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PHYSICO-MECHANICAL PROPERTIES OF THIN-SHEET ALUMINUM ALLOY D16 BUTT JOINTS PRODUCED BY FRICTION STIR WELDING

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A complex of investigations was carried out to study the strength characteristics of welded butt joints of structural aluminum alloy D16 of 2 mm thickness, produced by friction stir welding. It was shown that the use of friction stir welding provides the formation of a permanent joint with a minimum level of stress concentration in the transition zones from the weld to the base material and allows avoiding the formation of defects in the welds such as pores, macroinclusions of oxide film and hot cracks caused by melting and crystallization of metal in fusion welding. As a result of intensive plastic deformation in the weld metal, a homogeneous disoriented structure with a grain size of 3–4 μm and with dispersed phase precipitations of not more than 1 μm is formed, and in the regions adjacent to it the elongation and distortion of grains in the direction of movement of the plasticized metal occurs in the zone of thermomechanical action. Due to this, the hardness of metal in the joint zone, the tensile strength under uniaxial tension and the fatigue strength under cyclic loads are increased. 11 Ref., 6 Figures.

Keywords: *friction stir welding, aluminum alloy D16, hardness, tensile strength, fatigue resistance*

Aluminum alloys are the basic structural material in aerospace engineering and widely used in manufacture of different types of transport, providing strength, long life and weight efficiency of structures. The most widespread aluminum alloys include the alloy D16 of the Al–Cu–Mg system, which has a good combination of endurance characteristics, fracture toughness and resistance to growth of a fatigue crack. However, due to the increased tendency to formation of crystallization cracks, it refers to the alloys which are not weldable by the fusion methods [1–3].

It is possible to avoid melting of metal in the zone of a permanent joint formation by using the new method of friction stir welding (FSW) developed in 1991 at the British Institute [4]. The weld formation occurs in a solid phase as a result of heating due to friction of a small volume of metal until the plastic state, stirring it across the entire thickness of edges being welded and deformation in a closed space. Due to this, the FSW process has significant advantages over the fusion welding. First of all, these are a lack of defects in welded joints in the form of pores, macroinclusions of oxide film and hot cracks, formation of a fine-crystalline structure of welds, a decrease in the level of softening of the materials to be joined, and an increase in mechanical properties of joints [5–9].

The aim of this work is to determine the mechanical properties and characteristics of fatigue resistance of thin-sheet aluminum alloy D16 butt joints, produced by FSW.

Methods of investigations. For investigations the sheets of structural aluminum alloy D16 of 2 mm thick were applied. FSW of butt joints of sheets with 2 mm thick was carried out at 10 m/h speed in the laboratory installation developed at the E.O. Paton Electric Welding Institute. The speed of rotation of a special tool [10] with a conical tip and a collar of 12 mm diameter was 1420 rpm. For comparison, the same joints were produced by argon-arc welding with a non-consumable electrode (AAWNE) at a speed of 20 m/h at 165 A current using the installation MW-450 («Fronius», Austria). As a filler, a strip of base material was used to avoid changes in the chemical composition of weld metal. In this case, the width of welds produced by AAWNE was 6.5 mm in average and that of welds made by FSW was 3.5 mm (at the width of zone of thermomechanical action from the facial side of the weld was about 12 mm).

From the produced welded joints the sections for investigations of structure and specimens with the width of test part of 15 mm to determine the tensile strength at the uniaxial tension in accordance with GOST 6996–66 were manufactured. Mechanical tests of specimens were carried out in the universal servo-hydraulic complex MTS 318.25. The cyclic tests were performed at axial loads along the sinusoidal cycle with an asymmetry coefficient of $R_\sigma = 0.1$ and the frequency of 15 Hz until a complete fracture of spec-

