Materials Research Proceedings **25** (2023) 61-68 https://doi.org/10.21741/9781644902417-8

Investigation on the shear cutting of functional components manufactured in an orbital forming process

Andreas Hetzel[1,a *], Michael Lechner[1,b] and Marion Merklein[1,c]

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

[a]andreas.hetzel@fau.de, [b]michael.lechner@fau.de, [c]marion.merklein@fau.de

Keywords: Metal Forming, Cutting, Orbital Forming

Abstract. Applying forming operations for the manufacturing of complex functional components instead of conventional shearing or milling is an effective way to increase the material efficiency of the process as well as the mechanical properties of the part. Nevertheless, in many cases subsequent cutting operations are mandatory to reach the final geometry or to add functional surfaces for the later assembly. During forming, hardening effects or different strain states can cause difficulties for the subsequent cutting operation. These characteristics are commonly determined for sheet metal forming processes like deep drawing or bending. However, the complex stress and strain states during sheet-bulk metal forming operations and their influence on the cutting parameters or the part properties have not been investigated comprehensively so far. Furthermore, different assigned processes, like for example orbital forming, allow a local material distribution, realizing a gradient in sheet thickness. Therefore, this contribution focuses on the establishment of a fundamental process understanding on the influence of a sheet-bulk metal forming process on the cutting parameters and the resulting part properties. Functional components are manufactured from C10 sheet metal by orbital forming and subsequently shear cut to generate the final contour. During cutting, specific force-stroke diagrams are evaluated, in order to analyze the influence on the process parameters. The resulting properties of the parts are investigated regarding the quality of the cutting surface and a potential geometrical distortion in consequence of elastic spring back. The influence of the forming process is outlined by a direct comparison with conventionally cut components.

Introduction

Global trends, like an increased functionality or a reduction in greenhouse gas emissions, are facing the manufacturing industry with emerging challenges [1]. Functional integration and lightweight design can be possible answers to overcome current limitations. Nevertheless, an increase in geometric complexity as well as a wide variety of possible materials are accompanying these approaches. Thereby, conventional manufacturing processes like shearing are reaching their limits due to a lack in material efficiency and geometrical limitations [2]. In consequence, the development of innovative products as well as efficient forming operations is mandatory. One possible approach is the application of bulk forming operations to sheet metal, commonly defined as the process class of Sheet-Bulk Metal Forming (SBMF) [3]. Within this process class, a complex three-dimensional stress and strain state can be used to locally increase the sheet thickness or form functional elements like teeth or carriers out of the sheet plane [4]. One assigned process to manufacture functional components with a gradient in sheet thickness is orbital forming [5]. This process is derived from conventional upsetting by tilting of one tool component around the angle Θ, which is typically between 0 - 1°. A significantly reduced contact area between tool and work-piece results in a reduced forming force down to 10%, compared to conventional upsetting [6]. The consequence is a predominantly radial material flow from the center of the component towards the outside, thereby filling cavities attached to the punch in form of rotational or cyclic symmetric thickenings [5]. Nevertheless, the change in sheet thickness due to a three-dimensional material flow as well as an alternating punch movement results in tension inside the component. These residual stresses are hard to determine due to the complex forming zones [3].

These circumstances become challenging when applying cutting operations to realize the final geometry or obtaining functional surfaces for a later assembly. The residual stresses may be released in form of spring back behavior or distortion of the component [7]. The effect of strain hardening during the forming is expected to influence the occurrence of the cutting edge, which is a significant factor for the quality of the joint [8]. Since the influence of SBMF processes on the geometrical appearance of the components as well as relevant parameters after a subsequent cutting has not been investigated comprehensively so far, this investigation focuses on the establishment of a fundamental process understanding. Therefore, orbital formed components are shear cut in two different stages and compared to conventional parts without forming history. Besides the influence on the force-stroke curve, the appearance of the cutting edge as significant factor for the part quality [9] as well as the geometrical properties in consequence of a possible spring back are evaluated.

Experimental setup

In the following chapter, the properties of the applied material as well as the used lubricant are described. Furthermore, the geometrical dimensions of the component, the process setup of orbital forming as well as the subsequent cutting operation are presented.

