Materials Science Forum — *Submitted: 2015-09-25*
ISSN: 1662-9752, Vol. 854, pp 99-105 — *Revised: 2015-11-19*
doi:10.4028/www.scientific.net/MSF.854.99 — *Accepted: 2015-11-23*

Online: 2016-05-17

A new Strategy for Manufacturing Tailored Blanks by a Flexible Rolling Process

Philipp Hildenbrand[1,a *], Michael Lechner[1,b], Marion Merklein[1,c]

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

[a]philipp.hildenbrand@fau.de, [b]michael.lechner@fau.de, [c]marion.merklein@fau.de

Keywords: Forming, Rolling, Sheet metal

Abstract. Applying bulk forming processes on sheet metals enables the manufacturing of functional components with local wall thickness distributions. Using tailored blanks improves the forming of the functional components and increases the material efficiency. One process for manufacturing tailored blanks with defined sheet thickness distributions is a flexible rolling process. However, this process requires a complex process strategy. Additionally, tailored blanks out of high-strength steels from this process have failed in subsequent forming. Thus, a new rolling concept with a defined shaping of the material into a die cavity has been developed. This new concept requires the development of a new process strategy. In this paper, the general qualification and first results of the new concept are presented.

Introduction

Increasing material efficiency for saving resources is one key aspect for the 21st century [1]. In combination with economic demands like shortened process chains, the reduction of material and simultaneously enhancement of mechanical properties requires the development of new forming technologies. In this context, the increase of the density of functional elements and thus a reduction of individual parts for example in a gearbox enables an improved material efficiency [2]. This results however in new challenges like short and robust process chains due to the lack of state-of-the-art forming processes which can manufacture these components. The application of bulk forming operations on sheet metals, called sheet-bulk metal forming, is one promising approach to meet these challenges [3]. By using such processes functional components with locally adapted wall thickness distributions can be manufactured at shortened process chains [4]. A further increase of the forming of the component can be achieved by applying tailored blanks [5] which can be manufactured by various processes. Continuous rolling processes like strip profile rolling or flexible rolling allows a defined sheet thickness in width respectively in rolling direction from a coil [6]. Using discontinuous rolling processes like flow forming individual but only hollow and axial symmetric parts with adapted sheet thickness distributions can be manufactured [7]. In contrast to these processes, the flexible rolling process presented in [8] enables the manufacturing of single and planar tailored blanks even with circular sheet thickness transitions. However, a complex process strategy with four rolling strokes is necessary to manufacture these tailored blanks [8]. Additionally, tailored blanks out of high-strength steels from this process had failed in subsequent processing as the more strain hardened rolled side of the blank being the same side where the material has been piled up and being the same side taking the most stresses in the subsequent deep drawing [8]. Thus, a new rolling concept has been developed. Using the new one with a die cavity, the rolled side and the thickened side are separated. In this paper, the new rolling concept and its general qualification for the manufacturing of process adapted semi-finished parts as well as first results are presented.

Experimental Setup

Flexible Rolling Machine. The flexible rolling machine used for this investigation is presented in detail in [5] has two rolls and a rotary table as main machine parts, see Figure 1a. The rolls are pivoted on an x-axis for providing a free rotary movement. The rotary table rotates with

U = 0.5 rot/s and can be moved along the z-axis and thus controls the pass reduction of the sheet which is positioned on the rotary table and clamped by the blank holder with the maximum force of F_C = 100 kN. The rotating and vertical movement of the rotary table along with the horizontal movement of the rolls results in a radial material flow, thus sheet thickening and in the end forming of a tailored blank. During the forming process, data regarding strokes and forces are detected by distance and force measurement sensors for each axis.

