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Deep drawing behaviour of ultrafine grained copper: modelling and experiment

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Abstract Ultrafine grained materials produced by severe plastic deformation methods possess attractive mechanical properties such as high strength compared with traditional coarse grained counterparts and reasonable ductility. Between existing severe plastic deformation methods the Equal Channel Angular Pressing is the most promising for future industrial applications and can produce a variety of ultrafine grained microstructures in materials depending on route, temperature and number of passes during processing. Driven by a rising trend of miniaturisation of parts these materials are promising candidates for microforming processes. Considering that bi-axial deformation of sheet (foil) is the major operation in microforming, the investigation of the influence of the number of ECAP passes on the bi-axial ductility in micro deep drawing test has been examined by experiments and FE simulation in this study. The experiments have showed that high force was required for drawing of the samples processed by ECAP compare to coarse grained materials. The limit drawing ratio of ultrafine grained samples was in the range of 1.9–2.0 with ECAP pass number changing from 1 to 16, while a higher value of 2.2 was obtained for coarse grained copper. However, the notable decrease in tensile ductility with increase in strength was not as pronounced for bi-axial ductility. The FE simulation using standard isotropic hardening model and von Mises yielding criterion confirmed these findings.

Introduction

The quest for miniaturisation of various metallic parts and components—such as electrical connectors, micro-screws or fasteners used in electronic and telecommunication products—has grown substantially over the last decade. A recent trend is to manufacture such parts by 'microforming', which is defined as the production of metallic parts by forming with dimensions in the sub-millimetre range [1]. The use of material with a conventional grain size even in the micron range would lead to high mechanical heterogeneity across the section of samples during forming and consequent loss of dimensional control [2]. With dimensions of the part decreasing there is an impetus to use material with very small grain sizes to render a sufficient number of grains across the smallest dimension of the part.

Ultrafine grained (UFG) materials produced by severe plastic deformation (SPD) methods possess attractive mechanical properties compared with their traditional coarse grained counterparts. Of existing SPD methods equal channel angular pressing (ECAP) is the most promising for future industrial applications and can produce in materials a variety of ultrafine grained microstructures depending on route, temperature and number of passes used during processing [3].

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However, even when the dimension of the part and the grain size decrease proportionally, the technology for microforming cannot be scaled down from macro processing due to the change in material behaviour at the micro-level. 'Bulk' material behaviour is observed in metals with grain sizes in the order of microns to tens of microns when the thickness of a tensile specimen exceeds about 10–15 times the grain size [4–7]. For others, light alloys such as aluminium alloys despite a reduction in tensile ductility after ECAP processing the bi-axial properties can be significantly improved [8, 9].

Considering that bi-axial deformation of sheet is the major operation in microforming, the deep drawing behaviour of a 0.4 mm thick copper sheet with variety of grain structures produced by different number of ECAP passes have been studied. The investigation of the influence of the number of ECAP passes on the bi-axial ductility in micro deep drawing test has been examined by experiments and finite element (FE) simulation in this study.

Experimental procedure

The material used for this study was commercially available copper with a purity of greater than 99.95%. The specimens were annealed at 600 °C for 2 h under inert atmosphere before ECAP processing. To achieve the variety of UFG microstructures, bars of 20×20 mm^2 in cross-section were subjected to 1, 2, 4, 8, 12 and 16 passes of ECAP according route B_C (90 clockwise rotation of the specimen around its longitudinal axis after each pass).

The mechanical properties of the ECAP processed material were characterised by uniaxial tension testing in a screw driven Instron machine and a small-scale Swift (flat–bottom) cup test. Tensile tests were performed in duplicate at room temperature with a nominal strain rate of 1.6×10^{-3} s^{-1}. A detailed description of microstructures and properties obtained is given elsewhere [10]. The mini Swift test used a 6 mm diameter punch and round discs of diameters between 9.5 and 14.6 mm which had been ground and polished to the required thickness of 0.4 mm using Tenupol-1 equipment. Using this method, the limit drawing ratio (LDR)—which is defined as the ratio of the largest blank diameter drawn without failure to the punch diameter—was determined for the ECAP processed copper.

