Numerical study on cold extrusion of gears varying the extrusion shoulder geometry

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Abstract. Cold forging processes, such as cold extrusion and in particular the Samanta process, provide a considerable potential for improvement in gears production. The method behind the Samanta process is based on the principle of cold extrusion in stacks. After partial forming of a workpiece, another workpiece is inserted into the die in order to eject a completely formed gear in the direction of the punch movement. Although this operating principle offers great potential for high-volume production, the industrial relevance of this process is limited by disadvantages such as high tool loads, limited gear accuracy and deformations on both face ends of the gear wheel. In order to overcome the technological challenges associated with the Samanta process, the die geometry was adapted. In this case the die operating surface was modified in terms of an extended forming zone length combined with an undercut in the tooth cavities of the die. In this paper the numerical results for this novel process regarding the correlations between geometric die parameters and resulting process data, such as punch force, contact pressure and die filling, are presented. The spline-based tool was methodically varied between one linear and two square (concave, convex) designs and was numerically evaluated using Deform 3D™ software.

Introduction

As an integral part of the modern automotive and mechanical engineering industry, gears are used in a wide variety of drive systems. Due to the high demands placed on gears in terms of performance, operational reliability and smooth running, they are usually manufactured using machining processes [1,2]. Machining processes, especially for gear production, are time and material consuming. Due to the ecological disadvantages of machining processes, it is important to find better alternatives in the long term. Cold forming is an alternative with a high potential for substituting machining processes. Cold extrusion in particular offers the possibility of producing gears with high output and improved material utilisation. In addition, the gears benefit from process-related strain hardening and an uninterrupted fibre structure [3]. The most common process for cold extrusion of gears is the Samanta process, in which the blanks are pressed in stacks through a toothed die. In this process, the workpiece is partially formed, then the punch is retracted and a new workpiece is inserted into the die. By extruding the second workpiece, the partially formed and thus toothed workpiece is ejected downwards out of the die, enabling the manufacture of a fully toothed workpiece [4]. Due to the established die geometry in this process, there are some process-specific disadvantages, such as an extreme tool load, shape and dimensional deviations of the gearing and deformations on the face ends of the workpiece. To overcome these disadvantages, a new process based on the Samanta process was developed at the Institute for Metal Forming Technology in Stuttgart, Germany. The so-called Guided Material Flow (GMF) process differs from the Samantha process by means of a modified die operating surface. Main feature of this redesign is an extended extrusion shoulder and thus forming zone. This extended forming zone is hypothetically intended to distribute the required forming work over a longer stroke and therefore reduce the die load. An improved accuracy of the extruded gear is expected.

Extending the extrusion shoulder increases the friction surface between the workpiece and the die. Hence, an undercut was added into the die cavity as a second feature in order to compensate the increase in friction surface.

Cold Extrusion of Gears

Samanta process.

The Samanta process is a special process in the field of cold extrusion which can be performed with full and hollow blanks. The special feature of the process is the characteristic process principle, which is shown schematically in Fig. 1a. Blank 1 is placed in the die and partially formed by means of the hollow punch and the mandrel in the first phase of the process. For the second phase, the hollow punch and the mandrel are retracted until blank 2 can be loaded. Due to the partial forming of blank 2, blank 1 is completely pressed through the toothed active surface of the die. Thus, the toothed workpiece is dropped out the die on its lower side, eliminating the need for an ejection process [4]. No ejection simplifies the tools, eliminates the risk of ejector marks and offers the potential for higher production output [5]. Using the Samanta process a gear accuracy with a tolerance class between 10 and 11 for helical and straight gears can be achieved. However, the automotive sector demands gear accuracies of IT 6 or better [6]. In addition, gears formed using the Samanta process exhibit typical features such as partial tooth underfilling (inflow area) on the bottom side and “crown-shaped” deformation on the top side of the gears (see Fig. 2b). Both of these areas necessitate material removal by machining, which reduces material utilisation of the process and also calls for additional production steps [7].

