



Influence of component design on extrusion processes in sheet-bulk metal forming

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Received: 14 March 2019 / Accepted: 25 October 2019 / Published online: 13 November 2019
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Abstract

Nowadays, the functional integration of workpieces challenges existing forming processes. The combination of established forming processes – like sheet metal and bulk forming – offers the possibility to counter this issue. The application of bulk forming operations on sheet metal semi-finished products, also called sheet-bulk metal forming (SBMF), is an innovative approach. The potential of SBFM cannot be fully exploited, as there are no recommendations in terms of workpiece design and layout influence on the process result. Therefore, this paper focuses on the analysis of semi-finished products and component design parameters on resulting part and process properties in two extrusion processes in SBFM. The investigation is based on a combined numerical and experimental approach. It is shown that the investigated design parameters, in addition to the achievable dimensional accuracy, substantially influence the occurring tool loads as well as the required process forces.

Keywords Sheet-bulk metal forming · Extrusion · Sheet forming · Simulation · Component design

Introduction

Forming technology processes offer advantages compared to alternative production technologies in terms of part-complexity [1] and -properties [2]. The requirements on forming processes with regard to the functional integration are continuously increasing [3]. For this reason, the efficiency of standard processes is exceeded, whereby innovative process combinations gain in importance [4]. The combination of established forming processes – such as sheet metal forming and bulk forming – offers the possibility to combine the respective advantageous properties [5]. One such process technology that applies bulk forming operations on semi-finished sheet metal products is the so-called sheet-bulk metal forming (SBMF) [5]. Forward (FE) and lateral extrusion (LE) [6] are considered to be the standard processes for bulk and deep drawing [7] for sheet metal forming. The potential of sheet bulk metal forming is currently of only limited use. Compared to conventional methods there are no guidelines for workpiece

design or knowledge of their influence on the process result. With regard to this background, this article focuses on the research of two sheet-bulk metal forming processes to counter this issue.

Objective and methodology

The use of SBFM processes is currently limited by missing process knowledge in terms of the influence of the semi-finished product and workpiece-specific aspects on the process result. For this reason, the objective of this research work is to obtain an understanding of the fundamental relationships between the design of extrusion parts in sheet-bulk metal forming and its influence on relevant workpiece and process properties as well as to derive practical recommendations.

In order to achieve this purpose, the methodology described in Fig. 1 is applied.

A detailed comparison of the forward and lateral forming process is basis for this contribution. Thus, the design of the parts and processes are described and workpieces are formed. A combined numerical and experimental approach focuses on the comparative analysis of both sheet-bulk metal forming processes and the identification of process-specific characteristics. To determine the influence of part design and underlying mechanisms on relevant workpiece- and process-related

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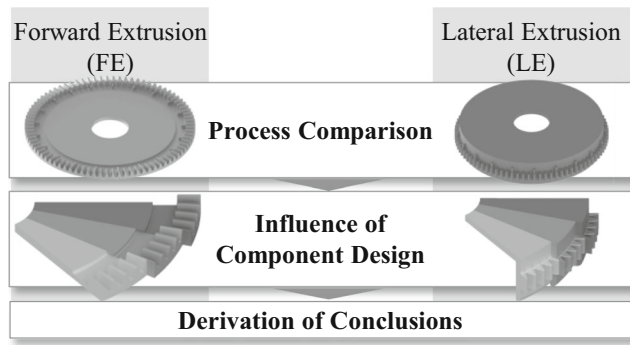


Fig. 1 Methodology to gain component design comprehension

parameters, numerical investigations are conducted on the basis of validated simulation models. The resulting cause-effect relationships are systematically summarized and evaluated in order to provide recommendations for the design of extruded parts in sheet-bulk metal forming.

Process comparison

Forward and lateral extrusion are core processes of SBMF [8]. In both process classes, the design of functional elements of the same type requires a different workpiece design and process control. Within the process variants, specific characteristics occur in particular with regard to the material flow during forming.

Workpiece design

Manufacturing of gears challenges the forming technology because of the sophisticated material flow and highly stressed

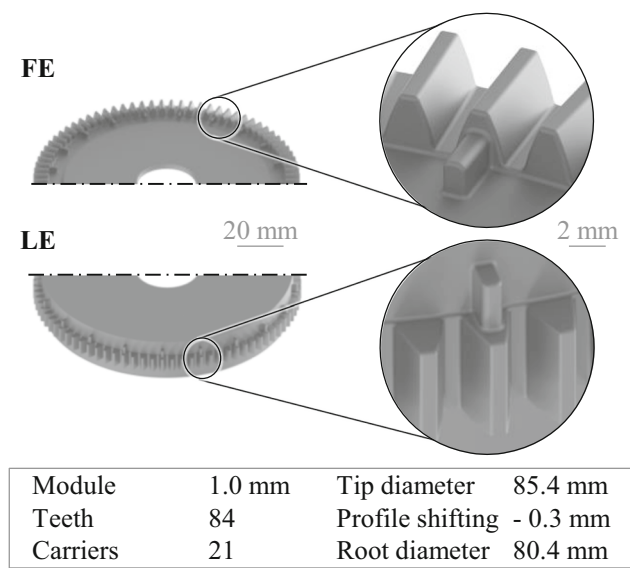


Fig. 2 Forward and lateral extrusion workpieces

tools [9]. The investigated parts and their functional elements are shown in Fig. 2.

To ensure transferability of the findings, both processes possess the same functional elements, a combination of gear and lock teeth. In case of gear toothings, involutes are typically used [10], whereby carriers are mostly applied as industrial locking elements [11]. The relevance of the findings is ensured by the selection of the formed geometries. In order to examine the influence of high functional integration on low workpiece bottom volumes, the parts have 84 involutes and 21 carriers in a cyclically symmetrical arrangement and an initial sheet thickness of 2.0 mm.

Process design

Based on the workpiece design, the respective active parts and process kinematics were designed. The usage of an adequate process control ensures that the displaced material corresponds to the required volume of the functional elements. An overview of the active parts is provided in Fig. 3.

Active parts

In order to minimize tool loads, split dies are used in both processes. This is a standard measure in tool design for cold extrusion to improve tool performance [11].

In both processes, a counter holder is positioned opposite to the punch, which enables a constant counterforce to be applied. In addition to forward extrusion, lateral extrusion requires the integration of a draw ring.

