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STRENGTH OF WELDED JOINTS OF HEAT-HARDENABLE ALUMINIUM ALLOYS IN TIG AND FRICTION STIR WELDING

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Influence of zirconium and scandium modifiers in the filler wire and of arc oscillations due to electric current flowing through the filler section in nonconsumable electrode argon-arc welding, as well as of friction stir welding process on formation of weld structure in sheet aluminium alloys 1460 and 1201, was studied. Curves of metal hardness distribution in the zone of permanent joint formation were plotted, and ultimate strength of samples was determined directly after welding and after their artificial ageing. It is shown that application of friction stir welding yields higher values of ultimate strength of the metal of welds and welded joints on aluminium alloys 1460 and 1201, than in automatic nonconsumable electrode argon-arc welding with weld pool oscillations, even at application of welding wire with zirconium and scandium. Here, the maximum strength level (75 % for alloy 1201 and 86 % for alloy 1460), compared to base material, is achieved after artificial ageing of samples, at which phase transformations and processes of stabilization of the structure of metal after thermal impact, take place. 16 Ref., 1 Table, 4 Figures.

Keywords: *heat-hardenable aluminium alloy, argon-arc welding with arc oscillations, friction stir welding, microstructure, hardness, strength*

In fabrication of structures from aluminium alloys, permanent joints are produced by fusion welding in most of the cases, where weld formation occurs as a result of melting of the edges being welded and welding wire with their subsequent crystallization [1–3]. Metal of such a weld has a cast, usually coarse-crystalline structure. Moreover, high-temperature heating of the blanks being welded leads to surface melting of grain boundaries and partial precipitation of secondary phases and eutectics along them in the zone of weld fusion with the base material. As a result the ultimate strength of welded joints is equal to 60–70 % for most of the heat-hardenable alloys, whereas the weld metal ultimate strength is equal to just 50–60 % of this value for base material [4].

Therefore, measures which are aimed at creating conditions for formation of a disoriented fine-crystalline structure of the welds and lowering of metal heating temperature in the zone of permanent joint formation, can be effective for increasing the strength of welds and welded joints as a whole. Among the known widely applied methods of influencing the crystallization processes in the weld pool, an important place is taken by application of zirconium as modifier of the 1st kind in the welding wire. It has a structure isomorphous to the crystallizing alloy, and acts as forced crystallization centers. Over the recent years, scandium, a modifier of the 2nd kind, has been used additionally. It creates favourable conditions for initiation and growth of new crystallization centers due to formation of Al_3Sc phase, having dimensional and structural similarity with aluminium crystalline lattice [5–7]. Moreover, microadditives of this element to aluminium alloys promote their hardening after artificial ageing, stabilizing the structural components of base material and weld metal exposed to thermal impact [8–10].

The nature of metal crystallization during welding can be changed also due to abrupt oscillations of weld pool melt, which are due to periodical change of the force impact of the arc as a result of welding current pulsations or arc deviation from its vertical position [11–13]. Such oscillations of molten metal lead to disturbance of the continuity of formation of extended oriented crystals as a result of melting of second-order axes and increase of activity of crystallization centers due to periodical change of crystallizing metal temperature.

An essential lowering of metal heating temperature in the zone of permanent joint formation can be achieved at application of one of the new methods of solid-phase welding — friction stir welding (FSW) [14]. Weld formation here occurs due to heating through friction by a special tool of a certain volume of the materials being joined in their contact zone to a plastic state and its stirring in a closed space that allows avoiding the problems of high-temperature heating, melting and crystallization of metal. Intensive plastic deformation of metal at FSW promotes formation of an ultradispersed structure in the weld nugget, and of long, extended along the metal movement path and fine recrystallized grains in the adjacent thermo-mechanical impact zone (TMIZ) [15].

The research objective was to study the influence of zirconium and scandium modifiers in the filler wire and arc oscillations, due to passage of electric current through the filler section in nonconsumable electrode argon-arc welding, as well as FSW process on formation of the structure of welds, metal softening and ultimate strength of butt joints of sheet aluminium alloys 1201 and 1460 directly after welding and after artificial ageing of the samples.