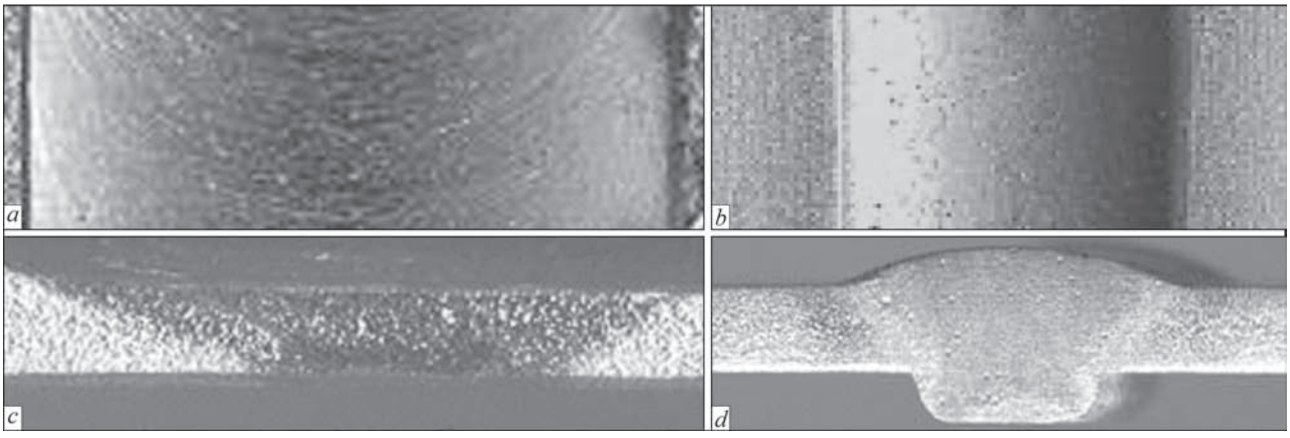

Figure 1. Appearance of facial surface (*a*, *b*) and cross sections (*c*, *d*) of welds of alloy D16 of 2 mm thickness, produced using FSW (*a*, *c*) and AAWNE (*b*, *d*)

imens. The experimental data of fatigue tests were processed by the methods of linear regression analysis generally accepted for this kind of investigations. Based on the results of the carried out tests, for each series of specimens a corresponding fatigue curve on the basis of the established limits of endurance, i.e. the regression line in the coordinates $2\sigma_a$–lg$N$, was plotted. The metal hardness was measured on the facial surface of the cleaned joints. The softening degree of metal in the welding zone was evaluated in the ROCKWELL device at the load P = 600 N. The structural features of welded joints were evaluated using an optical electron microscope MIM-8.

Results of investigations and their discussion. As a result of the carried out investigations it was revealed that the shape and dimensions of the weld in FSW are favorably different from those produced by fusion welding due to formation of a weld on the backing without the forming groove and the formation of a permanent joint without using a filler wire (Figure 1). The absence of reinforcement and through penetrations on it allows avoiding high levels of stress concentration in the places of transition from weld to the base material, which negatively affect the service and life characteristics of welded joints.

In addition, the formation of permanent joints in a solid phase without melting the base material prevents the arising of typical defects during welding aluminum alloys by fusion. Thus, the absence of a molten metal, in which the solubility of hydrogen sharply rises, allows avoiding additional saturation of welding zone by it due to migration of this gas from the adjacent layers of metal and the formation of pores. And the deformation and intensive stirring of plasticized metal throughout the whole thickness of welded edges in the process of welding contributes to crushing of oxide films located on them. The absence of molten metal in the zone of formation of a permanent joint allows avoiding its oxidation in the process of welding. Therefore, in the welds, produced by FSW, there are no defects in the form of macroinclusions of oxide film, arising by different reasons [11] in AAWNE of aluminum alloys (Figure 2).

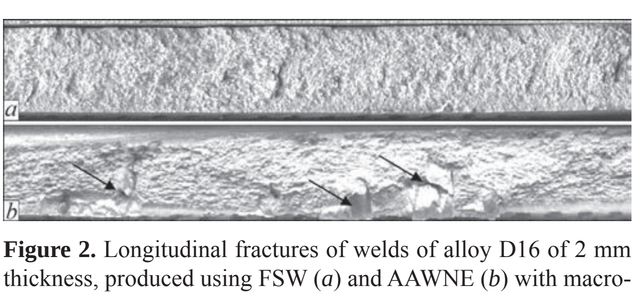

Figure 2. Longitudinal fractures of welds of alloy D16 of 2 mm thickness, produced using FSW (*a*) and AAWNE (*b*) with macroinclusions of oxide film (indicated with arrows)

The most dangerous and unacceptable defects for structures of critical purpose are the hot cracks formed in the process of crystallization of molten metal in the place of accumulation of low-melting eutectic inclusions. The carried out investigations showed that in AAWNE of the Coldcroft specimens of alloy D16, the formation of hot cracks occurs in the central part of a weld (Figure 3). As in the FSW the weld is formed in a solid phase and the processes of melting and crystallization of metal are absent, then the formation of such defects can be completely avoided.