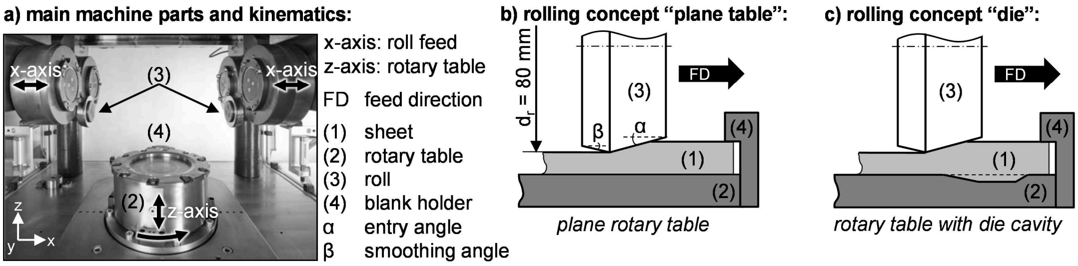

Figure 1: Main machine parts, kinematics and schematic depiction of the two rolling concepts

The rolling concept used so far with a plane rotary table is depicted in Figure 1b and the results on developed process strategies are presented in [8]. Using this concept named "plane table", a thickening of the sheet is achieved in a complex process strategy of four strokes with repeating radial movement of the rolls from the inside to the outside and vice versa. In addition, the rolling of the surface on the same side as the local thickening leads to a roughened surface with grooves whereas the other side, the one being in contact with the rotary table is almost unchanged. Regarding tailored blanks out of high-strength steels this has led to failure in a subsequent deep drawing and upsetting process [8]. The roughened surface in combination with the highest strain hardening on this side will sustain the highest tensile stresses during deep drawing resulting in cracks in the transition from the cup wall to the bottom. Thus, a separation of the rolling side and the functional side is necessary and a new concept has been developed, see Figure 1c. By using the new concept with a rotary table containing a die cavity with an imprint of the target geometry the local thickening will not be on the same blank side as the rolling zone.

Tailored Blank Geometry and Process Strategy. The target geometry of the semi-finished part manufactured by the rolling concept "die" is depicted in Figure 2. It is derived from the geometry of the rolling concept "plane table" presented in [8]. Thus, it has a rotational symmetric material thickening zone between $40 \leq r \leq 50$ mm for enabling a comparison between both concepts. With regard to a further processing this provides sufficient material in areas where needed [8]. The thickening is defined by the geometry of the die cavity in the rotary table. The depth of the die cavity is h = 0.9 mm at a constant zone between $42 \leq r \leq 50$ mm. Towards the center the die cavity inclines between $40 \leq r \leq 42$ mm with rounding radius 2.0 mm whereas toward the outside there is a chamfer of 45° with an edge rounding of 0.5 mm. The deep drawing steel DC04 with an initial sheet thickness of t_0 = 2.0 mm was used. The initial diameter of each specimen is d_0 = 180 mm.

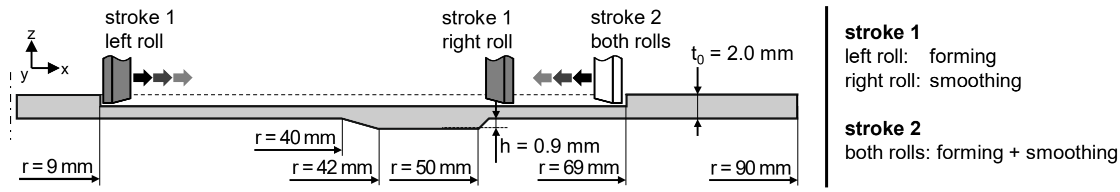

Figure 2: Schematic tailored blank geometry with rolls

As the local thickening is no longer realized by the movement of the rolls a new process strategy for the rolls has to be developed. The new radial movement of the rolls is schematically depicted in Figure 2. The geometry of the rolls as well as their rolling direction and path and the pass reduction are shown in Table 1. The pass reduction Δt is defined as the sheet thickness reduction in the rolling zone. Considering the machine deflection, the real pass reduction is lower than the ideal one set by the process parameters. For developing and realizing the general qualification of the new rolling concept the geometric properties of the rolls as well as the main kinematics were adopted. During stroke 1, the left forming roll is moving from the center towards the outside whereas the right smoothing roll is fixed at the outer end of the die cavity without radial movement. This is necessary because the radial movement to the outside creates a buckling of the material which is hereby levelled. First investigations for the new concept have shown that a forming roll with an entry angle of $\alpha = 30°$ and a smoothing angle of $\beta = 5°$ is necessary for realizing a sufficient pass reduction. The smoothing roll has an entry angle of $\alpha = 15°$ and a smoothing angle of $\beta = 0°$ for levelling the surface. The pass reduction in stroke 1 is $\Delta t = 0.70$ mm, the highest one possible without surface fracture. For stroke 2, which was adopted from the rolling concept “plane table” without changes, both rolls are moved from the outside to the inside with the left roll being delayed for realizing a better smoothing of the surface. This stroke is necessary to smoothen the surface and increase the thickening by the levelling of sheet thickness peaks. First, both rolls act as forming rolls followed by an additional smoothing sequence by lowering the rotary table and thus stopping the contact between rolls and blank necessary for forming the blank and enabling just a levelling of the peaks.

