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Microstructure, texture and mechanical characteristics of asymmetrically rolled polycrystalline copper

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ABSTRACT

The process of asymmetric rolling, as an alternative to the symmetric rolling, attracts attention of many researchers and technologists. Asymmetric rolling can modify rolling process parameters like normal forces and torques, sample shape (by bending) or power requirements. It can also change material properties. The enhanced shear deformation, characteristic for this process, leads to microstructure refinement, increase of material strength and texture rotation. Asymmetric rolling can be realized by a modification of existing rolling mills, therefore its industrial application is possible at a relatively low cost. In this aspect, the case of a moderate rolling asymmetry and moderate deformation in one rolling pass was examined; these parameters can be attained on typical industrial rolling mills.

The aim of the present study is to characterize this process and resulting material modifications in the case of the polycrystalline technically pure copper. The EBSD, XRD, calorimetry and microhardness measurements were performed. Texture and mechanical characteristics were studied using a crystal deformation model and the finite element method. The latter calculations enable to optimize some parameters of asymmetric rolling process.

1. Introduction

The structure and texture of a material after symmetric rolling (SR) exhibit a mirror symmetry with respect to the plane located at the centre of the sample and parallel to the rolling plane, determined by the rolling and transverse directions, RD and TD (and perpendicular to the normal direction, ND). The asymmetric rolling (AR) process can be realized in different ways: (i) using dissimilar roll diameters and the same angular velocity of rolls, (ii) using the same rolls and different angular velocities, (iii) applying different lubrication of two rolls. Therefore, AR can be industrially applied with a modest modification of typical rolling mills. It was found that AR can modify significantly a number of important technological parameters (e.g., rolling normal force, rolling torque, power requirement). Moreover, it can lead to grain refinement, intragranular fragmentation and texture homogenization as a result of the enhanced shear deformation characteristic for this process (e.g., [1, 2]). Therefore it is attractive for industrial practice. In order to examine a realistic case, which can be adopted at industrial rolling mills, a moderate rolling asymmetry and moderate deformation in one rolling pass were examined in the present study. However, there are some factors limiting AR applications. One of them is the rolled strip curvature. Usually, this effect results in a poor product shape and can significantly reduce productivity. In some cases it can also damage the mill equipment due to the impact between the strip and the roller tablet or impede the strip entry into a roll gap of the second mill. On the other hand, in some cases the bending tendency maybe beneficial, e.g., for rolled tape wrapping on the coil.

The available literature on AR often refers to steels (e.g., [3–6]), to aluminum (e.g., [1,7–10]) and to metals with hexagonal crystal structure (e.g., [11–14]). Less frequent are articles concerning the asymmetrically rolled copper (e.g. [15]). However copper is an important material in modern technology. Copper sheets are used for production of central heating pipes, as construction parts and in electronic industry. Another, more fundamental point is that copper, having the same crystal structure as aluminum (AR process of aluminum is widely studied in the literature), has a considerably lower stacking fault energy. The latter parameter determines some material properties, e.g., the ease of stacking faults formation, the frequency of cross-slip, influence on residual stress generation, etc. The aim of the present work is to examine technological and microstructure parameters characteristic for AR of

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technically pure polycrystalline copper. The experimental results are compared with the predictions of the finite element method (FEM) and of the crystalline deformation model. The obtained results enable to optimize some parameters of AR process.

2. Experimental procedure

The examined samples of commercial copper, of the size of $5 * 25 * 100$ mm^3, were annealed during 1.5 h at 450 °C and then they were rolled on the laboratory mill with the thickness reductions of 17%, 25% and 32% (always imposed in a single pass). The thickness reduction was expressed in % and calculated as: $100 * (t_0 - t) / t_0$, where t_0 and t are the initial and final sample thicknesses. Two identical rolls of 180 mm diameter were powered by independent motors, their angular velocities were ω_1 and ω_2. Therefore the rolling asymmetry ratio was defined as:

$$A = \frac{\omega_1}{\omega_2} \tag{1}$$

The angular velocity of the lower roll, ω_1, was constant and equal to 10 rpm, while the upper roll velocity was adjusted in order to provide the asymmetry ratios, A, between 1.0 and 1.50. Some of the rolled samples were bent up or down, thus their curvatures were measured. The curvature was defined as a height of an arch (*HA*) at the standard length of sample equal to 55 mm. Bending towards the upper roll was treated as positive and in the opposite direction - as negative.

The hardness distribution across the rolled samples thickness was measured on the longitudinal section of a rolled bar (i.e., on RD-ND plane) by the Knoop method under load 0.1 kg, using the Wilson Instruments tester Tukon 2500. Requirements of standards ASTM E384 and ISO-4545 were fulfilled. The long edge of the indenter was parallel to RD during measurements. The hardness measurements were performed in five material layers disposed at different heights along ND. Two near surface layers and the layers distant from the top of 1/4, 1/2 and 3/4 sample thickness were defined. In each of these layers at least 10 measurements were done. The samples were electrolytically polished in the same way as for a metallographic examination. Polishing was performed in the Struers solution D2 at the voltage of 15 V and at the temperature of 10 °C. All examined samples were prepared in the same manner. The thickness coefficient (S) was defined in order to simplify comparison of the results for different bars. The S value is equal to 1, 0 and −1 for top, centre and bottom layers of the rolled bar, respectively.

