Fundamental investigations of size effects in multi-stage cold forming of metallic micro parts from sheet metal

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Abstract

Product miniaturisation and functional integration are currently global trends to save weight, space, materials and costs. This leads to an increasing demand for metallic micro components. Thus, the development of appropriate production technologies is in the focus of current research activities. Due to its high efficiency and accuracy, short cycle times and its suitability for cost-effective net-shape mass production, microforming at room temperature offers the potential to meet the steadily increasing demand. When scaling down the forming processes into the micro scale, size effects occur. In general, this will negatively affect the part quality, process stability, tool life and the handling. Within this contribution, a multi-stage bulk microforming process from sheet metal is fundamentally investigated with regard to the basic feasibility and the occurrence of size effects. The materials Cu-OFE and AA6014-W are used in these studies. The experimental results reveal that the analysed process chain is basically suitable to produce metallic micro parts with a high repeatability. Size effects are identified during the process. Several research studies postulate that size effects can be minimised by scaling down the metallic grain structure. Thus, the grain structure of the aluminium material AA6014-W is scaled down to a grain size of less than one micrometre by using an Accumulative Roll Bonding Process (ARB). Subsequently, the effects of the ultrafine grain (UFG) structure on the forming process are analysed.

Keywords: size effects; microforming; accumulative roll bonding (ARB); ultrafine grain structure

1. Introduction

The demand for metallic micro parts is growing due to a steady miniaturisation with a simultaneous functional integration. These parts are widely applied in the fields of electronics, automotive, micro electromechanical systems, microsystems technology and medical technology [1]. To meet the great demand, manufacturing processes, which are capable to produce the micro parts in high quantities at short cycle times in a high quality, repeatable and cost-efficient, are required. In mass production of metallic parts, forming technology offers economical, technological and ecological advantages in comparison to other production technologies. Nevertheless, the scaling of forming processes into micro dimensions leads to size effects [2]. These are especially challenging for bulk microforming processes due to the complex handling. Hirota [3] has investigated the direct extrusion of metallic micro parts from sheet metal in order to simplify the handling considerably. In this process, the sheet metal serves both as a semi-finished product and as a component carrier between the multiple forming stages. The handling of sheet metal strip has already been established in industrial sheet metal microforming processes. In this paper, this strategy is further investigated by analysing the whole process chain of a multi-stage bulk microforming process from the sheet metal to the finished micro part. The focus of the study is to prove the basic feasibility of the process chain. Furthermore, size effects are identified by studying the process in both macro and micro scale. The transferability of the findings is guaranteed by the use of the two different materials Cu-OFE and AA6014. Numerous scientific studies prove that size effects can be minimised by using ultrafine grain structures. Thus, the microstructure of the material AA6014 is modified to this state by using an ARB-process. Subsequently, micro scale tests are carried out again with this material state. Afterwards, the impact on the size effects and the potential of UFG materials during this process are evaluated.

2. Experimental setup

The used three-stage process chain with the resulting geometry of each forming stage is shown in Fig. 1. To identify size effects, the process is investigated in the macro and micro scale by using the scaling factor of $\lambda = 0.356$. The blankholder pressure is set material-specific just below the yield stress of the material being tested. This ensures the highest possible material flow barrier without compressing the sample [4]. The process sequences, the material flow and other boundary conditions of the extrusion stages 1 and 2 are described in Kraus et al. [4] in detail. In the third process stage, the micro part is separated from the sheet metal by shearing. Here, the tool consists of an adapted blankholder and a cutting punch. After axial fixing of the sheet, the cutting punch moves downwards. As a result, the micro part is cut off from the carrier sheet and ejected downwards. All relevant process parameters are given in Table 1.