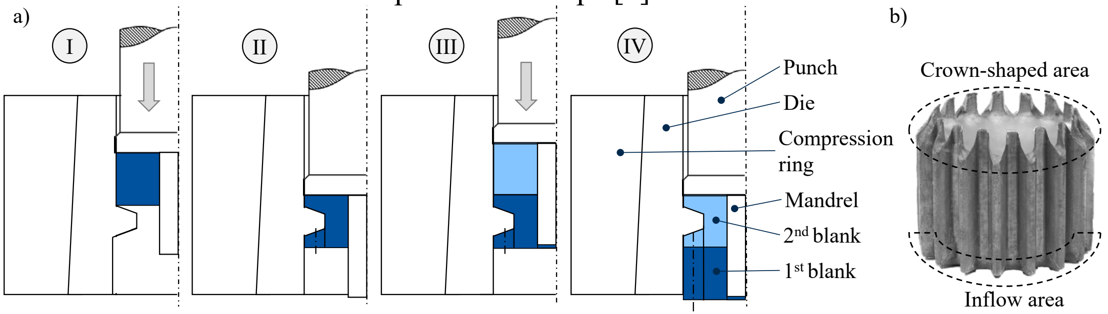


Fig. 1. Samanta process, a) process principle, b) toothed workpiece (according to [8,9]).

Guided Material Flow (GMF) process.

Based on the process principle of the Samanta process, a novel process for the cold forming of gears was developed at the Institute of Metal Forming Technology. The GMF process is a cold extrusion process for full and hollow blanks. It differs from the conventional Samanta process in the design of the operating die surface. Fig. 2a shows the sectional view of the tooth cavity in the GMF process and Fig. 2b a comparison of the die design between the two related processes.

Comparing both designs, two decisive features appear crucial: Characteristic 1 consists in the significantly extended length of extrusion shoulder and thus forming zone of the die. This has the effect of distributing the required forming work over a longer stroke, which on the one hand decreases the maximum punch force and on the other hand increases the friction surface between the die and the workpiece. In order to compensate the increased friction surface, the die cavity was modified by an undercut. Therefore, characteristic 2 consists of an undercut in the die cavity located at the area of the tip circle diameter of the toothing. This undercut highlighted with purple colour in Fig. **2**a serves to induce a contact separation between the die and the workpiece in the area of the tooth tip of the formed gear. Through this new design of the die active surface in the GMF process, the maximum punch force could be reduced by about 38% compared to a similar Samanta process [10]. Decreasing the maximum punch force leads to a reduction of elastic die deflection and thus to an improved accuracy of dimension and shape of the gearing as well as to a reduction of tool wear. All geometric die parameters in the design of the die operating surface of the GMF process were determined based on practical experience in the field of cold forming within the scope of preliminary investigations. The complex die surface was designed by simulative evaluation and iterative adaptation of the individual contours (see Fig. 2) on different levels along process direction. Since the tooth cavity varies steadily in process direction, the material flow is controlled systematically, which finally led to the name of this novel process.

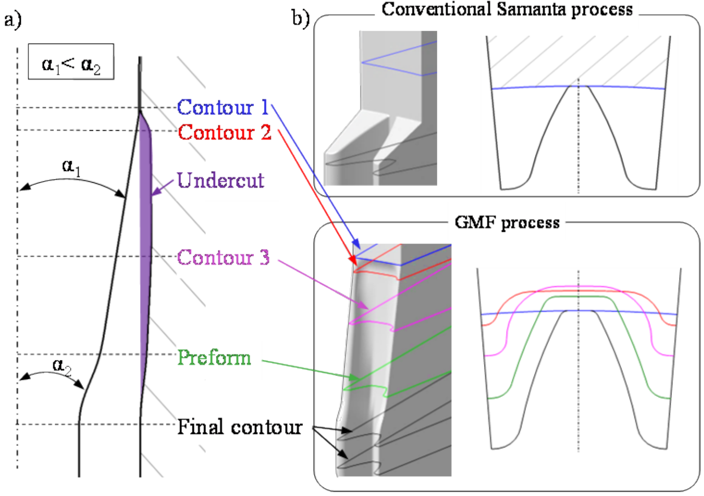


Fig. 2. GMF process, a) sectional view of die cavity, b) comparison of die design with Samanta process.

