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Forming of lightweight helical gears by means of sheet-bulk metal forming

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Abstract. A rising demand on resource efficient and highly functional products causes conventional metal forming processes to the reach their limits. For this reason, sheet-bulk metal forming (SBMF) for the production of thin-walled components with various filigree functional elements has been widely investigated in recent years. However, there is a research gap in the understanding of approaches within this process class for producing helical gears. These are in high demand in industrial environments due to their smooth running capabilities. In this study, a process combination of deep drawing and lateral extrusion for the production of helical lightweight gears is therefore examined. In the reference variant, the mild deep-drawing steel DC04 with a sheet thickness of t_0 = 2.0 mm is formed with a 20° helical die. General process limits are derived depending on the die filling of the tool-side cavities. In addition, the influence of the gear angle on process and component target variables is analyzed and discussed.

Introduction

According to UN forecasts, the number of people living on earth will increase from around 7.8 billion at present to about 9.7 billion in 2050 [1]. This growth is closely linked to the economic market integration of developing and emerging countries, which will rise international resource consumption [1]. In view of the limited global resources, it is essential to fundamentally rethink conventional production techniques and develop sustainable production methods that are still economically viable [2]. The major challenge for companies is the increasing complexity and the growing number of product variants [2]. The mobility sector in particular is affected by significant structural change. With increasingly shorter product life cycles, customers expect more models and product variations [3]. At the beginning of the 1990s, the product ranges of car manufacturers consisted of around eight models. At present, the product ranges comprise three times as many vehicle models [3].

Due to the legal requirements to reduce CO2 consumption, the innovation efforts of car manufacturers are growing. The objective is no longer primarily the comfort of the customer, but the efficiency and environmental friendliness of the vehicle [4]. Research and development is focusing in particular on innovative, more efficient powertrain concepts and lightweight construction [4]. There is significant potential for improvement to be explored in the area of the combustion engine, with electric motors also increasingly gaining market share [5]. However, the weight savings that can be achieved by implementing lightweight design concepts on the entire vehicle ought not to be underestimated for both power train concepts [6]. With the use of modern steel materials and forming technologies, a weight reduction of up to 25.5 kg can be achieved on a standard mid-range vehicle [6].

Downsizing engines is one approach that can be taken at system level [7]. This means reducing technical parameters such as engine cubic capacity or weight while maintaining the same driving performance and dynamics required by the customer. From this point of view, this is only feasible with higher specific engine outputs [7]. As a result, individual key components are permanently used at their load limits. In manual transmissions, the synchronizer ring is an example of this. Due to the integration of different functional elements such as driver and toothing elements, this component has a high level of geometric complexity. Helical gears are in this context well established in the industry for their low noise development and smoother running. Therefore, they are also used in lightweight designs of drive trains for electric car motors [8].

Sheet-bulk metal forming (BMF), which is characterized by the application of bulk forming operations to sheet metal blanks, makes an important contribution to the development of resource-efficient manufacturing processes for metallic components [9]. In this process class, the material flow is not just limited to the sheet metal plane, but it is also possible to extrude functional elements from the sheet metal plane [9]. This enables the production of complicated sheet metal components with high component functionality. While an in-depth understanding of the process class has already been developed for components with spur gear elements and carrier structures, there is a research gap for helical-toothed lightweight components. The geometry of helical gears results in higher flow paths and tooth volumes than with comparable sheet metal forming of spur gears. The achievable form filling therefore poses a particular challenge for the established processes such as upsetting or deep drawing combined with extrusion.

Methodology and Objective

The main goal of the investigation is the identification of process specific challenges and mechanisms that arise from the forming of helical gear elements in a combined approach of sheet-bulk metal forming. To achieve this objective, a gearing geometry with industrial relevance is first designed. The focus is on the running capability and a light-weight approach. However, the limits of die filling of filigree gearing elements in extrusion processes on sheet metal must be taken into account. The fundamental understanding of processes for straight-toothed functional components is used for this purpose [10]. A single-stage tool system for the efficient forming is subsequently designed based on the selected component geometry. The tool system consists of a unit for deep drawing and the following lateral extrusion.