3. Materials

The materials Cu-OFE and AA6014 are used in the experimental tests. Due to its high purity and the single-phase microstructure, the copper material is excellently suited to investigate size effects. Furthermore, it has a high application potential for electronic micro components, such as connector pins, due to its high conductivity. To achieve a homogeneous grain structure, the material is heat treated at 650 °C for one hour. The heat treatment results in an identical grain size for the copper material in macro and micro scale. The used precipitation hardenable aluminium alloy AA6014 is interesting for

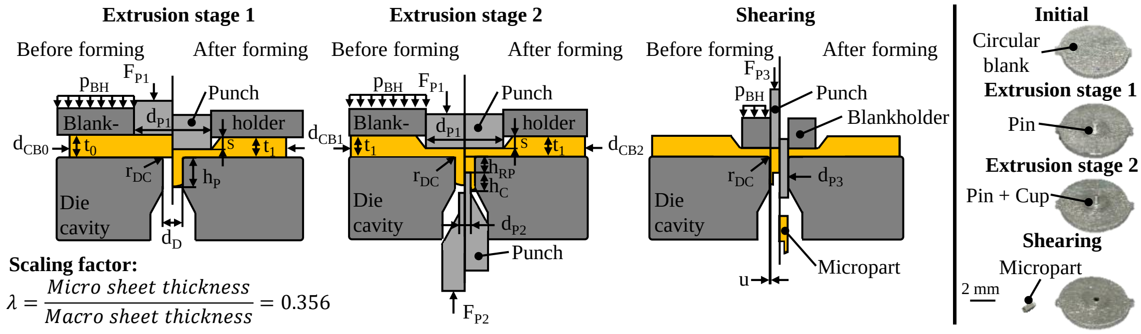

Fig. 1: Investigated process chain with resulting part geometries of the different forming stages

Table 1: Process parameters for cold bulk macro- and microforming from sheet metal

Parameters		Unit	Macro	Micro
Relative punch stroke	s/t_0	[%]	75 (Cu-OFE; AA6014-W); 56 (AA6014-ARB)	
Blank holder pressure	p_{BH}	[MPa]	50 MPa (Cu-OFE); 70 MPa (AA6014-W); 300 MPa (AA6014-ARB)	
Sheet thickness	t_0	[mm]	1.32	0.47
Blank diameter	d_{CB0}	[mm]	15.00	5.34
Restpin height	h_{RP}	[mm]	1.000	0.356
Punch diameter 1	d_{P1}	[mm]	4.00	1.42
Punch diameter 2	d_{P2}	[mm]	0.920; 1.120;	0.328; 0.399;
Punch diameter 3	d_{P3}	[mm]	-	0.43
Die diameter	d_D	[mm]	1.32	0.47
Die radius	r_{DC}	[mm]	0.14	0.05

applications in microforming technology due to its corrosion resistance and low density combined with a high strength. A potential application would be, for example, drive shafts for micro motors or micro gears. For studying size effects, the aluminium alloy is investigated in two different states. AA6014-W is solution heat treated at 545 °C for 15 minutes. For AA6014-ARB, accumulative roll bonding is used to achieve an ultrafine grain structure. For this purpose, the ARB-process chain, described in Hermann et al. [5], is used with four repetitions. The average grain size in rolling direction is 41 µm for Cu-OFE [6], 21 µm for AA6014-W and 0.64 µm for AA6014-ARB [5].

