Manufacturing of Geared Sheet Metal Components by a Single-Stage Sheet-Bulk Metal Forming Process

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Abstract
Due to ecological and economic challenges particularly the automotive industry demands closely-tolerated complex functional components with variants. Regarding short process chains and improved mechanical properties current forming processes are often limited. A promising approach to fulfil these requirements is the combination of traditional sheet and bulk metal forming processes. In fundamental investigations on this topic, a single-stage process combination of deep drawing and upsetting is developed. Whereas a laminar body is formed by deep drawing, variants in shape of gear teeth are upset at the pre-formed blank. Based on a reference geometry, the identification of process limits is shown by numerical simulation and the modes of failure are verified in experimental results. Furthermore geometrical variations of the part geometry are analysed to evaluate the results for an increasing range of components.

Keywords
Sheet-Bulk Metal Forming, Process Combination, Functional Integration

1 INTRODUCTION

The rising global competition and ecological challenges enforce the manufacturing industry to upgrade their products by improved technical properties and lower effort in production. In the automotive industry, especially the requirements on functional components for applications in the mechanical transmission become more complex [1]. Net-shape forming of functional components by cold forging processes is an established approach to manufacture those parts with sufficient surface quality and marginal subsequent machining at high material efficiency at all [2]. Regarding thin-walled functional components such products are machined at high costs and inefficient material consumption, as conventional bulk forming processes reach their limits [3]. A new approach to manufacture those parts is the application of conventional bulk forming operations on sheet metals in combination with sheet forming processes [4]. Concerning the production of geared components manufactured out of sheet metal by forming processes, different methods are pursued in research and industrial application. The specific challenge in forming gear teeth out of sheet metals is the realisation of these functional elements by keeping or increasing the initial sheet thickness [5].

The term of 'flow control forming' describes the combination of various sheet and bulk forming operation, which enable manufacture of sheet metal components with thickness variations throughout the component and forming of various gear shapes in multi-stage process set-ups [6]. Manufacturing of gear teeth at sheet metal parts in single-stage process is realised in a process combination of deep drawing and extrusion [5]. Forming of gear teeth at the flange of the cup identified a clear dependency of the mould filling behaviour from the sheet metal thickness and local friction. The interaction with the material thickness is also described for the combination of deep drawing and several upsetting stages used for the production of cups with hollow gear teeth. On the one hand local thinning at the tooth flank is undesired but strengthened with increasing thickness, on the other hand low sheet thickness causes buckling at the cup fillet during upsetting [7]. In an industrial application, these adverse effects could be avoided by using an upsetting stage at elevated temperatures in the production of gear rims. However, the advantage of work hardening is not available and a layer of scale can affect the surface quality [8]. To avoid the adverse effects of weakened strength, heat treatment and multi-stage process set-ups, this work presents a forming concept that enables cold forming of an external geared sheet metal part in a single press stroke.

2 FORMING CONCEPT AND COMPONENT CHARACTERISTICS

2.1 Tool functionality

The process combination of deep drawing and upsetting to manufacture cups with integrated external gearing causes several challenges regarding tool kinematics and tool load. Performing the forming sequence in a single press stroke the individual tool components have to fulfil different functions and movements during the process. To perform the required kinematics, a triple-acting hydraulic press and an additional gas spring are used. Figure 1 shows the tool set-up with its forming components in the opened position. Both, the upper and lower die cushion are extended and can be positive displaced during the process if a certain forming force is exceeded. The upper die cushion is connected to the reinforced internal geared drawing die, the lower die with the drawing punch. Both are provided with a force high enough to remain extended during the deep drawing operation, but get retracted with continuous stroke of the ram. In addition, a gas spring is also extended at the beginning of the process and clamps the blank between upsetting and drawing punch to inhibit warping of the blank due to the tool set-up without blank holder and the component design, which affords a little drawing ratio.

