Numerical and experimental investigation of a backward extrusion process for forming geared components from coil

LEICHT Miriam[1,a *], HENNEBERG Johannes[1,b] and MERKLEIN Marion[1,c]

[1]Institute of Manufacturing Technology (LFT), Friedrich-Alexander-Universität Erlangen-Nürnberg, Egerlandstraße 13, 91058 Erlangen, Germany

[a]miriam.leicht@fau.de, [b]johannes.henneberg@fau.de, [c]marion.merklein@fau.de

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Abstract. Stricter political regulations, increasing ecological awareness of society as well as the pursuit for higher performance of components motivate lightweight construction. Functional integration is one way to realize lightweight design, resulting in increased demands on component geometry. Sheet-bulk metal forming (SBMF) offers the potential to enable an economic and ecological production of functional components through short process chains. SBMF from coil also provides additional advantages regarding high output quantity and short cycle times. However, the industrially application of SBMF from coil is limited due to high tool load and coil-specific challenges like an anisotropic material flow, which negatively affects the part accuracy. In this study, a backward extrusion process from coil for forming functional components with gearing is investigated. Therefore, a numerical process model was built and validated based on experimental results. In order to generate a profound process understanding, a combined numerical-experimental approach was chosen for a fundamental process analysis. The influence of the semi-finished product geometry was investigated by forming rotationally symmetric, pre-cut blanks and coil material. The application of the different sheet geometries was compared based on component- and process-side target quantities. The results indicate an anisotropic material flow as a coil-specific challenge, which leads to a direction-dependent component forming.

Introduction

Climate change and the increasing exhaustion of resources are central challenges of the 21st century [1], which leads to an increasing awareness of sustainability and environmental protection among the population and in politics. In the industrial environment in particular, a trend towards reducing environmental pollution and using resources more efficiently is noticeable. Consequently, higher demands are being placed on efficiency and environmental compatibility of manufacturing technologies and products, which require the development of innovative approaches. One effective approach is the implementation of light-weight design in combination with increased functional integration [2]. However, conventional manufacturing processes are reaching their limits [3]. The innovative process class of sheet bulk forming (SBMF) combines the advantages of sheet metal and bulk forming by applying bulk forming operations to sheet metal semi-finished products [4]. SBMF enables the production of thin-walled components with integrated functional elements by means of a three-dimensional material flow [4]. The use of SBMF-processes is currently limited to the forming of pre-cut blanks as semi-finished products, since they offer flexibility in material supply [5]. However, due to the increasing demand for functionally integrated components, manufacturing processes with short cycle times and high output volumes are gaining in importance. With regard to high output rate, the forming from coil offers the possibility to avoid cycle-time limiting handling systems, because the transport of the components between forming stages is realized by coil [6]. Tajul et al. [7] identified an uncontrolled, anisotropic material flow and unequal forming components as challenges of SBMF from coil. Furthermore, Henneberg et al. [8] investigated the forming of rotationally symmetric pins and cups from coil by backward and lateral extrusion, which provided a basic process understanding of SBMF from coil. Additionally, process-, tool- and workpiece-side measures were investigated to reduce the anisotropic material flow and improve the component accuracy, whereby the greatest potential was achieved for local friction adjustment through the use of a modified blankholder surface [8].The investigation of the transferability of these findings for forming of more complex, functional components with secondary forming elements, such as gearing, is currently a subject of research.

Objectives and Methodology

The objective of this investigation is to develop a fundamental process understanding for the forming of functionally integrated, geared SBMF-parts from coil. The industrial use of SBMF from coil is limited due to significant process challenges. Including the coil-specific, anisotropic material flow, which restricts the dimensional accuracy of the component, as well as high tool stress. Against this background, in this research work a backward extrusion process from the coil for the forming of functional components with external gearing is investigated. The special focus is on the evaluation of the manufacturability of accurately formed gearing elements by extrusion from coil. Therefore, the aim of this research is to obtain a profound process understanding and to analyze causes of the forming limits. A process analysis based on a combined numerical-experimental approach is carried out. Thus, a finite element (FE) model of the process is set up and validated by comparison with experimental target values. In order to investigate characteristics of the coil-specific material flow and its causes, the sheet geometry is varied within the process analysis by examining pre-cut blanks and coil material. For this purpose, geometrical and mechanical component properties as well as the process force are analyzed based on experimental and numerical results.