Experimental procedure. Automatic nonconsumable electrode argon-arc welding (automatic TIG) of aluminium alloys 1201 (wt.%: 6.3 Cu; 0.3 Mn; 0.06 Ti; 0.17 Zr; 0.1 V; bal. being Al) and 1460 (wt.%: 3.0 Cu; 2.0 Li; 0.1 Mg; 0.12 Ti; 0.008 Sc; bal. being Al) 2 mm thick was performed at square wave alternating current of 200 Hz frequency with welding head ASTV-2m. MW-450 (Fronius, Austria) was used as the power source of the welding arc. Welding speed was 20 m/h; welding current was 170 A, and feed rate of 1.6 mm welding wire was 82 m/h. Batch-produced welding wire Sv1201(Al–6 % Cu–0.1 % Ti–0.3 % Mn–0.2 % Zr) and experimental welding wire Sv1201Sc of the same composition, but additionally containing 0.5 % Sc were used in welding. In order to induce arc oscillations, arising as a result of interaction of electromagnetic fields, generated at current flowing through the arc gap and filler wire [13], direct current (200 A) from power source TR-200 (Fronius, Austria) was passed through filler wire section 25 mm long directly before it entered the head part of the weld pool. Continuous variation of the arc force impact due to its deviation from the vertical position results in oscillations of weld pool molten metal, which disturb the continuity of its crystallization, and formation of a fine-crystalline structure of the welds. It should be noted that standard automatic TIG welding was not used for alloy 1460 in order to assess the ultimate strength of the welded joints, as extended oxide film inclusions form in the welds, while current passage through the filler wire section allows avoiding these defects.

FSW process was conducted in a laboratory unit developed at PWI. Speed of rotation of a special welding tool with a conical tip and 12 mm dia shoulder was 1420 rpm, and the speed of its linear displacement (welding speed) was 14 m/h. Before welding the sheet blanks were treated by chemical etching by the conventional technology. Mechanical scraping of just the end faces of the edges to be welded was performed for FSW, and for automatic TIG welding also the surface layers 0.10–0.15 mm thick were removed to avoid porosity in the welded joints.

Metal hardness was measured on the face surfaces of the produced welded joints. Degree of metal softening in the welding zone was assessed in Rockwell instrument at *P* = 600 N load. Evaluation of structural features of welded joints was performed using optical electron microscope MIM-8. Ultimate strength of welded joints produced by automatic TIG welding was determined at static tension in a universal servohydraulic system MTS 318.25, of standard flat samples with 15 mm width of the test portion and with reinforcement and removed weld back bead, while weld metal ultimate strength was measured on samples with removed weld reinforcement and back bead. Samples produced by FSW, were tested without reinforcement and back bead, as such a shape of the weld is due to the features of the process of producing permanent joints. To assess the effect of heat treatment on strength properties of welded joints, standard artificial ageing of samples of alloy 1201 was performed at the temperature of 170 °C for 17 h, and those of alloy 1460 were aged at the temperature of 130 °C for 20 h, and then at the temperature of 160 °C for 16 h.

Research results and discussion. As a result of the performed research it was found that in conventional automatic TIG welding of the studied aluminium alloys 1201 and 1460 the weld metal develops a fine dendritic structure with individual elements of the central crystallite, which form large crystals in some sections of the weld central part (Figure 1, *a*). Application of filler wire, containing zirconium and scandium, leads to refinement of weld metal crystalline structure due to partial formation of a subdendritic shape of the crystallites (Figure 1, *b*). Here, it is not possible to form a subdendritic structure of the crystallites over the entire volume of the weld. This is, apparently, attributable to the fact that in welding of sheet joints, when the share of filler wire in the weld is small, a sufficient (0.3–0.4 % [16]) concentration of scandium in the weld metal cannot be achieved. However, owing to weld pool molten metal oscillations, arising as a result of the arc deviation from its vertical position due to electric current passing through a section of filler wire Sv1201Sc, periodical melting of the crystallizing dendrites occurs during crystallization, that ensures formation of fine equiaxed crystals over the entire weld section (Figure 1, *c*).