Investigated material and lubricant. Within this contribution, the unalloyed case-hardenable steel C10 (1.1121) with an initial sheet thickness of $t_0 = 2.0$ mm is investigated. This steel is typically applied for pressed or shear cut parts. The mechanical properties of the material were analyzed via tensile tests and are summarized in Tab. 1. For improved tribological conditions and in order to reduce wear, the lubricant Beruforge 120DL from Bechem is used.

Table 1: Material properties from tensile test of the used steel C10 (1.1121) in rolling direction

C10 (1.1121), samples n = 3	Specification
Yield strength *YS*	335.4 ± 4.93 MPa
Tensile strength *TS*	423.4 ± 6.31 MPa
Uniform elongation *UE*	0.14 ± 0.004
Lankford coefficient *r (0°)*	0.897 ± 0.027
Strain hardening exponent *n*	0.137 ± 0.003

Geometrical dimensions of the functional component. The investigated component is derived from a conventional clutch disc carrier plate from ZF Friedrichshafen AG and features an outer diameter of $d = 120.0$ mm. The dimensions of the different thickenings as well as the final cut geometry are depicted in Fig. 1. The desired thickening should reach a height of $h = 0.5$ mm in both segments. A slide bevel of 1.0 mm is defined, in order to facilitate the material flow into the cavities. To reach the final part geometry for the later assembly to a clutch disc, different cuts are necessary. The friction lining is mounted via rivets on the outer edge of the part, which requires drilling holes with a diameter of $d = 5.1$ mm. The carrier plate is mounted onto a flange in the center with a diameter of $d_i = 36.5$ mm and fixed with rivets featuring a diameter of $d = 8.1$ mm. The dimension of the lightweight windows can be found in the detail view Z.

Materials Research Proceedings **25** (2023) 61-68 https://doi.org/10.21741/9781644902417-8

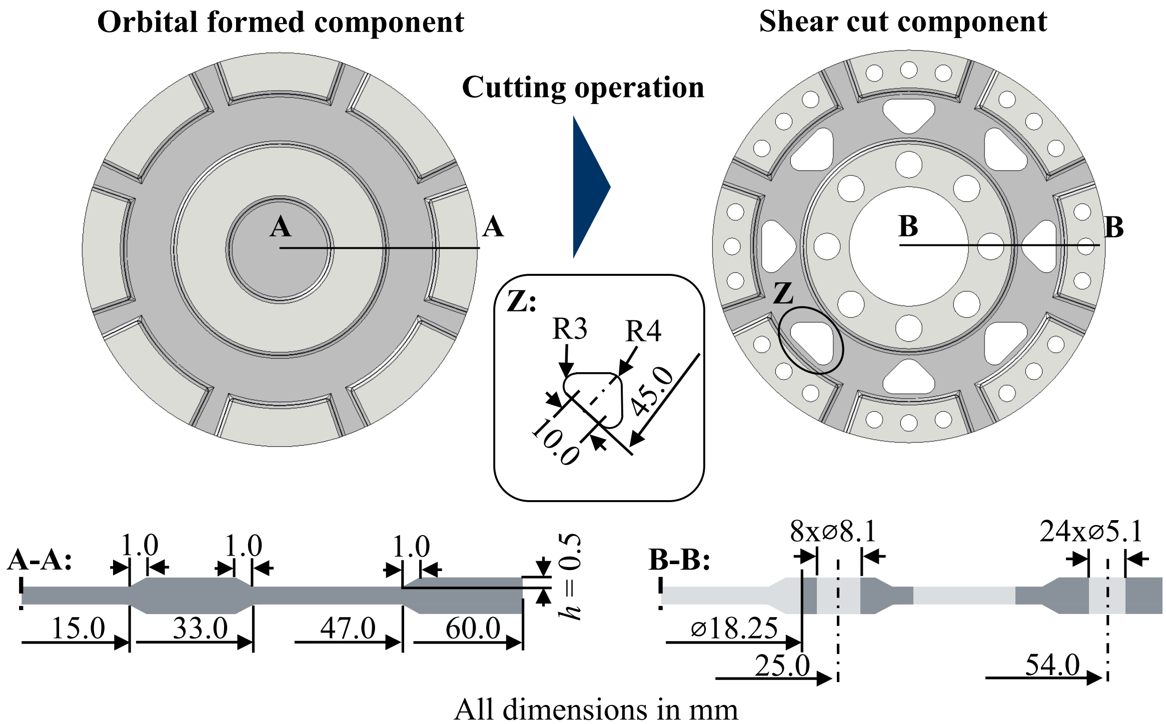

Fig. 1: Geometrical dimensions of the component after orbital forming and cutting

