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Extension of the forming limits of extrusion processes in sheet-bulk metal forming for production of minute functional elements

Florian Pilz, Johannes Henneberg*, and Marion Merklein

Institute of Manufacturing Technology, Egerlandstrasse 13, 91058 Erlangen, Germany

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Abstract. Increasing demands in modern production pose new challenges to established forming processes. One approach to meet these challenges is the combined use of established process classes such as sheet and bulk forming. This innovative process class, also called sheet-bulk metal forming (SBMF), facilitates the forming of minute functional elements such as lock toothing and gear toothing on sheet-metal bodies. High tool loads and a complex material flow that is hard to control are characteristic of SBMF. Due to these challenging process conditions, the forming of functional elements is often insufficient and necessitates rework. This negatively affects economic efficiency. In order to make use of SBMF in industrial contexts, it is necessary to develop measures for improving the forming of functional elements and thereby push existing forming boundaries. This paper describes the design and numerical replication of both a forward and a lateral extrusion process so as to create involute gearing in combination with carrier teeth. In a combined numerical-experimental approach, measures for extending the die filling in sheet-metal extrusion processes are identified and investigated. Here, the focus is on approaches such as process parameters, component design and locally adjusted tribological conditions; so-called 'tailored surfaces'. Based on the findings, fundamental mechanisms of action are identified, and measures are assessed with regard to their potential for application. The examined approaches show their potential for improving the forming of functional elements and, consequently, the improvement of geometrical accuracies in functional areas of the workpieces.

Keywords: Sheet-bulk metal forming / extrusion / sheet forming / simulation / process enhancement

1 Introduction

Changed ecological and economic requirements as well as the demand for higher performing systems motivate lightweight construction [1]. Functional integration is one possibility to achieve lightweight systems [2]. This trend results in a more complex component geometry and thus higher demands regarding the production technology. Compared to other manufacturing technologies, plastic forming technology has advantages in terms of part complexity [3] and properties [4]. But standard sheet- or bulk-metal forming processes are no longer fully sufficient to meet these requirements, and innovative process combinations are gaining in importance [5]. The combination of established forming processes offers the possibility of combining the advantageous properties of each [6]. For instance, in sheet-bulk metal forming (SBMF), the advantages of bulk-metal forming regarding a three-dimensional material flow for the forming of complex geometries are combined with semi-finished sheet metal products [6]. By this innovative process class parts derived from components such as synchronizer rings used in gear boxes can be manufactured in short process chains. Forward extrusion (FE) and lateral extrusion (LE) are considered to be core processes of bulk forming [7], as is deep drawing [8] for sheet-metal forming. By combining both processes local differences in forming conditions [6] result in insufficient control of the material flow in SBMF, which reduces the achievable geometric workpiece accuracy especially of the functional elements [9] and often necessitates rework. As a result, the economic potential of SBMF in industrial scenarios is reduced. A profound understanding of the effect mechanisms in forward and lateral extrusion is required in order to develop measures to meet these challenges.

* e-mail: johannes.henneberg@fau.de

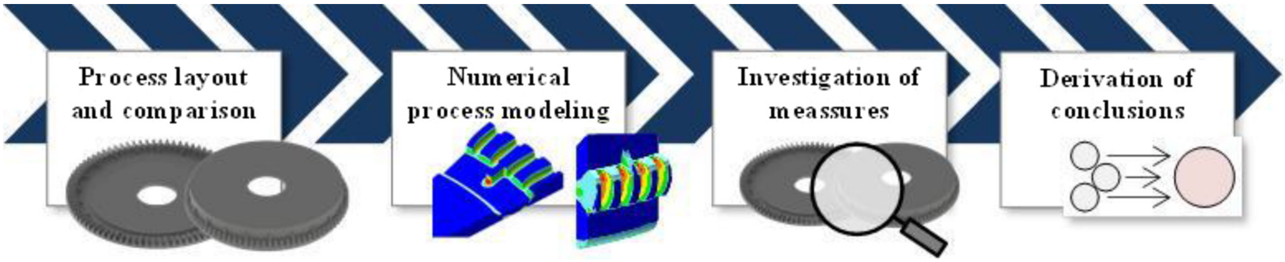

Fig. 1. Methodology for extending forming limits in extrusion of minute toothings on sheet metal.

2 Objective and methodology

Improving the forming of functional elements in sheet-bulk metal forming helps to increase the economic efficiency of the process class. The aim of this study is to yield measures for extending forming limits in the sheet-metal bulk forming of minute functional elements. To achieve this goal, the methodology in Figure 1 is employed.

The process layout includes the identification of component-specific and process-related requirements for the two extrusion processes (i.e. forward and lateral extrusion) and process implementation. An experimental approach is pursued for the comparative analysis of both sheet-bulk metal forming processes and the identification of process-specific characteristics. Forming simulations are used to avoid costly experiments and to enable efficient research into appropriate measures. Therefore, numerical process models are developed and validated: These models are employed in a combined numerical-experimental approach in order to identify approaches and investigate measures. Based on the findings, the measures are evaluated, and further research needs are derived.

3 Process layout and comparison

To design research processes, process- and component-specific requirements need to be determined. In literature, there is only limited knowledge concerning the forming of combined functional elements with SBMF. Moreover, it is not known how component properties – and the variation thereof – influence workpiece behaviour. Appropriate gear toothing is selected in order to investigate the component's behaviour in application. Increasing requirements for functional integration make the forming of combined functional elements a focus for research. The gearing is thus additionally complemented by lock toothing. In the case of gear toothings, involute profiles are typically used [10], whereby carriers are mostly applied as industrial lock elements [11]. For the findings to be transferable, high comparability of forward extrusion and lateral extrusion are required. For this reason, the functional elements formed in both extrusion processes are of the same size, and the characteristics of an ideal forming process are used. What is special here is that the displaced material volume is equal to the volume of the functional elements to be formed. The transferability of findings between materials requires the use of two steels common in industry – and with different flow properties – in one process. Therefore, the soft deep-drawing steel DC04 (1.0338) and the high-strength dual-phase steel DP600 have been chosen, whereby the investigations in this paper are carried out with DC04. The manufacturing of gears poses a challenge to forming technology because the material flow is sophisticated and tools are highly stressed [12]. The formed components and chosen functional elements are shown in Figure 2a.

The high degree of transferability between both process classes is ensured by transferring the forward extrusion workpiece into the lateral extrusion part by folding the sheet over into a cup shape. In order to examine the effect of high functional integration on low workpiece base volumes, the components have 84 involute teeth and 21 carriers. With the carriers being placed at every fourth tooth, the forming of a minute combination of functional elements can be investigated. The arrangement of the functional elements is cyclically symmetrical, using 21 segments of 17° each.

Based on the workpieces' geometry, the active parts in Figure 2b are derived in an iterative design process. In order to minimise tool loads, split dies are used in both processes. This is a common measure in tool design for cold extrusion with the aim of improving tool performance [11]. In both processes, a counterholder is positioned opposite the punch to apply a constant force and load to the workpiece centre. In addition to forward extrusion, the lateral extrusion process requires the integration of a draw ring to execute deep drawing and extrusion in one combined stroke.

