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Crystallographic texture of aluminum alloy samples produced by additive friction-stirred deposition

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Abstract
The crystallographic texture formation in the AK9ch aluminum alloy (9.6% Si; 0.3% Mg; 0.1% Fe; 0.1% Mn, Al balance) specimens manufactured using the Additive Friction Stir Deposition (AFS-D) technology at room temperature is investigated. The analysis was conducted using inverse pole figures (IPFs) obtained by X-ray diffraction methods. The results reveal the presence of shear, torsion, deformation, and recrystallization texture components in both types of specimens. The texture of horizontal and vertical samples differs in the set of texture components and the character of their dispersion. The texture intensity of both types of specimens is ill-defined. This testifies to the possibility of manufacturing the AK9ch alloy components using AFS-D technology with reduced anisotropy.

Keywords Additive friction stirs deposition · Crystallographic texture · Aluminum alloy · Inverse pole figures · Property · Anisotropy

Introduction

Additive friction deposition (AFS-D) is one of the promising methods for producing high-strength products from metallic materials [1–3]. It combines the concept of friction stirring with material feeding to produce components specific to a particular object [4]. The use of this technology makes it possible to manufacture products from not only existing metals and alloys but also to create new composite compounds and architectural materials with specified properties [3, 5, 6]. Unlike other AM (Additive Manufacturing) technologies, AFS-D methods usually do not require additional processing (hot isostatic pressing), which reduces production time and energy consumption.

The AFS-D method, patented in 2014 [7], is still in its early stages of development [8]. Interest in it is growing, particularly in the study of microstructure and crystallographic texture, which affects the anisotropy of the manufactured parts' properties. To date, there are a number of studies devoted to texture formation in blanks obtained by the AFS-D method. In the AA2219 aluminum alloy samples, the texture changed along the cross-section, which correlated with the strength characteristics [9]. The AA6061-T6 alloy was studied in [10], and different types of textures were established depending on the processing conditions, which affected the degree of recrystallization of the material. The study of the AA2024 alloy demonstrated a weakly pronounced texture [11], which changed in the direction of construction, and in [12], the AA7050 alloy was investigated, and a variation in texture was established for different sections and layers of the structure. The 6061-T651 alloy

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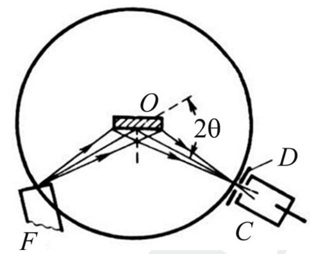

Fig. 1 Bragg-Brentano geometry for texture measurement. *F* is X-ray tube focus; *O* is flat sample; *D* is counter slit; *C* is counter; 2θ is reflection angle

showed different texture components, which affected the anisotropy of the yield point [13]. The study of the AA5083 alloy demonstrated the possibility of obtaining isotropic properties due to the formation of a specific crystallographic texture [14].

These and a number of other studies [15, 16] emphasize the importance of studying crystallographic texture for optimizing the characteristics of 3D-printed workpieces for aerospace and missile applications. However, the question of the texture formation of AK9 aluminum alloy workpieces depending on the direction of construction, its influence on the anisotropy of physical and mechanical properties, the composition and number of texture components, etc., is still open for discussion.

The work aims to investigate the crystallographic texture of the AK9ch aluminum alloy samples obtained by the friction additive deposition technology in the horizontal and vertical directions of construction.

Research methods

The construction of workpieces by friction stirring using the AFS-D method essentially consists of cutting a thin layer from the end of a rotating consumable rod, which is pressed against the substrate, and is described in detail in [8]. Cylindrical rods of diameter 10 mm made of AK9ch alloy (9.6% Si; 0.3% Mg; 0.1% Fe; 0.1% Mn; Al balance) are the starting material. To construct the samples using the AFS-D method, the rods were fixed on a special spring mandrel mounted on a vertical milling machine. They were deformed with a pressure of 5 GPa and torsion for 5 full revolutions at room temperature. The torsion speed was 1 rot/min.

The use of a spring mandrel made it possible to adjust and maintain at a constant level the pressing force applied by the end of the consumable rod to the substrate. A steel bar was used as the substrate.

The deposited samples were manufactured by the AFS-D method with longitudinal (horizontal samples) and transverse (vertical) tool feed. With a favorable combination of temperature, force, and kinematic parameters of the process, high-strength volumetric samples were obtained in both cases. Three layers were formed by deposition, which provided sufficient sample thickness for texture studies.

The crystallographic texture was studied by the X-ray method [17, 18] in the usual geometry with Bragg–Brentano focusing (Fig. 1; [19]) with the construction of inverted pole figures (IPF) in the direction of the normal (ND) to the plane of the deposition surface of the samples (IPF ND) and in the transverse direction (TD) perpendicular to their end surface (IPF TD).

