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ALUMINUM ALLOYS

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INTERRELATION OF CRYSTALLOGRAPHIC ORIENTATIONS OF GRAINS IN ALUMINUM ALLOY AMg6 UNDER HOT DEFORMATION AND RECRYSTALLIZATION

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The structure and texture of a pipe from steel AMg6 produced by the method of hot pressing (extrusion) are studied. The important role of special (special and "half-special") boundaries in the process of dynamic recrystallization is described.

Key words: alloy AMg6, hot pressing, extrusion, texture, recrystallization, special boundaries.

INTRODUCTION

Determination of the interrelation between deformation and recrystallization textures is a necessary condition for fabricating functional materials with specified anisotropy of physical and mechanical properties.

It has been shown in [1, 2] that the quite strict relation between deformation textures and textures of subsequent recrystallization in alloy Fe – 3% Si with bcc lattice is determined by the formation of special off-orientations of the elements of the mesostructure in these processes. In this respect, it is interesting to study such regular features in alloys with fcc lattice under normal and elevated deformation temperatures.

Articles from aluminum alloys of the Al – Mg system have found wide application in various industries [3, 4]. Specifically, semiproducts from aluminum alloys with elevated content of magnesium (up to 6 wt.%) are used in the petrochemical industry [3], aviation and shipbuilding [5, 6]. Fundamental studies of the structural and phase transformations in aluminum alloys have been performed in [7 – 10]. However, the interest in these alloys has not ceased until present [11 – 13].

The aim of the present work was to study the structure and texture of alloy AMg6 in the process of hot pressing (extrusion) and to determine the interrelation between the deformation and recrystallization textures in the alloy.

METHODS OF STUDY

We studied specimens of an aluminum alloy with about 6 wt.% magnesium cut from a pipe with a size of ∅ 90 × 12.5 mm produced by hot pressing (Fig. 1). The pipe was manufactured by a method including semicontinuous casting, homogenizing, cutting, boring, turning, heating for deformation, and pressing in a hydraulic press. The thermal regime of the pressing was as follows: container temperature 420°C, pressing tool temperature 250 – 400°C, temperature of heating of the ingot before pressing 470°C.

To understand the special features of the deformation of the material under the conditions mentioned we computed the stress state, the deformation rates, and the accumulated strain using the "RAPID-2D" software (Fig. 1). The conditions of the edge problem for this case are described in [14]. In the present study we changed the sizes of the preform to match the chosen templates.

The hot deformation yielded a structure containing comparatively coarse elongated deformed grains (sometimes with incrusted individual fine equiaxed grains) and bands consisting of fine equiaxed, i.e., recrystallized, grains. Thus, we could simultaneously observe in the specimens polygoni-

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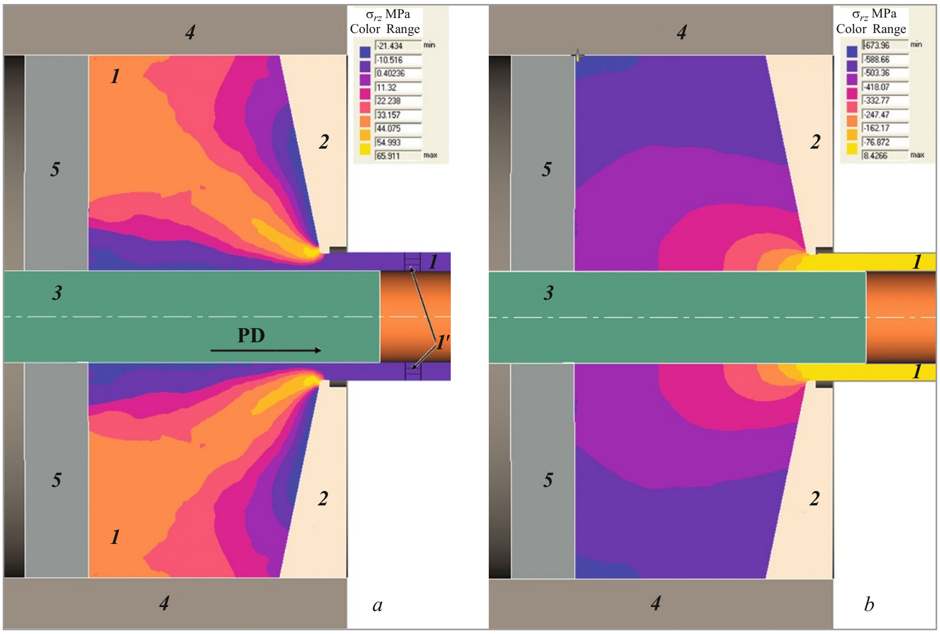