The basic procedure is comparable in both processes and is shown in Figure 2c. For flexible feeding of semi-finished products, sheets with an initial thickness of 2.0 mm are chosen and fed manually. Therefore, in both processes, circular blanks with an outer diameter of 90.4 mm in forward extrusion and 109.9 mm in lateral extrusion as well as an inner diameter of 20.0 mm for both processes are laser-cut from sheets using a TruLaser Cell 7020 from Trumpf. The outer diameter is selected based on iterative process design. The inner cut-out is utilized for the positioning of the parts. The length of a process chain can influence the economic efficiency of production [13]. Usually, short process sequences are preferred in forming [14], therefore the workpieces in forward and lateral extrusion are formed in one stroke. In both processes, a blank is inserted into the tool and then clamped by the punch's movement. In forward extrusion, the punch

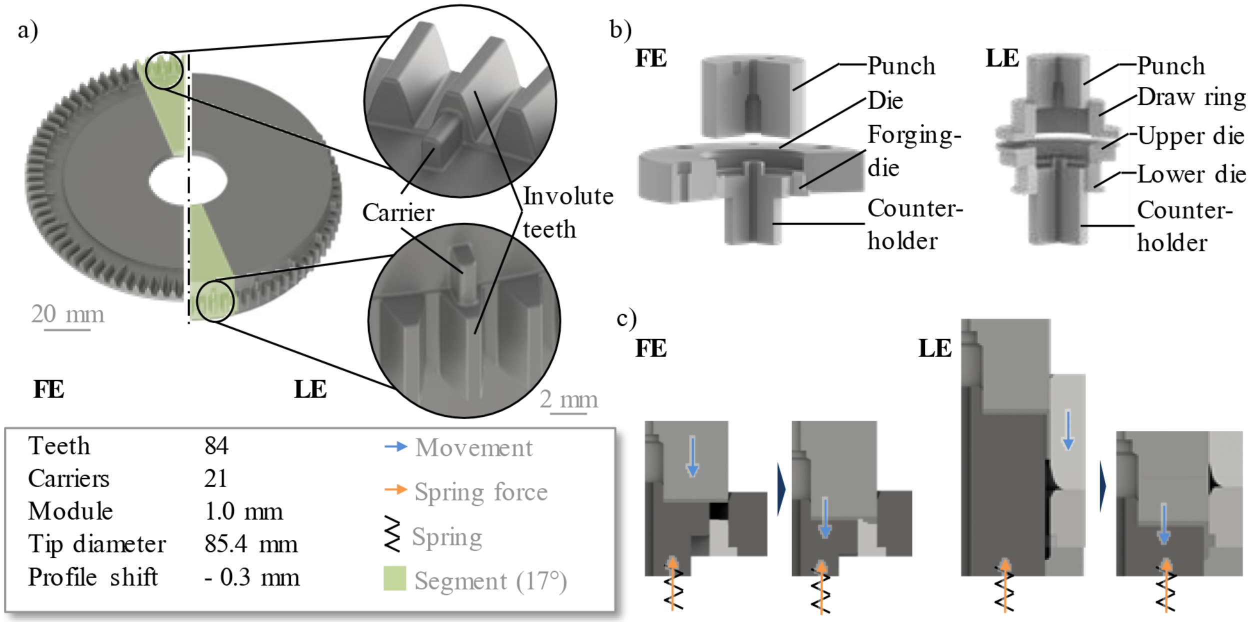

Fig. 2. Forward and lateral extrusion. (a) Parts; (b) active components; (c) process kinematics.

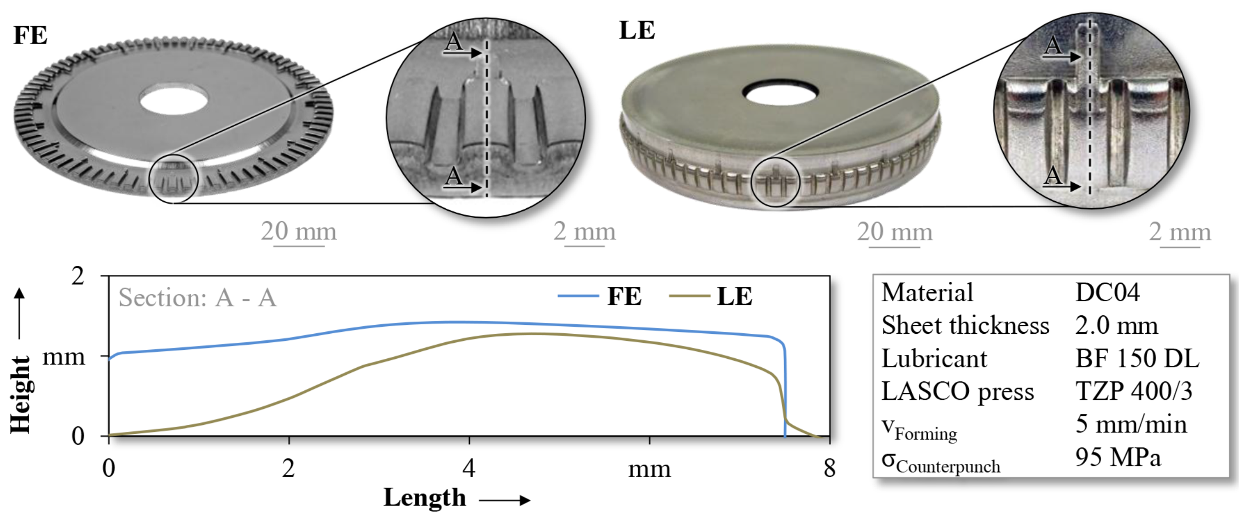

Fig. 3. Contour of the functional-element combination in forward and lateral extrusion.

displaces the counterholder and forms the component subsequently. However, in lateral extrusion, the draw ring is first used to form a cup after clamping. Without interrupting the stroke, the punch displaces the counterholder together with the cup and causes a radial material flow into the cavities.

The forming of the functional areas in forward extrusion and lateral extrusion are analysed based on the results in Figure 3. All experiments in this paper were carried out on the LASCO TZP 400/3 press with Beruforge 150 DL lubricant from Bechem. An ATOS topometric sensor from GOM GmbH is used to digitise the workpieces' geometry.

The forming experiments prove that it is essentially possible to form combinations of minute toothing by extruding sheet metal. A detailed analysis of the shape of the functional-element combination reveals that the nominal dimension of the involute tooth (2.7 mm) and the carrier (1.7 mm) which is also the depth of the die cavities is not achieved. For the analysis of the functional elements in detail the die filling, which is defined as the ratio of the volume of the functional element to the volume of the die cavity, is qualitatively discussed. For the analysis of material flow controlling measures in Section 5 it is also discussed quantitatively. The low die filling, which occurs independently of the process class used, is clearly evident.

