer. Contact occurs between gear ring and wheel body as well as between the sheet metal layers of the wheel body. The surface-to-surface algorithm with finite sliding describes the contact behavior, while the contact formulation defines normal and tangential interaction behavior. In normal direction, hard contact is set to omit overlapping in the press fit and in the wheel body. A penalty contact describes the tangential behavior using a friction value of 0.1. There are two boundary conditions within the model. Clamping a reference point in the center of the gearwheel is the first one. That reference point and the tooth flanks of the wheel body's gear shaft pocket are connected via kinematic coupling to hold the wheel body in place. This boundary condition is active in both stages. The second boundary condition applies a rotational displacement onto the gear ring and becomes active in the second stage. Elastic-plastic material models with the material properties shown in table 2 describe the material behavior in both parts.

Table 2: Material properties of wheel bodies and gear ring used in the FEM models

<i>Properties</i>	<i>Unit</i>	<i>Forged wheel bodies</i>	<i>Stapled sheet metal wheel body</i>	<i>Gear ring</i>	
Material	[-]	C15	Al 6082	CR700Y980T-DP	18CrNiMo7-6
E-Module	[N/mm ²]	210	70	213	210
Tensile strength	[N/mm ²]	400	260	980	835
Poisson ratio	[-]	0.3	0.3	0.3	0.3
Density	[g/cm ³]	7.87	2.7	7.8	7.77

4 Forged wheel body

The forging process of an assembled gearwheel will be performed by lateral extrusion of a blank placed between shaft and gear ring. Therefore, wheel body and gear ring have to be prepared separately. The forging process uses a completely finished gear ring. Gear hobbing and hardening are conducted before joining. Additionally, an out-of-round turning process produces an epitrochoid shape with six extensions at the inner side of the gear ring. This leads to varying inner diameters between 73 mm and 77 mm. The inner profile contains six 2 mm deep cavities in radial direction to enable a form and force fit in tangential and axial direction [6].

A tool in a one-stage hydraulic press performs the actual joining process (figure 3). Placing the gear ring between six preloading die segments prevents impermissible tangential tension stress in the gear ring during and after forming. An inner mandrel guides the blank. The upper punch initiates and conducts the lateral extrusion process. In order to obtain a symmetric homogenized lateral extrusion process on a one-stage hydraulic press, using a hydraulic closing device, equipped with hydraulic chamber and nitrogen storages, is necessary.

Previous research investigated the influences of the inner gear ring profile on punch force and material flow. Geometric parameters of tool and blank regarding material flow [6] and the tool concept resulted from this research [7].

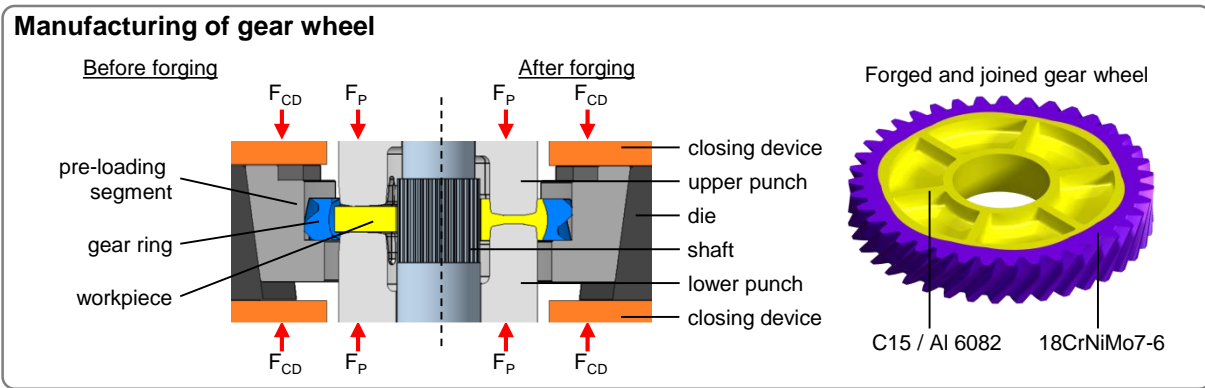


Figure 3: Manufacturing of the joined gearwheel by lateral extrusion

5 Numerical model setup for the gearwheel with forged wheel body

Two simulations were conducted – the forging process in DEFORM 3D and a subsequent structural analysis in ANSYS. The forging process uses the tool geometry described in [6]. Hence, the punch consists of six segments that produce an overall wheel body wall thickness of 3 mm. In order to save computing time, the calculation uses the smallest geometry model possible by considering axial and rotational symmetries. Blank and gear ring consist of 80.000 tetrahedral finite elements and are regarded elastic-plastic during forming. The structural analyses in ANSYS needs full body geometries as input data due to the unsymmetrical load. Creating these geometries takes place in CATIA V5 using the results from DEFORM 3D after an additional springback calculation. Due to this spring back calculation the geometries of gear ring and wheel body show interferences at the contacting surfaces. Therefore, an interference adjustment is the first step to obtain the same contact conditions in ANSYS as were present in DEFORM 3D before the springback calculation [4]. In the second step the inner side of the gearwheel is fixed and the gear ring rotated around the wheel body. Structural analyses of the stapled sheet metal wheel body uses the same load case. Simulation runs until plastic deformation within the wheel body occurs or until the torque of the reference gearing is reached.