The peculiarities of welds formation in FSW also favorably affect the degree of metal weakening in the zone of permanent joints formation. Thus, the measurements of metal hardness in the zone of a permanent joint formation showed that in welding of alloy D16 by FSW, the hardness of weld metal is practically at the level of the base material (Figure 4). In the zone of thermomechanical action, the hardness of the metal gradually decreases while moving away from the weld, reaching the minimum value (*HRB* 97–98) near the boundary of the heat-affected zone. Whereas in AAWNE using the strips of the base material D16 as a filler, the minimum metal hardness in the central part of the weld is only *HRB* 89–90. At the same time, in

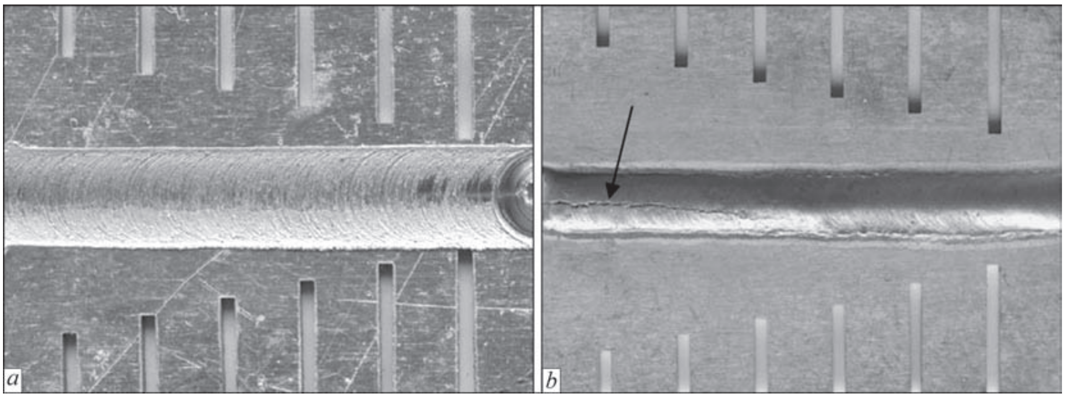

Figure 3. Coldcroft specimens of alloy D16 of 2 mm thickness, produced using FSW (*a*) and AAWNE (*b*) with crystallization crack (indicated with arrow)

the fusion zone of the weld with the base material the hardness of metal is at the level of *HRB* 92–94.

Therefore, at uniaxial static tension, the specimens of welded joints produced by FSW have the highest (425 MPa) tensile strength and are fractured near the interface of the thermomechanical action zone abutting to the heat-affected zone, where the metal has a minimum hardness. The minimum (295 MPa) tensile strength is observed in the specimens with removed reinforcements and through penetrations of welds produced by AAWNE. They are fractured along the weld, representing a cast metal with the lowest hardness. The specimens with weld reinforcement have a tensile strength at the level of 330 MPa and are fractured in zone of weld fusion with the base material, where the maximum level of stress concentration occurs (Figure 5, *a*–*c*).

At cyclic loads in specimens of welded joints produced by AAWNE, the initiation of fatigue cracks occurs at the place of maximum stress concentration in the zone of fusion with the base material. The lack of reinforcement of the weld on the specimens produced by FSW allows avoiding the high stress concentration at the weld interface with the base material. However, in their surface a small geometric irregularity near the edge of the thermomechanical action zone is observed, which is formed due to the immersion of the tool collar into the metal being welded. Therefore, the initiation of fatigue cracks in specimens of such welded joints occurs precisely in this place (Figure 5, *d*, *e*).

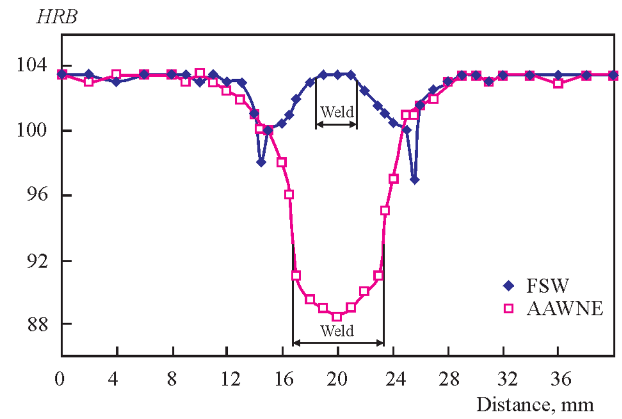

Figure 4. Distribution of hardness in welded joints of alloy D16 of 2 mm thickness, produced using FSW and AAWNE

