A METHODOLOGY FOR THE APPLICATION OF VIRTUAL EVALUATION METHODS WITHIN THE DESIGN PROCESS OF COLD FORGED STEEL PINIONS

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ABSTRACT

Gears are essential machine elements in the drivetrain and transmission technology. The operational behaviour of a gear pairing is influenced by the design of the gear kinematics as well as the component properties. With regard to an improvement of performance and service life, the targeted modification of tooth geometry and component properties offers a promising approach. Thus, the achievable geometric and mechanical component properties are influenced by the manufacturing process, which must be taken into account in the design process. The application of virtual evaluation methods is suitable for this purpose. For the manufacturing of steel gears, cold forging provides the potential of achieving beneficial mechanical properties in a highly productive process. Major challenges for the industrial application are the short service life of the cost- intensive tools and the low geometric accuracy in comparison to machining processes. Within this study the design of the tooth geometry as well as the associated forming tool are investigated. The aim is to derive recommendations regarding an optimization of the resulting component properties and operational behaviour.

Keywords: Design process, Simulation, Numerical methods, Gear design, Manufacturing processes

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1 INTRODUCTION

Gears rank among the most essential and common machine elements (Klocke, 2017). Large quantities of geared components are used in the automotive sector as well as in all fields of mechanical engineering. In order to obtain an improvement of gear performance and service life, targeted modifications of tooth geometry and component properties offer a promising approach. At the same time, a sustainable and efficient manufacturing is of major importance and processes, such as injection moulding and extrusion, offer potential for an economic production. Within the allocated research project, a demonstrator consisting of a steel-plastic gear paring was chosen in order to investigate the design processes of the plastic wheel and steel pinion (Heling, *et al*., 2017). The application of the material pairing offers great potential in regards to lightweight design and improved running behaviour, as it combines the specific advantages of both materials (Niemann & Winter, 1980). In this research work, the focus is on the application of cold forging for the manufacturing of the steel pinion. Cold forging offers the potential to manufacture components with beneficial mechanical properties in a highly productive process, while achieving excellent material utilization. As a basic extrusion process with comparatively simple process setup, the full-forward-extrusion is suitable to produce hub sleeves, gear shafts and spur gears with average tolerance specifications (Bausch, 2011). However, the industrial application is limited due to high tool loads during forming, which lead to a short service life of the cost intensive tools (Klocke, 2008). On that account, the presented research work analyses influences of the geometry of the gear tooth and the forming tool on the resulting component properties in order to derive design recommendations.

2 OBJECTIVE AND METHODOLOGY

This manuscript was conducted within the framework of a research group, which investigates the design and manufacturing of a demonstrator using virtual validation methods (Heling, *et al*., 2017). The demonstrator consists of a steel-plastic gear paring from which the steel gear is further analysed. Based on the related requirements, the basic gearing data including tooth profile, transmission and centre distance were determined. For the manufacturing of the steel gear a full-forward extrusion process was chosen, as it provides the potential to manufacture components with beneficial mechanical properties in a highly productive process. The achievable component properties and thus the application behaviour of the gearing and the forming tool are significantly determined by measures within the design process. In this context, the presented paper investigates the impact of influencing parameters within the design of the tooth and tool geometry on the component and process properties and thereby the operational behaviour. The applied methodology is shown in Figure 1.