Orbital forming. The investigated orbital forming process was invented and characterized by Merklein et al. [5] and is schematically shown in Fig. 2. The blank with initial thickness of $t_0 = 2.0$ mm is placed onto the counterpunch. At the beginning of the process, the press ram of a hydraulic deep drawing press TZP400/3 from Lasco closes the tool and applies the forming force of $F_{max} = 4000$ kN. Subsequently, the desired tumbling kinematic is applied by the deflection of four hydraulic cylinders on the corner of a specific tumbling plate mounted onto a spherical calotte. A circular kinematic and a process sequence of $U_u = U_c = U_r = 5$, during which the angle is ramped up, held constant and is reduced to the initial position again, are chosen as uniform parameter settings to compare the results along with [5]. By tilting of the lower tool component, the specific tumbling angle of $\Theta = 1°$ is realized. The quasi-rolling movement of the upper punch over the part results in a predominantly radial material flow [6], which is responsible for the filling of the respective cavities in the punch as well as in the counterpunch. In consequence, a local adaption of the sheet thickness in form of a thickening and corresponding thinning can be realized.

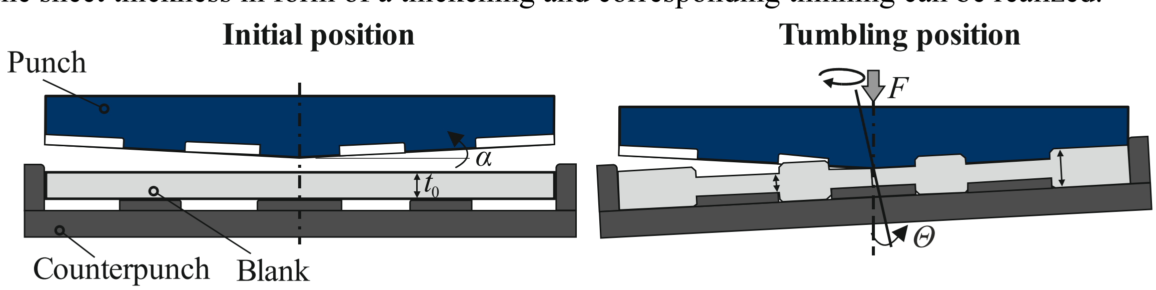

Fig. 2: Schematic process setup of orbital forming, adapted from [5]

Shear cutting setup. For the cutting process, a special tool setup had been developed and manufactured, which is schematically shown in Fig. 3. The component is placed onto the cutting plate and is positioned with circumferential pins and two adjustable levers. The press ram induces the cutting force via the upper tool plate. Gas pressure springs are responsible for the clamping of the orbital formed component trough the clamping plate. The process is divided into two single sequences, since the cutting stamps would be to close for a single stage process. Hence, the first

Materials Research Proceedings **25** (2023) 61-68 https://doi.org/10.21741/9781644902417-8

step consists of cutting the lightweight windows and the flange hub. Afterwards, the cutting stamps are changed for both rivet drillings and the final contour is realized. The cutting clearance is defined as 8% from the maximum thickness of $t_{max} = 2.5$ mm, resulting in a clearance of $u = 0.2$ mm. The process is force controlled and a breaking of the stamps is prevented by the use of stopping plates. During the process, the characteristic force-stroke curve is recorded.