Fig. 1. Distribution of tangential (σ_{rz}) and normal compressive (σ_{zz}) stresses over cross section of a pipe during its production by the method of hot pressing (extrusion): *1*) pipe; *1'*) places of withdrawal of test pieces; *2*) die; *3*) needle; *4*) container; *5*) cleanout disk; PD) pressing direction.

zation, nucleation of new grains and their growth, and trace the relation between the orientations of various objects of the microstructure.

The electron microscopic study of the alloy was performed with the help of a Jeol JSM-6490LV scanning electron microscope at an accelerating voltage of 20 kV. To determine the orientations of individual grains and to analyze the integral texture we used an EBSD KHL Inca attachment with an Oxford Instruments system for analysis. The scanning step was 0.5 – 2 μm, the error in the determination of the orientation of the crystal lattice was at most ± 1° (about ± 0.6° on the average); the low-angle boundaries between local volumes were plotted on orientation maps at off-orientations of from 2 to 10°; at off-orientations ≥ 10° we draw high-angle boundaries; the special boundaries (Σn) were separated from the high-angle ones by the method of Brandon.

RESULTS AND DISCUSSION

The structure and, especially, the texture of a pressed pipe depend on the scheme of the stress-strain state formed by the process of its production. Pressing is characterized by a scheme of three-dimensional all-sided compression, in which the axial stress exceeds (in the absolute magnitude) the tangential and radial stresses. This concerns the whole of the volume of the deformation source except for the zone adjoining the drawing cylinder. The scheme of the stress-strain state is described by one extending component (over the axis of the pipe) and two shortening components (in the radial and tangential directions). Analysis of the distribution of the tangential stresses (Fig. 1*a*) shows that the highest tangential stresses are localized in the zone of outlet from the source of deformation closer to the drawing cylinder of the die.

The microstructure of all the hot-deformed specimens consisted of alternating bands of two types (Fig. 2) with different textures (Fig. 3). The bands of the first type consisted of comparatively large grains stretched over the pressing direction without a manifested mesostructure (Figs. 2*a*, 4 and 5). The other type of bands was represented by a set of grains with developed mesostructure stretched over the same direction but having a substantially smaller size and elongated zones of fine equiaxed crystallites (5 – 15 μm), which were products of recrystallization (Figs. 2*c* and 4). Bands of the first type prevailed at the external surface of the specimens (external diameter of the pipe), and bands of the second type were arranged primarily at the internal surface. In the central zone we observed alternation of the two types of bands (Fig. 2*b*).

Inside some grains constituting the bands of the first type we could observe individual equiaxed, supposedly growing, crystallites, which were more frequent in the central zones and rarely occurred on the boundaries of the deformed matrix (Figs. 2*a* and 5). Recrystallization in the elongated (deformed) grains occurring in the bands of the second type was implemented as growth of grain colonies from high-angle boundaries (Fig. 5).

It is obvious that the texture of the material within the whole of the article (pipe) is axial (complex axial), which follows from the symmetry of the deformation to which the alloy has been subjected. However, it is more correct to analyze the orientations that have appeared within the specimens studied as limited ones and to single out the crystallographic directions parallel to the pressing direction as the texture axes. The planes of the texture are crystallographic planes perpendicular to the studied surfaces of the specimens and parallel to the pressing direction (Fig. 1).

