Micro-extrusion of ultrafine grained copper

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ABSTRACT: Because of the well known virtues of low cost and high productivity, metal forming technology is well suited for mass production of metal micro-components. However, scaling down metal forming processes proves to be problematic because, among other factors, the relatively coarse grain (CG) structure of micro-billets leads to non-uniform material flow and lack of repeatability during microforming. A substantial grain size reduction below one micron should help to prevent these problems. The aim of the presented study is to investigate a possibility of using an ultrafine grained (UFG) metal for micro-extrusion. The material used for this purpose is CP Cu often used for electrical applications. The UFG version of Cu is produced by severe plastic deformation at room temperature using up to 8 passes of equal channel angular pressing. The microstructure and compression properties of the UFG version of the material are tested. The microforming process of backward extrusion is carried out at room temperature using half cylindrical billets. The extrusion force, grain flow, shape representation and surface quality of the extruded micro-components are compared.

Key words: ultrafine grained metal, ECAP, micro-extrusion, in-situ process observation

1 INTRODUCTION

Micro technology is gaining an increasing interest due to mobile phones, digital cameras and other consumer electronics products, which become smaller every day. Following this trend, an increasing market for small parts must be satisfied by the production industry. Depending on the required functionality of these parts and the production volume, different manufacturing technologies are available like machining, moulding and forming. In the case of the smallest metallic parts, most of them are produced using machining processes like turning, grinding or milling. For small batch production, machining may be justified. If large quantities of micro-parts are requested, the forming technology is more appropriate due to its high production rate and remarkable accuracy. However, investigations on microforming processes have shown significant differences in the forming behaviour compared to the conventional scale forming, which prevents microforming from being used on a wider scale. Research activities in microforming during the last decade have identified and analyzed the two main size-effects, one with relation to the material flow and another one due to friction. The former can be explained by a dependency of the material flow on the grain size (Hall-Petch effect) and the ratio of the grain size and part's dimensions (contribution of surface grains) [2,3]. The size-effect related to friction has been first investigated using ring upsetting tests scaled-down according to the similarity theorem [4]. A more detailed study has been done using a double cup extrusion test [5,6] which confirmed the previous

findings and was used as a basis for theoretical approach [7] describing scale dependency of the friction factor m.
In this paper, the size-effect on friction is assumed to be constant for all of the experiments and thus not analyzed in detail. Since the microstructure has been identified to be one of the main reasons for process-scatter, as well as the uneven shape evolution in can backward extrusion, a novel approach is proposed here to use the ultrafine grained (UFG) material to reduce the scaling effects.

2 PREPARATION OF THE ULTRAFINE GRAINED MATERIAL

2.1 Technology and samples

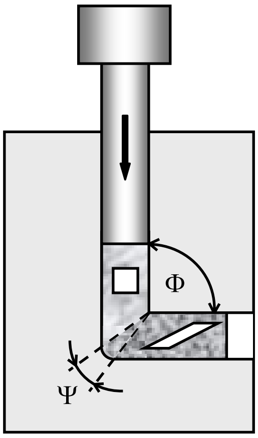

Fig. 1. Schematics of ECAP.

Fig. 2. Forward extruded copper bar and square samples processed by 4 and 8 passes of ECAP.

First, a copper (Cu 99.9%) bar was cold forward extruded to reduce its diameter from 20 mm to 13 mm. Next, samples of about 8x8x46 mm were cut from the middle of the extruded bar and processed by equal channel angular pressing (ECAP [8]) up to 8 times; Fig. 1 explains the principle of the ECAP process. The ECAP tooling used was based on a 90º one-turn channel made in a die insert prestressed with rings. The billet rotation between consecutive passes of ECAP was 90º (route Bc). The samples were lubricated with dry MoS2 and fat. Due to high ductility of copper, ECAP was performed at room temperature. The equivalent (logarithmic) strain produced was 0.86 for extrusion and 1.15 for each pass of ECAP. Fig.2 displays a round bar produced by forward extrusion and ECAPed samples after 4 and 8 passes.

2.2 Microstructure

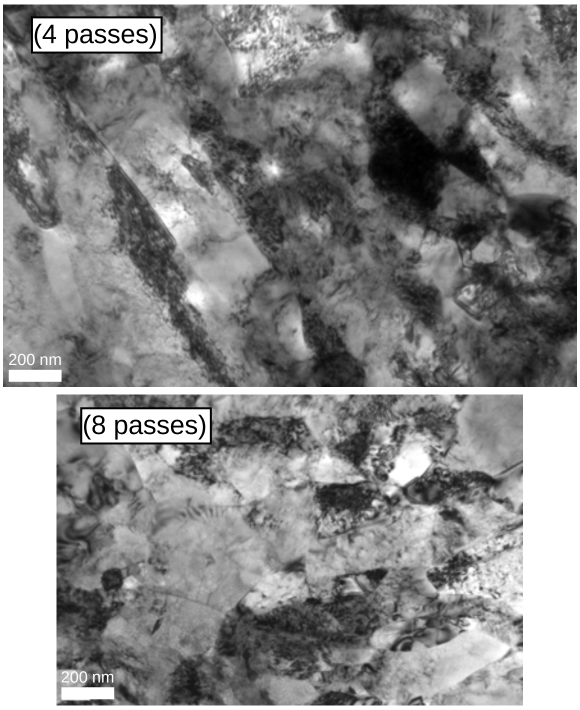

Fig. 3. Structure of copper subjected to forward extrusion followed by 4 and 8 passes of ECAP at room temperature.

