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FINITE ELEMENT AND EXPERIMENTAL ANALYSES OF REPETITIVE BENDING AND STRAIGHTENING OF COMMERCIALLY PURE COPPER

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Abstract. Feasibility of a repetitive bending and straightening (RBS) process to introduce fine-grained microstructures in sheets of commercially pure copper was investigated. The deformation behavior during RBS was analyzed using the finite element method to compare with the experimental results. The tensile strength increased after the first two passes but decreased for the third pass, probably due to the damage accumulated during the first two passes in the sample. The elongation to failure was also higher after the second pass than the third pass. The hardness increased significantly; however, the increase was not uniform throughout the length of the sample suggesting that the deformation is not homogeneous.

1. INTRODUCTION

In recent years, several manufacturing methods have been proposed to produce ultrafine grained (UFG) bulk materials [1-3] by imposing severe plastic deformation (SPD) [4-6]. It has been reported that materials with UFG structures show outstanding mechanical properties at ambient temperatures; the properties include high strength, high fatigue strength, good ductility, high strain rate superplastic deformation at elevated temperatures and high corrosion resistance. The UFG structures in metallic materials have been produced by several novel SPD techniques. Some of these techniques, such as equal channel angular pressing, were successfully applied to introduce a UFG structures in a variety of pure metals and alloys. Of these techniques, only accumulative roll bonding and groove pressing were appropriate to manufacture UFG sheets or plates which are the most widely used material shape in industrial fields. These processes allow a material to accumulate very large strains without changing the initial dimension of the original workpiece.

Repetitive bending and straightening (RBS) process [8] is a U-bending process carried out in two steps: bending followed by straightening. The schematic of the RBS process is illustrated in Fig. 1. Deforming the workpiece to a U-shape by bending is carried out in the first step. In the second step the bent sheet is straightened between two flat dies. The main deformation mode of the RBS process is bending. Basically, the bending strain is dependent on the radius of the die being used [9-12]. The equivalent plastic strain of $\varepsilon = 0.4$ ($\varepsilon = 0.2$ in bending and $\varepsilon = 0.2$ in straightening) is imparted to the specimen in RBS process for R-8 dies, per pass. In the present study, the feasibility of the RBS process to

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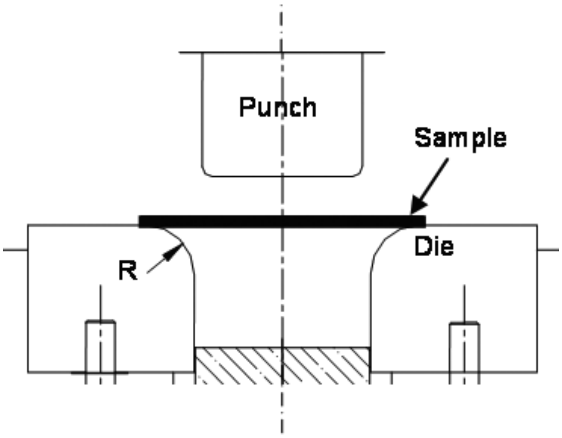

Fig. 1. Schematic of repetitive bending and straightening process.

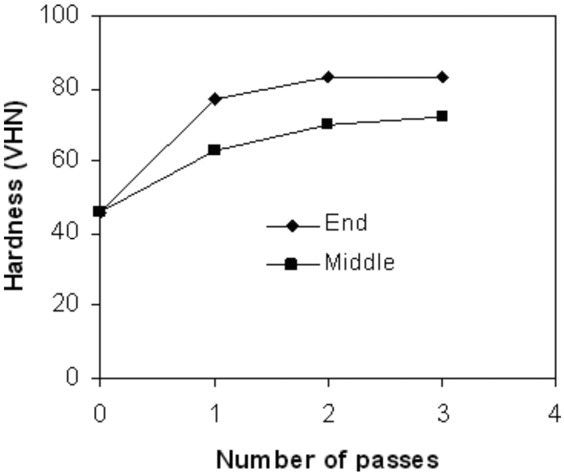

Fig. 2. Vickers hardness as a function of number of passes for copper processed through RBS using R-8 mm die.

introduce a fine-grained structure in sheets of commercially pure copper was investigated and the deformation behavior was analyzed by using the finite element method (FEM) to compare with the experimental results.