Process Layout

This chapter gives an overview of the process setup for the backward extrusion process as well as the workpiece target geometry. Subsequently, the material used and the lubricant are explained.

Process setup. In this study, a backward extrusion process from coil for the forming of externally geared components is investigated. With regard to a shortening of process chains, which is considered to be an aim of SBMF [9], the forming is carried out in a single punch stroke. In the reference process, a coil with an initial sheet thickness t_0 of 2.0 mm and a width of 30 mm serves as semi-finished product. During forming, the sheet thickness in the forming zone is reduced to a residual sheet thickness of 1 mm with a punch stroke of 1 mm, forming a blind cavity. The resulting workpiece geometry is a pin with abstracted external gearing, shown in Fig. 1a.

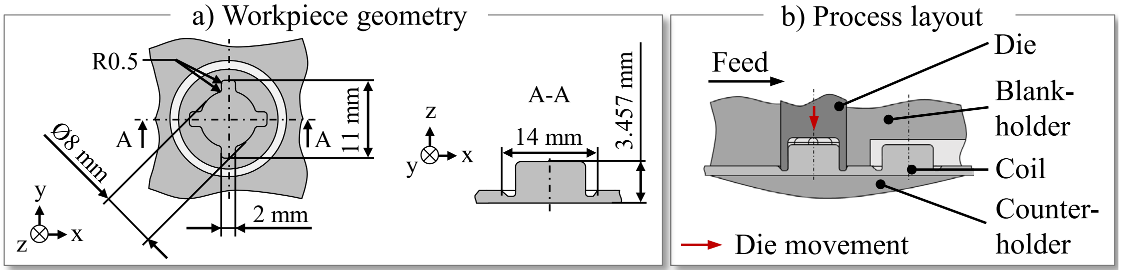
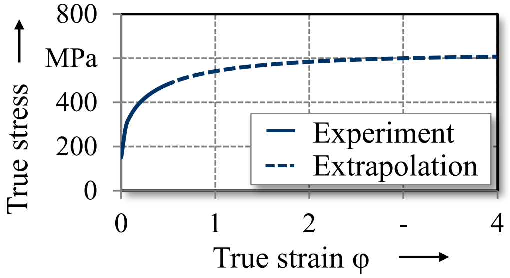


Fig. 1. (a)Workpiece geometry and (b) process layout.

The basic component, the pin, has a diameter of 8 mm and four gearing elements, which are positioned at 90° in and perpendicular to the feed direction. The width of the gearing elements is 2 mm with an outer diameter of 11 mm. The outer diameter of the workpiece has a value of 14 mm. Furthermore, the theoretical pin height with complete material flow into the cavity is 3.4569 mm. To control the material flow into the cavity and to reduce the tool stress, radii are applied at the edge of the blind cavity and at the edges of the pin and gearing. The geometry of the tool parts as well as the process kinematics were designed based on the workpiece geometry. The tool system, shown in Fig. 1b, consists of a die with an internal gearing, a blankholder and a counter-holder.

In the first process step, the blankholder moves in the negative z-direction and fixes the coil with a force of 130 kN by gas pressure springs. Additionally, the blank holder prevents the material flow out of the forming zone as well as the formation of wrinkles. In the next process step, the die moves downwards and the forming process is carried out with a punch stroke of 1 mm. After forming, the die removes, preventing the lifting of the coil by the blankholder. At the end of the process, the blankholder moves to its initial position and the coil is transported out of the forming zone by feed of 20 mm. In the experimental investigation, the active components are integrated into a tooling system, which is installed in the high-speed press BSTA 510-125B2 from Bruderer in order achieve high output quantities. This stroke-controlled press enables the production of 100 components per minute with a maximum nominal force of 510 kN.

Material and lubrication. The workpiece material used is the cold-rolled, mild deep-drawing steel 1.0338 as coil with a nominal sheet thickness of $t_0 = 2$ mm, which is an established material in SBMF [10]. The steel exhibits a purely ferritic microstructure. In addition, the material has a very good formability, which makes it suitable for the production of car body parts. In order to characterize the mechanical material properties, the flow behavior of the deep-drawing steel was experimentally determined in previous research work [11] in the layer compression test according to DIN 50106 [12] up to a true strain of $\varphi = 0.57$. Specimens with a diameter of 10 mm and a height of 14 mm were used in layer compression test, resulting in a compression ratio greater than one. To represent higher true strains, as occur in SBMF [11], the flow curve (Fig. 2) was extrapolated up to a true strain of $\varphi = 4.0$ using the Hockett-Sherby approach.