The estimated grain size in the extruded copper was 30 μm. The microstructure of the ECAPed copper was investigated using TEM. Fig. 3 presents TEM results for the microstructure of samples after 4 and 8 passes of ECAP. It can be concluded that, after 4 passes, an UFG structure is produced within a distinctive pattern of shear bands. After 8 passes the bands become less recognisable which leads to more equiaxed grains.
It is interesting that the average grain size measured on the plane perpendicularly to the sample axis after extrusion and 4 passes of ECAP was 150 nm while after extrusion and 8 passes of ECAP it was 200 nm.
This change might signal the onset of a bimodal structure being created as the result of a higher number of passes.

2.3 Properties

For micro-extrusion, the most interesting plastic property of the material is its flow stress in compression. Compression testing has been performed for the forward extruded copper and for the UFG copper after it has been extruded and ECAPed 8 times. The cylindrical specimens were prepared with shallow flat lubricant reservoirs on both ends. The specimens were 7 mm in diameter and 9 mm high. The lubricant used was paraffin. The tests were performed using the load control mode of a servo-press with the load rate of 2.5 kN/s. The initial strain rate was about 8×10^{-3} s^{-1}.

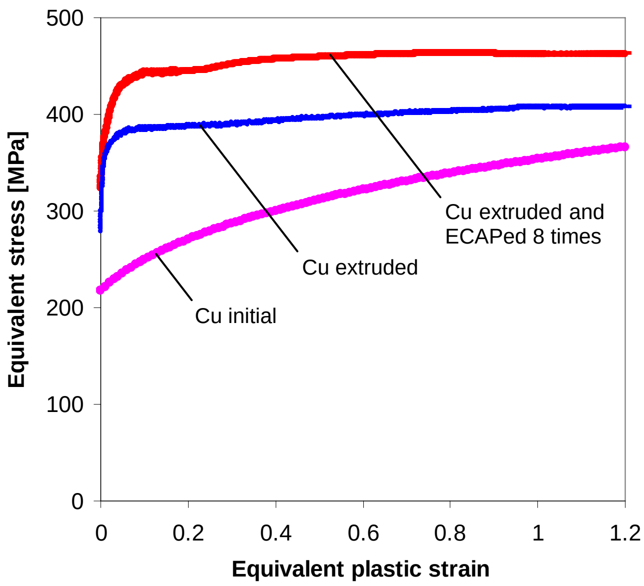

Fig. 4. Strain hardening curves for copper before extrusion, after extrusion and after extrusion and 8 passes of ECAP.

Fig. 4 displays the two strain hardening curves obtained in this way. For comparison purposes a strain hardening curve for the initial material before forward extrusion, is also presented. Judging by its yield strength of 220 MPa, the initial material was not annealed. After forward extrusion, the yield strength of the tested copper increased to 280 MPa but very quickly a relatively flat hardening curve was reached at about 400 MPa. The UFG material produced by extrusion and 8 passes of ECAP had a similar characteristic, just at a higher level of 460 MPa. It can be concluded that, for the material tested, the yield stress increase due to the UFG structure is rather modest compared to a traditionally cold formed copper. From the microforming point of view it is good news because the beneficial UFG structure can be used without much penalty in terms of stresses and forces required for microforming.

3 EXPERIMENT

3.1 Experimental setup

In order to investigate both, the overall deformation behaviour in terms of the forming force and its scatter and the local forming behaviour in terms of local deformation and shape evolution, a novel experimental setup has been developed [9]. By using a translucent tool, it enables the in-situ observation of the material flow during process and also a post-process analysis of the stress-strain state in the forming area. The process chosen for these investigations is backward extrusion of a can where the die and punch are cut in the centre to obtain a half cylindrical geometry. The die is closed by a side cover made from sapphire. Through this tool, using a CCD-camera system and a telecentric objective, the deformation process can be investigated. The tool consists of a die with an inner diameter of 1 mm and a punch of 0.7 mm in diameter. Thus the resulting wall thickness is about 150 micron. The setup of the tool system used is shown in Fig. 5.

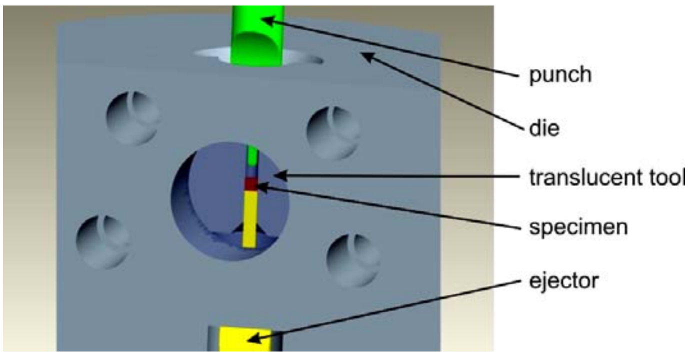

Fig. 5. Setup of the novel tool concept.