However, the finest structure of weld metal forms at FSW as a result of intensive plastic deformation of metal in the zone of permanent joint formation. Figure 2 shows very well how grain refinement occurs on the surface of the metal being welded at the edge of the tool shoulder on the boundary of HAZ (left) and TMIZ (right). An abrupt grain refinement occurs in the sections of the weld and TMIZ directly subjected

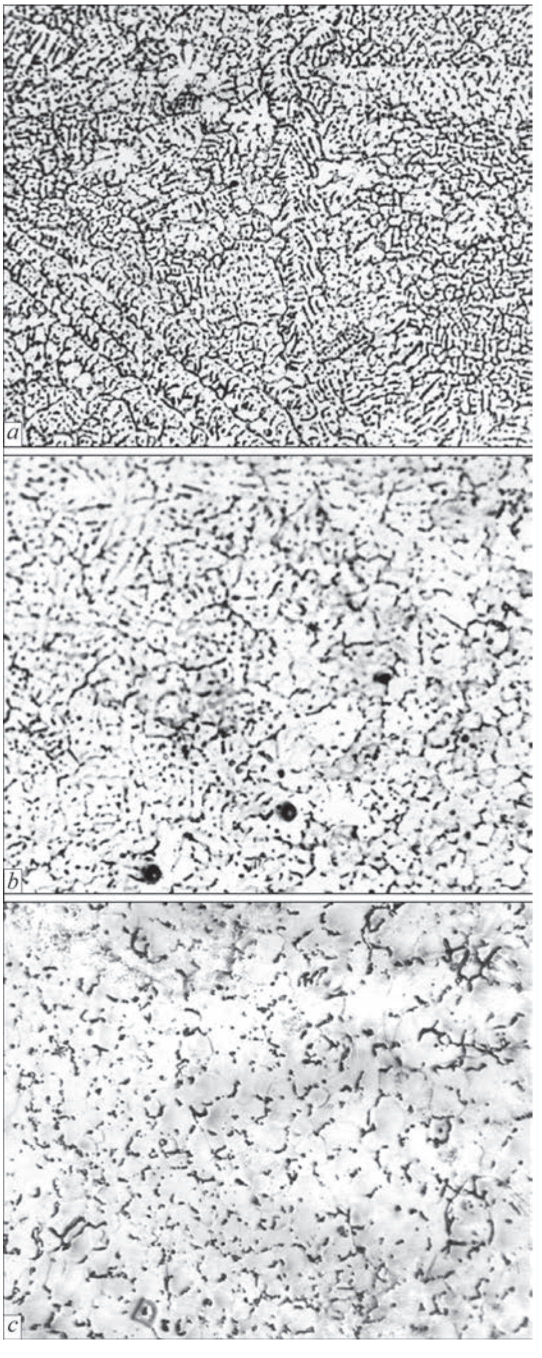

Figure 1. Microstructure (×200) of welds, made by nonconsumable electrode argon-arc welding of 2 mm sheets of alloy 1460 with application of filler wires Sv1201 (*a*) and Sv1201Sc (*b*), as well as arc oscillations, arising at current passing through the section of filler wire Sv1201Sc (*c*)

to the impact of the tool working surfaces (side surfaces of the tip and shoulder end face). Analysis of the transverse microstructure of joints produced by FSW showed that a nugget with finely-dispersed (3–5 μm) structure forms in the weld central part developing as a result of displacement of plasticized metal by the tool working surfaces. As the grain size is 5–7 times smaller than that in the base material, the volume fraction of their boundaries increases significantly (Figure 3). Here, deformed extended grains oriented in the direction of displacement of plasticized metal by the

