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Designing, manufacturing and processing of Tailored Blanks in a sheet-bulk metal forming process

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Abstract

Sheet-bulk metal forming is an innovative method for the manufacturing of functional components by applying bulk metal forming processes or combined sheet and bulk metal forming processes to sheet metal. The investigated process combines deep drawing and upsetting. Occurring 2D and 3D stress and strain states lead to challenges regarding the material flow control during the forming process to ensure a high die filling and accurate part geometry. Regarding these challenges, the application of conventional semi-finished products is not expedient wherefore Tailored Blanks with a process adapted sheet thickness distribution are applied to the forming process. The Tailored Blank geometry is designed by a numerical analysis and manufactured by an orbital forming process considering the resulting geometric part properties during deep drawing and upsetting. Therefore, the whole process chain from the conventional circular blank to the finished functional component is linked and modelled. This enables a realistic description of the part properties as the effective plastic strain caused in the manufacturing of semi-finished products is taken into account in the processing of the material. Subsequently the results are verified by experimental tests.

Keywords: Deep drawing, Finite element method (FEM), Sheet metal, Forming

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1. Introduction

Due to legal and social changes pushed by the society, reducing carbon dioxide emissions and resource consumption play a decisive role in industrial research and development. Focusing on more efficient products and

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processes recently is seen as a key capability recently. Particular the automotive industry was affected by these radical changings. Road Traffic causes 26 % of all carbon dioxide emissions in the European Union [1]. Hence the EU adapted regulations to limit carbon dioxide emissions for cars in 2009. By 2020 the average of the fleet of cars of every carmaker has to be lower than 95 g/km [1]. This leads to intensive research in several sectors. A way to reach the mandatory regulations is downsizing the car engines, which combines lightweight construction and reduction of gas consumption. Downsizing increases the loads on power train components what makes their production even more complex. This development makes complex and thin-walled elements, such as synchronizer rings necessary. Realizing that producing more efficient components with conventional forming processes turns out to be complicated, innovative forming processes need to be developed to reach its requirements. [2] To enhance process boundaries a combination of sheet and bulk forming, so-called sheet-bulk metal forming (SBMF) can be deployed. SMBF combines the advantages of both forming classes [3]. During forming with SMBF a 3-dimensional tension appears inside the parts and sheets with thickness between 1 – 5 mm can be formed [4]. Using SBMF enables new paths in realizing novel component geometries and further has several advantages, such as increasing the number of integrated functional elements, reducing the length and increasing the robustness of process chains. For example the production of a synchronizer ring can be realized with SMBF in a single forming step and long process chains are not necessary any more. A SMBF process can consist out of sheet forming process deep drawing and bulk forming process. This technique makes it possible to form cups in a single step with several functional elements. [5] Caused by lacks of know-how further investigations, especially to inquire material flow during the forming process, are necessary as these processes have proofed its potential in proceeding investigations.

2. Part properties and forming concept

In this section an overview of the part geometry, the forming process, the modelling and methodology is given to provide the necessary information for the investigation and discussion.

Geometric dimensions of the functional component, set-up and modelling of the forming process

The investigated demo part is a cup with a circumferential external gearing. Figure 1-a) shows the part geometry with the geometric dimensions. The gearing has 80 teeth with a flange angle of α = 90° each. The outer diameter of the cup amounts to d_o = 82.72 mm and the inner diameter amounts to d_i = 75.5 mm. The height of the cups depends on the geometry of the semi-finished product and on the forming force applied to the modular tool concept. The tool concept consists of an upper tool with internal geared drawing die and upsetting punch and a lower tool with upsetting plate and drawing punch as presented in Figure 1-b).

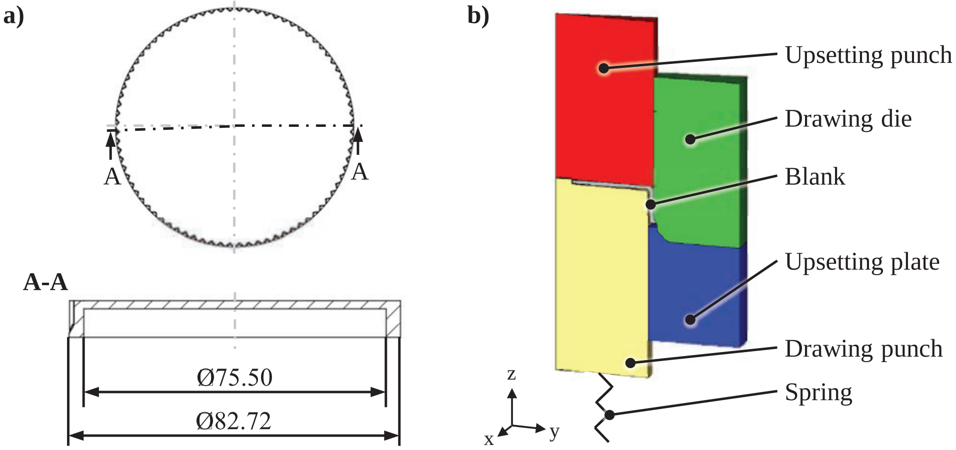

Figure 1: Part geometry (a) and process set-up (b)

Initially the workpiece is placed on the drawing punch and clamped by the upsetting punch. The cup is drawn by a downward movement of the drawing die. Subsequently, the drawing punch is displaced by the upsetting punch and the cup wall is upset causing a radial material flow into the geared die cavity.