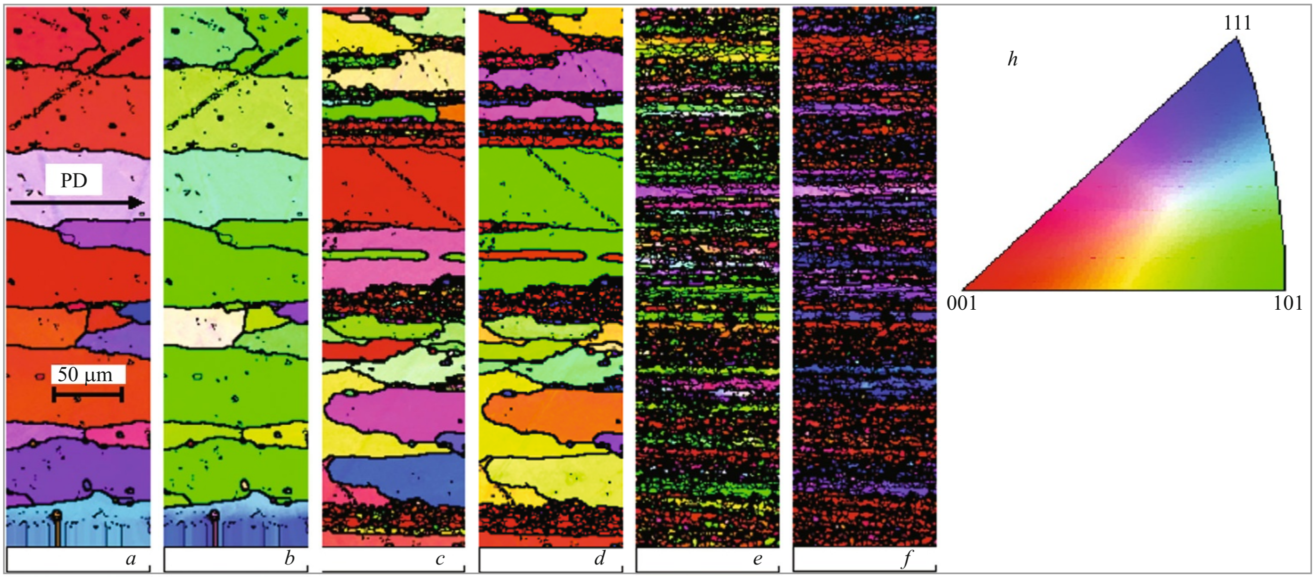

Fig. 2. Microstructure and texture of a pipe from alloy MG6 after hot deformation (extrusion): *a*, *c*, *e*) orientation maps (EBSD) from the direction vertical to that of pressing; *b*, *d*, *f*) stereographic triangle with color differentiation of crystallographic directions; *a*, *b*) region near the external diameter of the pipe; *c*, *d*) central region; *e*, *f*) region at the internal diameter.

The local orientation of the large not recrystallized grains constituting the bands of the first type is strongly spread {*h*, –*h*, *k*}⟨110⟩ (Fig. 3*a* and *b*), i.e., the bands of the first type may be characterized as an axial texture with axis ⟨110⟩ within the whole of the article.

When a pipe is manufactured, its regions located near the external surface experience high compressive stresses σ_{rz} (Fig. 1*b*) parallel to the pressing direction for a quite long time (as compared to the layers located near the internal surface). As a result, the alloy should acquire a texture with axis ⟨110⟩ [15]. It seems that the compression over the generatrix of the surface of the pipe (tangential stresses) has yielded a steady local orientation ~ {001}⟨110⟩. Under the action of the deformation source the surface layers of the alloy have

