PAPER • OPEN ACCESS

Surface Texture of Deformed Copper Wire

To cite this article: M A Zorina *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **969** 012080

IOP Conf. Series: Materials Science and Engineering **969** (2020) 012080 doi:10.1088/1757-899X/969/1/012080

Surface Texture of Deformed Copper Wire

M A Zorina, M S Karabanalov and Yu N Loginov

Department of Heat Treatment and Physics of Metals, Institute of New Materials and Technologies, Ural Federal University named after the first President of Russia B. N. Yeltsin, 19, Mira Street, Ekaterinburg, 620002, Russia

E-mail: m.a.zorina@urfu.ru

Abstract. The texture of the cold-drawn copper wire was investigated along the radius and on surface by means of EBSD. The wire fiber texture after drawing has been shown to consist of a set of a main orientations analogically to the rolling texture. These texture orientations are associated to the stress state in drawing. The central area of the wire was characterized by two main orientations: faint <001> and powerful <111>-fibers. Main orientations {110} <001> and {112} <111> were distinguished within these fibers. The peripheral region is represented by a shear texture that rotates 90° to the center texture and scattered at ± 10°. The surface texture scattered close to axial and also has deviated preferred components: strong {110} <001> and weak {112} <111> orientations.

1. Introduction

Crystallographic texture is one of the ways to obtain products with an improved set of orientation-dependent physicochemical and / or mechanical properties [1–2]. The emergence and development of texture occurs due to directed deformation effects, realized in cramped conditions [3, 4], which the product is subjected to at the stages of processing. Drawing is one of the main technological operations in the manufacture of a great number of metallic materials and products characterized by advanced electrical conductivity, such as Cu, Ag, Au, and Al. The electrically-conductive elements made of copper are subjected to the strong deformation impacts (rolling, drawing) during the processing, which result in the formation of intense crystallographic texture. The research of the features of texture transformations in copper with the use of modern techniques of structural analysis allows to develop approaches to controlling the operational and functional properties of the face-centered cubic (FCC) metals. Note that considering, the texture shaping on a specific treatment path allows you to optimize present technologies [5] or even develop new ones.

The location of deformation textures in metals can be explained from the point of view of the classical theories [6–8]. An important consequence of almost all present models of the development of principal grain orientations during deformation is the emergence of sustained orientations at comparatively high degrees of deformation [9]. These orientations, characterized by precise crystallographic indices, do not change their spatial position in the further deformation, which is associated with the equilibrium of slip systems acting in inverse directions. For a given deformation pattern, the stress state forms a set of distinct orientations of grains, located with a certain misorientation relative to each other and forming a complex limited texture. It is worth noting that the large amount (but well-defined) of stable orientations generated by deformation of metallic materials with a cubic lattice determines their symmetrical location relative to the state of external stresses [4, 9]. Crystal plasticity models are used to model high strain plasticity and texture evolvement. The main disadvantage of most present models is that in some cases they are unable to predict all types of experimentally obtained textures, as well as texture conversions.

It is known from the mechanics of a plastically deformable body that the spreading of deformation during drawing is influenced by boundary conditions such as a tool configuration (the half-angle of die taper), a friction stress, a back-pull stress, etc. [11, 12]. Shear textures are often found at the surface of rolled products. It needs to be investigated because it is immediately related to the anisotropy of the metal. Surface texture influences friction and transfer layer formation during sliding. Crystallographic reorientation (i.e. texture evolution) under the contact surface may be a possible cause of the decrease in the coefficient of friction during sliding wear. Crystallographic reorientation can lead to a decrease in the effective shear stress in the near-surface areas and a decrease in the frictional force required to maintain relative motion [12].

Drawing is known [13–15] to bring about the formation of the complex axial texture of the wire. The main characteristic of drawing texture of FCC-metals is that it contains two basic axial components: <111> and <100>. The authors of [16] report that during drawing of the copper wire the <111> texture component was observed along with the <112>. Namely the last has been considered to be metastable. The <112> axial texture is formed from the parent orientation <100> at high strains in the surface layer of the wire [17].

Studies by Lee, Park et al. [18, 19] have shown that the shear stresses can be ignored in the center of the wire and that they increase from the center to the surface of the wire. Differences in shear stresses might lead to heterogeneous allocation of the components of the axial texture along the radial direction of the drawn wire. Thus, the allocation of the components of the drawing texture in the radial direction of the deformed wire can differ significantly [11].