4. Results

4.1 Extrusion stage 1 (Pin-forming)

In Fig. 2, the achieved pin heights after extrusion stage 1 are presented for the macro and micro scale. For an improved comparability of the results, the original pin height h = 1.660 mm of the macro experiments is scaled in the diagram with the scaling factor λ = 0.356. It is noticeable that the pin heights between macro and micro scale are at a comparable level. The slightly lower pin height for the macro scale is attributed to manufacturing inaccuracies in the area of the die entry radius and not to size effects. The material utilisation for Cu-OFE is 18.3 % in the macro and 19.8 % in the micro scale. The standard deviation is slightly larger in the micro scale. However, with a maximum standard deviation of < 2.5 %, the pin extrusion process can be classified as repeatable, even in the micro scale. In micro scale, a relative penetration depth of $s/t_0 = 75$ % for the material AA6014-W (h = 634 µm) results in a comparable pin height as for Cu-OFE (h = 645 µm). The pin height for the material AA6014-ARB is significantly larger for the identical penetration depth. Since this pin height would exceed the cylindrical length of 1 mm of the die used in extrusion stage 2, an identical pin height to the AA6014-W material is set for the AA6014-ARB material. Here, the pin height of 639 µm is already achieved at a relative punch penetration depth of $s/t_0 = 56$ %. Thus, the material utilisation of AA6014-ARB is 26.8 % at this penetration depth. According to the findings of Ghassemali et al. [7], the utilisation rises further with an increasing punch penetration depth. The higher material utilisation can be traced back to the significantly increased strength of the ARB material. This effect has been already experimentally observed by Hirota and Michitsuji [8] for the aluminium A1050 and by Merklein et al. [9] for copper materials.

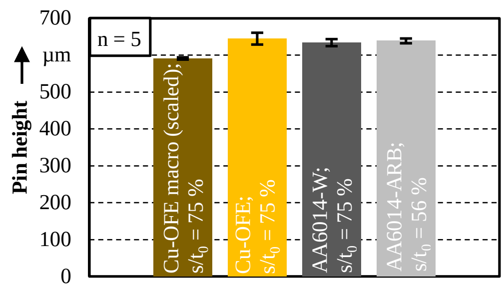

Fig. 2: Pin heights after extrusion stage 1 for macro (scaled) and micro scale

4.2 Extrusion stage 2 (Cup-forming)

The achieved cup heights for the different materials in relation to the wall thickness are compared in Fig. 3. Also here, the original cup heights $h_{1.120}$ = 1.475 mm and $h_{0.920}$ = 1.013 mm in the macro scale are scaled down with the factor of λ = 0.356 for an improved comparability. It is noticeable that the cup height in the macro scale is higher for the smaller wall thickness (wt). This can be explained by the fact that a larger punch diameter is used for the smaller wall thickness of 100 µm, which displaces more material. For the smaller wall thickness, the circular ring area of the cup is also significantly smaller. This results in higher cup heights for the same material volume. The opposite applies to the micro scale. Due to a size effect, the cup height is higher for the thicker wall thickness of 71 µm. This size effect is also present for the materials AA6014-W and AA6014 ARB.

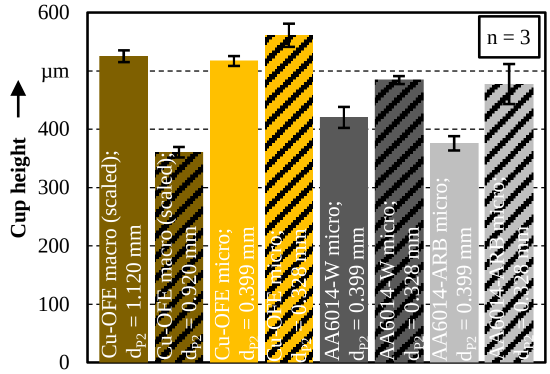

Fig. 3: Resulting cup heights in macro (scaled) and micro scale after extrusion stage 2

For a more detailed analysis of this size effect, the material utilisation of extrusion stage 2, shown in Fig. 4 by the ratio of the displaced material volume in the cup to the displaced material volume by the die, is considered. First, it can be observed that the material utilisation is higher for the micro as well as for the macro scale the bigger wall thicknesses. This can be attributed to the enlarged flow gap and the associated lower deformation resistance due to the higher distance between the two friction surfaces, punch and die. In macro scale, the material utilisation of 48.6 % for wt = 100 µm and 57.6 % for wt = 200 µm is only slightly different. This can be explained by the identical flow resistance in the sheet metal plane between punch/die and blankholder/die for both wall thicknesses. For the thinner wall thickness of 100 µm, the flow resistance is a little bit higher. However, the flow gap of 100 µm is large enough to displace the material into the cup wall without a significant increase in the deformation resistance.

