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Microstructure and mechanical properties of a welded joint obtained by friction stir welding of thin copper and aluminum plates

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Friction stir welding was used to produce a welded joint of 1 mm thick plates of copper M1 and aluminum alloy AMg2M. The microstructure of the shoulder-side of the joint had areas of mixing of aluminum and copper. In the area of aluminum, copper inclusions were observed, and in the area of copper, aluminum inclusions were observed in the form of particles and thin lamellas. The bottom side of the joint consists mainly of copper. X-ray diffraction showed the presence of intermetallic phases Al_2Cu, Al_4Cu_9 from the side of the shoulder. The formation of intermetallic phases occurred in the solid-state, without melting the initial materials. The presence of copper particles in the region of aluminum and aluminum particles and lamellas of various lengths in the regions of copper, intermetallic phases led to the formation of a composite-like structure. The formation of a composite-like structure during friction stir welding of copper and aluminum plates affects the mechanical properties of the joint. Thus, the microhardness of the joint increased in comparison with the microhardness of the initial plates. The distribution of microhardness over the thickness of the joint is almost uniform. The formation of composite-like structure using friction stir welding are discussed.

Keywords: friction stir welding, solid-state reaction, intermetallic compounds.

1. Introduction

Solid- state reactions are widely used in physical metallurgy, for example, to create structural materials [1–4] and to join difficult-to-weld materials using friction stir welding (FSW) [4–12]. During FSW, a rotating tool, which is a cylinder with a flat shoulder and a fixed pin-tip of a smaller diameter, is inserted into the contact line of two metal plates to be joined and moves along the contact line at a given constant speed. The welding tool has two main functions: heating the workpiece and stirring the material to create a joint. Heating occurs due to the friction between the tool and the workpiece and the plastic deformation of a workpiece [5,6].

FSW was developed as a technology for joining thick aluminum plates, but with the development of the process, this technology began to be used for welding materials with a higher melting point, for example, copper plates [7]. Currently, the scope of this process has expanded. Joining of dissimilar materials with strongly differing physical and mechanical properties using FSW is of a considerable interest.

The issues of joining dissimilar materials are discussed, for example, in reviews [5,6,8–10], where the following are considered: the influence of the parameters of a welded tool on the microstructure and mechanical properties of a welded joint, the mechanisms of formation and improvement of the quality of a welded joint. It should be noted that only last year several reviews devoted to FSW were published [8–10]. In [8], the focus is on understanding the basis of microstructure evolution during FSW of homogeneous and dissimilar welded joints. For this purpose, the mechanisms of formation of the microstructure, texture, and phase transformations in the process of FSW are considered. Review [9] is devoted to the consideration of new varieties of FSW for joining homogeneous and dissimilar materials, including polymers. Various methods of FSW are considered in [10], where the results of modeling the mixing process by the finite element method are presented. Modeling methods are widely used in the study of problems arising from FSW. In [11], the effects of the welding process parameters and the pin profile on defect formation during FSW were modeled. Based on the simulation results using the DEFORM-3D software package, in [12] the optimal pin geometry was selected to ensure good mixing in the workpiece plane and obtain the most symmetrical weld. It is important to note that shear deformations predominate in the FSW process, and the observed shear textures may indicate defect formation bands during welding [13,14].

In particular, the Al-Cu system is of industrial and research interest. During FSW of Al and Cu plates intermetallic compounds (IMCs) such as Al_2Cu, Al_4Cu_9 and AlCu are formed. The formation of intermetallic compounds occurs in the solid-state. In the literature, there is no generally accepted point of view on the mechanisms of formation of intermetallic joints, as well as their influence on the structure and properties of the joint [6, 8, 15–18].

Most of the work on FSW, the Al-Cu system was done on specimens with a thickness of more than 3 mm, and there are only a few works where specimens of lesser thickness are used [6,16,17].

The purpose of this work is to analyze the microstructure and mechanical properties of the welded joints of thin copper and aluminum plates obtained by FSW.