This paper examines the drawing texture of FCC metals in terms of copper wire and the accordance between the main orientations of the texture on center, peripheral areas and surface of the cold-drawn wire.

2. Experimental procedure

The semi-products of M001 copper (analogue of ETP copper) were used in the study. Wire 1.65 mm in diameter was obtained from copper rod 8 mm in diameter on a multi-pass drawing machine MCM 85. Drawing was carried out in 10 passes at a drawing speed on the last drawing block of 20 m/s. Deformation was carried out without intermediate annealing. Tandem drawing was carried out using a set of polycrystalline dies. The half angle of the taper of the drawing die was 10°. Stable boundary conditions for heat transfer and friction were ensured by a system for supplying liquid lubricant and devices for its regeneration and temperature control, which was equipped with a drawing mill. For this, the cutting fluid Unopol G 570 was used. The total deformation as a result of 10 drawing passes was 23.51, which corresponds to a logarithmic deformation of 3.16 and a reduction area (RA) of 95.7%.

The analysis of the texture state was carried out by the method of electron backscattering diffraction (EBSD) using a ZEISS CrossBeam AURIGA field emission gun scanning electron microscope (FEG SEM) equipped with Nordlys HKL Channel 5 hardware and software for recording and analyzing diffraction patterns. The scanning step was 0.2 μm, the error in determining the orientation of the crystal lattice was ± 1°. Orientation maps and pole figures (PF) of two types: 1) as a projection of the pole outputs (all existing in the analyzed region are shown); 2) as a distributed polar density (showing the main orientations and the degree of their scattering) were used in texture analysis. A laboratory coordinate system was taken to denote local crystallographic orientations, the axes of which refer to the axial direction (AD // X), normal to the horizontal plane (ND // Y) and directly transverse to them (TD // Z). All selected directions give the right triplet of vectors.

In order to simulate the stress-strain state under drawing of copper wire the boundary-value problem has been solved using RAPID-2D software. This calculation is based on the finite element method. The program unit makes it possible to transfer a coldworked workpiece from tool to tool and, thus, to simulate multistage drawing. The boundary-value problem of determining the angles of inclination of the main deformation axes along the radius of a copper wire is solved using a lightweight version of the

ABAQUS program with 1000 finite elements by the FEA. The die cone angle was set at 10° in accordance with the technological process. The reciprocity of the metal with the drawing tool was specified using the Coulomb friction law. Friction coefficient 0.05. Low and constant values of the coefficient of friction were taken from the average values of the experimental data for drawing copper products to simplify the calculation [20]. The copper wire was indicated as a nonlinear strain-hardening medium, namely, the power dependence between stress and strain was taken. The artificial diamond drawing die was regarded as an elastic medium in the simulation.

3. Results and discussion

The texture of the wire after 10 draw passes was a complex fiber (figure 1). Previous studies [11, 21] demonstrate uneven allocation of the main texture orientations along the radius of the cold-drawn copper wire. The texture of the metal after drawing within the entire product was complex axial, which was related by the symmetry of the deformation pattern during drawing. Though, a layer-by-layer (local) analysis of the crystallographic orientation of grains along the radius of the wire showed noticeable distinctions between the central, peripheral areas and the surface even in the type of the formed texture of deformation (figure 1).

