EFFECT OF TWIST EXTRUSION AND SUBSEQUENT ROLLING ON THE TEXTURE AND MICROSTRUCTURE OF ALUMINIUM ALLOY

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ABSTRACT

The crystallographic texture and microstructure of aluminium alloy AA6063 after twist extrusion and subsequent cold rolling along and across axis of twist extrusion were investigated. The torsion axial texture with axis <110> parallel axis of twist extrusion and vortex-like microstructure are formed during the twist extrusion. The subsequent rolling in direction across axis of twist extrusion promotes to formation of the rolling texture type brass and equiaxial microstructure. The rolling texture of type copper and highly elongated along rolling direction microstructure is formed during the rolling in direction along axis of twist extrusion. The mechanisms of texture formation discussed.

KEYWORDS

Twist extrusion, rolling, texture, microstructure

1.INTRODUCTION

It is well known that the structure and properties of deformed metals are largely determined by their stress-strain state and that the strongest effects are observed when using severe plastic deformation (SPD) [1-5]. Currently there are numerous methods of SPD processing for the production of bulk ultra fine grained (UFG) materials. There are a High-Pressure Torsion (HPT), Three-Dimensional Forging (TDF), Equal Channel Angular Pressing (ECAP), Accumulative Roll Bonding (ARB), Cyclic Extrusion and Compression (CEC), Repetitive Corrugation and Straightening (RCS), Twist Extrusion (TE). The long precision shapes (including cylindrical sections with the axial channel) may be prepared [2] by method TE. Such shapes are one of the most effective types of metal semi-finished in mechanic engineering [6]. No other known SPD methods do not allow receive products of this type [7]. Various SPD processes are outlined in [2].

Some of structural aspects and unique properties of bulk UFG materials and prospects of their use are presented in [3]. At the same time a limited amount of the works is devoted to the study of crystallographic texture formed during the severe plastic deformation. In these studies examined mainly development of texture during the ECAP [8 - 10] or ARB [11]. In [12] studied the crystallographic texture in copper, aluminium, low-alloy steel after TE. Article [13] is devoted to the study of texture formation in hexagonal titanium after TE. In two recent abovementioned studies have shown that the texture consists mainly of axial shear component and residues of rolling components. Texture formation occurs due to activation intra-granular slip systems, as well during fragmentation of grains and their inter-granular vortex-like slipping that is similar to turbulent liquid flow.
Control of texture and anisotropy of physical and mechanical properties is one of the major problems of modern metallurgy. Development of technologies to create of optimal texture can serve as an important reserve for improving of the properties of products in many ways. Such processes typically include a combination of different kinds of plastic deformation and heat treatment. For example, the shape of the final product obtained using ECAP limited to a bar or rod with a circular or square cross-section. This form is suitable when using the forging operations, but not suitable for obtaining the material as sheets and plates. In order to overcome this drawback of ECAP, in [14] investigated the combined process of ECAP and conventional rolling of Fe-Co-V alloy. A similar processing has been applied to aluminium alloy 8112 [15], and also for commercial Al-Mg alloy [16]. In the last three cited studies investigated in detail changes in the structure of alloys, mechanical properties, but the texture not taken into account. Texture, as is know, is the main cause of the anisotropy of mechanical properties of polycrystalline solids. In this connection it is important to examine the possibility of influencing on the texture of the work piece subjected to the TE, by means of subsequent its deformation that is differ from TE. For example, this may be the rolling or hydrostatic extrusion for long-length sections. The elongation of profile along its axis is main type of deformation in the rolling process, whereas the simple shear in a plane perpendicular to the extrusion axis is the main deformation type during the TE [7].

The aim of this work is the study of texture and microstructure of industrial aluminium alloy AA6063 at two stages of cold deformation. In the first stage the samples were subjected to the TE [12], which allowed achieving a high degree of deformation. Samples after TE were cold rolled as parallel, as well perpendicular to the extrusion axis on the second stage.

2. MATERIALS AND METHODS

2.1. Materials

The cylindrical castings of aluminium alloy AA6063 were used as starting material. The blanks were placed into a matrix [2] with a twist channel (with parameters $\beta_{\text{max}} = 60^\circ$, $h = 50$ mm). Cross section of matrix is constant along and orthogonal to the pressing axis (axis of TE). The angle $\gamma$ of inclination of helical curve to the pressing axis varies depending of the height $h$ matrix. The angle $\gamma$ equals zero at initial and final sites of matrix (Figure 1). Detailed procedure can be found in [2].

