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Investigation of the influence of material and sheet thickness on a three-stage process chain for cold forming of micro gears with a module of 0.1 mm

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Abstract. In many industries, there is a trend towards miniaturization of technical components, such as drive systems, which enable the solution of high-precision positioning tasks because of their low volume and high dynamics. Geared micro parts are currently mainly produced by cutting and LIGA processes, but in mass production cold forming offers ecological and economic benefits. However, the cold forming of micro gears is restricted to a lower module limit of m = 0.2 mm due to high tool stresses, size effects and handling difficulties. To solve these challenges, in this contribution a three-stage forming process chain for the manufacturing micro gears (m = 0.1 mm) is investigated. In the first stage, a pin as wheel blank is extruded from sheet metal, which is geared subsequently by lateral extrusion. Finally, the micro gear is separated from sheet by shear cutting. The aim of this study is to demonstrate the applicability of the process chain for the materials Cu-OFE and CuZn30. In addition, the influence of the sheet thickness, which has a major impact on the forming process and the material efficiency, is analyzed. The geometrical and mechanical component properties as well as the machine data are evaluated to assess the variables.

1. Introduction

Technological progress and the development of new products are significantly influenced by the increasing trend towards miniaturization of technical systems. This trend is characterized by a reduction of system dimensions and an increase in functionality due to the integration of micromechanical and microelectronic components. Consequently, in manufacturing, a lower use of resources is required. Application benefits also arise from high system dynamics because of lower mass inertia and from high precision. These potentials are offered, for example, by miniaturized drive systems with geared micro components, which are used in medical technology, watch industry, mechanical engineering and aerospace technology [1].

Metallic micro gears are currently manufactured industrially by lithographic manufacturing technology (LIGA), by cutting processes such as milling, grinding, electrical discharge machining or fine blanking as well as by primary forming via metal powder injection molding (µ-MIM) [2]. In view of the increasing demand for geared, metallic micro components, resource-efficient and productive manufacturing processes are gaining importance. Forming technology offers technological, economic and ecological advantages such as high output rates, high material efficiency and improved component properties [3]. The industrial application for cold bulk forming of micro gears with modules m < 0.2 mm is currently not possible due to handling difficulties, high tooling stress and size effects. However, in several research projects, it has already been achieved to manufacture gears below this module limit through various approaches [1]. Debin et al. [4] fabricated double gears with a module of 0.175 mm from aluminum using a two-step hybrid process. This process combines enclosed forging with two kinds of piercing methods. Chen et al. [5] investigated a two-stage hybrid forging process from upsetting and clamping type gear forging to produce micro stepped gears with modules 0.12 mm and 0.15 mm from pure copper. For the bigger micro gear, however, it was not possible to achieve complete die filling. These investigated micro forming processes were still not feasible on an industrial scale to enable the economic production of high production volumes and the challenge of efficient handling of micro components still remains.

In this context, a novel process chain presented in [6] offers potential to meet the challenges of manufacturing micro gears by cold forming. This process chain, which is a three-stage micro bulk forming process from sheet metal, is designed to enable the forming of micro gears with a module of 0.1 mm. In the first process stage, a pin is extruded from the sheet metal, which serves as a wheel blank. In the second stage, the toothing is formed from the pin by lateral extrusion. Finally, the micro gear is separated from the sheet metal by shear cutting. The process chain uses bulk micro forming from sheet metal to solve the handling problem. In this process, the micro components are formed directly from sheet metal, which is used as a workpiece carrier for transporting and handling the micro parts [7]. To reduce the load on the filigree internal toothed die structure, the tooth forming is achieved by lateral extrusion, which causes a lower die stress than forward extrusion [8]. Due to the radial material flow during lateral extrusion, no critical tensile stresses are induced on the filigree toothing with few carbides as occur in forward extrusion [8]. Only tangential tensile stresses result, which can be compensated by radial prestressing [8]. The basic feasibility of the first two stages of the process chain was demonstrated in preliminary work [6] for the coarse-grained copper Cu-OFE. In order to enable industrial application, it is necessary to transfer the knowledge to other application-relevant materials (brass) as well as to understand the component and process-related influencing variables.

2. Objectives and methodology

The aim of this research is the experimental investigation of a novel, three-stage process chain of a multi-stage bulk micro forming process from sheet metal to produce micro gears with the module $m = 0.1$ mm. The special focus is on evaluating the influence of the material on the process chain. The high-purity copper Cu-OFE and the two-phase brass CuZn30 are investigated to verify the applicability of the process chain for higher-strength materials. For the analysis of the influencing variable, the achievable component and process properties of each process stage are evaluated. Subsequently, the process results of both materials are compared to ensure the transferability of the results. Additionally, a variation of the sheet thickness is analyzed in the first forming stage to evaluate the influence of this parameter on the material efficiency and the quality of the wheel blank. The applied methodology is shown in Figure 1.