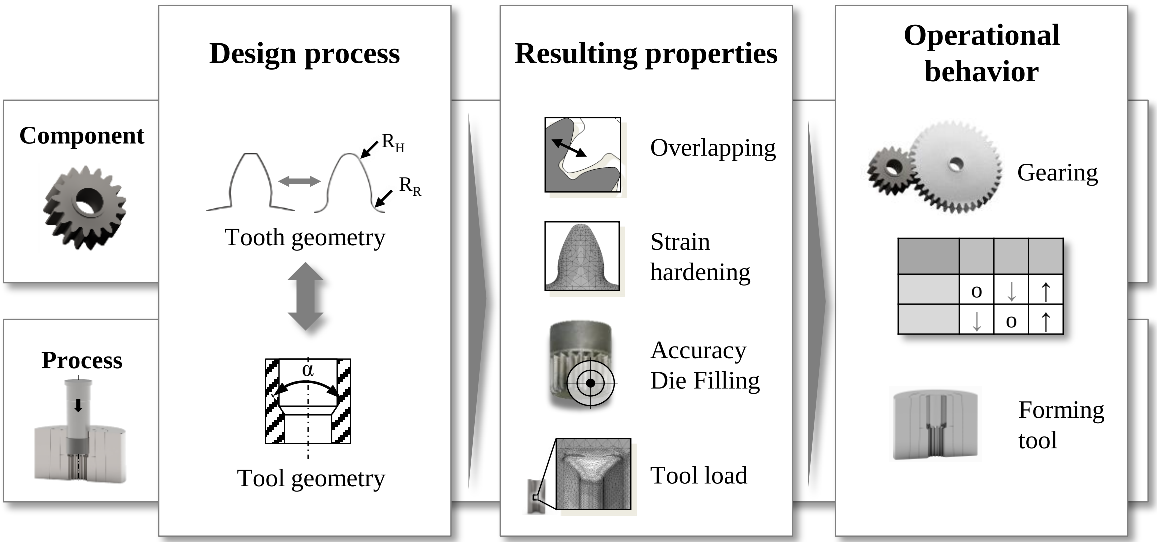

Figure 1. Methodology within this study

Initially, influencing parameters within the component and process design were selected. These are the tooth geometry of the steel gear and the tool geometry of the cold forging tool. The design of the tooth

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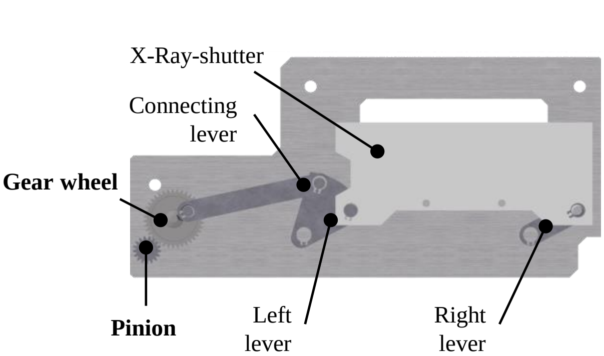
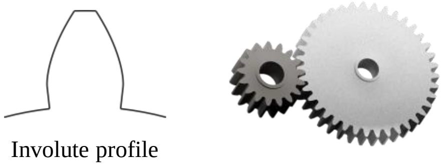
geometry does not only affect the gear kinematics and tooth contact (Klocke, 2017), but also the forming process with regard to tool load and achievable accuracy (Lange, *et al*., 2008). On the other hand, the design of the full-forward extrusion die affects the mechanical and geometrical component properties of the extruded gear. With regard to a load-adapted layout of the die, a trade-off between the component and process properties has to be made. The effects of a variation of the parameters on the resulting component and process properties were analysed, using a virtual process model. This allows an evaluation of the operational behaviour of the gear and forming tool. Based on the results, recommendations regarding influencing design parameters are derived in order to assist a targeted component and process design.

3 INVESTIGATED GEARING AND MANUFACTURING PROCESS

Within the associated research group, an X-ray shutter located between the X-ray source and the irradiated object is used as a demonstrator. It serves to limit the irradiation to the object. In the kinematics of this X-ray shutter, a gear wheel is driven by a steel pinion (Figure 2).





	Pinion	Gear wheel
Module	1	1
Number of teeth	17	39
Profile shift	0.2045	-0.3138
Tooth width	8 mm	6 mm
Material	16MnCr5	Ultramid® A3
Manufacturing	Extrusion	Injection molding

Figure 2. Demonstrator assembly and investigated gear pairing according to (Heling, et al., 2017)

This gear drives the left lever via a connecting lever, which in turn guides the X-ray aperture around a parallel kinematic curve. The demonstrator allows investigating the influence of the individual part tolerances on the application behaviour within further research. Precise manufacturing of the components is indispensable in X-ray aperture kinematics, since component deviations influencing the movement behaviour, which could lead to the object being exposed to an excessively high or low radiation dose (Heling, *et al*., 2017). Nevertheless, not only the tolerances but also the choice of nominal dimensions is decisive for the kinematic behaviour of the mechanism. For example, if the geometric deviations are identical, a system can be made more robust by selecting the nominal dimensions (Heling, *et al*., 2018). On that account, the design of the gearing (Figure 2) is briefly discussed. For the gear pairing an involute tooth profile was determined, as it enables uniform and constant transmission of motion. Furthermore, the profile reduces sliding between pinion and wheel and thereby decreases wear during operation (Klocke, 2017). In order to maintain the required centre distance, a profile shift was added to the paring.

When determining the remaining gear parameter, the manufacturing process has to be taken into account. Due to production restrictions, head and tooth radii are necessary for the manufacturing of the steel pinion by cold forging (Kawasaki, 2007). The choice of the head radii influences the gearing overlap (DIN 3990). The overlapping must be larger than one to ensure functionality, whereby a larger overlap is particularly advantageous with a small number of teeth, such as that of the steel pinion under investigation. (Radzevich, 2017). The tool system for the cold forging of the steel pinion is shown in Figure 3.