Table 1: Applied parameters for new rolling strategy

		feed direction FD	rolling path RP	entry angle α	smoothing angle β	pass reduction Δt
stroke 1	left roll	i → o	14 – 55 mm	30°	5°	0.70 mm
	right roll	-	57 mm	15°	0°	
stroke 2	right roll	o → i	forming: 69 – 54 mm smoothing: 54 – 30 mm	15°	5°	0.45 mm 0.00 mm
	left roll	o → i	forming: 69 – 54 mm smoothing: 54 – 30 mm	15°	0°	0.45 mm 0.00 mm

The flexible rolling process has a high reproducibility for the rolling concept “plane table” [5]. As these are the first results regarding the general qualification of the new rolling concept, the results of only one tailored blank are presented.

Manufacturing of Tailored Blanks by the new Process Strategy

Process Forces. The process force F_Z of the rotary table and F_X of the left, the forming roll for the applied rolling strategy are depicted in Figure 3 with characteristic positions marked. Additionally, a schematic depiction of the tailored blank is added to each plot. As the presented values are far below the maximum process forces possible, the progression of F_Z and F_X are not described here. A description will be given by the geometric results as they were determined by analyzing F_Z and F_X.

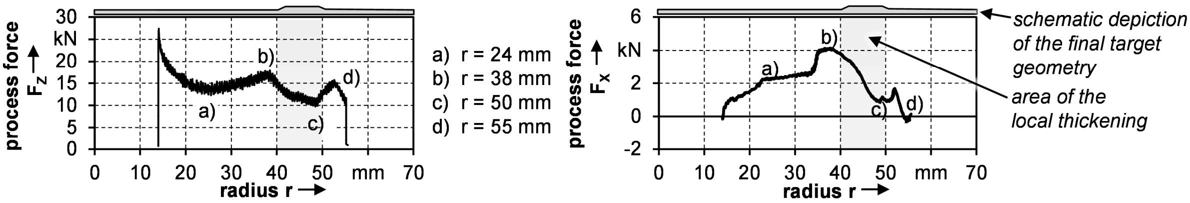

Figure 3: Process force F_Z for the new rolling concept with characteristic positions

Geometric Results. For analyzing the geometric results, the specimen were measured by digitizing the workpiece using the optical 3D scanner ATOS and analyzing the sheet thickness at rolling direction 0° from the digitized specimen. The contour line of the upper surface on the rolled side was measured at fixed state with the same optical 3D scanner positioned inside the workspace of the machine by stopping the process with the blank holder clamping the specimen. However, it has to be taken into account that stopping the rolling process results in a minimum safety release of the blank holder of about 1 mm due to a reduction in hydraulic pressure when the flexible rolling machine is stopped which cannot be prevented. As with this measurement setup it is only possible to one side, the rolled side, specimen were taken from the process for analyzing the sheet thickness.

The contour lines and corresponding sheet thickness at the characteristic positions are shown in Figure 4. The movement of the rolls as well as the rolling zone for each specimen is marked on the equivalent chart. Figure 4a shows the contour lines and sheet thickness at r = 24 mm. A buckling of the specimen can be detected which is caused by the radial material flow in front of the radial movement of the forming roll and the pressing of the material against the fixed roll. The increasing process force F_X of the forming roll up to this position results in increased radial stresses. In combination with the low stiffness of the blank described by the ratio diameter to sheet thickness this leads to the local buckling of the blank out of the sheet plane. Analyzing the contour line in released state a less bulging of the complete blank can be detected. Regarding the sheet thickness distribution, a reduction of $\Delta s \approx 0.25$ mm can be observed in the rolling zone. However, there is no thickening in front of the roll in feed motion direction, because of the buckling of the blank. As both rolls have the same diameter and are mounted on the same vertical position, the fixed right roll causes a material thinning at its position as well. Due to the short stroke of 10 mm by the left roll only a small increase of the diameter up to d = 180.71 mm by a material movement under the blank holder can be detected. The minor material movement at a small diameter as well as the buckling of the material reduces the radial pressure and thus causing a minor increase of the diameter.