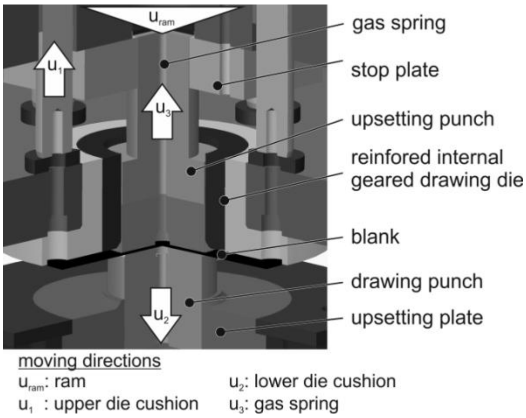

Figure 1 - Tool set-up and individual tool motions.

The performance of the two subsequent forming operations is illustrated in Figure 2. With beginning of the ram motion, the gas spring and the connected upsetting punch fix the blank, which is initially positioned on the drawing punch, with the clamping force F_c. As both die cushions remain extended, the drawing die moves over the drawing punch, which is fixed at this phase of the process. The cup is formed with the drawing force $F_{d,}$ while the gas spring is compressed and the upsetting punch performs a relative movement in the opposite direction of the press movement. Due to the cup stiffness, the shape of the internal geared die is already formed into the wall, despite the drawing clearance is larger than the material thickness.

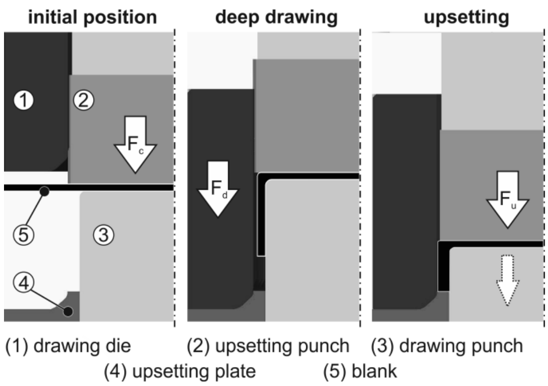

Figure 2 - Forming sequence and process forces.

With ongoing movement of the ram the drawing die is positioned on the upsetting plate, so that the upper die cushion is positively displaced. In addition, the gas spring gets compressed until the upsetting punch is in contact with the stop plate. From that moment, the ram force is directed into the upsetting punch and the upsetting operation begins. The drawing punch respectively the lower die cushion is positively displaced under the increasing force of the upsetting punch F_u and the drawn cup is driven against the stop surface of the upsetting plate. In consequence, the height of the cup is reduced with ongoing press stroke and results in a local wall thickening, as the material is forced to flow laterally into the unfilled gear shapes of the drawing die.

2.2 Process Limits

The presented forming concept enables a reduction of the process chain compared to previous approaches. But the integration of both forming processes in a single also demands compromises between the best respective boundary conditions. For example a certain minimum drawing clearance and punch radius are necessary in deep drawing to avoid excessive thinning. The upsetting process by contrast demands a minimum of unfilled areas within the tool beside the gear cavities. In consequence, both geometric boundary conditions result in locally unfilled areas and hence in inhomogeneous mould filling during the upsetting operation, see Figure 3. In the area of the punch radius (1) this causes folding and the occurrence of a forging lap with high local deformation. In addition, buckling of the cup wall under load (2) results in the formation of a groove which is only filled under very high forces and in consequence at high tool loads. A detailed view on the process limits was made in [9].

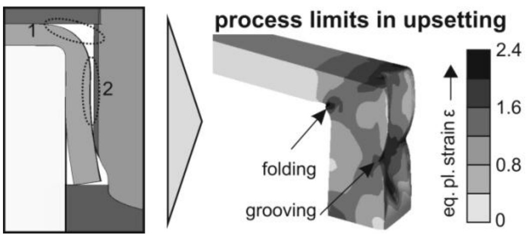

Figure 3 - Effects of the deep drawing operation on the mould filling in upsetting.

Both modes of failure can also be identified in specimens manufactured in the experimental setup. Figure 4 shows the work piece after the complete forming sequence of deep drawing and upsetting. The used material is a mild deep drawing steel DC04 with an initial sheet thickness t_0 = 2.0 and a diameter of 103 mm. The vertical sectional view through the tooth tip shows folding at the fillet of the drawing radius and the unfilled areas due to grooving. This indicates in consequence, that the numerical model is able to predict the process limits with mapping of the material flow and the resulting geometrical defects. In addition, the analysis of the local deformation characteristic is able to identify inhomogeneous mould filling or even be used to detect the incidence of forging laps.