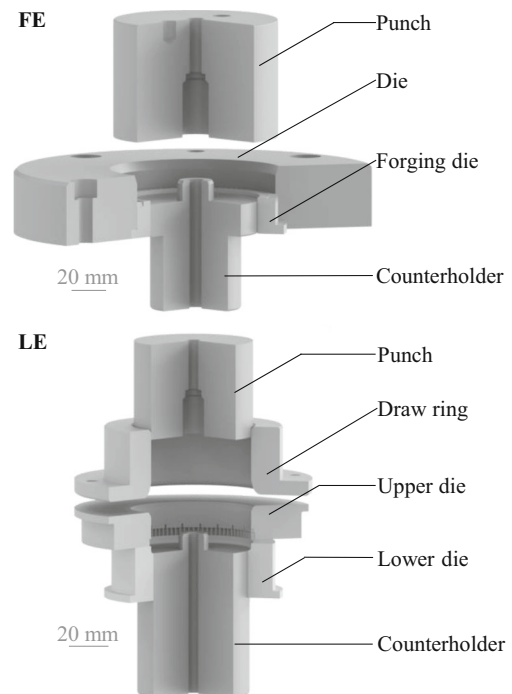


Fig. 3 Active parts of the forward and lateral extrusion process

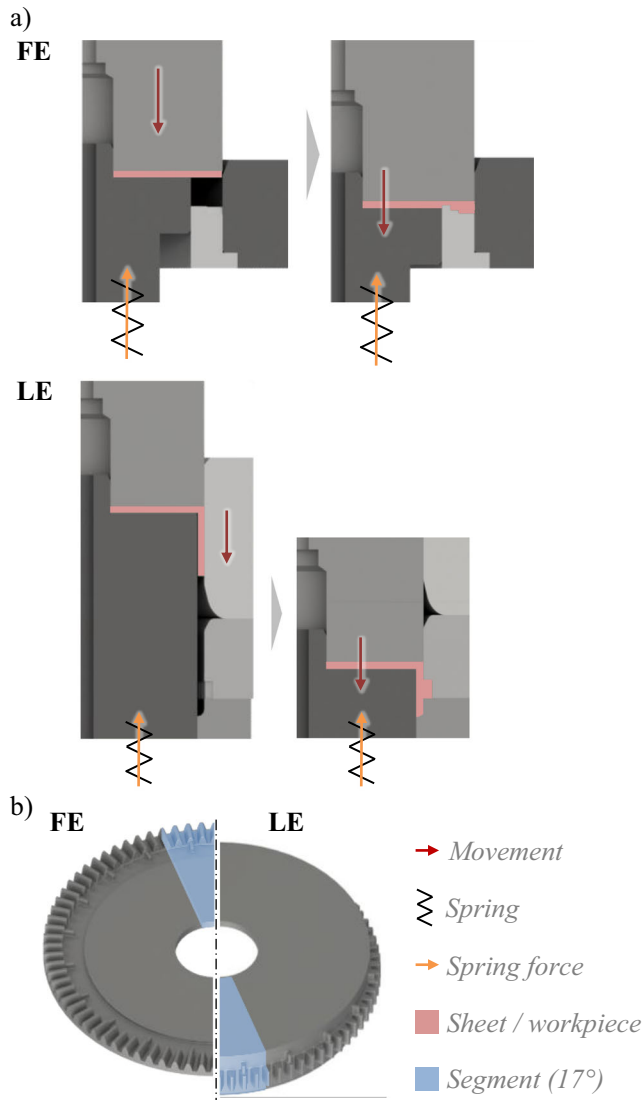


Fig. 4 a) Process kinematics and b) workpiece segments in forward and lateral extrusion

Process procedure

The basic procedure is comparable in both processes. A blank is inserted into the tool and then clamped by an axial downward movement of the punch (Fig. 4 a). In forward extrusion, the punch displaces the counter holder and forms the functional elements. In lateral extrusion a cup needs to be formed beforehand by the draw ring. Without interrupting the stroke, the punch displaces the counter holder together with the cup and causes a radial material flow.

Numerical model

To avoid cost-intensive real experiments, decoupled variant simulations are used [12]. Simufact.forming 14.0 is a

special forming software which is often used in SBMF [13]. It allows a robust simulation of extrusion processes on sheet metal. Therefore, it has been used for this contribution. In order to represent the described kinematics of both processes, the counter-holder in the simulation model is loaded with a pre-stressed spring, whereby a nominal stress of 95 MPa is applied in the workpiece center. The smallest possible symmetry unit for mapping a functional element unit is 17° (Fig. 4 b).

The form element combination contains 4 teeth and one carrier. In order to achieve a good balance between result quality and calculation time the workpiece is meshed with hexahedrons. The deformable tool components are discretized with tetrahedrons. To ensure good result quality, refinement boxes (≤ 0.1 mm) have been used in workpiece areas with functional elements and excessive distortion. In the remainder of the parts, coarser meshes (≤ 0.4 mm) are used [14]. An iterative solver was chosen to allow acceptable calculation times. The simulation time on a high performance computing cluster averages to 30 h in forward extrusion and to 50 h in lateral extrusion.

For the investigation of material influences, the industrially established steels DC04 and DP600 are used in the numerical investigations. The realistic mapping of the forming behavior of steels requires knowledge of their mechanical behavior [15] (Fig. 5).

Since sheet-bulk metal forming processes use sheets as semi-finished products, it is customary to determine the flow curves by layer compression tests according to DIN 50106 [16]. Each steel is tested with three repetitions ($n_{\text{Specimen}} = 3$). 7 layers of sheet with diameter 10 mm are stacked to one specimen. The materials show different initial yield stresses k_{f0} of 175 MPa (DC04) and 359 MPa (DP600) as well as varying hardening behaviour. In the experiment, the yield stresses were determined up to a true strain of about $\epsilon = 0.5$. Extrusion on sheet metal causes high deformation [8], for which reason the experimental data are extrapolated using suitable approaches for higher forming degrees.