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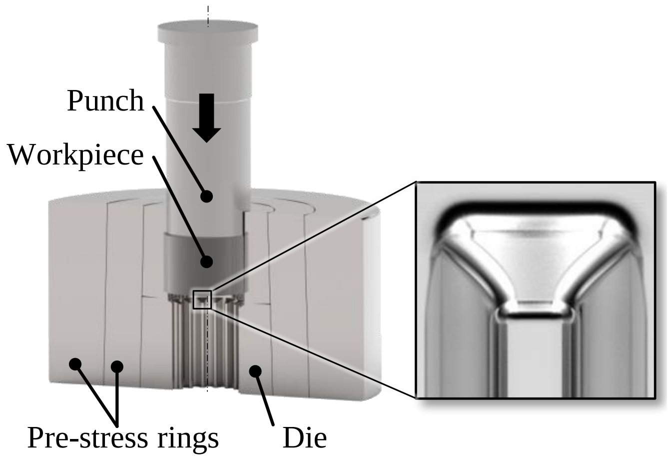

Figure 3. Process setup for the cold extrusion of gears

During the process, the cylindrical workpiece is pressed through the geared die with a punch. The material flows in longitudinal and radial direction while forming the tooth geometry. Due to great required forming forces, a high internal pressure results in the die (Schuler, 1998). This leads to tensile stresses which are critical in regards to fatigue fracture and wear (Lange, *et al.*, 2008). On that account, a pre-stress system consisting of two pre-stress rings is used according to VDI 3176, in order to apply sufficient compressive preload (VDI 3176).
The effects of influencing parameters within the design process on the resulting component as well as process properties are determined using a virtual process model. The numerical evaluation allows avoiding cost-intensive pre-tests. Within this investigation the finite element forming simulation software simufact.forming 14.0.1 is used. The FE model is built from the active tool components including the die, pre-stress rings, punch, ejector and the workpiece. The analysis is performed in two subsequent steps in order to determine the component properties and the tool loads. Initially, the material flow during tooth forming is simulated with rigid tool components. This allows a prediction of component properties as well as forming forces and contact stresses during the forming operation. The influence of an elastic deflection of the die is neglected in this stage. In the next step, the results of the material flow simulation are transferred to a decoupled simulation with elastic tool components for an evaluation of the occurring tool load. In order to ensure a realistic representation of the material behaviour in the simulation, the required input variables were determined in laboratory tests. In compression tests, the flow curve of the case hardening steel 16MnCr5 are recorded up to a forming degree of 0.8 and approximated for higher forming degrees according to the Hockett-Sherby approach (Hockett & Sherby, 1975). Double cup extrusion tests were performed to evaluate the tribological conditions and the associated friction factor (Lorenz, *et al.*, 2018). The prognosis quality of the virtual process model was confirmed by forming tests. For this purpose, components with reference geometry of the tooth and forming tool have been produced and the resulting component and process properties were aligned with the simulation (Figure 4).