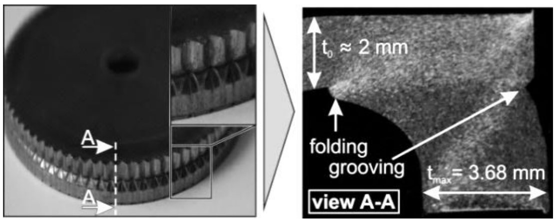

Figure 4 - Cup with external gearing and sectional view from the experimental set-up.

3 PROCEDURE AND METHODOLOGY

The validity of the identified process limits and interactions between deep drawing and upsetting should be proofed by the analysis of the forming process using diverse related component geometries. Due to the extensive tool manufacture common approaches are numerical analysis using variant simulations.

Based on both the experimental results and the validated numerical model, the focus of interest is the transferability of the attained results to components of different diameter. This variation results in varying boundary conditions on the upsetting process due to modifications in the prior deep drawing stage.

3.1 Boundary conditions in simulation

The numerical analysis is performed with the FE-software Simufact.forming 10.0. Due to the cyclic symmetric geometry of the investigated component, the forming process is calculated for one gear tooth with symmetric boundary conditions. As work piece material the mild deep drawing steel DC04 of the experimental set-up with a sheet thickness of t_0 = 2.0 mm is used. The flow curve is determined in a layer compression test, the flow criteria is modelled according to von Mises with isotropic hardening. Because of high appearing contact stresses Tresca friction law with m = 0.1 is used as contact condition. All processes are realized at room temperature. Compared to the experimental set-up, some additional simplifications are necessary. To keep the required numerical stability, burr formation in mould gaps is not considered using zero-gaps as well as elastic deformation of the tool components and resulting material flow into the cup bottom is not taken into account by rigid bodies.

3.2 Parametric part design and blank layout

To investigate the forming sequence of deep drawing and upsetting process for various part geometries, Figure 5 shows the relevant geometrical parameter of the component. Constant dimensions within the geometrical variation are the drawing clearance with u_c = 2.25 mm, which is due to [10] a small gap for conventional deep drawing processes using an initial sheet thickness of t_0 = 2.0 mm, and the shape and height of the gearing. An analysis of the interactions between geometry of the gearing and the process is made in [11] using a numerical process model. Variable dimensions of the component in these investigations is the nominal diameter d_n, representing the outer diameter of the cup without external gearing and in consequence the punch diameter d_p, which is due to the drawing clearance dependent on the nominal diameter. The nominal diameter of the reference geometry from the experimental set-up is d_{n_ref} = 80 mm. An extension of the investigated range beneath d_n < 60 mm is conducive, as the danger of wrinkling rises in this tool set-up without blank holder.

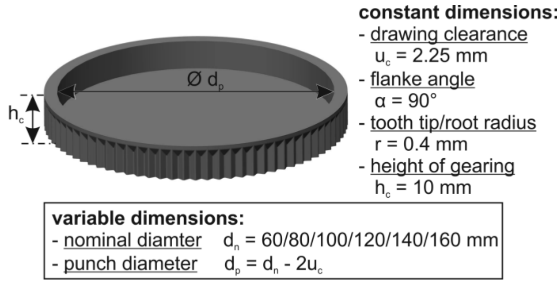

Figure 5 - Parametric part design.

To realise the target height of the gearing, the blank layout has to be determined for each nominal diameter due to volume constancy. Table 1 shows the calculated diameter of the blank d_o and the resulting drawing ratio $\beta = d_0/d_n$. As consequence of the constant height of the gearing, the drawing ratio decreases with increasing nominal diameter. The effect of this relation on the process combination is subject of the investigations.

h_c [mm]	d_n [mm]	60	80	100	120	144	160
10	d_0 [mm]	82.1	103.0	123.6	144.0	168.4	184.6
	β	1.37	1.29	1.24	1.20	1.17	1.15

Table 1 - Blank layout and drawing ratio for varying nominal diameter of the component.