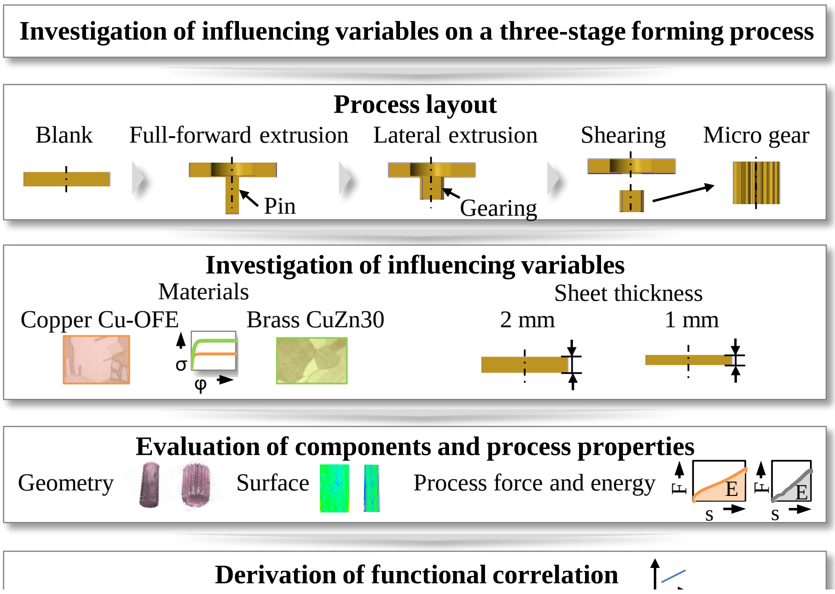


Figure1. Methodology.

3. Materials and experimental setup

In this chapter, the materials used and the process setup are described. In addition, the functioning of the tool system and the geometry of the active components are explained.

3.1. Materials

For the experimental tests, the materials Cu-OFE and CuZn30 were used. Cu-OFE is a high-purity, oxygen-free copper that is well suited as a model material for basic research due to its single-phase microstructure and its face-centered cubic crystal structure. In industrial applications, the copper is often used for electronic components. The brass CuZn30, is a copper alloy with a zinc content of 30 %. This material is characterized by a two-phase microstructure with face-centered cubic α-mixed crystals and a small proportion of body-centered cubic β-mixed crystals. Compared to copper Cu-OFE, CuZn30 shows higher mechanical strength values due to the alloying element zinc. The alloy is mainly used in mechanical and electrical engineering. In gear manufacturing, brass alloys are the most used non-ferrous metals [9]. As delivered, the materials were in cold-rolled condition, with Cu-OFE showing a prehardening of 86 %. In the case of CuZn30, the prehardening was 66 %. Both materials are analyzed in a heat-treated condition. The heat treatment of the cold-rolled materials is carried out in a tube furnace with inert gas atmosphere (argon) at a temperature of 650 °C for 1 h and a final slow cooling in the furnace. Through the heat treatment, a homogeneous microstructure with isotropic material properties is achieved and the formability of the materials is improved. The grain structure after heat treatment made visible by metallographic preparation and etching with ferric (III)-chloride is shown in Figure 2. Both materials are analyzed in sheet thicknesses of 1 mm and 2 mm, with the different sheet thicknesses originating from the same melt. The average grain size of Cu-OFE is 88.4 ± 11.4 µm for t_0 = 1 mm and 125.0 ± 17.2 µm for t_0 = 2 mm. For CuZn30, grain sizes of 106.7 ± 18.3 µm for t_0 = 1 mm and 125.0 ± 6.3 µm for t_0 = 2 mm are determined.

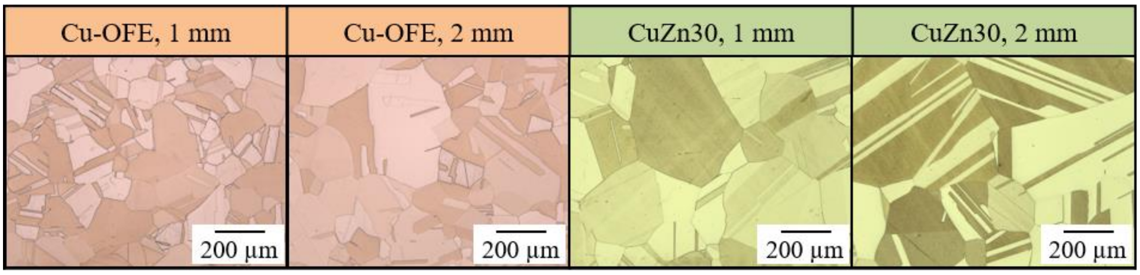
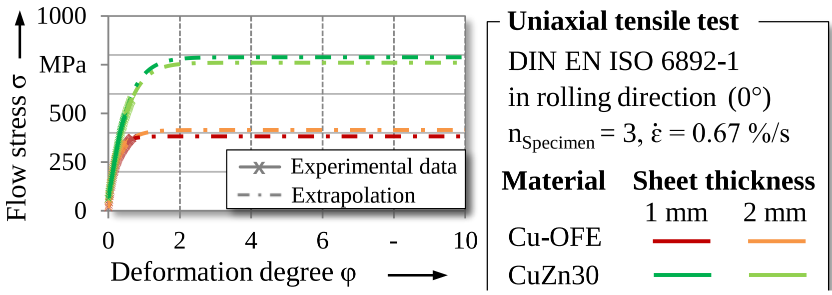


Figure 2. Grain structures of Cu-OFE and CuZn30 after heat-treatment.

