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PROPERTIES OF BUTT JOINTS OF FINE-SHEET ALUMINIUM-LITHIUM 1460 ALLOY, PRODUCED BY FRICTION STIR AND TIG WELDING

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The article analyzes the structural features, characteristics of strength and life of butt joints of aluminium-lithium 1460 alloy with a thickness of 2 mm, produced by friction stir welding and argon arc welding using nonconsumable electrode. It is shown that friction stir welding prevents the formation of a coarse-dendritic structure of welds, provides the formation of permanent joints with a minimum level of stress concentration at the place of transition from the weld to the base material and allows avoiding defects in the welds in the form of pores, oxide film and hot cracks, caused by melting and crystallization of metal during fusion welding. 16 Ref., 7 Figures.

Keywords: aluminium-lithium 1460 alloy, friction stir welding, hardness, defects, microstructure, tensile strength, fatigue resistance, fine structure

Light, durable and corrosion-resistant aluminium-lithium alloys have a low density and a high modulus of elasticity, which allows them to be widely applied in the creation of aircraft and rocket space engineering. 1460 alloy of the alloying system Al–Cu–Li (nominal composition is 3 % Cu; 2 % Li) with the addition of zirconium and scandium is the most high-strength (> 500 MPa at a density of 2.6 g/cm^3). A simultaneous increase in the values of strength and ductility of this alloy at ultra-low temperatures makes it promising for manufacture of welded cryogenic tanks [1–3]. In most cases, to produce permanent joints different methods of fusion welding are used. A weld is formed as a result of melting a certain volume of joined materials and filler wire in the common welding pool and their crystallization. This leads to significant structural transformations both in the weld metal as well as in the adjacent areas of the base material, as well as the formation of typical defects in the form of pores, macroinclusions of oxide films and hot crystallization cracks. Therefore, the tensile strength of such welded joints in most cases does not exceed 70% of this value for the base material [4, 5].

During friction stir welding (FSW), the weld is formed in the solid phase due to heating of a small volume of metal to a ductile state as a result of friction and stirring it across the entire thickness of the welded edges with the working surfaces of a special tool. Due to that it is possible to avoid the problems caused by melting and crystallization of metal, and to keep the properties of semi-finished products in welded assemblies applied at their manufacturing as much as possible [6, 7]. As compared to fusion welding, among the main advantages of FSW process there are formation of fine-crystalline structure of joints and complete preservation of alloying elements in them, absence of pores, oxide inclusions and hot cracks, reduction of metal softening in the welding zone and the level of residual stresses and strains in the joints, as well as increase in their tensile strength under static tension and fatigue resistance under cyclic loads [8–11].

The aim of the work is to evaluate the advantages of FSW process over argon arc welding using nonconsumable electrode (AAWNE) in producing butt joints of thin-sheet aluminium-lithium 1460 alloy.

For investigations, sheets of aluminium-lithium 1460 alloy with a thickness of 2 mm were used. Butt joints were produced by argon arc welding using nonconsumable electrode at a speed of 20 m/h at a current of 145 A in the MW-450 welding installation («Fronius», Austria) with the use of the filler wire Sv1201 of 1.6 mm diameter. FSW was performed in a laboratory installation designed by the E.O. Paton Electric Welding Institute, using a special tool with a conical tip and a bead of 12 mm diameter [12], the speed of rotation of which was 1420 rpm, and the speed of linear movement was 14 m/h. The produced welded joints were used to make microsections for the study of structural features of welds and specimens with a width of working part being 15 mm to determine their tensile strength at a uniaxial tension in accordance with DSTU EN ISO 4136x. The specimens produced by AAWNE were tested both with the melts removed