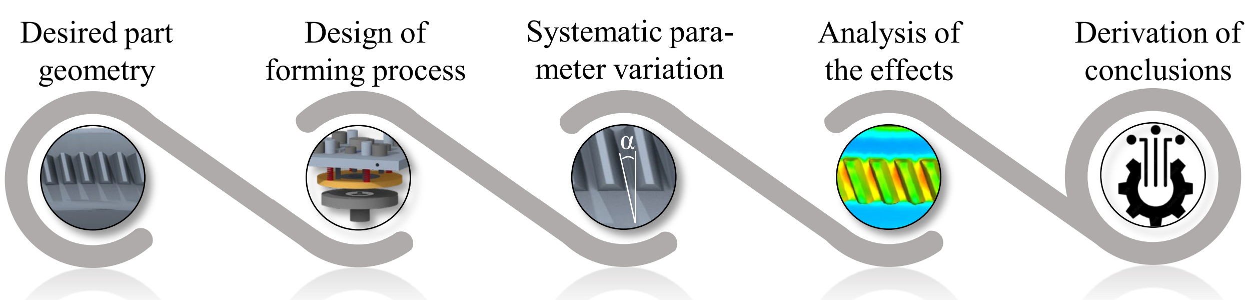


Fig. 1. Methodical approach of the research.

A systematic parameter variation moreover provides information about the effects that occur during the lateral extrusion of helical gear teeth. This knowledge is crucial for further research in measures of process improvement. Simulations of the finite element method are used to determine the process result parameters. This approach enables the elaboration of profound comprehension of the cause-effect relationships. The accuracy of the prediction of the applied numerical model was validated in [10] using process- and part-sided parameters. The flank angle is varied in accordance with industrial applications between 0 and 40 degrees. The analysis is based on the process target variables of forming force and tool load as well as on component-sided parameters like the material flow and the degree of deformation. Based on the research results, conclusions on the challenges and process limitations for the production of helical lightweight gears by sheet-bulk metal forming are drawn.

Tool setup and numerical model

In the process setup, the mild deep drawing steel DC04 is selected as workpiece material with an initial sheet thickness of 2.0 mm. Previous studies of this material have proven its suitability for SBMF extrusion processes with a high degree of deformation [10]. The tool setup for the forming of the lightweight helical geared part consist of a deep drawing stage for the component body and a lateral extrusion stage for obtaining functional elements. The associated process kinematic is shown in Fig. 2.

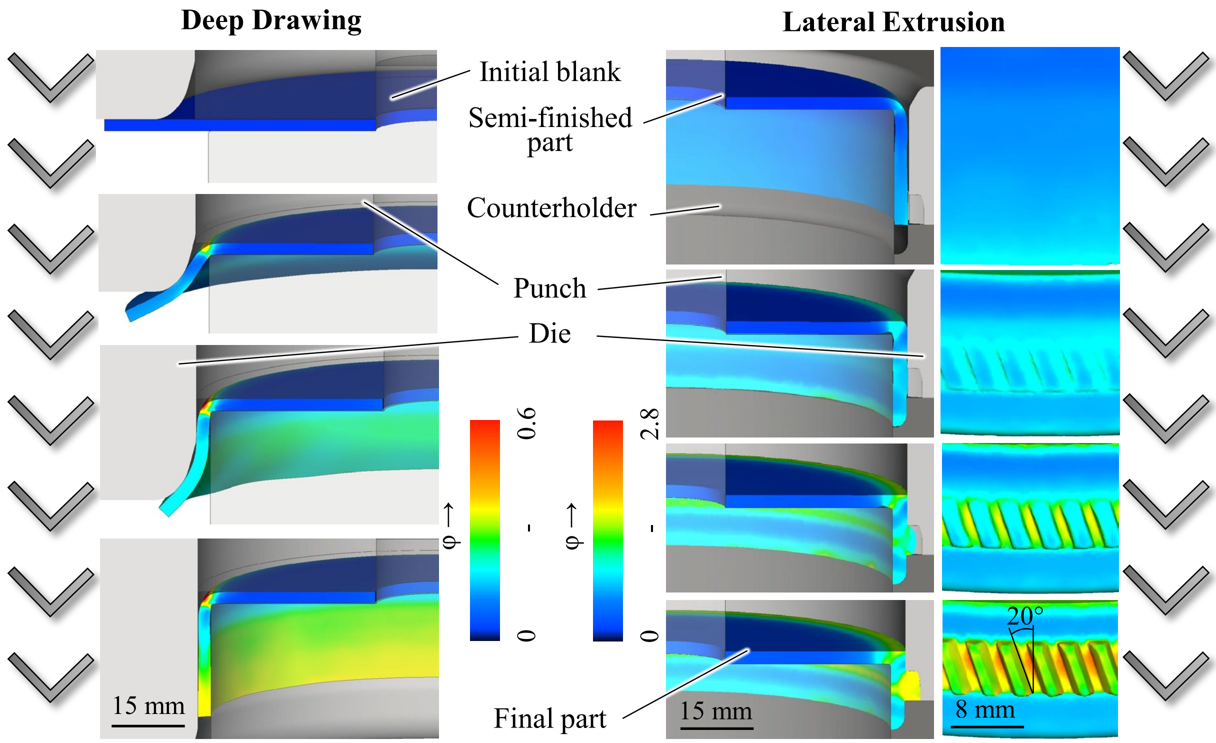
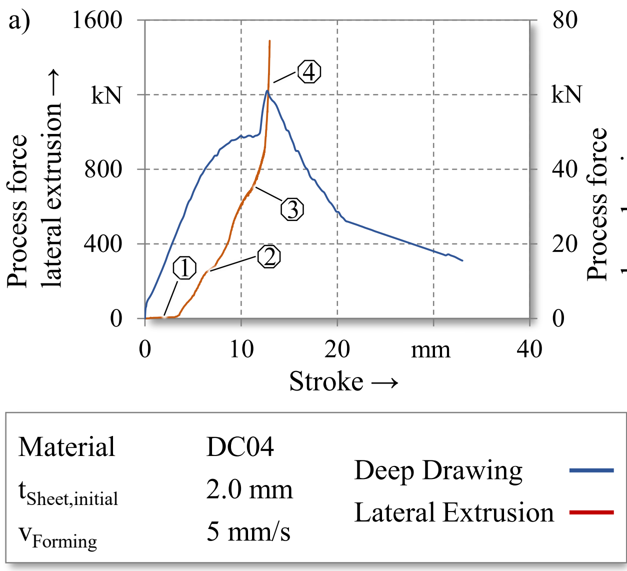