6 Results

Figure 4 shows the results of the simulations regarding von-Mises stresses, displacement and maximum torque for the stapled sheet metal wheel body. Stress distribution within the wheel body is quite even. Displacements in a stapled sheet metal wheel body at failure are smaller than those of a monolithic gearwheel, but the torque is as well. The diagram in figure 4 shows torque and tangential displacement for the reference gearwheel, gearwheels with stapled sheet metal wheel bodies without and with a lightweight structure. Displacement is taken from the middle of a randomly chosen tooth tip just before the press fit fails. Without a lightweight structure the gearwheel reaches a torque of 333 Nm and the maximum displacement at this state is 0.01 mm. With a lightweight structure the gearwheel fails at a torque of 283 Nm and a maximum displacement of 0.02 mm. Differences in torque and displacement are based on the higher stiffness of the wheel body without a lightweight structure. This leads to decreased contact pressure in the press fit.

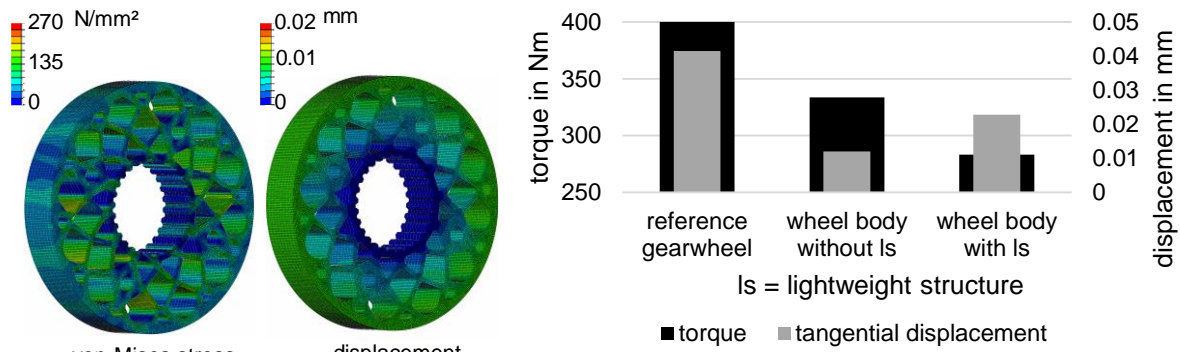


Figure 4: Simulation results for stapled sheet metal wheel body

Figure 5 shows von-Mises stresses and tangential displacement of the forged wheel bodies made of aluminium Al 6082 and steel C15. While the aluminium wheel body fails at 335 Nm, the steel wheel body transmits the reference torque. The non-uniform displacement mirrors the combined press and form fit that results from the non-circular inner gear ring profile.

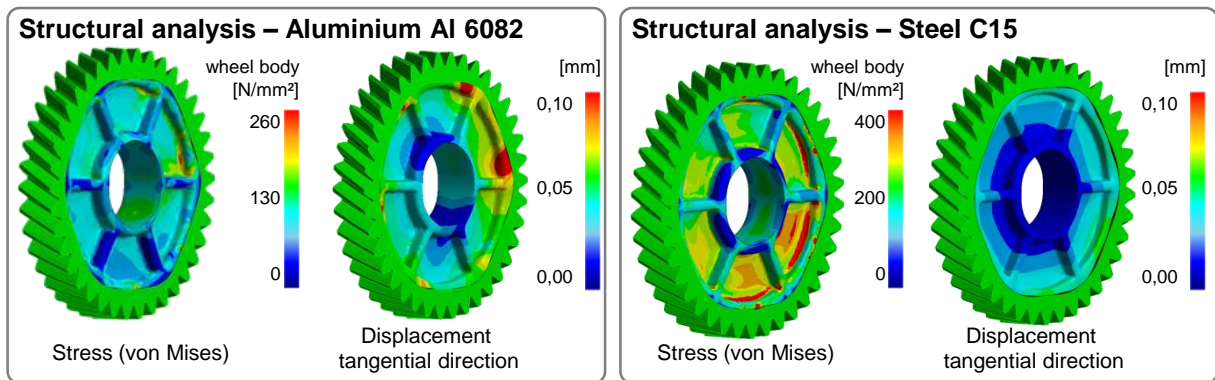


Figure 5: Stress and displacement of forged aluminium wheel body at 335 Nm torque and forged steel wheel body at 400 Nm torque

In figure 6, a comparison between the three different wheel bodies regarding torque and weight is shown. All wheel bodies reach the lightweight objective. The forged wheel body made of aluminium achieves the best torque to weight ratio.