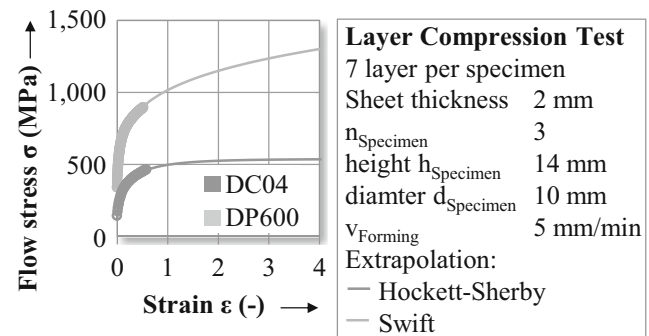


Fig. 5 Flow curves of steels DC04 and DP600

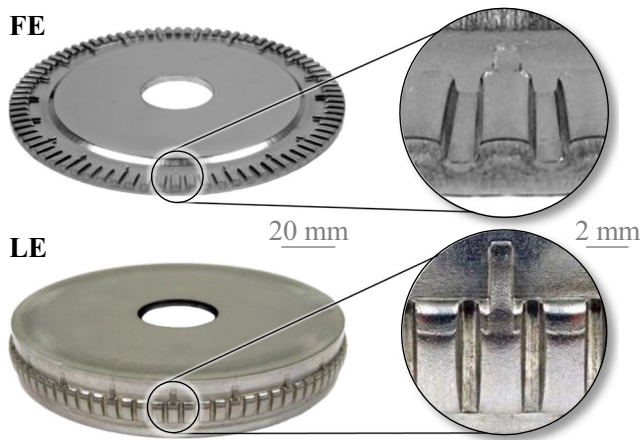


Fig. 6 Forward and lateral extrusion workpieces

Workpieces

A press LASCO TZP 400/3 is utilized to manufacture the workpieces. The formed parts are exemplarily shown for DC04 in Fig. 6.

It is possible to form combinations of gear and lock toothings by extrusion on sheet metal. The low die filling, which occurs independently of the used process class, is clearly evident. The demanding material flow in combination with the elastic deformation of the tools that occurs during forming influences the die filling behavior and thus the dimensional accuracy of the parts.

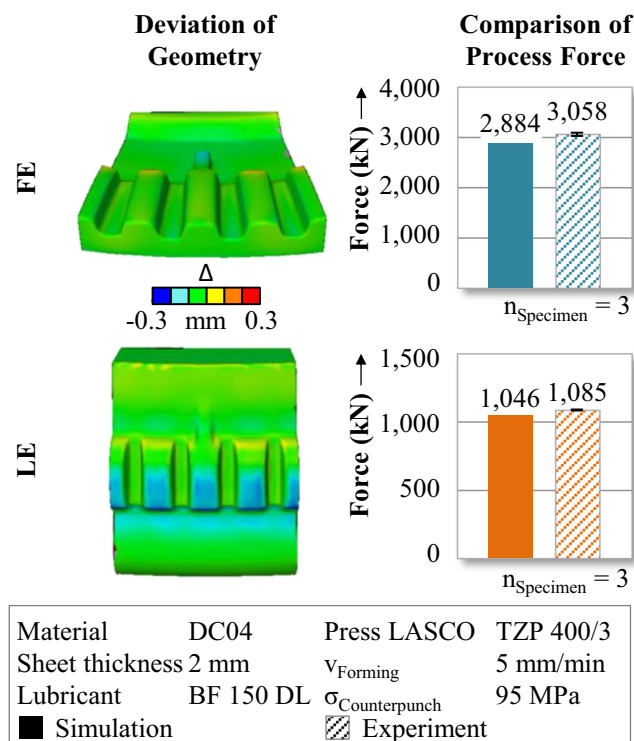


Fig. 7 Validation of the simulation models by comparison with the experiment

Comparison simulation and experiment

Numerical methods are used to gain an understanding of workpiece design and its effect on part and process parameters. For this purpose, the applied simulation models are evaluated on the basis of experimental results (DC04) with regard to their ability to represent application-relevant target variables (Fig. 7).

For the alignment between simulation and experiment, the geometry of the formed parts is recorded with the ATOS topometric sensor from GOM GmbH. While the macroscopic workpiece geometry is well represented by the simulation, the comparison of experiment and simulation reveals geometric deviations in the area of the functional elements. In forward extrusion, the simulation underestimates the height of the involute’s inner edge by up to 0.15 mm, whereas in lateral extrusion the involute’s height is underestimated slightly more, with up to 0.23 mm. This shows a challenge in the numerical representations of SBMF processes. One reason for this are the prevailing tribological conditions in SBMF, which cannot be represented sufficiently by the simulation models. The simulation shows higher maximum forces (2884 kN) in forward extrusion compared to lateral extrusion (1046 kN). Reasons are the force application perpendicular to the sheet surface [17] as well as higher friction due to longer glide paths in forward extrusion, caused by more uniform die filling. Forces are realistically predicted by the simulation, with deviations less than 5.8% (FE) and 3.7% (LE). Based on these findings, the validity of the model is confirmed, which enables its use in numerical investigations.

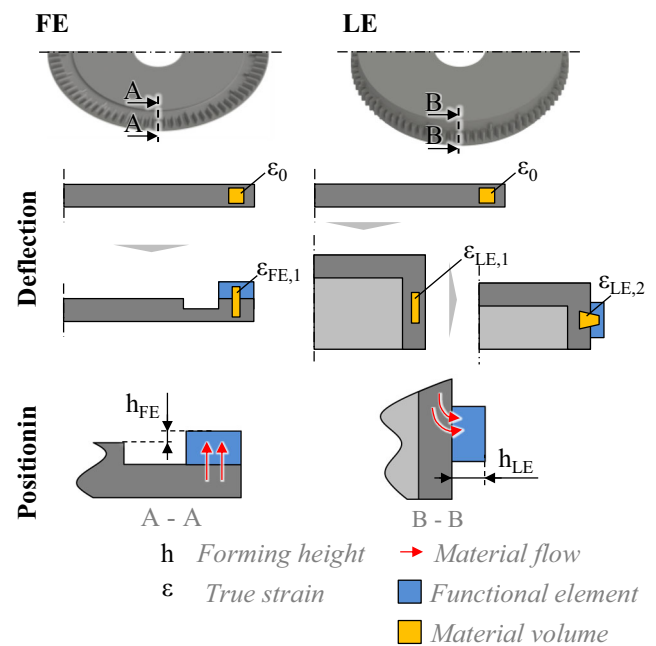


Fig. 8 Characteristics of forward and lateral extrusion processes in terms of material flow

Process characteristics

The workpiece area of the functional elements is designed analogously in forward and lateral extrusion. Within the process classes, essential differences can be stated in the material flow behavior during forming (Fig. 8).

Generally, axial material flow occurs during the forming of functional elements in forward extrusion, whereas lateral extrusion results in a material flow in radial direction. Furthermore, in forward extrusion a material volume in the area of the functional elements is deformed once, while in lateral extrusion it is deformed twice.

The reason for this is a double deflection of the material flow in lateral extrusion, first axially through deep drawing ($\epsilon_0: \epsilon_{LE,1}$) and then radially by extrusion ($\epsilon_{LE,1}: \epsilon_{LE,2}$). This results in a higher material pre-hardening in lateral extrusion, with values in the range of $\epsilon_{LE,1} = 0.3$ to $\epsilon_{LE,1} = 0.5$, depending on the height of the frame within the zone of functional elements. Compared to forward extrusion ($\epsilon_0 = 0$) forming conditions are fundamentally different in terms of work hardening and friction [18].

