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Production of materials with ultrafine-grained structure of aluminum alloy by friction stir processing

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Abstract. Methods of optical microscopy, scanning electron microscopy and EBSD analysis have been used to study the structure of ultrafine-grained materials obtained by friction stir processing. The data obtained indicate a complex and inhomogeneous character of the deformation at the processing area. When conducting TEM studies, it was revealed that grains of the \( \alpha \)-Al solid solution of the processed material have the zone axis of the type \( <110> \). The main differences in the structure of materials obtained by processing with different types of tool are determined. It was revealed that in addition to the difference in the use of the tool with the presence or absence of the so-called "pin", the shape and arrangement of grooves on the end part of the tool, the so-called "shoulders", are of paramount importance. The influence of the shape of the grooves affects both the depth of the processed layer and the average grain size of the stir zone.

1. Introduction

At the present time techniques based on the effect of adhesive-diffusion friction [1-9] are often used for the manufacture of parts for rocket and aero-space spheres of production. Such methods include friction stir welding (FSW), which is used mainly for joining sheet metal of various metals and alloys [1-3], and friction stir processing (FSP), used mainly for the manufacture of parts with a hardened surface layer or bulk materials with ultrafine-grained structure [6, 7]. Owing also to the FSP, it is possible to obtain materials with a strengthened structure without the use of expensive alloying components.

At this stage of the development of the concepts of FSW and FSP, mainly tools for FSW tools are used for surface processing. At this stage of the development of the concepts of FSW and FSP, for surface processing mainly tools for FSW are used. Such tools consist of a working part – "pin", serving to grind the structure in the weld and the auxiliary part – "shoulders", serving to create pressure on the welding zone and prevent extruding the material away from the welding or processing zone. With such a tool, friction stir processing of materials can be made to an arbitrarily large depth from the surface. However in a situation where it is necessary to create a thin hardened surface layer with a modified structure and an undeformed internal volume of the product, such a tool is not sufficiently acceptable. In this case, it is more expedient to use the so-called tool with no pin, which processes the surface only at the expense of shoulders. At the same time, such works are already available in modern literary sources. It is interesting to study at this stage to determine the effect on the formation of the structure of the stir zone of the shape and size of the grooves on the surface of the
tool, since by this method it is possible to obtain materials completely different in their characteristics from identical initial sheet products. In this work to determine the influence of the shape and arrangement of the grooves on the structure of the metal in the processing zone, two types of grooves were used. The "star" and "spiral" forms of tool's grooves shown in figure 1.

2. Materials and methods

Friction stir processing of sheet metal was carried out on laboratory equipment at the Institute of Strength Physics and Material Sciences SB RAS. As a tool for processing tools like "spiral" (figure 1a, d) and "star" type were used (figure 1b,c). The processing by both tools was carried out in identical modes to determine the influence of precisely the shape of the grooves. The surface of the rolled sheet of AA2024 alloy after processing, shown in figure 2, there are no significant differences from surfaces processed with the presence of "pin". From the obtained samples (figure 2) a thin section was made for metallographic studies. The foil was subsequently cut out from the stir zone of the samples for examination by the method of transmission electron microscopy.

After the preparation of the thin sections by grinding, polishing and chemical etching, the microstructure of the samples was photographed on an optical microscope Altami met 1C at various magnifications. Fine structure studies were carried out by transmission microscopy using the JEOL JEM-2100 microscope.

Figure 1. Image of tools for FSP (a, b – tools after work, c, d – tools not used in the work).

Figure 2. Appearance of the surface of rolled sheet of AA2024 alloy 10 mm thick after FSP.
3. Results and discussion
The carried out investigations of the structural features of the formation of materials by the FSP method show that the use of a tool with no pin leads to the formation in the structure of the metal the main structural zones identical to those observed with the use of a classical tool with pin. A stir zone (SZ) is allocated. It is a region of material with an almost completely recrystallized ultrafine-grained structure. The thermo-mechanical action zone (TMAZ) is a region with a highly deformed material, which is represented by a mixture of deformed, elongated and partially recrystallized grains. The heat affected zone (HAZ) is a zone with practically unchanged grain of the base metal, experiencing thus, a significant thermal effect during processing. In a number of alloys, for example AA2024, used in the work, the HAZ is clearly distinguished on metallographic sections due to increased etching. In contrast to the samples with pin, in the cases under investigation (figures 3 and 4), these zones are located inland from the surface, while the SZ is not round in cross-section, but semicircular, starting from the surface of the treated material.

As studies show, processing with a "spiral" type tool leads to the formation of a SZ with a depth of 1.2-1.5 mm, with a HAZ up to 4.5-5.5 mm. The stir zone (figure 3) is fairly homogeneous with an average grain size of 1.5-2.5 μm (figure 5a).

Processing with a tool of the "star" type led to the formation of a deeper region of the processed material to 1.8-2.2 mm with a HAZ of 7.5-8.5 mm. The stir zone had a number of inhomogeneities, connected mainly with the stratification of the structure (figure 4). The average grain size of the SZ (figure 5b) in this case was about 3-5 μm. Presumably, the increase in heat generation during processing, which is evident from the increase in the depth of the HAZ, influenced the growth of the grain.

![Figure 3](image-url)
**Figure 3.** The change in the structure of the metal in the cross section of a sample of AA2024 alloy, obtained using a tool like "spiral".

![Figure 4](image-url)
**Figure 4.** The change in the structure of the metal in the cross section of a sample of AA2024 alloy, obtained using a tool like "star".
Figure 5. The difference in the structures of the stir zones of samples obtained using a “spiral” (a) and “star” (b) types of tools.

Structural-phase features of the stir zone structure, determined with the use of transmission microscopy, show quite similar results for samples of both types. Firstly, as a result of TEM studies, the presence of two strengthening intermetallic phases AlMgCu and Al₂MgCu (S’-phase) was revealed in the material of the stir zone. In this regard both phases are nanostructured. With small differences in the sizes of the secondary phase’s particles, the general nature of the structure and phase composition remains the same for both types of samples. Also, for samples of both types, the arrangement of grains with crystallographic axes of the <110> type along the processing axis is indicative, which is also characteristic for samples obtained using a tool with the presence of a “pin”.

4. Conclusion
The carried out researches show that when the friction stir processing is performed without a pin with a different shape of the grooves, the structure of the samples essentially depends on the shape and arrangement of the grooves on the surface of the tool. The use of a “spiral” type tool is characterized by a smaller depth of the processed layer, but, in spite of this, by a smaller average grain size of the solid solution in the stir zone. On the other hand, the use of a “star” type tool is characterized both by the greater depth of the deformed layer and by the larger average grain size. At the same time, the structural-phase state of the samples is characterized by features similar to materials obtained by a tool with the presence of a pin. It was found that the grains of the α-Al solid solution of the processed material have the zone axes of the type <110> in the direction of processing, which is typical for many types of deformation of FCC metals and alloys.

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