https://doi.org/10.37434/tpwj2021.09.03

SOME ADVANTAGES OF WELDED JOINTS OF ALUMINIUM 1201 ALLOY PRODUCED BY FRICTION STIR WELDING

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The paper analyzes the structural features, characteristics of strength and resistance to initiation and propagation of in-service cracks of butt joints on 1201 aluminium alloy of 2 mm thickness, produced by friction stir welding (FSW) and argon-arc welding with nonconsumable electrode (argon TIG). It is shown that in FSW as a result of intensive plastic deformation of metal in the weld nugget, a fine-grained structure with a grain size of 5–6 μm is formed. In the zone of thermomechanical impact, deformed extended grains are observed, oriented in the direction of movement of plasticized metal, as well as small equiaxial grains, the size of which varies within 4–12 μm, whereas at argon TIG welding of this alloy the weld metal has a characteristic cast structure with large (0.20–0.25 mm) dendrites. The absence of beads and reinforcements in the welds produced by FSW, allows avoiding high levels of stress concentration in the places of transition from the weld to base material, which negatively affect the service and life characteristics of welded joints. The peculiarities of formation of permanent joints in the solid phase during FSW also help to reduce the degree of metal softening in the welding zone and increase their ultimate strength, and resistance to initiation and propagation of operational cracks. 15 Ref., 7 Figures.

Keywords: microstructure, hardness, ultimate strength, resistance to initiation and propagation of in-service cracks

For the last twenty years friction stir welding (FSW) has been widely applied in many countries of the world for integration of flat and three-dimensional panels, which are used in manufacture of the hulls of ships, ferries, bodies of railway cars, etc. [1–5]. Such a process of producing permanent joints in the solid phase has become applied in car-making, electrical engineering, construction, as well as in aerospace engineering, including fuel tanks for liquid hydrogen and liquid oxygen [2, 6–9]. In our countries heat-hardenable 1201 alloy of Al–Cu–Mn alloying system is used for fabrication of welded structures exposed to low temperature in service. This alloy contains 5.8–6.8 % Cu and 0.2–0.4 % Mn. It has high (>425 MPa) strength and preserves its ductility to –253 °C. In addition, presence of manganese and titanium in the alloy ensures its rather high heat resistance. Satisfactory weldability of the alloy allows its wide application to restore the welded structures, operating for a long time at up to 200 °C temperatures, and at up to 300 °C temperatures for a short time. However, in fusion welding, melting of a certain volume of the materials being joined and welding wire in a common weld pool and their subsequent solidification, considerable structural transformations take place in the metal of the weld and adjacent areas and defects appear quite often in the form of pores, oxide film macroinclusions, and hot cracks. As a result, the strength of welded joints of 1201 alloy produced by fusion welding does not exceed 70 % of that of the base metal in most of the cases [10, 11].

At FSW weld formation occurs in the solid phase, as a result of heating due to friction of a certain volume of the materials being joined up to a plastic state and its stirring by a special tool in a closed space, limited by the substrate and working surfaces of the tool shoulder and pin. That is, the process of permanent joint formation takes place without application of an arc discharge and without metal melting and crystallization, and here there is no need to additionally apply filler wire or shielding gas. Due to that the FSW process has several advantages, compared to fusion welding. Among them, we should note formation of a fine-crystalline weld structure, less pronounced softening of the joined materials, preservation of their chemical composition, absence of defects, characteristic for fusion welding and improvement of mechanical properties of welded joints [12, 13].

The objective of this work is determination of the advantages of FSW process, compared to argon TIG welding, when producing butt joints of sheet aluminium alloy 1201.

