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Analysis of the Part Quality and Process Stability when Producing Metallic Micro Parts by Multi-Stage Bulk Forming from Sheet Metal

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Abstract. Miniaturization of parts for technical products is an ongoing trend across all industries over the past decades. Due to the large number of possible applications, several billion micro parts are produced every year. In mass production, cold forming offers technological, economical and ecological benefits in comparison to other manufacturing methods. Unfortunately, due to size effects that negatively influence the part geometry, the process stability, the handling and the tool stress, this manufacturing technology is currently barely used. Previous research results have shown that bulk microforming from sheet metal has the potential to reduce the aforementioned restrictions decisively. Within this paper, a three-stage bulk microforming process from sheet metal is experimentally analysed to form a demonstrator geometry with dimensions in the sub-millimetre range in all spatial directions. In the first stage, material is provided in form of a pin for subsequent forming stages. During the second stage, a cup geometry is formed on the pin. Finally, the micro part is separated from the sheet metal by shear cutting. To ensure a wide range of applications, the investigations are carried out with copper, steel and aluminium material. This study is focused on the evaluation of the achievable part quality and the process stability. For the evaluation of the geometry and the surface quality, the micro parts are optically measured with a three-dimensional surface measuring system. The standard deviation of the part dimensions and the process forces are used to investigate the influence of size effects in relation to the material and the grain structure.

Introduction

A continuously ongoing trend towards product miniaturisation with a parallel increase of the functional extent enhances the importance of microproduction technology. The high demand for metallic micro components exists in particular with micro-electro-mechanical systems, so-called MEMS. The global MEMS market is expected to grow by 12.9% per annum until 2028 [1]. The rising demand is primarily assumed to be in smartphones and other portable electronic devices, as well as the enhanced application of these systems in aviation, automotive, consumer electronics and defence industries. However, there is also an expanding need for purely mechanical stressed micro parts. In micro-drive technology, high requirements are made on the performance of micro-drives in very confined spaces under extreme environmental conditions. Micro-drives have countless applications in production, healthcare technology and the consumer market. For example, there are on average more than 40 micro systems installed in a car alone for vehicle monitoring and safety systems such as anti-lock brakes and airbag release [2]. In order to meet the rapidly growing demand for metallic micro components, production methods are urgently required which can produce large quantities in very short cycle times at a high product quality, with repeat accuracy in a cost-efficient manner. In mass production, forming technology offers economical, ecological and technological advantages compared to other fabrication technologies [3]. Micro sheet metal forming is already widely used in industry. However, bulk forming of complex micro part geometries in multi-stage processes is rarely used at present, mainly as a result of handling difficulties. Furthermore, size effects negatively influence the repeat accuracy and the micro part quality [4]. The approach of bulk microforming from sheet metal, first presented by Hirota [5] in 2007, has the potential to transfer the handling benefits of micro sheet metal forming to bulk microforming. Here, the sheet metal strip serves both as a semifinished product and as a handling aid for the positioning of the micro parts between the forming stages. Within the scope of this study, a three-stage bulk microforming process from sheet metal for the fabrication of a metallic micro parts is analysed for different materials (copper, aluminium and steel). The main focus is on the feasibility of the process chain in general. It is assessed with regard to the process scatter and the part quality. Furthermore, the material utilisation is investigated in relation to the material during pin extrusion. The material utilisation describes the share of the pin volume with regard to the material volume displaced by the punch.

Materials and Experimental Setup

Materials. To ensure a good transferability of the results, the microforming process is investigated with different materials (Fig. 1). The copper material Cu-OFE represents potential applications for the micro-electro production. The copper material is tested in the as-received cold-rolled condition (Cu-OFE-AR) and also in a annealed condition (Cu-OFE-HT; 650°C/1h) to investigate the influence of grain size and strength in the forming process. Additionally, the mild deep-drawing steel DC04 and the precipitation-hardenable aluminum alloy AA6014 are investigated as representative materials for micro-drive components. The aluminum alloy is formed in W-temper (AA6014-W) condition. Therefore, the aluminum in naturally aged T4-condition is solution heat treated at 545 °C for 15 minutes.