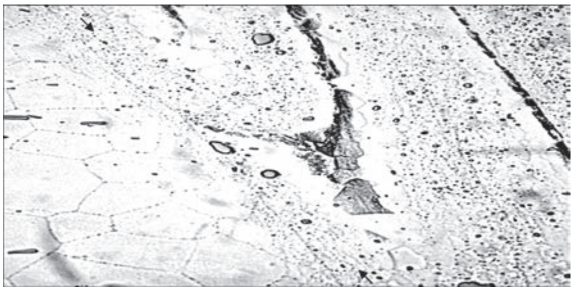

Figure 2. Microstructure (×500) of the surface of FSW joint of 2 mm alloy 1201

tool working surfaces, and fine-equiaxed grains, the size of which varies within 5 to 10 μm are observed in TMIZ. On the other hand, at conventional automatic TIG welding of these alloys using filler wire Sv1201 the weld forms a characteristic cast structure with dendrite dimensions of 0.15–0.20 mm. Moreover, high-temperature heating of the edges being welded near the weld causes melting of structural components of the grain boundaries. This results in formation of a coarse continuous network of fine-grained interlayers in the section adjacent to the weld metal. Such structural transformations in the metal in the zone of permanent joint formation lead to a change of metal hardness and its strength.

Measurements of metal hardness on samples of FSW joints showed that it is much higher than in samples produced by automatic TIG welding. Such welded joints of alloy 1460 have metal hardness in the weld and zone of its transition to base material (at about 1.5 mm distance from weld axis) on the level of *HRB* 90, and minimum hardness *HRB* 88–89 at about 5.8 mm distance from weld axis on TMIZ and HAZ boundary (Figure 4, *a*). On the other hand, in automatic TIG welding of this alloy even with application of filler wire Sv1201Sc and arc oscillations, metal hardness in the weld central part is equal to just *HRB* 69, and in the zone of weld fusion with base material (at about 3.3 mm distance) it is *HRB* 76–77.

In FSW of alloy 1201 metal hardness in the weld central part is on the level of *HRB* 82, in the zone of weld transition to base material it is *HRB* 81, and on the boundary of TMIZ and HAZ it is *HRB* 95–96 (Figure 4, *b*). Joints produced by automatic TIG welding with application of scandium-containing filler wire and arc oscillations, have weld metal hardness on the level of *HRB* 71, and in the zone of its fusion with base material it is *HRB* 73–74.

Metal softening in zone of permanent joint formation in welding of these heat-hardenable alloys occurs not only due to structural transformations, but also as a result of partial decomposition of the solid solution and coagulation of particles of the main alloying elements in zones, subjected to heating even