The intended forming of functional elements in lateral extrusion requires the material to rise completely from the initial sheet plane ($h_{LE} = 2.7$ mm) and thus to form a 41% larger relative maximum height compared to forward extrusion ($h_{FE} = 1.92$ mm).

Depending on the geometry of the workpiece, geometric relationships are present in both process classes, which not

only affect the material flow but also the process control. Principal influences are increasing functional integration by adding carriers on the same bottom volume and the change of the applied semi-finished product by variation of the initial sheet thickness (Fig. 9).

Change in forming volume

In lateral extrusion the stroke ($s_{LE} = 9.50$ mm) is 12.2 times greater, compared to forward extrusion ($s_{FE} = 0.78$ mm). When a carrier is added, additional forming volume (ΔV) is required. Therefore the strokes (s) have to be increased in forward (+ 3.9%) as well as in lateral extrusion (+ 0.8%). In forward extrusion this is accompanied by a reduction of the remaining sheet thickness t_R , which acts as a geometric constriction and influences the material flow. In lateral extrusion, only a stroke change Δs_{LE} is required to achieve the geometry.

Change in sheet thickness

An altered initial sheet thickness ($t_1: t_2$) directly influences the residual sheet thickness t_R and thus the material flow in forward extrusion. With an increase in the initial sheet thickness in lateral extrusion, the tool gap between punch and counterholder widens. Therefore the increase of semi-finished product thickness requires a reduction in the counterholder diameter and the forming stroke in order to manufacture unchanged functional elements by Δs_{LE} in lateral extrusion.

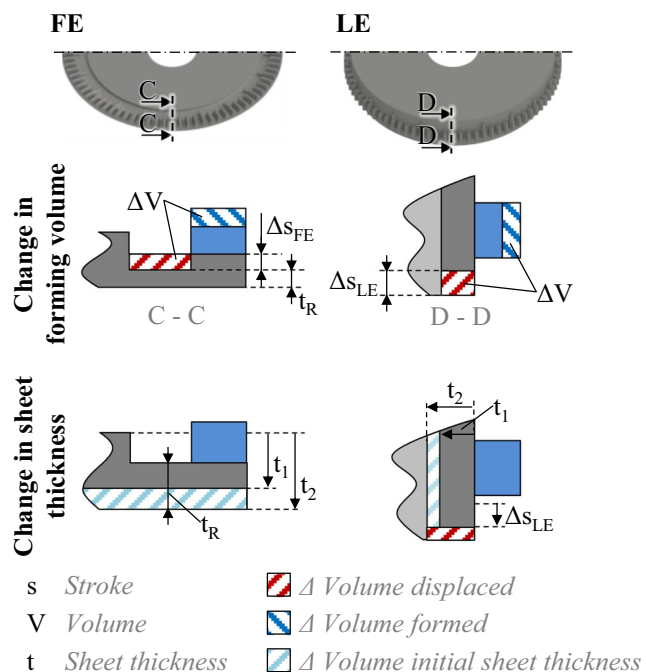


Fig. 9 Characteristics of forward and lateral extrusion processes in terms of part geometry

Influence of Workpiece design

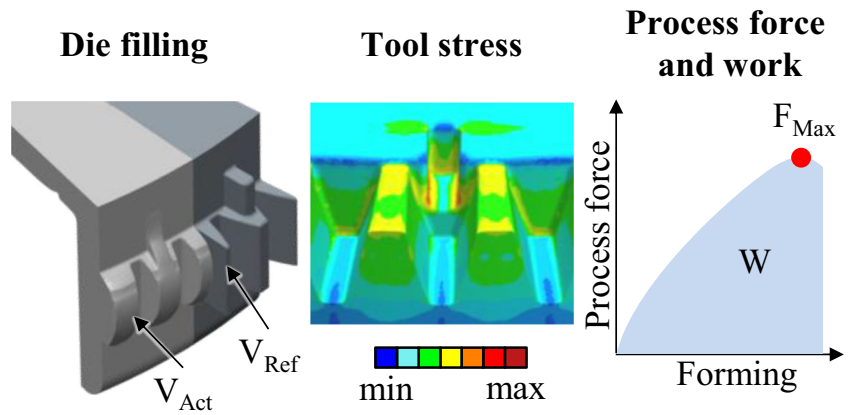
The focus of the workpiece layout lies on both part and process aspects. The aim is to identify their influence on the process result in order to provide the user with recommendations for workpiece design.

Design of Experiments

Successful design of experiments is based on the selection of relevant target and process-determining parameters [19]. Figure 10 provides an overview of the specified result variables for investigating both process classes.

On the workpiece side it is necessary to form parts with sufficient geometric accuracy in order to maintain the required tolerances and to avoid reworking as far as possible. In sheet-bulk metal forming, the die filling is used as a measure for the evaluation of the workpiece accuracy, which represents the percentage ratio between actual volume (V_{Act}) and target volume (V_{Ref}) [20]. The form filling of all functional elements (V_O), the teeth (V_T) and the carrier (V_C) is analyzed by using the workpieces formed

Fig. 10 Target quantities of the numerical investigations



in the simulation software. The degrees of die filling are determined with Boolean operations. In terms of the process, the choice of forming equipment determines the economic efficiency [21]. The basis for an appropriate selection is the knowledge of the maximum tool loads [22]. Tool failure is influenced both by the applied tool material [22] and the occurring stress states [23]. When designing extrusion dies, the analysis of the equivalent stresses according to v. Mises (σ_E), maximum principal stresses (σ_{Max}) and minimum principal stresses (σ_{Min}) allows an insight into the present load situation. To assess tool loads, representative die areas with five node elements (n_{Node}) in the zone of highly stressed cavities are evaluated (Fig. 11).

Furthermore, the required process forces are relevant for the selection of the forming machine [24].

Based on literature [8] and empirical process knowledge [11], influencing variables of the semi-finished products and workpieces were identified and compared with the target variables according to Fig. 12.