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to the level of the base material and with additionally cleaned weld reinforcements. The width of the working part of the specimens to determine fatigue resistance was 25 mm. Mechanical tests of the specimens were performed in the universal servohydraulic complex MTS 318.25. Cyclic tests were performed at an axial regular loading at a load cycle asymmetry coefficient $R_\sigma = 0.1$ and a frequency of 15 Hz until a complete fracture of the specimens. Under the same conditions, 5–7 specimens of the same type were tested. The experimental data of fatigue tests were processed by the methods of linear regression analysis, typical for this type of tests. Based on the obtained results, a corresponding fatigue curve was constructed for each series of specimens on the basis of the established limits of fatigue resistance — regression line of experimental data in the coordinates $2\sigma_a$ – lg/N. The hardness of metal was measured on the facial surface of the cleaned joints. The degree of softening the metal in the welding zone was evaluated in the device ROCKWELL at a load of $P = 600$ N. Evaluation of structural features of welded joints was carried out by means of the optical (MIM-8) and transmission microdiffraction electron microscopy (JEM-200CX). Thin foils for «transmission» were prepared by a two-stage method — preliminary electropolishing and a subsequent multiple ion thinning by ionized argon fluxes in a special installation [13], which allowed making all structural-phase components of the studied welds «transparent» for electrons.

As a result of the carried out investigations it was established that due to the formation of permanent joints on a substrate without a groove and without the use of a filler wire, the welds produced in FSW as to the shape and sizes favourably differ from the welds produced by fusion (Figure 1). The absence of penetrations and reinforcements on such welds allows avoiding high levels of stress concentration in the places of transition from a weld to the base material, which negatively influence the operational and life characteristics of welded joints.

In addition, the formation of permanent joints in the solid phase without melting the base material prevents the appearance of defects in the form of pores typical for fusion welding (see Figure 1, *b*, *d*). The absence of molten metal in the welding zone, in which the solubility of hydrogen increases sharply, avoids the additional saturation by it of this zone as a result of migration of this gas from the adjacent metal layers, whereas stirring and thickening of the welded metal in the zone of permanent joint formation provides producing welds without pores.

Deformation and intensive stirring of the plasticized metal throughout the entire thickness of the welded edges promotes the refinement of oxide films, which are instantly formed on them even after mechanical removal immediately before welding, whereas the absence of molten metal in the area of the permanent joint formation avoids its oxidation during welding. Therefore, in the welds produced by FSW, defects in the form of separate or extended [14, 15] macroinclusions of oxide films typical for the welds produced by AAWNE of aluminium-lithium 1460 alloy are absent (Figure 2).

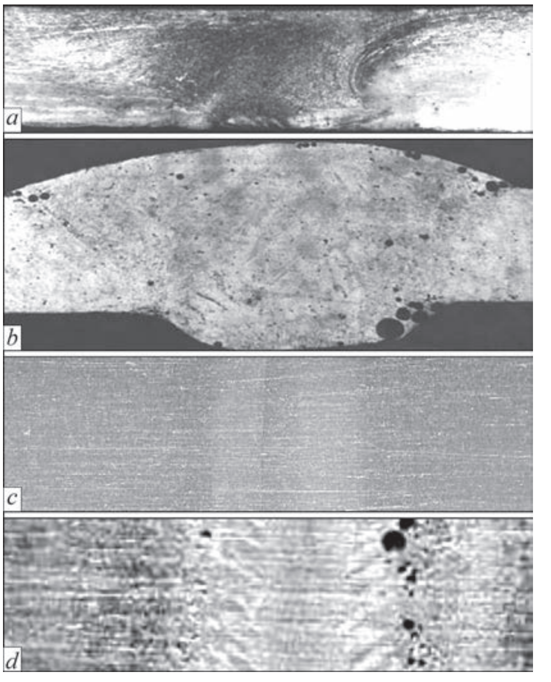

Figure 1. Cross-sections (*a*, *b*) and root parts (*c*, *d*) of welds of 1460 alloy of 2 mm thickness, produced by FSW (*a*, *c*) and AAWNE (*b*, *d*)

The most dangerous and inadmissible defects for structures of critical purpose are hot cracks, which are quite often formed in the process of crystallization of molten metal at the place of accumulation of low-melting eutectic inclusions. During fusion welding of aluminium alloys, such crystallization cracks can occur both in the weld metal as well as in the area of its fusion with the base material. The carried out investigations showed that in AAWNE of special Holdcroft specimens, which allow evaluating hot brittleness of alu-