The evaluated flow curves and the initial yield stresses are shown in Figure 3. The material is tested experimentally in the uniaxial tensile test according to DIN EN ISO 6892-1 up to a true strain of φ = 0.5. To map higher degrees of deformation, the experimental flow curves were extrapolated by using the Hockett-Sherby approach [10].



Material, sheet thickness	**Initial yield strength σ_0**
Cu-OFE, 1 mm	15.8 ± 0.8 MPa
Cu-OFE, 2 mm	22.8 ± 1.8 MPa
CuZn30, 1 mm	64.9 ± 0.5 MPa
CuZn30, 2 mm	62.1 ± 1.0 MPa

Figure 3. Flow curves and initial yield stresses of the different material configurations.

3.2. Experimental setup

Figure 4 shows the process layout of the three-stage process chain and the resulting gear geometry. The applied process parameters are listed in Table 1. For the experimental investigations, a multi-action tool system was used, which was installed in a universal testing machine of type FS 300 (Walter+Bai AG). The individual process stages are realized by different active components, which are sequentially installed in the tool system. The blankholder is controlled by the universal testing machine. The punches and the ejectors of the three process stages are driven by two hydraulic cylinders. The blankholder pressure is determined material-specifically by 99 % of the initial yield stress to avoid plastic deformation of the blank.

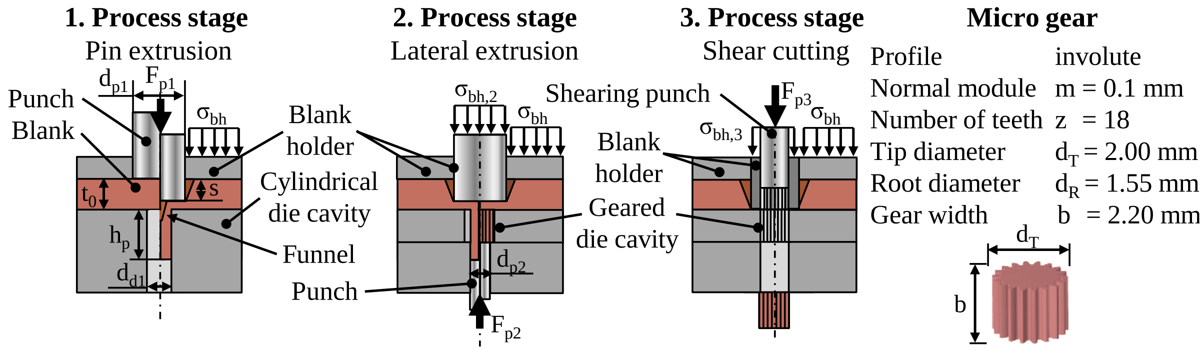


Figure 4. Setup of the three-stage process chain and characteristics of the micro gear.

Table 1. Process parameters.

	1. Process stage	2. Process stage	3. Process stage
Punch geometry	Cylindrical, $d_{p1} = 4$ mm	Cylindrical $d_{p2} = 1.55$ mm	Externally geared m = 0.1 mm, z = 18 $d_R = 1.52$ mm, $d_T = 1.97$ mm
Cavity geometry	Cylindrical $d_{d1} = 1.5$ mm	Internally geared m = 0.1 mm, z = 18 $d_R = 2.0$ mm, $d_T = 1.55$ mm	Internally geared m = 0.1 mm, z = 18, $d_R = 2.0$ mm, $d_T = 1.55$ mm
Blank holder diameter	20 mm	4 mm (residual sheet); 20 mm (blank)	4 mm (residual sheet); 20 mm (blank)
Blank holder pressure	$\sigma_{bh} = 0.99 \cdot \sigma_0$		
Punch stroke	Relative (s/t_0): 90 %	$= h_p-(b+t_0-s)$ (until complete form filling)	$= t_0-s$ (residual sheet thickness)
Forming speed	5.0 mm/min		0.5 mm/min

In the first extrusion stage, a pin is formed from the sheet metal, which serves as a wheel blank for the following forming stage. The diameter of the pin is 1.5 mm, which is slightly smaller than the root circle diameter of the gearing. The penetration depth of the punch is about 90 % of the sheet thickness of the blank. In the second process stage, the gearing is formed from the pin by lateral extrusion. The gearing is characterized by an involute profile with a normal module of 0.1 mm, 18 teeth and a tip diameter of 1.8 mm. In the final process stage, the formed micro gear is separated from sheet metal by shear cutting. For all process steps, the extrusion oil Dionol ST V 1725-2 from MKU-Chemie GmbH was used as lubricant in a quantity of more than 10 g/m². Due to the high contact pressures, the tribological conditions were determined in a previous research work by single sheet metal compression tests and numerical identification [11]. The friction factors $m_F = 0.029 \pm 0.006$ (Cu-OFE) and $m_F = 0.096 \pm 0.003$ (CuZn30) were determined [11].