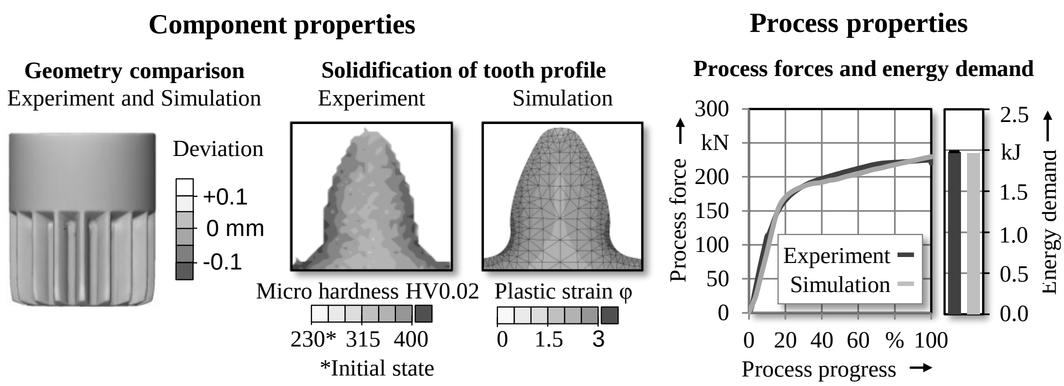

Figure 4. Validation of the virtual process model

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The evaluation of geometric deviations between the simulated gear and the experiment shows good agreement over the entire gear height. In order to evaluate the resulting solidification of the manufactured tooth profile, the micro hardness was measured at the medium width. The measurement indicates a strong solidification of the surface of the tooth profile, especially in the area of the tooth flank and root. The hardness increases from the initial state at 230 HV up to 400 HV in the tooth root in the course of the process. This solidification is caused by plastic deformation during forming (Lange, *et al.*, 2008). Thus, in the simulation the plastic strain can be evaluated in order to draw conclusions about the resulting solidification. The comparison of the micro hardness from the experiment and the plastic strain from the simulation provides a good qualitative prediction of the hardness distribution. With regard to the force curve and maximum process force as well as energy requirement, there is good agreement with deviations of less than 3%. Due to the good prognosis quality, the validated process model is used for the investigation of influencing variables in the further course of this research.

4 INFLUENCING PARAMETERS WITHIN THE DESIGN PROCESS

Essential design parameters are the gear radii on the component side and the opening angle of the die on the process side. In the following, the influence of the gear radii as well as the opening angle on the resulting component and process properties of cold forged steel gears is examined. Three different variations of the tooth and tool geometry are investigated (Figure 5).

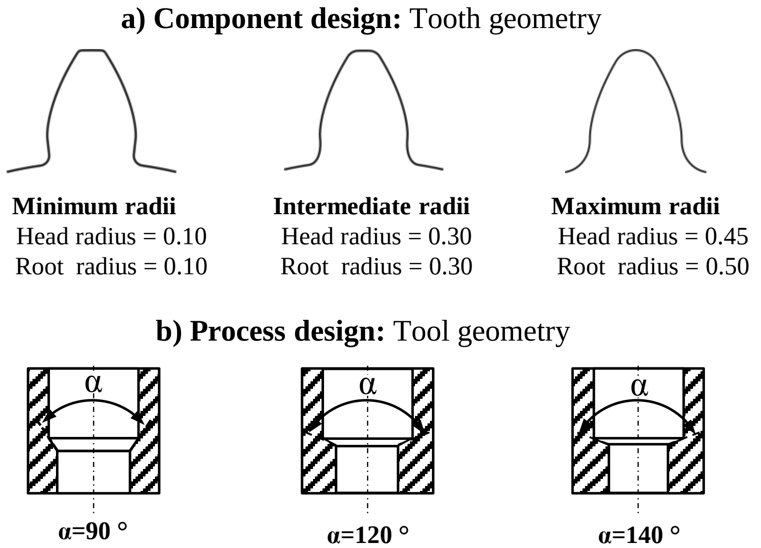

Figure 5: Variation of a) tooth geometry and b) tool geometry within this investigation

Minimum head and foot radii of 0.10 mm are required to enable the production of the tooth profile by cold forging. The maximum possible radii are limited as well. The root radius can be enlarged up to contact with the straight part of the involute. The head radius is limited by a conjunction of the left and right head radius at the tooth tip. On the process side, the opening angle represents the most important parameter within the die design for extrusion (ICFG Document 14/02, 2002). In general, larger opening angles cause greater stress of the die, but at the same time they have a positive effect on the achievable mould filling and strain hardening (König, *et al.*, 1985). Usually the die opening angle is designed in a range from 90 to 140°, with insufficient die filling in the lower area and high tool stress in the upper area affecting the tool lifetime (Lange, *et al.*, 2008). Three different die designs with opening angles of 90, 120 and 140° are examined in the context of this investigation.

5 ANALYSIS OF THE RESULTING COMPONENT AND PROCESS PROPERTIES

The first step is to determine how the choice of the gear radii affects the gear kinematics. For this purpose, the resulting overlap within the gear pairing is examined as a function of the size of the head radius. Figure 6 shows how the overlap decreases, depending on the selected head radii. The gearing overlap is reduced with an increasing head radius, as it limits the length of the active flank. In this

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respect, the minimum possible radii should be chosen in order to enable a precise and continuous transmission of motion. The choice of the die opening angle does not influence the theoretical tooth geometry and thus the overlapping.