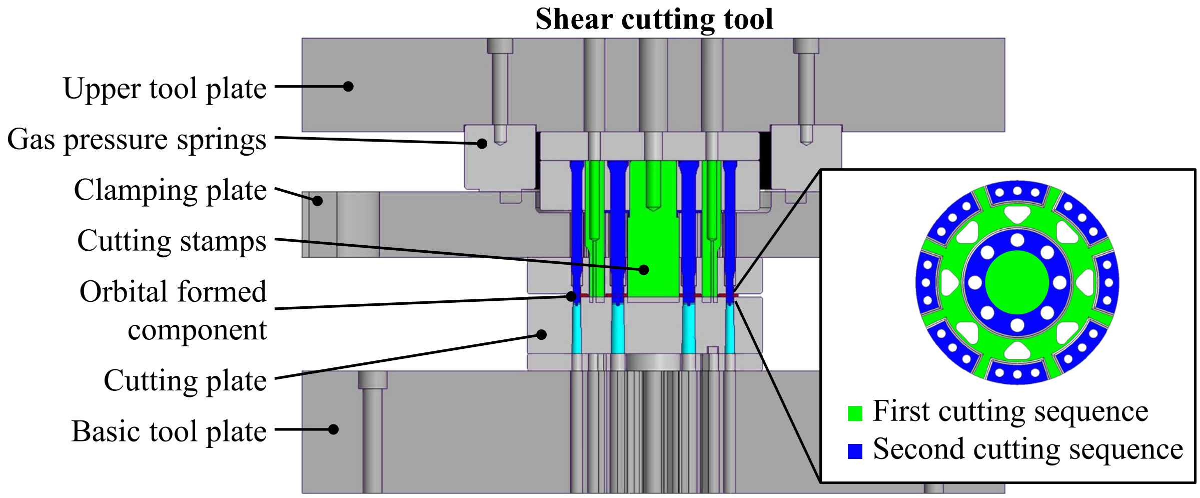

Fig. 3: Schematic process setup for shear cutting of the functional components

Influence on the cutting process

In order to evaluate the influence of varying part properties due to a different manufacturing process on the cutting parameters, the characteristic force-stroke diagram is compared between conventional (a) and orbital formed (b) components in Fig. 4. The characteristic sections can be divided into the tensioning of the gas pressure springs as clamping (1), the beginning of contact between punch and workpiece (2) with a subsequent increase of the required force. The maximum value is reached directly before the point of cut through in form of fracture of the residual sheet thickness (3). A significant drop in force is the consequence. The swinging increase on the end of the process (4) can be explained by the return stroke of the punch in combination with a partially stuck component.

The maximum cutting force for the conventional sheet with $t_0 = 2.0$ mm reaches values for $F_{c1} = 570.0 \pm 8.9$ kN and $F_{c2} = 681.8 \pm 7.6$ kN, thus tracing back to the different total equivalent cutting length of 455.2 mm and 588.1 mm for each sequence. The difference in stroke length of both peaks can be explained by an axial offset of the mounted cutting punches inside the tool.

When analyzing the diagram for the orbital formed component, a distinct appearance for both sequences can be detected. Due to the local gradient in sheet thickness, the engaged cutting line in the first sequence is varying with increasing stroke. First, the punch comes into contact with the inner segment, initiating the increase in force, which is lower compared to the force for the conventional blank. After the distance between the thickening is exceeded, the engaged cutting line increases promptly and the required force rises significantly (x). Since the inner segment is already partially cut, the maximum force reaches slightly lower values of $F_{o1} = 502.7 \pm 6.6$ kN. Due to the overall higher sheet thickness of $t_o = 2.5$ mm, the cut through is reached at a lower punch position and the punch force is increased. The influence of strain hardening during the forming operation influences the maximum cutting force as well, reaching values of $F_{o2} = 796.0 \pm 8.6$ kN for the second sequence. This value resembles an increase of 16.7%, compared to the conventional component.