For this experimental investigation, rotationally symmetrical blanks with a diameter of 20 mm were used instead of coil material. In this way, the influence of the coil geometry could be excluded for the basic research in laboratory tests. In the first process stage, blanks with sheet thicknesses of 1 mm and 2 mm were used. In the subsequent process stages, only blanks with a sheet thickness of 2 mm were analyzed. The surface roughness R_z of the Cu-OFE blanks in the initial state were 1.065 µm (1 mm) and. 0.993 µm (2 mm). For the brass blanks, surface roughnesses R_z of 1.15 µm (1 mm) and 1.16 µm (2 mm) were determined. Thus, the surface roughness of the rolling quality is similar for both materials.

4. Experimental results

In this section, the experimentally determined results of the three-stage process chain are described. The resulting component and process properties of each process stage are considered. The process properties are evaluated based on the force-displacement curves. The force and displacement values were recorded by force and displacement sensors installed in the upper and lower tool units. Sensors with a resolution of 1.5 N and 1.10 µm according to DIN EN 10002 part 4 with quality class 1 were used. In addition, the elastic tool deformation was corrected by linear compensation by comparing the recorded punch displacement with the penetration depth on the part. The process energy is calculated analytically by the integral of the process force in dependence of the displacement. Component properties include pin height, funnel volume, surface topography and die filling of the gearing. The pin height is measured tactilely with a digital absolute dial indicator from Mitutoyo Deutschland GmbH with an accuracy of ± 0.5 µm. The other component properties are measured optically with the 3D measurement system Alicona InfiniteFocus XL 200 G5 3D by focus variation. A lens with 5x magnification was used to determine geometrical properties. The surface topography of the blanks, of the pins and of the gearing are scanned by a lens with 50x magnification. The surface topography of the cut edges (third process stage) are measured using the confocal laser scanning microscope KEYENCE VK-X 200 (KEYENCE Deutschland GmbH), as this measuring device enabled more precise alignment of the cut micro gears. A lens with 50x magnification was used for measurement.

4.1. 1. Process stage: Pin extrusion

In the first process stage, the influence of the sheet thickness and of the material on pin forming is considered. Figure 5 shows the resulting process and component properties of the first process stage.

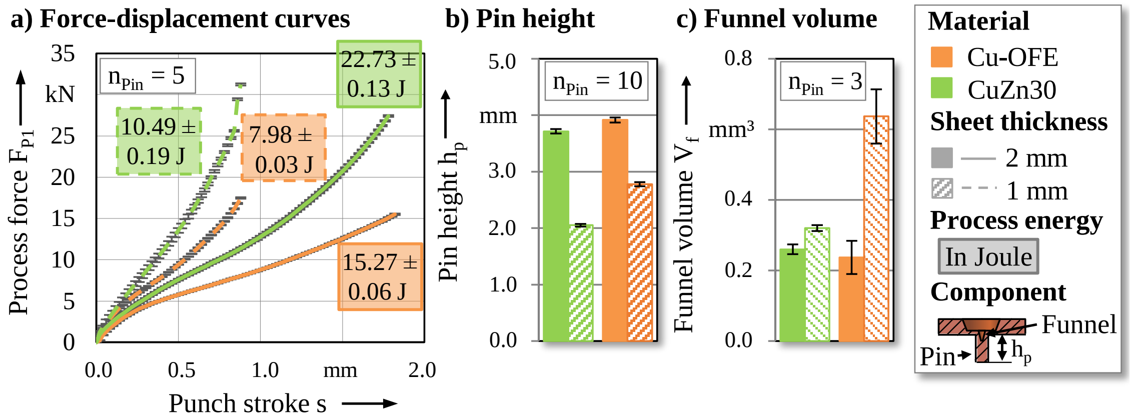


Figure 5. (a) Force-displacement curves, (b) pin height and (c) funnel volume after pin extrusion.

In order to draw conclusions for the tool stress, the force-displacement curves of the investigated configurations are considered in Figure 5 a). In general, the course of the process force has been classified by Ghassemali [12] into three process phases: The elastic deformation in the tool-workpiece system, the plastic deformation similar to the upsetting and a final increase of the process force due to the increased friction force component and the strong hardening in the residual sheet.