Properties of the UFG CU

Tensile properties of ECAP processed copper

The as-received annealed (coarse grained) Cu had a relatively low strength and a total elongation strain of 0.5 and upwards, whereas the ECAP processed samples showed a significant increase in strength but a considerable decrease in ductility (Fig. 1). The maximum or peak stress is achieved within 1–2% of uniform elongation; however, there is a relatively high post-uniform elongation of about 8–9%. The sample subjected to four ECAP passes has the poorest ductility but maximum tensile strength (Fig. 1) and this is consistent with our previous study [8] that showed with number of passes increasing up to four the tensile strength gradually increased while total elongation decreased, but thereafter some softening occurred and tensile strength decreased while total elongation increased (Fig. 2).

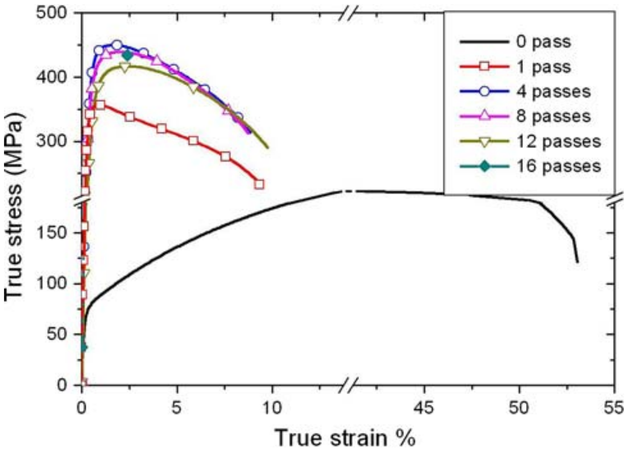

Fig. 1 True stress–strain curves for samples subjected to different number of ECAP passes (after [10])

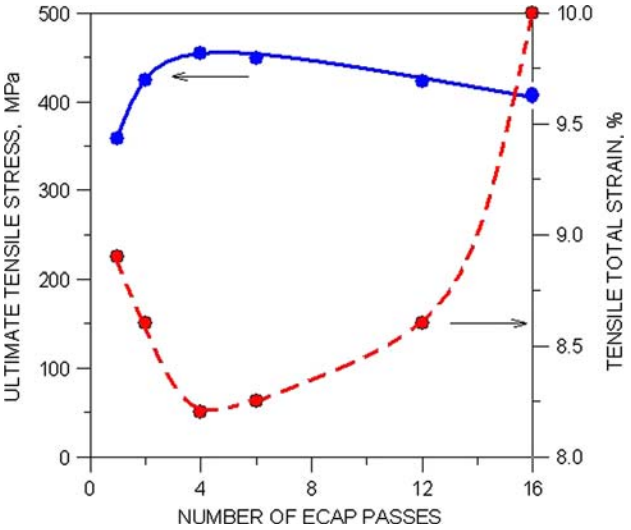

Fig. 2 Tensile strength (*solid line*) and tensile ductility (*dash line*) as functions of number of ECAP passes

Deep drawability of ECAP processed copper

Several typical drawn cups are show in Fig. 3 with decreasing the blank sizes from the left to the right hand side. The LDR versus number of ECAP passes is shown in Fig. 4. The material processed by one ECAP pass has a minimum LDR (below 1.9) which might correlate with the poorest tensile ductility. A slight increase in LDR can be seen with number of passes increasing up to four, confirming an improvement in deep drawability, perhaps, due to increased normal plastic anisotropy, $\bar{r}$ value ($\bar{r} = (r_0 + 2r_{45} + r_{90})/4$), as was observed for UFG aluminium [9]. However, a slight reduction of LDR was observed after four ECAP passes, opposite to increase of tensile ductility. Nevertheless, the LDR value for UFG Cu

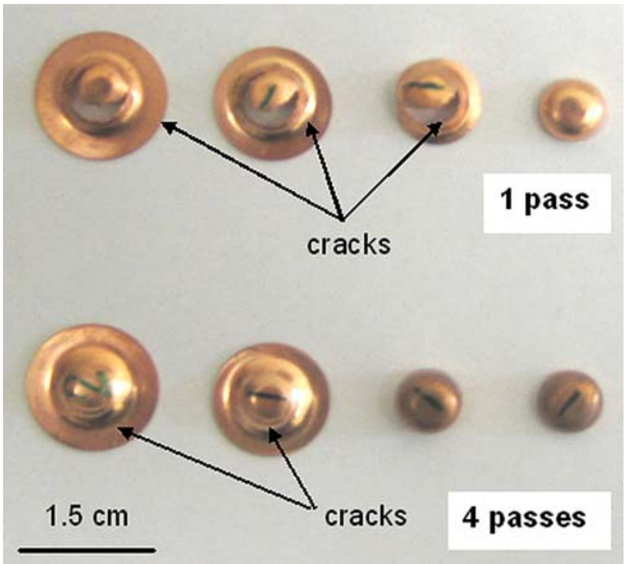

Fig. 3 Cups drawn from blanks with four different diameters from copper processed by one and four ECAP passes