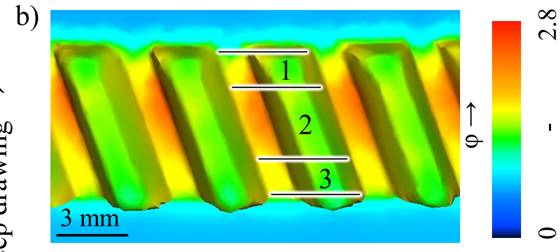
Fig. 2. Process kinematics of deep drawing and lateral extrusion.

The main body is manufactured using a conventional deep drawing process. At the beginning of the process, the sheet metal blank is clamped between a punch and a counterholder. The upper drawing ring is then moved downwards and forms the component frame. At the start of the subsequent lateral extrusion process, the sheet thickness is already increased from 2.0 mm to 2.25 mm. This results as the deep drawing process involves a drawing gap to prevent the ironing of the frame. In lateral extrusion, the synchronous downward movement of the punch and counterholder causes the workpiece to be displaced until contact is made with the lower die. The radius at the cup opening is then formed by the plastification of the component frame. The further increase in the process force introduced by the punch causes the plasticification of the material in the frame, which leads to the filling of the cavities between the workpiece and the tool. The cavities in the center of the die are designed as a negative form of the component-side teeth. This enables the cavities for the helical gearing elements to be filled as the process progresses.

Results and discussion

For the initial process investigation, the forming forces are analyzed for the reference setup with a gearing angle of 20°. The process forces for the deep drawing and the lateral extrusion are shown in Fig. 3(a). The linear ascent of the deep drawing force can be explained by the elastic strain shares at the beginning of forming. Due to the increase of friction force at the drawing ring radius, the reverse bending force and the ideal forming force caused by work hardening , the process force reaches its maximum of 61 kN at a stroke of 13.4 mm. As soon as the frame has finished bending at the outer radius of the counterholder, the process force decreases. The force-displacement curve is typical for deep drawing and has been verified in numerous publications [11]. With a maximum process force of 1.310 kN, the lateral extrusion forming of the helical-toothed functional elements far exceeds the force required for deep drawing.





φ	1	2	3
Bottom	1.2 - 2.1	2.2 – 2.6	1.5 – 2.0
Left tooth flank	1.5 – 2.3	1.7 – 2.4	1.6 – 1.9
Tooth head	1.3 – 1.4	1.3 - 1.5	1.1 – 1.3
Right tooth flank	1.4 – 1.6	1.5 – 1.8	1.5 – 1.7

Fig. 3. Force-stroke curve of deep drawing and lateral extrusion (a) and the distribution of the degree of deformation of the finished part (b).

