Forming of components with microgearings from coil material - Numerical modeling of the process chain and experimental validation

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Abstract

Compared to alternative production methods, cold forming offers technological, economic and ecological potential for the mass production of microgears. According to the current state of the art, cold forming of modules $m < 0.2$ is no possible due to size effects, high tool stresses and handling problems. The investigations of this contribution present a novel process chain for multi-step forming of microgears with a module of $m = 0.1$. For this purpose, a numerical model of the first two steps of the process chain is set up and confirmed on the basis of experimental forming tests. The results have proven the feasibility of the process chain by a complete forming of the gear teeth.

Keywords: Micro forming, microgear, sheet-bulk metal forming, multi-step micro forming

1. Introduction

One trend in today's industry is the miniaturization of technical systems with electronic and mechanical functions. This includes miniaturized drive systems, which are used in large numbers, for example in the automotive industry, in mechanical engineering, in aerospace technology, in medical technology, in the watch industry as well as in robotics [1]. Due to the high production volumes, the use of productive manufacturing processes is of great economic importance. At present, the production of microgears is done industrially by primary shaping by metal powder injection molding, cutting by means of fine cutting, spark erosion, laser ablation, honing, milling, broaching, grinding, shaping and additive processes [2]. However, these technologies have process-specific limitations. Micro metal injection molding (µ-MIM) requires a complex process chain and the achievable part density and surface quality are primarily limited by the particle size of the used powder [3]. Also long process times reduce the application in mass production [4]. With cutting the obtainable gear width is restricted and for hobbing processes producible geometries are limited and no internal gears or conical gears can be produced [1].

Compared to established processes, cold forming of microgears offers great potential. In macroscopic size mass production of geared metallic parts, cold forming has technological, economic and ecological advantages. High volume output with short cycle times, improved component properties due to strain hardening in the tooth root and flank area, a ductile core and an uninterrupted fiber flow and a high surface quality are achieved [5]. However, the application in micro scale is limited due to the high stresses on the small gear cavities [2] and occurring tool wear [1], as well as size effects. The lower module limit for the use of cold forming for the production of microgears is at a module of $m < 0.2$ according to the review of Jain and Chaubey [1].

During forward extrusion of gears, critical tensile stresses occur in the area of the die teeth [6]. The high stress on the small tips of the gearing leads to wear, resulting in a decrease in the quality of the components as well as potential tool failure [2]. To achieve a reduction of the producible module by cold forming, it is necessary to reduce the tensile stresses. Furthermore, there are challenges with regard to incomplete die filling and inhomogeneous shaping when forming microgeometries by polycrystalline metals due to the forming mechanisms of grain boundary sliding and grain rotation [7]. According to Saotome and Xu, the die filling is improved by decreasing the grain size [7]. A homogeneous forming can be achieved by using nanocrystalline microstructures [8].

A promising approach to meet these challenges is offered by micro bulk forming of geared components from coil in a multi-step process. Within this contribution, a novel process chain is presented. In the first step, a pin is extruded from the sheet metal plane in order to provide material for the second process step. This kind of pin extrusion was first introduced by Hirota [9]. In the second stage of the investigated process chain, upsetting and lateral extrusion are used to form the gear teeth. Previous investigations on the production of filigree functional elements by sheet-bulk metal forming show that significantly lower die stresses occur during lateral extrusion than during full forward extrusion [10]. In addition, through the approach of multi-step forming, a high degree of grain deformation is achieved, which results in grain refinement and may improve die filling. After microgear forming, the gear can be separated from the sheet by means of shear cutting. In addition to reduced tool stresses, the process chain offers the potential to achieve simplified handling of microcomponents and high productivity through the use of coil material.

2. Objective and methodology

The objective of this investigation is the development and validation of a numerical process model of the described process chain, as well as the proof of the process feasibility. Possible size effects are assessed with the help of geometric measurements and metallographic examinations. Subsequently, the validated FE model is used to further analyse the material flow and process force progression. This provides the basis for additional research. A high model accuracy is achieved by characterizing the anisotropic flow behaviour and determining the tribological conditions by laboratory tests.

3. Process layout

The investigated microgear has an involute profile with a normal module of m = 0.1 and a root radius of 0.06 mm. The tip diameter is 1.8 mm and the root diameter is 1.55 mm. The gear width is 2 mm. Fig. 1 shows the applied novel process chain.

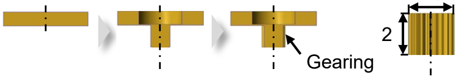


Fig. 1. Multi-step forming process for microgear production.