The initially designed die model was not suitable for the performance of comprehensive numerical investigations within the scope of a research project. The reason for this is the large number of geometric parameters and thus process influencing variables. Therefore, the number of geometric die parameters was significantly reduced in a new die model. Main objective of this simplification was performing a numerical analysis more effectively in order to identify relationships between geometrical die parameters and relevant process data in the GMF process. New design of the die used in the GMF process was achieved by means of splines and mathematical functions, as shown in Fig. 3. As boundary conditions for the adaptable design of the GMF die, the tip and root diameters of the involute toothing were selected. These two boundary conditions located at the respective ends of the forming zone enabled the geometrical profile of the extrusion shoulder to be implemented as a polynomial function *f(z)*. Corresponding polynomial function $f(z)=a_n\text{-}z^n+a_{n-1}\text{-}z^{n-1}+\ldots a_1\text{-}z^1+a_0$ allows the variation of the geometric profile of the extrusion shoulder by changing the exponent.

This paper presents the numerical results for the linear and quadratic versions of the extrusion shoulder geometry in the GMF process. Aim of the numerical investigations was to determine the effect of different extrusion shoulder geometries on relevant process data during cold extrusion of gears in the GMF process. For this purpose, the toothing to be formed was kept fixed and the shape and length of the extrusion shoulder were varied for each version. The variation of the linear extrusion shoulder version was based solely on the forming zone length, since in this case the extrusion shoulder angle results from the gear data. In the case of the quadratic extrusion shoulder, there are two types - convex and concave. They differ in terms of the sign of the coefficient for the highest order of polynomial in the polynomial function. In the evaluation of the simulation, the geometric modification of the quadratic polynomial function is based on the angle α at the vertex of the parabola (see Fig. **3**).

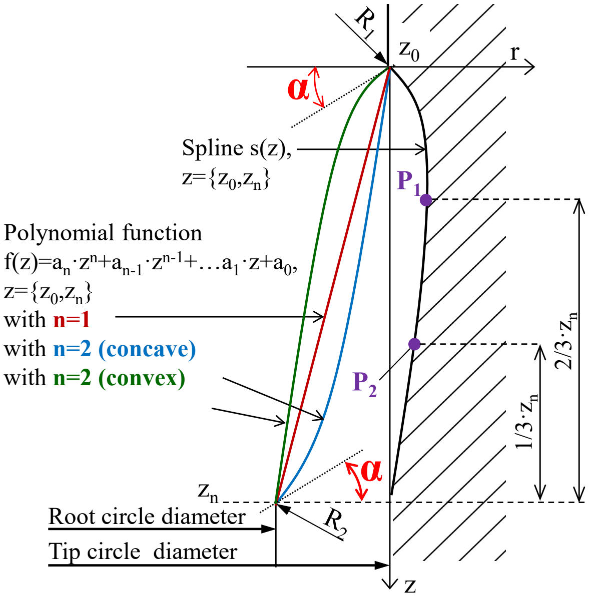


Fig. 3. Sectional view of re-designed die cavity in the GMF process with variation of extrusion shoulder profile.

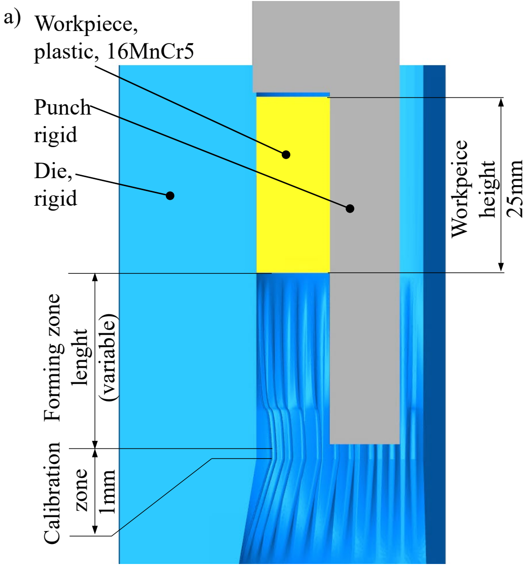
The undercut in the area of the tip circle diameter of the gearing was designed with a spline as a guide curve. This spline was approached by four points as boundary conditions. The first point was at the beginning (z_0), the second at the very end of the forming zone (z_n) and thus also define the starting and end points of the spline. Two further points are located at 1/3 and 2/3 of the forming zone's length. The radial position of the two points along the spline was defined in relation to the tip diameter of the teeth. Point P_1 was defined 0.1 mm and the point P_2 0.3 mm larger than the tip diameter of the toothing.