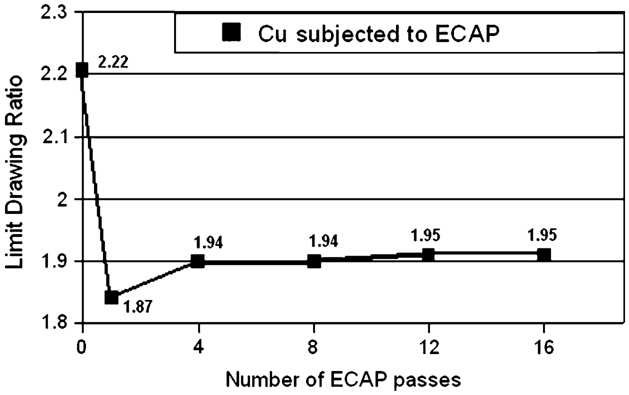

Fig. 4 Limit drawing ratio versus number of ECAP passes (experimental data)

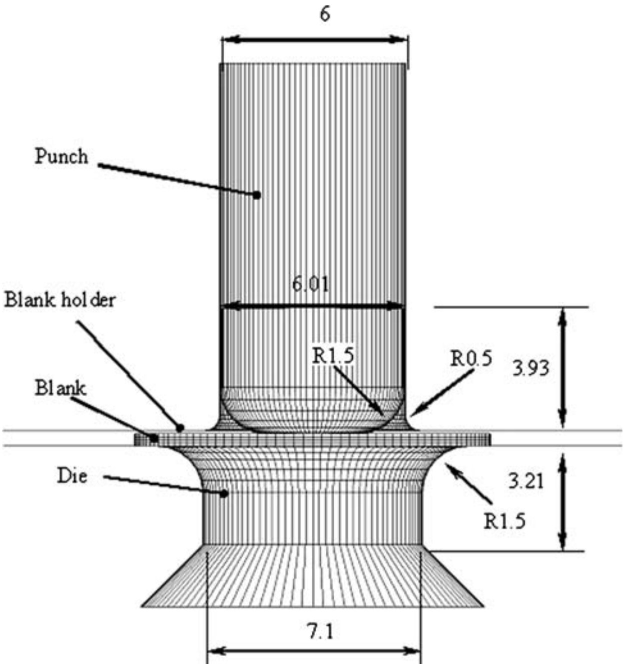

Fig. 5 Tool configuration for FE simulation (dimensions are given in mm)

Table 1 Blank size (mm)

Thickness	0.4				
Diameter	14.6	13.1	11.5	12.6	9.5

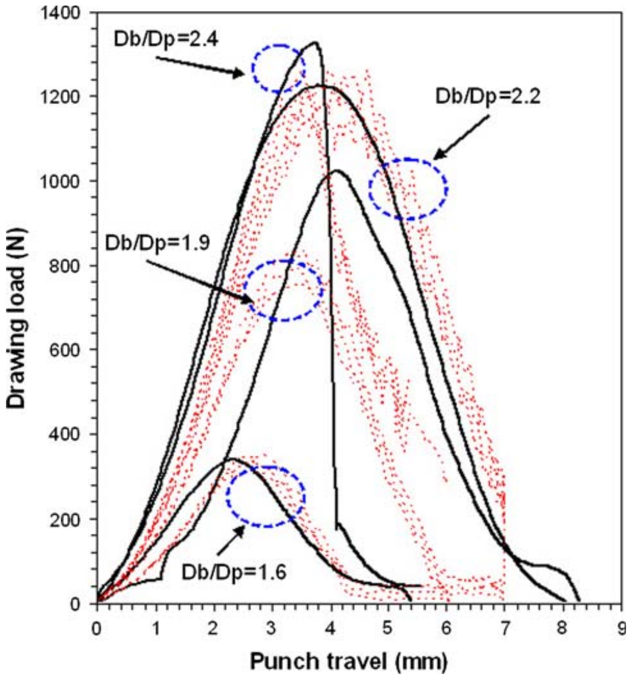

Fig. 6 Drawing load versus punch travel distance for cup test on coarse grained copper, experimental data (*solid lines*) and simulation with different coefficients of friction (*dotted lines*)

is fairly close to the range of 2.0–2.2 as seen in the normal scale deep drawing process with traditional coarse grained materials [11]. It is important to note that despite the big decrease in tensile ductility from about 50% for annealed copper to below 10% for ECAP processed copper, LDR of those materials differs insignificantly and, therefore, the drawability suffers insignificantly from grain refinement.