In contrast, there is with an average difference of 60 % between wt = 71 µm and wt = 36 µm a high dependency of the material utilisation on the wall thickness in micro scale. By using the smaller punch diameter of d_{P2} = 0.328 mm, the material utilisation increases unexpectedly in comparison to the macroscopic process. This anomaly can be explained by the grain structure after extrusion stage 1. In the pin head, the initial grain structure is nearly undeformed in both, the macro and micro scale [6]. In micro scale, the number of grains over the cross section is significantly lower. Thus, fewer dislocations can be accumulated at the grain boundaries. In accordance to the Hall-Patch relation, the hardening and also the strength is therefore lower in micro than in macro scale. This assumption can be also confirmed by the microhardness measurements of the pin in Kraus et al. [6]. Here, the pin head shows a lower hardness in micro scale. This is why the material can flow more easily into the cup wall. Thus, both the material utilisation and the pin height are significantly higher for d_{P2} = 0.328 mm compared to the larger wall thickness in macro scale.

A further size effect is the significantly lower material utilisation (Fig. 4) and cup height (Fig. 3) for the smaller cup wall thickness of 36 µm (d_{P2} = 0.399 mm) in micro scale. Actually, the lower material utilisation can be well explained by the in the state of the art known surface layer model. Wang et al. [1] has applied this model for bonded forming in a comparable micro-coining process. Here, it is postulated that the friction inhibited the material flow via the surface grains. With a decreasing number of grains, an increase of the flow resistance is assumed. Once a grain count of two is reached, all grains are constrained in movement by the tools and the flow resistance reaches its maximum. For the materials Cu-OFE and AA6014-W, this model fits to explain the low material utilisation at d_{P2} = 0.399 µm, since there are just 1-5 grains across the cross-section [4]. In order to verify the surface layer model in this process, additional tests are carried out with the ultrafine grain material AA6014-ARB. Due to its grain size, at least 58 grains are present over the smallest wall thickness of wt = 36 µm. Thus, according to the surface layer model, more material should flow into the cup wall due to the relatively small proportion of surface grains. Nevertheless, the size effect of a significant decrease in material utilisation in extrusion stage 2 can be observed here as well. Considering the results with the different materials and grain sizes, it can be interpreted that the increasing flow resistance in the cup is not significantly dependent on the grain size, but mainly on the width of the flow gap and, if possible, on the material strength. This independence of the material utilisation from the grain size in a geometrical correctly scaled process leads to the conclusion that the laws for calculating the deformation resistance are not valid for very small wall thicknesses. A possible explanation for this might be the very small flow gap between the two tool surfaces. Due to the large ratio between tool contact surface and workpiece volume, the material flow is heavily inhibited by the wall friction. The higher the material strength, the more wall friction can be transferred. Thus, the material utilisation decreases with an increasing material strength. This assumption is confirmed for the materials Cu-OFE and AA6014-W in Fig. 4. Despite the decreasing material utilisation, the material AA6014-ARB cannot be used to verify this theory since the die penetration depth in extrusion stage 1 is 19 % lower. Thus, the flow resistance between punch/blankholder and die is lower, which might be also a factor for the lower material utilisation of the ultrafine grained material.

