Acta Materialia 139 (2017) 30–38

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

Texture effects due to asymmetric rolling of polycrystalline copper

A. Uniwersał [a], M. Wroński [b], M. Wróbel [a], K. Wierzbanowski [b,*], A. Baczmański [b]

[a] AGH University of Science and Technology, Faculty of Metals Engineering and Industrial Computer Science, al. Mickiewicza 30, 30-059, Kraków, Poland
[b] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, al. Mickiewicza 30, 30-059, Kraków, Poland

ARTICLE INFO

Article history:
Received 17 May 2017
Received in revised form
31 July 2017
Accepted 31 July 2017
Available online 1 August 2017

Keywords:
Asymmetric rolling
Polycrystalline copper
Texture heterogeneity
Crystalline deformation model
Orientation stability

ABSTRACT

Texture modifications of polycrystalline copper, caused by asymmetric rolling, were studied experimentally and theoretically analysed. Orientation distribution functions and its intensity along the skeleton lines were examined. It was found that texture components after asymmetric rolling are rotated, approximately around transverse direction, as compared with those after symmetric rolling. The rotation angles were determined for characteristic texture components as a function of the rolling asymmetry ratio. Texture heterogeneity across the rolled sheet thickness was also studied. Theoretical predictions of rolling textures were done using two crystalline deformation models. The orientation distribution functions, rotations of texture components and their variation across the sample thickness were determined and compared with theoretical results. Also the stability of final orientations after asymmetric rolling texture was tested.

1. Introduction

In recent years the technique of asymmetric rolling (AR) has attracted interest of engineers in the field of metallic materials processing. The reason is that the normal force magnitude as well as productivity of the rolling process can be improved in a relatively simple way [1–3]. Moreover, some beneficial changes in the product microstructure and properties can be obtained by the control of the degree of rolling asymmetry and deformation [4–6]. It is thought that this way of microstructure modification can offer new possibilities of producing long and flat metals products with significantly improved material properties. Despite numerous studies devoted to technological aspects of the AR process, carried in many countries (e.g., [7–13]), some characteristics of this process are still not known sufficiently. This concerns in particular the development of crystallographic texture of copper formed in AR process and its distribution through the thickness of the rolled sheet.

Some number of papers were devoted till now to the problem of AR textures formation. The change of intensity of copper texture rolled asymmetrically was reported in Ref. [4]. The effect of texture heterogeneity through the thickness of the asymmetrically rolled sheet was discussed in the case of aluminium [14,15], ferritic steel [16,17] and titanium [18,19]. It was found that AR induces rotation of texture components about the transverse direction (TD) of the rolled material [15–23] and that this rotation is due to a characteristic change of the stress state induced in the AR process. However, no information on rotations of individual texture components during AR is available. The behaviour of crystallographic orientations during classical forming processes was characterized in detail in literature. It was shown that final textures contain stable orientations and also slowly rotating ones and these orientations were identified for typical technological processes such as symmetric rolling (SR), drawing, extrusion, shearing, etc. [24,25]. Also after recrystallization some characteristic orientations are observed (e.g., cubic orientation in the previously rolled polycrystalline aluminium and copper [25,26]). The analysis and modelling of texture components is particularly simple in the case of f.c.c. metals with high and medium values of the stacking fault energy (SFE), such as aluminium and copper, which deform only by glide on the {111} ⟨110⟩ slip systems. This assumption eliminates problems met for materials with more complex deformation crystallography like h.c.p. metals or f.c.c. metals with low SFE (which deform by slip and twinning) or b.c.c. metals (which deform by the pencil glide). In these materials the critical stresses for slip and twinning are generally different for different system families and their precise values are difficult to measure.

The results of stability tests for crystallographic orientations of copper and aluminium during SR can be found elsewhere [27,28]. It was shown that the stability of a given crystallographic orientation

* Corresponding author.
E-mail address: wierzbanowski@fis.agh.edu.pl (K. Wierzbanowski).

http://dx.doi.org/10.1016/j.actamat.2017.07.062
1359-6454/

depends on the stress state and symmetry of the orientation. Therefore one can expect different characteristics of texture components during SR and AR.

The goal of the present work is the analysis of texture of the polycrystalline copper formed during AR and its comparison with that formed during SR. As the stress distribution in the rolled material is generally heterogeneous, the texture variation across rolled sample thickness has to be examined. Also stability of the final texture components has to be tested.

2. Experimental procedure

Samples of commercial Electrolytic Tough Pitch copper, Cu-ETP grade, number CW004A (EN 13599:2014, UNS 11000), size 5*25*100 mm^3, were annealed during 1.5 h at 450 °C and then symmetrically and asymmetrically cold rolled on the quatro mill up to the final thickness reduction of 80%. For both considered processes the equivalent partial deformations imposed in each rolling pass were the same. The rolling asymmetry ratio was defined as:

$$A = \frac{D_1}{D_2} \tag{1}$$

where D_1 and D_2 are the diameters of the used rolls turning with the same angular velocity. The roll with larger diameter was the bottom one in the used working set. The examined asymmetry ratios, A, were equal to 1.0, 1.1, 1.2 and 1.3.