2. EXPERIMENTAL AND FEM PROCEDURES

2.1. RBS of copper

In the present study, the sample is a commercially pure (99.3%) copper sheet. Before bending, the samples were annealed at 700 °C for 2 h to increase its average grain size to about 78 μm. This large initial grain size was desired to effectively demonstrate the grain refinement ability of the RBS process. Annealed copper specimens with dimensions of 58 mm × 20 mm × 2 mm were pressed using U-bending dies [13] with bend radius of 8 mm. The tooling (die and punch) was fabricated using H11 die steel in a normalized condition. A basic RBS process consists of two steps: bending and straightening. Deforming the workpiece to a U-shape by bending was carried out in the first step. In the second step the bent sheet was straightened between two flat dies. This bending and straightening cycle was repeated 3 times (one free bending, one die bending and one straightening is called one cycle) with 180° (upside down) rotations between consecutive cycles. All experiments were conducted using a 1000 kN LUKAS hydraulic jack at room temperature with a cross head speed of approximately 0.33 mm/s. The free bending and die bending loads were measured using 5 ton DARTEC proving ring during testing. Straightening force required was also measured during the straightening of the sheet between the two flat dies.

In order to examine the homogeneity of the deformation, Vickers microhardness measurements were made at the bending regions and middle of the specimens, applying a 3 kg indent load for 15 s. The hardness values were taken as the average of a minimum of 10 measurements. Tensile testing was carried out on specimens with gage length 20 mm, width 5 mm and thickness 2 mm using a 50 kN tensile testing machine at a cross head speed of 0.12 mm/s. Three tensile tests were carried out for each pass. Data acquisition system and 500 kg load cell was used to record the tensile data for all passes. The ultimate tensile strength (UTS) was determined from the load-displacement graphs, recorded during the testing. The yield strength (YS) was measured by the 0.2% offset method. The difference in gauge length before and after fracture was measured by using digital vernier and the percent elongation to failure was reported. The microstructure of the deformed sample was characterized by optical microscope for the RBS processed and annealed specimens.

2.2. Procedure for finite element analysis

FEM simulations have always assisted researchers to simulate and interpret the experimental results observed. Recently, several researchers [14-17] have carried out systematic FE studies on various SPD processes, but not on the RBS process. In the present study, the plastic deformation behav-

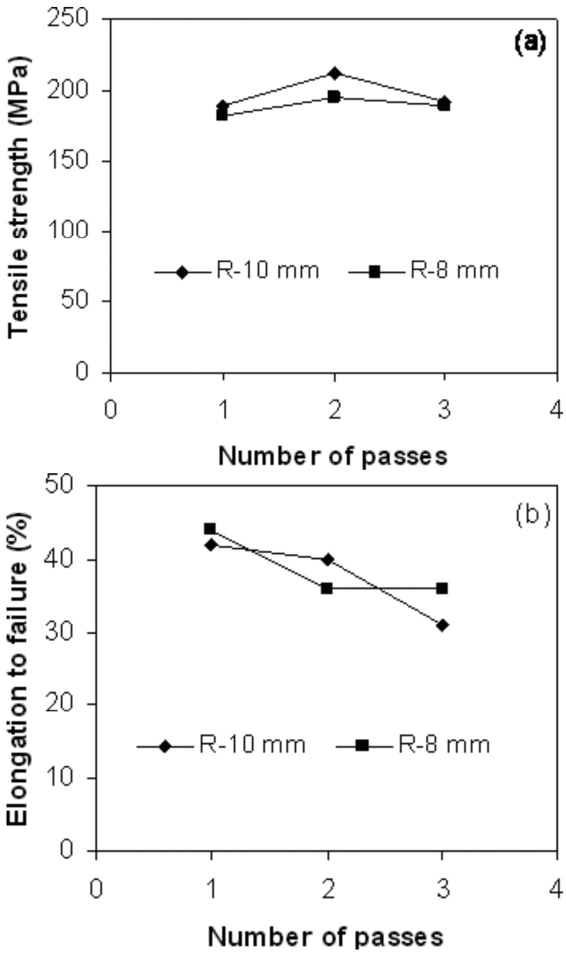

Fig. 3. Mechanical properties of RBS processed Cu using R-8 mm die: (a) tensile strength and (b) elongation to failure.

ior of the copper specimen during RBS was simulated up to three passes with bending radius of curvature of R-8 mm. The simulations were performed using the commercial implicit finite element analysis code DEFORM-2D (SFTC) [18]. An isothermal two-dimensional plane-strain problem was considered, as deformation along the normal direction is negligible. Pure copper material properties were used in all FE simulations. The stress-strain data of the material was reported in the work of Yoon *et al.* [15]. The specimen with dimensions of 60 mm in length and 2 mm in thickness was considered for simulations (width is unity along the plane normal direction in plane-strain condition). Die and punch were modeled as rigid elements. Specimen was modeled with 3000 four-node plane strain elements. A friction factor m = 0.1, which is within the typical range (0.05~0.1) in cold forming of metals, was used between the die–specimen interface and the specimen was allowed to slide along the longitudinal axis in the die cavity. All simulations were performed with a punch speed of 1 mm/s.