At the start of lateral extrusion, the process force is around 8 kN (1). In this phase of the process, the component is pushed down into the lower die. Consequently, only frictional forces between the component and the tool have to be overcome. The material is not yet plasticized. From a stroke of 3.0 mm, there is a steep increase in process force. This is due to the contact of the lower cup wall with the die-side radius and the resulting material deformation. The slight drop in the gradient from a stroke of 6.5 mm (2) can be explained by the formation of a fold at the corner between the component base and the cup wall. The upsetting of the frame causes an increase in the degree of deformation and consequently work hardening as the process progresses. The forming of the helical-toothed cavities begins at a stroke of approximately 9.0 mm. As the cavity filling increases (3), the process force also rises, resulting in a linear increase due to the almost complete contact between component and tool (4). In the comparable process for the forming of straight teeth elements, a maximum process force of about 1.050 kN is reached [10]. However, direct comparability is not given due to the significantly lower die filling in the straight tooth process. While a die filling of 95 % is used in the investigated process for more precise identification of the effects, the die filling in the compared process is only 63 %. At a die filling of 63%, the process of the helical gear parts is with 1.060 kN at a comparable level. The variation of the helix angle therefore appears to have only a minor influence on the force required for forming. To understand this behavior, the distribution of the degree of deformation for the helical gear elements is shown in Fig. 3(b) and the underlying material flow is discussed using Fig. 4.

In the tooth root, the degree of deformation is generally highest. This is the case for all differentiated areas 1-3. The localization of the highest degrees of deformation in this area is comparable with the results of the investigations of the lateral extrusion of spur gear components. The reason for this is the strong material deflection caused by the geometric flow restriction of the tooth heads on the tool side.

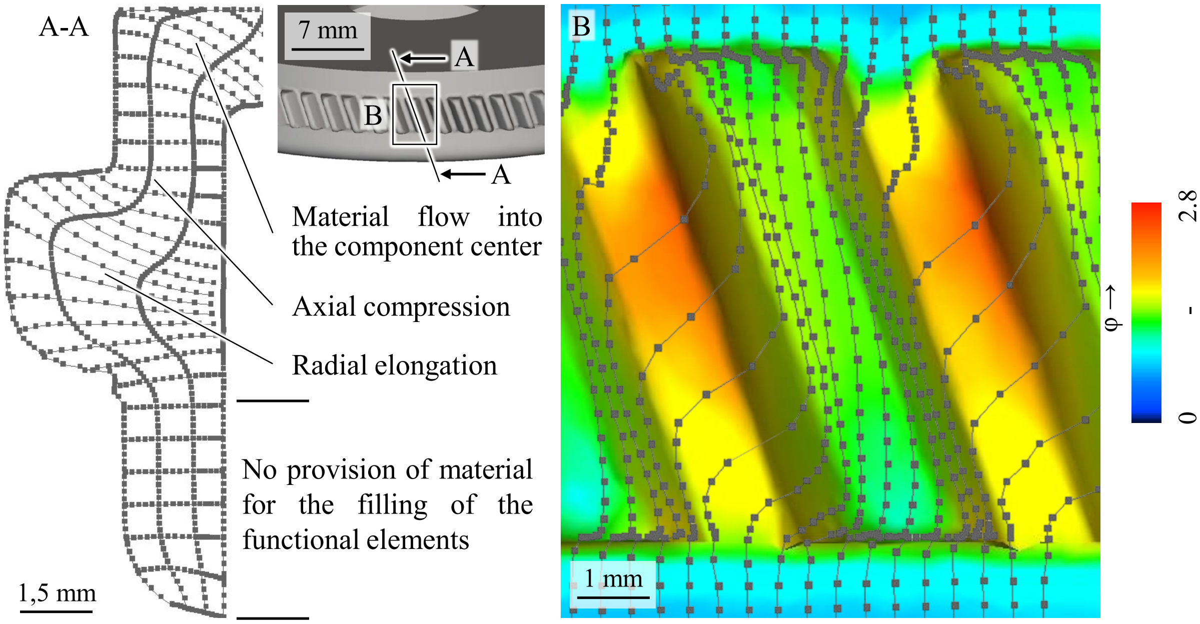


Fig. 4. Material flow analysis of the helical gear elements.