All four curves in Figure 5 a) resemble this described course. The highest process forces is determined during the forming of CuZn30. The maximum process forces are 31.22 ± 0.12 kN (1 mm) and 28.05 ± 0.13 kN (2 mm). For the copper material, the maximum process forces amount to 18.09 ± 0.11 kN (1 mm) and 15.58 ± 0.11 kN (2 mm). The comparison of the two materials shows a significantly higher force requirement for forming the brass and a steeper increase in force due to the higher yield stress of the material. In addition, there is a higher energy requirement of 49 % (2 mm) and 31 % (1 mm). The reduction of sheet thickness leads to an increase in the maximum process force. A force increases of 16 % is determined for Cu-OFE and of 11 % for CuZn30. The higher force requirement can be explained by the Siebel compression force formula. Accordingly, there is a higher influence of friction with a lower sheet thickness, which increases the forming force. In addition, the thickness of the residual sheet is relevant, which has the same relative value of 90 %, but a different absolute value. The absolute residual sheet thicknesses are about 0.1 mm for an initial sheet thickness of 1 mm and about 0.2 mm for 2 mm. However, there is a lower energy requirement for forming the smaller sheet thickness due to the lower absolute punch stroke of 0.882 ± 0.009 mm (Cu-OFE) respectively 0.829 ± 0.003 mm (CuZn30) for the sheet thickness of 1 mm instead of 1.770 ± 0.008 mm (Cu-OFE) respectively 1.779 ± 0.005 mm (CuZn30) for the sheet thickness of 2 mm. The forming energy is reduced by 48 % (Cu-OFE) and 54 % (CuZn30).

Figure 5 b) shows the pin heights for the materials and sheet thicknesses investigated at a relative penetration depth (s/t_0) of 90 %. It is noticeable that the highest pin height of 3.92 ± 0.04 mm is obtained for Cu-OFE with a sheet thickness of 2 mm. By reducing the sheet thickness, a lower pin height of 2.78 ± 0.04 mm is achieved. Also, for the brass, the pin height decreases by reducing the sheet thickness. Due to the higher sheet thickness and, for the same relative penetration depth (s/t_0), a higher volume of material is displaced during forming, resulting in a higher pin height being formed. It is also noticeable that slightly higher pin heights are determined for the copper when comparing the two materials.

In addition to the pin height, the funnel volume is decisive for evaluating the material efficiency of the process stage as well as the quality of the wheel blank. Funnel formation is considered an undesirable damage to the component during pin extrusion from the sheet metal and is a material deficit inside the pin. The formation of the funnel occurs during forming when the flow rate of the material into the cavity, which is composed of the radially inward and axial material flow, is higher than the punch speed [13]. This causes the material to detach from the punch and a funnel is formed. Other research has established that funnel formation can be influenced by the choice of process parameters [13]. In this paper, the influence of material and sheet thickness on funnel formation is investigated. Figure 5 c) compares the funnel volumes of the pins. It is noticeable that the reduction in sheet thickness increases the funnel volume by 169 % (Cu-OFE) and 23 % (CuZn30). Due to the lower sheet thickness, the funnel formation already occurs at a lower penetration depth. This can be justified by the stronger hardening within the residual sheet according to Siebel's compression force formula. Due to the increased forming resistance with reduced sheet thickness, the frictional force component in the outer sheet increases, which favors the radial flow into the cavity and a bigger funnel is formed. In the comparison of the materials, a significant difference between the materials is only present for the sheet thickness of 1 mm, which suggests a higher radial flow rate of the copper. As another component property, the surface topography of the extruded pins is considered below. Figure 6 shows the surface parameters and the surface topography of the pins.

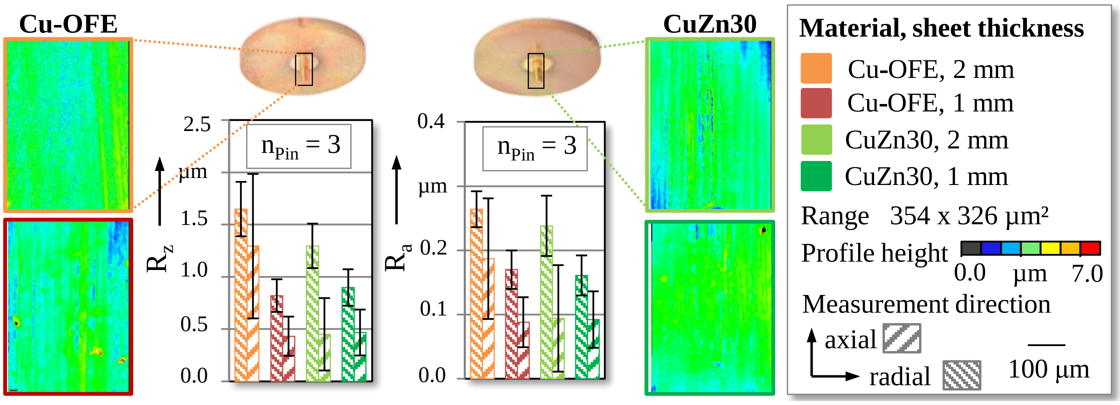


Figure 6. Surface roughness and surface topography after pin extrusion.