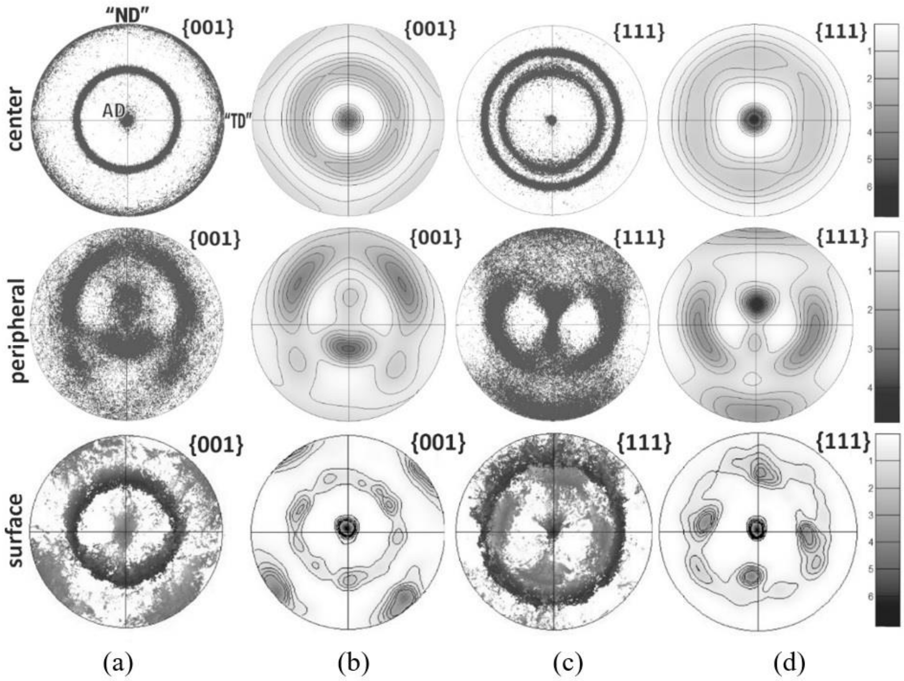

Figure 1. The EBSD analysis in various areas along the radius of the copper wire: {001} and {111} PF: (a), (c) – separate poles (scattered data); (b), (d) – pole density distribution (contouring data).

The central area of the wire was characterized by two main orientations: <001> and <111> fibers (figure 1). Main orientations {110} <001> and {112} <111> were distinguished within these fibers (figure 2).

A bounded texture with two lines symmetric with respect to the AD, unequal in intensity of components, close to {332} <113> (in the used coordinate system) was formed in the peripheral area as a result of deformation (figure 1). Apparently, the inequality of the {332} <113> components (asymmetry of the deformation texture) is associated with the asymmetry of the stress state, which is implemented at drawing in the peripheral area. The scatter of both orientations is of a complicated nature, mostly rotating around the axes belonging in the TD – AD plane.

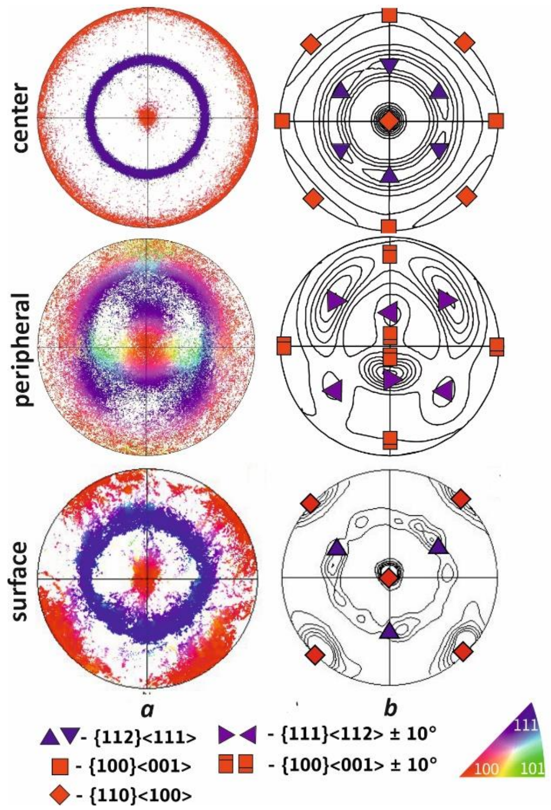

Figure 2. {100} PF of the copper cold-drawn wire texture; (a) – scattered data; (b) – contouring data + ideal orientations.

An analysis of the relative location of the main components of the peripheral and central areas of the crystal geometry indicates that they are associated with spinning around the TD by an angle of nearly 80°, or 90° ± 10°, where ± 10° is the drawing conicity angle. Analogous distinction in the center and on the surface were noted during cold rolling of aluminum with colossal friction between the rolls and the strip [9, 22] or during hot rolling of electrical steel [23].

Thus, in the peripheral area (figure 1) texture was submitted by deviated main components, that are faint, scattered {100} <001>, {112} <111> – orientations and powerful {111} <112>, {332} <113>. Importantly that this texture can be viewed not as axial, but as a complex bounded texture. Main orientations in the peripheral area can be viewed as a shear texture component that are connected with the main orientations of the central area by the rotation at an angle of 90° about the axis perpendicular to AD (figure 2). Therefore, orientation {332} <113> corresponds to {112} <111> rotated at 90°, scattered at ±10° and {100} <001> scatters from AD at ±10 °.