For the numerical investigation the implicit FE-code simufact.forming 12 is used. The workpiece material applied is DC04 and the initial sheet thickness is t_0 = 2 mm. The flow curve is determined in a layer compression test and the flow criterion is modelled according to von Mises with isotropic hardening. In the numerical simulation the forming process proceeds stroke-controlled and the tools are modelled as rigid bodies. Due to the cyclical and symmetrical arrangement of the functional elements a 4.5°-section of the workpiece geometry is used to model the process. To prevent contact problems and to enhance numerical stability a larger tool segment is used. In contrast to the experimental set-up the numerical process is divided into the two process steps deep drawing and upsetting to leave out passive components and decrease the calculation time. Furthermore, this enables a specific adaption of the meshing for sheet and bulk metal forming operations. For the modelling of deep drawing the mesher Sheetmesh is applied with 6 elements in thickness direction and an edge length of 0.35 mm. Before the upsetting operation is calculated the mesher Hexmesh generates a hexahedron mesh with an edge length of 0.3 mm. The numerical model was validated by an alignment of the numerical results with experimental data. Therefore, a quantitative comparison of the geometric dimensions as well as a qualitative comparison of the strain hardening induced by the experimental process and the effective plastic strain in the numerical model was made with high correlation.

3. Numerical design of Tailored Blanks

As an increased initial sheet thickness is not expedient, a semi-finished product with a process adapted material thickness distribution has to be designed. Based on the initial sheet thickness of t_0 = 2.0 mm a Tailored Blank with two areas of different thickness within the blank is designed. In the outer area where the teeth geometry is formed the sheet thickness has to be higher to provide enough material for an adequate die filling whereas the sheet thickness in the bottom of the cup has to be lower to realise a component with a weight as low as possible. The fundamental qualification of the application of blanks with varying sheet thicknesses was shown in [5]. These blanks, however, were not designed specifically for this process. To determine a suitable design of the Tailored Blank geometry the radial position r_1 and length of the transition zone l_t as well as the sheet thicknesses t_1 and t_2 in the two areas are varied. While simplified 2D models are used to analyse the influence of position and length of transition, the variation of sheet thickness is made using a 3D model and assuming volume constancy. The basic geometry of the Tailored Blank with the geometric parameters is presented in Figure 2. To create ideal conditions for the upsetting process the workpiece should fill the free space completely. After deep drawing the thickness profiles at the top of the tooth should converge to the profile of the idealised geometry.

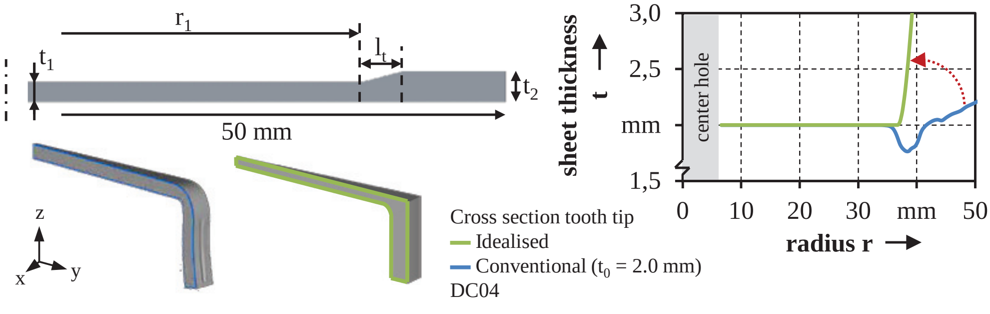

Figure 2: Geometric Tailored Blank properties and derivation of an idealised geometry

Variation of the radial position r_1

To determine the appropriate position of the area with an increased sheet thickness the radius r_1 is varied. The sheet thickness is set to 1.5 mm in the inner area and 2.5 mm in the outer area. For an initial sheet thickness of

t_0 = 1.5 mm the material thinning begins at a radius of 34.7 mm. This value is set as base value for r_1 and varied by ± 1 mm and by ± 5.3 mm respectively to investigate the influence of the variation in a smaller and larger range. This range was chosen to cover the dimensions of the blanks applied in [5]. The length of the transition is set to 2 mm, also in accordance to [5]. The resulting sheet thickness profiles after deep drawing are presented in Figure 3.
For r_1 = 29.4 mm and r_1 = 33.7 mm there is no thinning of the material but a steep increase of the sheet thickness as the area with higher material thickness partially lies in the bottom of the cup. The profiles of r_1 = 35.7 mm and r_1 = 40 mm also show high deviations to the idealised profile as strong thinning occurs. Because of the smallest deviations to the idealised sheet thickness profile r_1 is set to the base value of r_1 = 34.7 mm for further investigations.