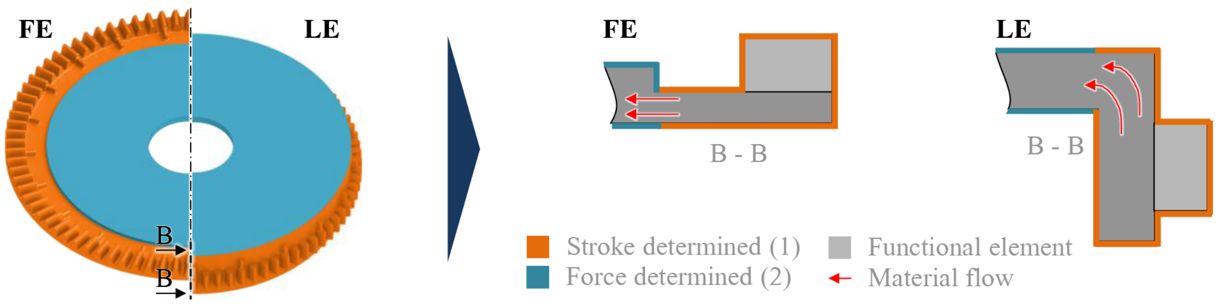

Fig. 4. Schematic zones of different forming conditions in forward and lateral extrusion.

In forward extrusion, the entire contour is filled in a better and significantly more homogeneous way than in lateral extrusion. This leads to a larger cross-sectional area of the toothing in forward extrusion and, consequently, to potentially improved mechanical properties of the gearing. The deviations within the process classes are particularly large with regard to the forming of the carrier. The sheet thickness in the component centre increases up to 11.5% (+ 0.23 mm) in forward extrusion and up to 6% (+0.12 mm) in lateral extrusion. The sophisticated material flow during forming influences the die filling behaviour and thus the dimensional accuracy of the workpieces. The reasons for the complex material flow are the locally differing forming zones in Figure 4.

In both extrusion processes, the forming of the functional area is stroke-bound (1), while the workpiece centre is continuously subjected to force by the counterholder (2). During the forming of the toothing area, the material flows into the tool cavities and from zone (2) into zone (1). The internal pressure in the workpiece centre increases until the counterholder pressure in (2) is exceeded – the counterholder is displaced and proceeds ahead of the punch. This results in an unintended material flow from zone (1) into zone (2). This effect reduces the available material that is needed to form the toothings. The result in both processes is insufficient die filling.

4 Numerical process modelling

The application of numerical methods facilitates the efficient identification of possible measures for controlling the material flow. By means of the simulation, approaches are identified in this paper and – if potential advancements in forming are found – investigated in subsequent forming experiments. Simufact.forming 14.0 software was chosen since it is frequently used in the design of extrusion processes in sheet-bulk metal forming [15].

4.1 Setup

In extrusion, high process forces can cause elastic deformation of active parts and influence the forming process [11]. This can be taken into account by using a coupled simulation. In particular, the feedback between the workpiece and the tool is considered for each calculation increment [16]. While this enhances the simulation accuracy, it also significantly lengthens the duration of the calculation [16]. For this reason, a coupled analysis of 3D models in forming technology is rarely used in practice [16]. In this paper, the coupled model provides the basis for a detailed analysis of the extrusion processes, while the investigation of measures – with a high number of simulations – is based on decoupled variant simulations. To ensure the high quality of the findings, they are subsequently verified in forming experiments. As proposed by Gröbel, a friction-factor model with $m = 0.1$ was chosen for the simulations [16].

In order to take the elastic deformation of the tools into account, tool parts are modelled elastically [16]. Material data for the dies (1.3344) and frames (1.2343) are taken from the simufact.forming database. Since sheet metal is used as semi-finished product, flow curves are determined by the layer compression test in SBMF according to DIN 50106 [17]. The DC04 steel used shows an initial yield stress k_{f0} of 175 MPa and a true strain of approximately $\varphi = 0.5$. It is known from literature that local true strains above $\varphi = 3.0$ occur in SBMF [16]. In order to achieve a material flow simulation of sufficient quality, the experimental data are extrapolated up to a true strain of $\varphi = 4.0$ using the Hockett-Sherby approach [18]. The test speed is 5 mm/min, which is equal to the speed in the forming experiments.

The process kinematics in the simulation are analogous to Figure 2c. The counterholder force is represented by springs with a low stiffness of 10^{-06} N/mm and a constant preload force in both processes, thus a steady nominal pressure is applied to the centre of the workpieces during forward and lateral extrusion.

The smallest possible symmetrical unit for representing the workpieces is a segment of 17° (Fig. 2a). Both processes are modelled by holding planes on the top and bottom of the dies and symmetry planes at the edge of the 17° segments. This reduces the calculation time while the findings and quality remain constant [19]. One challenge of modelling SBMF processes in simulation is the typical scale conflict between functional-element dimensions and the overall size of the workpiece [19]. The formed teeth and carriers require fine meshing in order to achieve accurate calculation results [20]. Even fine meshing of the workpieces results in long calculation times and/or causes the calculable number of elements within the software to be