The IPF method was used for texture analysis, since the studied samples had small geometric dimensions, which made it impossible to photograph straight pole figures. Samples without texture (reference) were manufactured from fine recrystallized chips of the alloy under study, which were obtained using fine sawing. This chip was annealed in a vacuum furnace at a temperature of 150 °C for 1 h for recrystallization. Then, mixed with PVA glue, it was applied to a flat glass substrate. After the glue dried, a reference sample without texture was obtained. The thickness of the chip layer was approx. 2 mm.

A set of samples in the form of a package of 3 mm wide strips glued together, cut from samples obtained by the AFS-D method, were used to record the IPF of the DN. The defective surface layer was polished by chemical etching to a depth of 0.1 mm to prevent undesirable effects on the texture of the samples. The results of X-ray θ–2θ diffraction of the deposited samples and the corresponding standards in filtered MoK_α-radiation on a DRON-3m diffractometer under the same geometric conditions of the survey were used to construct the corresponding IPFs.

The polar density P_i is proportional to the ratio of the intensity of the i-th diffraction line in the textured sample I_i to the intensity of the corresponding line I_R in the sample without texture:

$$P_i = \frac{K \times I_i}{I_R}. \quad (1)$$

Here, the Morris normalization factor K [20] was determined by the formula

$$K = \frac{1}{\sum_\Delta A_i \times \left(\frac{I_i}{I_R}\right)}, \quad (2)$$

where A_i is the statistical weights of the i-th reflex on the IPF. The coefficients A_i, given in [14], are calculated as a percentage of the surface area of the stereographic triangle around the normal to the i-th reflex of the corresponding inverted polar figure of the IPF. Therefore, the pole density is defined as:

$$P_i = \frac{I_i}{\sum_\Delta A_i \times \left(\frac{I_i}{I_R}\right)}. \quad (3)$$

Results and discussion

Workpiece manufacturing means the deposition of thin concentric layers of rotating tool material on a substrate through friction and heating during contact with the substrate, and then with the previous layer at each subsequent step.

The formation of two zones, conventionally called the main and peripheral zones, was observed at the tool exit point [8]. The crystallographic texture for the main zone of samples obtained by the AFS-D method with longitudinal feed was studied, where the stability of the material structure was achieved.

After preparation of the horizontal sample surface for study of its texture, the total average thickness and length of the layer were 2.5 and 12 mm, respectively. The vertical samples had a close to cylindrical shape. The diameter and height of the vertical samples were 10 and 4 mm, respectively.

The IPF of the samples of the studied alloy obtained by the AFS-D method are presented in Fig. 2. As we can see, P_i on the IPF is small, which indicates a weakly expressed texture. The P_i density on the IPF of the ND, recorded in the plane of the sample with vertical tool feed during AFS-D (Fig. 2a), has a wide scattering region near the pole <110>, covering the poles <331>, <531>, <210>, <320>. In addition, an increased density in the poles <533>, <733> is observed.

The crystallite orientations in the transverse direction of this sample are divided into two broad regions with increased pole density, as can be seen from the IPF of the TD recorded from the side surface (Fig. 2b) of this sample. The poles <211>, <533>, and <331> bound one region of increased density around the pole <111>. The second region around <100> is bounded by <311>, <320>, <210>.

The analysis showed that the texture consists of a combination of weak shear components (110) [100] (Goss texture) and a rotated torsion texture (110) [111], deformation textures (110) [112] (brass-like), (135) [211] (copper-like), and recrystallization texture (120) [211], and (320) [332].

The pole density on the IFR of ND, recorded in the plane of the sample with longitudinal tool feed during AFS-D (Fig. 2c), has several regions with increased values. These are regions of orientation around the poles <111>, <331>, <210>, <320>, <100>. The regions of increased density on the IPF of TD, recorded from