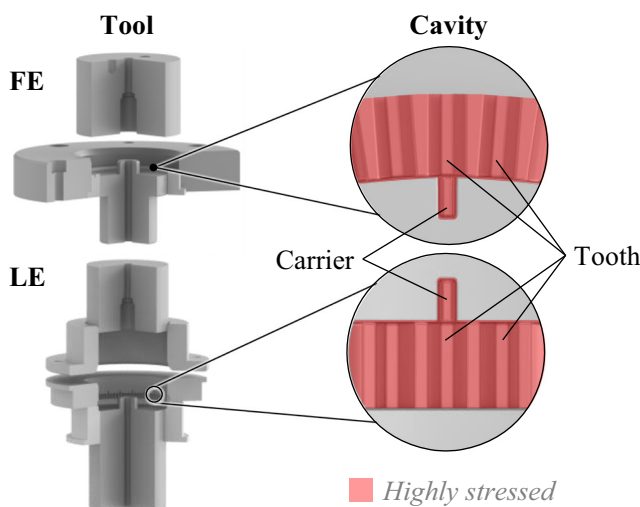


Fig. 11 Tool cavities with schematic zones of high loads

Semi-finished product side

The forming result in production of challenging workpieces is fundamentally influenced by the used semi-finished product [25]. The mechanical properties of a material determine its forming behavior [15]. The steels DC04 and DP600 are applied to analyze a broad spectrum of mechanical properties (Fig. 5). A low ratio of functional element height to sheet thickness is typical for sheet-bulk metal forming processes [2].

In this contribution, typical SBMF sheet thicknesses in the range of 1 mm to 3 mm are investigated. Changes in the supplied semi-finished product affect the investigated processes dissimilarly (Fig. 9). In forward extrusion, an ascending sheet thickness requires the reduction of the press stroke, which increases the residual sheet thickness. For lateral extrusion, the selected sheet thickness determines the drawing gap and requires an adjustment of the active parts. In addition to geometric changes, the counter holder force is adapted to ensure constant workpiece center tension (Fig. 4 a). The required forming volume is independent of the sheet thickness and leads to changed cup heights and strokes. To investigate higher sheet thicknesses, strokes (s_{LE}) need to be adjusted from 14.5 mm ($t_0 = 1$ mm) over 9.5 mm ($t_0 = 2$ mm) to

		Reference	Specification			
Influencing factor	Semi-finished part	Material	DC04	DP600	-	-
		Sheet thickness	1 mm	2 mm	3 mm	-
Workpiece sided	Number of teeth	76	80	84	-	
	Carrier per 4 teeth	0	1	2	4	

Fig. 12 Design of numerical investigations

8.5 mm ($t_0 = 3$ mm), while the functional element volume remains constant.

Workpiece side

On the part side, the number of teeth which determine the workpiece size and the forming volume is examined. The number of teeth is investigated in the interval of 76 to 84 teeth in three stages, each a difference of 4 teeth. The variation of the number of teeth has neither an influence on the fundamental geometric conditions nor does it require a stroke adjustment.

Increasing demands for functional integration lead to a rising number of form elements on a workpiece. To analyze this, the number of carriers on the segment is increased, which requires larger strokes in both processes to provide the required forming volume (Fig. 9).

Numerical influence analysis and their causes

The validated simulation models of both processes are the basis to investigate the influence of workpiece design on the process result. In addition, the underlying effects are verified by physical effects and/or models.

Semi-finished product side: Material

The material of a semi-finished product influences the resulting part properties [15]. A central quality criterion in the assessment of workpiece quality is the forming of the functional areas [26] (Fig. 13).

In forward extrusion, the die fillings decrease when the higher-strength material DP600 is used. Due to the reduced tooth ($V_T = -5\%$) and carrier ($V_C = -9\%$) filling the overall die filing V_O decreases by 5%. This effect is more pronounced in lateral extrusion. The entire filling degree (-11%) and the filling of the teeth (-11%) show a greater reduction. In both processes, the reason for the decrease in die filling is the reduced shapeability of the DP600 material due to higher initial

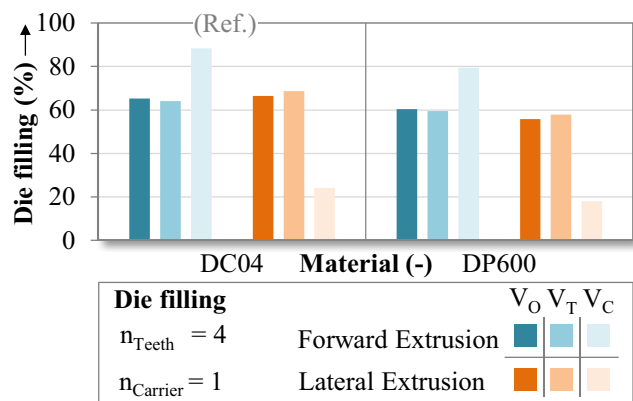


Fig. 13 Effect of workpiece material on die filling

flow stress and greater work hardening tendency (Fig. 5). This makes it more difficult to ensure material flow into the functional elements. Reason for the higher effect in lateral extrusion is the double deflection (Fig. 8) – axial cup forming and radial extrusion – whereby the material shows pre-hardening ($\Delta\epsilon = 0.5$) and the shapeability is further decreased. Work hardening additionally influences friction conditions and thus material flow in SBMF [18]. The carrier filling is significantly better in forward than in lateral extrusion. The reason for this, with comparable tool deformation, is the significantly lower characteristic forming height h_{FE} of the functional elements in relation to the initial sheet plane in forward extrusion (Fig. 8). As a result, the material flows more easily into the carrier’s small tool opening (1.0 mm \times 2.5 mm) in forward extrusion. Since the carriers in lateral extrusion have only very low filling, a further reduction in the forming (-7%) due to the use of DP600 material is particularly critical.

The effect of the formed material on the tool load is shown in Fig. 14.

In forward extrusion, the use of DP600 increases occurring tool stresses significantly, as expected. The equivalent stress σ_E (+ 100%) and the minimum principal stress σ_{Min} (+ 82%) increase comparable to the maximum principal stresses σ_{Max} (+ 65%). The evaluation of 5 nodes (n_{Node}), shows stress components with values of up to $\sigma_{Max} = 1758$ MPa, $\sigma_E = 4664$ MPa and $\sigma_{Min} = -4986$ MPa. The high compressive stresses are critical for failure, because they are within the compressive yield stress range (2853 MPa) of the tool material ASP 2023 [27]. The increase in tool stresses can be explained by lower shapeability and greater work hardening tendency of the DP600. For lateral extrusion, the use of DP600 also increases the maximum stresses of σ_E (+ 61%) and σ_{Max} (+ 68%) – critical for tool failure is also the 94% increase in compressive stress to values above 3000 MPa. These stresses exceed the compressive yield strength of the tool material and could cause tool damage through local plasticization while forming.

The effect of the workpiece material on the process forces in forward and lateral extrusion is shown in Fig. 15.