Detail B of Fig. 4 visualizes the strong elongation of the material in the tooth root due to the material deflection. The flow lines are tracked using a grid with connected points at a fixed distance during forming. Based on the change compared to the initial grid, the material flow can be estimated. In addition, a gradient of the degree of deformation results while higher values result in the left tooth root and decreasing values towards the left bottom area. According to the material flow visualization of section A-A, the upper component wall solely provides the material volume for the cavity filling. In the area below the toothing elements, the grid shows no distortion, which indicates little material flow. This circumstance therefore leads to a downward displacement of the material, which is subsequently deflected by the inclined die teeth. This axial displacement causes the gradient of the degree of deformation due to the changed angle of impact of the material between the left and right tooth flank. This results in an asymmetrical material flow between the right and left tooth flank. In addition, cross-section A-A shows the basic mechanism of filling the functional elements in radial direction. It is characterized by material displacement due to axial compression as well as radial expansion because of the hollow volume between the workpiece and the die cavities.

The asymmetrical material flow is moreover verified by analyzing the material flow velocity in the gearing elements. In this context, Fig. 5(a) shows the material flow velocity in the radial direction at different phases of form filling. There is a strong gradient in material flow velocity between the left and right side of the tooth. While the values for the left half of the tooth average 4.2 mm/s, the material flow velocity in the right half of the tooth reaches only an average of 3.1 mm/s. The main reason for the differences in material flow speed is the superposition of axial and radial material displacement (Fig. 4 section A-A) with the different deflection angles on the tool-side tooth flanks (Fig. 4 detail B). As a result of the asymmetrical material flow rates, the tooth cavity is filled unevenly, with the material of the left half of the tooth running ahead of the material of the right half. The tooth profile is therefore only symmetrical when the cavity is entirely filled.

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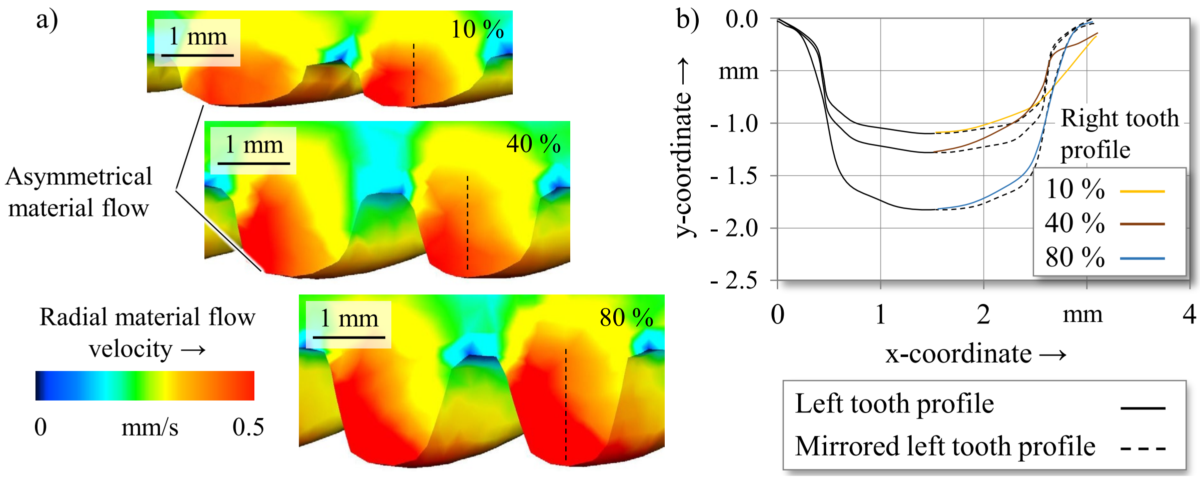

Fig. 5. Radial material flow velocity (a) and tooth profile comparison (b) at different die filling stages.

Fig. 5(b) shows the deviation between the left and right tooth profile, taking the left tooth flank as reference. In all three stages of die filling from 10-80 %, the right tooth is less filled at the tooth face and topland. As the form filling increases, the difference between the left and right tooth filling is equalized due to the smaller remaining cavity. Only a slight deviation remains, which is eliminated with complete die filling due to the geometric limitation of the die cavities. Since, depending on the strength of the blank material, the tool load often exceeds the permissible range during sheet metal forming of filigree gearing elements [12], it is often not possible to achieve complete die filling. It can therefore be concluded that the accuracy of the tooth flank profiles represents a decisive process limit due to the uneven form filling.

