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Research article

STUDY OF SOLID STATE JOINTS OF COPPER PROCESSED BY ULTRASONIC WELDING

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Abstract. By means of ultrasonic welding, solid-state joints of copper sheets with the initial coarse-grained structure were obtained. It is shown that in the course of ultrasonic welding, significant structural changes occur in the material in the joint region. A layer with an ultrafine-grained structure with a grain size of less than 1 μm is formed near the contact interface of the sheets, and elongated grains with developed substructure are observed in the bulk of the sheets in the welding zone. There are no structural changes outside the weld spot zone. The average lap shear strength of the specimens was 36 MPa. It is shown that the structural changes occurring during welding result in an increase in microhardness by factors of 1.2 and 1.5 in the bulks of sheets in the weld spot zone and in the weld joint as compared to that of the initial sheet (950, 1200, and 790 MPa, respectively).
Keywords: ultrasonic welding, copper, ultrafine grained structure

1. Introduction

Rapid progress in mechanical engineering requires the development of advanced manufacturing technologies, which include, among others, new methods of welding metallic materials. When joining materials to which conventional fusion welding is not applicable or its use is undesirable from the viewpoint of subsequent applications, various solid-state welding processes are used. One of the widely used methods of solid-phase joining is pressure welding (or diffusion welding) [1]. The diffusion welding allows for obtaining high-strength joints [2], but its disadvantages are the long process duration, the need for careful cleaning of the surfaces to be joined and for the presence of a vacuum. The fastest welding processes are explosion welding [3], friction stir welding (FSW) [4], and ultrasonic welding (USW) [5]. The former has an area of applicability limited to the sheets of large dimensions, is poorly controllable, and almost impossible to automate. FSW is a highly efficient method that allows for processing butt welds of sheet materials and is used to create large structures from them, such as tanks, aerospace structures, etc. This welding method is not applicable when welding small parts, for example, joints in microelectronic products, batteries of electric vehicles, etc. due to the tiny sizes and variable thickness of the components. Ultrasonic welding of metals is a relatively new and largely universal method that is widely used in various industries, such as electrical and electronic industries, automotive, aerospace, and medicine [6,7].

One of the materials which can be best welded by ultrasound is copper. Copper and its alloys are widely used in electric batteries, automobiles wires, and many other fields due to its advantages such as the high electro- and thermal conductivity. Joining copper by conventional fusion welding processes is difficult due to the high thermal conductivity and intensive oxidation at welding temperature [8,9]. For the same reasons, spot-resistant welding is also ineffective [10,11]. Therefore, FSW and UST are considered as prospective methods of

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welding copper parts in many cases, for instance, in the fabrication of electric batteries. Among these two, the USW has additional advantages consisting of the short duration and low energy consumption [12], and the studies on ultrasonic metal welding have attracted considerable attention from researchers [13-15].

Welding of metals by ultrasound is based on the application of oscillating shear movements to two sheets pressed to each other and to the anvil by a static clamping force. Friction and deformation of contacting surfaces in the process breaks and refines the surface oxide layers resulting in the creation and bonding of pure metallic surfaces. The bonding occurs in time intervals from tenths of a second to several seconds at a temperature well below the melting point of welded materials. USW is particularly well suited for welding thin and miniature components such as metal foils, tapes, wires of various diameters and plates [5]. The thickness of the ultrasonically welded materials can vary from a few microns, as in the case of wire connections, to a few millimeters, as in the case of current-carrying copper connectors. The required pressure, time and ultrasonic energy depend on the properties and geometry of the materials used and determine the quality and strength of the joint. In Ref. [16] the ultrasonically welded joints of Cu, Al, and Ni in lithium-ion batteries, which are widely used in electric and hybrid vehicles, were studied. In these joints, high values of strength can be achieved by controlling such process parameters as the amplitude of ultrasonic vibrations, pressure and welding time. In Ref. [17], experiments on USW of similar and dissimilar combinations of materials were carried out. The authors found that the quality of welding is strongly influenced by the choice of parameters such as clamping force and vibration amplitude. In [18], an attempt was made to optimize the process of welding copper foils by varying the parameters, however, the achieved values of the strength of the joints are very low. It has been shown that the ultimate strength of the joint increases with an increase in the welding parameters (time, static clamping force) only up to a certain value, but after reaching a certain threshold limit it decreases [19]. Although a number of works provide data on the structure of copper joints processed by ultrasound, systematic studies of the microstructure in various zones inside and outside the weld spots are absent. The purpose of this work is to study the effect of ultrasonic welding on the microstructure of copper sheets in the regions of the welding zone and near it and the corresponding changes in the microhardness in the welding zone, as well as the strength of the joints obtained.