Simulation of small-scale swift cup test

Simulation setup

A three-dimensional FE simulation was carried out using a commercial package *ABAQUS/Explicit* (version 6.5). The tools including punch, blank holder and die were treated as rigid bodies (see Fig. 5). The copper blank was a deformable body with a thickness of 0.4 mm and different diameters (see Table 1). von Mises yield criteria and isotropic hardening law were assumed. In all cases, the blank holder force was 112 N.

The equivalent stress–strain curves for Cu from Fig. 1 were used in the simulation. To estimate the post-necking effect in flow curves on simulation of bi-axial behaviour the simulation has been done twice: (i) with hardening only; and (ii) with hardening followed by softening. The first simulation ignored strain softening after the critical strain and the stress was assumed constant after reaching the peak stress. The second simulation considered both parts of the flow curve including strain hardening and softening. For course grained materials the flow curves do not have a softening part, while the UFG materials

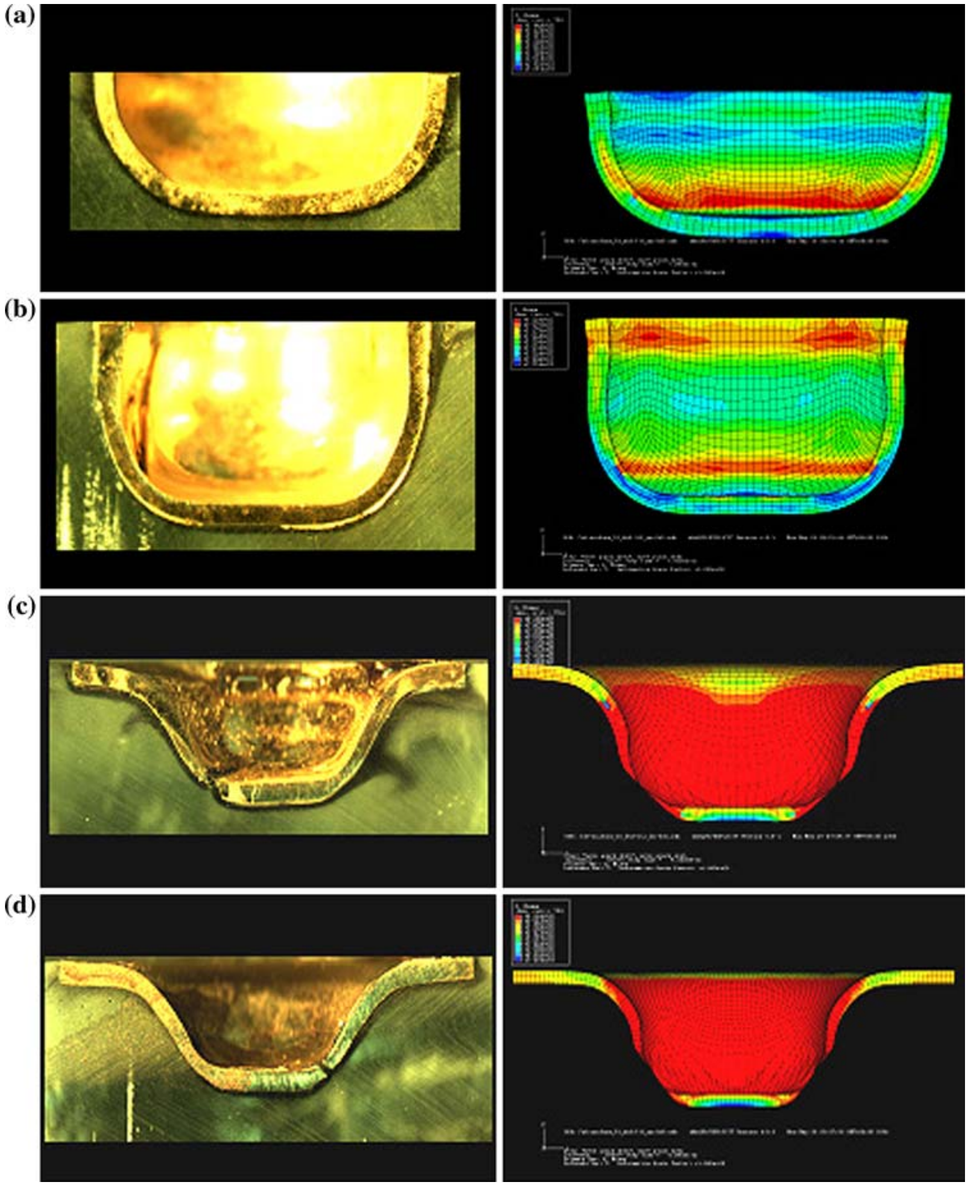

Fig. 7 Cups drawn from copper subjected to eight passes of ECAP: experiments (*left*) and simulations (*right*). **a** $D_b/D_p = 2.4$; **b** $D_b/D_p = 2.2$; **c** $D_b/D_p = 1.9$; **d** $D_b/D_p = 1.6$

normally have a considerable softening behaviour [12]. The simulation of the drawing of coarse grained material was used to define the coefficient of friction as discussed in the section "Simulation results and discussion".

Simulation results and discussion

To define the coefficient of friction the simulation of drawing test for annealed coarse grained material has been done with its value varied in the range of 0.01–0.3 and results were compared with experimental data. In Fig. 6 the drawing load calculated for different coefficient of friction (dotted lines) is compared to the experimental data (solid line) for different blank diameters. The major influence of friction coefficient occurred in the descending part of the loading curve where the free drawing or fracture has been happening. The most reasonable approximation has been obtained at the coefficient of friction equal to 0.1, which was used in further simulations.