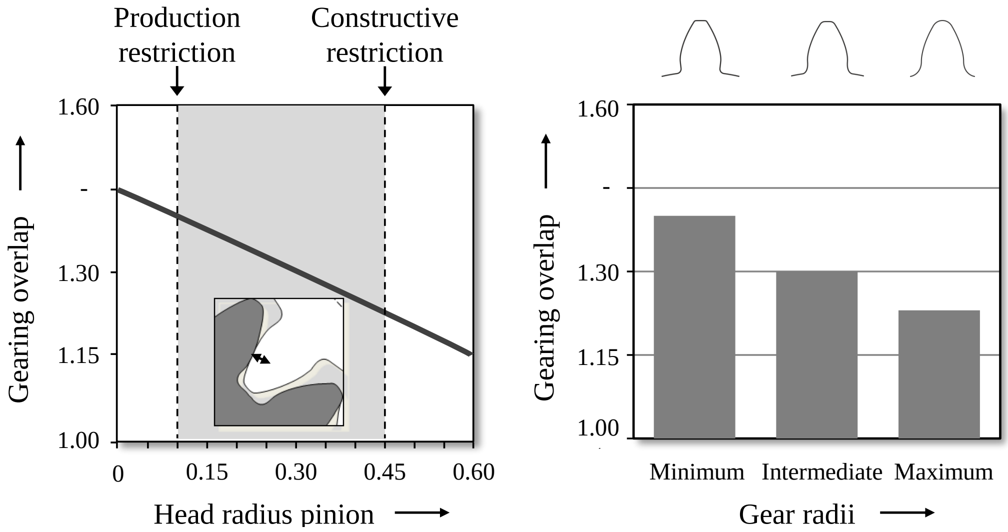

Figure 6. Resulting overlapping within the gear pairing

The plastic deformation in the forming process results in strain hardening, which has a positive effect on the load-bearing capacity of the tooth root and the wear resistance of the tooth flank (Bausch, 2011). From the simulation, a qualitative statement about the strain hardening can be made on the basis of the degree of deformation. The highest strain hardening occurs in the tooth root and in the lower area of the tooth flank. There are low degrees of deformation in the tooth head, since the workpiece diameter already corresponds to the head diameter of the gear and only a minor deformation is required. Figure 7 shows the qualitative and quantitative true strain distribution in dependence of the tooth and tool geometry. The quantitative evaluation was done by a calculation of the local true strain in the tooth head, the tooth flank and the tooth root. For this purpose, the determined true strain values of the FE mesh nodes in the respective areas were averaged.

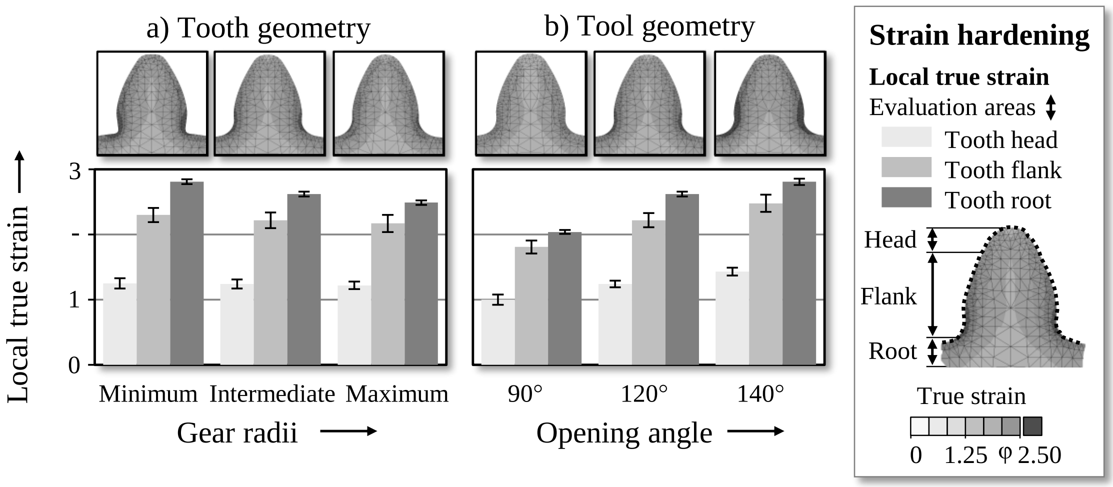

Figure 7. Resulting strain hardening in dependence of a) tooth geometry and b) tool geometry

An enlargement of the gear radii results in a more uniform deflection of the material flow, which reduces the degree of deformation in the tooth root. For minimum gear radii, the average local true strain in the root area is 2.81 and reduced to 2.49 for maximum gear radii. Though, a change in the radii has no effect on the degree of deformation of the tooth flank and the tooth head. An enlargement of the die opening angle causes a more abrupt deflection of the material flow when entering the die cavity (Figure 5 b). This considerably increases the strain hardening over the entire tooth profile. For an opening angle of 90°, the locally evaluated true strain values in tooth root and flank are 1.81 and