The axial direction of measurement corresponds to the forming direction. The radial direction is orthogonal to the forming direction. For both materials, a lower surface roughness in the axial direction can be observed due to forming-related axial grooves. These are also visible in the topography images by the blue lines in the axial direction. The comparison of the two materials shows a slightly lower surface roughness for CuZn30, which is attributed to the higher strength of the material. The reduction in sheet thickness also results in lower surface roughness due to the higher process force. In table 2, the influence of material and sheet thickness on the first process stage are evaluated.

Table 2. Evaluation of influencing parameters for the pin extrusion.

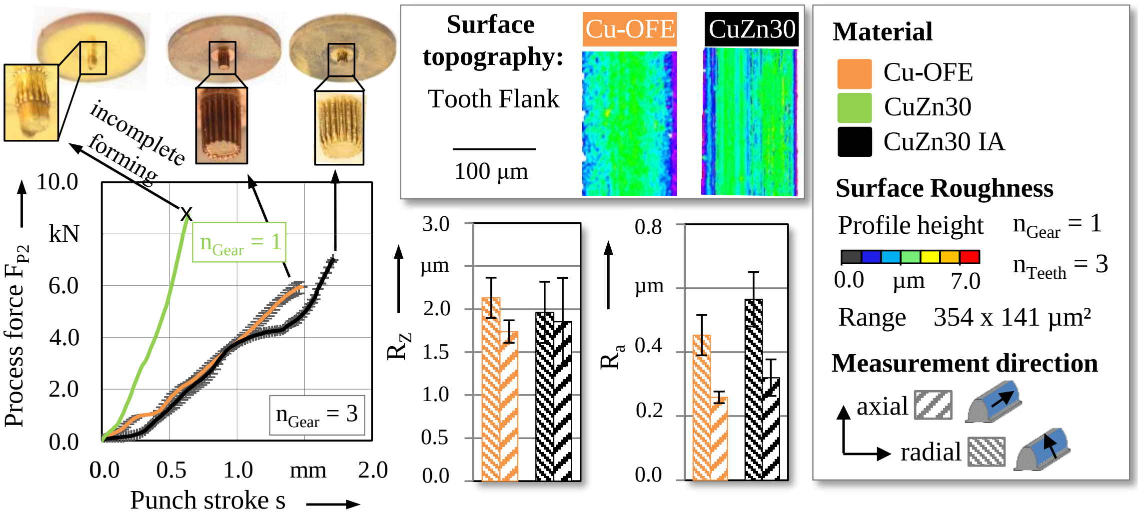
Resulting properties and influencing parameters		Component: Material (Yield stress σ_0↑)	Component: Sheet thickness s ↑
Component	Pin height	o (-)	↑ (+)
	Funnel volume	↓ (+)	↓ (+)
	Surface roughness	↓ (+)	↑ (-)
Process	Process force	↑ (-)	↓ (+)

Effect	Evaluation
Decrease ↓	negative (-)
no effect -	neutral (o)
Increase ↑	positive (+)

In the following process stages, the components with a sheet thickness of 2 mm are formed due to the higher pin volume and the higher quality of the extruded pins.

4.2. 2. Process stage: Lateral extrusion

The resulting process properties of the second process stage, as well as the surface topography of the gearing, are shown in Figure 7. A maximum process force of 5.95 ± 0.22 kN is required for forming gearing with the copper pin, extruded in the first process stage. Due to the pre-hardening of the material, a prediction of the process force curve is difficult. The force-displacement curve of the brass shows a strong hardening of the material during forming with an approximately linear increase of the process force. However, the forming of the brass was stopped at a maximum force of 8.92 kN due to the achievement of a critical failure contact pressure of the used punch of 4700 MPa. Nevertheless, in order to demonstrate the manufacturability of CuZn30 micro gears using standard carbides as the tool material, an intermediate annealing of the brass specimens was necessary due to high tool stress. The heat treatment was performed at a temperature of 650 °C and a holding time of 1 h in a tube furnace.



a) Force-displacement curves **b) Surface Roughness**

Figure 7. (a) Force-displacement curves and (b) Surface roughness after lateral extrusion.

The black curve shows the forming of the intermediate annealed brass. A maximum forming force of 6.32 ± 0.75 kN is required for the completely filling of the gearing. Due to the homogenous material condition, there was an axial material flow in the direction of the punch at the beginning of forming, resulting in less material flowing into the geared cavity area and thus a larger punch stroke was required for the complete forming of the gearing. Apart from that, the force curve corresponds to the expected phases of the forming process. At the beginning, elastic deformation of the material occurs. This is followed by plastic deformation of the material with upsetting of the pin. In the further course, the filling of the gearing starts. At the end of the process, there is an increase in the process force due to the higher friction because of the increasing contact between tool and workpiece and the increasing material hardening. The comparison of pin extrusion and lateral extrusion shows a significantly lower force requirement for lateral extrusion, which is advantageous for the stress of the internally toothed die. The die filling of the micro gears is evaluated in Figure 8.

