3D-Swivel-Bending—A Flexible and Scalable Forming Technology

Michael Schiller, Peter Frohn-Sörensen, and Bernd Engel

Abstract Established forming processes in the automotive industry are used for series with annual production runs of more than 100,000 units. Until now, there has been a lack of forming technologies for the economical production of batch sizes below 100,000 units. This trend is also changing production. Swivel-bending is suitable as a flexible and low-tool process to produce variable cross-section geometries. The manufacturing technology developed for 3D-swivel-bending significantly expands the application possibilities of the basic process by enabling the production of non-linear, three-dimensional bending edges, to manufacture cross-section variable and load-adapted components. The process is designed to be scalable and thus adjustable for processing variable workpiece thicknesses, materials, and spring-back behavior. With additively manufactured joint structures, the effective surfaces of the tools can be adapted to individual requirements. The joint structures can also be manufactured as a print-in-place solution within a significantly shorter product development process.

Keywords 3D-swivel-bending · Additive manufacturing · Bending · Lightweight design · Cross section adapted · Load adapted · Forming · Flexibility · Scalability

Introduction

Many products show the way from mass production to the manufacture of individualized products. This trend is also fundamentally changing production which requires the ability of production techniques to meet the demand for flexibility. This can only be fulfilled economically if the main techniques (forming processes) also perform a change in extension to construction. The requirements for manufacturing processes, in particular, for forming processes, are flexible tool production, fast setup, and fast product changeover. Scalability must be achieved in terms of component geometry, machinable materials, and batch sizes to meet market requirements.

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In the automotive industry, body components are manufactured using production techniques designed for mass production. Medium and smaller batch sizes can often only be produced uneconomically by automotive suppliers using rigid manufacturing techniques and production systems with inflexible capacities. The use of new technologies often fails because of the investment required for new machine technologies, which discourage SMEs in particular.

A survey the authors conducted specifically for sheet metal parts suppliers in 2021 indicates a critical number of units at an annual batch size <100,000 components, cf. Figure 1. Of the nine companies surveyed, 60% are SMEs with a size of less than 250 employees. On average, an annual quantity of 100,000 components per article is produced today. On average, companies have <500 " living" components. The "ideal" annual quantity is already above 100,000 components today. The companies surveyed can hardly produce economically below 50,000 components. Limiting factors for the economic production of smaller quantities are the setup and the tooling costs. The analysis shows that sheet metal component suppliers stick to high-volume processes even if the critical cost-covering number of units is not reached. Compensation takes place through the production and supply of order packages with low and high quantities. Majority of SME parts suppliers use progressive manufacturing.

Established forming processes in the automotive industry are used for series with annual production runs of more than 100,000 units. Until now, there has been a lack of forming technologies for the economical production of batch sizes below

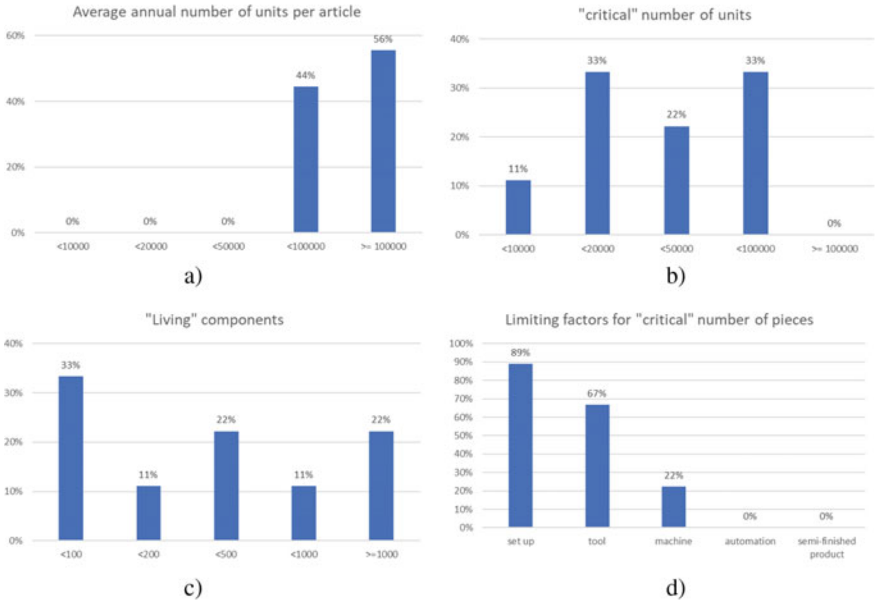


Fig. 1 Analysis of critical batch size survey. **a** Average annual number of units per article in the company portfolio, **b** "critical" number of units, **c** "living" components, **d** limiting factors for "critical" number of pieces