In the first process step, full forward extrusion is used to form a pin from the sheet metal plane and to provide material for the manufacturing of the gearing in the second process step. The diameter of the pin is 1.5 mm. In the second process step, the gearing is formed from the pin by lateral extrusion. The extrusion dies are made of submicron grain cemented carbide (CFS18Z) and reinforced according to VDI 3176 with a pre-stress ring with 5 ‰ excess. During both processes, a blank holder with a pressure of 15.6 MPa, which represents 99% of the materials initial yield stress, is used to ensure no plastic deformation by the blank holder.

Due to its high purity and the single-phase grain structure, the copper material Cu-OFE is excellently suited to investigate size effects. A uniformly coarse grain structure without influence of the rolling process of the sheet is achieved by soft annealing the material at 650°C for 1 h under inert gas atmosphere. In order to simplify the experimental setup and the conduction of the forming tests, the investigations are carried out on separate circular blanks instead of strip material. The geometry of the sheet material as well as the forward extrusion punch were chosen based on preliminary numerical studies. The diameter of the blank is 20 mm with a thickness of 2 mm. They were made by water jet cutting to avoid heat influence. A punch with a diameter of 4 mm is used during full forward extrusion. *Dionol ST V 1725-2* impact extrusion oil from *MKU-Chemie GmbH* is used as a lubricant in a quantity of more than 10 g/m^2.

4. Numerical process model and experimental validation

Fig. 2a shows the grain structure and flow curve of the gear material. The grain structure was made visible by metallographic preparation and etching with ammonium peroxodisulfate. The heat-treated material is coarse-grained with an average grain diameter of 125 µm according to ISO 643.

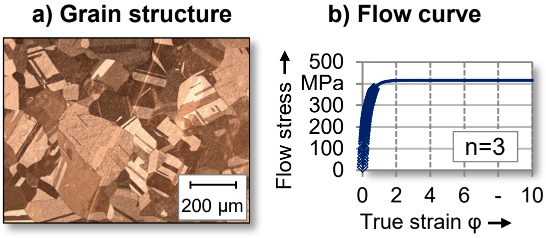

a) Grain structure **b) Flow curve**

Fig. 2. a) Grain structure and b) flow curve determined by tensile tests 0 ° to the rolling direction and extrapolated with the hockett-sherby approach.

The flow curve (Fig. 2b) has been determined by uniaxial tensile tests in rolling direction (0°) up to a true strain of φ=0.25. The experimentally determined flow curve was extrapolated to map higher strains as they occur during gear extrusion with the Hockett–Sherby approach [11]. The anisotropic flow behavior has been determined by uniaxial tensile tests in 0°, 45° and 90° direction according to ISO 6892-1 and hydraulic bulge tests (ISO 16808). Material anisotropy was considered in the simulation using the yield function Barlat91 [12]. Due to comparable contact pressures, the tribological conditions have been evaluated by single sheet metal compression tests within a prior investigation [13]. The corresponding friction factor m=0.045 ± 0.012 was determined by numerical identification. The FE software *simufact.forming 16.0* is used within the investigation. In order to reduce calculation effort, a 90° segmented model has been applied. This enables the consideration of planar anisotropy. The workpiece is meshed with hexahedrons to accurately map the three-dimensional material flow. During first process step the center area of the workpiece as well as the area with reduced sheet thickness is meshed with a minimum edge length of 40 µm. In the outer area of the sheet blank, the mesh is coarsened up to 100 µm edge length in order to reduce the element number. Likewise, in the second process step, the geared area is more finely meshed than the remaining area with an element size of 40 µm. The workpiece is remeshed if the elongation exceeds 40%. The calculation of both process steps is divided into 1000 increments and solved with the multifrontal method.

After the process chain had been modeled and designed numerically, it was implemented in forming tests. Based on these, the numerical model is validated and possible size effects that cannot be represented in the simulation are identified. The forming tests were carried out on an universal testing machine *walter+bai FS-300*. A total number of 30 gears has been produced. The measurement of the component geometry and surface topography was done with the 3D measurement system *Alicona InfiniteFocus XL 200 G5* by focus variation. Fig. 3 shows the numerical and experimental components after the both process steps.

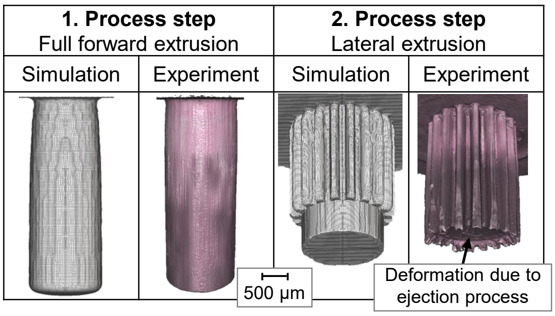


Fig. 3. Numerically and experimentally determined geometries.