The {111}, {100}, {110} and {311} incomplete pole figures were determined using the Empyrean diffractometer from PANalytical Co with the parallel beam of Cu Kα X-ray radiation. The measurements were done for nine material layers parallel to the rolling plane.

The positions of layers in the rolled samples were identified by the depth parameter z ($z = 1$ for the sample top, $z = 0$ for the half thickness and $z = -1$ the for sample bottom). The examined specimens were gently polished and etched to pre-set thickness. The LaboTex commercial software [29] was used for calculation and analysis of the orientation distribution functions (ODFs). The Bunge convention for Euler angles (φ_1, Φ, φ_2) was used for the presentation

Table 1
Rolling f.c.c. texture components used for analysis in the present work [37].

Name of component	Symbol	Miller indices	Euler angles [°] φ_1, Φ, φ_2
Copper	C	{112}⟨111⟩	(90, 35.26, 45)
Brass	B	{011}⟨211⟩	(35.26, 45, 0)
S	S	{213}⟨364⟩	(58.98, 36.70, 63.44)

of crystallographic orientations and textures [24].

3. Modelling

In order to better understand the studied rolling process the model calculations were done. Two micro-macro crystalline deformation models, describing elasto-plastic interaction between a crystal grain and its environments, were used in order to have a better theoretical insight of the studied deformation type:

- the elasto-plastic crystalline self-consistent model, originally developed by Berveiller and Lipinski [30] and next modified by Baczmanski et al. [31,32] (SC model),
- the elasto-plastic crystalline deformation model, developed in its initial version by Leffers [33] and next generalized by Wierzbanowski [34–36] (LW model).

The hardening law of Voce [37] and saturation law [38] were used in SC and LW models, respectively.

The assumed interaction laws between crystallites and the neighbouring average material enable to calculate the stress state inside grains. This in turn enables determination of active slip systems and deformation of grains and the sample. The main input variable in both models, determining the geometry of the process, is the applied stress tensor. It is well known that during AR process strong shear stress and strain components arise (i.e., '13' components, where x_1 is parallel to rolling direction, RD, and x_3 is parallel to normal direction, ND), therefore the applied stress tensor was of the classical following form:

$$\Sigma_{ij} = M \begin{bmatrix} 1 & 0 & K \\ 0 & 0 & 0 \\ K & 0 & -1 \end{bmatrix} \tag{2}$$

where M is its magnitude (incrementally increased in consecutive calculation steps) and K is the proportion of the applied Σ_{13} shear stress component. In the case of SR: $K = 0$ and in the case of AR process K took values between 0.1 and 0.3 in order to simulate corresponding rolling asymmetries (e.g., [39]). It was checked that in spite of texture evolution, the components of the macroscopic strain, E_{ij}, are nearly in the same proportions as those of stress from Eq. (2), i.e.: $E_{33} \approx -E_{11}$ and $E_{31} \approx E_{13} \approx K E_{11}$, while other components, including E_{22}, are approximately equal to zero.

To calculate texture distribution versus the rolled sample thickness the crystalline LW model was implemented into the Finite Element code (ABAQUS/Explicit) via the user subroutine VUMAT [18,38] and referred as LW-FEM model. A representative

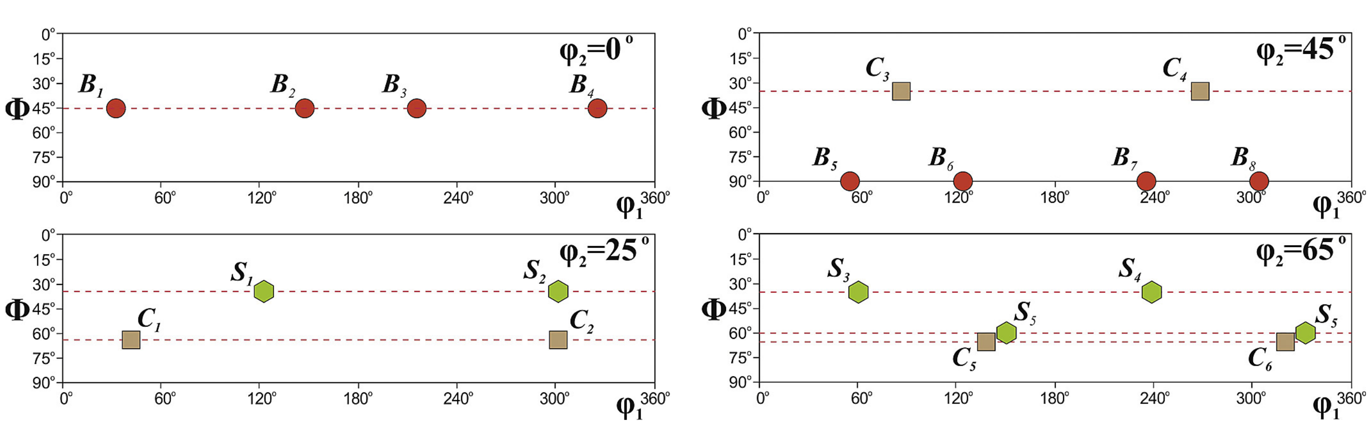

Fig. 1. Positions of selected ideal orientations in the Euler angles space.