The Regularities of Structure Formation during Friction Stir Processing of Bimetallic Materials Based on Copper and Aluminum Alloys

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Abstract. The structure of polymetallic materials samples obtained by friction stir processing of a sheet package made from AMg5 aluminum alloy and L63 copper alloy is studied. The regularities of structure formation at the deformation-initiated stirring of system components in comparison with the similar process at sample production from homogeneous materials are determined. The localization of the main defective zones in the samples during coatings formation is studied. Intensive diffusion and mechanical mixing of system components, leading to the formation of a large number of different phases in the "coating-substrate" system, has been revealed.

1. Introduction
Obtaining the tribotechnical materials for aviation and rocket-space industry is associated with the attempts to reduce the volume weight of the received products. At the same time, one of the most applicable materials in sliding bearings is various high-density copper alloys.

One of the ways to solve this problem is the formation of tribological surfaces on sufficiently light and durable materials such as titanium or aluminum alloys. For this purpose, a sufficiently large number of material deposition techniques by galvanic method, from gas phase, plasma or colloidal solution are suitable. However, in most cases there is a disadvantage in the form of difficulty in obtaining a high thickness coating or a sharp structure and properties gradient during the transition from coating to substrate.

Friction stir processing is one of the methods that allows to create hardened gradient surface structures with a smooth gradient from coating to substrate [1-5]. The method of friction stir processing is based on the phenomenon of adhesive friction [6-9] and refers to the class of techniques that also include friction stir welding [10-14] and friction drilling [15-17]. With the use of friction stir processing it is possible to combine materials with different physical and mechanical properties in one product and to obtain structures with different types of surface hardening. In addition to solid solutions, intermetallic hardening particles are formed in large quantities in the surface layer, which also increases tribological properties of the obtained materials.

Thus, at formation of coatings from copper and its alloys on an aluminum or titanium alloy surface by the various additive methods based on melting, various intermetallic layers in a boundary zone inevitably arise, that leads to sharp decrease in mechanical properties in a system "covering-substrate".
Formation of similar interlayers is also revealed at friction stir welding or friction stir processing, but the size of interlayers is much smaller compared to other methods and does not have such an impact on the strength properties [18-20]. But, in the modern literature there is a lack of information on the formation of gradient structures by friction stir processing of a sheet package containing aluminum and copper alloys, which is the purpose of this paper.

2. Materials and methods

The samples were obtained by friction stir processing with standard tools on the equipment of the laboratory for quality control in materials and structures at ISPMS SB RAS, Tomsk, according to the scheme presented in Figure 1. The sheet of copper alloy L63 with the thickness of 2 mm interfered with the surface layer of aluminum alloy AMg5 using a rotating tool with the pin length of 3 mm. The structure obtained in the stir zone was represented by a material mixture of both alloys with different dispersion and structural-phase state. Structure studies were carried out by the optical, confocal and scanning electron microscopy with the laser scanning microscope Olympus LEXT 4100 and scanning electron microscope Zeiss LEO EVO 50. Mechanical properties of coatings and adhesion of the coating to the substrate were studied on the universal testing machine UTC 110-M. Samples for determining mechanical properties were cut along the processing direction. Cross-shaped specimens were prepared to determine the tear-off adhesion.

![Figure 1. The scheme of the material formation process by friction stir processing technology.](image)

3. Results and discussion

The process of friction stir processing of L63 and AMg5 alloys in comparison with earlier conducted experiments on processing of pure copper and AMg5 alloy occurred more evenly practically without the uncontrolled heating of the material. The structure of the stir zone, thermo-mechanical action zone (TMAZ) and heat affected zone (HAZ) have a typical shape, determined by the features of the material flow during processing (Fig. 2, a,b,c). Aluminum alloy as a result of friction stir processing rises through the entire volume up to the tool shoulders rotation zone. The main zone with an increased amount of mixed aluminum alloy is the S-shaped central zone (the area of the flaw formation fig. 2, c) located from the lower part of the retreating side to the right part of the advancing side of the
processing zone. Also noted in some areas of the sample is the extrusion of aluminum alloy material at the edge of the advancing side.

In areas with excessive materials mixing interaction, the formation of extended intermetallic interlayers with the inevitable formation of cracks is possible when the material is cooled (Figure 2, b). It is noteworthy that for the flows of aluminum alloy material formed in different areas, the area of rise on the copper alloy sheet surface coincides and is located at the edge of the tool shoulders on the advancing side. (fig. 3, b)

The structure of the stir zone is represented mainly by a mixture of aluminum alloy layers, copper alloy and the results of their mutual diffusion mixing (Fig. 3). According to the results of scanning electron microscopy and micro-X-ray spectral analysis, both solid solutions and intermetallic phases are formed in the layers. At the same time, there is a substitution of a zinc solid solution in a copper alloy by a aluminum solid solution in copper.
Figure 2. Formation of the stir zone and defects along the zone contour during processing of the copper-aluminum system (a), crack in the boundary zone of aluminum alloy upward flow (b) and the area of the aluminum alloy central flaw formation (c).
Mechanical properties of the material in the stir zone are at a sufficiently high level and are about 320 MPa, which corresponds to the strength of rolled aluminum alloy sheet. Adhesion of the coating to the substrate can be disturbed in case of excessive formation of intermetallic compounds in the boundary zone and makes up from 55 MPa in defective samples to 278 MPa in samples with normal structure.

4. Conclusion
The carried out structural researches and mechanical tests of the coating-substrate system formed in the process of friction stir processing of copper and aluminum alloy sheets show that an inhomogeneous layered structure is formed in the stir zone, consisting of the system components initial layers and their reaction products. Various interaction mechanisms are possible in the layers, from the replacement of some solid solution components by others to the formation of intermetallic particles or interlayers. The most complicated processes to describe are observed in the formation of aluminum alloy flows from the aluminum alloy sheet surface through the entire thickness of the copper alloy sheet. The formation of such flows is primarily related to the process mechanics and pressure distribution in the area under the tool during processing. This results in extrusion of the material in the central S-shaped zone to the extreme point of the tool shoulders from the advancing side. Mechanical properties and adhesion of the coating to the substrate in defect-free samples are at a sufficiently high level. In the presence of solid intermetallic layers and cracks a sharp drop in mechanical properties is possible.

Figure 3. Formation of solid solutions and intermetallic phases in the stir zone.
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