In addition to the lateral extrusion, an ejection process is carried out in the experiment, which was not taken into account in the simulation. Due to the high force required to eject the gearing (max. 2 ±0.3 kN), deformation of the cylindrical shoulder occurs. While the component is pushed upwards through the geared die, the cylindrical shoulder is therefore also formed into the gear geometry.

The numerically determined process properties are validated based on the force curve progression and the component geometry. Fig. 4 shows the process force curves from simulation and experiment.

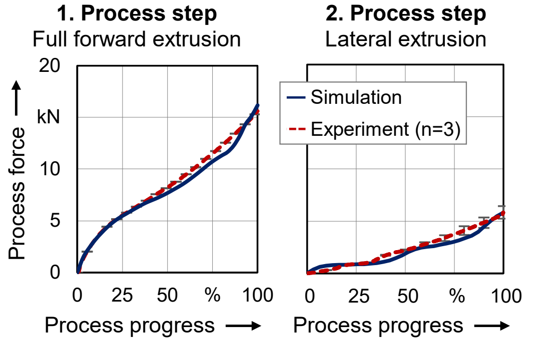


Fig. 4. Comparison of force curve progression in simulation and experiment.

The process force curves show good agreement. The maximum process forces required for forward extrusion (16.2 kN simulation and 15.6 ±0.7 kN experiment), as well as for lateral extrusion (7.0 kN simulation and 6.6 ±0.5 kN experiment) deviate less than 6%. A comparison of the geometric properties is made in Fig. 5. Also regarding the die filling the simulation shows a good agreement.

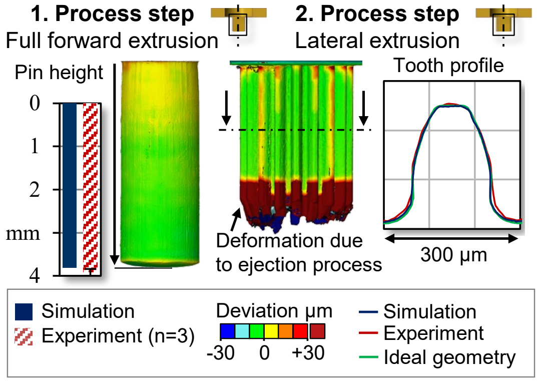


Fig. 5. Comparison of component geometry in simulation and experiment.

The pin heights differ slightly, with 3.8 mm in the simulation and 4.2±0.1 mm in the experiment. With regard to the gearing formed in the second process step, there is good agreement between experiment and simulation for the majority of the gear width. In the lower area of the workpiece, however, there is a deformation of the cylindrical shoulder due to the ejector process, which was not taken into account in the simulation. The evaluation of the tooth profiles in the face section shows very high form filling of the experimentally produced gears with minimal deviation from the ideal geometry. It is noticeable that the experimentally determined tooth geometry shows a slight material excess in the tooth root area. Reasons for that could be manufacturing-related deviations as well as the elastic deflection of the die, which were not considered in the simulation. The surface roughness depth of the pin is R_Z 1.7 ±0.2 µm, the roughness depth of the tooth flanks R_Z 1.8 ±0.3 µm. Thus, a ready-to-use surface quality is achieved.

Fig. 6 shows the resulting grain structure after both process steps. As seen in Fig. 5, no problems due to size effects [7] in the shaping of the micro teeth (m = 0.1) can be detected, despite the large grains in the initial grain structure. This is attributed to the grain refinement within the multi-step process route.

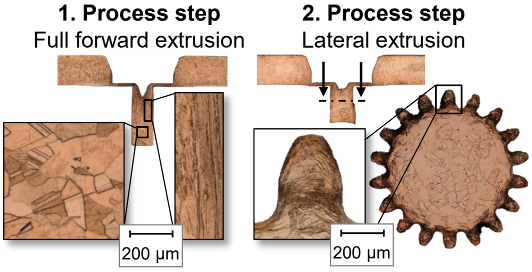


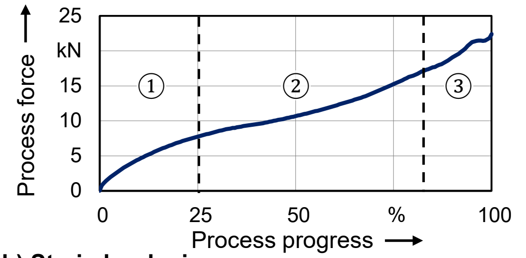
Fig. 6. Resulting grain structure.