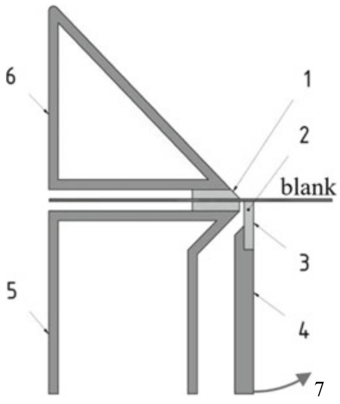
100,000 units. In the past decade, additive manufacturing has become established to produce quantity 1. Incremental forming processes are used for 10–100 pieces per year. However, no forming processes have been established for the critical range between 100 and 100,000 units per year. Accordingly, there is a lack of scalable and low-tooling processes that can also be used to manufacture economically in this quantity. Conventional swivel-bending can be used economically here. Swivel-bending is suitable as a flexible and low-tool process to produce variable cross-section geometries. However, the component complexity required by automotive components cannot be guaranteed by the restriction to bending only straight bending edges.

The manufacturing technology developed for 3D-swivel-bending significantly expands the application possibilities of the basic process by enabling the production of non-linear, three-dimensional bending edges, to manufacture cross-section variable and load-adapted components. Such components are often found in developments for body and structural components, e.g., in the automotive and aerospace industries. Due to the possibility of manufacturing non-linear bending edges and bending surfaces, 3D-swivel-bending can be used to produce many required geometries for the automotive industry and close the gap of the critical quantity range. The process is designed to be scalable and thus adjustable for processing variable workpiece thicknesses, materials, and springback behavior. With additively manufactured joint structures, the effective surfaces of the tools can be adapted to individual requirements. The joint structures can also be manufactured as a print-in-place solution within a significantly shorter product development process.

State of the Art

Swivel-bending is bending with rotating tool movement. The tool structure essentially consists of the three basic tools: upper, lower, and swivel or bending beam. The sheet to be bent is clamped between the upper and lower beams. The bending beam is placed against the part of the sheet metal protruding over the upper and lower beams and swiveled with it around the bending edge, with a generally circular rotation, around a bending axis which is usually stationary. In Fig. 2, the schematic structure of a swivel-bending machine and the associated kinematics of swivel-bending are shown.

A wide variety of cross-sectional geometries can be produced with standard tools. Incremental operation or special tools can also be used to produce roundings, cf. Figure 3. The bending is still carried out via linear bending edges. To increase process speed, swivel-bending machines are equipped, for example, with automated tool change systems and 3D graphic controls with automated program generation and learning material-dependent databases. To ensure product quality, angle measurements are carried out by laser and crowning of the bending beam by means of dynamic systems [1]. In addition, swivel-bending is characterized by high flexibility and good automation capability.



1 upper beam rail
2 lower beam rail
3 bending beam rail
4 bending beam
5 lower beam
6 upper beam
7 rotation

Fig. 2 Principle of the swivel-bending process

Fig. 3 Geometric manufacturing range of CNC swivel-bending machines (center image) according to [2]

The following is a presentation of manufacturing processes with which it is possible to realize non-linear bending edges. In the state of the art, these are in comparison with the 3D-swivel-bending developed.