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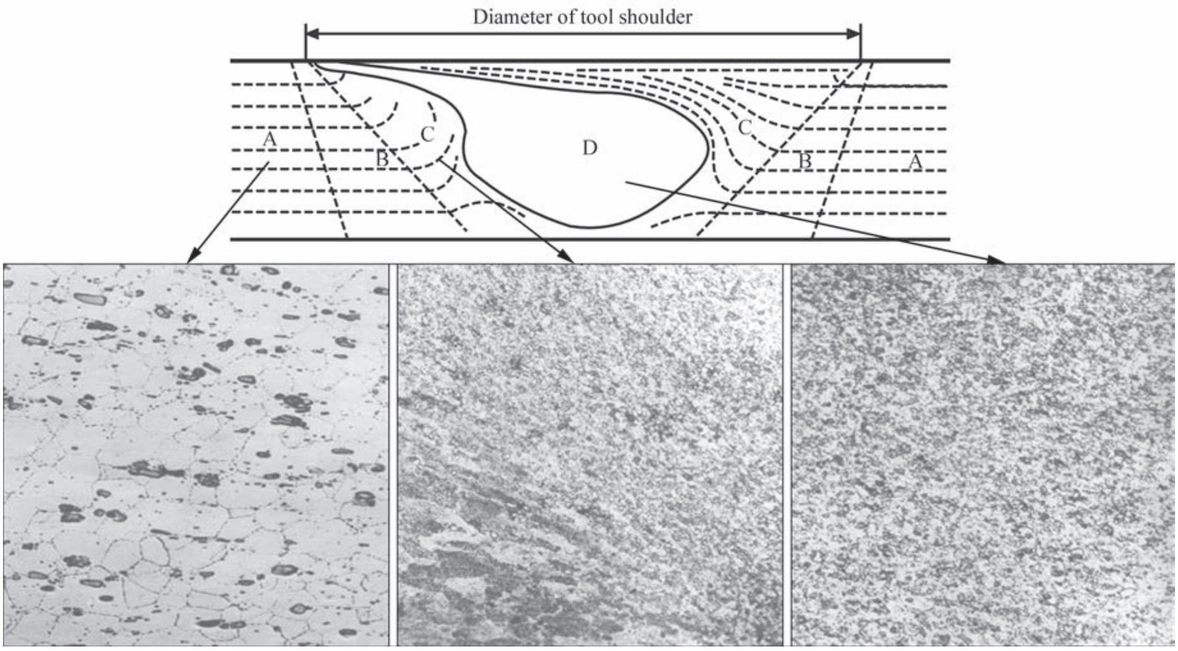

Figure 1. Schematic representation of characteristic zones in FSW joint and metal microstructure (×400) in these zones of a butt joint of 2 mm 1201 alloy

Sheets of 2 mm 1201 aluminium alloy were used for investigations. Butt joints were produced by nonconsumable electrode argon-arc welding with 20 m/h speed at 145 A current in MW-450 welding machine («Fronius», Austria), using 1.6 mm Sv1201 filler wire. FSW was performed in a laboratory unit developed at PWI, using a special tool with a conical pin and shoulder diameter of 12 mm [14], the rotation speed of which was 1420 rpm, and linear displacement speed was 14 m/h. The produced welded joints were used to prepare sections to study the structural features of welds and samples with 15 mm width of the working part, in order to determine their ultimate strength at uniaxial tension, in keeping with GOST 6996–66. Argon TIG welded samples were tested both with the beads removed to base material level, and with additionally cleaned weld reinforcement. Mechanical testing of the samples was performed in an all-purpose servohydraulic complex MTS 318.25. Fracture resistance characteristics of base material and welded joints were determined on Kan samples [15] with a sharp notch ($R = 0.1$ mm), which ensures crack initiation at a relatively low energy level, using an all-purpose testing machine RU-5. The notch was placed so that its tip coincided with the weld axis. The ultimate strength at simultaneous stretching and bending of the sample and specific work of crack propagation were determined, using «load-deformation» diagrams, obtained during testing. Metal hardness was measured on face surface of scraped joints. The degree of metal softening in the welding zone was assessed in ROCKWELL instrument at the load of $P = 600$ N. Structural features of welded joints were evaluated using optical electron microscope MIM-8.

Performed research revealed that the features of FSW process lead to formation of a specific structure of welded joints (Figure 1). They are divided into the central part of the weld (nugget), formed mainly in the zone of action of the working surfaces of the tool pin (D); zone of thermomechanical impact, adjacent to it, where the metal was exposed to thermal and mechanical impact as a result of the tool rotation and linear displacement (C), as well as HAZ (B), where structural changes of the base metal (A) are due only to temperature change, similar to fusion welding.