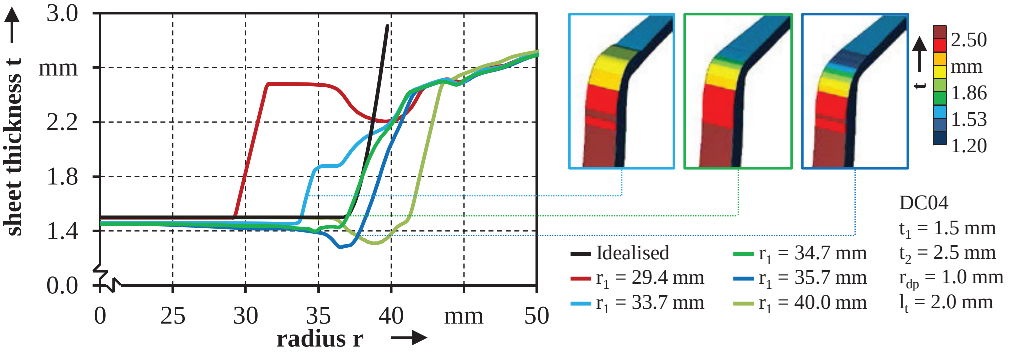

Figure 3: Influence of the radial position r_1 on the resulting sheet thickness

Variation of the length of transition l_t

To analyse the influence of the length of transition on the thickness profile the length is varied between 1 and 3 mm. As variations of the length of transition cannot be investigated under volume constancy only 3 variations are analysed to present the resulting geometrical properties after deep drawing. The resulting material thickness profiles for the deep drawn Tailored Blanks are presented in Figure 4. For l_t = 1 mm the profile shows slight local thinning due to the intensified notch effect. This leads to a disadvantageous stress concentration and can initiate cracking at the corner radius of the drawing punch. Furthermore, the profile shows an early increase of the sheet thickness compared to the idealised profile. When l_t is set to 3 mm intensified thinning occurs as the area with increased sheet thickness is shifted to the outer edge of the blank and cannot compensate thinning during deep drawing. The highest convergence to the idealised profile was identified for a length of transition of l_t = 2 mm. Therefore the base value for l_t remains at 2 mm.

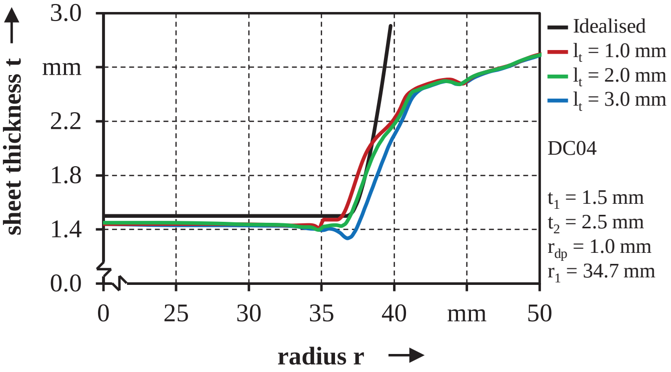

Figure 4: Influence of the length of transition l_t on the resulting sheet thickness

Variation of the sheet thickness t_2

To analyse the influence of the sheet thickness, a 3D model is used to increase the level of accuracy. Thus, the influence of the internal geared drawing die and the ironing which is induced by the die can also be taken into consideration. The sheet thickness in the outer area t_2 is varied between 2.4 mm and 2.9 mm in steps of 0.1 mm assuming volume constancy. The sheet thickness t_1 in the inner area results from the volume calculation. Figure 5 presents the force-displacement curve progressions for the Tailored Blanks during deep drawing. At the beginning of the deep drawing process the material is drawn over the outer drawing die radius and the drawing force increases slightly until the material is subsequently drawn over the inner drawing die radius at a stroke of 8 mm. The shortening of the lever arm causes a steep increase of the drawing force up to approximately 75 kN. Afterwards the force required slightly decreases until a stroke of 12 mm is reached. Up to this point all curves show a similar progression. With ongoing process the progressions differ significantly. While the drawing force for blanks with a sheet thickness of 2.4 mm, 2.5 mm and 2.6 mm does not reach the value of 75 kN again the force for Tailored Blanks with a higher sheet thickness t_2 increases significantly due to intensified ironing. For a sheet thickness of t_2 = 2.9 mm the maximum force amounts to 150 kN. Tailored Blanks with a sheet thickness t_2 higher than 2.9 mm cannot be deep drawn in this process set-up without cup base fracture. Caused by intensified ironing the Tailored Blanks with increased sheet thickness show a higher effective plastic strain in the tooth root of the part. As presented in Figure 5 the free space is reduced by increasing the sheet thickness t_2 from 2.5 mm by 0.2 mm. A further increase of the thickness to t_2 = 2.9 mm yet causes a renewed increase of the free space. Thus the variation of t_2 shows no linear connection to f^2.