Incremental swivel-bending has been developed over the last decade. The profile bending process allows a pronounced manufacturing flexibility due to the incremental process sequence and its indistinct tooling [3]. The major application use cases of this technique have been suggested for automotive structural parts where high variances are demanded, for instance, length, bending radii, and angles. In particular, longitudinal members were focused due to their strong substitution potential for profile intense structural body layouts [4]. As a swivel-bending technique, ISB transmits the forming forces by clamping. In contrast to the aforementioned standard procedure of swivel bending, a blank or profile working piece is clamped on both sides in ISB, the stationary and rotatory sides. Moreover, while the conventional process achieves bends out of the blank plane, in-plane bent geometries result from ISB [5]. Because the bending force is transmitted by friction in ISB, unlubricated forming conditions are preferred due to their higher friction coefficients, and thus higher efficiency of force transmission. For a purposeful layout of ISB, it was proven crucial to apply pressure-dependent functions of static friction coefficients [6]. Due to its continuous process sequence, the herein presented manufacturing technology 3D-swivel-bending might on the one hand substitute parts preferred for ISB. On the other hand, both processes could be combined to drastically increase the specific complexity limitations in terms of manufacturable geometries.

Deep Drawing of automotive body parts is used to produce irregular components. Within this process, deep drawing, stretch forming and bending sections can be found. During the linear movement of the punch, bending sections also occur around concave or convex edges, cf. [7].

With flexible roll forming, load-optimized profiles with adapted cross sections can be produced. Using an NC-controlled forming stand, component families of cross-sectionally variable profiles can be realized by simply modifying the control system. Separate halves of the stand each have a translational and a rotational degree of freedom, thus enabling the production of variable profile shapes cf. [8, 9].

In slide draw bending, sheet metal strips or coils are bent by drawing through a forming tool. By changing the cross-sectional geometry of the drawing gap, variable cross-sectional geometries can be produced in flexible slide draw bending with a split and adjustable fixture, cf. [10]. Here, the use of multi-stage tool concepts is also possible in order to produce more complex geometries.

Motivation

In the development of the production structure in automotive engineering and the development of alternative drive systems, a large variety of models are produced in decreasing time-to-market, including in some cases smaller batch sizes. Despite increasing complexity and variety, development times are shortened [11, 12].

In the specially conducted study indicated above, it was found that no forming processes have been established for the critical range between 100 and 100,000 units per year in automotive production.

With the invention of 3D-swivel-bending, the swivel-bending manufacturing process, which is well suited for this range of units, is enabled to produce cross-section variable and load-adapted geometries that can also be used in automotive production.

Table 1 Material parameters determined in the tensile test

$R_{p0,2}$ (MPa)	R_m (MPa)	A_g [%]
233	342	19,1

3D-swivel-bending is intended to meet the requirements of bending non-linear bending edges, technically favorable design and manufacture of tools, low-tool production of sheet metal components, fast setup, and fast possible product changes.

The stated goal is to develop and design a flexible manufacturing process that can also be used to economically produce smaller batch sizes in order to close the existing gap of the lack of a suitable forming process.

Material

For the experimental investigations as well as the associated FE simulations, the material used was 1.0038, which is suitable for steel and mechanical engineering. To characterize the material, tensile tests were carried out according to [13] on a universal testing machine of the type Zwick/Roell Z250. The determined material properties can be taken from Table 1. For input to the FE simulation, the yield curve was calculated according to the Swift-Krukowski approach [14], see Eq. (1).

$$k_f = b \cdot (c + \varphi_v)^d \tag{1}$$

Process Development of 3D-Swivel-Bending

Following on from the demand defined in the introduction for the further development of standardized production processes, the development of 3D-swivel-bending was taken up [15].

3D-swivel-bending extends the swivel-bending process in so far as cross-sectional changes in the form of non-linear bending edges can already be introduced into the sheet metal to be formed on longitudinally oriented components during production. The bending tools have a curved bending edge and complementary bending surfaces that correspond to the desired shape on the component. In this way, 3D-swivel-bending can be used to produce cross-section variable and load-adapted components. The process and application limits of the established manufacturing process, which was previously limited to the production of straight bending edges, are significantly extended. Compared to deep drawing, progressive, and transfer presses, the developed process is characterized by low required machine and tool investments, low-tooling requirements, short start-up and setup times, and the associated fast possible product changes. This favors the production of smaller batches and enables

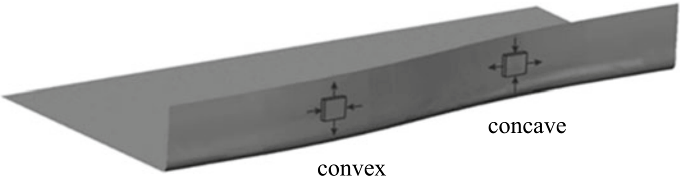


Fig. 4 Characteristic plastic longitudinal and transverse strains in the sheet metal leg of the s-shape

high production flexibility with regard to variable component geometries. Above all, it is thus possible to use 3D-swivel-bending economically in the automotive industry for the market demand for production quantities <100,000 components p.a.