Microstructural analysis of the transverse sections of the produced butt welded joints of 2 mm 1201 alloy is indicative of the fact that a fine-crystalline structure forms in the weld nugget as a result of intensive plastic deformation, with grain size of 5–6 μm. Here, the size of grains and intermetallic inclusions is 5–7 times smaller than in the base material, so that the volume fraction of their boundaries becomes much greater. In the thermomechanical impact zone deformed extended grains which are oriented in the direction of plasticized metal movement, and fine equiaxed grains, the size of which varies in the range of 4–12 μm, are observed, whereas in nonconsumable electrode argon-arc welding of this alloy using Sv1201 filler wire, the weld forms a characteristic cast metal structure with rather large (0.20–0.25 mm) dendrites, as a result of molten metal crystallization (Figure 2). In the zone of weld fusion with the base material, the impact of high-temperature heating of metal leads to partial melting of structural components of the grain

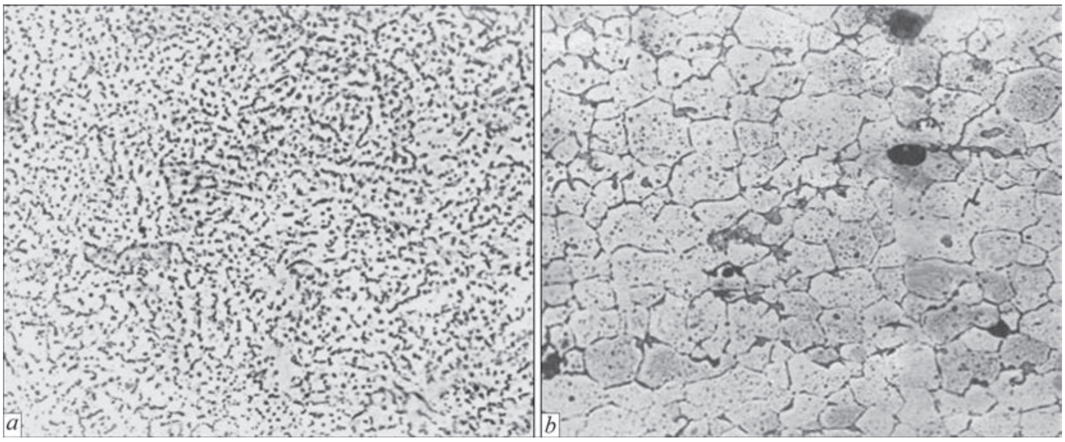

Figure 2. Microstructure (×400) of weld metal (*a*) and zone of its fusion with base material (*b*) obtained at argon TIG welding of 2 mm 1201 alloy using Sv1201 filler wire

boundaries at permanent joint formation. It results in formation of a coarse continuous net of brittle fine-grained interlayers, which have a negative effect on the mechanical properties of such joints.

The microstructure of welded joint surface, shown in Figure 3, can provide a visual illustration of structural transformations in the FSW metal, as a result of its intensive plastic deformation. It clearly shows the change of grain sizes in the metal being welded near the tool shoulder edge on the interface of the HAZ (on the left) with the thermomechanical impact zone (on the right). In the areas, which directly interacted with the tool working surfaces (thermomechanical impact zone and weld) a pronounced refinement of welded metal grains takes place.

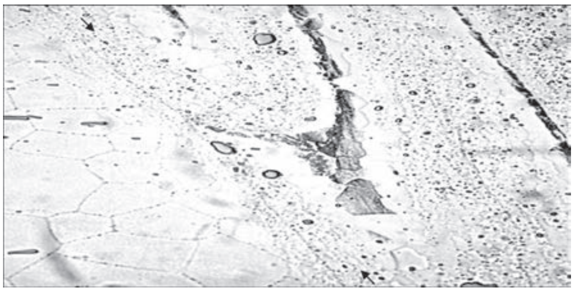

Figure 3. Microstructure (×500) of the surface of 2 mm 1201 alloy welded joint on the interface of the HAZ (left) and thermomechanical impact zone (right) of FSW joint

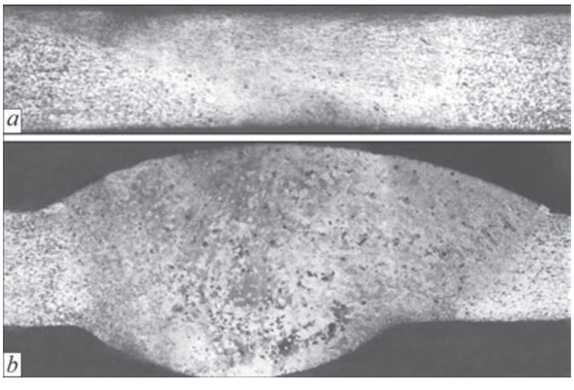

Figure 4. Cross-sections of welds of 2 mm 1201 alloy, produced by FSW (*a*) and argon TIG welding (*b*)