The tool life time is a decisive factor with regard to the economic efficiency of the lateral extrusion process at higher quantities. In this context, the tool lifetime is considerably affected by the external forces acting on the tools [13]. As the tool loads are expected to be highest in the die due to the fine cavities, this area is examined for the reference variant at a helix angle of 20°. Failure-critical stress components are evaluated in order to identify areas with a high risk of fracture. Stress concentrations are localized using the $\sigma_{v.Mises}$ (Fig. 6(a)), while the principal stresses σ_{Max} (Fig. 6(b)) and σ_{Min} (Fig. 6(c)) are used to determine the maximum tensile respectively compressive stresses.

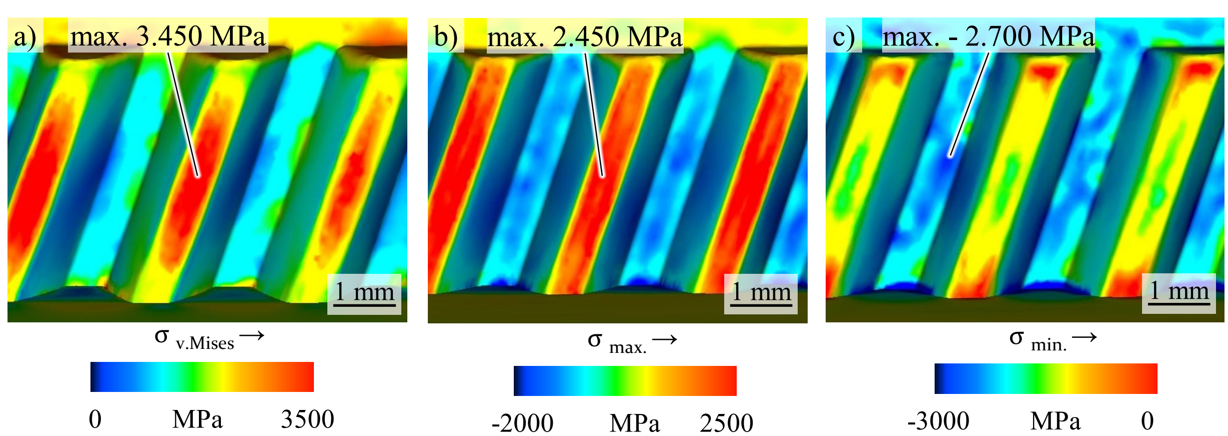

Fig. 6. Tool stresses of the helical geared forming die.

The evaluation is carried out at a form filling of 95 %. Stress concentrations are detected on the basis of $\sigma_{v.Mises}$ as well as σ_{Max} in the tooth base of the die cavities. Due to the superposition of the axial and radial material flow, a lateral bending stress on the tooth elements on the tool side is induced, which leads to a tensile load in the tooth foot area. The teeth themselves are primarily subject to pressure. These are in direct contact with the material during forming and are exposed to high normal pressures due to the deflection of the material. This behavior is also demonstrated in the investigation of spur gear dies with filigree functional elements [10]. Furthermore, no asymmetry of the tool loads can be detected. This leads to the conclusion that the axial force components acting when the material impacts the tooth flanks on the tool side are still low at a helix angle of 20°.

The transferability of the process and component-side results at a helix angle of 20° is examined in the following section with regard to their comparability with other helix angles. For this purpose, the angle is varied between 0° and 40° with a step width of 10° and the effects on the target variables of process force, work hardening and tool load are analyzed and discussed. Fig. 7 shows the influence of the helix angle variation on the tool loads.