Flow curve	
Layer compression test (DIN 50106)	
Forming speed	5 mm/min
n	3
Height	14 mm
Diameter	10 mm
Extrapolation	Hockett-Sherby

Fig. 2. Flow curve of the workpiece material 1.0338.

The lubricant Beruforge 150 DL from Carl Bechem GmbH, a water-based lubricant with a high solid wax content, was used in the experimental investigation. The suitability of this lubricant for usage in sheet-bulk metal forming has already been demonstrated in [13].

Numerical Process Model and Experimental Validation

In the following, the setup of the simulation model is described. Subsequently, the quality of the numerical model is evaluated by means of an experimental validation.

FE-Model setup. The simulation software Simufact.forming 14.0.1 of Simufact engineering GmbH is used for the numerical investigation of the backward extrusion process. The suitability of this software for SBMF extrusion processes has already been demonstrated in previous research work [11]. Within the analysis of the material flow, the tools are modeled as rigid. To reduce the computational time, the symmetry of the process along the X-axis is applied, resulting in the analysis of a 180° segmented model, as shown in Fig. 3. In addition, a constraint plane was defined in the negative X-direction to represent the influence of the coil.

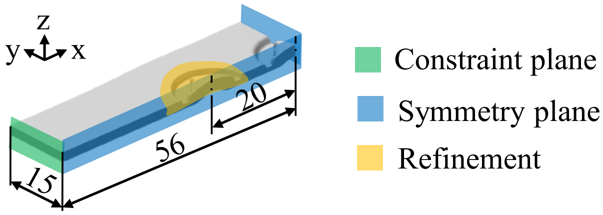


Fig. 3. Setup of the numerical part model.

Two strokes are simulated to evaluate the influence of the preceding forming operation. The workpiece was meshed with hexahedral elements with a maximum element size of 0.5 mm according to the recommendations of Tekkaya [14]. This element type allows an accurate map of the three-dimensional material flow. In addition, a cylindrical refinement box (Fig. 3) with a diameter of 14 mm is applied in the forming zone, reducing the element size to 0.125 mm. The tool components are discretized with tetrahedral elements. The blankholder tension is applied by springs with a low stiffness of 10^{-6} N/mm² and a constant value of 37.8 MPa. Due to the high local contact pressures in SBMF [4], the friction factor model is used to represent the tribological conditions. A global friction factor of $m = 0.1$ is chosen, which was identified for the material 1.0338 in previous research [11]. The mechanical properties of the workpiece material are mapped by the determined flow curve (Fig. 2).

Experimental validation. For the evaluation of the quality of the virtual process model, the numerical model is validated according to the recommendations of Tekkaya [14]. This includes the comparison of process- and workpiece-related target values of the experiment with the numerical results. The validation is carried out for the reference process with a coil width of 30 mm and a feed rate of 20 mm, which corresponds to the distance between the centers of the components. In the experiment, six components are formed on one coil section. In order to take the influence of the preceding forming into account, only the last five components are considered for validation. First, the numerical process model is validated based on a comparison of workpiece-related target parameters. Fig. 4 represents a comparison of geometric component parameters.

For the validation, the diameter of the blind cavity is evaluated in X- and Y-direction (Fig. 4a). The determined experimental and numerical values show a good agreement with a deviation of 0.39 % in X-orientation and of 2.30 % in Y-direction. Furthermore, differences in X- and Y-direction can be identified in experiment and simulation, with a larger cavity diameter in Y-orientation, which indicates an anisotropic material flow. Consequently, the numerical model depicts the anisotropic material flow during coil forming. As a further component-side target quantities, the distance of the geared elements is analyzed, shown in Fig. 4b. In experiment and in simulation, this geometric target quantities also exhibits differences in the considered directions with higher values in Y-direction, which indicate an unequal material flow. The deviations between experiment and simulation are 1.2 % in X-direction and 1.0 % in the Y-orientation. In addition, numerically and experimentally an incomplete forming of the gearing is observed, as the theoretical distance of 11.0 mm is not achieved. Furthermore, the determined pin height is analyzed quantitatively (Fig. 4c). With a complete material flow into the cavity, a theoretical pin height of 3.46 mm is obtained. Experimentally (3.02 ± 0.02 mm) and simulatively (3.25 mm), however, the theoretical pin height is not achieved because of the partially uncontrolled material flow. Furthermore, a deviation of 7.1 % between simulation and experiment is determined caused by the complex tribological conditions in SBMF, which cannot be mapped in the simulation [5].