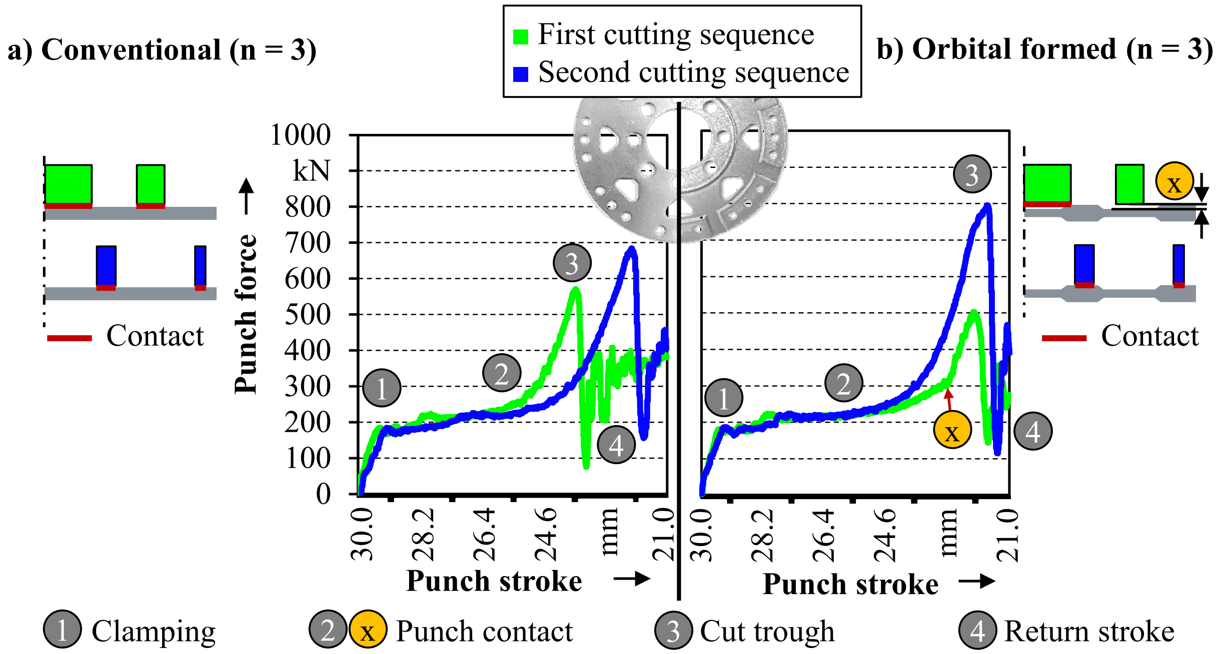

Fig. 4: Characteristic force-stroke diagram of a) conventional and b) orbital formed parts

Influence on the resulting part properties

Besides the process parameters, the resulting part properties are of importance to evaluate the influence of the manufacturing process on the shear cutting of functional components. Therefore, the appearance of the cutting edge as well as the geometrical properties of the manufactured parts are analyzed.

Shear cutting edge. The cutting edge resembles a relevant factor for the quality of the later joint. Since the material properties of the components vary during the orbital forming process, referring to the effect of strain hardening [5], the resulting cutting edge has to be analyzed. Therefore, the cutting edges are analyzed with a three-dimensional laser scanning microscope Keyence VK-X200 from Keyence. The resulting images with a perpendicular view on the edges are shown in Fig. 5. On the top side, the conventional component features burnish depths between 0.57 mm on edge 1, resembling 29% of the sheet thickness, up to 0.95 mm or 47% on edge 4, depicted in the diagram. This ratio is partially depending on the punch geometry but is in general in good accordance with the results in [10], which also show values of 37% - 47% for a comparable material strength class.

On the bottom side, the cutting edges for the orbital formed component are depicted. It can be seen, that the ratio of burnish zone to overall thickness in the diagram is significantly lower in all four segments. The values of this ratio reach from 15% in segment 1 up to 39% in segment 4, which is compared in the diagram as well. Due to the mentioned hardening during forming, the material strength increases as well. As presented by Levy and Tyne [10], the ratio of burnish zone to thickness is strongly depending on the tensile strength, reaching comparable values for the tensile strength of the initial and the orbital formed material C10 (1.1121).