In conventional swivel bending, pure bending stresses occur. In 3D-swivel-bending, the bending stresses are superimposed by tensile and compressive stresses and thus also strains depending on the geometry, which are critical for failure. In Fig. 4, the resulting characteristic plastic longitudinal and transverse strains are shown on an S-beat component with inwardly directed concave circular arcs and outwardly directed convex circular arcs.

Figure 5 on the left shows an example of the characteristic longitudinal plastic strains occurring in the longitudinal direction of the sheet, which increase in magnitude with the height of the sheet leg. The longitudinal plastic strains form a compression region in the convex part (blue) and a tension region in the tapered concave part (red). Figure 5 on the right shows an example of the characteristic transverse plastic strains occurring in the sheet height direction, which increase in magnitude with the height of the sheet leg. The transverse plastic strains form a tensile region in the convex part (red) and a compressive region in the tapered concave part (blue).

At the forming limits, this consequently leads to wrinkle failure for both concave and convex geometries before crack criteria set in. The limiting geometric factor is the height of the bent sheet leg, cf. Figure 6.

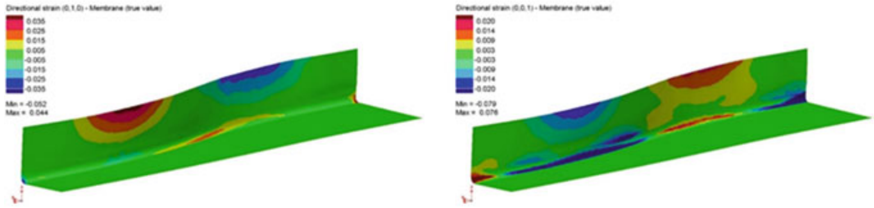


Fig. 5 Characteristic plastic strains—longitudinal direction (left), height direction (right)

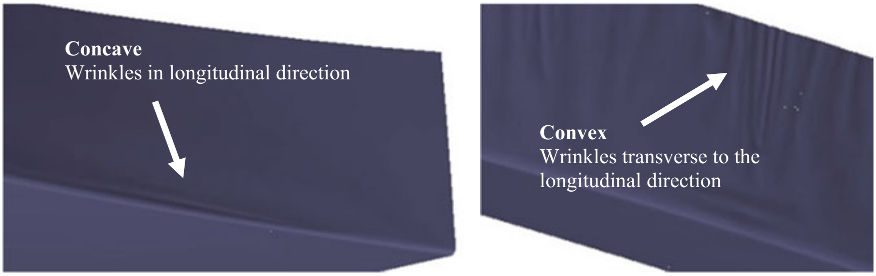


Fig. 6 Wrinkling as a case of failure—concave (left), convex (right)

Process Design of 3D-Swivel-Bending

To design the process limits, a sensitivity analysis was first performed using FE simulations to determine the process-critical geometric parameters. Simplified elemental geometries were derived from the geometric features cataloged as characteristic of 3D-swivel-bent products. To simplify the analysis, circular, concave, and convex bending edges were selected as elementary geometries. Starting from a flat sheet blank, a sheet metal leg is bent to produce an L-shaped component. Calculation models were set up for these elementary bends in the finite element simulation with PAM-STAMP 2019.0 with shell elements. The geometrical variables—radius, plate thickness, chord length, plate leg height, and resulting geometrical properties such as circular arc angle and cross-section offset were systematically varied in the sensitivity analysis. In Table 2, the variation parameters are listed.

The definition of the geometry parameters is shown in Fig. 7 using a concave cross-section geometry.