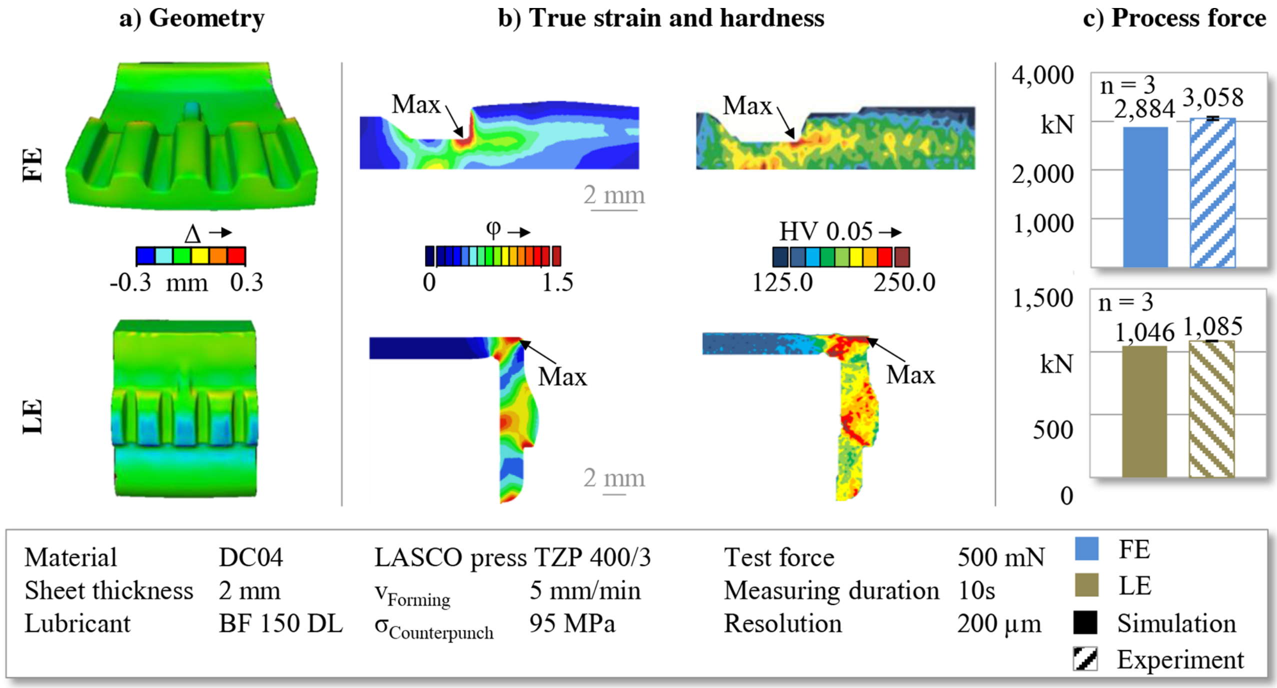

Fig. 5. Comparison between simulation and experiment of: (a) geometry; (b) true strain and hardness; (c) process force in forward and lateral extrusion.

exceeded [16]. An established solution in SBMF is the local refinement of meshes in the functional-element area and in zones with large deformations [16]. Meshes used in the workpiece are thus coarser (≤0.4 mm) and locally refined (≤0.1 mm) in the zones of high strain, as with the functional elements [21]. If a permissible mesh deformation is exceeded, the workpiece is re-meshed [21].

4.2 Validation

Numerical methods are used to gain an understanding of the extrusion processes and the measures' effects on the material flow. In order to assess the validity of the simulation models in Figure 5, these are analysed and evaluated in accordance with the recommendations of Tekkaya on process- and component-relevant target values [22]. In both processes, a quantity of three components $n_{\mathrm{Component}}$ formed from DC04 are used for the validation alongside the simulation models.

While the macroscopic workpiece geometry is well represented by the simulation, the comparison of the experiment and simulation reveals minor geometric deviations in the area of the functional elements. In forward extrusion, the simulation underestimates the height of the involute tooth's inner edge by up to 0.15 mm, whereas its height deviates slightly more in lateral extrusion – by up to 0.23 mm. This is due to the prevailing tribological conditions in SBMF, which is extremely difficult to simulate using numerical models.

The true strain distribution is an important workpiece property for assessing operational behaviour. In order to assess the simulation quality with regard to the microstructure, the calculated true-strain distribution was compared with the measured hardness distribution in Figure 5b. The hardness HV 0.05 was determined with the Fischerscope® HM2000 from Helmut Fischer GmbH according to ISO 14577-1 [23]. Areas with a high degree of deformation show increased strain hardening, and this hardening correlates with increased hardness values [24]. The comparison shows that the distributions of true strain and hardness – as well as the areas with maximum values – correspond well in both extrusion processes.

As a process-related property, Figure 5c compares the maximum process forces of the simulation and forming experiment in forward and lateral extrusion. In forward extrusion, the maximum forces (2884 kN) are 2.75 times higher than in lateral extrusion (1046 kN). The reason for this is the force application perpendicular to the sheet surface [25], as well as higher friction due to longer glide paths in forward extrusion caused by more uniform filling. The simulation predicts forming forces realistically with deviations of less than 5.8% (FE) and 3.7% (LE). These findings confirm the validity of the models and prove that they are suitable for investigating both forward and lateral extrusion processes.

5 Investigation of measures

To improve workpiece quality, it is necessary to reduce unintended material flow (Fig. 4) from the functional area into the centre of the workpiece. In forming technology, the material flow is largely determined by the stresses, the workpieces' geometry and the tribological conditions between the workpiece and tool (Fig. 6).

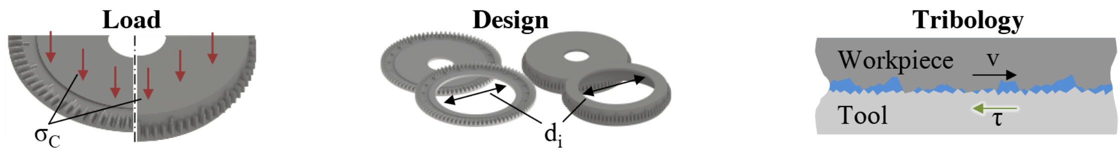

Fig. 6. Investigated approaches for enhancing die filling in forward and lateral extrusion.

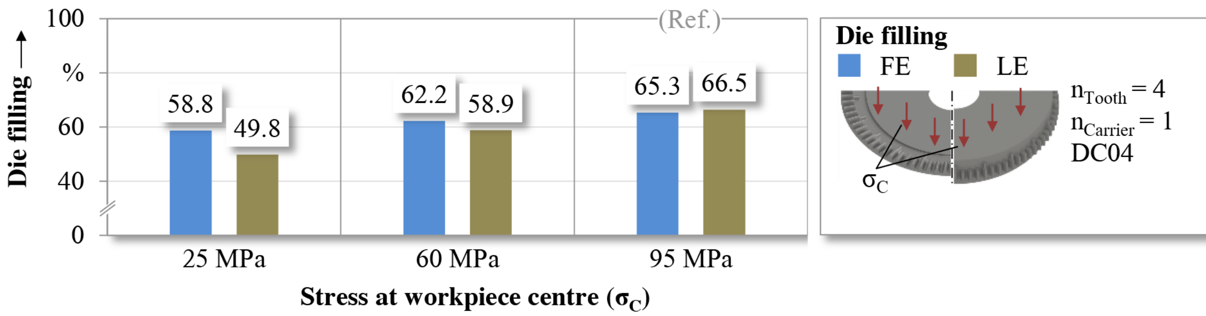

Fig. 7. Influence of the stress at the workpiece-centre on the die filling of forward and lateral extrusion in simulation.

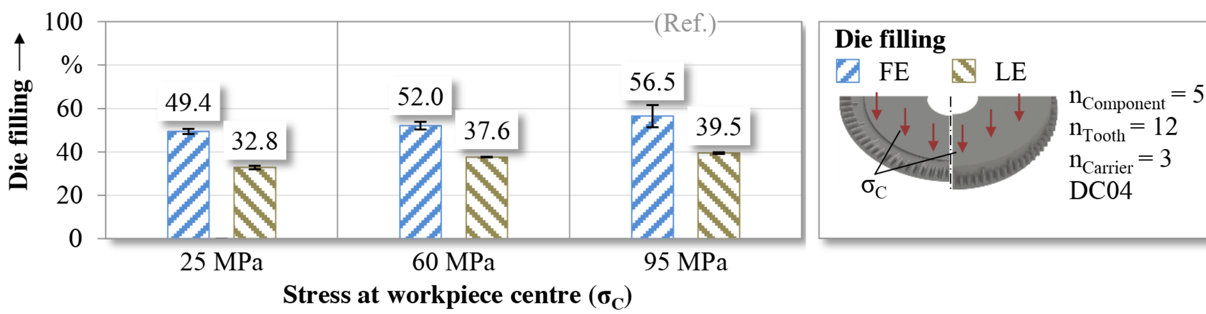

Fig. 8. Influence of the stress at the workpiece centre on the die filling of forward and lateral extrusion in forming experiments.