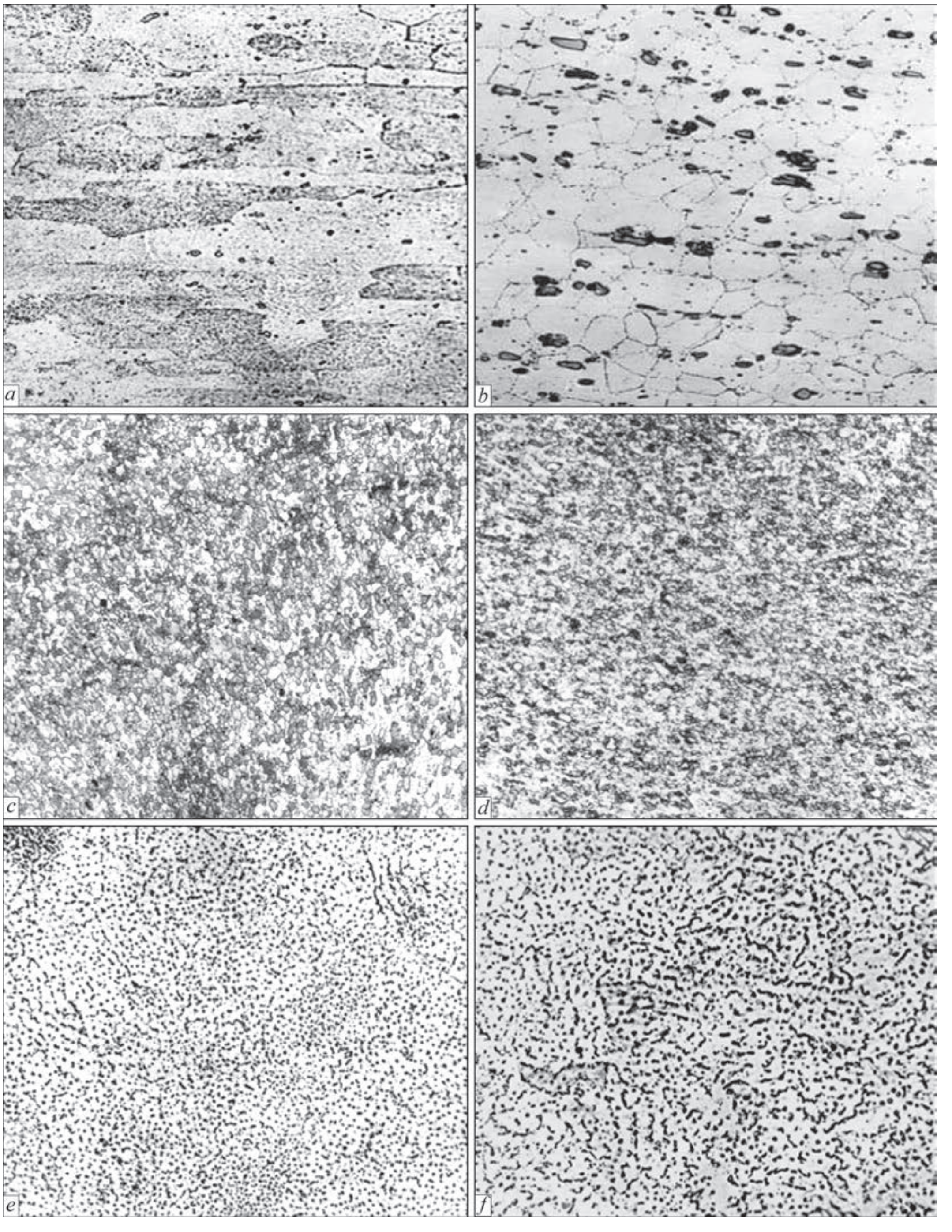

Figure 3. Microstructure (×400) of base metal (*a*, *b*) and welds (*c*–*f*) produced at FSW (*c*, *d*) and automatic TIG welding (*e*, *f*) of 2 mm alloys 1460 (*a, c, d*) and 1201 (*b, d, f*)

in FSW process. Therefore, heat treatment (HT) is used for their welded joints, if required. It involves artificial ageing, resulting in metal hardening due to phase transformations and metal structure stabilization. Analysis of metal hardness distribution in FSW joints of alloy 1460 after artificial ageing of the samples (see Figure 4, *a*), showed that metal hardness in the weld and in the zone of its transition to base material increased up to *HRB* 104. Here, the same hardness level is observed right up to the boundary of TMIZ and HAZ, where it decreases to *HRB* 100, and then smoothly increases up to base material hardness level (*HRB* 108–109). In welded joints produced by automatic TIG welding with filler wire Sv1201Sc, through a section of which electric current was passed to induce arc oscillations, increase of metal hardness also occurred after heat treatment. However, it increased just to *HRB* 80 in the weld central part, and up to *HRB* 90–91 in the zone of fusion of the weld with base material.

Such changes of metal hardness after artificial ageing of the samples are observed also in welded joints of 1201 alloy (see Figure 4, *b*). In FSW weld, metal hardness increases up to *HRB* 86, and in the zone of its transition to base material it increases up to *HRB* 85. On the other hand, at automatic TIG welding weld metal hardness increases just to *HRB* 77, and in the zone of its fusion with base material — up to *HRB* 81–82.

