Experimental study of the potential for extending the process limits in multi-stage forming of micro gears from sheet metal by a local short-term laser heat treatment

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Abstract. Cold forming of micro gears is currently not possible for modules m < 0.2 mm due to the occurrence of high tool stresses, handling problems and size effects. A multi-stage process chain of micro bulk forming from sheet metal offers the potential to solve these challenges. However, the industrial applicability is limited due to material efficiency. Against this background, the aim of this research work is an improvement of the material utilization as well as a further reduction of the tool stresses. Therefore, the influence of different heat treatment strategies as well as the materials copper Cu-OFE and brass CuZn30 are analyzed. Thus, a local laser heat treatment and a global heat treatment of the blanks are investigated. The focus of this research work is on the first process stage, pin extrusion, which is used for forming of the wheel blank. Since this process setup provides the material for the further forming stages, it has a huge influence on the material efficiency and on the forming of the gearing in the second process stage. Therefore, the component and process properties are evaluated to assess the influence of the measures. The results prove higher material efficiency at a similar tool stress by using local short-term heat treatment.

Introduction

In times of scarcity of resources and energy, increasing global warming and the awareness of the necessity for reduction emissions, the efficiency of production methods and the performance of technical systems have gained even more importance. In order to solve these global challenges, a transformation in the industry is required. The product miniaturization as well as the increasing functional integration offer the potential for the saving of raw material, space, costs and energy. Due to a lower use of resources and benefits for applications, there is a rising demand for micro components [1].

Important micro parts for motion and power transmission are micro gears as components of micro driving systems, which are used in watch industry, medical applications and in aerospace technology [2]. Microdrive systems enable high-precision and backlash-free motion transmission in a small space [3]. Metallic micro gears are industrially produced by cutting processes such as milling, hobbing or electrical discharge machining [4]. Furthermore, lithographic manufacturing technology (LIGA) as well as micro metal powder injection molding (μ-MIM) are used for production of micro gears [4]. However, these technologies are limited due to productivity, material and energy efficiency, mechanical properties and producible gear geometries [2].

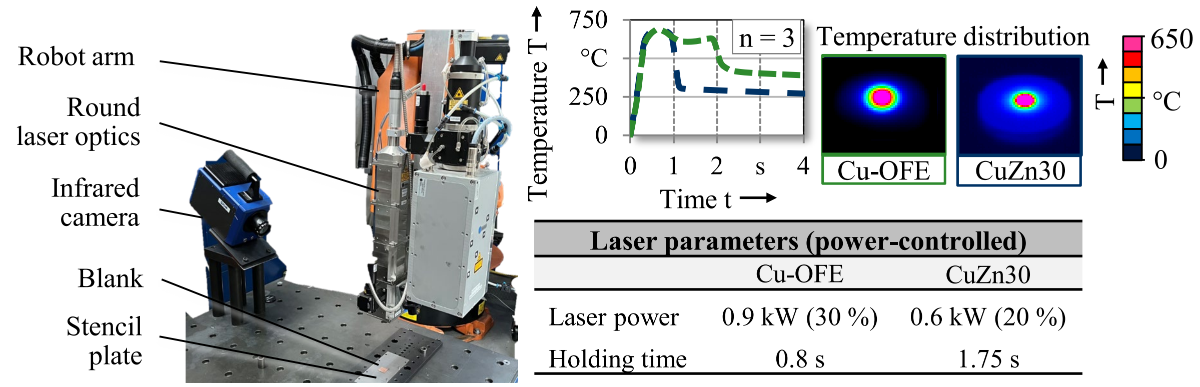
In view of the increasing demand for geared, metallic micro components, resource-efficient and productive manufacturing processes are gaining importance. In macro scale, cold forming of gears offers technological, economic and ecological benefits like high output volume, energy and material efficiency and improved component properties [5]. However, due to the occurrence of size effects [6], handling problems [7] and high tool load [4], the production of micro gears with modules m < 0.2 mm by cold forming is currently not industrially possible [2]. In Rohrmoser et al. [8], a new multi-stage process chain for forming micro gears from sheet metal was presented for the first time. In the first stage, a pin is extruded from sheet metal, which serves as a wheel blank for the further process stages. Subsequently, the pin is geared by lateral extrusion. In the last stage, the micro gear is separated from the sheet by shear cutting. By forming from sheet metal, which serves as a workpiece carrier, the handling and transport of the micro components is facilitated. Additionally, the multi-stage forming process causes grain refinement, which can reduce size effects [8]. In addition, the die stress is significantly lower compared to single full-forward extrusion [9]. Furthermore, the applicability of the process chain for the materials copper Cu-OFE and brass CuZn30 has already been demonstrated. However, a limited material utilization is one of the existing challenges, which currently limit an industrial establishment. Furthermore, the forming of cold-rolled materials is not possible due to high tool stress. An approach of sheet metal forming to extend these process limitations is the application of a local short-term heat treatment in the forming zone. The local modification of material properties is a promising method to control the material flow purposefully. In addition, the hardness gradient within the circular blank offers the potential to achieve an increase in material utilization, by limiting the lateral flow of material outwards.