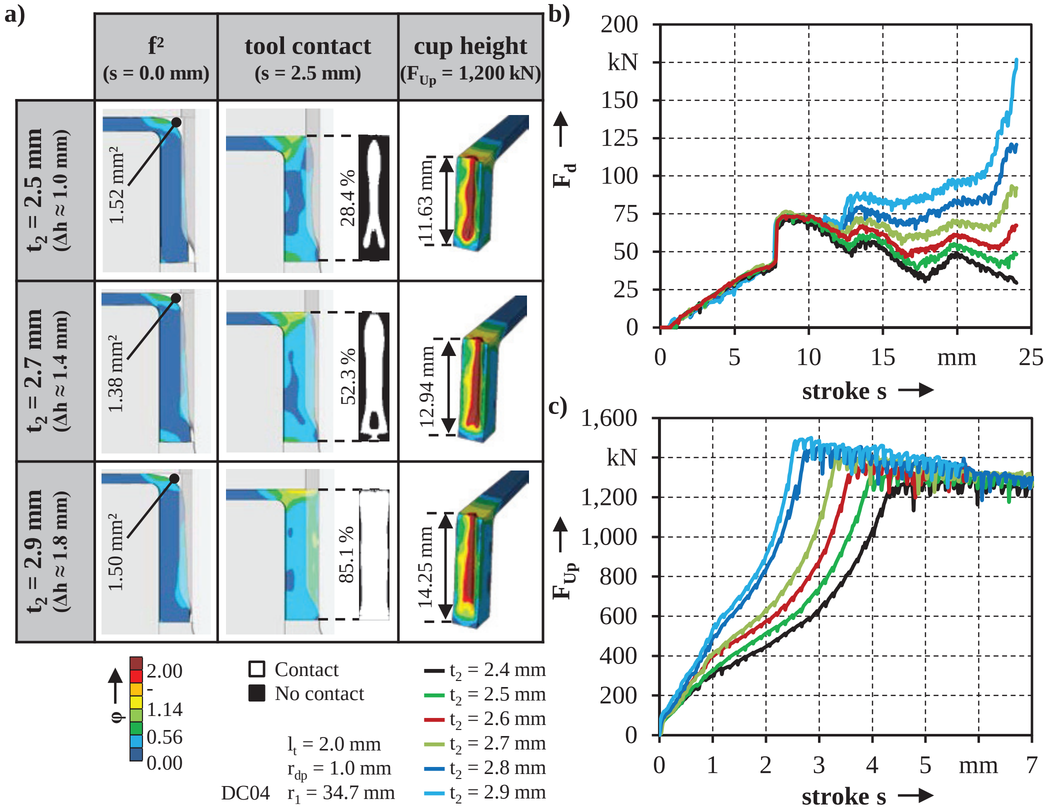

Figure 5: Free space, tool contact and cup height for varying sheet thickness t2 (a), required drawing force (b) and upsetting force (c)

When the cup is further processed in the upsetting process the sheet thickness t_2 has a significant influence on the resulting upsetting force F_{up} as presented in Figure 5. An increased sheet thickness t_2 causes a steeper increase of the upsetting force and a higher maximum upsetting force. After reaching the maximum force the curve progression is no longer relevant, as materiaf flow into the bottom of the cup occurs. For the evaluation of the cup height the upsetting force is set to 1,200 kN. Caused by higher material volume in the area of the cup wall the upsetting force of 1,200 kN is reached at smaller strokes for Tailored Blanks with an increased sheet thickness t_2. The smaller stroke effects a larger cup height. For a sheet thickness t_2 = 2.5 mm the cup height h amounts to 11.63 mm. For a sheet thickness t_2 = 2.7 mm the height increases to h = 12.94 and to h = 14.25 mm for t_2 = 2.9 mm. Thus, at an upsetting force of F_{up} = 1,200 kN an increase of the sheet thickness t_2 of 16% induces an increase of the cup height of more than 22%. Furthermore, the increased sheet thickness t_2 results in an improved die filling of the external gearing. The die filling can be measured by tool contact in percentages. To ensure comparability the values are calculated at a stroke of s = 2.5 mm for all Tailored Blanks as the die cavity is almost completely filled for t_2 = 2.9 mm. The resulting tool contact amounts 28.4%, 52.3% and 85.1% for a sheet thickness t_2 of 2.5 mm, 2.7 mm and 2.9 mm respectively.

In summary, it was shown that an increase of the sheet thickness in the outer area of the circular blank improves the die filling significantly. However, a strong increase also leads to renewed enlargement of the open space during deep drawing caused by intensified ironing. The material thinning in the area of the corner radius of the drawing punch reinforces the risk of crack formation. Besides that ironing causes disadvantageous burr formation. Therefore, the selection of geometric parameters has to be made in this field of tension considering the manufacturability of the Tailored Blanks.