3. RESULTS AND DISCUSSION

3.1. Mechanical properties

In the present study, commercial purity copper specimens with purity of 99.30% were used for experimental investigations. All specimens were annealed at 700 °C for 2 h before bending to give an average grain size of ~ 78 μm. Microhardness of Cu specimens deformed by RBS at different pass and sample position (middle and edge) conditions is shown in Fig. 2. The hardness is higher at the bending regions compared to the middle of the sample, due to the localized deformation. The hardness at both the bending region and the middle of the sample increased with increasing number of passes. The maximum hardness of 87 VHN was obtained at the bending regions after pass three, using R-10 mm die. In RBS process, the deformation was not uniform along the length of the specimen due to the localized deformation i.e. the deformation is more at the bending regions than in the middle of the specimen.

Tensile strength and percent elongation to failure of Cu specimens deformed by RBS at room temperature for die radii of curvature (R-10, R-8) are shown in Figs. 3a and 3b, respectively. It can be observed that the strength is higher after pass two and drops after pass three due to micro cracks development in the specimen. Micro cracks developed due to the damage accumulation and the lack of sufficient formability to withstand repeated bending and straightening. These observations are similar for all conditions of bending radius. Annealed copper had an ultimate tensile strength (UTS) of 182 MPa. Specimens bent with R-10 die gave higher UTS (212 MPa) than R-8 die (195 MPa) after pass two. The percentage (%) elongations to failure decreased from pass one to pass three for all conditions. Annealed Cu had a ductility of 47% and this decreased to 31% after pass three of RBS through R-10 die. This decrease of ductility is due to the micro cracks developing in the specimen after pass three and is also evident from the tensile strength results. Previous research [19] has shown that the as-processed strength of Cu through repetitive corrugation and straightening (RCS) process are 100 percent higher (1360 MPa) than that of the initial, course grained Cu (678 MPa). However, RBS processed Cu investigated in this study showed very

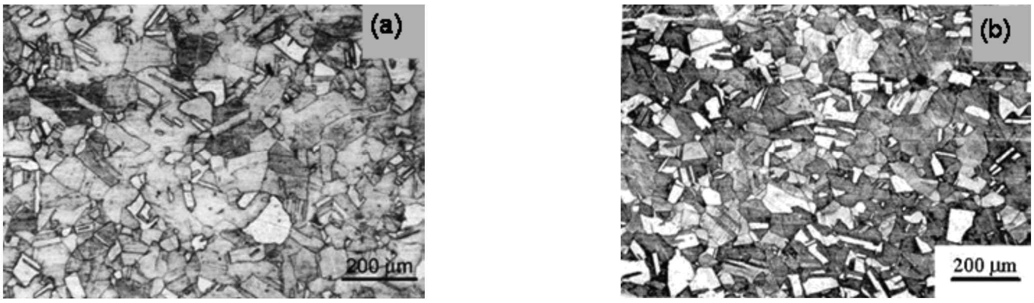

Fig. 4. Optical microstructure of CP copper after (a) annealed at 700 °C for 2 h and (b) RBS processed using R-8 mm die, pass two at bending regions.

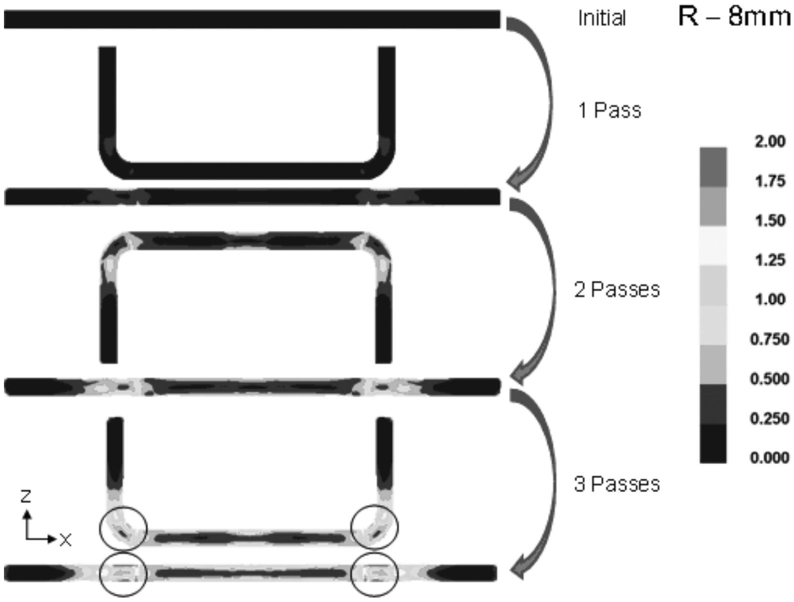

Fig. 5. Effective strain distributions in RBS processed Cu after three passes.

little improvement in strength (212 MPa) as compared to initial annealed (182 MPa) copper. Therefore the present RBS process is not suitable as it is for the production of UFG materials with improved mechanical properties. Research to enhance the deformation homogeneity by modifying the process and the die designs are underway.