The loads on the workpiece are changed by adjusting the counterholder force F_c during forming. The applied force creates a constant nominal stress in the workpiece centre σ_C during forward and lateral extrusion. The macroscopic workpiece layout determines the flow length and, thereby, potentially the die filling. One approach for changing the flow conditions is to alter the inner diameter in the centre of the workpiece. The friction condition in the contact area between the workpiece and tool can influence the material flow in SBMF [26]. The effectiveness of global and local adjustment of friction in the forming of minute functional-element combinations is examined.

5.1 Load approach

The counterholder load is changed so that the stresses σ_C result in an interval of between 25 MPa and 95 MPa. Due to the equipment of the forming machine, the maximum stress is limited to 95 MPa. The effect of the workpiece-centre stress on the forming result is shown in Figure 7. For the investigation, a quantity of four tooth per parts n_{Tooth} and one carrier n_{Carrier} are evaluated.

In forward extrusion, the stress increase from 25 MPa to 60 MPa improves tooth forming by 3.5%. If the stress σ_C is elevated up to 95 MPa, the die filling increases by an additional 3.1%. In lateral extrusion, the stress σ_C rising from 35 MPa to 60 MPa increases the involute-tooth and carrier forming by 9.1%. The maximum stress (95 MPa) at the centre of the workpiece results in an additional 7.6% of cavity filling. An increase of σ_C from 25 MPa to 95 MPa benefits forming in forward extrusion (+6.6%) as well as in lateral extrusion (+16.7%). The reason for the enhanced filling of the die is the decrease of material flow into the workpiece centre due to the higher centre stress, which facilitates a flow of material into the die cavities. The effectiveness of the counterholder force in increasing the forming of functional elements is verified in forming tests (Fig. 8).

The die filling in forward extrusion increases from $49.4 \pm 1.2\%$ (25 MPa) to $52.0 \pm 1.8\%$ (60 MPa) and $56.5 \pm 5.1\%$ (95 MPa). In lateral extrusion, die filling increases from $32.8 \pm 0.8\%$ (25 MPa) to $37.6 \pm 0.2\%$ (60 MPa) and $39.5 \pm 0.4\%$ (95 MPa). The load at the workpiece centre has the potential to increase the die

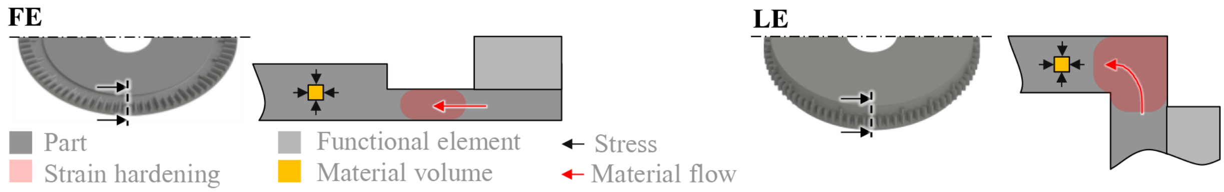

Fig. 9. Identified effect mechanisms of work hardening and stress at the workpiece centre on unintended material flow.

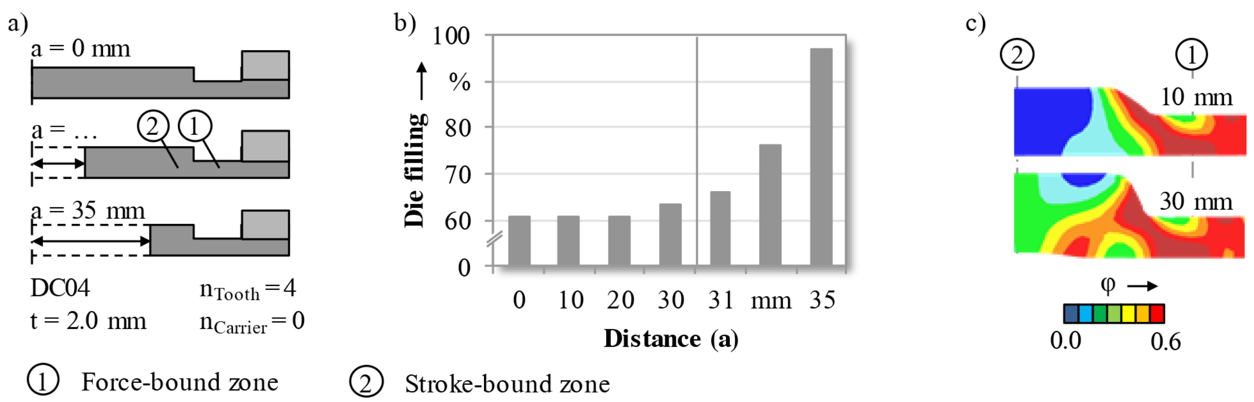

Fig. 10. Effect of the schematic workpiece geometry (a) on die filling (b) and the resulting work hardening in simulation (c).

filling, which has been confirmed by the experiments for both forward extrusion (+7.1%) and lateral extrusion (+6.7%). Differences between the simulation and experiment are due to the complex tribological conditions in SBMF and the deflection of the tool due to elastic deformation, which cannot be fully reproduced in numerical terms.

The results of the analysis of the process characteristics (Fig. 4), micro-hardness measurements (Fig. 5) and forming experiments (Fig. 3) provide the basis for identifying the effect mechanisms in Figure 9.

An unintended material flow from the functional elements into the centre of the workpiece is influenced in both processes by strain hardening in the transition area. Furthermore, the counterholder applies a normal stress to the workpiece centre, which additionally reduces the material flow into the workpiece centre by impeding sheet thickening.

5.2 Geometric approach

The manufacturability of a workpiece in forming is essentially defined by its geometry [27]. For a fundamental investigation, the application scenario of forward extrusion has been transferred into a model involving a gear toothing without carriers. Any variation in the radial position of functional elements on a circular segment area requires adjustment of the component configuration. This influences the flow paths of the material and thereby the die filling. To avoid this, a rectangular base area has been chosen. The model in Figure 10a is used to evaluate the effect of the relationship between the functional element (V_F) and workpiece volume (V_C) on forming.

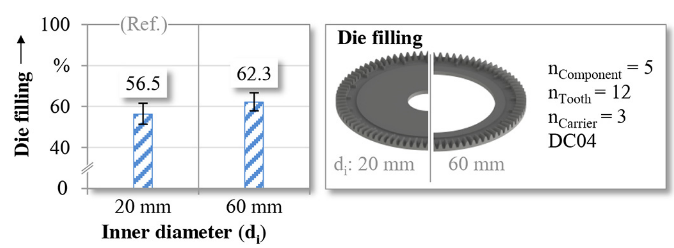

Fig. 11. Effect of the workpiece geometry on die filling in the forward-extrusion forming experiment.