3.3 Determination of evaluation variables

For the analysis of the interactions between geometry and process, several process parameters and component properties are evaluated. Subsequently, the forces of the deep drawing and upsetting process represent the forming force in each case. Counterforces of the virtual die cushions or the gas spring are not considered within these results. The value of mould filling indicates, how much of the volume of the target geometry is filled at a certain stroke or forming force during the process. The stated values for equivalent plastic strain of sheet thicknesses are measured at a minimum of five nodes and are averaged to avoid outliers.

4 DEEP DRAWING OF THE BASE BODY

4.1 Forming forces in deep drawing

Effects of the variable nominal diameter on the deep drawing process can directly be indicated by the analysis of the force to stroke characteristics, see Figure 6. The force paths of the different set-ups show a drop of the forming force during the whole forming operation with increasing nominal diameter. This result is confirmed by the determination of the maximum drawing forces after the Siebel equation [12]. As the final height of the cup after deep drawing is nearly uniform comparing the six configurations, the deformation resistance rises with decreasing nominal diameter due to the higher specific stiffness of the blank, which can be described in this case by the quotient of drawing ratio to initial sheet thickness. Beside this superior effect, the sharp rise of the forming force at a stroke of about s_d = 7 mm is apparent in Figure 6. At this drawing depth, the cup wall touches the conical drawing profile with an angle of 45° with a maximum contact surface. With ongoing press stroke, the bending operation during the draw in is shifted from the outer fillet radius of the cone r_1 to r_2, which results in an abrupt reduction of the lever arm and in consequence to a rise of the forming force.

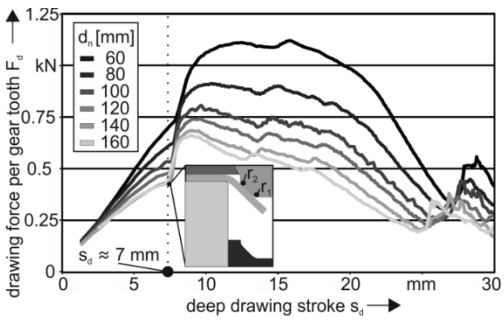

Figure 6 - Deep drawing forces per gear tooth and shifting of the bending radius.

4.2 Indentation of the gear shape into the cup

The interactions between component and blank layout affects not only the force paths, but influence the intendation of the gear shape of the internal geared die into the cup wall during deep drawing as well. Figure 7 illustrates the intendation which is beside its geometrical form also represented by an increased local deformation and in consequence higher equivalent plastic strains. Regarding the component with nominal diameter of d_n = 60 mm, the gear geometry is intended just at the open lower section of the reverse formed cup. This is caused by the prementioned high stiffness respectively deformation resistance at lower nominal diameters, which inhibits a raising of the cup wall after reaching the inner bending radius r_2 of the drawing profile. In addition, the highest drawing ratio causes the highest tangential material flow for the lowest nominal diameter, if the target height of the cup is unvaried. This results in the strongest thickening of the blank in the edge area of the cup compared to the other component geometries and hence in most obvious indentation of the gear shape. Another consequence of these facts is burr formation at the cup edge, which causes in Figure 6 the second deviation to conventional force paths with an anew rise of the forming force at the end of the deep drawing operation. With increasing nominal diameter, the inherent stiffness of the work piece is reduced during deep drawing, so the resistance against lifting of the cup wall at the incisive deep drawing stroke of about s_d = 7 mm is gradually reduced. Hence, the cup wall is at an earlier press stroke perpendicular and parallel to the internal gearing, so the surface of the cup wall with intended gear shape is enlarged with increasing nominal diameter. Furthermore, the tangential material flow is decreased compared to smaller diameters, so thickening at the cup edge is lower as well as burr formation and the resulting rise of the forming force are reduced.