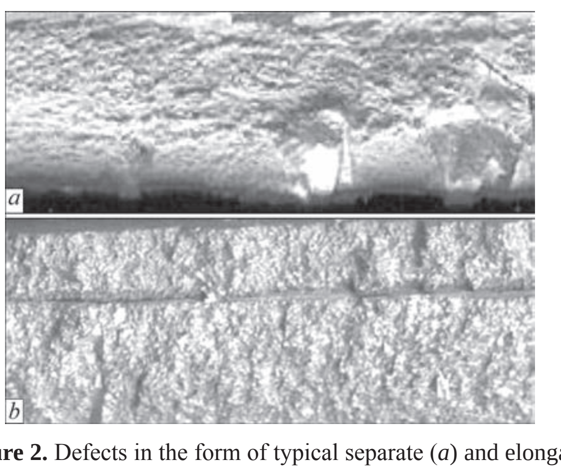

Figure 2. Defects in the form of typical separate (*a*) and elongated (*b*) macroinclusions of oxide films on longitudinal fractures of welds of 1460 alloy of 2 mm thickness, produced by AAWNE

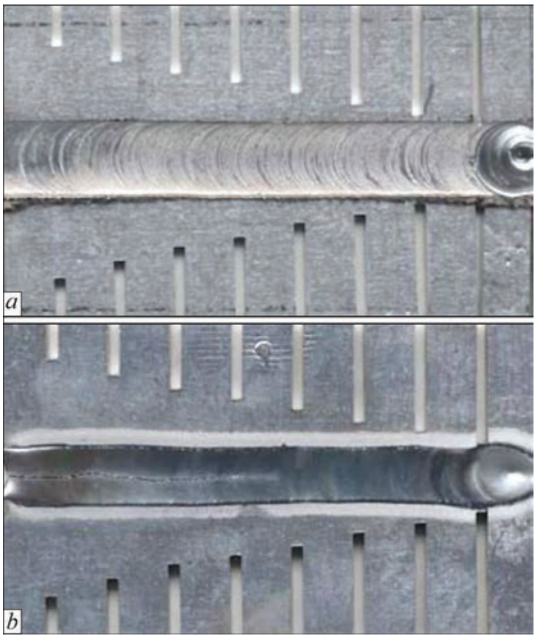

Figure 3. Holdcroft specimens of 1460 alloy of 2 mm thickness, welded by FSW (*a*) and AAWNE (*b*)

minium alloys during fusion welding without the use of filler wire, hot cracks are formed in the central part of the welds (Figure 3). Of course, in case of FSW of such specimens hot cracks cannot appear, as far as welding occurs in the solid phase, when the processes of metal fusion and crystallization are completely absent.

Analysis of the microstructure of welded joints of aluminium-lithium 1460 alloy, produced by AAWNE, showed that the weld metal has a mainly fine-crystalline structure with manifestations of central crystallite in some parts of individual fragments (Figure 4). Near the zone of fusion of the weld with the base material, a layer with a small subdendritic structure is observed in it (Figure 4, *b*–*d*). In the heat-affected zone (HAZ) near the zone of fusion of the weld with the base material there are areas of overheating and recrystallization. The length of the melting zone of the structural components is about 2.25 mm from the fusion boundary of the weld with the base material. In the HAZ, the grains that are directly adjacent to the abovementioned zone have the largest size.

When this alloy is welded by friction stir method, in the central part (core) of the weld, as a result of intensive plastic deformation of the metal, very fine (3–5 μm), equiaxed grains are formed (Figure 4 *d*, *e*, *f*). In the zone of thermomechanical impact, a smooth change of grain orientation in the direction of movement of working surfaces of the tool occurs. As a result, long elongated grains are formed in it, oriented along this trajectory, as well as small equiaxed grains.