A comparison of the shape after cup test predicted by simulation and obtained in experiments is shown in Fig. 7 for samples subjected to eight ECAP passes prior to drawing. The flow curves for simulation had a hardening and softening part reflecting the real behaviour of copper processed by eight passes of ECAP shown in Fig. 1. Reasonable agreement between these shapes was achieved especially in a case were full drawing has taken place without fracture. In case of fracture the simulated shape was larger due to the difference in failure criterion. In experiment failure was defined by appearance of a crack while in simulation the failure was defined by the loss of thickness. However, in case of full drawing without fracture the experimental and simulated shapes and loading curves were particularly close.

To define LDR the load–displacement curves have to be obtained from FE simulation. Modelling has been done for constitutive equation with only hardening and with hardening followed by softening. The calculated load–displacement curves for UFG copper processed by four ECAP passes and two blank sizes are shown in Fig. 8 and compared with the experimental data for the same conditions. A relatively good agreement was achieved between tests and simulation with lower and upper estimation of maximum drawing load given by both constitutive models, though a fluctuant curve was obtained in simulation which was due to the dynamic nature of ABAQUS/Explicit.

The maximum drawing load plotted versus diameter of the blank to diameter of the punch ratio gives the value of LDR, which is defined by an intersection of two linear parts of diagrams. One part defines the range of D_b/D_p for safe drawing (climbing curve on the left) and the second part defines the range of D_b/D_p where the fracture will happen (horizontal or slightly descending curve on the right).

LDR values obtained in experiments and simulation as shown in Fig. 9 are compared in Fig. 10. It can be seen that the simulation using only the hardening flow curves tended to over-estimate the drawing load–displacement curve and

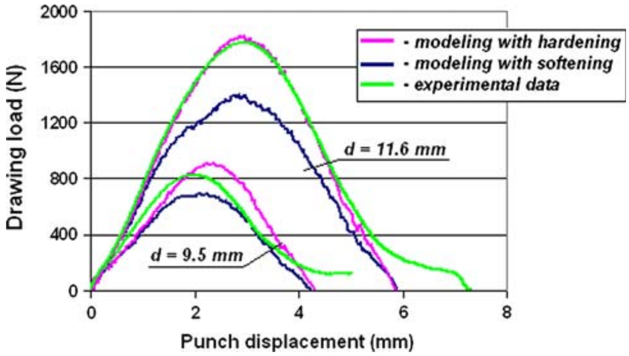

Fig. 8 Simulated and experimental load–displacement curves (four ECAP passes)