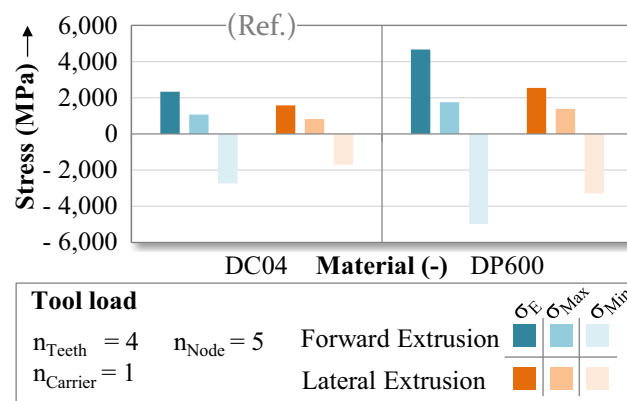


Fig. 14 Effect of workpiece material on tool stress

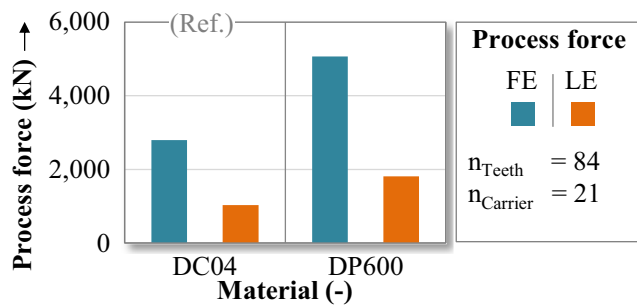


Fig. 15 Influence of workpiece material on process force

In forward extrusion, the use of DP600 causes an increase in force from around 2800 kN to 5100 kN (+ 82%). DP600 has a higher forming resistance, which increases the required forming forces. In lateral extrusion, the increase in force from about 1000 kN to 1800 kN is about + 80%. In forward extrusion, the forming force increases by more than 2000 kN, whereas lateral extrusion only experiences a force increase of about 800 kN. The reasons for the unequal rise are the fundamental differences in workpiece geometry and material provision in Fig. 9. Compared to the lateral extrusion, forward extrusion plasticizes a comparatively large material cross-section over a short stroke – an increase in the materials’ forming resistance requires a large rise in process force due to the large area involved.

Semi-finished product side: Sheet thickness

The initial sheet thicknesses are varied in order to investigate the influence of the semi-finished product on the forming process. Figure 16 shows their influence on die filling.

In forward extrusion, overall and tooth die filling decreases by about 19% with higher sheet thicknesses. The reason is an ascending residual sheet thickness (Fig. 9), which favors material flow from the cavities into the center of the workpiece and thus reduces forming. The carrier reacts particularly sensitive with a reduction of more than 35%. Reason is the

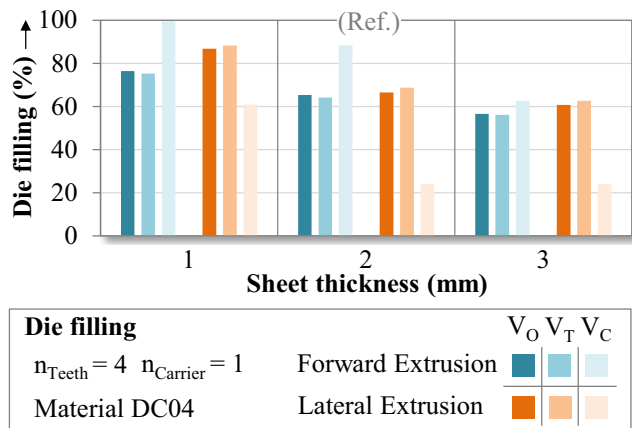


Fig. 16 Influence of initial sheet thickness on die filling

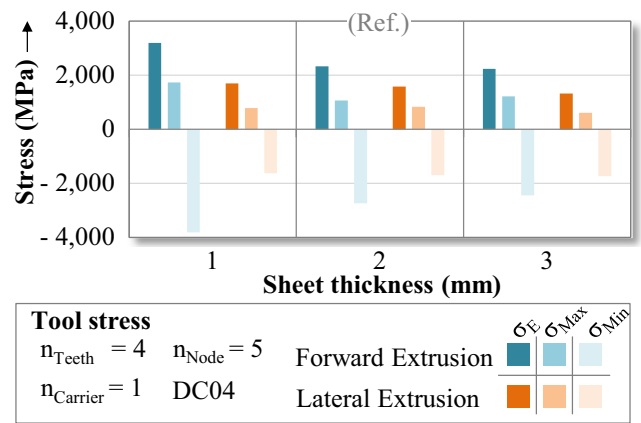


Fig. 17 Effect of initial sheet thickness on tool stress

process characteristic and arrangement of the functional elements, with carriers closer to the workpiece center than the teeth. This leads to element specific differences in the material flow. The effect is more pronounced due to the comparatively low material volume of the carrier – if the material volume decreases slightly, the die filling degree drops significantly. In lateral extrusion, higher sheet thicknesses also reduce the die filling. The volume of all functional elements (– 26%), the teeth (– 25%) and the carrier (– 37%) decreases. This is due to the rising distance between punch and counter holder (Fig. 9), which results in a material flow into the workpiece’s centre area.

The effect of changed semi-finished product dimensions on stresses in the tool is shown in Fig. 17.

In both processes, equivalent tool stresses σ_E are decreased by more than 20% with increasing sheet thicknesses. Due to the lower die filling, pressure on the die cavities is reduced. In lateral extrusion, the overall load level is also lowered, while compression stresses remain almost unchanged. Cause is that with increasing sheet thickness the material flow in the middle of the workpiece rises. This changes the main direction of the resulting material flow in the cavity, whereby small radii (R 0.1) in the cavity are increasingly stressed.

The influence of the sheet thickness on the required forming forces is shown in Fig. 18.

Maximum process forces in forward extrusion are reduced by around 43%, from 4352 kN (1 mm) to 2486 kN (3 mm).