The investigation shows that the process limits are dependent on the geometric parameters' radius R, sheet metal thickness s, and sheet metal leg height h. The circular arc angle α has no influence on the achievement of a process limit, so that

Table 2 Variation parameters for the sensitivity analysis

Variation parameter	Value
Radius R (mm)	400; 800; 900; 1200; 1600; 2000; 2400; 3200; 4000; 6000
Sheet thickness s (mm)	1, 2, 3
Arc angle α (°)	28, 96; 43, 43; 57, 91
Sheet metal leg height h (mm)	Indirect
Circular chord length S (mm)	Indirect
Cross-section offset Q (mm)	Indirect
Radius bending edge r (neutral fiber) (mm)	3

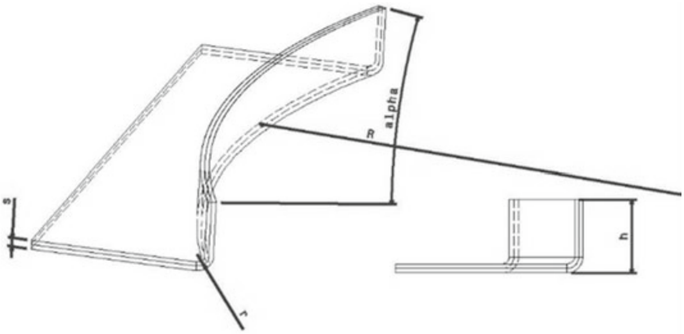


Fig. 7 3D-swivel-bending—geometric parameter definitions

semi-circular bending geometries with a circular arc angle of 180° can also be bent, see Fig. 8.

Model experiments were carried out to validate the results on the possible working field of 3D-swivel-bending. Likewise, a corresponding wrinkling failure for concave and convex bending geometries could be determined here when exceeding a critical sheet metal leg height, cf. Figure 9. The failure limits also depend on the radius of the non-linear bending edge and the sheet metal thickness.

Fig. 8 Semi-circular concave cross-section geometry

Fig. 9 Wrinkling as a case of failure—concave (left), convex (right)

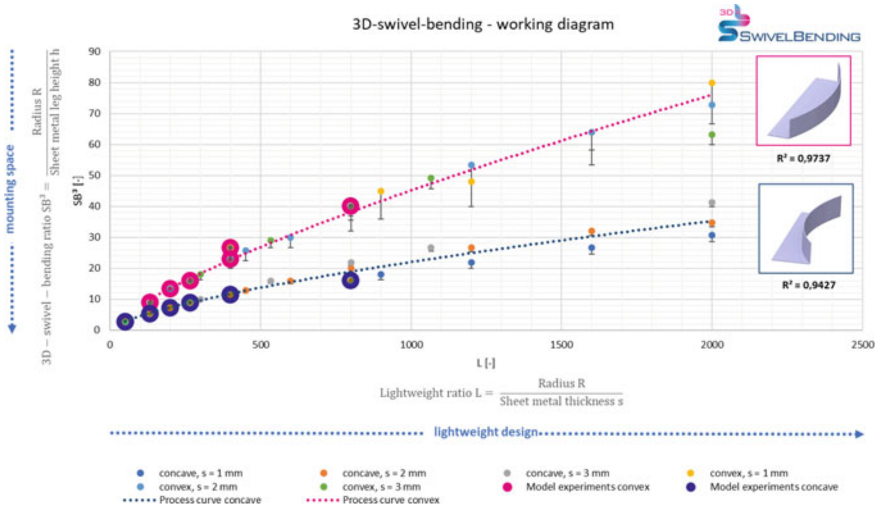


Fig. 10 Working diagram for 3D-swivel-bending

The working diagram for 3D-swivel-bending is shown in Fig. 10. Here, concave and convex geometries are shown simultaneously. Each point in the process window represents a parameter setting in the FEM model as well as the model experiments of the sensitivity analysis. The investigation and evaluation of the sheet metal leg heights were carried out in a step size of 5 mm.

Compared to the process boundary points designed using the FE simulation, those validated with the model experiments are shown as larger blue (concave)- and pink (convex)-colored points.

Bending below the respective limit curve for concave or convex geometries is not possible. For the concave process curve, it can be seen that it extends further to the left. With a lightweight ratio L = 50 and a 3D-swivel-bending ration $SB^3 = 2.5$, the concave 180° bend is noted. With the bending of a 180° circular arc angle, a theoretical process limit is reached than then an undercut would be present.