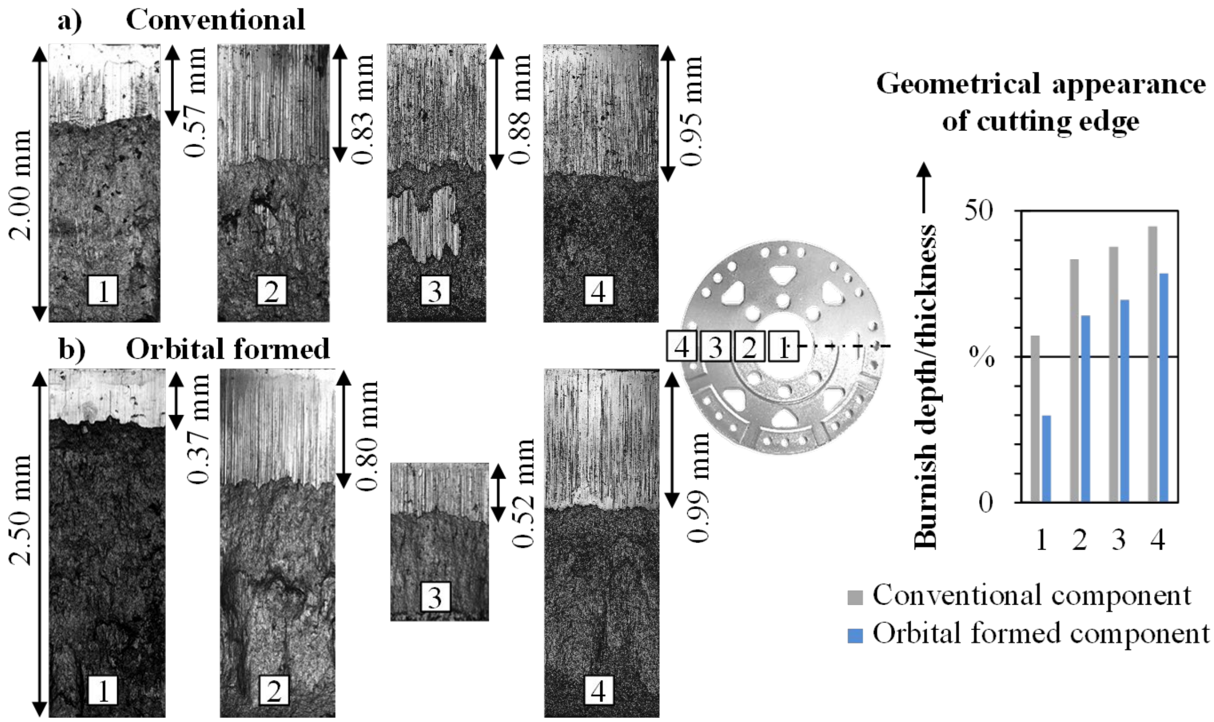

Fig. 5: Shear cutting edge and ratio burnish depth to thickness for both components

Besides the cutting edge itself, the influence of the cutting process on the mechanical properties of the component are evaluated, especially in the direct proximity of the cutting edge. Therefore, the micro hardness distribution of a radial cross section is evaluated, using the measuring system Fischerscope HM2000 from Fischer. The hardness plots for the different sections are depicted in Fig. 6. The effect of strain hardening close to the cutting edge due to the influence of the punch can be detected, since values of 288 HV0.05 could be reached. Achouri et al. [8] explain this influence by the plastic deformation of the material in the vicinity of the cutting edge. This plastic deformation is responsible for crack initiation and growth until fracture. This effect is visible for all segments, independent on the location of the cut or the respective thickness. To validate the influenced zone from the hardness plot, micro structural analysis of the material are prepared by different grinding and polishing operations and a subsequent edging. The microstructure is shown exemplarily for the outermost cross section in Fig. 6. The orientation of the grain structure indicates an influenced zone on the top side of the component of around 0.4 mm from the cutting edge. Furthermore, the rollover depth, the burnish zone as well as the fracture zone can be detected.