Analysis of the fine structure of the weld metal produced by AAWNE and FSW showed that in both cases two types of phase precipitations are formed. Some of them (grain boundary phases or phases of intergranular type), which are located along the intergranular boundaries, are represented by eutectic formations (Figure 5). Another type of phase formations is intergranular phase precipitations or phases of intergranular type. The welding method significantly affects the size of such phase precipitations. Thus, in the welds produced by fusion, grain boundary phases can have a thickness of up to 0.2–0.5 μm and a rather considerable elongation (up to 2.0–2.5 μm). Phases of the intergranular type differ in a globular shape and can be 6 times higher than similar precipitations in the base material. In the welds produced by friction stir welding, the sizes of phase precipitations are by 2.5–3.5 times smaller. At the same time, a significant increase in their amount at a uniform distribution both over intergranular as well as over grain boundary volumes is observed. In addition, a significant part of phase precipitations is surrounded by a near-phase shell,

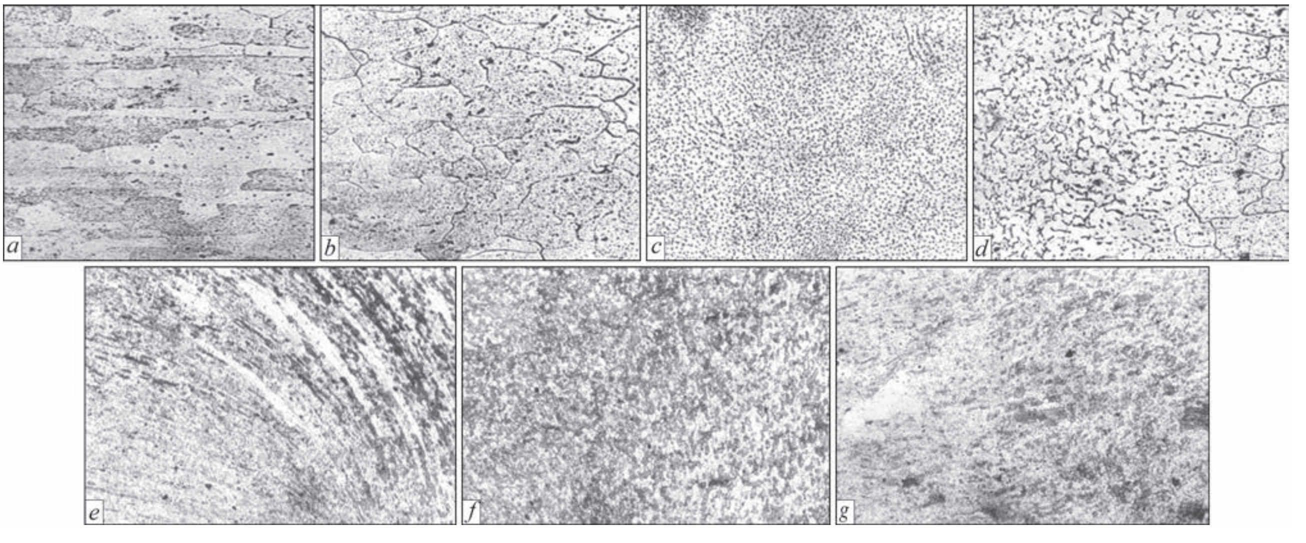

Figure 4. Microstructure (×400) of the base metal (*a*) and welded joints of aluminium-lithium 1460 alloy of 2.0 mm thickness, produced by AAWNE with the use of a filler wire Sv1201 (*b*, *d* — zones of fusion of the weld with the base material; *c* — weld) and FSW (*e* — zone of thermomechanical impact on the side of the tool; *f* — core of the weld; *g* — zone of thermomechanical impact on the side of its moving away)