![Figure 1. Circuit of processing by twist extrusion](image-url)
The treatment was performed under the settings:
- Treatment was performed at room temperature;
- Speed of load application was 3 mm/s;
- Strain rate was of 0.2 (s⁻¹);
- Pressure during the TE was 200 MPa;
- Work piece size: cross-section was 18 × 28 mm, length was 100 mm.

It was held 4 passes of TE. Average true strain through one pass of TE was ~1.2, so that the total average strain for 4 passes of TE was 4.8.

Work pieces of thickness of 5 mm for the subsequent rolling along the extrusion axis and perpendicular to its axis and the appropriate samples for study of texture from the alloy after TE were cut.

Rolling was carried out at room temperature by a laboratory rolling mill with a diameter of rolls 180 mm of the small reduction (~3 - 5%) up to 56 and 80% of reduction by thickness, which corresponded to 0.82 and 1.6 of true relative logarithmic strain (ε).

### 2.2. Methods

Crystallographic texture of metal was investigated by X-ray method with the construction of the inverse pole figures (IPF) [17, 18]. The texture of the samples after TE was investigated in parallel and perpendicular directions to the pressing axis in the central and peripheral parts of extruded samples. The texture of the samples after rolling was investigated in the normal direction (ND) to the rolling plane and rolling direction (RD). The composite samples were prepared in the latter case. Before the study of texture all samples were chemically polished to a depth of 0.2 mm to remove the distortions introduced by mechanical treatment. The θ - 2θ scanning of samples was carried out in molybdenum Kα-radiation by means diffractometer DRON 3m. Diffraction patterns of initial, extruded and rolled samples, as well as of the sample without texture were recorded. The sample without texture was prepared from the fine sawdust of alloy after vacuum recrystallization annealing. The integral intensities of diffraction lines of the above samples were measured and constructed the corresponding inverse pole figures [17, 18]. The normalization of IPF by Morris was used [19]. Microstructure was examined by means a metallographic microscope MIM-7 using the camera VEB-E-TREK DEM 200. The extruded samples microstructure was studied by means reflection from the surfaces of specimens cut parallel and transversally to the pressure axis. Microstructure of rolled samples was investigated by means reflection from the rolling plane.

### 3. Results and Discussion

#### 3.1. The twist extrusion

The Figure 2 shows the structure of alloy AA6063 after twist extrusion. The traces of vortex-like strain are traced in cross-section perpendicular to the axis of pressure.

The microstructure of pure aluminium after TE previously studied in detail in [20]. In [21] similar studies have been conducted on an alloy of Al - 0.13% Mg. In above mentioned papers is showed that the microstructure of the materials after TE is inhomogeneous and in the peripheral regions is more deformed than in the central areas. The grains in the peripheral regions mainly are elongated. The flow of material is created due geometry of the tool of TE. In the central regions are contained more large grains, some of which are equiaxial. In the peripheral regions the grains mainly are elongated. Microstructure has a clear picture of vortex flow of the material. Such
structure means that the sample was subjected to a high strain on the outer edge, but less severely deformed in the centre. The blank after the TE has axial symmetry in the microstructure.

The radial inhomogeneity in the distribution of areas with different reflectivity ability should also out our microstructure of alloy AA6063 after TE (Figure 2), which may indicate the heterogeneity of texture.

Figure 2 Structure of alloy AA6063 after 4 passes of twist extrusion. On pictures a, b is show the structures observed perpendicular and parallel to the pressure axis correspondingly. A magnification is 600 times. Photos were increased by 2 times when printing

The experimental IPF of samples of alloy AA6063 are shown on Figure 3.

Figure 3. Experimental IPFs of alloy AA6063: a – initial sample (perpendicular to the axis of cylindrical workpiece); b, c – the central part of workpiece after TE (respectively perpendicular and parallel to the pressure axis of TE); d, e – the peripheral section of the workpiece (respectively perpendicular and parallel to the pressure axis of TE)
Texture of cast initial sample of alloy AA6063 characterized by the distribution of the casting axis within the orientations region $<733>/1.26 - <211>/1.16 - <533>/1.02$ along the side of the $<100> - <111>$ stereographic triangle and $<320>/2.36; <210>/1.02; <310>/1.34; <100>/1.21; <931>/1.04$ lying along and near the side of the $<100> - <110>$ stereographic triangle (Figure 3, a). Texture of alloy AA6063 changed significantly after TE (Figure 3, b). The axis of extrusion is oriented close to $<110>/1.98$ in the central part of cross-section perpendicular to the pressure direction. The region scattering is limited by orientations $<331>/1.07; <531>/1.04; <931>/1.49; <210>/1.34$ (Figure 3, b). The pole density is distributed almost evenly in the section of sample parallel to the pressure axis (Figure 3, c). Pole density exceeds unity only for orientations $<733>/1.17; <211>/1.00; <533>/1.12; <311>/1.11; <931>/1.51$, which indicates the absence of preferred orientation.