The effect of distance (a) on the filling of the abstracted functional area in the forward-extrusion workpiece is shown in Figure 10b. With distance (a) increasing, the forming of the toothing increases from 61% ($a = 0$ mm) to 97% ($a = 35$ mm). The material flow into the workpiece centre causes a thickening in the components' mid-section, rising from 2.1 mm ($a = 10$ mm) up to 2.6 mm ($a = 30$ mm). This increases the true strain and work hardening in the transition area from force-bound zone (1) to stroke-bound zone (2) (Fig. 10c). This effect reduces the material flow into the workpiece centre – especially from distances of over 30 mm. The die filling increases due to the greater ratio of functional-element volume V_F to workpiece-centre volume V_C.

The effect of the workpiece geometry on the extrusion of the involute teeth and carriers is proven in forming experiments by means of forward extrusion, as shown in Figure 11. A reference centre stress of $\sigma_c = 95$ MPa is used. The workpiece geometry is adjusted by enlarging the inner diameter from 20 mm to 60 mm. To achieve a constant load

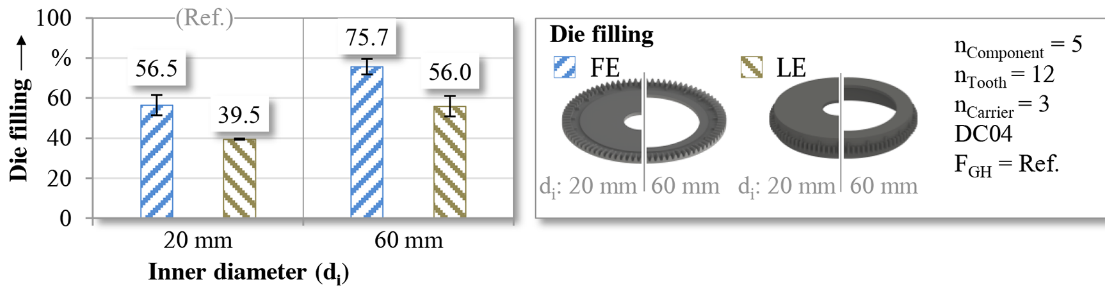

Fig. 12. Effect of the workpiece geometry and increased centre stress on die filling in the forward- and lateral-extrusion experiments.

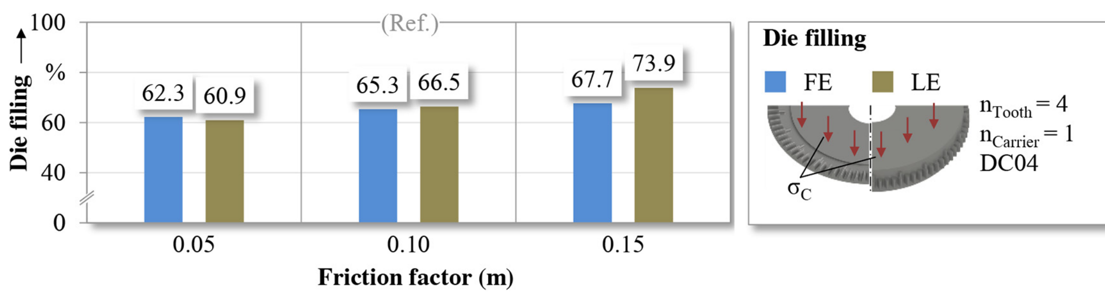

Fig. 13. Effect of global friction on die filling in simulated forward and lateral extrusion.

in the centre of the workpiece, it is necessary to reduce the counterholder force. In lateral extrusion, this cannot be achieved through process technology: the deep-drawing step necessitates higher clamping forces.

With a larger inner diameter – and thus a greater volume ratio V_F/V_C – die filling in forward extrusion is increased by Δ 5.8% from 56.5 ± 5.1% to 62.3 ± 4.4%. This is due to the increased work hardening in the remaining central area of the workpiece during forming. In turn, this reduces the material flow into the workpiece centre and therefore promotes the forming of minute cavities. With a constant counterholder force, the geometry can be adjusted to increase the limited workpiece-centre stress on the side of the press (Fig. 12).

The combination of an increased volume ratio and greater workpiece-centre stress causes the die filling to increase by Δ 19.2% from 56.5 ± 5.1% to 75.7 ± 3.9% in forward extrusion. In lateral extrusion, the forming of the functional area increases from 39.5 ± 0.4% to 56.0 ± 5.1% (Δ 16.5%). Consequently, the geometric adjustment has the potential to improve the forming of extruded, minute functional elements in SBMF in two distinct ways.

5.3 Tribological approach

In conventional forming processes, tribological conditions influence the material flow during forming and therefore affect the forming result significantly [28]. Figure 13 shows the effect of increasing friction factors on the die filling.

As friction increases, the overall die filling in forward extrusion also increases by 6%; from 62% to 68%. In lateral extrusion, overall forming increases by 13%, while the forming of the contour area increases from 61% ($m = 0.05$) to 74% ($m = 0.15$). It is therefore more sensitive to friction adjustments. The process responses differ for the following reason: as opposed to forward extrusion, the geometrical bottleneck (Fig. 5) in the transition zone from the functional area into the workpiece centre is absent in lateral extrusion. The constriction reduces the components' cross-section locally and thereby reduces the material flow into the workpiece centre. If this bottleneck is absent, the material-flow-regulating effect of the friction increases during extrusion.

The effects examined in the preceding section are used to identify effect mechanisms during the extrusion of involute teeth and carriers. The analysis results are shown schematically in Figure 14.

The macro-structure of the workpiece has the potential to improve the forming result by enlarging the volume ratio of V_F to V_C. In forward and lateral extrusion, a global increase in friction reduces the material flow from the area of the functional elements into the workpiece centre. Due to these effect mechanisms, more material is available for forming the minute toothings, which improves the process result. In extrusion-based SBMF, the friction adjustment by modifying the tool surfaces offers economic advantages over adjustments made to workpieces as not every semi-finished product needs to be modified. Increasing the friction globally also results in higher friction stresses in the area of the functional elements. This prevents a material flow into the cavities and thereby hinders forming. As a result, the potential of friction adjustment cannot be fully realised. A promising approach to increase the effectiveness is to only implement friction adjustment locally by means of so-called tailored surfaces. The

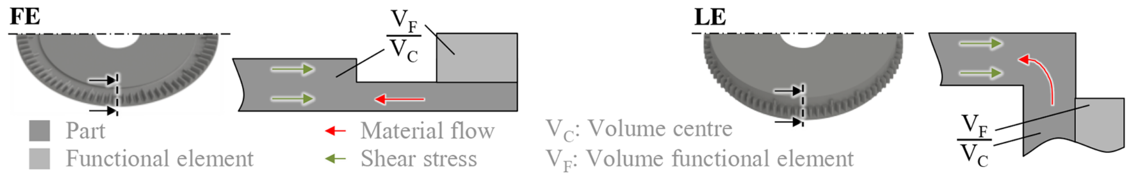

Fig. 14. Identified effect mechanisms of friction-induced shear stresses and the volume ratio of V_F to V_C on unintended material flow.