Objectives and methodology

The objective of this study is to determine the influence of a local short-term heat treatment on a multi-stage bulk micro forming process from sheet metal for manufacturing micro gears with a module m = 0.1 mm. For this purpose, the type of heat treatment is varied by a global heat treatment of the semi-finished products as well as by a local laser short-term heat treatment in the forming zone. Furthermore, the influence of material using the single-phase copper Cu-OFE and the two-phase brass CuZn30 is evaluated. The focus is on the first process stage, the pin extrusion, which determines the material efficiency of the process chain and the quality of the wheel blank. For this purpose, the resulting component and process properties are analyzed. The evaluated component properties are the pin height and funnel depth, as well as the micro hardness distribution and grain structure. For the analysis of the process properties, the force-displacement curves are investigated. Additionally, the process results of both materials are compared to ensure their transferability.

Materials and experimental setup

Setup for local short-term heat treatment. For local modification of material properties, a short-term laser heat treatment is used. The process setup is depicted in Fig. 1. The blanks are heat treated with a diode laser Laserline LDM3000-100, which emits light at a wavelength of 900 to 1070 nm with a maximum power of 3 kW. The beam is focused with the optic OTS-5, which has a round spot geometry with a diameter of 4 mm. The laser unit is attached to a multi–axial robot arm from Kuka AG to enable precise positioning of the laser spot. To increase the absorption rate, the surface of the blanks is coated with a thin layer of graphite for a uniform emission coefficient of $\varepsilon = 0.95$ [10]. The rotationally symmetrical specimens are positioned with the help of a stencil plate. An infrared camera of type FLIR SC 7600 is installed to control and monitor the temperature distribution along the blank during the laser process.



Laser parameters (power-controlled)		
	Cu-OFE	CuZn30
Laser power	0.9 kW (30 %)	0.6 kW (20 %)
Holding time	0.8 s	1.75 s

Figure 1: Setup for local short-term heat treatment.

Materials and setup for global heat treatment. The sheet materials used in this work are the single-phase copper Cu-OFE and the brass CuZn30. The oxygen-free Cu-OFE is frequently used in electronics and in vacuum technology. In addition, the high-purity copper is well suited as a model material for fundamental research of micro forming processes. Brass CuZn30 is mainly used in metal goods industry as well as in mechanical and electrical engineering. Both materials exhibit excellent cold formability. However, the high zinc content of the brass increases mechanical strength and decreases thermal conductivity. Thermal conductivity has a major influence on the local short-term laser heat treatment process. For copper, the thermal conductivity is 394 W/mK. Brass, at 121 W/mK, has only 30 % of the thermal conductivity of copper.

In this study, the materials are analyzed in global and local heat-treated condition. On delivery, the materials were in cold-rolled condition with a high pre-hardening of 86 % for Cu-OFE and 66 % for CuZn30. For global heat treatment of the entire blank, a tube furnace NR 40/11 from Nabertherm GmbH with inter gas atmosphere (argon) is used. The temperature of 650°C was held for one hour. Then the specimens were cooled slowly in the furnace. In Fig. 2, the grain structure in cold-rolled and global heat-treated state are shown. Through the heat treatment, a homogeneous grain structure with large grains is achieved over the entire blank. To characterize the mechanical properties and the flow behavior, uniaxial tensile tests were carried out in rolling direction according to DIN EN ISO 6892-1. The experimental flow curves are presented in Fig. 2.