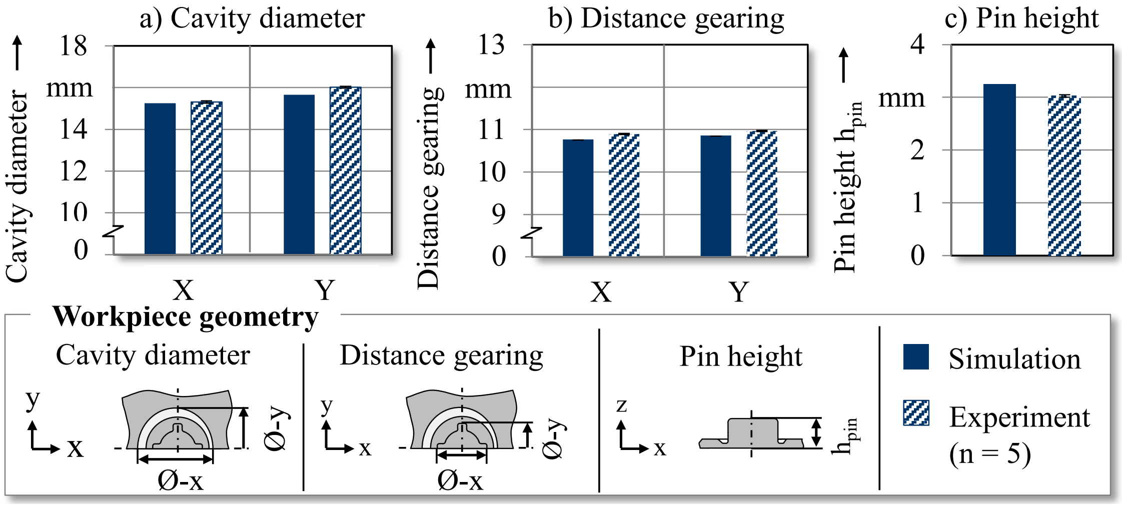


Fig. 4. Validation of the numerical model based on the workpiece geometry: (a) Cavity diameter, (b) distance of the gearing and (c) pin height.

The experimental microhardness distribution is compared with the numerical determined true strain distribution to evaluate the accuracy of the mapping of internal component properties (Fig. 5a). In this regard, a high true strain is considered an indicator of increased strain hardening. The microhardness HV0.05 was determined on sections of the parts with the Fischerscope® HM2000 from Helmut Fischer GmbH according to ISO 14577-1 [15].

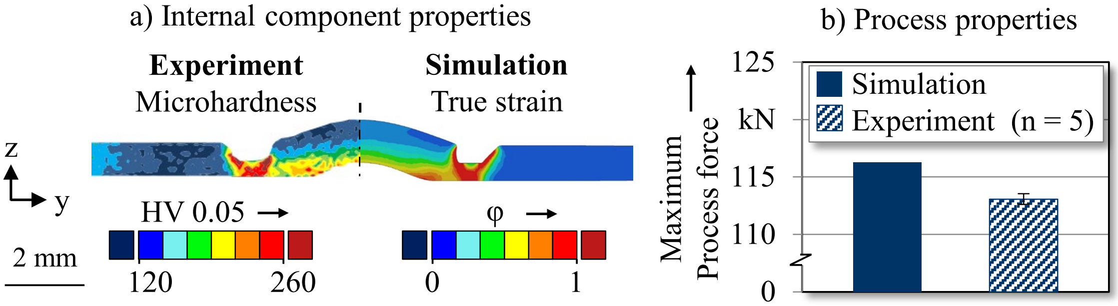


Fig. 5. Comparison of distribution of microhardness and true strain (a) and maximum process (b) force.