4. Numerical investigations of manufacturing and processing Tailored Blanks

Tailored Blanks are process adapted semi-finished parts with designed optimized properties for their specific field of application [6]. For example, it is possible to specifically adjust the sheet thickness distribution in order to provide sufficient material just in the areas of interest for a subsequent processing [7]. This leads to an improved die filling of functional elements in subsequent processing [5]. To manufacture these Tailored Blanks different processes or process combinations [8] can be used. For this investigation an orbital forming process is applied.

4.1. Manufacturing of Tailored Blanks by orbital forming

In the following section a numerical simulation of the orbital forming process is investigated to analyze the geometrical and mechanical properties of orbital formed Tailored Blanks. The process characteristics, the modelling of the process and the manufacturing of Tailored Blanks as the first step in a linked process chain are presented below. The calculated result serves as input value for the processing of the Tailored Blanks in the combined deep drawing and upsetting process subsequently.

Process characteristics of the orbital forming process

Orbital forming which was first presented as a cold-forming process [9] is an incremental bulk forming process [10]. The corresponding tool design with the main geometric parameters is shown in Figure 6 and used for this investigation.

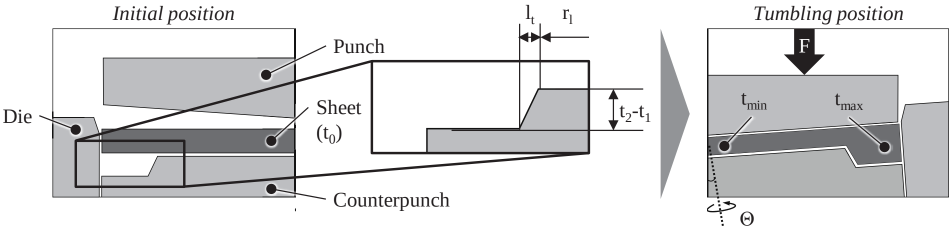

Figure 6: Tool design of the orbital forming process

The tilted upper or lower die leads to a continuously moving contact area between workpiece and die. In comparison with conventional upsetting a reduced contact area of up to 80% [11] results in lower process forces up to 90% [12] which enables the extension of existing process limits. In [13] an orbital forming process was presented to manufacture Tailored Blanks with defined sheet thickness characteristics out of conventional sheet metal.

Unlike most orbital forming processes, the tilted part of the machine with the tool design is the bottom half with a die and a counterpunch which has the negative imprint of the target geometry. The die prevents a material elongation in radial direction. The process force is initiated in the tool system by the conical upper punch. The tilted tool components in combination with the rotational movement lead to a radial material flow from the centre to the outside and into the cavity. The usage of different counterpunches enables the manufacturing of various Tailored Blank geometries. The orbital forming process can be divided in three main process phases. Starting at a tumbling angle of $\Theta = 0°$, the tumbling angle is ramped up to its maximum angle of $\Theta = 1°$ in the first phase U_u. In the second phase U_c the tumbling angle is held at a constant level followed by the third phase U_d.

Modelling of the orbital forming process

For the numerical modelling of the orbital forming process a 360° model with the main tool components as bodies is set up. Due to the 3-dimensional material flow during orbital forming no symmetric effects can be used. As the counterpunch and die have the same kinematical movement both components are combined as one and modelled as rigid body. The upper punch is modelled as a deformable body and enclosed by a punch socket which is a rigid body in order to initialize the forming force into the system. The workpiece is meshed using a sheetmesher with hexahedron elements at an element length of 2.0 mm and five elements along the sheet thickness. In the outer rim area, the area where the sheet is thickened a local refinement of the sheet is applied between the radial position r = 36 mm and r = 50 mm. The same material data as presented in chapter 2 is used for the workpiece.

Manufacturing of Tailored Blanks and linking the process chain

Using the FE-model of the orbital forming process, Tailored Blanks with the geometric layout identified in chapter 4 are manufactured using a forming force of F = 3,000 kN and a number of tumbling cycles of $U_u = U_c = U_d = 5$. The corresponding numerical results are shown in Figure 7. For the effective plastic strain the highest values can be detected in the outer rim area and the transition zone due to the strain hardening caused by the radial material flow from the centre to the outside. Regarding the sheet thickness distribution, a thinning of the sheet in the centre of up to t = 1.5 mm. The thickening in the outer rim area of up to t = 2.5 mm matching the defined target value.

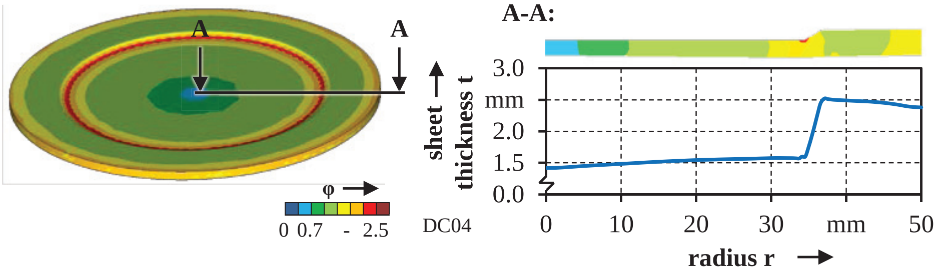

Figure 7: Strain distribution and sheet thickness of the Tailored Blank manufactured by orbital forming

For further processing of the Tailored Blanks in the subsequent deep drawing and upsetting process a virtual trimming operation step has to be integrated in the process chain in order to virtually link both the manufacturing of Tailored Blanks and their processing. This additional trimming operation is necessary to get a 4.5° segment of the Tailored Blank which equals one tooth for the subsequent process.