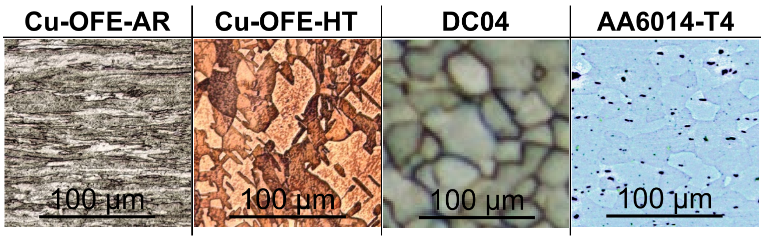


Figure 1: Micrographs of the used materials

Caused by the rolling process, the grains of Cu-OFE-AR are long, wide and flat resulting in a high anisotropy. The average grain size is 18 µm in rolling direction (RD), 14 µm 90° to the RD and 5 µm in sheet thickness direction. Cu-OFE-HT, DC04 and AA6014-T4 have uniform cubical grains with no measurable anisotropy in the micrographs (Fig. 1). The average grain size is 41 µm (Cu-OFE-HT), 33 µm (DC04) and 21 µm (AA6014-T4). The mechanical properties are determined in tensile tests according to DIN EN ISO 6892-1. The extrapolated flow curves, the initial flow stresses σ_{iys} and the strain hardening exponents in RD are shown in Fig. 2.

Material	Cu-OFE -AR	Cu-OFE -HT	DC04	AA6014-W
Sheet thickness t_0 [µm]	485	485	468	482
Initial yield stress σ_{iys} [MPa]	243.99	40.38	180.98	76.82
Strain hardening exponent [-]	0.028	0.561	0.214	0.316

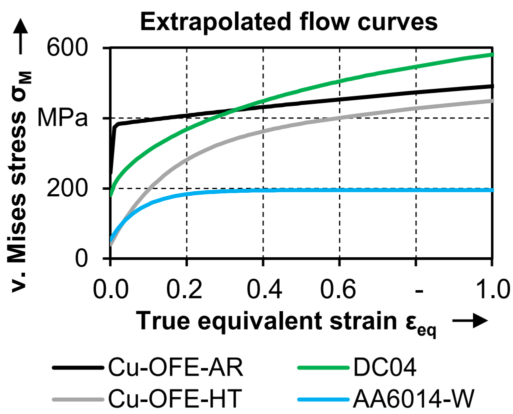


Figure 2: Flow curves, sheet thickness and mechanical properties

Experimental setup. Fig. 3 illustrates the investigated 3-stage process chain. To enhance the industrial relevance of the entire process, standard parts made of CD30 carbide metal are used for the extrusion and cutting punches. The die is made of CF-S18Z carbide metal. For all process stages, impact extrusion oil Dianol ST is used in a quantity of at least 10 g/m^2 to reduce the frictional forces. In order to achieve a high material utilisation, a material-specific blankholder pressure of just below the initial yield stress is applied. The forming speed is 5 mm/min for all forming and cutting stages. Relevant process parameters are given in Table 1.

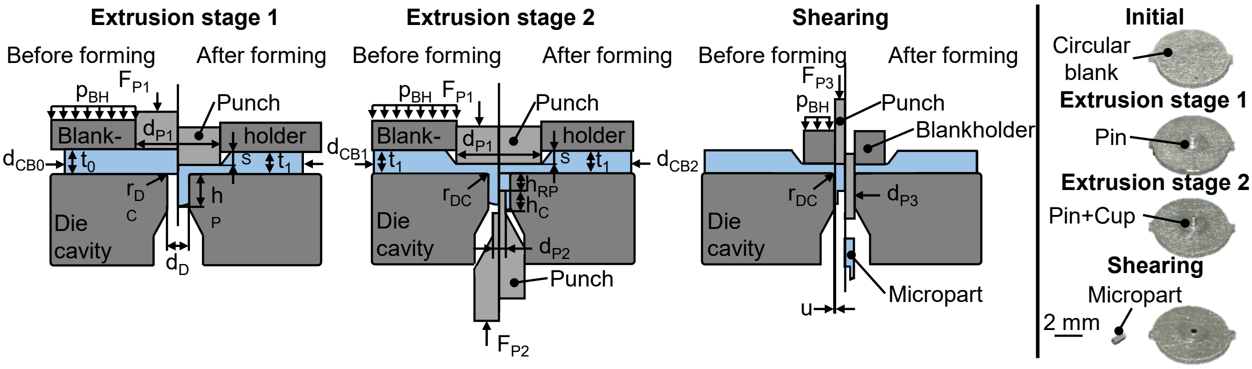


Figure 3: Process sequences of the investigated 3-stage bulk microforming process from sheet metal