2. Material and Methods

As the material for studies, commercially pure copper of grade M1 according to Russian classification (purity 99.9%) was chosen. Workpieces for welding in the shape of cards with dimensions of 40×20 mm were cut from as-received sheets having the thickness of 0.8 mm. The surfaces to be joined were ground with P80 grit sandpaper, washed in ethanol, then in acetone, and dried before bonding. USW was carried out using the homemade setup described in [20] with a frequency of 20 kHz and an amplitude of vibration of the welding tip of 9 μm. The welding tip had the shape of a circle with a diameter of 5 mm. Lateral teeth were made on its surface for its better binding to the surface of the upper sheet. The welding time amounted t = 2 s, the static clamping force P = 3.5 kN. To obtain a weld joint, the first card was placed on the anvil, and the second was put on it so that there was an overlap zone with dimensions of 20×15 mm, in the center of which the welding was carried out. Lap shear tests of the weld samples were carried out by tension on an Instron 5982 machine at room temperature with a crosshead speed of 0.5 mm/min. Three specimens were tested, the shear strength was calculated by dividing the force obtained by averaging the three values of the maximum force observed in the deformation curve by the area of the weld tip, which determines the joint spot area. The standard error was taken as a measurement error. One of the samples obtained by the method described above was used to study the microstructure. For this, the sample was cut in an electric discharge machine along the direction of ultrasonic vibrations. The cut surface was mechanically ground and polished, and the final treatment was performed on a diamond suspension with a particle size of 0.05 μm with the addition of hydrogen peroxide. Microstructure studies were carried out on a TESCAN MIRA scanning electron microscope in the backscattered electron (BSE) mode and by the method of orientation analysis (EBSD analysis). The results were processed using the CHANNEL 5 software package. The Vickers microhardness in different zones of the welded sample (see below) was measured on an AFFRI DM8A instrument with an indenter load of 10 g and an exposure time of 10 s. The average value of microhardness at each zone was determined from the results of at least 10 measurements with a confidence level of 95%.

3. Results and Discussion

Images presented in Fig. 1a,b are the typical cross-sectional views of the microstructure of the initial copper sheet used in the studies. The structure is composed of grains with sizes 5-15 μm, containing annealing twins which are typical structural elements of annealed metals with an fcc lattice having medium and low stacking fault energies. The distribution of misorientation angles in the sample is shown in Fig. 1c. At the used minimum detectable misorientation angle is equal to 2°, the fraction of high-angle grain boundaries (boundaries with misorientations above 15°) is approximately 94%. The grain boundary misorientation spectrum has a pronounced maximum near the angle of 60° which corresponds to ∑3 twin boundaries. The fraction of the twin boundaries is about 0.5.

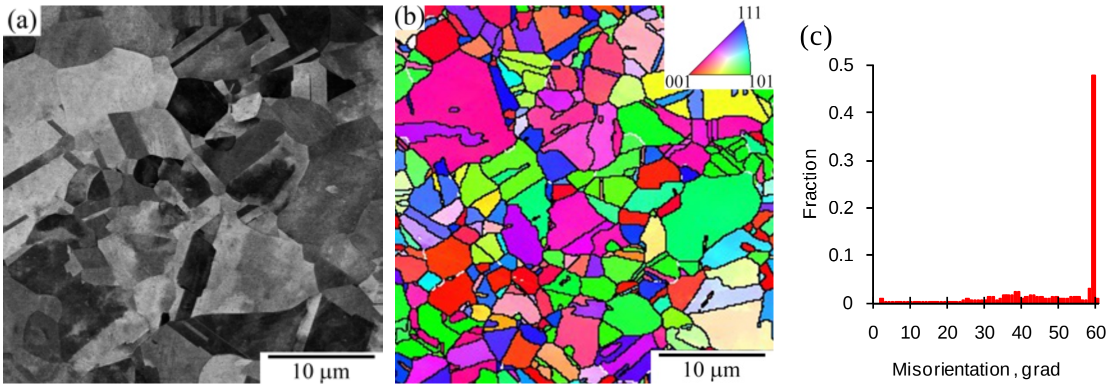

Fig. 1. The initial microstructure of commercial copper sheet in the cross-section: BSE-image (a), EBSD- map (b) and grain boundary misorientation spectrum (c)

Figure 2 shows the macrostructure of the welded sample. It can be seen that after welding in the used mode, there are no extended defects, which indicates a satisfactory quality of the joint. In the presented photograph, typical zones are designated where the microstructure and microhardness were investigated. Zone I-II contains the weld joint. The zones I-1 and II-1 are located at half the thickness of the bottom and top sheets, respectively, in the center of the weld spot. The bulks of the bottom and top sheets remote from the weld spot are zones I-2 and II-2, respectively. The study shows that each of the designated zones has its own characteristic microstructure after USW.