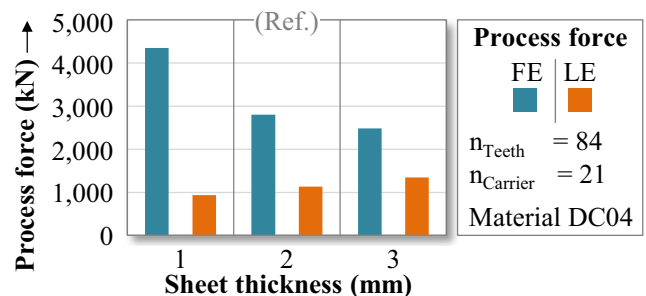


Fig. 18 Effect of initial sheet thickness on process force

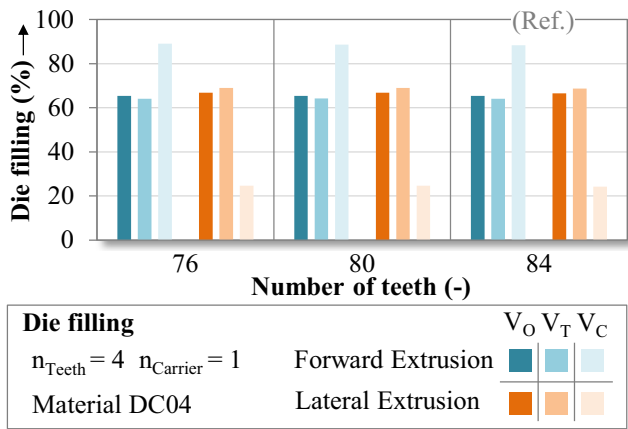


Fig. 19 Influence of tooth number on die filling

Decreasing material flow into the cavities results in lower material deformation and consequently reduced process forces. In contrast, forces in lateral extrusion are increased by around 45% from 932 kN to 1348 kN. The reason is the process-specific characteristics of a change in sheet thickness. This causes a larger material cross-section to be plasticized (Fig. 9), which requires higher forming forces.

Workpiece side: Number of teeth

The geometry of a workpiece has a major impact on the forming process [28]. The effect of changes in the number of teeth on tool filling is illustrated in Fig. 19.

In the interval of the examined number of teeth no noticeable changes occur in forward extrusion. Accordingly no effect can be stated in lateral extrusion. With the segmental increase, the ratio of functional element volume to workpiece bottom volume is not substantially changed. Thus the flow and sliding paths are not altered and the die filling remains almost unaffected.

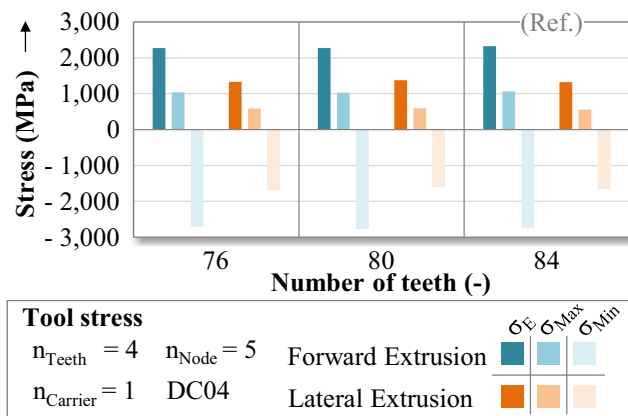


Fig. 20 Effect of tooth number on tool stress

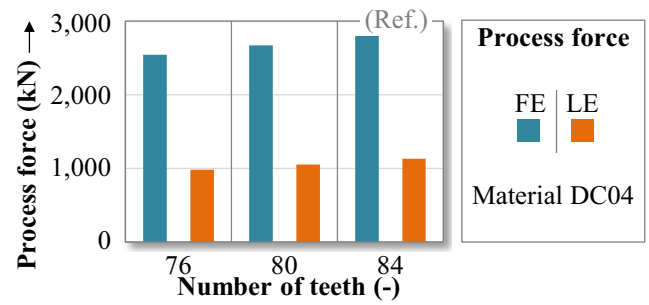


Fig. 21 Influence of tooth number on process force

In addition to the attainable die filling, knowledge of the cavity loads is essential for process understanding [23] (Fig. 20).

For forward and lateral extrusion, the tool stress values in the area of the functional elements are not substantially influenced with the increasing number of teeth. The values of the equivalent stresses σ_E are at a level of around 2300 MPa in forward extrusion and significantly lower in lateral extrusion with around 1400 MPa. This is explained by the unchanged stress situation in the cavities within the variation of the number of teeth.

The effect of different numbers of teeth on the required forming forces is shown in Fig. 21.

The part forming in forward extrusion causes an increase in process forces of about 10% from 2546 kN (76 teeth) to about 2800 kN (84 teeth) as the number of teeth rises. In lateral extrusion, the process force is also elevated by 15% as the number of involutes increases. The workpiece size and required forming volume rise proportionally to the number of teeth, which leads to higher process forces. However, the required process force per tooth remains constant, in forward extrusion with around 33 kN compared to lateral extrusion of around 13 kN. This explains that the number of teeth has no influence on the tool load, since the force and thus load level in relation to the number of form elements stays constant.

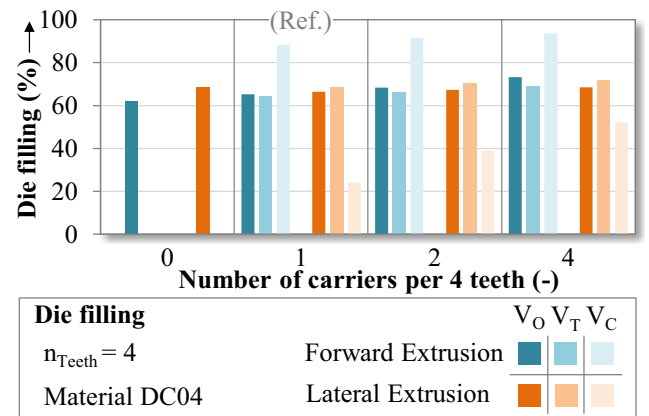


Fig. 22 Influence of carrier number on die filling

Workpiece side: Number of carriers

The potential of modern manufacturing processes is decisively determined by increasing functional integration. In order to assess the effect of increasing functional element combinations on the die filling behavior, the influence of the integration of carriers on the process result is presented in Fig. 22.

The forming of gears without carriers in forward extrusion results in lower die fillings ($V_O = 62\%$) compared to lateral extrusion ($V_O = 69\%$). This is due to differing flow paths between the area of functional elements and the workpiece's center as well as the pre-hardening by deep drawing in the transition from frame to the center. Both prevent unwanted material flow into the center of the workpiece in the lateral extrusion.

By adding a second carrier to the first one, the tooth filling in both processes increases by around 2%. With an increasing number of carriers, the total die filling in forward extrusion is increased by 8% and 2% in lateral extrusion. The tool filling of the carrier rises significantly in lateral extrusion from about 24% to 52%. Due to the integration of carriers, the bottom areas of the functional elements and the die openings are enlarged (Fig. 11), which favors the material flow into the cavities. The carriers have a comparatively low nominal volume. This is the reason for the low influence on the overall die filling despite a significant increase in the carrier forming.

Figure 23 shows the influence of increasing numbers of carriers on the load situation of the tools.