Numerical Investigations

The numerical investigations were intended to determine any effects of geometric changes on the die operating surface in the GMF process and on significant process parameters. Analysis was performed by variation of design of the extrusion shoulder and numerical computation of the punch force, the contact pressure on the die and the die filling. By adjusting the coefficients of the polynomial function within most suitable intervals, a methodical evaluation could be conducted. Through numerical preliminary investigations, suitable range of intervals for the polynomial coefficients were determined for the very first practical trials. The geometric profile of the undercut was not varied in this FE analysis.

Simulation setup.

Fig. 4a shows the general setup of the simulation model in software Deform 3D™. All simulations within the numerical analysis were conducted according to this depicted simulation setup. In order to perform a DOE study based on 3D models, a corresponding simulation had to be set up for each process variation. Here, only the die models were replaced. Punch and die in simulation were implemented as rigid objects. The hollow workpiece segment of 4,615 ° (half tooth) has a height of 25 mm was defined as a plastic object made of material 16MnCr5. Workpieces were modelled with 80,000 mesh elements and simulatively deformed at room temperature at a punch speed of constant 40 mm/s. The friction in the simulation was defined as shear friction with a friction factor of 0.12 [11]. All dies were designed for extrusion of the same gear geometry. The simulated gear has involute teeth with a modulus m of 1 mm and a number of teeth z of 39. Dimensions of gear and utilized simulation data are listed in Fig. 4b. In the DOE, the extrusion shoulder geometry was varied between a linear and two quadratic (concave, convex) geometries. Also, the length of the extrusion shoulder and therefore the forming zone length as well as the tangent angle α at the apex of the quadratic extrusion shoulder were varied between 30°, 50° and 70° within predefined intervals.



b)

Gear dimensions	
Tooth geometry	Involute
Nr. of teeth	39
Module m	1.00 mm
Tooth height	2.17 mm
Tooth width	1.57 mm
Tip circle diameter	41,00 mm
Root circle diameter	36.67 mm

Simulation parameters	
Software	DEFORM 3D
Mesh workpiece	80,000
Temperature	20 °C
Friction	shear, 0.12
Punch speed	40 mm/s
Simulation type	Lagrangian incremental
Solver	SPOOLES

Fig. 4. Simulation, a) Setup in Deform 3D™, b) Gear dimensions and simulation parameters.

Results and Discussion

This chapter presents the numerical results for geometrically varying extrusion shoulder versions in the GMF process in relation to relevant process parameters. Relevant process parameters in cold extrusion do include the punch force, the contact pressure onto the die active surface and the die filling of the toothing. A comparison with the conventional Samanta process for forming the same gear (see Fig. 4b) also was performed.

Linear design for extrusion shoulder in GMF process.

As shown in previous publication [10], the highest contact pressure onto the die surface is located in the area of the extrusion shoulder and thus at the root circle diameter of the formed toothing.

Fig. 5 shows the numerical results for the DOE study with a linear extrusion shoulder. The red dashed line in the diagram represents the numerical reference results obtained from simulation of the conventional Samanta process with an equivalent simulation setup. Based on preliminary numerical investigations, the forming zone length was varied between 2 mm and 13 mm for analysis objectives. Beyond this interval, no complete die filling or increased process forces were detected using the linear extrusion shoulder in the GMF process for forming this gear. The results in Fig. 5 indicate that the die in GMF process having a linear extrusion shoulder design in every case is exposed to lower loads compared to the conventional Samanta process. The conventional Samanta process requires a maximum punch force of 430 kN, and, in contrast, the linear design of die in GMF process requires 415 kN (2mm length of forming zone) with a decreasing tendency as the forming zone length increases. This shows that when extending the forming zone length from 2 mm to 9 mm, the maximum punch force can be reduced from 415 kN down to 270 kN. In case of lengths of forming zones beyond 9 mm, the peak punch force converges to this measured value. Also, underfilling in the tooth tip occurs at a forming zone length of 13 mm. Comparing the results with the conventional Samanta process reveals that with the linear design of die in the GMF process for forming this gear, a punch force reduction of approx. 38 % can be achieved. In addition, it can be observed that the contact pressure in the die also decreases as the forming zone length increases. Thus, the maximum contact pressure decreases from 2,920 MPa (length of forming zone equals 2mm) to a value of 2,150 MPa (length of forming zone equals 12 mm). Compared to the conventional Samanta process, a reduction in die contact pressure from 3,000 MPa to 2,150 MPa also was achieved, which equals a drop by approx. 28 %.