2. Materials and experimental methods

For friction stir welding, plates of copper M1 and aluminum alloy AMg2M, 1 mm thick were used. Welding was carried out on a 6V75 milling machine. The plates to be welded were fixed end-to-end using a specially designed fixture (Fig. 1), placing a copper plate on the advancing side (AS), and aluminum, respectively, on the retreating side (RS). A welding tool was used in the form of a cylinder with a flat shoulder 12 mm in diameter and a fixed tip — a pin 4 mm in diameter and 0.8 mm in length. Steel 3 was chosen as the material for the welding tool. The following welding parameters were used: tool rotation speed of 1050 rpm and traverse speed of 104 mm/min and an indentation depth of 1 mm. The length of the obtained welds was 40 – 45 mm. To study the microstructure, test specimens were cut from the surface of the joint, which were ground on abrasive discs (P320, P800, P1200, P2000) using water.

The study of the microstructure and energy dispersive spectrometry (EDS) of the surface of the deformed sample was carried out on a VEGA 3 SBH scanning electron microscope with a secondary electron detector. EDS was carried out both at individual points and along lines normal to weld line. On the lines, the elemental composition was measured every 2.5 μm.

The samples obtained were investigated by X-ray diffraction (XRD) on a DRON 4-07 diffractometer using a graphite crystal monochromator on a diffracted beam in Cu-K_α radiation.

Microhardness of the sample was tested by an AFFRI DM8A microhardness tester. Static load applied to the diamond tip for 10 seconds was 100 g.

3. Experimental results

The macrostructure of the weld is shown in Fig. 1b (welded joint number 12). It can be seen that the weld is free from welding defects such as cracks and cavities When examining the microstructure of the weld surface from the shoulder side (upper side), an area of mixing of aluminum and copper is observed. On the opposite (down side) side of the joint, copper predominates.

Figure 2 shows the microstructure of the mixing region of aluminum and copper on the upper side of the joint, obtained in a scanning electron microscope. There is no clear interface

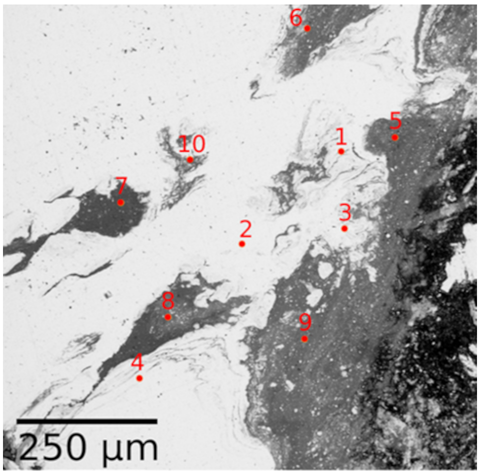
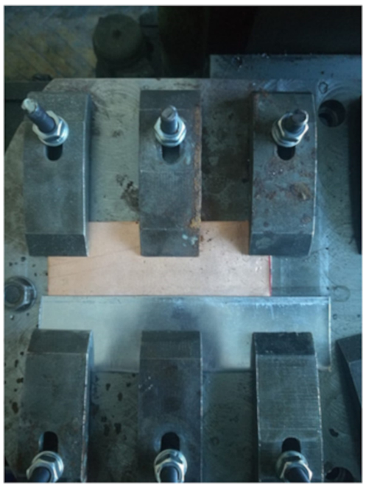


Fig. 2. The microstructure of the welded joint after the FSW from the side of the shoulder.



a

b

Fig. 1. (Color online) Attachment of the original plates (a) and the appearance of the joint (b). Copper fixed on the advancing side (AS), aluminum on the receding side (RS).

between aluminum and copper. The dark-colored region is the Al-rich one and the light-colored one corresponds to the Cu-rich region. In the area of aluminum, copper inclusions are observed, and in the area of copper, aluminum inclusions are observed in the form of large and small particles, as well as in the form of thin lamellas of various lengths. The EDS results obtained in individual points of the Al-rich regions showed that they all contain a considerable amount of copper, while in the Cu-rich region the fraction of aluminum in the studied points is significantly less than 1 at. % (Table 1).