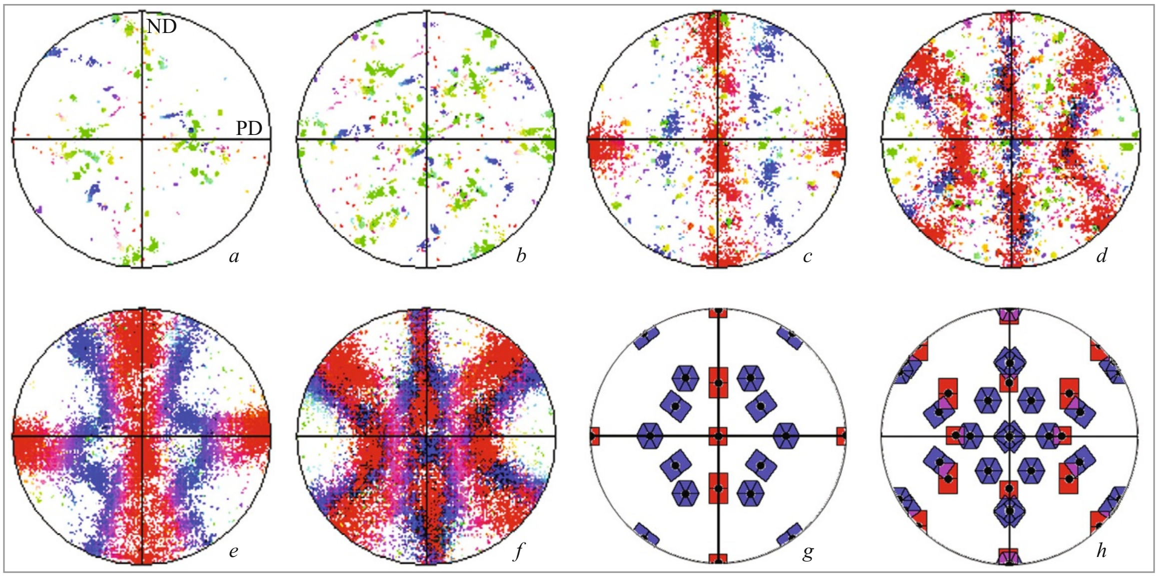

Fig. 3. Direct pole figures in the form of individual poles obtained from the regions presented in Fig. 2: *a*, *c*, *e*) DPF (100); *b*, *d*, *f*) DPF (110) (the coloring of the DPF corresponds to that of the orientation maps from the PD (Fig. 2*b*, *d*, and *f*); *a*, *b*) region at the external diameter of the pipe; *c*, *d*) central region; *e*, *f*) region at the internal diameter of the pipe; *g*, *h*) computed DPF (100) and (110) of ideal orientations corresponding to those of the region at the internal diameter of the pipe in Fig. 3*e* and *f* with deposited projections of elementary cells; ☐) orientations (100)[001]; ⊟) (110)[001]; ◇, ◇) two orientations from {112}⟨111⟩; ⬡) two orientations from {110}⟨112⟩.