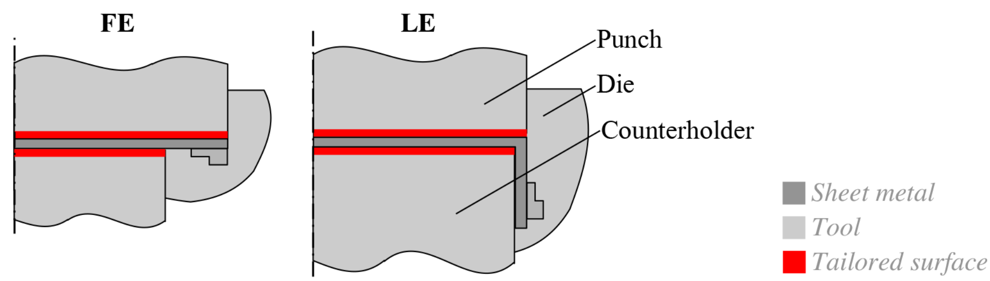

Fig. 15. Partitioning of forward- and lateral-extrusion tools in order to use tailored surfaces.

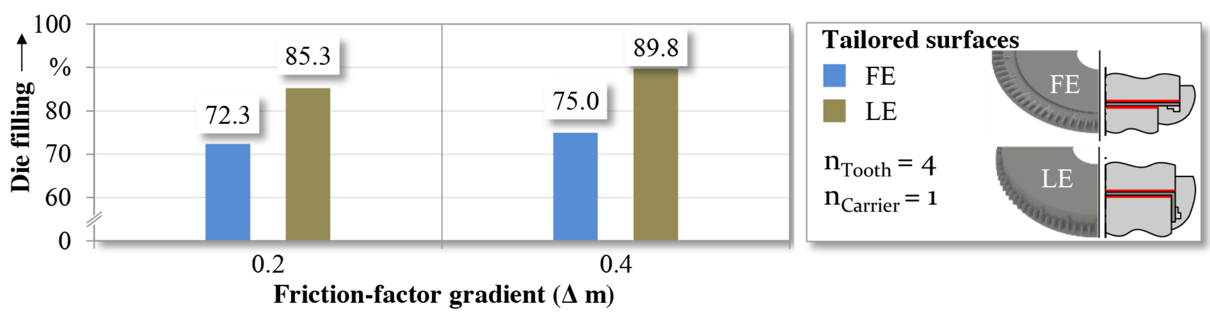

Fig. 16. Effect of local friction adaption on die filling in simulated forward and lateral extrusion.

partitioning of forward-extrusion and lateral-extrusion tools alike is shown in Figure 15.

Based on the effects identified in Figure 14, the aim of the chosen partitioning is to reduce the material flow into the workpiece centre and thereby increase the forming of the involute teeth and carriers. In both processes, the front surfaces of the punches and counterholder are modified with a friction-increasing tailored surface. Friction gradients (Δm) thus result between unaltered tool surfaces with reference friction ($m = 0.1$) and modified tool surfaces. The result of local friction adjustments is shown in Figure 16.

In forward extrusion, the friction gradient $\Delta m = 0.2$ increases die filling by approximately 7%, from 65.3% to 72.3%, compared to the reference. An even higher friction gradient of 0.4 increases forming to 75.0%. In lateral extrusion, the difference in friction of 0.2 enhances the extrusion result from 66.5% (Ref) to 85.3%. With an increase of local friction to $\Delta m = 0.4$, die filling increases by approximately 4% up to 89%. This shows that tailored surfaces increase the forming of minute cavities in relation to the friction-factor gradient.

The experimental verification of these findings requires the selection of surfaces whose application creates friction-factor gradients ($0 < \Delta m \leq 0.4$) that correspond to those in numerical investigations. Opposing the alternative methods for modifying tool surfaces, such as milling or grinding, blasting offers a high degree of geometrical freedom regarding the treated surfaces. Investigations have shown that abrasive blasting in an upsetting process has significant potential for controlling the material flow [29]. In Figure 17, the surfaces used in forming experiments for this study are shown.

In laboratory tests, the blasted surfaces were tested with friction coefficients of 0.2 ± 0.02 (abrasive 1) and 0.5 ± 0.03 (abrasive 2). Both surfaces were generated with a jet pressure of 3 bar and the jet medium Al_2O_3. Particles with a diameter of 50 to 70 µm comprise the surface of abrasive 1, which features roughness values of Rz 0.84 ± 0.12 µm. Using larger particle diameters (100 to 400 µm) causes an increase in the roughness to Rz 10.20 ± 0.80 µm at surface 2. The effect of the chosen surface modifications on the process result is shown in Figure 18.

In forward extrusion, the local adjustment of friction ($\Delta m = 0.1$) has no significant effect on die filling because the differences in the local friction conditions are too small to influence the forming essentially. Cavity filling is increased by approximately 15% compared to the reference when using a friction gradient of $\Delta m = 0.4$. The reason for this is a reduction of the material flow into the workpiece centre, as shown in Figure 14. More material therefore fills

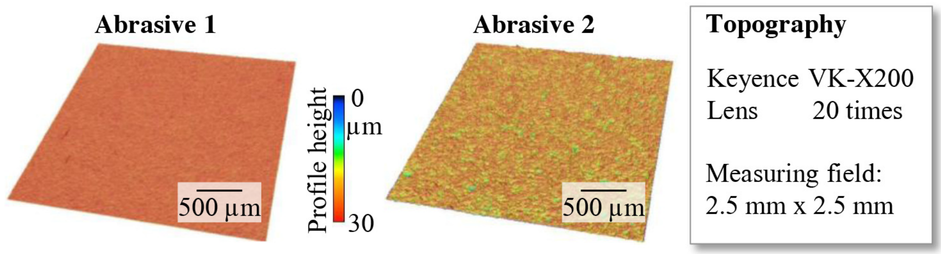

Fig. 17. Topography of applied abrasive-blasted surfaces.