4.2. Processing of Tailored Blank

The Tailored Blanks manufactured in the orbital forming process are further processed into functional components by the combined deep drawing and upsetting process. The properties of the semi-finished product, such as the dimensions and effective plastic strain, are taken into account, as the numerical simulations of both processes were linked. This enables a more precise analysis of the process chain on the one hand, but on the other hand requires adaptions in comparison to previous investigations. After the adaption of the Tailored Blank layout the deep drawing and the upsetting of the orbital formed Tailored Blanks and the resulting properties of the functional component are analyzed.

Adaption of Tailored Blank layout

Due to the cold hardening induced in the orbital forming process the mechanical properties of the Tailored Blank and the resulting geometric part properties differ from those manufactured from constructed blanks without forming history. The differences regarding required process forces, sheet thickness profile, open space, tool contact and cup height are presented in Figure 8. Therefore, the geometric properties of the Tailored Blank identified in the previous investigation have to be adapted. This can either be realised by an increase of the radial position r_1 or by an increase of the length of transition l_t. The radial position is increased by 0.5 and 1 mm whereas the length of transition is increased by 1 and 2 mm. The difference in height between the inner and outer area of the Tailored Blank remains at 1 mm. Figure 8 shows the sheet thickness profiles for the variation of radial position and length of transition. By increasing r_1 to 35.2 mm an early rise of the sheet thickness in the bottom of the cup can be prevented and the open space decreases. A further increase to r_1 = 35.7 mm leads to intensified thinning of the material at the drawing die radius and causes an increase of the open space of 0.6 mm^2. An extension of the transition in both cases effects an enlargement of the open space. For a length of transition of 3 mm the open space is 1.90 mm and for l_t = 4 mm it is 2.19 mm due to an increased sheet thickness t_1. Therefore, the radial position r_1 is set to 35.2 mm, the length of transition l_t to 2.0 mm and the difference in height to 1 mm for the final Tailored Blank layout.

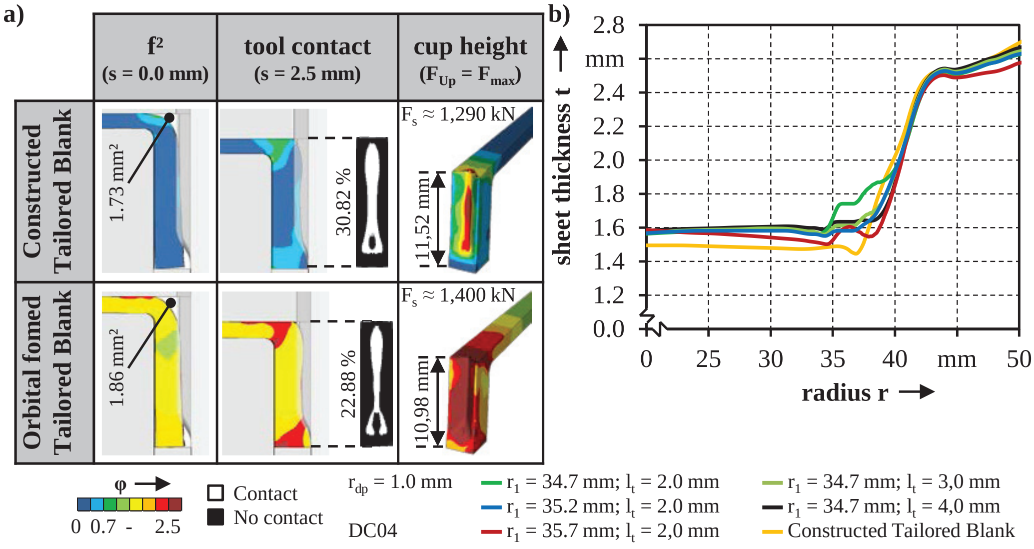

Figure 8: Differences between constructed and orbital formed blanks (a) and influence of varying r_1 and l_t (b)

In consideration of the forming history induced in the orbital forming process the adapted Tailored Blank layout is applied to the single-stage forming process. The further processing of the Tailored Blanks in deep drawing and upsetting is presented in the following sections.