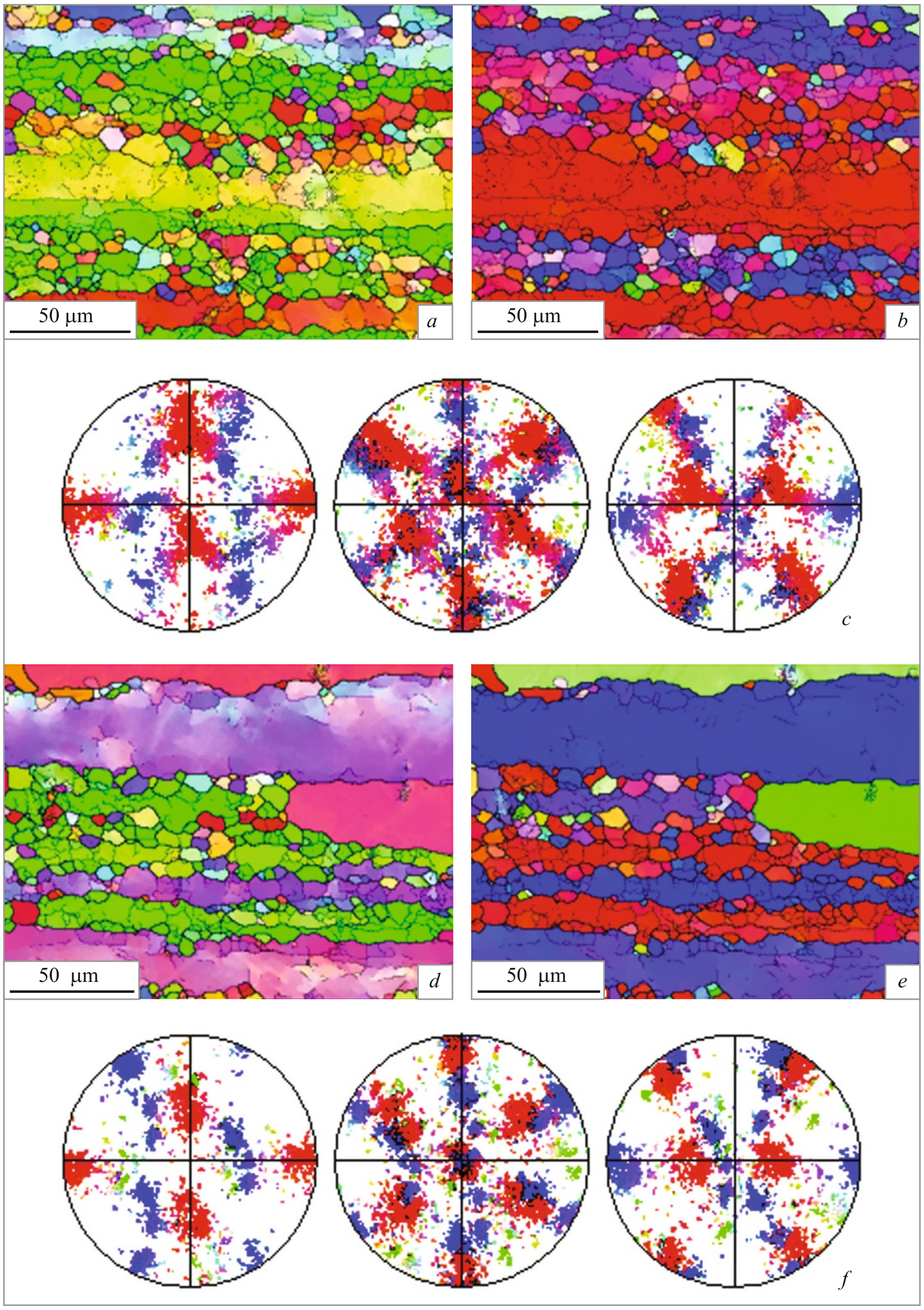

Fig. 4. Microstructure and texture of band regions represented by polygonized and recrystallized grains in alloy AMg6 after hot deformation: *a*, *d*) orientation maps (EBSD) from the vertical direction; *b*, *e*) from the pressing direction; *c*, *f*) DPF {100}, {110} and {111} in the form of individual poles obtained from the regions presented in Fig. 4*a*, *b* and Fig. 4*d*, *e*, respectively; the coloring of the DPF corresponds to that of the orientation maps from the PD.

experienced the action of tangential stresses (σ_{rz}) that vary both in the absolute magnitude and in the sign (Fig. 1*a*). Therefore, the earlier formed compressive texture is preserved due to the successive implementation of quite many slip systems in the material and formation of a dislocation structure (net) resistant to polygonization and recrystallization.

Both the deformed grains and the recrystallized grains in the bands of the second type are represented by the following set of orientations: orientations spread about the pressing direction (100)[001] and (110)[001] (in fact, they form one more axial orientation with common axis [001]), two orientations {110}⟨112⟩ with antiparallel axes ⟨112⟩, and two orientations {112}⟨111⟩ with antiparallel axes ⟨111⟩ (Fig. 3*e*, *f*, *g*, and *h*).