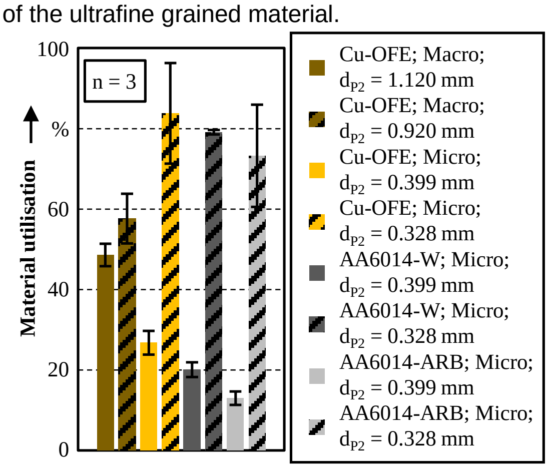

Fig. 4: Material utilisation during extrusion stage 2

4.3 Shearing (Separation of the micro part)

To evaluate the cutting edge after shear cutting and the surface quality of the parts, the surface topography of the parts is analysed by confocal laser scanning microscopy on a Keyence VK-X200. A 50x magnification lens is used to achieve a high resolution.

The surface images for the materials AA6014-W and AA6014-ARB are presented in Fig. 5. Comparing the two components, a damage of the surface of the micro part made of AA6014-W is noticeable. This damage is located in the area of the transition between the cup wall and the remaining pin. This can be related to the ejection process after extrusion stage 2. During ejection, the micro part is subjected to tensile stress due to the wall friction. As a result of the reduction of the cross-section in the pin/cup wall transition zone, particularly high tensile stresses occur in this area. Thus, the considerably lower material strength of AA6014-W leads to damage to the cup wall. For this reason, materials with the highest possible strength are recommended for a stable process.

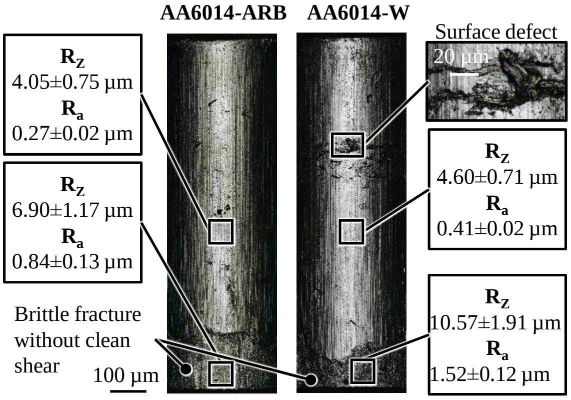

Fig. 5: Comparison of the surface and component quality of the micro parts made of AA6014-W and AA6014-ARB

For both materials, the cutting edges show a brittle fracture without a clean-shear area. This is caused by the high work hardening in the pin foot area during pin forming in extrusion stage 1. As a result of the lower punch penetration depth, the fracture zone for AA6014-ARB is longer than for AA6014-W. For AA6014-ARB, the cutting edge shows a slightly smoother fracture surface overall. This can be explained by a more brittle fracture due to the higher pre-hardening. The component surface is at a comparably good level for both materials with R_Z 4.05 µm for AA6014-ARB and R_Z 4.60 µm for AA6014-W. With this roughness, the micro parts are in the range of the achievable surface quality for formed aluminium parts.

5. Conclusion and outlook

In this article, multi-stage bulk forming of cylindrical micro parts with cup from sheet metal is investigated. It has been proven, that the 3-stage forming from the sheet metal to the finished micro part can be performed with a high reproducibility. The process scaling into the micro scale leads to an occurrence of size effects. Depending on the geometry, these effects improve or reduce the material utilisation. It has been shown that these size effects cannot be reduced or even prevented by using ultrafine grain structure materials. Furthermore, it is evident that the grain size has no measurable influence on the material flow. In micro scale, the material utilisation decrease for low wall thicknesses due to the increasing ratio between tool contact area and component volume. Besides the changed geometrical aspect ratio, only the strength of the material seems to influence the die filling. During ejection of the pin with cup after backward extrusion, damage to the cup surface occurs in soft material conditions due to high tensile stresses in the cup area. For this reason, high-strength materials are recommended for the forming of filigree, large-area form elements in the micro scale.

Future research work will focus on the transferability of the successful laboratory tests to mass production. In this context, it should be demonstrated that the micro parts can be fabricated in a progressive die on a high-speed press in high quantities with a high repeat accuracy.

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