The amount of the stored deformation energy was measured using differential scanning calorimetry - DSC (Mettler Toledo DSC 821e instrument was used). The samples of 6 mm diameter and of the thickness of 1 mm, with the mass of ca. 230 mg, were cut from the top, bottom and centre layers of the rolled bars. Before the measurement, the cut samples were treated by electrochemical etching and polishing. For each sample, 2 cycles of DSC measurement were performed in a pure argon atmosphere. In each cycle the constant heating rate of 15 °C/min was applied in the temperature range from 25 °C to 450 °C. During heating, the gas flow was equal to 80 ml/min and was still kept during 10 min after completion of a heating cycle. After reaching the final temperature, a sample was cooled down to the room temperature and then re-heated to 450 °C (the second run) to obtain the DSC baseline.

The {111}, {100}, {110} and {311} incomplete pole figures were measured, using the parallel beam of Cu Kα X-ray radiation, on the Empyrean diffractometer from PANalytical Co. The measurements were performed in the central layer of each sample. The orientation distribution functions (ODFs) were calculated next using the LaboTex commercial software [16].

The Electron Backscatter Diffraction (EBSD) patterns were registered using the Scanning Electron Microscope FEI Nova NanoSEM 450. The measurements were done at the area of 1190 × 1025 μm^2, with the step size of 0.2 μm, on the longitudinal sample sections (RD -ND planes) located in the half of the rolled bars width and thickness. Requirements of standards ASTM E2627-10 and ISO-13067 were fulfilled. The TSL OIM Analysis 7 software was applied for the EBSD data treatment.

The commercial package Abaqus v. 6.11 was used for the finite element method (FEM) modeling. The stress-strain curve, required for the definition of the modeled material, was determined in the uniaxial tensile test on Zwick/Roller Z050 machine. The plastic part of a typical tensile curve, used in calculations, is shown in Fig. 1.

3. Results and discussion

3.1. FEM calculations

The ABAQUS FEM software [17] was used and the model samples were built from 8-node linear brick elements C3D8. More precisely, the elements C3D8R with reduced number of integration points were chosen (one integration point located in the centre). A 3D FEM model was applied. The number of 13,750 elements were used in calculations: 55 elements along RD (the length of the real sample was 100 mm), 25 along TD (the real length was 25 mm) and 10 elements along ND (the thickness of the real sample was 5 mm). The isotropic yield criterion was used. The rolls were modeled as non deforming rigid ones, using the *RIGID BODY option in ABAQUS software [17]. A rigid body is a collection of nodes, whose motion is governed by the motion of a single node called a "reference point". In order to take into account a finite strain, the non-linear approach with the option *Nlgoem was used. The Coulomb friction model was applied to describe the interaction of contacting surfaces (rolls and deformed material). Accordingly, the limiting frictional shear stress between these surfaces is $\mu \cdot p$, where p is the contact pressure between the two surfaces and μ is a friction coefficient.

3.1.1. Specimen curvature

The experimentally determined relation of the strip curvature for the sample rolled to 17% reduction vs. rolling asymmetry parameter (A) is compared with those predicted by FEM calculation (for $\mu = 0.3$ and $\mu = 0.4$) in Fig. 2. Predicted and experimental plots show the same character. A small increase of the rolling asymmetry, starting from $A = 1$, produces a significant bending of the rolled sample (with positive curvature). The maximal positive values of *HA* parameter appear for A = 1.05 (predicted) and A = 1.10 (experimental). It can be noted that a straight rolled strip (i.e., $HA = 0$), appears around $A =$ 1.13, as obtained from FEM calculation, and for $A = 1.18$, as interpolated from the experimental curve. Further increase of rolling asymmetry (A) leads to a strong negative curvature. Therefore, it can be concluded, that

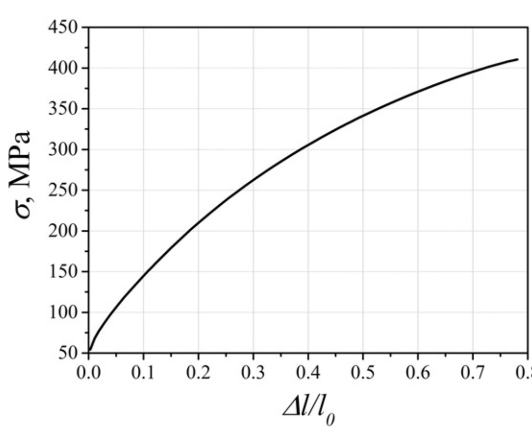

Fig. 1. Plastic part of a typical tensile curve (stress vs. relative elongation $\Delta l/l_0$) used in the finite element calculations.