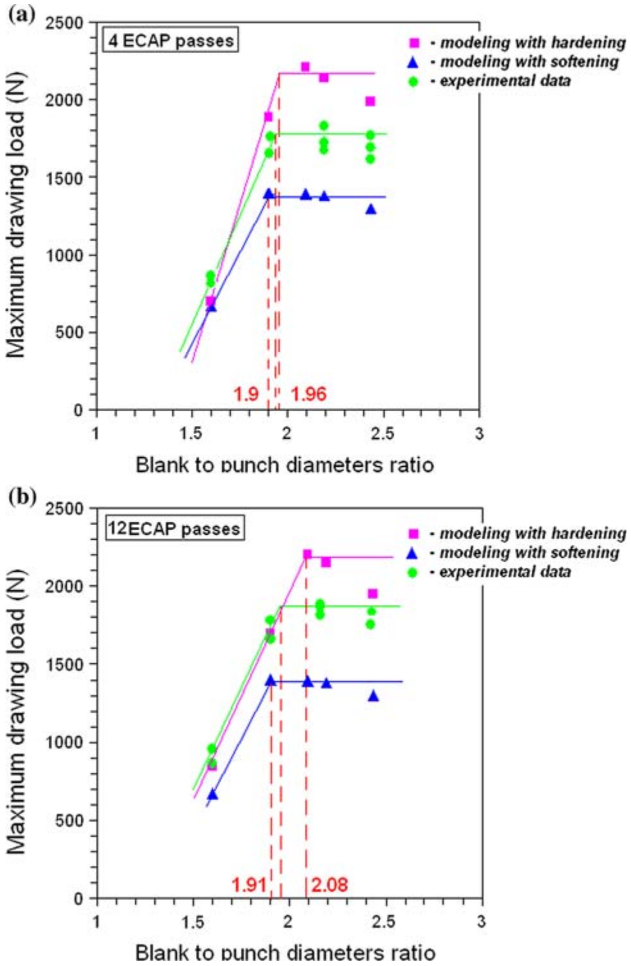

Fig. 9 Determination of LDR from simulation results and comparison with experiments for copper subjected to: **a** 4 ECAP passes and **b** 12 ECAP passes

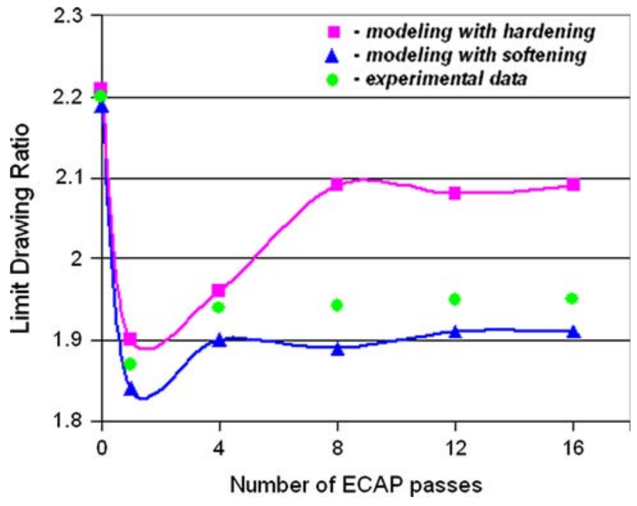

Fig. 10 LDR values for copper subjected to different number of ECAP passes from simulation and experiment

the limit drawing ratio, while the consideration of both parts of flow curves with hardening and softening gives the low bound for both drawing load-displacement curve and LDR. The experimental data are more distant from simulation with hardening only, which reflects that real flow curves have both hardening and softening parts; and, therefore, the simulation with hardening followed by softening behaviour taking into account gives better prediction of the cup test and LDR.

It can be seen that the decrease in LDR value was insignificant for UFG copper regardless number of passes, compare to the significant loss of tensile ductility from 50% to below 10%. That can be explained by the enhanced strain rate sensitivity in UFG materials, which controls the local thinning and localised necking and improves post-necking elongation. However, the effect of enhanced strain rate sensitivity is expected to be more pronounced at higher than room temperatures.

Conclusion

In this study, UFG copper was used in micro deep drawing process. Material has been processed with different number of ECAP passes. Both the experimental deep drawing and FE simulation of Swift cup test were performed. Tests showed that a much higher drawing force was required for high strength UFG copper compare to annealed material. The limit drawing ratio of ECAP processed copper was in the range of 1.9–2.0, while a higher value of 2.2 was observed for the coarse grained copper. The FE simulation using standard isotropic hardening law and von Mises yield criterion confirmed these findings. The decrease in LDR value was insignificant for UFG copper regardless number of passes, compare to the significant loss of tensile ductility from 50% to below 10%, which supports the potential application of UFG copper for microforming operations.

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