After the first process step, the grains are elongated and compressed in the edge area of the pin in which the toothing is later formed. During lateral extrusion, the grain structure is further refined and the elongated grains are aligned along the tooth profile. These grains are small enough to fill the micro gearing (m = 0.1) completely. Due to the high agreement of the experiment regarding process force and die filling with the FE model, significant influences of size effects in the process chain can be excluded.

5. Analysis of the material flow

In the following, the validated FE model will be used for a detailed analysis of the material flow, in order to enhance the process understanding. Fig. 7 shows the progression of the process force and material flow during full forward extrusion. Three distinct process phases can be identified in the force progression (Fig. 7a), which have already been described by Ghassemali et al. [14]. At the beginning of the process (1), elastic then plastic deformation occurs when the punch moves downwards and contacts the sheet metal (1). After that, the sheet is further compressed and the pin is shaped while forming force rises as a result of increased wall friction and material hardening (2). Towards the end of the process (3), as the thickness of the remaining sheet decreases, the process force increases up to a maximum of 16.2 kN. The highest degree of deformation (φ=6.0) arise at the lateral surface of the pin (Fig. 7b) where the gearing will subsequently be formed and grain refinement was observed (Fig. 6).

a) Force curve progression



b) Strain hardening

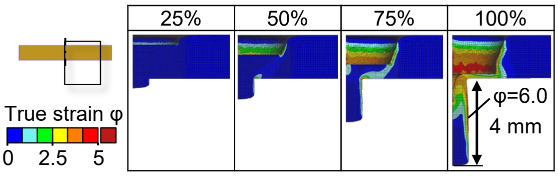


Fig. 7. a) Force curve progression and b) strain hardening during full forwards extrusion.

After the first process step, the extruded pin is positioned in the geared die for lateral extrusion.

Based on the process force curve and the material flow, different phases can be identified (Fig. 8a).

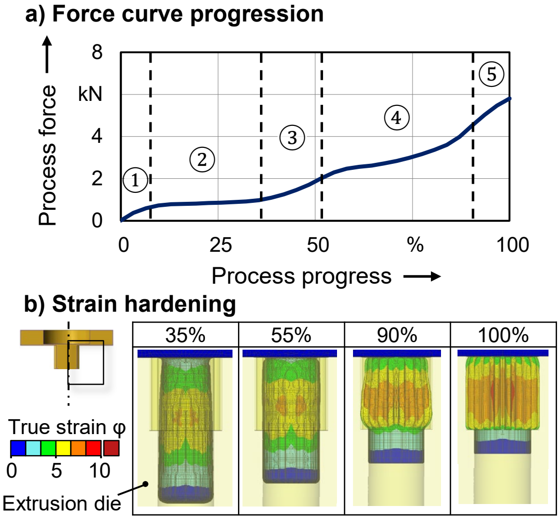


Fig. 8. a) Force curve progression and b) strain hardening during lateral extrusion.

Initially, there is upsetting of the pin (1), until the pin makes first contact with the cylindrical area of the die (at about 8%). The further upsetting process takes place due to the decreasing pin height with declining wall friction and increasing upsetting force, resulting in a constant force requirement (2). At about 35% process progress, the diameter of the pin reaches the root diameter of the toothing, leading to an elevated forming force due to the increased deformation resistance as a result of wall friction rising again (3). After the pin is in complete contact with the root diameter of the die, the forming of the gearing begins. The force requirement rises as the gearing is filled and wall friction increases (4). Towards the end (5), the force ascends to a maximum of 7.0 kN due to maximum wall friction and the influence of the increasing work hardening of the material. The force level in lateral extrusion is significantly lower than that of pin extrusion. Since the volume of the pin is greater than the volume of the gear, a cylindrical shoulder remains in the lower area (Fig. 8b).

6. Summary and outlook

Within this contribution, a numerical process model of a novel multi-step forming process for the manufacturing of microgears from sheet metal has been built. The feasibility of the process chain was proven and the prediction quality of the FE model was validated, followed by a detailed analysis of the material flow. The gears produced with a module of m = 0.1 represent an enhancement of the state of the art for the cold forming of microgears. No size effects regarding die filling have been determined and complete tooth filling was achieved.

There is need for additional research with regard to the further development of the process chain. The forming tests have shown that the ejection process after lateral extrusion leads to additional deformation of the cylindrical area and must be taken into account. Against the background, that the forming of the microgears from the coarse-grained copper material was successful, other relevant gear materials such as brass or steel should be investigated.

Particular potential is seen in the industrial implementation of the process chain in a multi-step serial production starting from coil material. However, this requires the realization of the third process step by separating the gear from the remaining sheet. Since the residual sheet thickness is only 0.2 mm, shear cutting is feasible according to the state of the art.

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