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2.04. They are significantly increased to 2.48 and 2.81 at an opening angle of 120°.The solidification enables an improved wear resistance of the tooth flank and an elevated strength of the tooth root.
The high material utilization represents a major advantage for the application of forming processes. In the production of gear wheels by extrusion, however, insufficient die filling represents a key challenge. Insufficiently filled areas of the gear reduce the usable gear height and require an increase of the initial blank height. In order to evaluate the mould filling, a geometric comparison between the simulated and the nominal gear geometry is applied. There are two areas with insufficient die filling, limiting the usable gear height. At the lower part of the workpiece is an inflow area, in which the teeth show a material deficit in the head as well as in the flank area. Due to the low resistance when entering the unfilled die, the material flows axially ahead at the beginning. This leads to an insufficient tool contact of the material in the feed area and thus incomplete mould filling. The development of this inflow area has already been described by Jütte (2008). Furthermore, an impression of the extrusion shoulder of the die remains in the upper part of the workpiece. The height of the shoulder imprint depends on the geometry of the shoulder area, in particular the opening angle. The total formed height of the workpiece is 11 mm for all investigated variants. From this height the insufficiently filled areas have to be removed. In the course of this investigation an insufficient filling is defined as a deviation of the formed tooth geometry from the ideal geometry of more than 0.1 mm. For the reference process with intermediate gear radii and an opening angle of 120°a shoulder imprint of 1.50 mm and an inflow area of 1.45 mm height are determined. This leads to a useable gear height of about 8 mm (73 %), which corresponds to the target height of the steel pinion. Figure 8 shows the determined usable height for the other investigated variants.

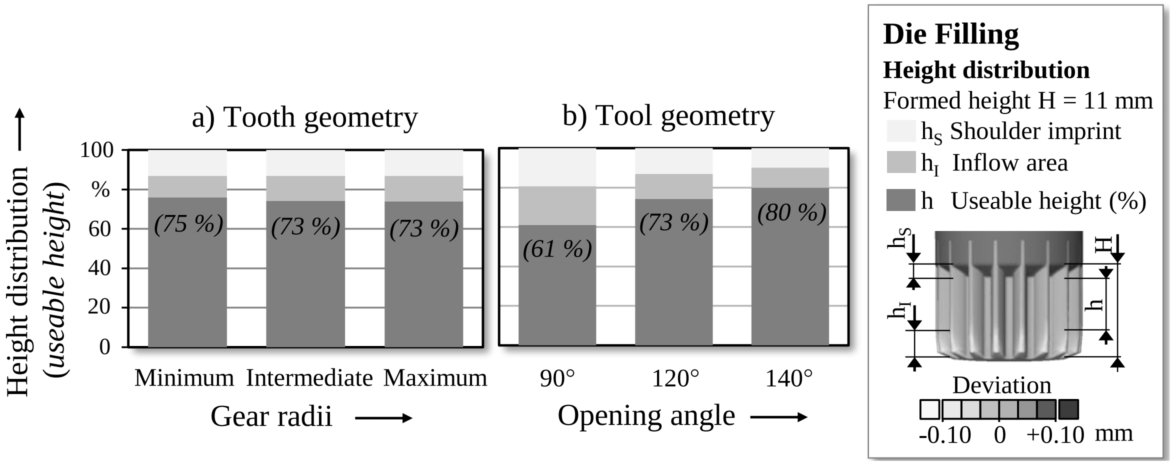

Figure 8. Resulting die filling in dependence of a) tooth geometry and b) tool geometry

The height of the shoulder imprint is not influenced by a change of the gear radii. The inflow area is slightly reduced for minimum head and foot radii, but not affected by further enlargement. An increase of the die opening angle directly reduces the shoulder height (Figure 5 b) of the die and thus also the shoulder imprint. Furthermore, a larger opening angle and reduced shoulder height lead to a more abrupt deflection of the material flow when entering the die. The increased upsetting improves the die filling and reduces the height of the inflow area. Compared to an opening angle of 90° at which a usable height of 61% is achieved, the usable height at an angle of 140° is significantly increased to 80%. This is mainly due to the reduction of the height of the inflow area from 2.35 to 1.05 mm. The improved material utilization allows a significant reduction of the initial blank height and thus material savings.
In the following, the geometry of the gear is further analyzed with regard to the gearing accuracy. The achieved accuracy has a significant influence on the running behaviour of the gear pair and allows an evaluation of the gear quality. The international standard ISO 1328 (ISO 1328-1, 2013) defines the procedure for determining the deviations from the ideal geometry and the assignment of a tolerance class. A standard parameter is the total profile deviation which is evaluated in the transverse section over the medium width of the toothing. In order to determine the profile deviation of the simulated gear geometry, the coordinates of the tooth profile have been exported and the profile deviations were calculated. Figure 10 presents the determined profile deviations of the investigated variants.