The comparison of the microhardness with the true strain distribution shows a high agreement. The maxima of the distributions are achieved in the contact area with the punch. In contrast, low values occur on the upper side of the pin geometry, as the material can flow without flow inhibition in this area. The maximum process force is evaluated as the process-side target variable, which is shown in Fig. 5b. The experimental process force is determined using a piezoelectric load cell 9106A from Kistler AG. In the experiment, a maximum force of 113.08 ± 0.46 kN is required. The maximum numerical force is 116.26 kN. Therefore, the deviation between experiment and simulation is of 2.81 %. In summary, after comparing the part and process-related target values, the numerical process model built up is suitable for realistically representing the forming process.

Process Analysis

The challenge of SBMF from coil is the anisotropic material flow, as demonstrated in the validation by differences in the process results in the X- and Y-direction. The material flow represents a central difference to the SBMF of pre-cut blanks [8], whereby the sheet geometry is considered as a cause for the occurring anisotropic material flow. In order to generate a profound process understanding of coil-specific challenges as well as extrusion of geared components from coil, the influence of the semi-finished product geometry is investigated in the following. A comparison of forming from coil through single stroke with forming from pre-cut blanks is presented. The selected diameter of the blanks corresponds to the coil width of 30 mm. To analyze the material flow, the numerical radial displacement is depicted in Fig. 6, which provides the displacement of the material elements with respect to their initial position. The numerical results were verified by comparison with the experimental component geometry. A negative radial displacement indicates a displacement in the direction of the component center.

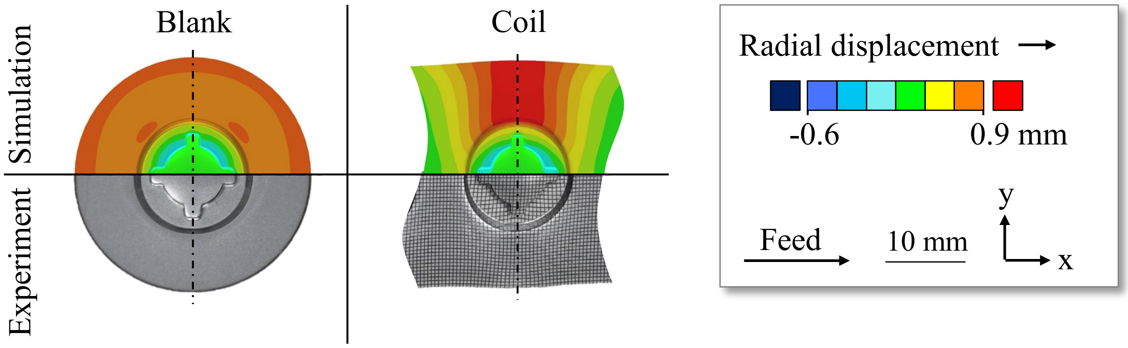


Fig. 6. Influence of the sheet geometry on the radial displacement.

The radial displacement of the circular blank shows a cyclic symmetrical distribution in 90° [5], with an increase in radial displacement outside the bulk forming zone occurring with increasing distance from the centre of the component. Due to the asymmetry of the pin geometry caused by the abstracted gearing, there is also an increased radial displacement locally outwards at an angle of ± 45° to the Y-axis. In contrast to the circular blank, the radial displacement of the coil geometry shows a symmetry with respect to the Y-axis with a high radial displacement perpendicular to the feed direction and a significantly reduced radial displacement in the feed direction. Consequently, an unequal material flow occurs. However, due to the geometry of the coil, the distance from the centre of the part to the outer edge of the coil varies depending on the direction. This leads to a larger contact area between coil and blankholder in X-direction, which reduces the material flow due to the higher friction in this area. In order to analyze the influence of the sheet geometry on the forming of secondary form elements, the form filling of the gearing elements is evaluated by the nominal distance of the abstracted external gearing to the component centre, which is shown in Fig. 7a. The parameter is considered relative to the ideal target values.