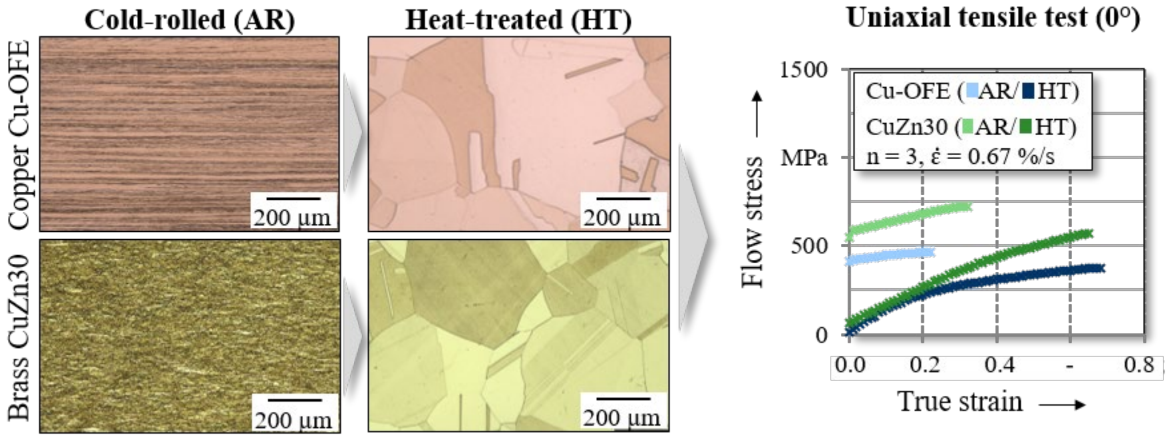


Figure 2: Grain structure and flow behavior of Cu-OFE and CuZn30 in cold-rolled and global heat-treated condition.

The flow curves show a behavior typical of the material, with the global heat treatment resulting in a reduction in strength and an increase in elongation at fracture. As a further heat treatment strategy, a short-term laser heat treatment is investigated in order to locally influence the material structure. The efficiency of this strategy is qualitatively evaluated based on the grain size change of the grain structure, which is depicted in Fig. 3. In the area of local heat treatment, uniform, small grains are located, which replace the grains deformed by the rolling process through recrystallization processes and grain growth. This indicates a decrease in strength in this area. In the border area elongated grains are still visible as in the cold-rolled condition, suggesting higher strength in this zone. Furthermore, there is a difference between the two materials in the size of the heat-treated zone. In case of copper, the heat-treated zone has a diameter of about 4 mm. For brass, a diameter of about 6 mm is identified, thus the heat-treated zone is more pronounced.