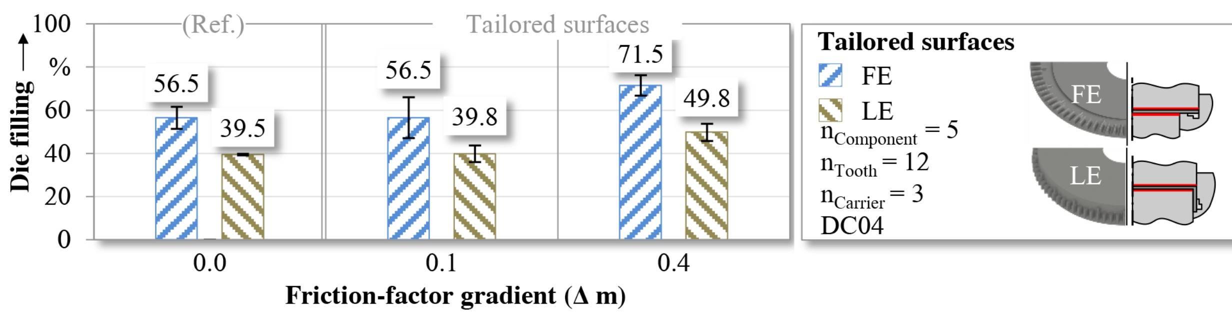

Fig. 18. Influence of friction-factor gradients on die filling in forward- and lateral-extrusion forming experiments.

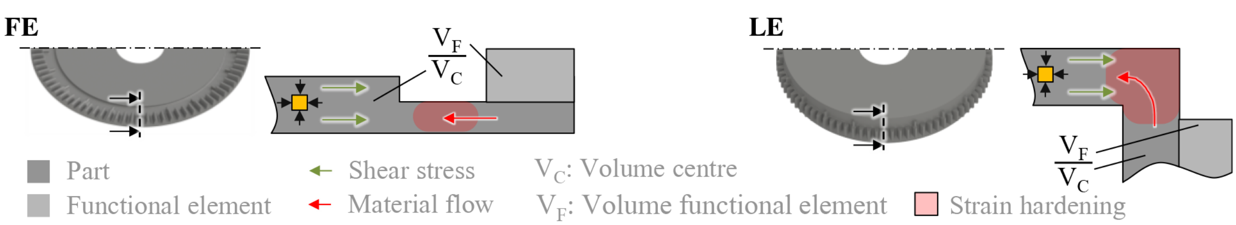

Fig. 19. Conclusion of identified effect mechanisms in forward and lateral extrusion.

the functional area. In lateral extrusion, as in the case of forward extrusion, only the use of the friction coefficient $m = 0.50$ ($\Delta m = 0.4$) causes an increase in workpiece forming of approximately 11%. The use of tailored surfaces therefore enhances forming in both extrusion processes. In the experiments conducted for forward and lateral extrusion, the effect of the tailored surfaces is not as significant as the simulations predicted. The reason for this is that elastic deformations of the tools due to high loads which cannot be numerically fully reproduced and complex friction conditions experienced in extrusion on sheet metal [16].

6 Derivation of conclusions

Based on the investigations, findings were derived, and the potential for application of the investigated measures was assessed. Effect mechanisms have been identified in Figure 19 that improving the understanding of cause-effect relationships in extruding functional elements on sheet metal via forward and lateral extrusion.

In the transition zone between stroke-bound and force-bound forming, there is a material flow from the toothing area into the workpiece centre. Since the plasticised workpiece volume is equal to the required functional element volume, the material flow into the workpiece centre reduces the achievable die filling. If the geometrical accuracy of the functional area is to be improved, unintended material flow – that does not contribute to the toothing forming – needs to be reduced. In both processes, the material flow into the workpiece centre is reduced through local work hardening, resulting from a process-class-specific supply of workpiece material for forming: in forward extrusion, material is supplied by the local reduction of the sheet thickness. This creates a geometrical bottleneck that hinders the flow of material into the workpiece centre.

In terms of the process, the counterholder pressure can be used to create a load in the component centre to promote forming. The ratio of functional-element volume to workpiece volume has been identified as an additional mechanism for enhancing the process result. An assessment

		Measures							
		Load		**Design**				**Tribology**	
		Counterholder force		Volume adjustment		Volume adjustment (with load change)		Tailored surfaces	
		FE	LE	FE	LE	FE	LE	FE	LE
Evaluation	**Effectiveness**	↗	↗	↗	-	↑	↑	↑	↑
	Practicability	↑	↑	↗	-	↗	↗	↑	↑

Fig. 20. Evaluation of the investigated measures for enhancing die filling in forward and lateral extrusion.

of measures with regard to their effectiveness and their potential for application is shown in Figure 20.

The increase in counterholder force improves die filling in forward and lateral extrusion by approximately 7%. In processes with areas of force-bound and stroke-determined forming conditions, measures can be realised with existing active components. If this measure is applied, the limits of the forming equipment must be taken into account. In the investigated extrusion processes, it is detrimental for the counterholder to be positioned opposite to the stamp's direction of action. This could increase the required forming force and work when increasing the counterholder force. The economic efficiency of extrusion processes can therefore be influenced directly.

The adjustment of the workpiece layout allows the forming to be enhanced by altering the volume ratios, with (up to 19%) or without (+6%) an increased stress in the workpiece centre. A ratio of V_F to V_C that is as large as possible helps reduce unwanted material flow. One advantage is that the measure does not need a direct increase of process forces due to force adjustments that are not necessary. These findings can already be used while designing the process by using cutting operations to control the material flow at an early stage. Functional elements with the same volume achieve higher die filling for workpieces with a smaller overall volume. The degrees of freedom are detrimental to the component and the process design required for adjustment of the workpiece geometry.

An increase in friction that is both global and local results in increased filling of the tool cavities in the investigated extrusion processes. The local adjustment of friction enhances the forming of toothings in forward and lateral extrusion by over 10%. This measure does not necessitate a direct adjustment of the process forces of active parts and is – in the case of abrasive blasting – associated with only minor effort. One advantage of this approach is the option of retrofitting existing processes relatively easily. When using tailored surfaces in SBMF, it must be taken into account that changes in tool roughness can influence the quality of the components' surface [30]. If friction is adjusted using higher tool-surface roughness, the tool life might be reduced due to fatigue failure. Feature consistency of the tools-surface modifications is to be examined for each individual case to ensure that there is no shortening of tool maintenance intervals and/or tool life.

7 Summary and outlook

It was proven that sheet-bulk metal forming (SBMF) can be applied to form minute combinations of functional elements (involute teeth and carriers) from sheet metal. Requirements for SBMF research processes were identified, and the process development of a forward- and lateral-extrusion process were described. The processes were modelled in a finite-element simulation and validated for use in investigation of the extrusion processes. In terms of the simulation, measures were identified and analysed with regard to their ability to improve the forming of functional elements. Additionally, in forward and lateral extrusion, fundamental effect mechanisms were identified. The investigations focused on the application of loads during forming, the workpiece design, and the modification of global and local tribological conditions.

The force of the counterholder was used to increase the local stresses during forming and improved die filling by up to 7%. The adjustment of the workpiece design exhibited the greatest potential: this achieved an increase of up to 19%. With regard to the tool, local adjustments of friction conditions – also known as tailored surfaces – improved the forming result by around 11%.

In future research activities, the effect of the measures on application-relevant criteria such as tool loads, process forces and process work needs to be expanded. Since SBMF tools are highly stressed, the effect of the measures on tool performance, for example in fatigue tests, must be additionally investigated.

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