Performed studies showed that FSW welds differ favourably by their shape and dimensions from those made by fusion welding, due to permanent joint formation on a backing without a groove and without filler wire application (Figure 4). Absence of beads or reinforcements in such welds allows avoiding the high levels of stress concentration in the points of weld to base metal transition, which have an adverse

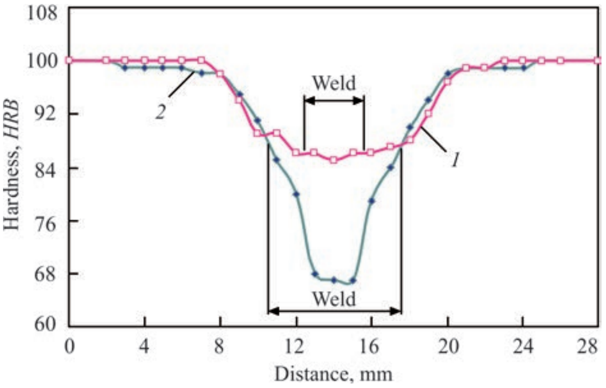

Figure 5. Hardness distribution in welded joints of 2 mm 1201 alloy produced by FSW (*1*) and argon TIG welding (*2*)

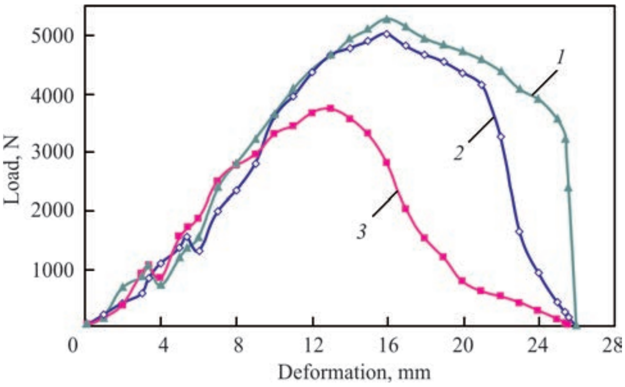

Figure 6. «Load-deformation» diagrams recorded at simultaneous stretching and bending of Kan samples with a sharp notch from BM (*a*) and welded joints of 2 mm 1201 alloy produced by FSW (*2*) and argon TIG welding (*3*)

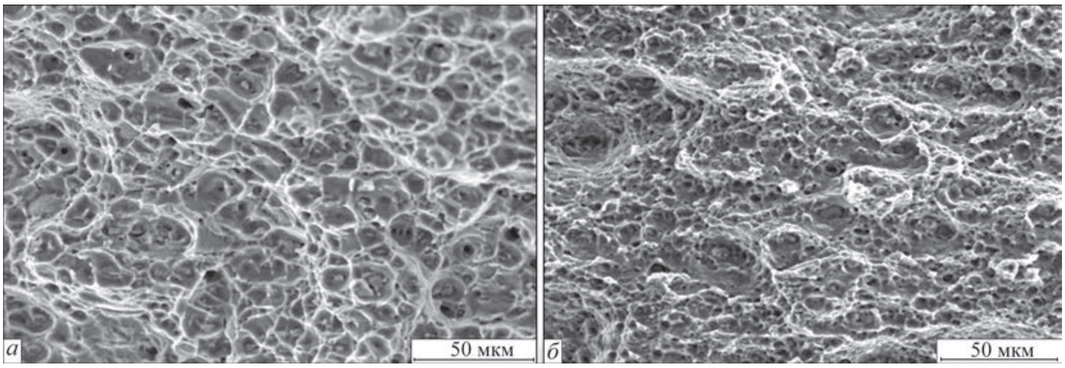

Figure 7. Fractograms of fracture surfaces of samples of FSW welded joints on 2 mm 1201 alloy in the weld metal (*a*) and in the weld to base material transition zone (*b*) (×500)

effect on the service and life characteristics of the welded joints.