When forming the circular blanks, an equal and complete forming of the gearing elements in X- and Y-orientation is achieved with a nominal value of 1.000 ± 0.001. In contrast, the usage of coil results in a difference in nominal distances in the X- and Y-direction, with underfilling of the gearing occurring in both orientations. In Y-direction a value of 0.997 ± 0.001 is determined. In -X-direction a lower nominal distance of 0.993 ± 0.001 occurs. Consequently, the anisotropic material flow leads to an unequal forming and an incomplete form filling of the gearing elements.

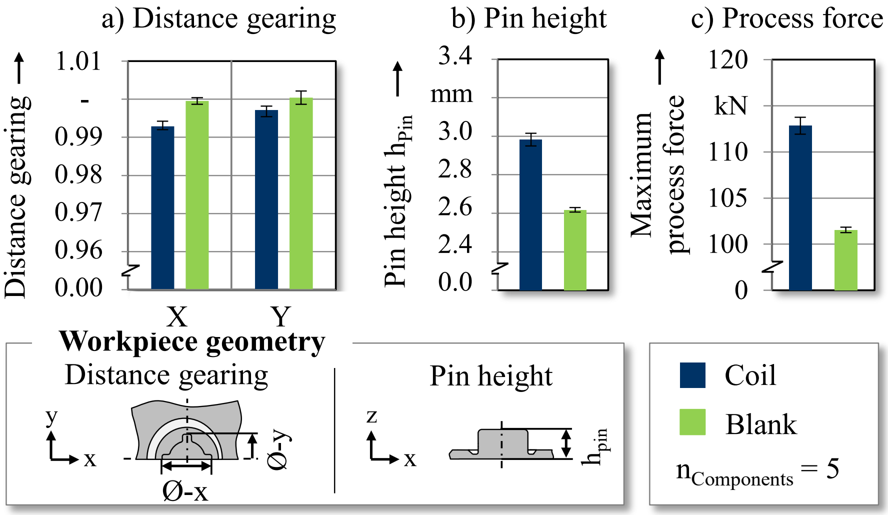


Fig. 7. Influence of the sheet geometry on the distance of the gearing (a), the pin height (b) and the maximum process force (c).

In Fig. 7b, the pin height is considered as further geometric target quantities, which is a parameter for the evaluation of the material utilization. The pin height is 2.62 ± 0.01 mm for the blanks and 2.98 ± 0.03 mm for a coil. Consequently, there is a higher material flow into the cavity when forming the coil. Due to the higher length of the coil in feed direction compared to the diameter of the blank, there is a higher contact between coil and tools as well as a higher material supporting effect, which inhibits the material flow to the outside. Thus, a higher volume of material flows into the die cavity resulting in a greater pin height. The influence of the sheet geometry on the tool stress is evaluated by the maximum process forces (Fig. 7c). When forming the blank, a maximum force of 101.55 ± 0.28 kN is required. For the forming of the coil as sheet geometry, a 10 % higher maximum force results with a value of 112.08 ± 0.84 kN. The increased process force during the forming of the coil is justified by the higher material flow into the bulk forming zone.

Summary

Within this research, a backward extrusion process from coil for the forming of functionally integrated components with geared secondary forming elements is investigated. The focus was on research SMBF- and coil-specific challenges like an anisotropic material flow. In the first step, the process was set up and numerically modeled. Subsequently, the numerical model was validated based on experimental results. In a next step, a combined numerical-experimental approach was used for a fundamental process analysis. The sheet geometry was varied using pre-cut blanks and coils in order to investigate the causes of the anisotropic material flow.

In contrast to the use of circular blanks, the forming of coils leads to an unequal, incomplete forming of the component geometry in and orthogonal to the feed direction. The reason is the non-circular sheet geometry, which causes a higher supporting effect parallel to the feed direction due to the additional material and the higher contact area between coil and tools. Consequently, an anisotropic material flow results. Furthermore, the greater contact between coil and blank holder as well as coil and counter-holder leads to a greater flow of material into the bulk forming zone, resulting in a higher pin height. Therefore, a higher maximum process force is required for the forming of the coil. Despite the higher material flow into the bulk forming zone, the gearing elements were not completely formed, which can be explained by the higher material flow velocity.

In future research work, the influence of the operating mode should be investigated by comparing single stroke and multi-stroke to analyze the influence of previous forming operations.

Furthermore, the investigation of measures for the target control of the material flow represents major research potential to prevent anisotropic material flow and improve part accuracy.

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