In the zone of weld joint I-II, as a result of intensive friction and deformation effect during ultrasonic welding, an ultrafine-grained (UFG) interlayer with a width of about 10 μm is formed, in which grains/subgrains with sizes less than 0.5 μm predominate (Fig. 3a). In zone II-1, which is located between the welding tip on one side and the contact interface of the welded sheets on the other, an inhomogeneous microstructure is observed. There are misorientated fragments with sizes both significantly less than 1 μm and more than 5 μm

(Fig. 3b). In zone I-1, which is located between the anvil and contact interface, a structure with a grain/subgrain size of 5-8 µm prevails (Fig. 3c). Outside the region of direct influence of the welding tool, that is, in zones I-2 and II-2, the coarse-grained structure of the initial sheet is preserved (Fig. 3d,e).

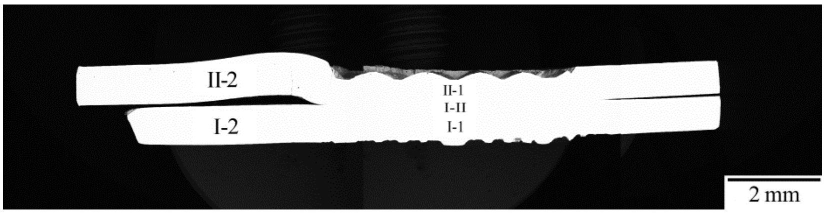

Fig. 2. Macrostructure of the welded sample and the zones in which the microstructure and microhardness were investigated

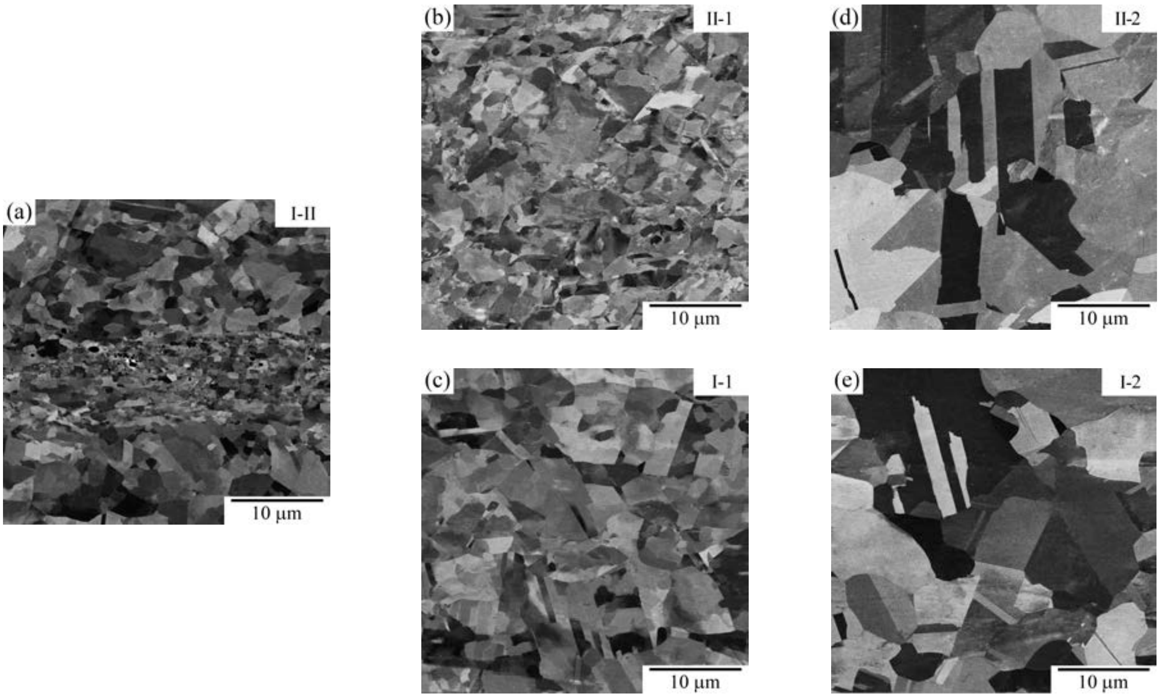

Fig. 3. BSE images of the microstructure of the welded sample: zone of the welded joint (a); zones of the interaction of the material with the tool (b, c); outside the zone of interaction of the material with the tool (d, e). In the upper right corners of the images, the designations/numbers of the zones are shown in accordance with Fig. 2