In the first extrusion stage, a pin is formed in order to provide material for the subsequent forming stages. During pin forming, the active forming tool consists of a die, a punch and a blank holder. At the beginning of the forming process, the workpiece is axially fixed by the blank holder to avoid a bulging of the sheet metal. Next, the extrusion punch moves axially downwards and displaces the material axially and radially in the direction of the cavity as well as radially outwards into the sheet metal plane. The objective of this forming stage is to maximize the material flow into the die cavity while keeping the deformation of the carrier sheet as low as possible. During the second extrusion stage, a cup is formed on top of the pin from the first forming stage. For this purpose, the tool remains closed after the first forming stage and another forming punch moves axially upwards. As a result, the material in the pin is plastically deformed and a cup is formed. In the third process stage, the micro part is separated from the sheet metal by cutting. The cutting tool consists of an adapted blank holder, a cutting punch and a cutting die. Also here, the sheet metal is first axially fixed by the blank holder. Afterwards, the cutting punch moves axially downwards and the finished micro part drops down through the die.

Table 1: Process parameters

Parameters		Unit	
Relative punch stroke	s/t_0	[%]	aprox. 75
Blank holder pressure	p_{BH}	[MPa]	$0.99*\sigma_{iys}$
Blank diameter	d_{CB0}	[mm]	5.34
Punch diameter 1	d_{P1}	[µm]	1420
Punch diameter 2	d_{P2}	[µm]	328
Punch diameter 3	d_{P3}	[µm]	430
Die diameter	d_D	[µm]	470
Die radius	r_{DC}	[µm]	50

Results

Stage 1 – Pin extrusion. Table 2 summarises the achieved pin heights, the material utilisation and the maximum tool stress depending on the material and the punch penetration depth. It is noticeable that the pin height of Cu-OFE-AR is with 972 µm the highest, despite the lower relative punch penetration depth of 68.3%. The parallel length of the die is only 1 mm. For this reason, pins > 1 mm cannot be formed in the second forming stage with the existing tooling system. Thus it was necessary to choose a lower pin height compared to the other materials, since a pin height of 1 mm is exceeded at 75%. For DC04, the pin height is 848 µm with a relative punch penetration depth of 72.4%.For Cu-OFE-HT and AA6014-W, the process is adjusted to achieve an approximately comparable pin height. This is 679 µm for Cu-OFE-HT and 634 µm for AA6014-W. Nevertheless, the relative punch penetration depth for AA6014-W is 7.1% lower. With a very low maximum standard deviation of 1% for all materials, the pin extrusion process can be rated as precise and with high repeatability. Due to the low standard deviation, it can be assumed that size effects do not negatively influence the accuracy of the process stage.

Table 2: Pin height, penetration depth, material utilisation and maximum tool stress; (n=3)

Material	Cu-OFE-AR	Cu-OFE-HT	DC04	AA6014-W
Pin height [µm]	972±5	679 ± 7	848±8	634±6
Penetration depth [µm]	332±2	360±2	340±1	323±3
Relative punch stroke s/t_0	68.3%	74.1%	72.4%	67.0%
Material utilization	31.9%	20.6%	27.2%	21.4%
Max. tool stress [MPa]	1695±14	877±14	1867±19	731±50