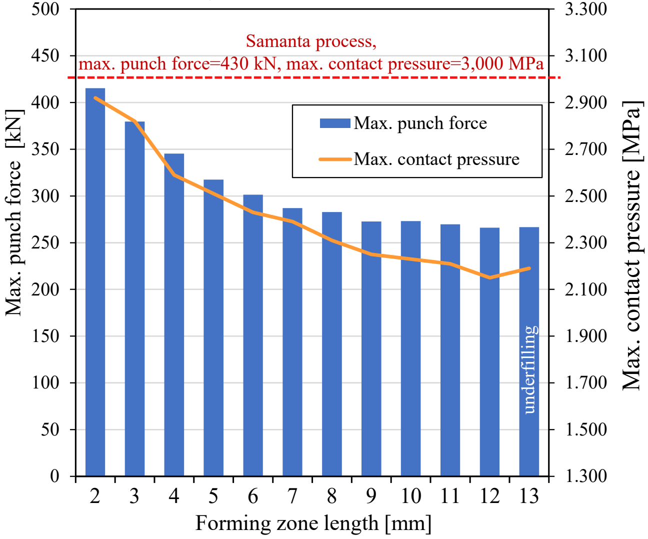


Fig. 5. Numerical results for linear extrusion shoulder geometry in GMF process.

Quadratic design of extrusion shoulder in GMF process.

In this chapter, the numerical results for a concave and a convex extrusion shoulder design being used for the GMF process are presented. The geometry of the extrusion shoulder with a quadratic polynomial function was varied based on the angle α. Here, the numerical investigation was performed at three different angles α - 30°, 50° and 70° (as shown in Fig. 3). In addition, the forming zone length was varied between 15 mm and 40 mm by 5 mm increments.

Concave extrusion shoulder design.

The chart in Fig. 6 summarizes the numerical results of the GMF process with a concave extrusion shoulder at an angle α of 30° and 50°. For the concave design with a tangent angle α of 30° (see Fig. 6a), obviously, the maximum punch force appears independent from the length of forming zone. Also, a maximum punch force of approx. 280 kN was determined. Thus, almost the same punch force reduction can be achieved with this process as with the linear extrusion shoulder design. Furthermore, the maximum contact pressure with this concave extrusion shoulder (α=30°) was observed at the same level as in the conventional Samanta process. Fig. 6 b shows the numerical results for the GMF process with concave extrusion shoulder design having an angle α of 50°. By increasing the tangent angle α at the vertex of the parabola from 30° to 50°, the level of the maximum punch force decreases marginally. Also, analogous to Fig. 6a no dependence was found between the forming zone length and the maximum punch force when using an angle of 50° at the concave extrusion shoulder. In this figure the maximum punch force consistently remains at a level of approx. 268 kN. It was found also, that the maximum contact pressure in this process was calculated as high as in the conventional Samanta process. As the forming zone length increases, underfilling of the toothing occurs, starting at a forming zone length of 20 mm. Such underfilling was also found in the process variant with a tangent angle α of 70°, regardless of the forming zone length. This underfilling was always found in the area of the tooth tip, since the corresponding extrusion shoulder design achieved insufficient material displacement in radial outward direction.