At the periphery of the cross-section sample cut perpendicular to the pressing axis (Figure 3, d), orientation distribution is similar to its distribution in central part, but pole density in pole of $<110>$ has higher value $<110>/2.16$. The pole density is distributed mainly along the diagonal 001–111 of stereographic triangle on the periphery of the sample parallel to the pressure axis (Figure 3, e). Value of pole density is slightly greater than 1. The wide range of crystals orientations in directions perpendicular to the pressure axis (Figure 3, c, e) can be explained by activation of the non-crystallographic deformation mechanisms induced by vortex motion of fragments crushed grains. Such motion is a certain extent similar to fluid turbulent flow [22]. Such vortex motion of crystallites is displayed on the photo of microstructure (Figure 2).

The twist extrusion may be represented by means model of compression along the direction pressing and shear and rotation in the plane perpendicular to the direction pressing [12]. To a certain extent this is confirmed by traces of vortex structure (Figure 2).

It is known that normal to active slip plane tends to rotate in the pressing direction under uniaxial compression [23]. Thus, the texture of uniaxial compression represents the axial texture, whose axis coincided with the compression direction.

For most pure FCC metals (with the possible exception of silver [23]) texture of compression consists of a strong component $<110>$ with scattering of orientations from $<110>$ to $<113>$ plus a weak component $<100>$. Component $<110>$ with scattering from $<110>$ to $<113>$ still prevails for many FCC alloys such as alpha-brasses (10-30 % Zn); Cu-Al alloys (4-8 % Al).

But there appear an additional component near $<111>$ however orientations $<100>$ are practically absent. Copper-nickel alloys behave as pure metals in the development of compression texture. Such texture characteristics are presumably associated with the value of the stacking fault energy of metal or alloy [23]. It can be seen that the texture after TE (Figure 3) differs from the above texture of uniaxial compression.

Effect of torsion deformation under high pressure on the development of texture in Ni-Al alloy studied in [24, 25]. Cylindrical samples with different axial texture were as starting material in this case. In the first case, the $<100>$ direction, in the second case, the $<111>$ direction were parallel to the torsion axis. It was shown that in all samples develops torsion texture of type $\{110\}$ $<100>$ (designation $[\text{plane of shear}] <\text{direction of shear}>$). This corresponds to the arrangement of planes $\{110\}$ parallel to the primary plane of shear and the Burgers vectors $<100>$ parallel to the shear direction. The torsion texture $\{110\}$ $<100>$ was formed more rapidly in the case of axial

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1 Here and below after the slash is shown the corresponding value of pole density on IPF. In curly brackets is shown combinations of crystallographic planes perpendicular to the pressing axis. In the angle brackets are shown the combinations of crystallographic directions lying in abovementioned crystallographic planes and perpendicular to the pressing axis.
initial texture <111>. The intensity of abovementioned torsion texture increases from the centre of the cross section of the sample to the periphery in accordance with increasing strain [24]. Formation of torsion texture type {110} <100> was confirmed by numerical simulation using finite element method based on Taylor model of deformation [25]. The mechanism of plastic deformation slip in systems of {110} <100> taken into account during the modelling the torsion strain.