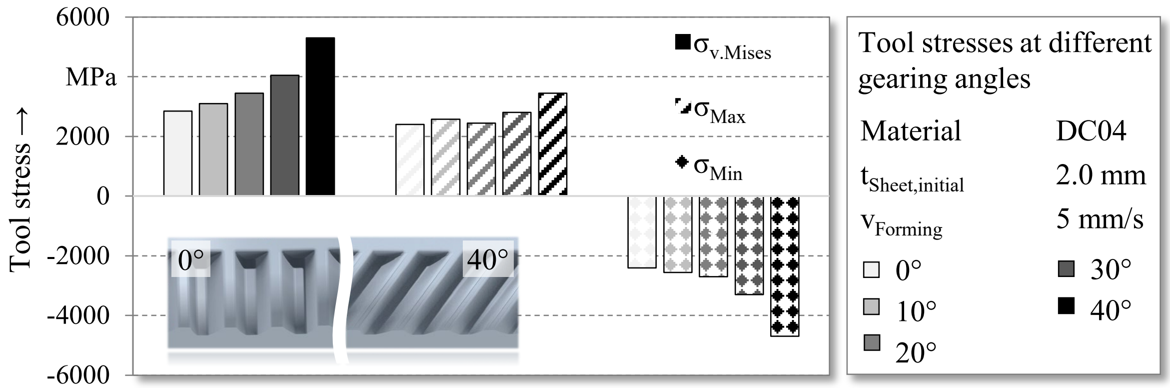

Fig. 7. Influence of the helix angle on the tool loads.

The maximum $\sigma_{v.Mises}$ detected with a spur die is 2.850 MPa and increases to up to 5.300 MPa (+85 %) when the toothing angle is increased. The maximum tensile stresses show no clear trend for the 0°-30° variants. Only with a helix angle of 40° do the maximum tensile stresses increase noticeably to up to 3.450 MPa. The bending load due to the axial material flow components therefore has an influence on the resulting tensile stresses at large helix angles. This this is due to the increasing lateral force components that act on the gearing as the angle increases. However, these only exceed the prevailing tensile stresses in the base area resulting from the compressive load on the teeth from an angle of 40°. In the investigated process, the compressive stress state shows a continuous increase in stresses with increasing flank angle. This increase is also due to the rising lateral forces.

An increase in the helix angle therefore has to be considered as having a negative effect on the tool loads and therefore also on the lifetime of the tools. The loads also exceed the load limits of conventional tool materials at a mold filling of 95 % at higher flank angles. Carbide tools are one possible solution to this challenge. These have great potential to withstand the forces in sheet bulk metal forming processes for helical-toothed lightweight components, particularly with regard to the high compressive loads [14]. To gain further understanding of the effect of the helix angle on process-sided parameters, Fig. 8(a) shows the reached maximum process force values at the different helix angles. Starting with a spur gear, the angle is increased in steps of 10° to 40°.

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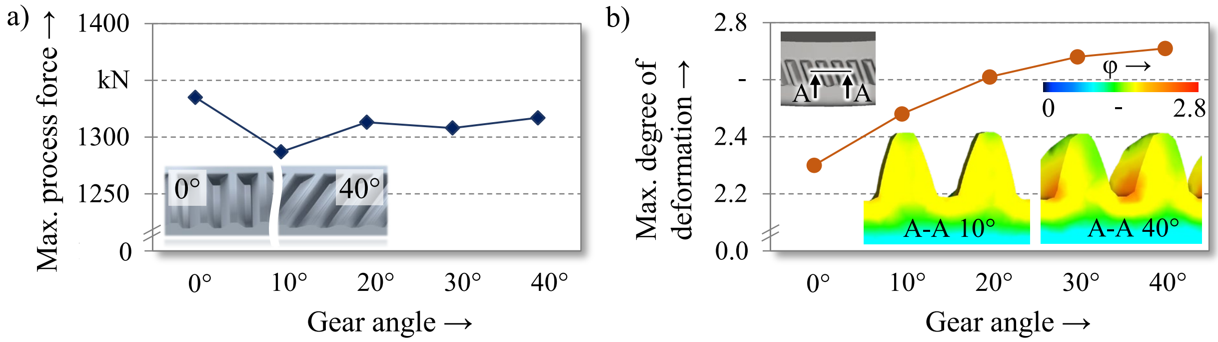

Fig. 8. Maximum process force (a) and maximum degree of deformation (b) at helix angles from 0° to 40°.