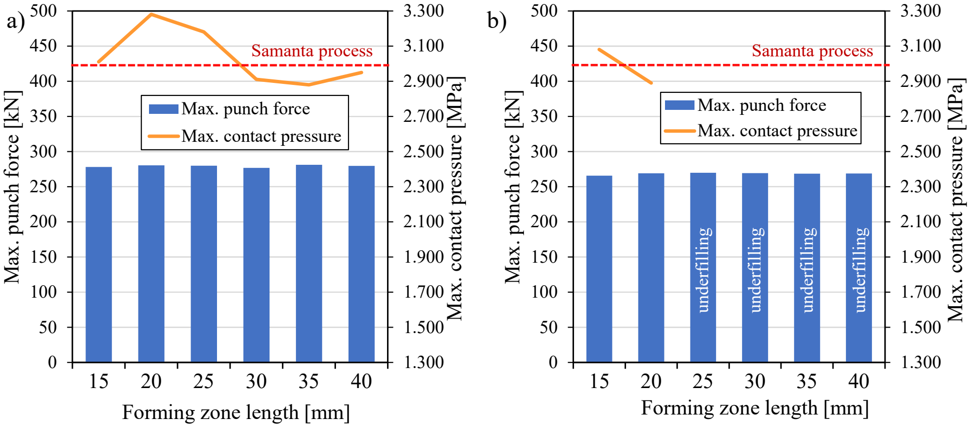


Fig. 6. Numerical results for concave extrusion shoulder geometry in GMF process, a) α=30°, b) α=50°.

Convex extrusion shoulder design.

The diagrams in Fig. 7 summarise the results of the convex extrusion shoulder in the GMF process with tangent angle α at 30°, 50° and 70°. Fig. 7a illustrates the results of the convex process version with angle α at 30°, indicating a significant reduction of the maximum contact pressure compared to the conventional Samanta process. The contact pressure of this extrusion shoulder design seems to correlate inversely with the maximum punch force. While the maximum punch force may reach a local maximum at a forming zone length of 25 mm, a local minimum of the maximum contact pressure appears here. In addition, the maximum punch force for this convex extrusion shoulder design appear remarkably lower than in the conventional Samanta process, irrespective of the forming zone length. However, even the lowest value of the maximum punch force in this process variant is higher than the lowest in the process variants having a concave design. Furthermore, underfilling also occurs at the toothing tip starting at a forming zone length of 35 mm.

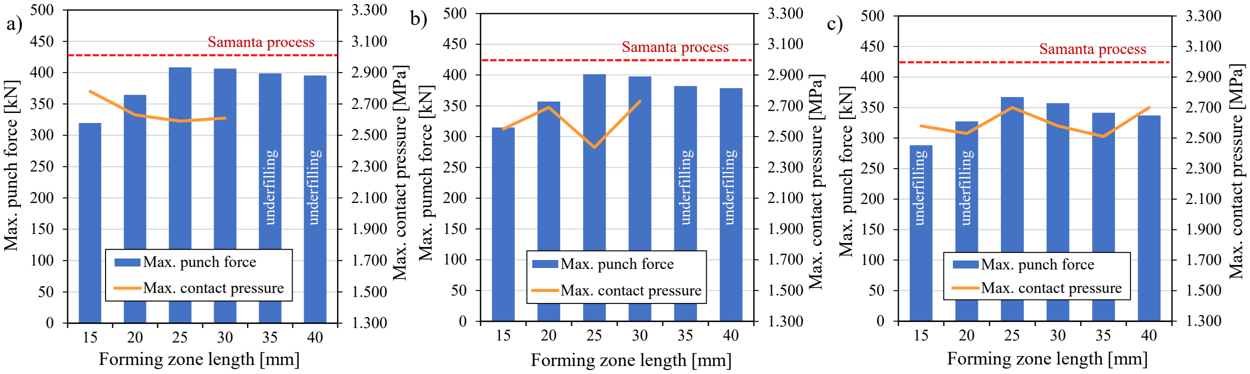


Fig. 7. Numerical results for convex extrusion shoulder geometry in GMF process, a) α=30°, b) α=50°, c) α=70°.

Fig. 7b shows the numerical results for the convex extrusion shoulder design in the GMF process with an angle α of 50°. The results are almost identical to the results for the convex version with a tangent angle of 30°. One difference however is observed: the maximum contact pressure does not show a clear correlation with the maximum punch force. Fig. 7c shows the numerical results of the convex extrusion shoulder in the GMF process having an angle α of 70°. By increasing the tangent angle α up to 70°, an underfilling of the tooth tip already occurs at a forming zone length of 15 mm. This underfilling also occurs at a forming zone length of 20 mm. A further increase of the forming zone length results into complete die filling. Increasing the angle to 70° also leads to a general reduction in the maximum punch force for the convex extrusion shoulder variant. In addition, a local maximum of the maximum punch force at a forming zone length of 25 mm was observed. Maximum contact pressure was calculated at a level of 2,500 to 2,700 MPa and therefore was found lower than the maximum contact pressure occurring in the Samanta process. Hence, the maximum contact pressure appears nearly independent from the tangent angle α for the convex extrusion shoulder design in the GMF process.