Figure 10 R^2 denotes the coefficient of determination and thus the quality with which the measured values fit the model formed. The model for the coefficient of determination was empirically fitted in Microsoft Excel.

A significant result is that higher sheet metal leg heights can be achieved when bending concave geometries than when bending convex geometries. The reason for this lies in the stress ratios present and the resulting failure modes. For concave geometries, tensile stresses in the bent sheet metal leg along the bending edge have a favorable effect. In comparison, convex geometries are subject to corresponding compressive stresses. It can also be seen that with increasing sheet thickness, it is also possible to shape greater sheet metal leg heights.

Overall, the practical model experiments meet the process limits determined in the simulation without any further anomalies.

The following dimensionless key indicators (2) and (3) were derived to represent a working diagram for 3D-swivel-bending:

$$Lightweight\ ratio L = \frac{Radius\ R}{Sheet\ metal\ thickness\ s} \tag{2}$$

$$3Dswivel\ bending\ ratio\ SB^3 = \frac{Radius\ R}{Sheet\ metal\ leg\ height\ h} \tag{3}$$

Demonstration of 3D-Swivel-Bending

A demonstrator was developed to represent 3D-swivel-bending in a proof-of-concept. For the design of a demonstrator, a geometry was chosen that contains a variable progression along the bending edge and is not represented by a single circular arc, as is the case with the model test parts. The course of a straight bending edge is also linked with a non-linear one. The special feature in the design of the bent sheet metal leg, in addition to the variable curvature progression, is that starting from a 110° bend, i.e., >90°, there is a bend opening with the longitudinal progression down to a 70° bending angle. This is intended to demonstrate the potential of 3D-swivel-bending to reproduce such variable curves and to realize bends >90°. This would lead to considerable additional tooling costs in the case of substitution processes. In principle, the demonstrator design is based on bulkhead parts, wheel housing elements, cover plates, and taillight mounts used in automotive engineering in order to demonstrate realistic application potential. When looking at potentially manufacturable components using 3D-swivel-bending, it was recognized that secondary forming elements such as embossing are often introduced into components. This was also included in the design of a pocket which could be used as a tethering surface, for example, cf. Figure 11.

The demonstration component can be manufactured in variable lengths and sheet metal leg heights with little tooling effort, see Fig. 12. For example, the component

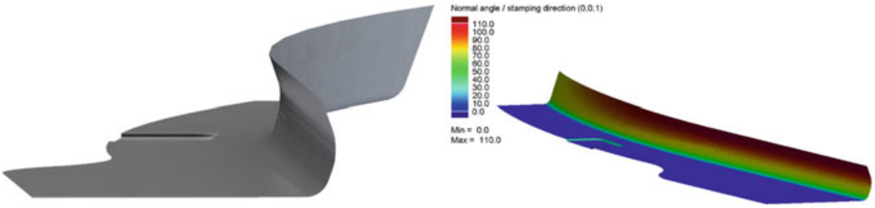


Fig. 11 Demonstration component 3D-swivel-bending (left), bending angle course (right)

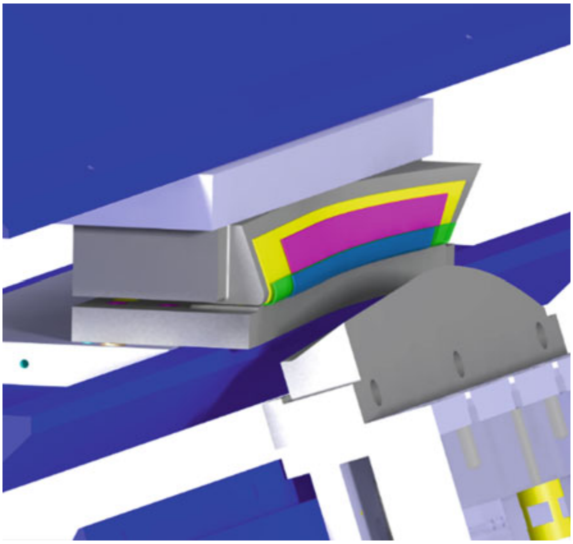


Fig. 12 Scalable demonstrators in a single tooling design

shown in green and yellow was manufactured from material 1.0933. The parameters, which are relevant for bending, are listed in Table 3.

The proof-of-concept shows successful bending results in Fig. 13.