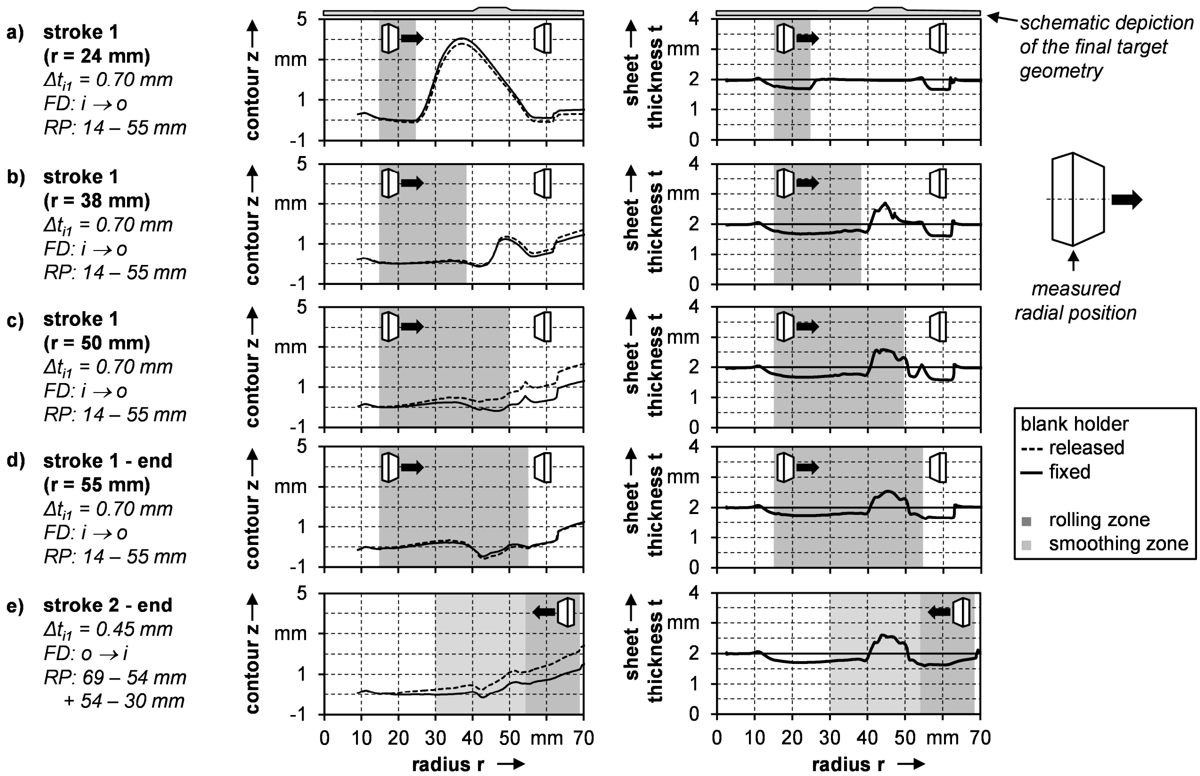

Figure 4: Contour lines and sheet thickness of tailored blanks manufactured by the new concept

The second characteristic position of stroke 1 at r = 38 mm is shown in Figure 4b with the left roll being located at the beginning of the die cavity. A leveling of the buckling and material flow into the die cavity can be detected. Yet, a remainder of the buckling is still visible between 45 ≤ r ≤ 55 mm as the forming roll has not passed the area of the die cavity. The imprint of the right roll is visible as well. In contrast to the first stop at r = 24 mm a bulging of the specimen of about 1.5 mm can be detected and be explained by the minimum release of the blank holder described above. As the rolling zone is at a small diameter, the complete release of the blank holder does only lead to a small additional bulging. The longer rolling path compared to position one and higher deformation of the sheet results in higher residual stresses which lead to the increased spring back.