Analysis of material flow.

An analysis of the material flow in Fig. 8 shows that the geometric shape of the extrusion shoulder has a significant influence on the material flow. Blue dots in that figure indicate contact areas between workpiece and die.

Linear extrusion shoulder design.

The linear extrusion shoulder design as depicted in Fig. 8a results into a steady increase of the friction surface between workpiece and die during the process. Friction surface at the tooth flanks increases only slightly when increasing the forming zone length, resulting into a reduction of the maximum punch force due to the forming work distribution. In Fig. 8b a difference in flow velocity of the material in the cavity and at the centre of the blank can be detected. The difference of about 5 m/s consists at a horizontal level on the blank. Due to this fact, there is a temporary reduction of the tooth height during the process. Here, the reduction of the tooth height is hindered by any effects of friction between the workpiece and the die in the area of the tooth flank. When enlarging the forming zone length, the axial material flow near the centre of the blank dominates, which evidently reduces the tooth height and finally results in underfilling of the toothing.

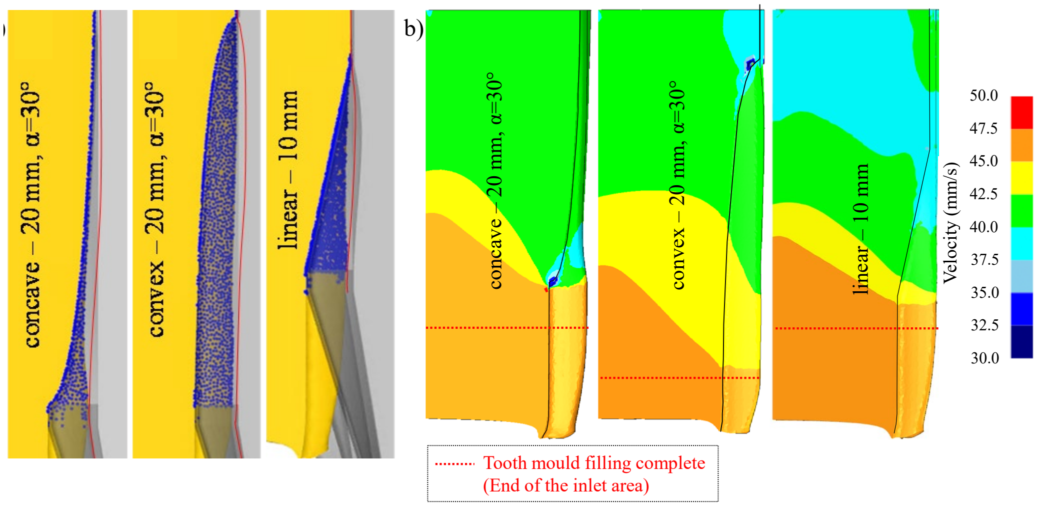


Fig. 8. GMF process at steady condition, a) contact area, b) material flow velocity.

Concave extrusion shoulder design.

Due to its shape, the concave extrusion shoulder design leads to a radial displacement of the material into the tooth cavity mainly at the lower end of the extrusion shoulder. This means that the effect of the undercut is barely noticeable and that the friction surface between workpiece and die in the area of the tooth flanks becomes minimal. Therefore, the friction surface and thus also the maximum punch force appear almost independent of the forming zone length. In the upper area of the concave extrusion shoulder, the low angle of the extrusion shoulder leads to a very slight deformation of the teeth. The material flows in an axial as well as radially inward direction, which causes the instantaneous workpiece in the toothing area to become temporarily smaller than the original blank diameter (blank diameter equals tip diameter). The temporary reduction of the tooth height results from the different flow resistances in the process along process direction, which results into different flow velocities on the inner and outer diameter of the workpiece. In Fig. 8b, the maximum difference in flow velocities in process direction is observed around 10 mm/s. The low friction surface between the workpiece and the die in the area of the tooth flank favours the reduction of the tooth height, as the accumulated material can flow unhindered into the centre of the blank. As the forming zone length increases and the angle α increases, the reduction of the tooth height dominates, resulting into underfilling of the toothing.