Table 3 Geometric properties scaled demonstrator

Bending parameter	Unit	Demo 1	Demo 2
Sheet metal length l	mm	600,00	600,00
Sheet metal leg height h	mm	20,00	60,00
Sheet thickness s	mm	1,50	1,50
Radius r	mm	5,00	5,00
Min. radius bending edge R	mm	1537,96	1537,96
Min. radius sheet metal leg R	mm	1307,92	833,03
Lightweight ratio L bending edge	–	1025,31	1024,93
Min. lightweight ratio L	–	871,95	555,35
3D-swivel-bending ratio SB^3	–	76,90	26,62
Min. 3D-swivel-bending ratio SB^3	–	65,40	13,88

Fig. 13 Bending results 3D-swivel-bending

Increasing Manufacturing Flexibility Through Adjustable Tooling Technology

For 3D-swivel-bending, as according to the presented state of research, adjustable die faces might enhance manufacturing possibilities of the process. A spring loaded, displaceable upper die could, for instance, help to flexibly compensate springback influences of material variations. Moreover, adjustable faces would help to compensate variations in sheet metal thickness, both in terms of product variations, as well as using tailored blanks. Moving one step further, segmented tool faces would allow to change the whole bending geometry by tool surface adjustments.

In order to make tool surfaces adjustable for a wide geometrical variety, its segmentation is required, as known from multipoint forming processes [16]. For the controlled movement of the segments, actuators such as hydraulic pistons are needed, but these systems require a large amount of space. However, for some process adjustments, a finer segmentation might be necessary, leading to a conflict of objective. At this point, other tool structures behind the segments could be useful, e.g., single and multiple connected joint structures. A conventional manufacturing method of such joint structures is to assemble several standardized pieces. Generative technologies, in particular, additive manufacturing have paved the way to manufacture complex structures in one single process sequence without assembly, including joint structures [17–21]. With additively manufactured joint structures, the effective surfaces of the tools can be adapted to individual requirements. The joint structures can also be manufactured as a print-in-place solution within a significantly shorter product development process.

In future work, it will be focused, if additively manufactured joint structures are applicable to allow to adjust tool surfaces in order to increase manufacturing flexibility in terms of scalability. The principal idea is to design the upper die of 3D-swivel-bending as adjustable structure to allow for compensating variable sheet thicknesses and springback effects during bending.

When using articulated structures to adjust the tool contact surface, low forces must be absorbed compared to the required bending force and calibration force. The calibration force during bending should be absorbed by an end stop so that the joints can be used with as little space as possible.

Conclusions

3D-swivel-bending was developed to produce cross-section and load-adapted components. Such components are used in lightweight structures, which are often found in developments for car bodies and structural components, for example, in the automotive and aerospace industries. In 3D-swivel-bending, characteristic plastic longitudinal strains occur in the bent sheet leg in the form of a tensile region in the inwardly curved part of the sheet and a compression region in the outwardly curved part of the sheet. The opposite is the case in the transverse direction. The failure criterion for both cases is wrinkling. With a validated working diagram determined via FE simulations and model experiments, the feasibility of components can be evaluated depending on the material and geometric features. Following a proof-of-concept, the developed process for 3D-swivel-bending demonstrates the applicability of the invention. Due to the high process flexibility compared to deep drawing, faster product changes are possible due to shorter development times, lower tool volumes, and quicker setup. Investment requirements in machinery and tooling are also low compared to forming presses. The possible near net shape manufacturing also enables sustainable resource conservation. 3D-swivel-bending which is characterized by low-tool manufacturing, a high degree of flexibility and good automation, so that rapid product changes are possible and previously used manufacturing processes can be substituted. Longitudinally oriented components with L-, Z-, U-, and O-shaped cross sections and non-linear bending edges can be produced in variable sheet thicknesses and materials for a wide range of applications. With the help of the developed working diagram, the manufacturability of desired components can be evaluated in advance and without further simulation effort. For variable materials, an adaptation of the limit curves is required. Due to the possibility of manufacturing non-linear bending edges and bending surfaces, many required geometries can be produced by means of 3D-swivel-bending and the gap described at the beginning of the critical quantity range for the production of automotive components <100,000 components/year could be closed or at least supported.

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