The helix angle does not unambiguously influence the maximum process force reached in lateral extrusion. This can be explained with the material flow behavior presented in Fig. 4. The material is displaced by the axial compression of the frame in a radial direction. During the cavity filling, axial material flow is rather superpositioned by the radial elongation. With regard to the relative movement between the workpiece and the tool-side gear teeth, it is primarily the axial displacement that leads to increased frictional forces as the gear tooth angle increases. The displacement of the material in the radial direction can be described as the material clinging to the tool wall and does not result in an increase in the process force due to the merely lower frictional forces at higher helix angles. From a volumetric point of view, the geometric flow restriction caused by the teeth on the tool side is independent of the tooth angle. Therefore, the required process force remains at a comparable level with varying helix angles. Despite higher axial forces, this effect is also demonstrated in the full forward extrusion of helical-toothed components [15]. In addition, the internal mechanical component properties are compared on the basis of the maximum degrees of deformation. Fig. 8(b) presents the corresponding maximum values as well as an exemplary cross-section of the teeth at a helix angle of 0° and 40°. The maximum dregree of deformation φ_{max} increases from 2.3 at 0° in a logarithmic saturation curve to $\varphi_{max} = 2.7$ at a helix angle of 40°. The increasing strain hardening results from the axial components of the material flow, which cause a deflection of the material on the left tooth flank. As the analysis is based on a die filling of 95%, the values on the right tooth flank are also increased in the 40° variant compared to the spur gear. This is due to the fact that the material is also deflected on the right tooth flank at the end of the forming process. For the gear application, the rise in the toothing angle can therefore be classified as positive, as the increased hardness of the teeth results in a reduction in wear [16].

To put the different effects into relation, Fig. 9 summarizes the mechanism of the toothing angle based on the model concept. The deflection of the axial material flow component (Fig. 4) increases with larger flank angle. This results in an increase in the lateral force F_l introduced, which acts on the toothing on the tool side. For this reason, the tensile loads in the base area between the teeth increase, as do the compressive loads in the tooth itself (Fig. 7). Furthermore, the axial force F_a and the radial force F_r are independent of the angle. The deflection angle also increases the hardening, particularly in the tooth area near the surface (Fig. 9).

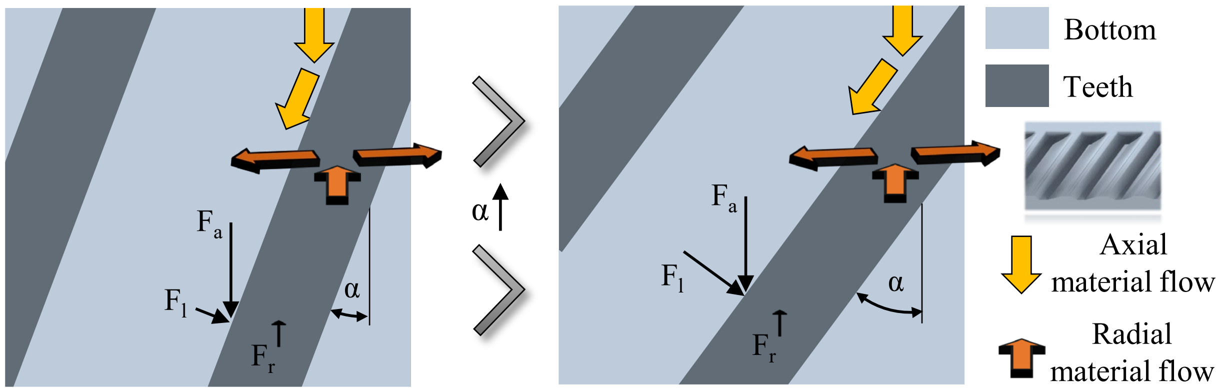

Fig. 9. Conceptual model of the effect of the helix angle.

Conclusions and Outlook

The investigation presents the general demonstration of the suitability of the process combination of deep drawing and lateral extrusion for the production of helical-toothed thin-walled lightweight components by means of sheet metal forming. It has been shown, that an asymmetric hardness distribution in the teeth results from the deflection of the axial material flow component. The asymmetric hardness distribution can be exploited for defining the working direction of the gear to gain a higher wear resistance. Moreover, two main process limits are identified. At low form filling, the primary process limit is the precision of the tooth flank profile due to asymmetric material flow. With high die filling, the flank profile is equalized, but the process restriction becomes the high tool loads, which can be addressed by the use of carbid forming tools to increase the compressive strength. Similar to forward extrusion process for helical gears, higher tooth angles in lateral extrusion improve the application properties due to the increased tooth hardness. This positive effect is contrasted by increased tool loads due to the higher lateral force components acting on the tooth flanks.

Further research should focus on the development of process-adapted ejector concepts. Due to the necessary rotation of the component for demolding and the associated contact pressures, there is a risk of deterioration in gear quality. Possible approaches in this context are rotating dies or inverse pre-correction of the gear geometry. In addition, further contributing factors such as the semi-finished product material, the sheet thickness and the gear geometry need to be investigated with regard to process and component-related results.

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