More over, it was shown as a result of the performed studies that the features of formation of solid-phase permanent joints at FSW also promote lowering of the degree of metal softening in the welding zone and improvement of its mechanical properties. So, measurement of metal hardness in the weld formation zone showed that it is much higher at FSW than at argon TIG welding (Figure 5). Solid phase welded joints have minimum metal hardness on the level of *HRB* 85–86 in the weld and zones of its mating with the base material, whereas at argon TIG of 2101 alloy using Sv1201 filler wire the minimal metal hardness in the weld central part is on the level of *HRB* 67–68, and in the zone of fusion with the base material it is on the level of *HRB* 87–88.

The ultimate strength of samples of 1201 alloy welded joints with reinforcement, produced by argon TIG, using Sv1201 filler wire, is on the level of 296 MPa. Fracture of such samples at static tension takes place in the zone of the weld fusion with the base material, where a network of brittle fine-grained interlayers forms during welding. Samples with removed weld reinforcement fail at stretching in the weld central part, where metal hardness is minimal, and have the strength on the level of 241 MPa. As filler wire is not used at FSW, the welded joints have no weld reinforcement. However, due to lower metal softening in the welding and forming zone in the welds and in the adjacent areas of the deformed fine-grained structure of the welds, the ultimate strength of samples of such welded joints at uniaxial tension is on the level of 303 MPa. Here, their fracture takes place in the zone of thermomechanical impact in the area of weld transition to base material.

Curves, obtained at simultaneous tension and bending of Kan samples with a sharp notch, are indicative of susceptibility of 1201 alloy to rapid initiation and propagation of cracks (Figure 6). At testing of argon TIG welded joint samples, the crack initiating near the stress raiser tip in the form of a sharp notch propagates through the weld metal, whereas in friction stir welded samples after initiation in the weld, it shifts to the zone of weld transition to base material. Here, the presented diagrams demonstrate that the rate of crack initiation and nature of its propagation in FSW samples, are approximately the same as those in the base metal. However, fracture of such samples occurs at loads, close to those in the base metal, or much higher, than that in fusion welded samples. Minimum value of specific work of crack propagation in the base metal is on the level of 2.7 J/cm^2, indicating that crack propagation proceeds more readily in it than in welds produced in the solid phase and by melting, for which these values are 3.8 and 3.5 J/cm^2, respectively.

Analysis of fractograms of fracture surface on samples of FSW joints reveals the tough mode of their fracture (Figure 7). In the weld central part, near the notch tip, shallow pits without any flat areas of the relief are clearly visible. Propagation of the main crack through the metal of such a weld will require high-energy consumption and will be accompanied by considerable plastic deformation. Therefore, at testing such samples, the crack shifts into the zone of weld transition to base material, where the fractogram of fracture of this region shows pits limited by sharp ridges, that is indicative of quasicleavage mechanism, which requires lower energy consumption.

Conclusions

1. Intensive plastic deformation of metal at FSW of 1201 alloy results in formation of a fine-crystalline structure with 5–6 μm grain size in the weld nugget. Deformed extended grains oriented in the direction of plasticized metal displacement and fine equiaxed grains, the size of which varies within 4–12 μm, are observed in the thermomechanical impact zone, while at argon TIG welding of this alloy the weld forms a characteristic cast structure of the metal with grain sizes of 0.20–0.25 mm. In the zone of the weld fusion with the base material partial melting of the structur-

al components of grain boundaries takes place, and a continuous net of brittle fine-grained interlayers is formed, which have an adverse effect on the joint mechanical properties.

2. Owing to formation of permanent joints on a backing without a groove and without application of filler wire, FSW welds have no beads or reinforcement that allows avoiding high levels of stress concentration in the places of transition from the weld to base material, which have a negative impact on the service and life characteristics of the welded joints.

3. FSW process runs in the solid phase that ensures considerable lowering of metal softening in the welding zone and improvement of mechanical properties of 1201 alloy welded joints. Hardness of FSW weld metal is on the level of *HRB* 85–86 that is 25 % higher than at argon TIG welding. Ultimate strength of samples of such joints at uniaxial tension is on the level of 303 MPa, while for samples without weld reinforcement, obtained at argon TIG welding, this value is just 241 MPa. Fracture resistance values at simultaneous stretching and bending of samples of FSW welded joints are indicative of their higher resistance to crack initiation and propagation in operation, than of those produced by fusion processes.

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Received 08.07.2021

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