Deep drawing of orbital formed blanks

The drawing force required increases as Tailored Blanks are applied due to cold hardening induced by the orbital forming process. The comparison of the thickness profiles shows the improved geometric properties of the cup drawn from a Tailored Blank and is presented in Figure 9. The sheet thickness in the bottom is decreased by 0.40 mm and at the same time the mechanical strength is increased by cold hardening. In the area of the drawing punch radius the curve progression for the application of a conventional semi-finished product shows intensified thinning. The sheet thickness locally decreases to 1.78 mm and flatly increases over the cup wall up to 2.20 mm. For the application of Tailored Blanks there is no significant thinning at the drawing punch radius as this is compensated by an increased sheet thickness t_2, an adopted radial position r_1 and an adequate length of transition l_t. The sheet thickness towards the cup wall steeply increases up to a maximum of 2.64 mm. The application of the Tailored Blank enables a significant improvement of the geometric properties of the deep drawn cup compared to the application of conventional semi-finished products. With ongoing process the cup is upset to a functional component.

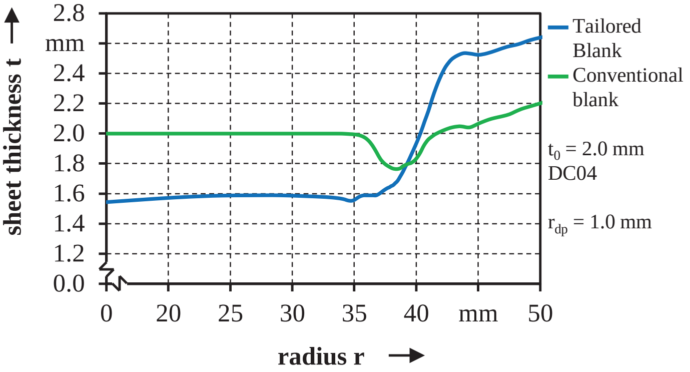

Figure 9: Sheet thickness progression for conventional semi-finished products and Tailored Blanks

Upsetting of orbital formed blanks

The functional components are evaluated regarding their geometric properties. In accordance with the analysis of the deep drawn cup the result of the application of a Tailored Blank is compared with the result of the application of a conventional semi-finished product. The contours are presented in Figure 10. Figure 10-a) shows a decrease of the sheet thickness in the inner area by 20% for the application of the Tailored Blank as the sheet thickness t_1 remains at 1.60 mm. An application of Tailored Blanks enables an increase of the die filling from 67.72% to 94.88%. The contour progression of the component at the corner radius over the entire process is shown in Figure10-b).

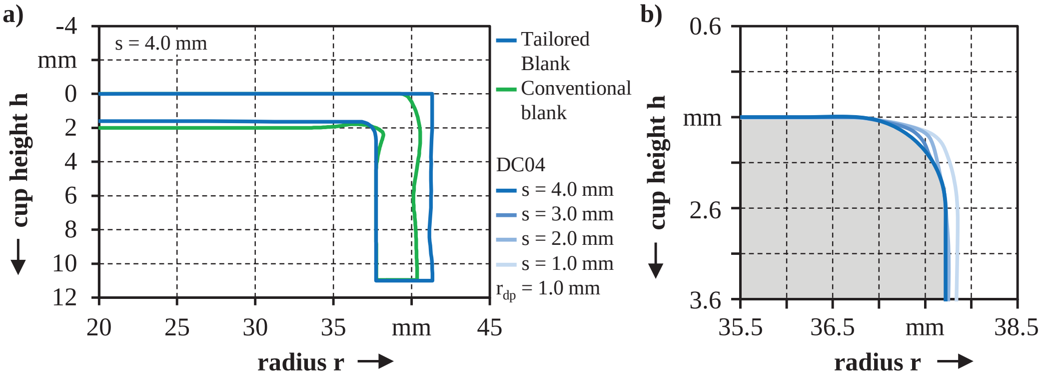

Figure 10: Comparison of part contours (a) and contour at corner radius at different strokes (b)

By the end of the upsetting process the contours of the workpiece and the drawing punch correspond. The increased material volume in the area of the cup wall and the cold hardening induced by the orbital forming process yet causes an elevation of the upsetting force for the application of a Tailored Blank.

5. Experimental results

In this section experimental tests are presented to verify the numerical investigations shown before. For this purpose a conventional semi-finished product is processed into a Tailored Blank with the geometric properties determined in the numerical investigation and then further processed into a functional component. The geometric properties of the component are analyzed and compared to the numerical results.

For the measurement of the Tailored Blanks a coordinate measurement machine with a probing uncertainty of 0.8 µm and a spatial length measurement uncertainty of 0.7 µm is used. The geometrical dimensions of the functional components are measured by an optical measurement system and with a measurement uncertainty of ±0.01 mm. Both, Tailored Blanks and functional components are measured in 0°, 45° and 90° towards the rolling direction. The values presented below represent the average values.

The results of the experimental investigations are presented according to the sequence of the processes applied. For the orbital forming process to manufacture the Tailored Blanks as well as the combined deep drawing and upsetting process a triple acting 4,000 kN hydraulic press is used. The kinematic to enable the orbital forming process is realized by four hydraulic cylinders and a tumbling plate with a spherical calotte.