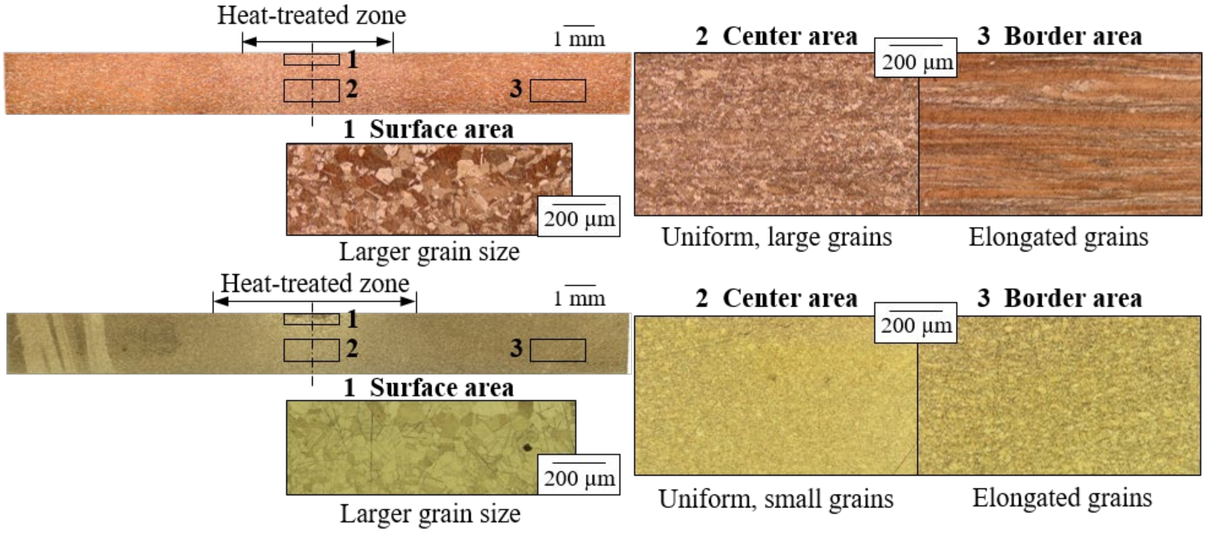
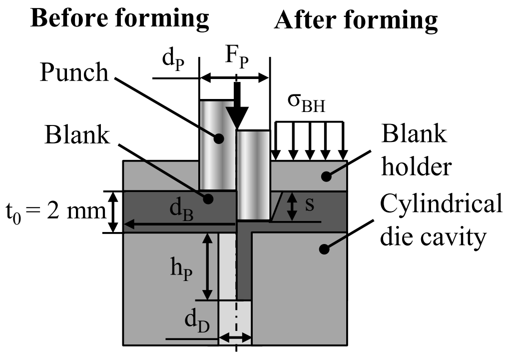


Figure 3: Grain structure of Cu-OFE and CuZn30 blanks after local heat treatment.

Process setup for pin extrusion. For the manufacture of micro gears, a multi-action tool system is required, which is installed in a universal testing machine Walter+Bai type FS 300 with a maximum testing force of 300 kN. The process scheme and the parameters are illustrated in Fig. 4. The extrusion punch and the ejector are driven by hydraulic cylinders. The blank holder is controlled by the universal testing machine, which prevents a lifting of the blanks and reduce the radial material flow outwards in the direction of the sheet metal. The blank holder pressure is set material-specifically in order to prevent plastic deformation due to the blank holder.



Process-related parameters	
Punch stroke s	1.8 mm
Blankholder pressure σ_{BH}	Global HT: 0.99 * $\sigma_{0,\,HT}$ Local HT: 0.60 * $\sigma_{0,\,AR}$
Forming speed	5.0 mm/min
Tool-related parameters	
Punch diameter d_P	3.0 mm
Die diameter d_D	1.5 mm
Blankholder/ Blank diameter d_B	20.0 mm

Figure 4: Process scheme of pin extrusion and process parameters.

At the beginning of the process, the blank holder moves downwards and constrains the circular blank on the die. The blank has a diameter of 20 mm and an initial sheet thickness of 2.0 mm. After applying the blank holder pressure, the extrusion punch moves axially downwards with a constant forming velocity of 5 mm/min and penetrates the blank. This movement causes an axially and a radially material flow. The material located above the cavity is displaced axially downwards into it. Furthermore, the material under the punch, which is not directly above the cavity flows laterally into the cavity and radially outwards into the sheet plane. Mechanical stops limit the punch penetration at a depth of 1.8 mm, which corresponds related to the sheet thickness to a relative penetration depth of 90 %. As lubricant, the extrusion oil Dionol ST V 1725-2 from MKU-Chemie GmbH is used in a quantity of more than 10 g/m².

Experimental results and discussion

In this chapter, the experimental results of pin extrusion are presented. As geometrical properties, the pin height as well as the funnel depth are compared. The funnel depth quantifies the resulting piping defect. This represents a material deficit inside the pin, which can occur during extruding pins from the sheet plane. Funnel formation occurs when the axial material flow velocity, which corresponds to the forming velocity of the punch, is lower than the lateral material flow velocity towards the die cavity. This velocity gradient inside the pin causes the funnel forming. Therefore, in order to improve the material efficiency of the process, the objective is to maximize the pin height and minimize the funnel depth. Furthermore, mechanical properties in form of the micro hardness distribution are analyzed in order to analyze the influence of the local heat treatment. By evaluating the grain structure of the components, the material flow should be confirmed.