For the further rolling process it can be assumed that there is no bulging of the blank on the outside while the process is not stopped. The sheet thickness distribution shows at this moment besides a local thinning in the rolling zone a material thickening in the die area up to s = 2.6 mm. However, the thickening is not regular and decreases towards the outside as the material is not displaced completely in the edge of the die cavity. In the area of the remaining buckling at about r = 50 mm no increase of the sheet thickness can be detected. As the fixed roll is still at the same position, its imprint is still the same. Analyzing the diameter, the increased rolling path leads to an increasing elongation of d = 181.05 mm. Thus, a radial material flow below the fixed roll and the blank holder by the radial movement of the forming roll towards the outside has taken place.

Position three with the forming roll being at the outer edge of the die cavity is depicted in Figure 4c. For the contour line the remaining buckling has been nearly leveled by the roll with a still visible small peak at r = 55 mm. The longer rolling path leads to an increased bulging of the specimen. Compared to position two, the bulging increases as can be seen by comparing the contour lines for the completely released blank holder at both positions. An explanation is the increased material flow and thus increasing residual stresses in the blank. Regarding the sheet thickness, the leveling of the buckling leads to an increased die filling and thus increased sheet thickness in the corresponding die area. The maximum sheet thickness is lower than for position two at r = 38 mm. However, a more regular level can be detected with a decline towards the outside. This is comparable to measuring position two and the non-complete filling of the die cavity in the edge. r = 55 mm there is a peak in the sheet thickness distribution, a remaining buckling. As for the previous positions, the diameter increases up to d = 182.12 mm with increasing rolling path.

The result for the completed stroke 1 is presented in Figure 4d. As a difference for the contour, the small peak at r = 55 mm has been leveled by the forming roll. This can be detected as well by regarding the sheet thickness distribution. The incomplete die filling in the inner and outer edge is again visible and has not been eliminated. Comparing the contour lines for fixed and released blank holder, no difference between both states is visible. In contrast to the previous position the complete release of the blank holder does not further increase the bulging of the specimen. One possible explanation might be that the additional 5 mm longer rolling path and levelling of the buckling leads to a release and thus decrease of the residual stresses. However, as these are the first results, this effect has to be analyzed in detail. Due to the small difference in the position of the forming roll of a 5 mm longer rolling path, the diameter does only increase up to d = 182.13 mm.

Figure 4e shows the final result after the second stroke. As stroke 2 is primarily for levelling sheet thickness peaks at a low pass reduction, only a minimum increase of the local thickening by transferring material from the outside towards the die cavity can be detected. The contour line after completely releasing the blank holder shows a bulging of the tailored blank up to 2 mm at the edge. The rolling near the outer edge benefits the bulging of the blank. As shown in [8], the movement of the rolls from the outside towards the center leads to a radial material flow below the rolls. Thus, the movement to the inside results in a material flow in and opposite to the feed direction because of accumulated material in front of the rolls which is transferred towards the center benefiting a sheet thickening. In contrast, the material below the rolls and near the bottom side is transferred towards the outside due to the pressure of the rolls and the accumulated material. The radial material flow towards the outside leads to a diameter increase up to d = 183.1 mm. In comparison with the rolling concept “plane table” a similar tailored blank geometry [8] can be achieved with the same maximum sheet thickness however less even distributed thickening. As these are the first results for the new concept further experiments and adjustment of process parameters have to be carried out.

Surface. As presented in [8], flexible rolled tailored blanks show the highest strain hardening on the rolled surface which is, using the concept “plane table”, the same side as the thickening. Especially for the application of tailored blanks out of high-strength steels in subsequent processes this in addition to the notch effect caused by the rolled surface has led to failure. By using the new concept rolled and local thickened side are separated. For both sides a 3x3 mm² area was measured in both rolling zones by using the confocal laserscanning microscope Keyence VK-X 200, see Figure 4.