Figure 4 presents the results of the EBSD analysis of the structure near the welded joint (zone I-II). It can be seen that the UFG layer near the weld interface consists of a mixture of elongated and equiaxed grains with mean values of grain size and aspect ratio 0.9 µm and 1.9, respectively. In this layer, the fraction of low-angle boundaries (LAB), i.e. boundaries with misorientations from 2 to 15°, sharply increased to 0.4, and a fraction of twin misorientations decreased to 0.1 (Fig. 4b) as compared to the initial state (Fig. 1c). In the adjacent areas, above and below the UFG layer, elongated grains with sizes in the longitudinal and transverse directions of 15-35 and 7-15 µm, respectively, are observed (Fig. 4a). In a comparison with the structure of the initial sheet, the fraction of LAB increased to 0.3-0.35 (Fig. 4c), the peak in the vicinity of 60° becomes noticeably wider and, as a result, the fraction of twins decreased to 0.15-0.2. Thus, about 90% of the volume in the zone I-II is occupied by a microstructure that is typical for copper subjected to hot compression by 20-30%. The thin layer with an UFG structure near the contact surface is formed as a result of dynamic recrystallization under intensive action of friction and shear deformation during welding.

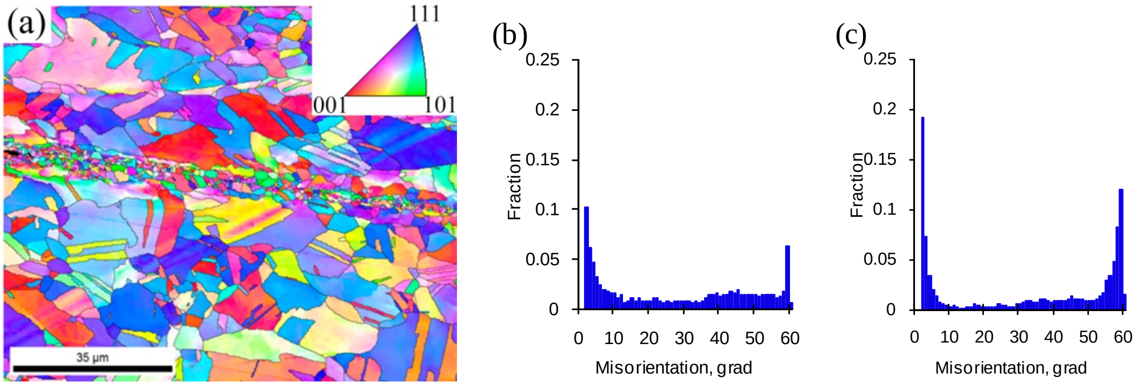

Fig. 4. EBSD- map of welded joint in zone I-II (a) and misorientation angle distributions of in an ultrafine-grained interlayer (b) and adjacent areas (c)

The formation at the interface of ultrasonically welded sheets of a structure with refined grains in copper was observed in [21]. Recrystallized "necklace" type structures in the joint zone after USW were also found in aluminum alloys [22-25]. At the same time, it was shown in [21] that the recrystallized grains remain small at a relatively low energy input during welding, and with an increase in the latter, the grain size in this zone increases, at high energies becoming even larger than the average grain size in the initial sheet. Friction and high-speed alternating shear deformation lead to an intense generation of dislocations, on the one hand, and to an increase in temperature, on the other, which creates favorable conditions for dynamic recrystallization. In particular, the maximum temperature measured in the process of USW during welding of copper in [21] was 270-450°C at welding energies of 400-2400 J.

Dynamic recrystallization near the contact surface is a factor that improves the quality of the welded joint since in this process grain boundaries can move and the nascent grain grows through the interface, which leads to a strong metallurgical bond between the sheets. The fine grains that form during this process also contribute to an increase in the strength of the material in the joint zone.