Process properties. The force-displacement curves are analyzed to draw conclusions about the tool stresses. During the forming process, forces and displacements are recorded by sensors with a resolution of 1.5 N and 1.0 µm, which are installed in the upper tool unit. In Fig. 5 a the force-displacement curves of the pin extrusion processes are presented.

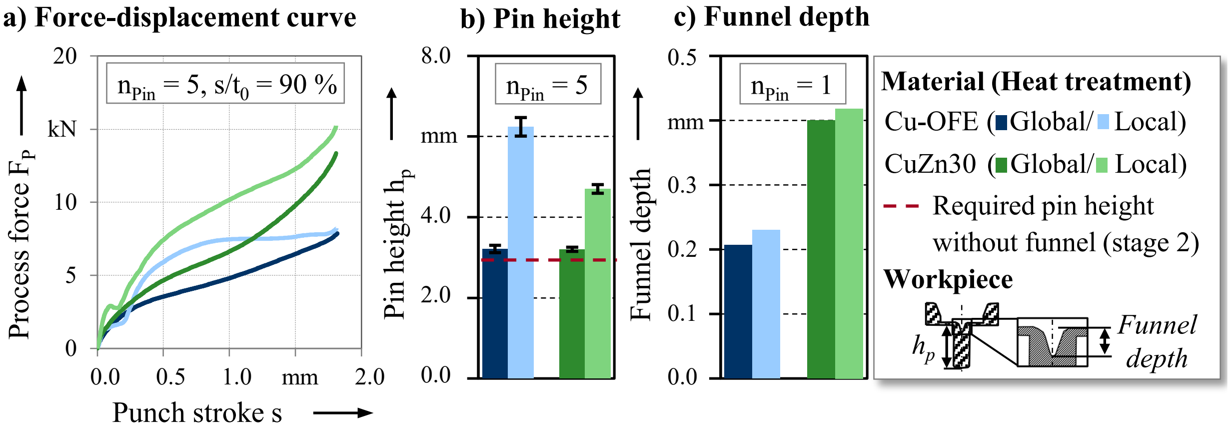


Figure 5: Force-displacement curve (a), pin height (b) and funnel depth (c).

The force-displacement-curves of the global heat-treated materials are similar to the curves during upsetting and corresponds to the described phases by Ghassemali [11]. Compared to Cu-OFE, CuZn30 shows a higher increase of the force curve and a 70 % higher maximum force, which can be explained by the higher yield stress and stronger work hardening of the brass. However, the force-displacement curve of the local heat-treated specimens displays differences from the typical progression for both materials. The process starts with a nearly linear increase of the process force until a displacement about 0.1 mm (CuZn30) respectively 0.07 mm (Cu-OFE). Subsequently, a slight decrease of force occurs, before increasing again. For Cu OFE the process force reaches a saturation value at 8.2 kN, while for CuZn30 it continuously rises to 15.2 kN. This can be explained by the previously described grain structure across the sheet thickness. Due to the larger, softer grains in the upper area of the sheet (Fig. 3), there is a slight drop in force or a stagnation of the increase in force after elastic deformation. Thus, a low force is required for the plastic deformation of material in the upper area. In the further process, the punch penetrates deeper into the sheet, forming the area with smaller, harder grains, which required a higher forming force. The force-displacement curves of the two types of heat treatment differ significantly during the force progression. The maximum forming forces are only 4 % higher for Cu-OFE and 14 % higher for

CuZn30 due to the local heat treatment, which does not significantly increase the tool stress. A forming of the cold-rolled materials was not feasible due to high force requirement and tool stress.

Component properties. The pin height and the funnel depth are displayed in Fig. 5 b, c in order to analyze the material efficiency of the process. A digital absolute dial indicator from Mitutoyo is used to measure tactile the pin height with an accuracy of ± 0.5 µm. The funnel depth is measured by using micrographs.