During the whole of the pressing process the material located on the internal diameter of the pipe experiences the action of comparatively uniform (with respect to the magnitude and sign) tangential stresses σ_{rz} (Fig. 1*a*). A natural result is formation of axes ⟨111⟩, ⟨100⟩, and even ⟨112⟩ (intermediate between the first two) and the axes of the texture [15]. The formation of local steady and limited orientations with such axes is a consequence of the symmetry of the stress state of the material during its treatment. It seems that in the pressing process the crystal lattice of the grains near the internal surface of the pipe is reoriented into one of the possible steady

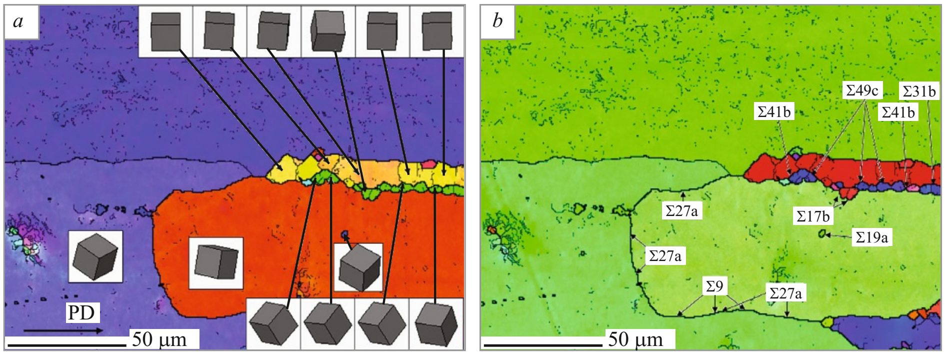

Fig. 5. Orientations of local regions detected by scanning electron microscopy with the use of EBSD on a lap from the surface of alloy AMG6 after hot deformation (start of recrystallization): *a*) orientation map from the vertical direction with spatial image of elementary cubic cells of the crystal lattice of individual grains and local regions; *b*) orientation map from the PD with indication of zones of special boundaries.

orientations, which is then preserved dynamically due to implementation of a comparatively little number of slip systems mutually balancing each other. As a result of the hot deformation and subsequent dynamic polygonization these crystallites acquire a mesostructure represented by comparatively large blocks separated from each other by low-angle boundaries (Fig. 5). The susceptibility of this structure to recrystallization seems to be connected with the many off-orientations between the objects of the mesostructure of grains with different orientations that appear as a result of the deformation.

Frequently enough, the deformed grains constituting bands of the first type are in special off-orientations Σ9, Σ19a, Σ27a, and Σ33a with respect to each other, which finds manifestation in the presence of regions of special boundaries between them (Fig. 5*b*). In fact, these special off-orientations constitute a "family" of orientations formed by rotation about one and the same axis ⟨110⟩ by close angles (see Table 1). It seems that the appearance of special off-orientations of this family is a result of formation of an integral axial deformation texture ⟨110⟩ and some adjustment of near-boundary volumes of crystallites to each other. The latter effect has been detected in [2] in cold rolling of alloy Fe – 3% Si with bcc lattice. It is natural that its probability increases substantially in hot deformation of the material.

A more general consequence of formation of such an axial texture is parallelism of crystallographic axes ⟨110⟩ at elongated deformed grains. It is obvious that the planes of the boundaries parallel to the pressing direction (PD) belong to the zone of axis ⟨110⟩, i.e., contain coinciding sites over this axis at any angle of rotation relative to each other. Thus, these boundaries may be classified on the whole as a "semi-special" type, i.e., as boundaries with one-dimensional periodicity [16], which take an intermediate position between special and arbitrary boundaries. It has been shown in [17] that the dependence of the energy of the special boundaries on the reciprocal density of the coinciding sites Σ is not monotonic in the general case. For this reason, despite the fact that the semi-special boundaries are formally characterized by quantity Σ that tends to infinity, they can have a lower energy than the special boundaries with high values of Σ. This occurs under the condition of one-dimensional coincidence implemented over a close-packed crystallographic direction. In our case direction ⟨110⟩ is indeed the direction of closest packing of the fcc lattice.

Another interesting fact is the presence of the same family of special boundaries (Σ9, Σ19a, Σ27a, Σ33a) at crystallites growing in large deformed grains (Fig. 5*b*). This fact is an obvious indication of the important role of special and semi-special boundaries in the process of formation (nucleation) of new grains under recrystallization.