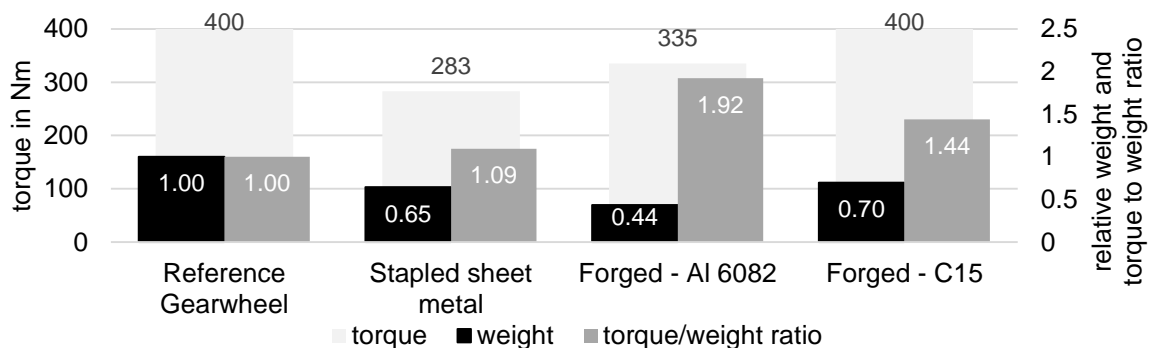


Figure 6: Comparison between the wheel bodies regarding torque, weight and torque to weight ratio

7 Conclusions

Both manufacturing concepts for wheel bodies reach the lightweight objective. The forged wheel bodies support higher loads than the stapled sheet metal wheel body. So, a forged wheel body is the first choice for weight critical, high torque applications. Manufacturing of the stapled sheet metal wheel body will be cheaper though, since there is no need for a complex shaped inner surface at the gear ring and blanking tools usually generate more output per

1 time while having a higher lifetime than forging tools. The forging process needs less process
2 stages than the fine blanking process, since forging the wheel body and joining it with the
3 gear ring is done simultaneously. Finally, it is up to the end user to decide, which
4 manufacturing process fulfils the requirements best.
5
6

7 **8 Outlook**

9 Further investigations will show, if using different FE solvers for the structural analysis
10 influences the results.
11

12 Our project partners (see chapter 9) in Bremen will join the stapled sheet metal wheel body
13 with the gear ring. Afterwards, the partners in Munich perform intensive testing of the
14 assembled gearwheels. This includes deformation, maximum torque and fatigue tests.
15
16
17

18 **9 Acknowledgment**

19 The research project “Intelligent lightweight design through multi-
20 component processes” (IGF-No. 18189 N) of the Research Association for
21 steel Application (FOSTA), Heat Treatment and Material Engineering
22 Association (AWT), Research Association for Drive Technology (FVA) and
23 Research Association of Steel Forming (FSV) is supported by the Federal
24 Ministry of Economic Affairs and Energy through the German Federation of Industrial
25 Research Associations (AiF) as part of the program for promoting industrial cooperative
26 research (IGF) on the basis of a decision by the German Bundestag.
27
28
29
30
31
32
33

Supported by:



on the basis of a decision
by the German Bundestag

34 The authors want to thank their project partners Christoph Leonhardt, Michael Otto, Karsten
35 Stahl (all three from the Gear Research Centre, Technical University of Munich), Dawid
36 Nadolski, Holger Surm and Hans-Werner Zoch (all three from the Stiftung Institut für
37 Werkstoffwissenschaften, Bremen) for the collaboration.
38
39
40
41

42 **10 Literature**

- 43 [1] Severin, F.: Massiver Leichtbau. Potenziale massivumgeformter Komponenten. Hagen:
44 Industrieverband Massivumformung e. V 2014
- 45 [2] Niemann, G., Winter, H. u. Höhn, B.-R.: Konstruktion und Berechnung von Verbindungen,
46 Lagern, Wellen. Maschinenelemente, Bd. 1. 2005
- 47 [3] Hörmann, F.: Einfluss der Prozessparameter auf einstufige Scherschneidverfahren zum
48 Ausschneiden mit endkonturnaher Form. Technische Universität München. utg-
49 Forschungsberichte, Bd. 46. München: Hieronymus 2008
- 50 [4] Meissner, R., Benkert, T., Liewald, M. u. Volk, W.: Lightweight gearwheel design using
51 separate gear ring and wheel body. Part II: Different manufacturing concepts for replacing
52 a full body gearwheel. Steels in Cars and Trucks 2017 Proceedings. 2017
- 53 [5] Mattheck, C.: Denkwerkzeuge nach der Natur. Karlsruhe: Karlsruher Inst. für Technologie
54 - Campus Nord 2010
- 55 [6] Meissner, R. u. Liewald, M.: Numerical investigations of multicomponent process
56 lightweight design for joining gearwheels by lateral extrusion. MATEC Web of
57 Conferences 80 (2016), S. 13005
- 58 [7] Meissner, R. u. Liewald, M.: Verfahrenskonzept zur umformtechnischen Herstellung von
59 gebauten Zahnradern im Mehrkomponentenverfahren mittels Quer-Fließpressen. 7. VDI-
60 Fachtagung Welle-Nabe-Verbindungen. Gestaltung - Fertigung - Anwendungen. VDI-
61 Berichte, Bd. 2287. Düsseldorf: VDI-Verlag GmbH 2016
62
63
64
65