In forward extrusion without carrier, the equivalent stresses σ_E are 49% higher (1900 MPa) than in lateral extrusion (1277 MPa). The reason is the application of forming force perpendicular to the sheet surface in forward extrusion. If a combination of functional elements – 1 carrier on 4 teeth – is formed in forward extrusion, equivalent stresses increase around 23%. Compressive and tensile stress components increase comparatively more significantly (+ 100%). The reason for this is the local change in tool stiffness by adding the cavity opening of the carrier, in combination with the process-

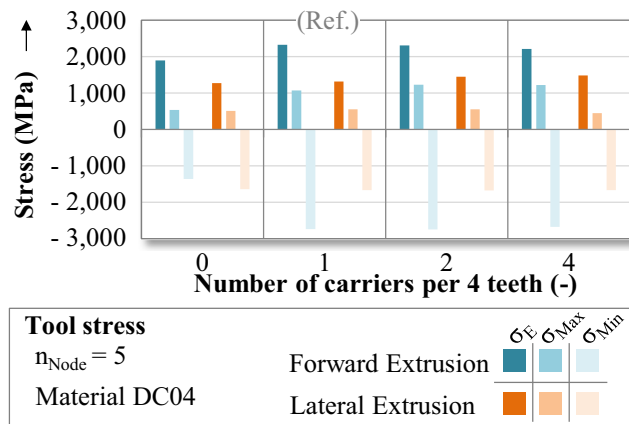


Fig. 23 Effect of carrier number on tool stress

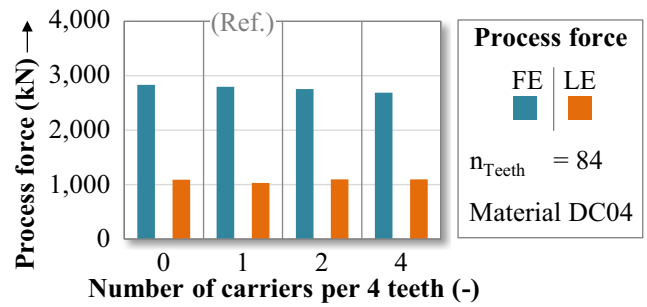


Fig. 24 Influence of carrier number on process force

specific application of force perpendicular to the sheet plane. In lateral extrusion, on the other hand, only minor changes occur in the stresses σ_E (+ 4%) and the values of σ_{Max} (+ 2%) and σ_{Min} (+ 10%). Differences between the process classes result from deviating force application and from design-related differing system stiffness (Fig. 3). Rising functional integration by adding carriers has – related to each process class – no fundamental influence on the stress situation. In forward extrusion, tensile stress components are elevated (+ 14%), while in lateral extrusion they decrease (– 20%).

A central design criterion is the process force as a function of the shaped carriers (Fig. 24).

Regardless of the functional element combination, forces of about 2800 kN are present in forward extrusion and about 1100 kN in lateral extrusion. The higher force level in the forward extrusion compared to the lateral extrusion can be explained by the application of forming force perpendicular to the sheet plane and different material flow. As the number of carriers increases, the forces in forward extrusion are reduced (4%), contrary to this the process forces in lateral extrusion rise (7%). In forward extrusion, the force-reducing influence of shortened flow paths and enlarged cavity base areas predominates. The higher stroke extension for material

		Target criteria			
		Part	Process		
		Die filling	Tool stress	Process force	
Increase cause variable	Semifinish-sided	Material strength	⬇	⬆	⬆
		Sheet thickness	⬇	⬇	⬇ ⬆
	Part-sided	Number of teeth	↔	↔	⬆
		Number of carriers	⬆	⬆ ⬇	⬇ ⬆

Effect: ⬆ increase ↔ none ⬇ reduction
 Evaluation: ⬆ positiv ↔ neutral ⬇ negativ

Fig. 25 Evaluation of the effects of the investigated parameters

supply in lateral extrusion (Fig. 9) increases local work hardening and thus the process force.

Derivation of conclusions

The results from the numerical analysis are used to gain an understanding of the influence of the component design on the process result. The aim is to derive findings on the semi-finished product and workpiece side for the layout of parts for sheet-bulk metal forming (Fig. 25).

Material strength

An increased material strength – for example when using DP600 instead of DC04 – has an effect on the material flow into the die cavities and causes a reduction in die filling. Process related parameters are also negatively influenced with regard to the tool stress and the required forming forces. Materials with suitable shapeability need to be selected to ensure sufficient die fillings. In case of a change of the used materials, permissible design parameters such as resulting tool stresses and process forces have to be considered.

Sheet thickness

Higher sheet thicknesses reduce forming of the functional elements and thus workpiece accuracy. However, an increase in sheet thickness has an advantageous influence on the maximum tool stress. Depending on the process, the process forces decrease in forward extrusion and increase in lateral extrusion. The usability of a sheet thickness reduction to improve die filling is limited by the tool material and its allowable loading capacity. In lateral extrusion the increase of the process forces of about 80% must be taken into account.

Number of teeth

A change in the number of teeth and thus in the absolute workpiece size, with an almost constant ratio of functional element to workpiece bottom volume, has no decisive effect on the die fillings and tool stresses. As the number of teeth increases, the functional element volume also rises, which is why more material volume has to be plasticized. This requires a higher maximum process force.

Number of carriers

The integration of carriers increases the material flow into the tool cavities. This change in geometry has process-specific effects on the tool loads. Tensile tool stress is increased in forward extrusion and reduced in lateral extrusion. Contrary

to this, forces are reduced in forward extrusion and increased in lateral extrusion.

Summary and outlook

It has been shown that sheet-bulk metal forming (SBMF) is usable to form combinations of toothing elements on sheets. The workpiece design crucially influences the process control and forming result. The modification of the part design requires the specific adaptation of tool cavities and process control regarding the required strokes. The workpiece layout and materials influence the material flow during forming and thus the achievable dimensional accuracy, regardless of the process class. With regard to the process parameters, the workpiece design affects occurring tool stress levels and required process forces. Based on these results, findings were derived that must be taken into account in the part design for forward and lateral extrusion in SBFM. In future research activities, the spectrum of selected criteria concerning workpiece design and the determination of their influence on the process result needs to be expanded. Furthermore, the developed process comprehension provides a basis for investigating measures to increase workpiece quality and/or reduce tool loads.

Acknowledgements This work was supported by the German Research Foundation (DFG) within the scope of the Transregional Collaborative Research Centre on sheet-bulk metal forming (TCRC 73, Subproject A2). The authors are in addition grateful to all laboratory assistants and students who supported the realization of this work.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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