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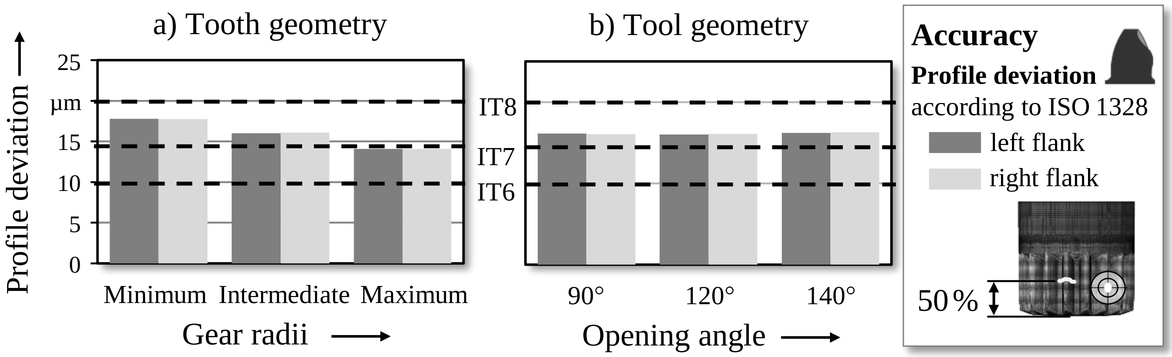

Figure 9. Resulting accuracy in dependence of a) tooth geometry and b) tool geometry

Positive profile deviations of the gearing are measured for all examined geometries. The tooth profile shows an excess of material in the lower tooth root area. With minimal gear radii, the material flow is abruptly deflected, especially in the foot area, and the narrow radii are insufficiently shaped. This results in high profile deviations of about 18 µm, which can be assigned to IT class 8. Enlarging the radii to the maximum possible constructive size encourages the shaping of the tooth profile, whereby profile deviations are reduced to 14 µm and IT class 7 is achieved. A change in the opening angle does not affect the profile deviation at medium gear width. However, as already described in Figure 8, the mould filling in the lower area of the gear is significantly impaired.

On the process side the stress of the tools is determined. The high tool load during extrusion and the associated limited service life of the forming die represent major challenges in the industrial application of cold forging for gear manufacturing. For this reason, the resulting tool load must be taken into account, when designing the tooth geometry and the extrusion die. During the forming process the high internal pressure in the die leads to elevated contact stresses on the tool surface. The largest compressive stresses are exerted on the tip of the teeth of the die. Besides of compressive and tensile stresses there are critical bending stresses overlapping in the shoulder area of the die (Figure 10).

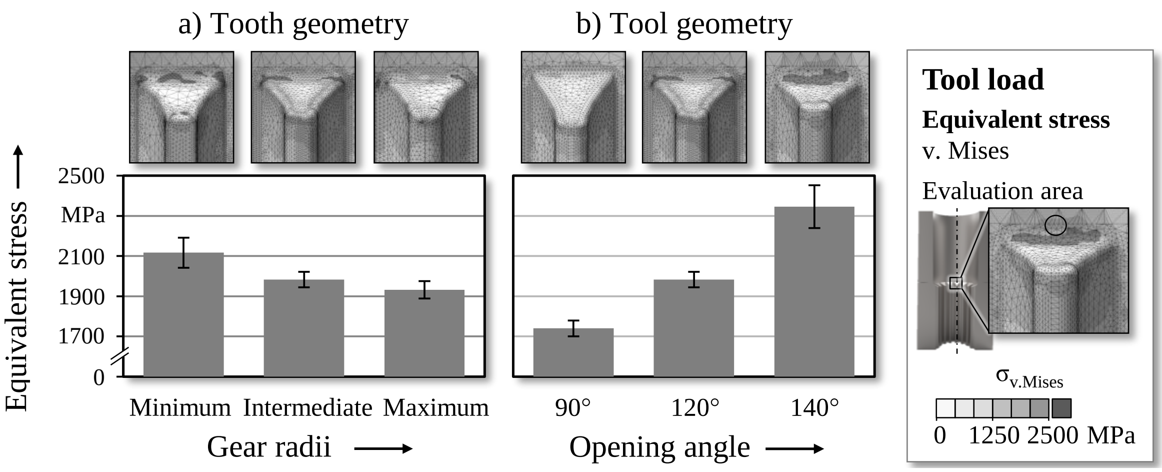

Figure 10: Resulting tool load in dependence of a) tooth geometry and b) tool geometry