As a result of carried out fatigue investigations it was revealed that the margin of limited endurance of welded joints produced in a solid phase by friction with stirring, on the base of $2 \cdot 10^6$ cycles of load changes amounts to 120 MPa that is equal to 85 % of corresponding values for the base metal (Figure 6). The characteristics of fatigue resistance are higher than the values for the joints produced by AAWNE in

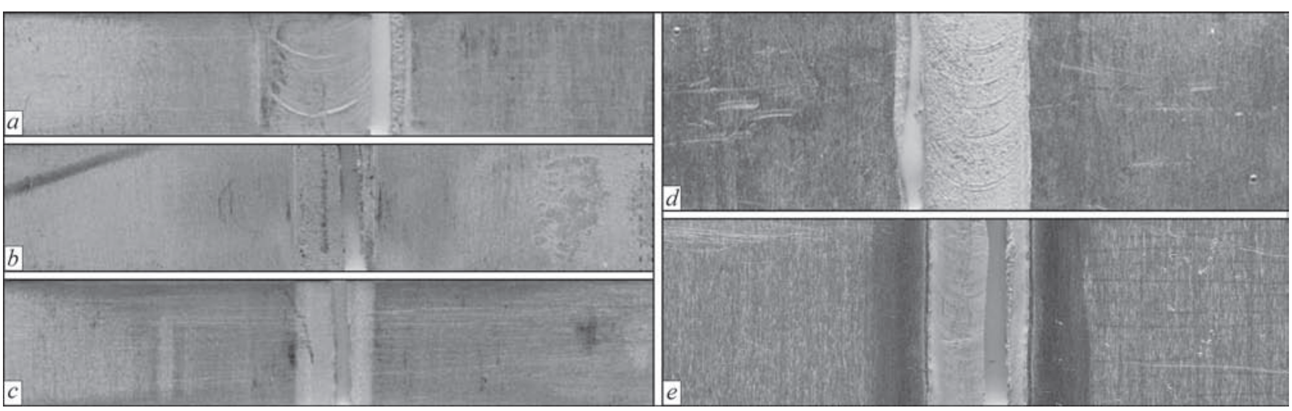

Figure 5. Fragments of specimens of welded joints produced using FSW (*a*, *d*) and AAWNE (*b*, *e* — with weld reinforcement; *c* — without weld reinforcement) fractured at uniaxial static tension (*a*–*c*) and cyclic load (*d*, *e*)

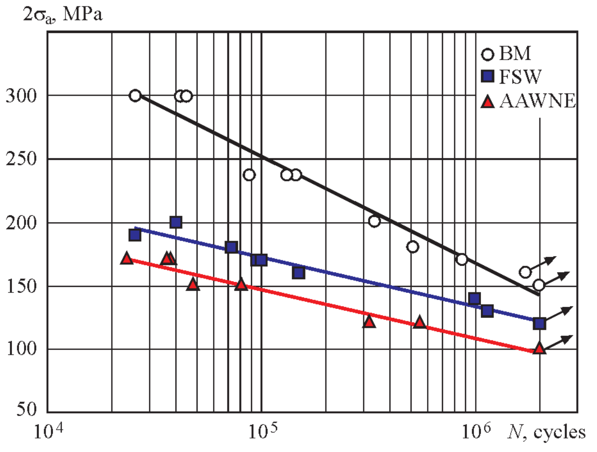

Figure 6. Curves of fatigue of base material and welded joints of aluminium alloy D16 of 2 mm thickness at the asymmetry of loading cycle $R_\sigma = 0.1$ (BM — base metal)

the whole region of fatigue lives of 10^5–$2\cdot10^6$ cycles of load changes, and their margin of limited endurance on the base of $2\cdot10^6$ cycles amounts to 110 MPa, which is by 15 % lower than that for the joints produced using FSW. The decrease in the values of fatigue life of welded joints produced using AAWNE is resulted mainly by decrease in hardness in weld metal, high concentration of acting stresses, caused by geometric parameters of weld and formation of residual welding stresses.

Conclusions

1. The use of FSW provides the formation of a permanent joint with a minimum level of stress concentration in the places of transition from weld to the base material and allows avoiding the formation of defects in the welds such as pores, macroinclusions of oxide film and hot cracks.

2. The physico-mechanical properties of joints produced using FSW are superior to those for the joints produced using AAWNE method.

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