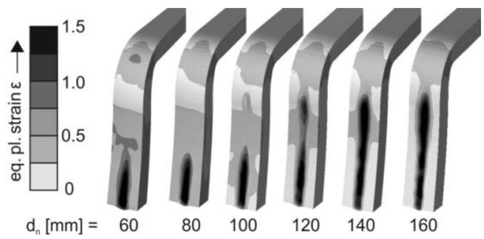

Figure 7 - Indentation of the gear shape represented by increased local deformation.

4.3 Sheet thickness reduction at the punch fillet

The identification of the process limits has shown that folding occurs in the area of the punch radius due to unfilled volume in the tool after the deep drawing process. Investigations on the complete forming sequence require in consequence also the analysis of the sheet thickness reduction in the relevant area as it is of major significance for the subsequent upsetting operation. Figure 8 shows the components' properties at the punch radius after deep drawing. Regarding the minimum occurring sheet thickness in the fillet, there is an obvious trend to higher thinning with decreasing nominal diameter. This trend is caused by the occurring maximum forming forces in deep drawing. The higher the tensile stresses during the process, the higher also the thickness reduction in the fillet. The effect of the bending operation at the punch radius is also visualised by the graph of Figure 8. Bending causes an elongation at outer edge fibre which results also in thinning of the blank. This thickness reduction is dependent on the bending geometry but not on the tensile load during deep drawing. In consequence, there is a saturation of the maximum occurring thinning due to the dominating effect of the bending operation compared to the decreasing influence of the tensile forces for high nominal diameters. Beside the sheet thickness reduction itself, also the resulting mechanical properties can affect the upsetting process. Figure 8 shows higher plastic strains in the fillet for d_n = 60 mm compared to d_n = 160 mm. Due to strain hardening, plastification starts at higher forming forces and the material flow is locally more restricted, which can also favour folding.

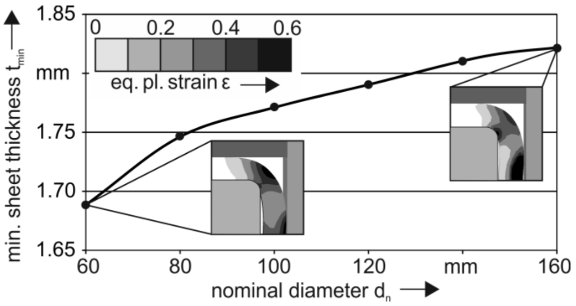

Figure 8 - Sheet thickness reduction and plastic strains in the fillet after deep drawing.

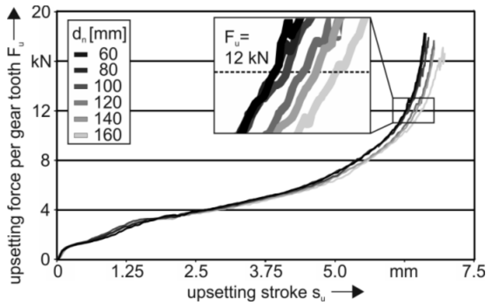

Figure 9 - Upsetting forces per gear tooth and force value for the mould filling analysis.

5 UPSETTING OF THE GEAR TEETH

5.1 Forming forces in upsetting

The identification of the process limits shows that the geometrical and mechanical properties of the component after the deep drawing operation affect the subsequent upsetting process. In consequence, forming of the gear teeth by a compression load on the cup wall has to be analysed for the different nominal diameters, too. Again, the force paths of the upsetting operations are used to identity deviations caused by the diverse target geometries of the components. Figure 9 shows the upsetting force per gear tooth against the upsetting stroke. Considering all graphs, the typical force characteristic of closed-die forming processes occurs. The approximately linear rise of the forming forces at the beginning of the process turns into a sharp rise, which occurs for all nominal diameters at an upsetting stroke of about $s_u = 5.0$ mm. Until this process progress, free volume due to the drawing clearance is filled predominantly. Afterwards there is an increased material flow into the gear cavity of the drawing die. Due to the rise of the contact surface at the tooth flanks and the occurring contact normal pressures, the friction resistance rises. In addition, there is increasing strain hardening due to stronger deformation of the material in the narrowed gear cavity. Within this sharp rise of the upsetting forces, a dependency of the component geometry is detectable. As the highest tangential material flow at a nominal diameter of $d_n = 60$ mm causes the strongest thickening of the cup wall, the resulting height of the cup after deep drawing is the lowest one within the investigated range of diameters. Hence, the required upsetting stroke for the realisation of a complete mould filling is reduced and the material flow into the gear cavity starts at a shorter stroke. With increasing nominal diameter, the sharp rise of the upsetting force is shifted to longer upsetting strokes, as shown in the detailed shot in Figure 9. This view illustrates the shift of the graphs intentionally around an upsetting force of $F_u = 12$ kN, which is used for the determination of values for a quantitative validation of the mould filling depending on the nominal diameter.