EDS carried out along the line (Fig. 3) showed that at the border of the dark and light regions there are points at which the ratio of aluminum and copper atoms corresponds to copper, a solid solution of aluminum in copper and intermetallic compounds Al_3Cu_2, Al_4Cu_9, Cu_3Al, Cu_4Al, AlCu, Al_2Cu, and Al_9Cu_{11}.

In the lower surface of the joint mainly copper with small areas where aluminum and copper are mixed is observed (Fig. 4).

EDS by point showed the presence of points with a predominance of copper, where aluminum is present in an amount from 27 to 46 at.%, and the points where the composition corresponds to intermetallic compounds rich in copper, i. e., Al_4Cu_9, Cu_3Al, and Al_9Cu_{11} (Table 2). EDS of the lower side of the joint along the line showed a similar result.

The above-described differences in the microstructures of the joint on both sides affect the X-ray diffraction pattern.

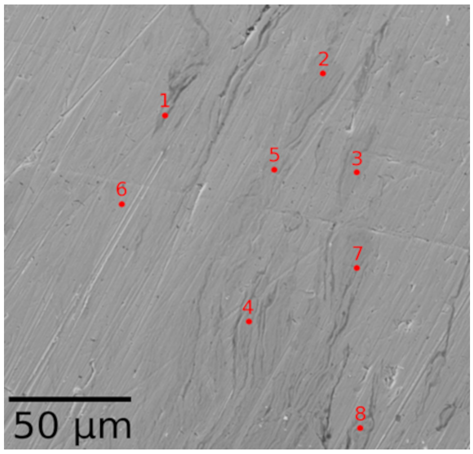


Fig. 4. The microstructure of the welded joint after the FSW from the bottom side.

XRD was performed on both sides of the weld. The formation of intermetallic compounds was found only on the upper side (Fig. 5).

XRD pattern contains diffraction maxima of copper, aluminum and intermetallic compounds Al_2Cu, Al_4Cu_9. In this case, the diffraction maxima of copper have a higher intensity, which indicates that on the upper surface of the joint there is more copper than aluminum and intermetallic compounds. The diffraction pattern on the down side of the

Table 1. EDS results for the points shown in Fig. 2.

Point	Elemental composition (at.%)		Possible IMCs
	Al	Cu	
1	56.36	43.64	Al_3Cu_2
2	0.28	99.72	Cu(Al)
3	0.32	99.68	Cu(Al)
4	0.83	99.17	Cu(Al)
5	89.58	10.42	-
6	90.52	9.48	-
7	93.7	6.3	-
8	86.17	13.83	-
9	88.66	11.34	-
10	86.12	13.88	-

Table 2. EDS results for the points showed in Fig. 4.

Point	Elemental composition (at.%)		Possible IMCs
	Al	Cu	
1	44.37	55.63	Al_9Cu_{11}
2	31.47	68.53	Al_4Cu_9
3	30.14	69.86	Al_4Cu_9
4	43.44	56.56	Al_4Cu_9
5	27.29	72.71	Cu_3Al
6	0	100	Cu
7	46.63	53.37	-
8	45.88	54.12	-