Both materials show high form filling over almost the entire tooth width. The average gear width of the CU-OFE micro gears is 2.32 ± 0.06 mm with a maximum burr height of 0.21 ± 0.01 mm. The CuZn30 micro gears have an average gear width of 2.01 ± 0.06 mm with a maximum burr height of 0.08 ± 0.04 mm. The differences between the two materials can be explained by an undesired axial material flow of the annealed brass at the beginning of forming, which displaces a smaller volume of material into the geared cavity, resulting in a smaller gear width and burr height. The material deficit on the punch side in the toothed area results in usable toothing areas with complete die filling of 95 % for CU-OFE and 87 % for CuZn30. The evaluation of the tooth profile in the face section (Figure 8) shows very good agreement with the ideal tooth profile for both materials. In the case of brass, however, there is a slight material excess in the tooth root area, which can be addressed to the elastic deflection of the die.

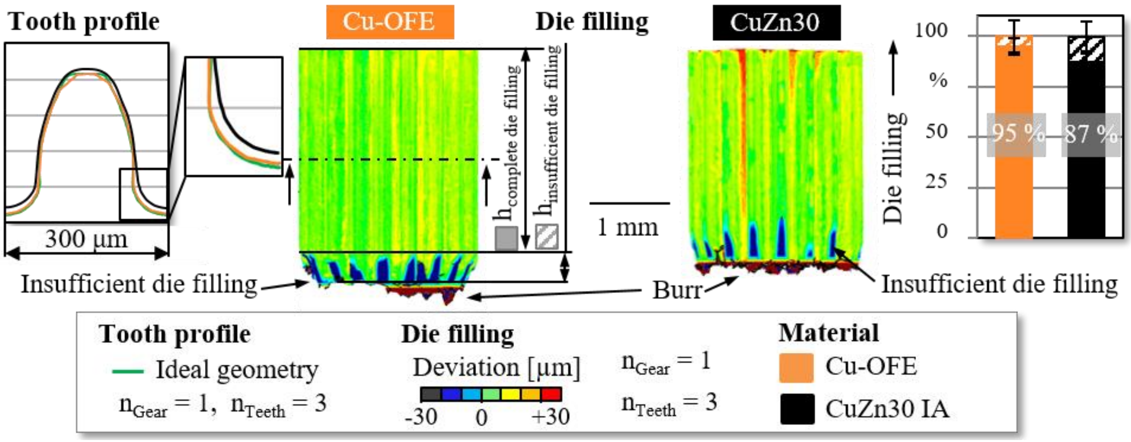


Figure 8. Die filling and tooth profile after lateral extrusion.

Another evaluation parameter is the surface quality of the tooth flanks, which are important for precision and operating behavior with regard to the application of micro gears. The surface roughness of the tooth flanks of the formed micro gears is presented in Figure 7 b). The radial direction of measurement corresponds to the direction of material flow during the forming of the gearing, the axial direction of measurement is orthogonal to this and corresponds to the direction of the ejection process. Despite the radial flow direction of the material during forming, the surface roughness in the axial direction is lower than in the radial direction for both materials. This difference is due to the ejection process in the axial direction towards the end of the process, which results in the formation of axial grooves on the tooth flanks, as shown by the blue lines in the topography images. Surface roughness R_Z of 1.74 ± 0.14 µm (Cu-OFE) and of 1.85 ± 0.51 µm (CuZn30) are measured in the axial direction. In the radial direction, the surface roughness R_Z is slightly higher at 2.13 ± 0.23 µm (Cu-OFE) and 1.96 ± 0.36 µm (CuZn30).

4.3. 3. Process stage: Shear cutting

The results of the third process stage, shear cutting, are shown in Figure 9. The force curves of the shear cutting of the micro gears (Figure 9 a) are compared with the shear cutting of cold-rolled sheet with a thickness of 0.2 mm. This comparison is intended to illustrate the influence of the forming-induced hardening. A maximum process force of 645.7 ± 89.6 N is required to cut the formed Cu-OFE micro gears. Despite the intermediate annealing of the brass, there is a higher force requirement for cutting the CuZn30 micro gears with a maximum cutting force of 1353.5 ± 111.9 N. Both force curves of the micro gears end with a residual force level which is due to the high friction between the micro gears and the internally geared cutting die. Maximum forces of 323.0 ± 6.2 N (Cu-OFE) and 496.2 ± 26.0 N (CuZn30) are determined for shear cutting of the rolled sheets. The higher process force for shear cutting of the micro gears is due to the strong forming-induced hardening in the residual sheet. This can be justified by the cutting force formula in equation (1).

$$F_{cut,max} = s \cdot l_c \cdot k_c \tag{1}$$

Accordingly, the cutting thickness s, the length of the cutting line l_s and the cutting resistance k_c, which depends on the tensile strength of the material, have a significant influence on the maximum cutting force $F_{cut,max}$.