Since the punch penetration dephts and sheet thicknesses are compareable, the material utilisation can already be derived from the pin heights. It is highest for Cu-OFE-AR with 31.9%. For DC04 the material utilisation is 27.2%, for AA6014-W 21.4% and for Cu-OFE-AR lowest with 20.6%. In the state of the art it is assumed that materials with low ductility and high strength increase the material utilisation. This was observed by Hirota and Mitchitsuji [6] for A1050, by Merklein et al. [7] and by Fu and Chan [8] for copper materials. But the results from Table 2 show a higher material utilisation for DC04 than for AA6014-W. With an elongation at fracture of 45%, the deep drawing steel DC04 is more ductile than AA6014-W with 21%. Furthermore, it can be seen that the material utilisation for AA6014-W is higher than for Cu-OFE-HT, despite its lower strength. The results of the pin height from Table 2, taking into account the flow curves from Fig. 2, allow the conclusion that it is not the ductility or strength that influence the material utilisation. It is the strain hardening exponent which is crucial for the material flow. This phenomenon is clearly illustrated in Fig. 4.

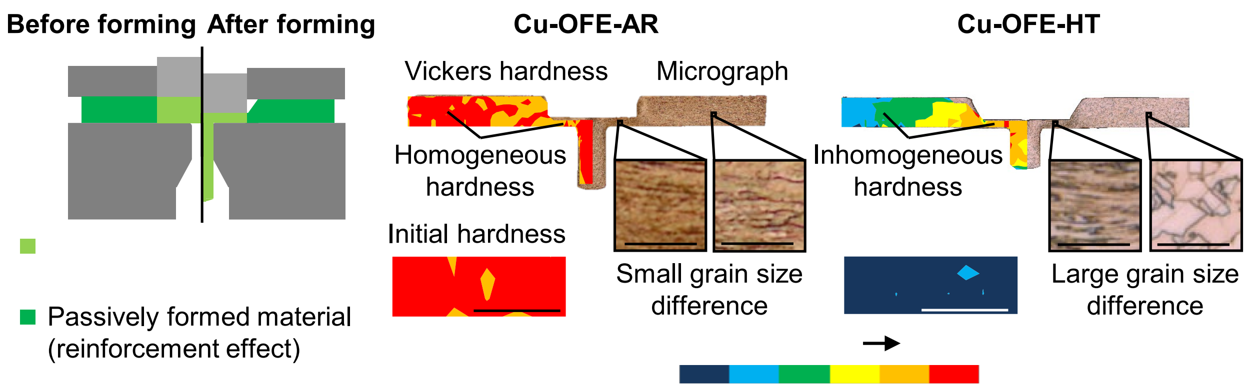


Figure 4: Micro-hardness distribution and grain structure images from the active and passive forming zone

In principle, the material can be divided into two forming zones. In the active forming zone, the material is directly displaced by the punch and work-hardened. In the passive forming zone, the material flow indirectly results from the displaced material from the active forming zone. Thus, the true strain here is rather low compared to the active forming zone. The passive forming zone acts as a kind of reinforcement that impedes the material flow radially outwards. For almost ideally plastic materials with a low strain hardening exponent, such as Cu-OFE-AR, there is barely an increase in strength in the active forming zone as a result of the insertion of the punch. Thus, the material strength in the active and passive forming zone is almost identical, which can be seen in the micro-hardness measurements and micrographs in Fig. 4. For materials with a high strain hardening exponent, such as Cu-OFE-HT, a high degree of strain hardening occurs in the active forming zone as a result of the forming process. In comparison, the passive forming zone remains relatively soft (Fig. 4). Due to the large strength gradient between the active and the passive forming zone, the hardened material flows more radially outwards into the sheet metal plane. This strength gradient is minimal for materials with a low strain hardening exponent. As a result, there is a greater reinforcement effect in the solid passive forming zone, which inhibits the material flow outwards into the sheet metal plane. During micro pin extrusion, the tool stress is not critical for all materials tested. The compressive strength of the used punch is 4760 MPa. Due to the maximum tool stress of 1867 MPa, both tool steel or carbide punches made of standard parts can be used for the first process stage.