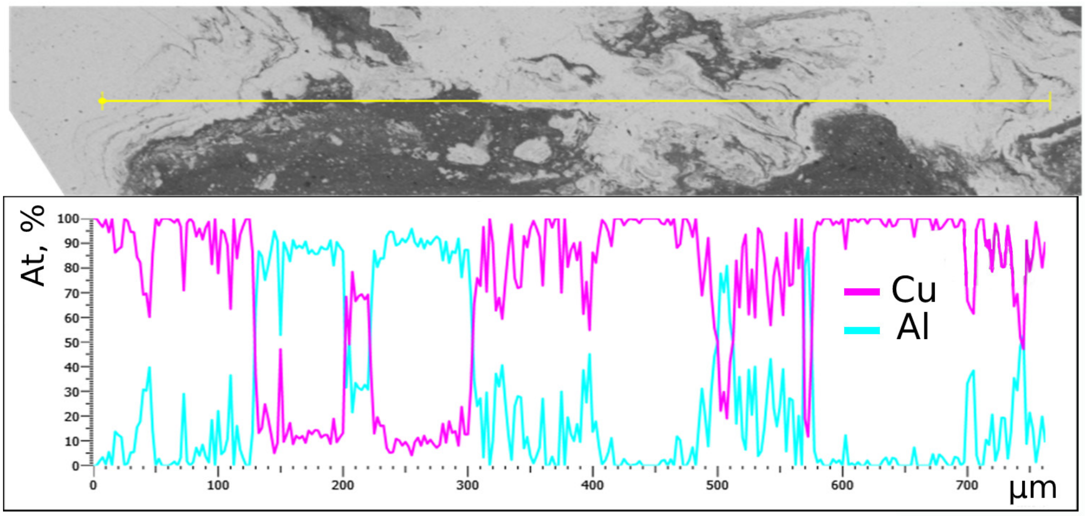


Fig. 3. (Color online) EDS along the line of the joint after the FSW from the shoulder side.

welded joint contains only diffraction maxima of copper. The integral width of the diffraction maxima of copper on the down side of the joint is larger than that from the atomic planes with the same indices on the side of the shoulder. This suggests that the value of the strain of materials on the down side was higher.

The results of measurements of the microhardness on both sides of the joint showed a significant increase of its value during the friction stir welding (Fig. 6). Although the values of of microhardness on different sides of the weld are similar, this similarity is caused by different origins a discussed below.

4. Discussion

The studies have shown that the microstructure of the joint on the side of the shoulder has areas of mixing of copper and aluminum. The presence of particles and lamellas of various lengths of copper in the Al-rich region and aluminum in the Cu-rich regions and the presence of intermetallic phases such as Al_2Cu, Al_4Cu_9 led to the formation of a composite-like structure. EDS showed the presence of points, the composition of which is close to intermetallic compounds possible according to the phase diagram in the Al-Cu system. On the down side of the joint, we observed points whose composition was close to intermetallic compounds with a high copper content, such as Al_4Cu_9, Cu_3Al, Al_9Cu_{11}. As shown by XRD, the formation of intermetallic phases did not occur, but as can be seen from Table 2, there was a noticeable mixing of copper and aluminum. A composite-like structure after FSW and the formation of intermetallic phases Al_2Cu, Al_4Cu_9 were observed, for example, in [6,16,18].

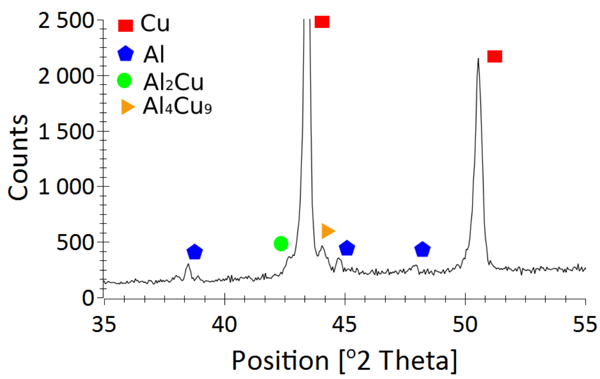


Fig. 5. (Color online) XRD pattern of the joint from the shoulder side.

The presence of a composite-like structure in the welds obtained by FSW of copper and aluminum plates affects the mechanical properties of the joint. As can be seen from Fig. 6, the microhardness of the welded joint increases. The value of the microhardness is practically the same on both sides of the joint. As can be assumed from the analysis of the microstructure and XRD pattern, the microhardness is affected by the presence of intermetallic phases and the deformed state of the components being welded, especially copper. On the upper side, the contribution to the microhardness is made by the intermetallic phases and the deformed state of the weld, and on the down side, only the contribution from the deformed state.