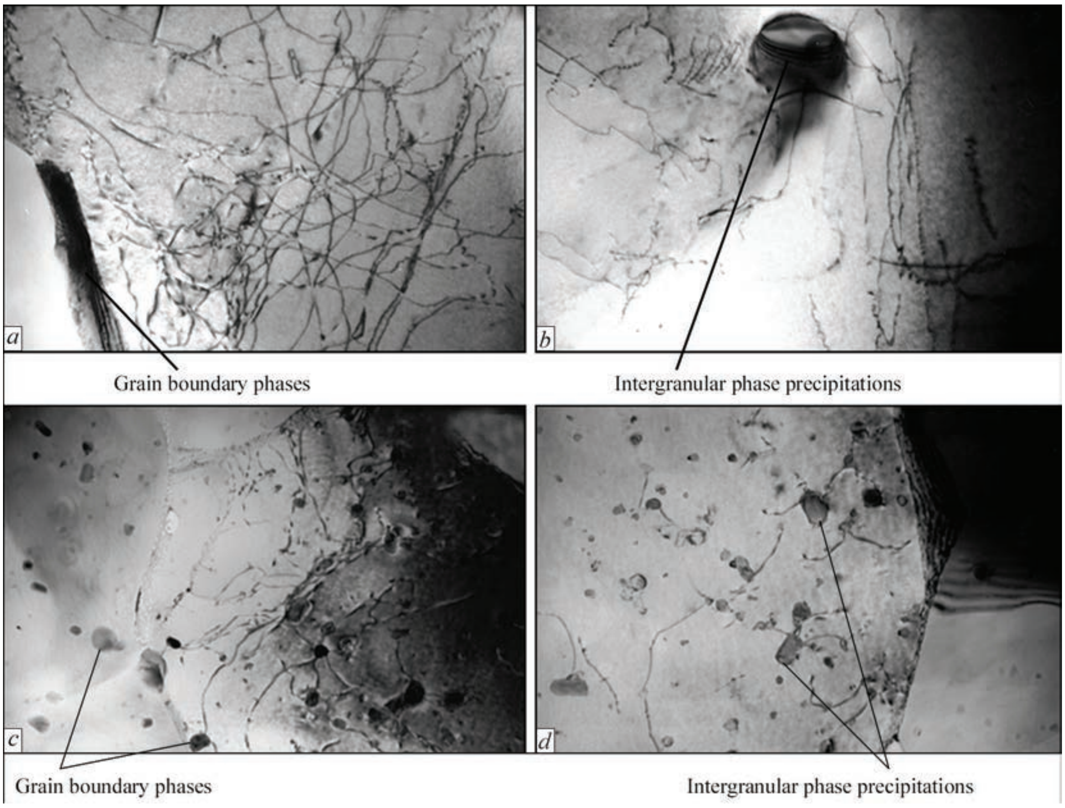

Figure 5. Fine structure of weld metal of aluminium-lithium 1460 alloy produced by AAWNE (*a*, *b*) and FSW (*c*, *d*) with the grain boundary phases (*a*, *c*) and intergranular phase precipitations (*b*, *d*), typical for these methods of producing permanent joints (*b*, *d*): *a*, *b*, *d* — 30000; *c* — 20000

which may indicate an intensive alloying of a local near-phase space in the volumes of matrix grains.

Due to a lower temperature of heating welded edges and the formation of fine-crystalline weld structure, in the process of FSW, the level of softening of the metal is less than in AAWNE (Figure 6). Therefore, as a result of measurements of hardness of metal in different areas of welded joints it was established that the minimum hardness of weld metal produced by AAWNE with the use of a filler wire Sv1201 amounts to *HRB* 71, and in the zones of its fusion with the base material it is *HRB* 82–83. Whereas, in FSW the hardness of the metal in the weld and its zones of mating with the base material is at the level of *HRB* 85–86.

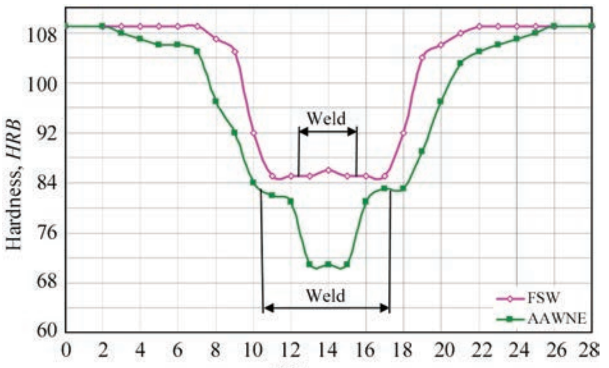

Figure 6. Distribution of hardness in welded joints of 1460 alloy of 2 mm thickness, produced by FSW and AAWNE

Therefore, in the case of uniaxial static tension, the specimens of welded joints without reinforcement of the weld, produced by AAWNE with the use of a filler wire Sv1201, are fractured along the weld metal and have the lowest (257 MPa) strength. The fracture of welded joint specimens produced by FSW occurs in the zone of thermomechanical impact. In this case, their tensile strength is at the level of 310 MPa as in the specimens with the weld reinforcement produced by AAWNE, which are fractured in the area of fusion of the weld with the base material.