The resulting three-axial stress condition is examined by means of the equivalent stress (von Mises). In order to ensure comparability, the equivalent stress is measured at a defined evaluation area located above the die tooth and averaged over five nodes of the FE mesh for all analyzed variants. For minimum gear radii, the equivalent stress is 2117 MPa and is reduced to 1932 MPa for maximum radius size. This can be explained by a less abrupt deflection of the material flow. In addition, a small opening angle of the die leads to a lower deflection of the material flow, which reduces the stress on the die. Compared to an opening angle of 140° and an equivalent stress in the die inlet of 2346 MPa, the stress at an angle of 90° is significantly reduced to 1740 MPa. Commonly applied die materials have a compressive strength of usually not more than 2800 MPa (Lange, *et al*., 2008). Therefore, at a die opening angle of 140° local stress peaks, especially in the shoulder area, are critical with regard to

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fatigue and wear. In this regard the reduction in tool load due to a smaller opening angle is to be evaluated positively with regard to the service life of the die.

6 DERIVATION OF CONCLUSIONS

Within this paper the influence of a variation of the tooth as well as tool geometry on the resulting component and process properties of cold extruded steel pinions has been investigated. For this purpose, a virtual process model has been used, which makes it possible to determine the effects of modifications within the component and process design on the resulting mechanical and geometric properties of the gears. On the component side, an adaption of the tooth geometry by variation of the gear radii was investigated. On the process side, the targeted design of the forming tool by selection of the die opening angle was evaluated. Figure 11 summarizes the results and the derived conclusions.

Resulting properties and influencing design parameters			**Process** Opening angle ↑ (α)		**Component** Gear radii ↑ (R_H, R_R)	
Component	Overlapping		—	o	↓	-
	Usable height		↑↑	+	—	o
	Profile deviation		—	o	↓	+
	Strain hardening	Tooth head	↑↑	+	—	o
		Tooth flank	↑↑	+	—	o
		Tooth root	↑↑	+	—	o
Process	Tool load		↑↑	-	↓	+

Effect				
Decrease			Increase	
high	low	no	low	high
↓↓	↓	—	↑	↑↑

Evaluation		
negative	neutral	positive
-	o	+

Figure 11. Evaluation of influencing design parameters within the component and process design

Increased gear radii reduce the achievable overlapping within the gear pairing and thus impair the transmission behaviour. At the same time, they have a predominantly positive effect on the achievable component and process properties of cold extruded gears. By choosing maximum possible gear radii, the gearing accuracy is improved and the tool stress during extrusion is significantly reduced. The opening angle of the die does not affect the theoretical overlapping of the formed gear. However, it has a significant influence on the component and process properties. The mound filling and thus the producible usable gearwheel height increase significantly for larger opening angles. In addition, all areas of the tooth profile undergo an elevated strain hardening, which is advantageous for the wear resistance and load-bearing capacity of the gearing. Nevertheless, the tool load is significantly increased, which must be taken into consideration with regard to the service life of the forming tool. On that account a trade-off between the desired component and process properties has to be made within the design process. The derived conclusions provide an important guideline in this regard.

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7 SUMMARY

For the design of gear wheels, the kinematics of the gear pairing as well as the manufacturing process must be taken into account. The manufacturing method has a significant influence on the achievable component properties, especially when unconventional processes, such as cold extrusion, are applied. The design of the tooth geometry does not only affect the gear kinematics, but also the forming process with respect to the geometrical and mechanical properties of the gear. Besides of the component design, the design of the forming tool provides an important control lever to influence the process result. In this context, a trade-off between the component and process design has to be made when designing cold forged steel gears. Within this paper, essential parameters regarding the design of the tooth and tool geometry have been analysed by utilizing a virtual process model. This allows the derivation of recommendations regarding the component and process design of extruded gears and a targeted modification of the operational behaviour of the gearing and forming tool.
In future work, the transfer of the knowledge to actually produced gears and their operational behaviour should be verified. For industrial production, in particular the increase of material efficiency by adapting the tool geometry is relevant. Further potential is also offered by the application of the virtual process model to other components whose properties are influenced by the manufacturing process and the component geometry. For example, shafts, bolts, bearing components or joints produced by forming processes.

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