Convex extrusion shoulder design.

In the convex shoulder design, depicted in Fig. 8, the main part of the tooth forming occurs in the upper area of the extrusion shoulder. As a result, the material in the upper area of the extrusion shoulder increases marginally in diameter compared to the original blank diameter. This means, the cavity is filled with material at the start of the process and the friction surface between the die and the workpiece increases rapidly. Due to the gradual tapering of the cavity in process direction, the die cavity was completely filled towards the end of the stroke. However, at mid-height of the extrusion shoulder, it can be observed that the material flows in a radially inward direction, causing the tooth height to temporarily decrease. Reason for this is also the differing flow velocity of the workpiece material in process direction. Enlarged friction surface between workpiece and die in the area of the tooth flank hinders the reduction of the tooth height, since the accumulated material is held in the die by the friction forces and the die tapering. Therefore, the tooth height reduction is less prominent in this process. When using the convex extrusion shoulder designs at 30° and 50°, a complete die filling was not achieved as the forming zone length increases. The more the forming zone length increases, the more material flows in the radially inward direction and thus the tooth height decrease seems to dominate. The reduced volume of workpiece material in the cavity cannot be compensated by tapering the tooth cavity to a complete die filling. In case of the process with a tangent angle of 70°, a complete die filling could not be achieved at small forming zone lengths. The reason for this is the big tangent angle in the upper area of the die shoulder. This steep design in the upper part of the forming zone results into a low radial displacement of workpiece material. Less material is thus displaced into the cavity at the start of the process. Moreover, the shortened forming zone length prevents any further displacement of material volume into the cavity. The material in this process variant is not formed sufficiently towards the cavity into the toothing area, which is why the axial material flow dominates here. As a result, despite the taper of the cavity in process direction, the die is not completely filled. An extension of the forming zone length results into complete die filling, as more material can be formed into the cavity through a longer path of the extrusion shoulder.

Summary

In this paper, the newly invented GMF process was numerically investigated under variation of the extrusion shoulder design. The extrusion shoulder design was modelled internally by linear as well as quadratic polynomial functional splines. Using this model, a three-dimensional simulation was performed to form the required gearing shape, whereby the geometric parameters of the extrusion shoulder were varied. In this way, the model of die was modified in the simulation between the two extrusion shoulder types (linear, quadratic), the forming zone length and the tangent angle α at the vertex of the quadratic polynomial function. As a result, the influence of these parameters on the maximum punch force, the maximum contact pressure acting internally in the die and the die filling of the gearing could be determined. In summary, it can be stated that a significant reduction of the maximum punch force can be achieved when using the new GMF process compared to the conventional Samanta process. In the case of a linear extrusion shoulder design, a steady decrease in the maximum punch force was observed when enlarging the forming zone length from 2 mm up to 12 mm. Overall, a reduction of the maximum punch force by approx. 38% was achieved compared to the conventional Samanta process. For the concave extrusion shoulder design, it was found that the maximum punch force remains almost independent of the forming zone length. A reduction in the maximum punch force equal to that of the linear extrusion shoulder design was also achieved here. Maximum contact pressure was calculated at the same level as with the conventional Samanta process. With the convex variant, only a slight reduction in force and contact pressure was observed. Authors as next will focus on progressive optimisation of the die´s active surface, since a reduction of the maximum punch force by somewhat 50% was detected compared to a corresponding Samanta process design. The numerical results have also shown that the different extrusion shoulder geometries lead to different flow velocities of the material in the cavity and near the centre of the blank. This effect strongly influences the underfilling of the tooth at the lower end of the gear. Although the linear and concave shoulder designs show extremely low process forces, the inlet area was found extended in these variants compared to the concave shoulder design. This in fact results into a higher loadable gear height when applying the convex shoulder design, so, more effort will be put on further numerical investigations to assess the tooth underfilling in the inlet area. Therefore, future developments will consider the loadable gear height in order to analyse the grade of material utilisation in these processes.

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