Stage 2 – Cup extrusion. In the second extrusion stage, different punch penetration depths and residual pin heights were selected, as both the tool stress and the tool-related maximum cup height would have been exceeded. Due to the geometric similarity, the components made of Cu-OFE-HT and AA6014-W, as well as Cu-OFE-AR and DC04 are comparable to each other. Table 3 shows the cup heights as a function of the residual pin heights and the punch penetration depths. Overall, cup heights between 185 and 590 µm with a wall thickness of 71 µm could be produced with the settings made. First of all, it is noticeable that the residual pin height could be set very precisely with a maximum absolute standard deviation of 2 µm. Considering a similar standard deviation of the pin heights between 5-8 µm in Table 2, a comparable absolute standard deviation of the cup height can be expected for the cup extrusion when size effects are not present. The standard deviation for the micro cup forming in the second forming stage is between 6 and 18 µm in absolute terms. Especially for the smaller cup heights, the standard deviation is larger. The relative standard deviation for the small cups is 9.7% for Cu-OFE-AR and 7.6% for DC04. For the larger cup heights, the relative standard deviation is significantly lower at 1% (Cu-OFE-HT) and 1.4% (AA6014-W). With a sufficient cup height, the second forming stage can be considered as very repeatable.

In comparison with the first forming stage, the material utilisation in the second process stage is with 85-100% significantly greater. This can be attributed to the changed boundary conditions. Before the material can flow back into the sheet metal plane, it has to be deflected by 90° at the pin head. In addition, the reinforcement effect of the circular blank is at a maximum at the pin foot. The additional high pressure of the extrusion punch from the first forming stage further reduces the material flow into the sheet metal plane.

Table 3: Residual pin height, cup height, material utilisation and maximum tool stress; (n=3)

Material	Cu-OFE-AR	Cu-OFE-HT	DC04	AA6014-W
Restpin height [µm]	904±1	366±2	765±1	366±2
Cup height [µm]	185±18	590±6	143±11	484±7
Punch stroke [mm]	0.075	0.291	0.101	0.273
Material utilization	100.0%	94.9%	90.6%	85.3%
Max. tool stress [MPa]	1456±27	2291±82	1980±33	2185±995

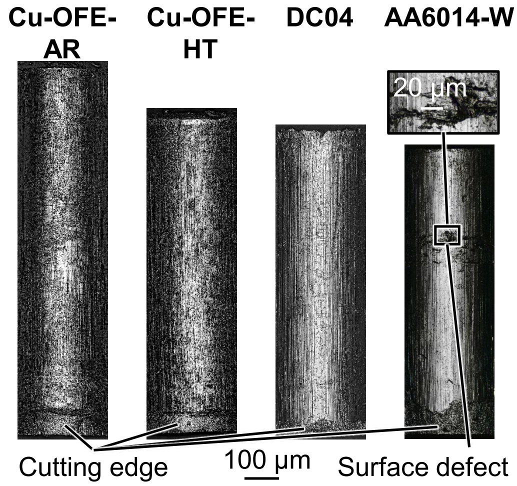
Viewing the tool stress in Table 3, the first thing to notice is the large standard deviation of 995 MPa of the punch force at AA6014-W. This variation of the forming force is not reflected in the geometric dimensions of the micro part. A possible cause could be a hydrostatic pressure due to the lubrication oil or even individual precipitations. It can also be observed that the tool stresses are already significantly higher than in the first forming stage. With a maximum average tool stress of 2291 MPa, it is still clearly below the compressive strength of the standard part punch. Thus, the presented micro pin-cup geometries can be fabricated with normal parts. However, with Cu-OFE-AR and DC04 the punch path is very small. For this reason, the choice of a higher-strength carbide metal should be considered for stronger materials combined with greater cup heights.

Stage 3 - Separation by shearing. Table 4 shows the maximum cutting force and tool stress when separating the micro parts from the carrier sheet in relation to the residual sheet thickness. It is evident that the tool stress is not critical at a relative punch penetration depth of approx. 75 %, despite the high pre-hardening of the residual sheet at the pin foot as a result of the first process stage. The maximum tool stress of 840 MPa for DC04 is clearly below the compressive strength of the cutting punch. The cutting forces are also subject to a relatively low scatter with a maximum standard deviation of 5.7%. For this reason, the shearing stage can also be classified as uncritical and thus feasible. The cutting gap is 20 µm, which is 4.2% of the part diameter.