It is considered [9] that the shear texture components develop in the surface layer. The texture of directly to the surface is studied in this paper. The surface texture of the cold-drawn wire is different from the one of the peripheral areas. The surface texture scattered close to axial (figures 1, 2), but also has deviated main components: powerful {110} <001> and faint {112} <111> orientations. Moreover, the {112} <111> component is blurred around the AD, and the {110} <001> component has a limited character. Such a difference in the surface texture could be associated with the dynamic recrystallization processes occurring in the surface layers as a result of heating. But it was shown in [24] that the precise orientation {100} <001> is the main component of recrystallization in a copper wire. This orientation is absent in the surface layer. This orientation is not present in the surface layer. Apparently, this textural state is associated with the stress-strain characteristics of surface layers of the wire.

The rotation of texture in drawing is related to the specific features of the state of stress in this processing method. To estimate this rotation, a number of boundary value problems were solved for drawing of a copper wire. The distribution of the principal elongation directions (PED) calculated for each finite element is shown by arrows in Fig. 3. Here, the term PED is used as a special case of designating the principal elongation directions during drawing: one main deformation of elongation and two main deformations of shortening. The inclination of the PED was measured at the level of metal exit from the calibrating die strip. As is seen from this PED distribution, the inclination of PEDs increases with the coordinate along a radius. Its nonlinear character is clearly visible, and the rate of change of the angle of inclination is seen to decrease when the periphery (i.e., the wire surface) is approached (figure 3).

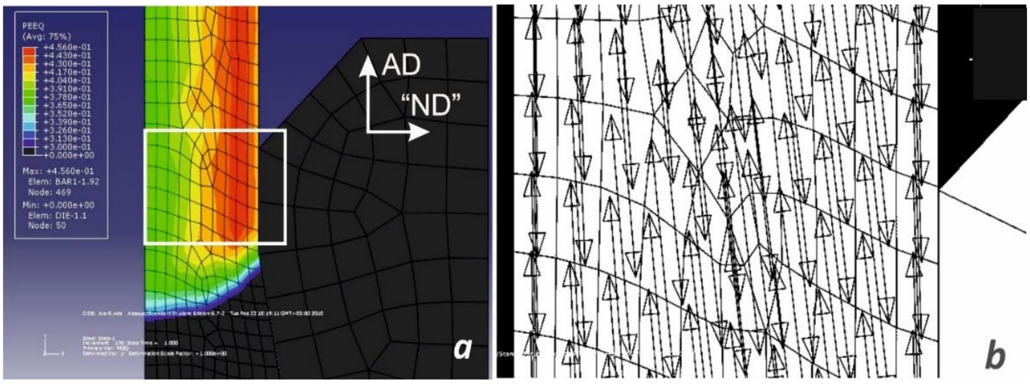

Figure 3. The formulation of the drawing problem in the ABAQUS software package with a finite element mesh: (a) – half of the deformation zone with the distribution of the deformation degree (levels); (b) – coordinate grid in half the deformation zone with indicated principal elongation directions (PED) along the radius.

It follows from the changes in the coordinate grid that its rectangular cells elongate without line distortions at the center of the workpiece; that is, tensile deformation takes place (figure 3(b)). Tensile deformation is principal, since additional shear are absent. Rectangular grid cells transform into parallelograms near the periphery (i.e., the workpiece surface). The long diagonals of the parallelograms in peripheral regions are inclined to the AD. Thus, shown that the deformation zone is nonuniform in drawing: the strain rates are different in this zone, and principal elongation axes have different angles of inclination along a workpiece radius. If the texture forms due to the elongation of material fibers, the directions of the principal strain axes indicate the deviation of the texture from the workpiece axis. Note, that the inclination of PEDs from AD on the surface becomes minimal, and it follows that the surface texture should rotate, as in the center of the wire. There is no complete coincidence of the texture of the center and the surface, because obviously, the real (3D) stress state is significantly more complicated than the modeled (2D) state.

4. Conclusion

Identity of texture of cold-drawn wire are associated with the stress state during drawing. Thus, the drawing texture is more correctly considered as a complicated rolling texture rather than a complicated fiber one.

The paper shows that the texture of deformed copper wire is a series of main orientations analogically to rolling texture. The texture orientations are associated with the deformation state in the drawing. The subsequent fibers develop locally in the central part of the wire: {112} <111> is referred to overall <111>-fiber and {110} <001> and {100} <001> is referred to overall <100>-fiber. Texture analogically to the shear one was generated in the periphery area of the wire. But it was revolved to the texture of the central area at an angle of 90±10°. The surface texture scattered close to axial and also has deviated preferred components: strong {110} <001> and weak {112} <111> orientations.