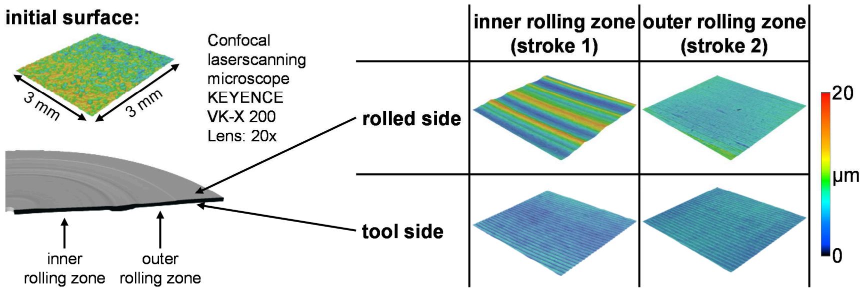

Figure 5: Surface of the tailored blank manufactured by the new concept

For the rolled side, a rougher surface in the inner rolling zone can be detected and explained by the higher pass reduction and thus higher deformation. The average height difference is 10.7 µm compared with 25 µm for the rolling concept “plane table” [5]. For the outer rolling zone a levelling of the height difference can be detected as well, from 10 µm [5] to 1.9 µm. For both zones, the roll marks are visible. For the tool side, the side with the local thickening, no direct deformation by the rolls has taken place which results in a lower surface profile for both rolling zones. However, roll marks are visible in both zones. Thus, besides a levelling of the surface, an imprint through the sheet thickness must have taken place as the initial surface shows no roll marks, see Figure 5. The average height difference for the inner rolling zone is about 4.5 µm compared with about 1.1 µm for the outer rolling zone and can be explained by the higher deformation in the inner rolling zone.

Summary and Outlook

In this paper a new rolling concept for a flexible rolling process is presented. It enables the rolling of the material in a defined die cavity in the tool surface and thus allows a sheet thickening on the opposite blank side as the rolling. In this context, a new process strategy was developed and successfully applied for the first time. The new concept results in a nearly unaltered surface on the thickening side which is crucial for preventing possible failure in subsequent processing. One major challenge regarding the new concept is the controlling of the buckling of the material during the forming as this results in an insufficient die filling and by now lower sheet thickness. The transfer of the rolling strategy on materials such as high-strength steels and the application of the tailored blanks in a subsequent forming process for manufacturing functional components is planned.

Acknowledgement

This work was supported by the German Research Foundation (DFG) within the scope of the Transregional Collaborative Research Centre on sheet-bulk metal forming (SFB/TR73) in the subproject A1. Further thanks to Mr. Lukas Maussner for his bachelor thesis within this research.

References

[1] J.M. Allwood, J.M. Cullen, Sustainable Materials with Both Eyes Open, Uit Cambridge, 2011.

[2] ZF Friedrichshafen AG, Weight-Saving ZF Technology for the Chassis, http://www.zf.com/media/media/en/document/corporate_2/press_3/press_kits_1/2015_naias_1/tx08_NAIAS15_ZF_Lightweight_Design_EN.pdf [March 27, 2015]

[3] M. Merklein, J.M. Allwood, B.A. Behrens, A. Brosius, H. Hagenah, K. Kuzman, K. Mori, A.E. Tekkaya, A. Weckenmann, Bulk forming of sheet metal, Annals of the CIRP 61 (2012)2 725-745.

[4] T. Schneider, M. Merklein, Manufacturing of geared sheet metal components by a single-stage Sheet-bulk metal forming process, Dimitrov, D.; Schutte, C. (Edtrs.): Proc. Conf. Competitive Manufacturing, 2013, 177-182.

[5] S. Opel, Herstellung prozessangepasster Halbzeuge mit variabler Blechdicke durch die Anwendung von Verfahren der Blechmassivumformung, Erlangen, Meisenbach Verlag, 2013

[6] R. Kopp, C. Wiedner, A. Meyer, Flexibly Rolled Sheet Metal and Its Use in Sheet Metal Forming, Adv.Mat.Res. 6-8 (2005) 81-92.

[7] O. Music, J.M. Allwood, K. Kawai, A review of the mechanics of metal spinning, J. Mater. Process. Tech. 210 (2010)1 3-23.

[8] P. Hildenbrand, T. Schneider, M. Merklein, Flexible Rolling of Process Adapted Semi-finished Parts and its Application in a Sheet-Bulk Metal Forming Process, Key Eng.Mat. 639 (2015), 259-266.