Table 4: Maximum force during shear cutting; (n=3)

Material	Cu-OFE-AR	Cu-OFE-HT	DC04	AA6014-W
Residual sheet thickness [µm]	153±2	125±2	128±1	159±3
Max. cutting force [N]	78±2	58±3	122±7	64±3
Max. tool stress [MPa]	537±14	399±21	840±48	441±21

In Fig. 5, surface images of the different micro parts are shown along with the achieved surface parameters R_Z and R_a. In the case of the micro part made of AA6014-W, a surface damage is apparent. It is located in the transition zone between the cup wall and the pin. This damage occurs during the ejection of the micro part after the second extrusion stage. Due to the small cup cross-section combined with the high surface pressure and friction in the die, high tensile stresses occur in this area during ejection. AA6014-W has the lowest tensile strength of all tested materials. As the tensile stresses exceed the tensile strength of the material during ejection, damage occurs. Thus, in the case of the aluminium micro parts, a more solid condition such as naturally aged T4 or artificially aged T6 is recommended.



R_Z [µm]	4.54 ± 0.91	4.65 ± 1.32	2.60 ± 1.07	4.60 ± 0.71
R_a [µm]	0.28 ± 0.05	0.33 ± 0.11	0.15 ± 0.08	0.41 ± 0.02

Figure 5: Images of the surface topography by confocal laser scanning microscopy; 50x lens

The quality of the cutting edge is strongly influenced by the workpiece material. Ductile materials tend to have a much smaller fracture surface than brittle materials, since the fracture starts later [9]. Thus, the clear cut surface is larger for ductile materials. This can be seen clearly when looking at the surfaces. The shearing zones of Cu-OFE-AR and AA6014-W are clearly larger than those of the more ductile materials Cu-OFE-HT and the deep-drawing steel DC04. The average roughness of Cu-OFE-AR is R_Z = 4.54 µm, of Cu-OFE-HT R_Z = 4.65 µm and of AA6014-W R_Z = 4.60 µm, which is almost at a the same level. The roughness of DC04 is significantly lower with R_Z = 2.60. Possible reasons for this could be that the copper and aluminium materials are soft materials. Due to the lower strength, the surface topography of the tool can be mapped more strongly with these materials. The steel may have a better surface finish due to the higher strength, as this is additionally more resistant to scratches during handling between the forming stages. The achieved surface quality is for all materials within the achievable tolerance for cold extrusion.

Conclusions

Within this contribution, it could be shown that the three-stage bulk microforming process is suitable for the reproducible production of metallic micro parts made of Cu-OFE, AA6014 and DC04 on a laboratory scale. The capability for the different metallic materials opens up a wide range of applications for electrical, mechanical and electro-mechanical micro parts. Due to the unbound forming process, the absolute variation of the pin height is max. 8 µm and below 1% in relation to the total height. For the cup extrusion in the second forming stage, the standard deviation of the cup height is between 6 µm and 18 µm in absolute terms. For large cup heights, the percentage deviation is less than 1.4%. Nevertheless, with very small geometric shapes of the cup height, there is a relatively high process variation of up to 9.7%. The shear cutting process in the third forming stage is not subject to any notable variation with regard to the process force with a maximum deviation of 5.7%. Thus, the multi-stage bulk microforming process from the sheet metal plane can be evaluated as repeatable depending on the final geometry. As already known from the state of the art, the material utilisation during pin extrusion shows also in this study a strong material dependency. While the other studies assume ductility, strength or grain size as the cause, it was proven that the strain hardening exponent is the decisive material parameter. The lower the strain hardening exponent, the higher is the material utilisation. In the case of AA6014-W, a local part defect occur after the second forming stage when the part is ejected caused due to the tensile stresses in the pin/cap transition zone. With regard to the material utilisation and the component quality, highly pre-strengthened materials are therefore recommended, as long as the maximum load capacity of the forming tools is not exceeded.

After the basic feasibility has been demonstrated on a laboratory scale, further research work will focus on the transferability of the findings to the mass production in a high-speed press with coil material. In particular, the achievable process stability as a function of the cycle rate is the focus of these investigations.

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