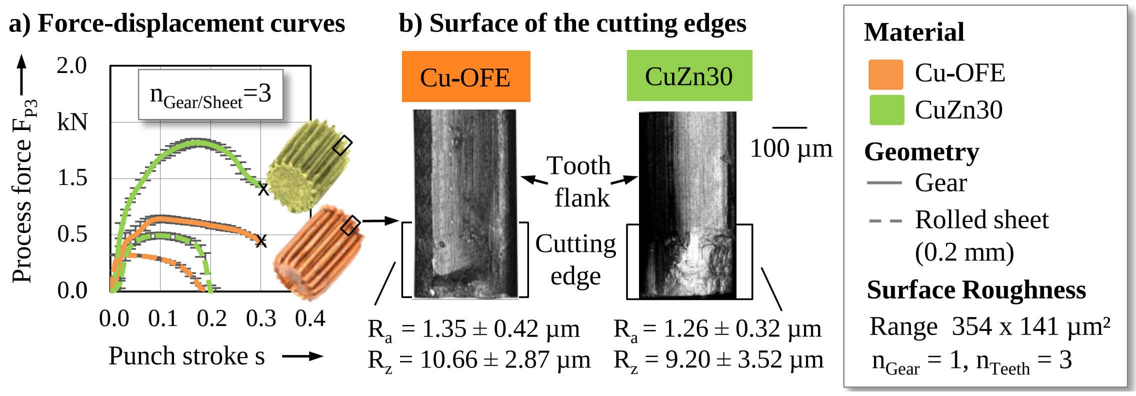


Figure 9. (a) Force-displacement-curves and (b) surface after shear cutting (third process stage).

The cutting surfaces of the micro gears and the surface parameters R_a and R_z are shown in Figure 9 b). In general, the quality of the cutting edges of the shear cutting is significantly influenced by the material properties. Accordingly, a smaller fracture zone is formed in ductile materials than in brittle materials [14]. In the surface images of the two materials, an inhomogeneous cutting zone be seen. The cutting edge of the copper shows a small brittle fracture zone and a large clean-shear area. On the other hand, the brass shows a significantly larger brittle fracture zone. This can be explained by the intermediate annealing of the brass specimens, which causes a higher material ductility. The surface parameters in the cut edge are also significantly higher than those of the tooth flanks. Due to the different zones of the cut edge, the surface roughness R_z is 10.66 ± 2.87 µm (Cu-OFE) and 9.20 ± 3.52 µm (CuZn30). However, the measured values have only an exemplary character due to the limited measuring range.

5. Conclusion and outlook

In this paper, a multi-stage process chain for the cold bulk forming of micro gears with a module of 0.1 mm from sheet metal was investigated. The transferability of the process results with the model material copper Cu-OFE to the potential application material brass CuZn30 was analyzed. Furthermore, the influence of the sheet thickness on the process chain was evaluated. The key findings of this study can be summarized as follows:

In the first process stage, advantageous process and component properties are achieved by increasing the sheet thickness from 1 mm to 2 mm. On the process side, the required process force is reduced by increasing the sheet thickness, which has a positive effect on tool stress. On the component side, pin height and material utilization are improved. At the same time, there is a reduction in the funnel volume, which represents a material deficit within the pin. In a comparison of the two materials Cu-OFE and CuZn30, similar material utilization can be obtained for the sheet thickness 2 mm. The surface of the extruded pins of both materials achieved a ready-to-use surface quality. In view of these results, the use of a higher sheet thickness is considered recommendable.

In the second process stage, lateral extrusion, the gearing on the extruded Cu-OFE pin were completely formed. The hardening behavior of CuZn30, which is caused by the first process stage, leads to critical tool stresses in the second stage. For CuZn30, a further heat treatment of the pin was required for gear forming. Thus, CuZn30 micro gears could be successfully formed. For both materials, a high form filling of the gear teeth was achieved with a slight material deficit of the tooth tip as well as burr formation in the contact area on the punch side. Additionally, the tooth flanks of the Cu-OFE and the

CuZn30 micro gears had a ready-to-use surface quality. Consequently, for the single-phase Cu-OFE and the multiphase Cuzn30 similar qualities of micro gearing could be obtained.

The third process stage (shear cutting) was successfully implemented. However, the prehardening in the residual sheet due to the forming process significantly increased the cutting force. Therefore, further reduction of the residual sheet thickness in the first process stage is required to reduce the tool stress.

In future research work, other relevant gear materials, such as aluminium and steel, should be investigated. Furthermore, it is necessary to investigate suitable measures for material flow control during pin extrusion to improve the material efficiency and the achievable quality of the wheel blank. The main potential of the process chain is seen in industrial implementation in mass production. For this purpose, the realization of the process chain in a progressive die on a high-speed press should be demonstrated.

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