In order to completely fill the gearing in the second process stage, a minimum material volume of 5.1 mm³ is required. This corresponds to a height of 2.9 mm without funnel formation. In the globally heat-treated state, the pins formed from both materials only slightly exceed this specification, while the material deficit due to funnel formation (Fig. 5 c) lead to incomplete die filling of the gearing. The application of a local heat treatment results in a 95 % (Cu-OFE) increase in pin height up to 6.24 mm and a 47 % (CuZn30) increase up to 4.70 mm. This is attributed to the hardness gradient along the diameter of the blank and the higher hardness in the passive forming zone, which inhibits the lateral flow of material outward in the sheet metal, resulting in an increase in the lateral flow of material into the die cavity. In the global heat-treated condition, on the other hand, softer material is present in the outer area, resulting in less outward flow inhibition and thus more material being able to flow into the sheet metal. Thus, the use of local heat treatment is a suitable strategy to increase material efficiency during pin extrusion. Furthermore, a comparison of the materials shows a 33 % higher pin for Cu-OFE in the local heat-treated state. This can be explained by different sizes of heat-treated zones (Fig. 3) of the materials. Due to the larger heat-treated zone of the brass, there is a lower hardness gradient along the blank diameter compared to copper, which results in a higher material flow radially outward into the sheet plane.

Another parameter is the funnel depth, which quantifies the resulting piping defect (Fig. 5 c). For both materials, the depth of the funnel increases slightly by 0.02 mm due to the local heat treatment. However, in relation to the pin height, the relative proportion of the funnel depth is significantly reduced. For copper, the proportion has been minimized from 6.5 % to 3.7 %. For brass, a reduction from 12.5 % to 8.9 % can be identified. Furthermore, for CuZn30 a larger funnel depth is observed independent of the heat-treated state, which could be due to the higher yield stress and the stronger work hardening of the brass, as shown in the flow curves in Fig. 2.

In Fig. 6 the hardness distribution and the grain structure are shown. For micro hardness measurement, the Vickers hardness test method according to ISO 14577 is used. The measurement was carried out with a Fischerscope HM2000 (Helmut Fischer GmbH) with a test force of 100 mN (HV0.01) and a holding time of 10 s The initial micro hardness in heat-treated condition has a value of 66 ± 7 HV0.01 for copper and of 92 ± 5 HV0.01 for brass. The highest forming induced strain hardening for all specimen results in the residual sheet and in the upper zone of the pin. A maximum micro hardness of 170 ± 9 HV0.01 (Cu-OFE) and 294 ± 8 HV0.01 (CuZn30) is achieved in the pin of global heat-treated condition, which equals an increase of 158 % and 220 %, compared to the initial hardness. Furthermore, the micro hardness decreases in the direction of the pin head, with a hardness of 85 ± 4 HV0.01 (Cu-OFE) and 128 ± 10 HV0.01 (CuZn30). This is attributed to the forming of the pin head at the beginning of the process, where the material flows predominant axially downward into the cavity. Thus, low strain hardening is achieved. In the outer area of the blank, no significant hardening can be determined due to the limited blank holder force.