5.2 Analysis of the mould filling characteristics

The quantitative validation of the percentage mould filling in the chart of Figure 10 shows only small differences between the different components at an upsetting force of $F_u = 12$ kN. There is no trend regarding the increasing nominal diameter discernible. Also the maximum deviation within the measured values is less than 1.5%, while there is even a loss of material volume up to 1% due to remeshing in the numerical simulation of the upsetting processes. As consequence, no quantitative statements about the interactions between nominal diameters and percentage mould filling at the chosen forming force can be done. However, an evaluation of the mould filling behaviour is possible by analysing the plastic strain distribution of the components. The focus is on the identified modes of failure, folding and grooving, which can be linked with the local material deformation and are dependent on the deep drawing operation. The more uniform indentation of the gear shape for increasing nominal diameters, see Figure 7, provides a strengthened supporting effect in the cup wall against buckling under compression load. Hence the development of the grooving is reduced, which results in a more homogeneous material flow and strain distribution in the cup wall, even the percentage mould filling is not improved. Figure 3 shows that the unfilled area at the punch radius impact folding. Consequently, the lower sheet thickness reduction for larger diameters reduces the probability of folding, which is represented by reduced deformation in the relevant section comparing the plastic strains of the components in Figure 10.

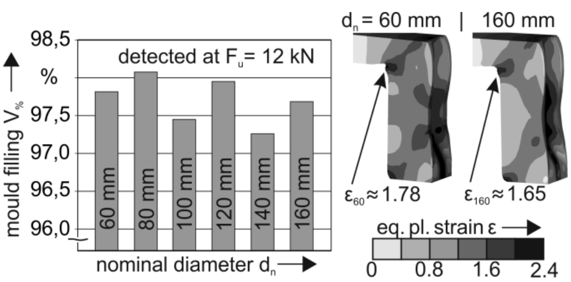

Figure 10 - Percentage mould filling and deformation characteristics at $F_u = 12$ kN.

6 SUMMARY AND OUTLOOK

The realisation of thin-walled functional elements by the application of bulk forming operations on sheet metal in combination with conventional sheet forming processes is an appropriate approach to meet the current ecological und economical challenges of the manufacturing industry. To reduce the process chains for the production of external geared components a single-stage forming sequence of deep drawing and upsetting is developed. The combination of both processes within one tool requires the adaption of the individual process control. Nevertheless, negative interactions between deep drawing and upsetting cannot be excluded. Based on the process limits of a reference geometry, which could also been identified in experiment, the transfer of the results to other geometries was possible. Although the knowledge of the process could be expanded, a faultless forming result is not ensured.

To further upgrade the quality of the component a promising approach is the application of semi-finished products made by flexible rolling or orbital forming, which is numerically investigated in [9]. Figure 11 shows, that the positive effect of this approach of reducing the unfilled section after deep drawing can be verified in experimental results with a nominal diameter of d_n = 80 mm.

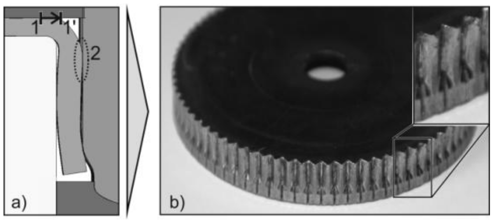

Figure 11 - Reduction of folding and grooving by the application of tailored blanks.

Based on the results of the geometrical variation, design guidelines for tailored blanks with adapted thickness characteristic have to be developed for applications in components with an enlarged geometrical range in continuative investigations.

7 ACKNOWLEDGMENTS

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