The axial torsion texture of type {110} <uvw> is formed after TE as can seen of our IPFs (Figure 3). This means that the planes of type {110} coincide with the plane of shear and <uvw> crystallographic directions coincide with the shear direction. There is the gradient of texture along a radial direction of the work piece that indicates on intensification of axial texture torsion of type {110} <uvw> radially from the centre to the periphery of the work piece. Such a texture gradient probably is caused by the uneven distribution of the degree of deformation in the radial direction of the work piece during the twist extrusion [2]. The intensity of deformation increases linearly from zero at the centre of the section to the maximum value in the most remote areas from the centre during the twist extrusion. This approximate estimate was obtained in [2] by the assumption of "screw-type" flow of metal. For example [21], the true deformation on the axis of work piece of alloy Al - 0.13% Mg after one pass of twist extrusion was equal to 0.6. At the same time it was equal to 2 at the edge of cross-section perpendicular to the pressure axis of TE. Moreover, each cross section of work piece material resulting from the helical passage through the channel is deformed so that primarily a screwing is carried out on a certain angle in one direction and then on the same angle in the opposite direction. At the same time there is not only flow of metal screw-type but and the movement of the material points inside the contour of the cross section. This component was called a "back streaming" by authors of [2]. They proved by numerical simulation that the "back streaming" leads to a substantial alignment deformation through cross-section. The axial torsion texture and its gradient along radial direction of the work piece were observed probably due to the "screw type” and “back streaming” of metal during the TE.

Torsion deformation under high pressure Ni-Al alloy is monotonic [24, 25]. In contrast, during the TE each material section of work piece by passing them a screw channel, is deformed so that primarily a screwing is carried out on a certain angle in one direction and then on the same angle in the opposite direction, as mentioned above [2]. This probably explains the difference between the shear texture {110} <100> Ni-Al alloy and shear axial texture {110} <uvw> of alloy AA6063 after TE in our study.

2.2. A Rolling after twist extrusion

2.2.1. The Rolling in the direction transverse to the pressure axis of TE

The texture of type brass {110} <112> begins to form in sample of alloy A6063 during the rolling with $\varepsilon = 0.82$ (Figures 4, a, b).
Figure 4. Experimental IPFs of alloy AA6063 after consequent rolling in the direction transverse to the pressure axis of TE (a, b corresponds to $\varepsilon = 0.82$; c, d corresponds to $\varepsilon = 1.61$). 

A broad area of elevated pole density is limited by orientations $\langle 110 \rangle / 1.25; \langle 320 \rangle / 1.31; \langle 210 \rangle / 1.02; \langle 931 \rangle / 1.67$ on the IPF (ND) (Figure 4, a). The practical all crystallographic directions along the diagonal $\langle 100 \rangle - \langle 111 \rangle$ of stereographic triangle are present as can see on IPF (RD) (Figure 4, b). However, the region of high pole density is limited by orientations of $\langle 733 \rangle / 1.20; \langle 211 \rangle / 1.20; \langle 321 \rangle / 1.20; \langle 931 \rangle / 1.77$.

Texture of type brass becomes clearer with increasing of true logarithmic degree of deformation to 1.61 (Figure 4, c). The maximal value of pole density on the IPF (ND) corresponds to the orientation $\langle 110 \rangle / 2.33$. However, scattering on the IPF (ND) is still quite extensive and covers the region bounded by orientations $\langle 531 \rangle / 1.10; \langle 311 \rangle / 1.00; \langle 931 \rangle / 1.43; \langle 210 \rangle / 1.27; \langle 320 \rangle / 1.48; \langle 110 \rangle / 2.33$ (Figure 4, c). The pole density on the IPF (RD) takes maximal value in the pole $\langle 211 \rangle / 2.12$. At this can see that scattering decreased markedly and is restricted by the poles of $\langle 311 \rangle / 1.00; \langle 733 \rangle / 1.73; \langle 211 \rangle / 2.12$ (Figure 4, d).

2.2.2. The Rolling in the direction parallel to the compression axis of TE

The rolling after TE in direction parallel to the pressure axis of TE promotes to the formation together with the rolling texture of type brass of the texture of type copper $\{112\} \langle 111 \rangle$, as can be seen on corresponding IPF (Figures 5, a, b). With increasing of true logarithmic degree of deformation to 1.61 during the rolling along the pressure axis of TE (Figures 5, c, d) there is a tendency to form on the IPF (ND) of continuous distribution of crystal orientation from pole $\langle 110 \rangle$ to pole $\langle 211 \rangle$ through $\langle 531 \rangle$, which is typical for rolling texture of type copper [17 - 19].
Figure 5. Experimental IPFs of alloy AA6063 after consequent rolling along the pressure axis of TE (a, b corresponds to $\varepsilon = 0.82$; c, d corresponds to $\varepsilon = 1.61$).