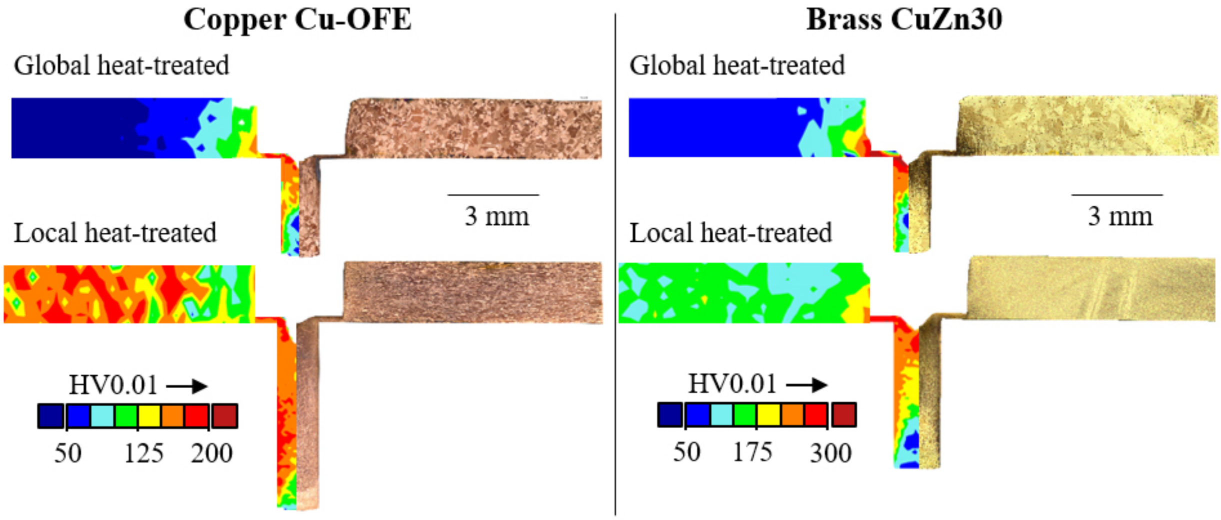


Figure 6: Micro hardness distribution and grain structure of the investigated components.

In initial local heat-treated condition, the micro hardness in the border area is 172 ± 11 HV0.01 for copper and 182 ± 15 HV0.01 for brass. In the forming zone, the micro hardness is 69 ± 4 HV0.01 (Cu-OFE) and 83 ± 3 HV0.01 (CuZn30). Due to the forming induced hardening, a maximum hardness in the upper area of the pin of 165 ± 1 HV0.01 for copper and 245 ± 5 HV0.01 for brass is achieved. In the head area, the micro hardness is 123 ± 7 HV0.01 for copper und 125 ± 3 HV0.01 for brass. Thus, a similar distribution of micro hardness and strain hardening in the pin area is present for brass for both heat treatment types. For copper, there is a 145 % increase in micro hardness in the pin, which is clearly visible from the larger red color details in the image. The differences between the materials can be explained by the different laser heat treatments.

In addition to the investigated micro hardness distribution, micrographs (Fig. 6) are analyzed to evaluate the expected material flow through an interpreting of the grain deformation. In the border area of the blank und in the area of the pin head of the investigated specimens, there is no significant deformation in grain structure in comparison with the initial grain structure visible. Furthermore, in residual sheet as well as in the upper part of the pin near the funnel, there is a significant deformation of the grains corresponding to the evaluated micro hardness. The comparison of the heat treatment strategy shows especially for copper significant differences in the grain structure in the pin area. In the local heat-treated condition, many small grains are visible in the pin area, whereas in global heat-treated condition large grains are present.

Summary and outlook

In this paper, the potential for extending the process limits during pin extrusion from sheet metal by a local short-term laser heat treatment was investigated. Therefore, the influence of the heat treatment strategy was evaluated. In order to analyze the transferability of the results, the investigations were carried out with the single-phase copper Cu-OFE and the application material brass CuZn30. The following main conclusions can be drawn:

- Using a laser as heat source, the heat treatment can be locally limited to the area of the forming for Cu-OFE and CuZn30. This type of heat treatment offers the potential to save process time and energy in comparison with heat treatment in a furnace.
- Through local heat treatment an improvement of the material flow and an increase in material utilization is achieved. The pin height was increased by 95% for Cu-OFE and 47 % in case of CuZn30.
- In addition, no significant influence on the funnel formation was identified. Only a small funnel depth occurs.

- The maximum force requirement of the two types of heat treatment and thus the tool stress is very similar, but the course of the force-displacement curves differs significantly.
- By using local short-term heat treatment, the micro hardness of the pin in the direction of the pin head is increased, especially for copper. In the case of brass, however, the hardness distribution is similar to the global heat-treated condition. Furthermore, the maximum micro hardness in the area of the funnel is in similar range.

Future research should focus on the investigation of the influence of heat treatment strategy on the forming of micro gearing by lateral extrusion. In addition, the investigation of different laser process parameters offers the potential to adjust the material properties and the size of the heat-affected zone to achieve desired material properties for pin extrusion.

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