A similar, rather uniform, distribution of microhardness in the welded joint of copper and aluminum plates with the thickness of 1 mm was obtained in [17]. At the same time, in work [16], where ultrathin plates of copper and aluminum were welded, the microhardness of the upper part of the joint was higher than that of the lower one. Probably, the reason for such a distribution of microhardness is related to the conditions of the FSW process, primarily, to the rotation and traverse speeds of the welding tool. This could have led to a more uniform temperature distribution in the weld due to the small thickness of the original samples, which, in turn, resulted in the formation of intermetallic phases on the side of the shoulder and significant mixing of copper and aluminum on the down side of the weld. At the same time, the formation of intermetallic phases during FSW is influenced not only by the temperature, but also by the mechanical mixing of the initial components during plastic deformation, which promotes solid-state diffusion of atoms of the initial components. In the review [6] this point of view is well substantiated.

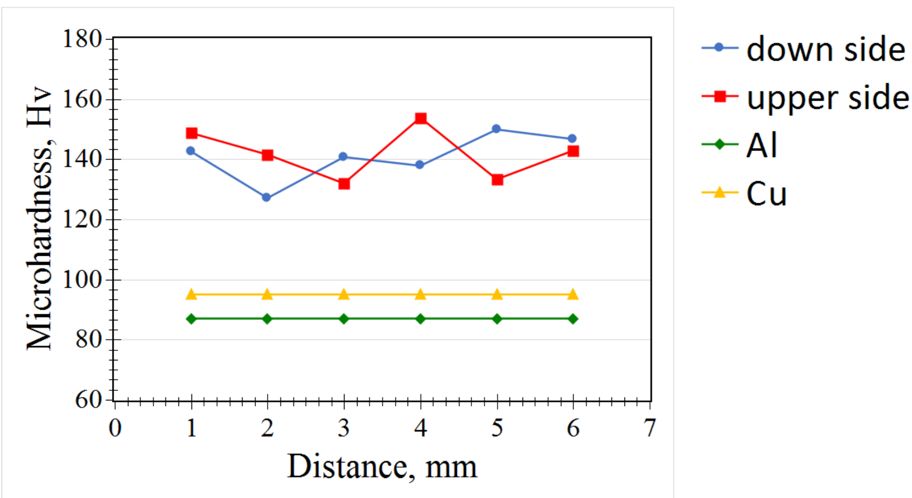


Fig. 6. (Color online) Microhardness of the joint.

In the process of mixing, various discontinuities and microcracks can occur. In [16], a scheme of the process is proposed, where microcracks play a positive role in mixing ultrathin copper and aluminum plates. However, the presence of microcracks does not lead to a good weld quality.

One of the possible ways to improve the quality of the welded joint is to control the axial force of the tool on the joint of the materials to be welded. In [10], the authors show that the occurrence of defects is affected by axial force. There are several studies of the effect of axial force on the microstructure, chemical composition and mechanical properties of the welded joints [19,20]. For instance, it was shown in [19] that an increase in the axial force on the tool during the FSW of aluminum leads to a rise of temperature in the core of the weld, increase in the degree of mixing of the materials under welding, and, as a result, enhances the hardness of the weld. Increase in the axial force from 10 to 15 kN during the FSW of copper plates with a thickness of 2 mm led to a significant effect on the microstructure and mechanical properties of the welded joint. The destruction of specimens welded with axial forces of 10 and 12 kN during tensile tests was observed in the mixing zone, and the destruction of specimens welded with an axial force of 15 kN occurred along the base metal [20]. During the tensile test, the samples obtained by welding with axial forces of 10 and 12 kN failed along the weld, and the sample obtained by welding with axial forces of 15 kN failed along the base metal.

It is possible that a change in the axial force during the FSW of dissimilar specimens will affect the formation and distribution of intermetallic phases and the properties of the weld.

5. Summary and conclusions

Friction stir welding of thin copper-aluminum plates produced a welded joint. In the upper side of the weld, intermetallic phases Al_2Cu and Al_4Cu_9 and a composite-like structure are formed. In the down side, only mixing of copper and aluminum atoms was observed.

The microhardness of the joint obtained by friction stir welding is significantly higher in a comparison with the microhardness of the original plates of copper and aluminum.

The solid-state formation of intermetallic phases is activated by temperature and the action of plastic deformation. The process of mixing copper and aluminum occurring during FSW promotes the formation of regions, the composition of which is close to intermetallic phases.

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