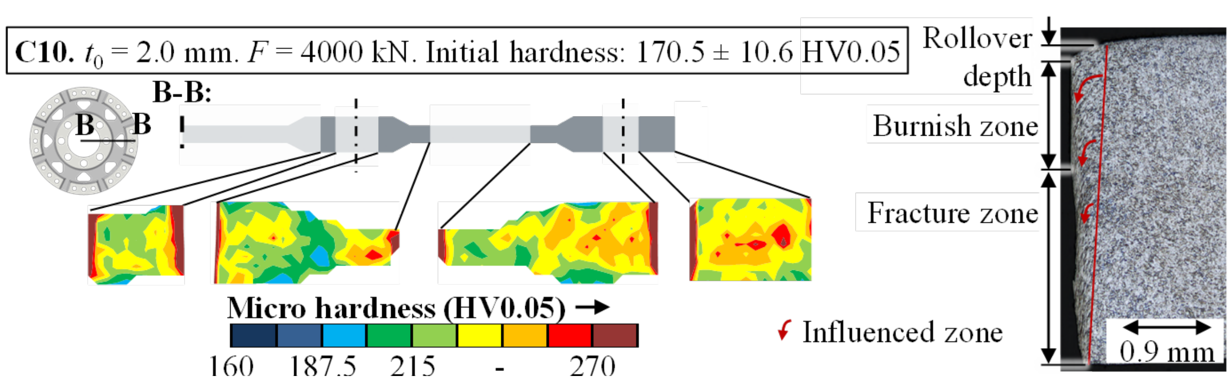

Fig. 6: Hardness distribution and influenced microstructure of the orbital formed component

Geometrical distortion. Another important factor for the later assembly is the resulting geometrical dimension in consequence of a possible distortion due to elastic spring back after the cutting process [11]. To evaluate this distortion, the part contour over the radius is measured using the three-dimensional measuring system ATOS from GOM, which is depicted in Fig. 7. When comparing both contours, the occurring distortion on the outer edge of the part with an offset of 0.28 mm and a resulting angle of 9° can be observed. This distortion can be explained by the elastic spring back due to a release of the residual stresses in combination with the missing support function of a die, as it exists for example during the orbital forming process. A distortion in upward direction is the consequence. This spring back is not a severe process failure but needs to be kept in mind for the later assembly. A possible solution could be a calibrating step with the orbital forming tool.

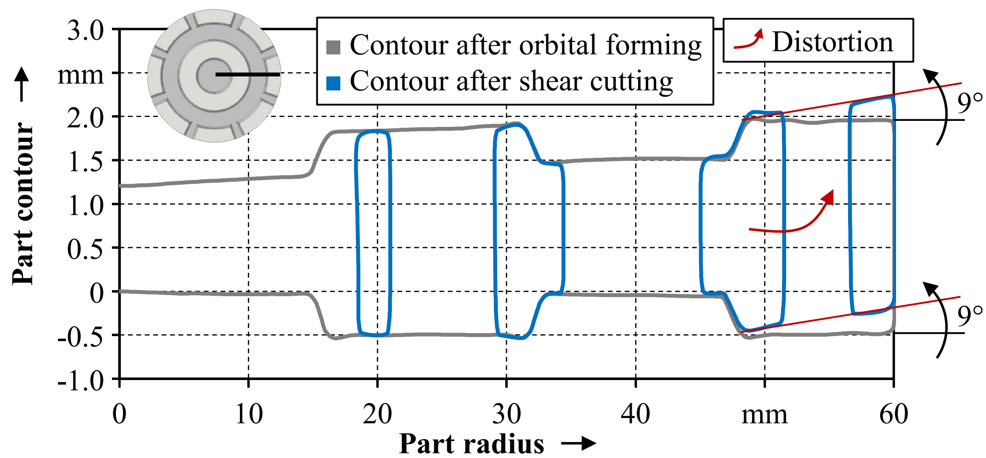

Fig. 7: Geometrical distortion of the shear cut orbital formed component

Conclusion and outlook

The aim of this contribution was to establish a fundamental process understanding on the influence of the three-dimensional stress and strain state during Sheet-Bulk metal forming processes on the resulting part properties after a subsequent shear cutting process. Therefore the characteristic force-stroke diagram was evaluated. Furthermore, the cutting edge and the strain hardening effect were analyzed. The geometrical distortion in consequence of elastic spring back outlines current limitations of the cutting process.