3.2 Experimental results

The results of the experiments have been analyzed in terms of the forming force, process scatter, shape evolution and local deformation behaviour. With respect to the forming force and its scatter, it can be shown (Fig. 6) that UFG copper produced by 4 (NC_4) and 8 (NC_8) ECAP passes shows some noticeable differences. This can be explained by the differences in the material properties and microstructure: the forming force for NC_8 is slightly higher, and, since the material structure of NC_8 is more homogeneous, scatter of the forming force is reduced which can be interpreted as an increased process stability as well as shaping accuracy.

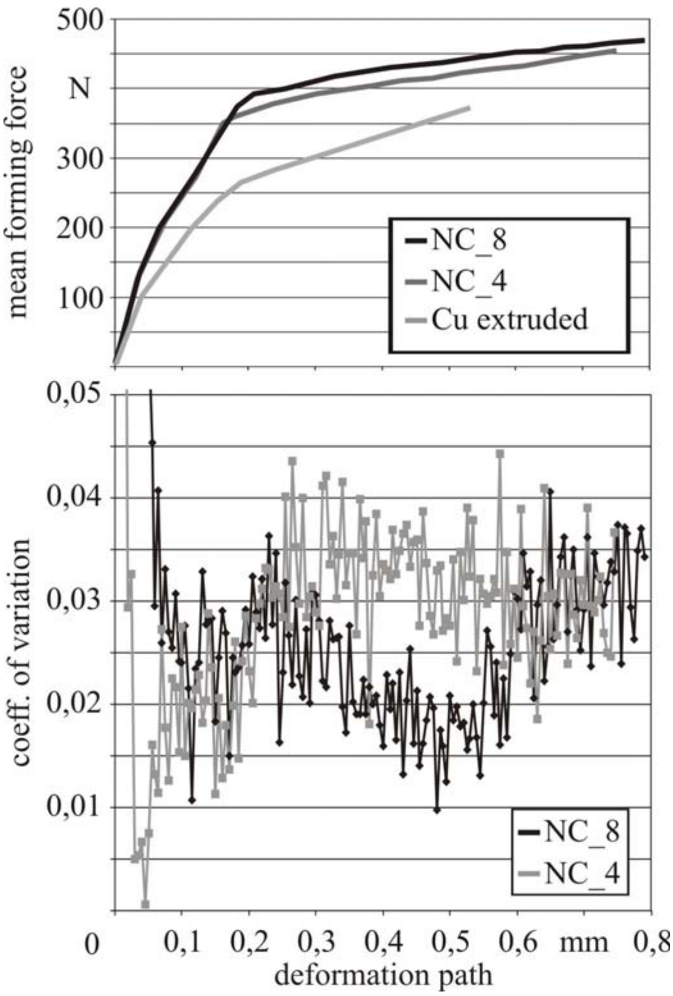

Fig. 6. Forming force and process scatter during backward extrusion of a UFG copper can.

The local deformation recorded by a CCD camera, with resolution of about 2 microns, shows nearly no differences between NC_4 and NC_8. In both cases the deformation area is tightly and homogeneously distributed around the punch (Fig. 7). In terms of shape evolution, the optical measurements of the top surface of the extruded wall clearly show that the surface of NC_8 is less rough than that of NC_4.

4 CONCLUSIONS

The results show that microforming processes benefit from the UFG structure of the metals formed. Scaling effects, like process scatter and uneven shape evolution, can be significantly reduced compared to the conventional coarse grained (CG) metals. Therefore, it is expected that further research activities, necessary to understand the micro and macro aspects of deformation of CG and UFG metals, will lead to even better results and help introduce the microforming into industrial practice.

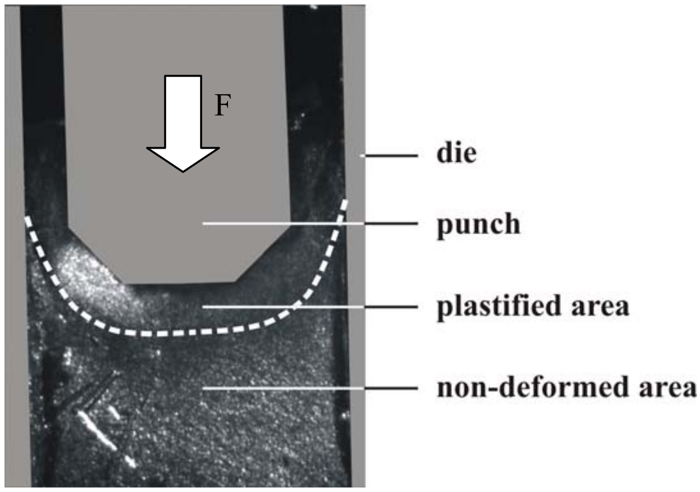

Fig. 7. Local deformation during backward extrusion of an NC_8 UFG copper can.

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