2.2.3. Microstructure

Microstructure of alloy AA6063 rolled after twist extrusion is shown in Figure 4. The rolling in the direction perpendicular to the pressure axis of TE reduces difference of sizes of sides grains (Figure 6, a). The formation of nearly equiaxial grains (Figure 6, c) was the result of increasing of true relative logarithmic deformation to 1.61 during the further rolling in direction perpendicular to the pressure axis of TE.

Figure 6. The microstructure of the alloy AA6063 rolled after twist extrusion: a, b correspond to $\varepsilon = 0.82$; c, d correspond to $\varepsilon = 1.61$; a, c corresponds to the rolling in the direction transverse to the pressure axis of TE; b, d corresponds to the rolling along pressure axis of TE.
Photographed from the rolling plane. After rolling with the true relative logarithmic deformation $\varepsilon = 0.82$ in direction parallel to the pressing axis of TE the grain boundaries still carry signs of twisting remaining after process of twist extrusion (Figure 6, b). The further rolling with true relative logarithm deformation of 1.61 along the compression axis of TE leads to significant elongation of the grains in the RD (Figure 6, d). Similar microstructure of elongated grains with a high aspect ratio previously was observed in [26] after cold rolling. Grains are lengthened along the direction of cold treatment, whereas in the ND the grains sizes are reduced.

At higher deformation in the cold state a grain look like long strips parallel to the machining direction as and in our study (Figure 6, d).

2.2.4. Discussion of the deformation mechanisms during the rolling

The above-described difference of texture of samples after rolling across and along pressing axis of TE is suggests about different mechanisms of texture formation. The process of rolling can be represented by the model of compression in normal direction to the rolling plane and tensile in rolling direction [19]. Under this model, the difference in the texture of rolling of work pieces along and across pressure axis of TE can be explained as follows.

During the rolling in direction transverse to the pressing axis of TE the texture formation carried out mainly by means octahedral of primary and conjugate slip systems. The planes of {011} will aspire to lie perpendicular to the direction of compression in ND, while the crystallographic directions of <112> will aspire to lie along tensile in RD [19]. So may be explained the formation of texture type brass {011} <112> (see Figure 4).

It is known that pure aluminium is characterized by high stacking fault energy (SFE). Alloying aluminium by magnesium and silicon reduces somewhat the SFE [27, 28]. However, despite this, the alloy AA6063 of system Al - Mg - Si has high SFE, and therefore it is prone to the cross slip under load, as is shown experimentally in [29]. It is possible that additionally is activated the cross-slip during the rolling along the pressing axis of TE. In this case, the direction of tensile in RD will aspire to lie parallel to crystallographic directions <111> and {112} planes will aspire to lie perpendicular to the axis of compression in ND [19]. So may be explained the formation of texture of type copper {112} <111> (see Figure 5).

4. CONCLUSIONS

The axial torsion texture of {110} <uvw> was formed in aluminium alloy AA6063 after four passes of twist extrusion. At this there is the radial texture gradient that indicates on the texture gain in the direction from the centre to the periphery of cross-section of work piece. The not uniform distribution of strain in the radial direction of the work piece during the twist extrusion is cause of formation in the alloy AA6063 of torsion axial texture and its gradient. The heterogeneous deformation of the cross section of the work piece during the twist extrusion promotes to the activation of the vortex-like motion of milled fragments of grains that is reflected in the microstructure. This vortex motion of grains is somewhat similar to turbulent fluid flow.

Texture of type brass of {110} <112> with the equiaxial microstructure is formed in alloy AA6063 with an increase of true relative logarithmic degree of deformation to 1.61 during the cold rolling after twist extrusion transversely of its axis. The formation of such texture can be explained by means of activation mechanism of octahedral primary and conjugate slip systems.

In cold rolling along axis of twist extrusion with an increase in the true relative logarithmic degree of deformation of the alloy AA6063 up to 1.61 is formed the texture, which can be
described by a continuous distribution of crystals orientations from \{110\} <112> through \{135\} <112> up to \{112\} <111> and microstructure of highly elongated grains in the rolling direction. The formation of such texture can be explained by means activation together with octahedral primary and coplanar slip also of cross dislocation slip.

REFERENCES


Authors

Short Biography Shkatulyak Natalia was born 17.05.56, professor of physics of South-Ukrainian National Pedagogical University after K.D. Usinsky, Odessa, Candidate of Physics and Mathematics sciences, has more than 100 publications. Research interests - new substances and materials, texture, fractal nature of the anisotropy of physical properties of crystalline solids.