Geometrical properties of Tailored Blanks

For the orbital forming of Tailored Blanks a counterpunch with the negative imprint of the target geometry was manufactured. The parameters of the orbital forming process are chosen according to the parameters of the numerical analysis presented above. The sheet thickness profiles of the Tailored Blanks show a high degree of consistency and are presented in Figure 11. The sheet thickness decreases towards the middle of the blank due to centre thinning. In the experimental test increased centre thinning occurs. This effect is underestimated by the numerical model.

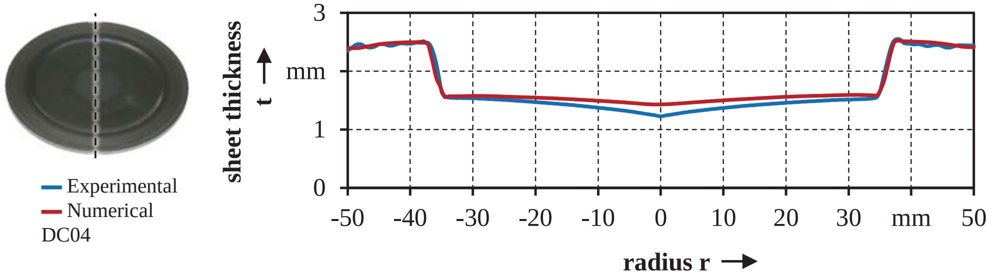

Figure 11: Comparison of numerical and experimental Tailored Blank contour

Geometrical properties of functional components

For the processing of the Tailored Blanks the tumbling plate is removed from the press table and the subsequent forming operation in order to manufacture geared components shows a high accordance of the experimental results and numerical analysis after the deep drawing, as shown in Figure 12-a). The height of the cup after deep drawing amounts to 15.30 mm in the experimental test. The numerical analysis shows a deviation of only 0.80%. Regarding the contour also only minor deviations occur. The process parameters of deep drawing and upsetting process are also chosen according to the numerical investigation.

Upsetting of the deep drawn cup determines the geometric properties of the functional component. The outer contour of the experimentally manufactured and the numerically calculated components are presented in Figure 12-b). An upsetting force of F_{Up} = 1,200 kN leads to a die filling of 91.10% for the experimentally manufactured part.

The comparison shows a deviation to the numerical analysis of 3.78% and confirms the result of the numerical analysis.

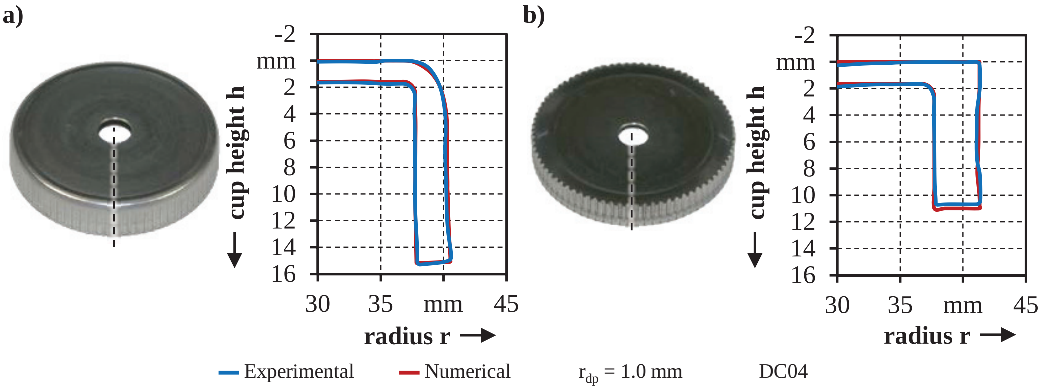

Figure 12: Numerical and experimental contour after deep drawing (a) and upsetting (b)

6. Summary and outlook

The application of Tailored Blanks is an established approach to meet the challenges in sheet metal forming. The design, manufacturing and further processing of Tailored Blanks in a sheet-bulk metal forming process is analysed and presented using numerical models and verified by experimental tests. The process combination of deep drawing and upsetting enables the single-stage manufacturing of cups with an external gearing. Specific challenges regarding the material flow control are considered to enhance the resulting geometric properties of the functional component. Therefore the application of conventional semi-finished products is analysed initially. Specific process failures like buckling and grooving are prevented by a process adapted material distribution. After appropriate geometric properties for the Tailored Blank are determined by numerical variant simulation these blanks are manufactured by an orbital forming process and further processed. The linkage of the different numerical models enables a realistic simulation of the process chain. The application of Tailored Blanks enables a significant reduction of the component weight at enhanced mechanical properties for a defined cup height and takes account of the current efforts to manufacture innovate lightweight components. Key result is the understanding of the influences of the parameters varied in this study. Especially the difference in sheet thickness within the Tailored Blank and the position of the transition are crucial for a process adapted blank design. Following this approach further investigations concerning the transferability of these results to other materials have to be conducted. To develop additional potential regarding the reduction of the total weight of the functional component an application of this approach to high-strength steel seems expedient.

Acknowledgement

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