The experimentally determined fatigue curves of butt joints of aluminium-lithium 1460 alloy produced

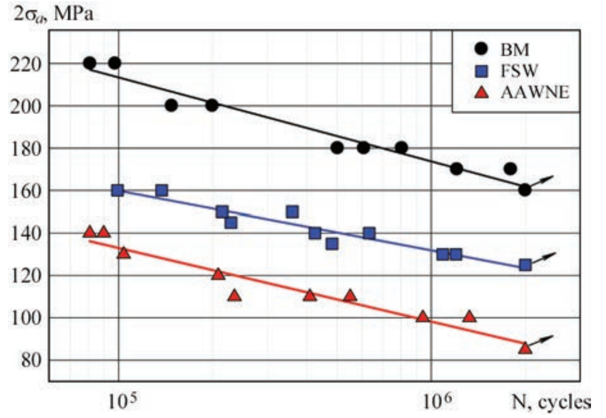

Figure 7. Fatigue curves of base metal and welded joints of aluminium-lithium 1460 alloy of 2 mm thickness at an asymmetry of the stress cycle $R_\sigma = 0.1$

by FSW indicate a high fatigue resistance of such joints [16]. The limits of fatigue strength of specimens of the joints of aluminium 1460T1 alloy produced by FSW at an asymmetry of a cycle of stresses $R_\sigma = 0.1$ amount to 75–77 % of the corresponding indices of the base metal in the entire area of life of 10^5–$2\cdot10^6$ of stress change cycles and for the base 10^5 and $2\cdot10^6$ amount to 160 and 123 MPa, respectively (Figure 7). The limit of fatigue resistance on the base $2\cdot10^6$ of stress change cycles for the joints produced by AAWNE do not exceed 88 MPa, which is by 28 % lower than the same index for the joints produced by FSW.

Conclusions

1. The FSW process provides the formation of permanent joints of aluminium-lithium 1460 alloy with a minimum level of stress concentration at the places of transition from the weld to the base material and allows preventing the formation of defects in the welds in the form of pores, macroinclusions of oxide films and hot cracks typical for AAWNE and those predetermined by melting and crystallization of metal.

2. The formation of permanent joints in the solid phase allows avoiding the formation of a cast coarse-dendritic structure of the welds, inherent in the processes of fusion welding. At the same time, around the tip of the tool, where the metal experiences the greatest thermomechanical impact, due to its intense plastic deformation a refinement of grains and the formation of a new homogeneous disoriented structure in the weld core with a grain size of 3–5 μm and dispersed (0.06–0.40 μm) eutectic phase precipitations occur. Near the core in the zone of thermomechanical impact a combined zone is formed, which contains small equiaxed grains and deformed thin elongated grains, oriented along the direction of movement of the working surfaces of the tool.

3. In FSW of thermally strengthened aluminium-lithium 1460 alloy as a result of thermomechanical impact besides a refinement of grains in a welding zone, which promotes an increase in the hardness of metal, at the same time a partial precipitation of excessive phases from a supersaturated solid solution and their coagulation occurs, as a result of which a hardness of metal is slightly reduced. However, the degree of softening the metal in the zone of a permanent joint formation in FSW is much lower than in AAWNE. Due to that, the tensile strength of the specimens of welded joints produced by FSW is at the same level with this index for the specimens with the weld reinforcement and is by 20 % higher than for the specimens without the weld reinforcement, produced by AAWNE with the use of a filler wire Sv1201.

4. As a result of experimental studies, it was found that the butt joints of aluminium-lithium 1460 alloy, produced by FSW, have a high fatigue resistance and can be successfully used in structures operated under variable loads. The limits of fatigue resistance of the specimens of welded joints at an asymmetry of a cycle of stresses $R_\sigma = 0.1$ amount to 75–77 % from the corresponding indices of base metal in the entire area of life of 10^5–$2\cdot10^6$ of stress change cycles and for the base $2\cdot10^6$ it amount to 123 MPa.

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