3.2. Microstructure evolution

Figs. 4a and 4b show the optical microstructures of the annealed copper and the deformed copper after pass two by using R-8 die of RBS process, respectively. It is important to note that, the grain size was smaller at the bending regions than in the middle of the sample, due to the localized deformation of the specimens. Processing of Cu through RBS (starting grain size of 78 μm) using R-10 mm die gave more refinement (57 μm) as compared to R-8 mm die (62 μm) after three passes. The deformed microstructures of copper specimens by RBS process revealed that there is very little overall refinement in the microstructures.

3.3. Plastic deformation

Fig. 5 shows the simulated effective strain distribution in RBS processed samples up to three passes. It can be seen that, the deformation was induced in the specimen at two bend regions (see Fig. 5, regions marked with circles) and other flat regions along the longitudinal direction. The bend regions receive more strain and the flat regions receive very little strain during the deformation. It can be observed that, the deformation is heterogeneous not only in longitudinal direction (*x*-direction) but also in thickness direction (*z*-direction). This heterogeneous plastic deformation can be clearly seen in path plots of effective strain at the central points of the deformed sample, along the longitudinal direction (Fig.

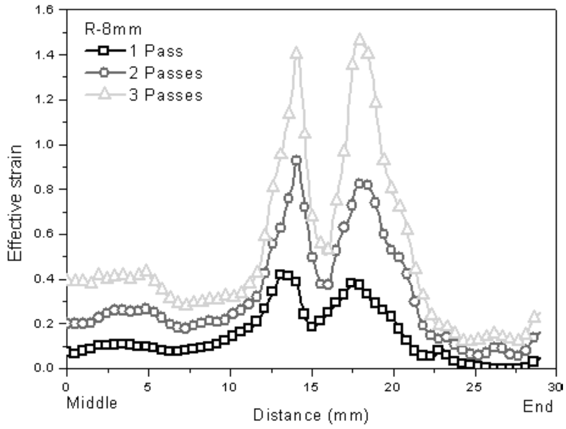

Fig. 6. Effective strain path plots at the central points along the longitudinal direction.

6). Plastic deformation is concentrated in two bending regions (15 mm from the centre of the specimen), and spreads over the length of the specimen with number of passes. However, it should be noted that the difference in maximum and minimum strain values increase with increasing the number of passes. In other words, deformation homogeneity is not achieved after increasing the number of passes.

It can be observed that the deformation is heterogeneous along the thickness direction also. This result can be seen in Fig. 7 more clearly. The effective strain at the deformed corner regions is higher at the top surface and lower at the bottom surface. As the number of passes increases, the differences in strain value also increases, hence the deformation homogeneity cannot be achieved by RBS process.

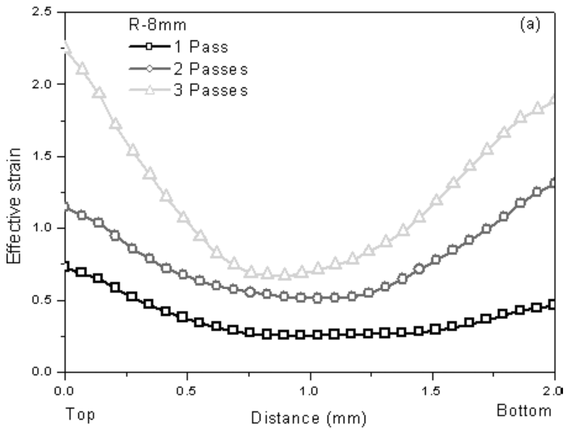

Fig. 7. FE simulated effective strain versus distance (in the thickness direction) plots of RBS processed copper measured at bending regions up to three passes using R-8 mm die.

4. CONCLUSIONS

The RBS processed Cu shows poor improvement in mechanical and microstructural properties. There is not much scope for producing higher strength and ultrafine grained microstructures in the sheet specimens. RBS for Cu is not an effective process for producing UFG microstructures. Processing of Cu using RBS did not lead to significant increase in strength and in grain refinement. Hence, RBS is not an effective method for producing UFG microstructures. The FE analysis of copper also showed that the deformation is inhomogeneous along the length as well as in thickness directions.

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