Summarizing the most important results within this contribution, the following conclusion could be derived:

- The effect of strain hardening during forming is responsible for an increase in required cutting force [7]. This increase is furthermore depending on the length of the engaged cutting line due to the locally varying sheet thickness and material properties.
- The increased hardness is responsible for a decreased ductility and consequently an increased fracture depth on the cutting edge. This results in an overall decreased ratio of burnish depth to total thickness, as already stated in [10].
- An occurring plastic deformation of the material near the cutting edge due to the penetrating punch can be obtained by microstructural analysis. Furthermore, this deformation is the reason for a significant strain hardening directly next to the cutting edge [9].
- The geometrical accuracy of the final part is limited with regard to an appearing distortion after the cutting process. This distortion offers values of 9° compared to the

initial formed component and can be explained by the elastic spring back [11] in combination with the missing support function of a die during the cutting process.

Since a fundamental process understanding on the influence of sheet-bulk metal forming processes on a subsequent cutting operation and the resulting part properties could be established, future research should focus on the expansion of this process knowledge. Therefore, the transferability of the presented results between different forming processes within SBMF as well as different material strength classes should be investigated. The implementation of a numerical model, representing the forming as well as the cutting process would be beneficial, in order to allow a deeper process analysis on the interdependencies between the forming and the cutting operation.

Acknowledgement
This work was supported by the German Research Foundation (DFG) within the scope of the Transregional Collaborative Research Center on sheet-bulk metal forming (SFB/TR73) in the subproject T10 - “Development of a manufacturing process for functional components with a varying sheet thickness profile” under grant number 457204991.

References

[1] H.A. Kishawy, H. Hegab, E. Saad, Design for Sustainable Manufacturing: Approach, Implementation, and Assessment, sustainability. 10,3604 (2018) 1-15. https://doi.org/10.3390/su10103604

[2] R. Neugebauer, W. Drossel, R. Wertheim, et al., Resource and Energy Efficiency in Machining Using High-Performance and Hybrid Processes, Procedia CIRP. 1 (2012) 3-16. https://doi.org/10.1016/j.procir.2012.04.002

[3] M. Merklein, J.M. Allwood, B.-A. Behrens, et al., Bulk forming of sheet metal, CIRP Annals - Manufacturing Technology. 61 (2012) 725-745. https://doi.org/10.1016/j.cirp.2012.05.007

[4] K. Mori, Y. Abe, K. Osakada, et al., Plate forging of tailored blanks having local thickening for deep drawing of square cups, J. Mater. Proc. Technol. 211 (2011) 1569-1574. https://doi.org/10.1016/j.jmatprotec.2011.04.010

[5] M. Merklein, R. Plettke, S. Opel, Orbital forming of tailored blanks from sheet metal, CIRP Annals - Manufacturing Technology. 61 (2012) 263-266. https://doi.org/10.1016/j.cirp.2012.03.130

[6] J. Nowak, L. Madej, S. Ziolkiewicz, et al., Recent development in orbital forging technology, Int. J. Mater. Forming. 1 (2008) 387-390. https://doi.org/10.1007/s12289-008-0076-2

[7] W. Volk, J. Stahl, Shear Cutting, in: L. Laperrière, G. Reinhart (Eds), CIRP Encyclopedia of Production Engineering, Springer, Berlin, Heidelberg, 2015, pp. 1-9. https://doi.org/10.1007/978-3-642-35950-7_16823-1

[8] M. Achouri, G. Germain, P. Dal Santo, et al., Experimental and numerical analysis of micromechanical damage in the punching process for High-Strength Low-Alloy steels, Materials and Design. 56 (2014) 657-670. https://doi.org/10.1016/j.matdes.2013.11.016

[9] A. Totre, R. Nishad, S. Bodke, An Overview Of Factors Affecting In Blanking Processes, Int. J. Emerging Technol. Advanced Engineering. 3-3 (2013) 390-395.

[10] B.S. Levy, C.J. Van Tyne, Review of the Shearing Process for Sheet Steels and Its Effect on Sheared-Edge Stretching, J. Mater. Engineering Performance. 21-7 (2012) 1205-1213. https://doi.org/10.1007/s11665-011-9997-x

[11] K. Mori, Review of Shearing Processes of High Strength Steel Sheets, J. Manuf. Mater. Process. 4-54 (2020) 1-14. https://doi.org/10.1016/j.jmapro.2020.02.041