A different structure is observed in areas of sheets outside the zone of their direct contact. In the volume of the lower sheet, only a slight decrease in the grain/subgrain size is observed (Fig. 3c), which indicates a much lower deformation effect in this area. Mechanically, the top sheet, which is directly exposed to the welding head, undergoes more intense shear deformation than the bottom one, but, unlike the contact surface, there is no friction there. In this regard, apparently, there is an intense formation of LAB and curvature of the initial high-angle and twin boundaries of deformation origin, and the observed structure is characterized by the presence of both large and smaller grains or subgrains (Fig. 3b). Zones distant from the weld zone are practically unaffected by structural changes.

Figure 5 shows welded specimens before and after mechanical shear tests. The destruction of the joints in all 3 cases occurs along the seam. Figure 6 shows the curves of elongation-load when testing samples of a welded joint for shear. The average value of the maximum tensile load calculated from these curves is about F = 700 ± 35 N. For all samples, the value of the welded spot area corresponded to the area of the waveguide tip and was S = 19 mm^2. The average shear strength calculated from these data was 36 ± 5 MPa. The obtained value is somewhat higher than the strength of the joints investigated in [17,20] but is significantly inferior to the strength of the joints obtained in [21] (up to 100 MPa). These differences can be explained by the quality of equipment and tools, as well as the power of the impact during welding.

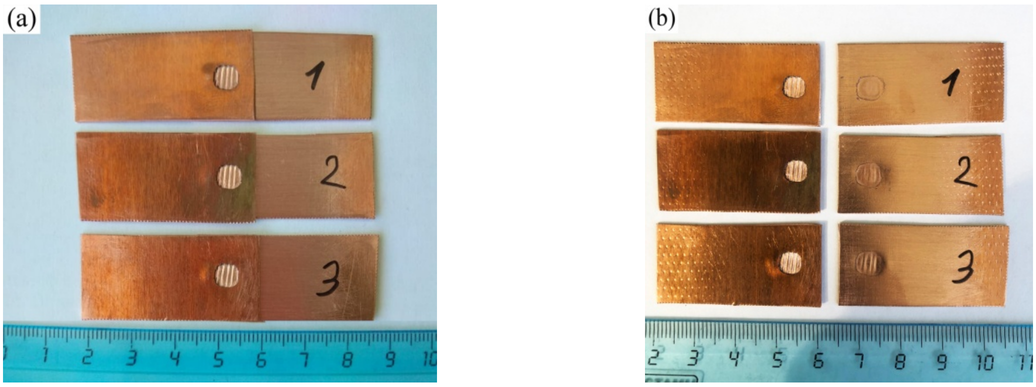

Fig. 5. General view of samples before (a) and after (b) mechanical tests

Figure 6 shows the results of microhardness measurementson the cross-section of the sample, which were carried out similarly to the microstructural studies, in characteristic zones. The microhardness measured on the cross-sectional surface of the sheet blank in the as-received state was 790 ± 15 MPa. The microhardness in the zone of the welded joint I-II is more than 1.5 times higher than the microhardness of the original sheet, which is quite consistent with the microstructural data showing the formation of an ultrafine-grained structure there. Strengthening the volumes of sheets in the zone of the welded spot due to deformation leads to an increase in microhardness by about 1.2 times. In areas remote from the welded point, the microhardness did not change.

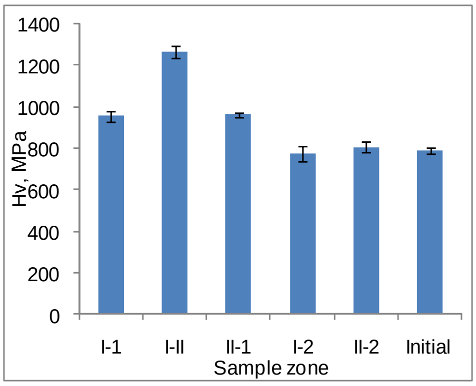

Fig. 6. Microhardness values in different zones of the sample obtained by USW

4. Conclusions

Using ultrasonic spot welding, sound welds of copper sheets with a thickness of 0.8 mm have been obtained. The studies have shown that the processes occurring during the USW result in the formation of a nonhomogeneous microstructure in the sheets. Near the weld interface, an ultrafine grained microstructure consisting of deformation induced and recrystallized grains is formed. The bulk regions of the sheets experiencing oscillating shear strains have a structure with slightly smaller grain/subgrains than the initial sheet. No structure changes occur in regions outside the weld spot. Structural changes result in an increase of the microhardness of copper by approximately 1.2 and 1.5 times in the bulk of sheets and weld interface, respectively, as compared to the initial sheet.

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