Dynamic recrystallization, i.e., replacement of elongated deformed grains by equiaxed crystallites, develops in bands of the second type in the process of hot deformation (Fig. 5). Crystallites with orientations {110}⟨112⟩, {112}⟨111⟩ grow in grains with local deformation orientations (100)[001], (110)[001] and, vice versa, crystallites with orientations (100)[001], (110)[001] grow in grains with local deformation orientations {110}⟨112⟩, {112}⟨111⟩. Thus, the recrystallization is accompanied by a mutual "transformation" of the orientations.

In this case the recrystallization process is also connected with the presence of special boundaries between new and deformed grains (Fig. 5*b*). It should be noted that it is impossible to distinguish strictly the special boundaries of some specific type. In addition, such boundaries are commonly characterized by a low density of coinciding sites ($\Sigma n > 30$) and high-index rotation axes (see Table 1). It may be assumed that the "semi-special" boundaries also play an important role in the recrystallization process in this situation. In the case of recrystallization (in contrast to deformation) the coinciding crystallographic direction of a semi-special boundary is not necessarily parallel to the pressing direction.

CONCLUSIONS

1. We have studied the structure and texture of a pipe from alloy AMg6 with fcc lattice produced by the method of hot pressing (extrusion).

2. The main components of the texture are local orientation {*h*, –*h*, *k* }⟨110⟩ the axis of which coincides with the pressing direction (on the external surface) and axial orientation ⟨001⟩, two orientations ~ {110}⟨112⟩ with antiparallel

TABLE 1. Characteristics of Most Frequent Special Boundaries in the Structure of Alloy AMg6 after Hot Deformation

Place of formation	Off-orientation	Axis ⟨*uvw*⟩	θ, deg
(1) between DG of orientations ~ {*h*, –*h*, *k* }⟨110⟩; (2) between DG of orientations ~ {*h*, –*h*, *k* }⟨011⟩ and RG of the same orientations growing within the former	$\Sigma 9$	110	38.94
	$\Sigma 19a$	110	26.53
	$\Sigma 27a$	110	31.59
	$\Sigma 33a$	110	20.05
(3) between DG of orientations ~ (100)[001], ~ (110)[001] and RG of orientations ~ {110}⟨112⟩, ~ {112}⟨111⟩; (4) between DG of orientations ~ {110}⟨112⟩, ~ {112}⟨111⟩ and RG of orientations ~ (100)[001], ~ (110)[001]	$\Sigma 31b$	211	52.20
	$\Sigma 41b$	210	40.88
	$\Sigma 49b$	511	43.57
	$\Sigma 49c$	322	49.23
(5) between DG of orientations ~ (001)[110] and RG ~ (110)[001]	$\Sigma 17b$	221	61.93

axes ⟨112⟩ and two orientations ~ {112}⟨112⟩ with antiparallel axes ⟨111⟩ (on the internal surface).

3. Under hot deformation, orientation {*h*, –*h*, *k* }⟨110⟩ is not susceptible to recrystallization due to the absence of developed mesostructure. The pairs of local orientations ~ (100)[001], ~ (110)[001] and ~ {110}⟨112⟩, ~ {112}⟨111⟩ which form the integral complex axial texture of the article when turned about the pressing axis, acquire a developed mesostructure in the process of hot deformation and pass one into another under recrystallization.

4. The special (special and "semi-special") boundaries play an important role in the process of dynamic recrystallization. The primary recrystallized grains forming in the crystallites with local deformation orientation {*h*, –*h*, *k* }⟨110⟩ have common domains of special boundaries of one family $\Sigma 9$, $\Sigma 19a$, $\Sigma 27a$, $\Sigma 33a$ with the latter. The crystallites with local deformation orientations (100)[001], (110)[001] and {110}⟨112⟩, {112}⟨111⟩ passing one into another under recrystallization form domains of special boundaries with a low density of coinciding sites ($\Sigma n > 30$) and high-index rotation axes.

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