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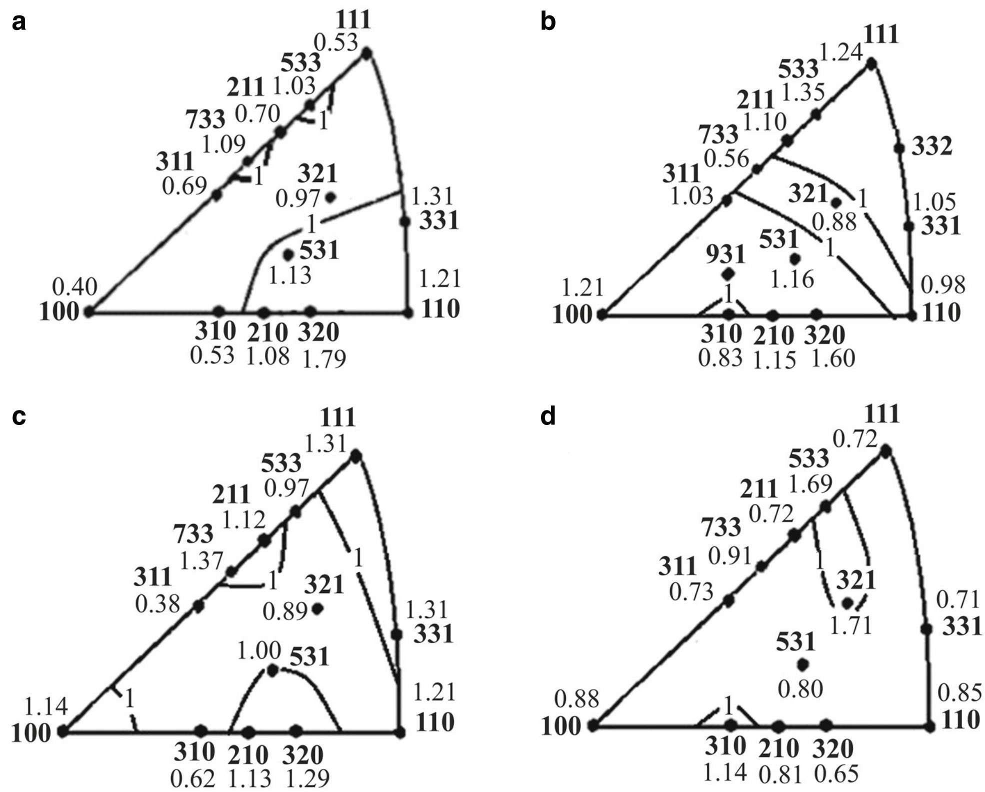

Fig. 2 Inverse pole figures (IPF) of AK9ch alloy samples obtained by AFS-D method with **a**, **b** transverse and **c**, **d** longitudinal tool feed: **a**, **c** IPF of normal direction; **b**, **d** IPF of transversal direction. Darker numbers indicate poles, lighter numbers indicate pole densities

the side surface of this sample (Fig. 2d), are more compact. They are localized around the poles <533>, and <321>, as well as around the pole <310>.

The analysis showed that the texture can be described by a combination of weak components of the rotated torsion texture (111) [132], the rotated deformation texture (112) [312], and the recrystallization texture (001) [310].

Thus, the textures of the samples of the studied aluminum alloy, obtained by the AFS-D method with longitudinal (horizontal samples) and transverse (vertical) tool feed, differ both in the set of texture components and in the scattering character. Literature analysis [9–14] showed that the type of texture and the character of its distribution depend on the deposition parameters. However, since the texture of both samples of the studied aluminum alloy is weakly expressed, it should be expected that the anisotropy of their physicomechanical properties should be insignificant, as previously noted [9–12, 14]. This is in contrast with the results in [21, 22] on the influence of 3D printing on the texture and anisotropy of metal alloys obtained by additive technology. During 3D printing of alloy samples based on titanium [21], nickel [16], obtained in the horizontal and vertical directions of construction, there is a rather pronounced texture and, accordingly, anisotropy of elastic and mechanical properties.

Comparison of the texture of the studied aluminum alloy samples with the results of the textures of samples of other aluminum alloys obtained by the AFS-D method showed their similarity [9–14]. The general fact is that after such treatment, the texture of samples of different aluminum alloys contains components of torsion, shear, deformation, and recrystallization, since these processes are typical of additive deposition by friction with stirring.

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Conclusions

The crystallographic texture of the AK9ch aluminum alloy samples obtained by the additive friction deposition (AFS-D) technology at room temperature with longitudinal (horizontal samples) and transverse (vertical) feed of the consumable tool differs in both the set of texture components and the character of scattering. The texture of the sample obtained by the AFS-D method with vertical feed of the consumable tool consists of a combination of weak shear components (110) [100] (Goss texture) and a rotated torsion texture (110) [111], deformation textures (110) [112] (brass-like), (135) [211] (copper-like), and recrystallization texture (120) [211] and (320) [332]. The texture of the sample obtained by the AFS-D method with horizontal feed of the consumable tool can be described as a combination of weak components of the rotated torsion texture (111) [132], the rotated deformation texture (112) [312], and the recrystallization texture (001) [310]. The texture of the studied samples of AK9 aluminum alloy obtained by AFS-D technology is similar to the textures of other aluminum alloys after deposition by AFS-D methods and contains components of torsion, shear, deformation, and recrystallization, since these processes are typical of friction stir additive deposition. Despite the difference in the textures of the studied alloy samples obtained by the AFS-D method in the horizontal and vertical directions of the structure, texture is weakly expressed in both samples, so a slight anisotropy of physicomechanical properties should be expected. The intensity, composition, and number of texture components depend on the technological parameters of deposition: the process speed, the pressure of the consumable rod, the speed of its rotation, and the substrate during longitudinal movement. Therefore, the prospect of further research is to study the influence of these parameters.

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