The results of the study indicate the opportunity and need of progress numerical models of the evolution of texture and physical and mechanical properties depending on the stress-strain state. This contribute to the forecast of the products properties both at the stage of manufacturing and during operating.

References

[1] Belyaevskikh A S, Lobanov M L, Rusakov G M, and Redikul'tsev A A 2015 Improving the production of superthin anisotropic electrical steel *Steel Transl.* **45(12)** 982–986
[2] Lobanov M L, Danilov S V and Urtsev V N 2020 Effect of structure and texture on failure of pipe steel sheets produced by TMCP *IOP Conference Series: Materials Science and Engineering* **709(4)** 044010
[3] Gottstein G 2004 *Physical Foundation of Materials Science* (Berlin: Springer-Verlag)
[4] Vusnyakov Ya D, Babareko A A, Vladimirov S A, and Égiz I V 1979 *Theory of Texture Formation in Metals and Alloys* (Moscow: Nauka)
[5] Wright R N 2011 *Wire technology: process engineering and metallurgy* (Elsevier Inc.)
[6] Sachs G 1928 *Trans. Faraday Soc.* **24** 84–92
[7] Taylor G I 1938 *J. Inst. Met*. **62** 307–324
[8] Bishop J F W and Hill R 1951 *Philos. Mag.* **42** 414–427
[9] Hölscher M, Raabe D, and Lücke K 1994 Relationship between rolling textures and shear textures in f.c.c. and b.c.c. metals *Acta Metall. Mater.* **42** 879–886
[10] Kraft F F, Chakkingal U, Baker G and Wright R N 1996 *Proc. 6th Int. Conf. Met. Form.* **60** 171–178
[11] Zorina M A, Karabanalov M S, Stepanov S I, Demakov S L, Loginov Yu N and Lobanov M L 2018 Fiber vs Rolling Texture: Stress State Dependence for Cold-Drawn Wire *Metall. Mater. Trans.* **A 49** 427–433
[12] Kuhlmann-Wilsdorf D 1980 *Dislocation concepts in friction and wear Fundamentals of Friction and Wear of Materials* (Metals Park Ohio) p 119
[13] Linben G, Mengelberg H D and Stuwe H P 1964 *Z. Met.* **55** 600–604
[14] Schlafer U and Bunge H J 1972 *Texture* **1** 31–49
[15] Montesin T and Heizmann J J 1992 *J. Appl. Crystallogr.* **25** 665–673
[16] Wang Y, Huang H Y, and Xie JX 2011 *Mater. Sci. Eng.* **A 530** 418–425
[17] Chen J, Yan W, Liu C X, Ding R G and Fan X H 2011 *Mater. Charact.* **62** 237–242
[18] Park H and Lee D N 2003 *Metall. Mater. Trans. Phys. Metall. Mater. Sci.* **A 34** 531–541
[19] Park H and Lee D N 2002 *Mater. Sci. Forum* **408–412** 637–642
[20] Komori K 2003 *Int. J. Mech. Sci.* **45** 141–160
[21] Demakov S L, Loginov Y N, Illarionov A G, Ivanova M A and Karabanalov M S 2012 *Phys. Met. Metallogr.* **113** 681–686
[22] Lobanov M L, Loginov Yu N, Danilov S V, Golovin M A and Karabanalov M S 2018 Effect of Hot Rolling Rate on the Structure and Texture Condition of Plates of the Al-Si-Mg Alloy System *Met. Sci. Heat Treat.* **60** 322−328
[23] Lobanov M L, Redikul'tsev A A, Rusakov G M and Danilov S V 2015 Interrelation between the orientations of deformation and recrystallization in hot rolling of anisotropic electrical steel *Met. Sci. Heat Treat.* **57** 492–497
[24] Zorina M A, Lobanov M L, Makarova E A and Rusakov G M 2018 Primary recrystallization texture in FCC-Metal with low packing defect energy *Met. Sci. Heat Treat.* **60** 329–336

Acknowledgments

The authors are grateful for cooperation of the support program of leading RF universities with the aim of increasing their competitiveness No. 211 of the RF government No. 02.A03,21.0006.