Nature of metal hardness distribution in the zone of permanent joint formation allows finding the weakest regions, in which fractures are the most probable at mechanical testing of the samples. So, at static tension of samples without weld back bead and reinforcement, produced at automatic TIG welding of alloy 1460 with filler wire Sv1201Sc and arc oscillations, their fracture occurs across the weld metal, where metal hardness is minimal. Their ultimate strength is on the level of 265 MPa (Table). Similar samples with weld reinforcement fail in the zone of weld fusion with the base material and their ultimate strength is about 285 MPa. Here, FSW joints have the highest ultimate strength (345 MPa). Samples of such joints without either weld back bead or reinforcement (owing to the features of this welding process), fail on the boundary of TMIZ and HAZ from the tool retreating side.

Postweld heat treatment allowed increasing the weld metal ultimate strength up to 275 MPa, and welded joint ultimate strength — up to 300 MPa. However, artificial ageing has the maximum effect on FSW joints. Their ultimate strength rises up to

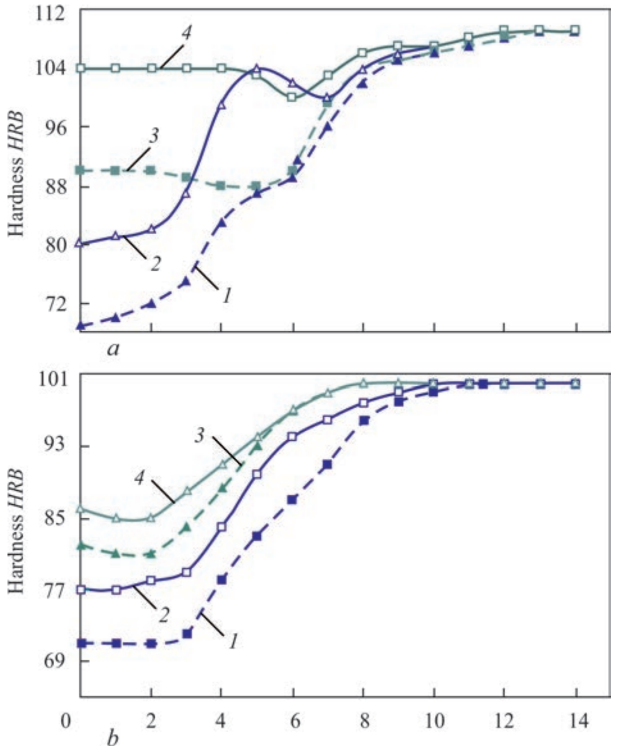

Figure 4. Hardness distribution in welded joints of 2 mm alloys 1460 (*a*) and 1201 (*b*) produced by automatic TIG welding with arc oscillations with application of filler wire Sv1201Sc and by FSW, directly after welding and after heat treatment of the samples: *1* — Sv1201Sc; *2* — Sv1201Sc (HT); *3* — FSW; *4* — FSW (HT)

Ultimate strength of butt joints of 2 mm aluminium alloys 1460 and 1201 produced by FSW and automatic TIG welding

Alloy	Welding process	Condition	Filler wire	Ultimate strength σ_t, MPa: Samples without back bead with weld reinforcement	Ultimate strength σ_t, MPa: Samples without back and without weld reinforcement
1460	FSW	After welding	–	–	339–348 / 345
		After HT		–	416–424 / 420
	Automatic TIG welding with arc oscillations	After welding	Sv1201Sc	283–289 / 285	262–270 / 265
		After HT		295–309 / 300	269–279 / 275
1201	FSW	After welding	–	–	305–315 / 310
		After HT		–	318–323 / 320
	Automatic TIG welding	After welding	Sv1201	274–277 / 275	232–237 / 235
		After HT		303–315 / 307	259–264 / 261
	Automatic TIG welding with arc oscillations	After welding	Sv1201Sc	287–296 / 290	240–252 / 245
		After HT		310–317 / 315	265–277 / 270

Note. The numerator gives the maximum values of the parameter; and the denominator — its average values by the results of testing three — five samples.

420 MPa, that is equal to 86 % of ultimate strength for base material. Here the sample fracture location remains unchanged, as metal hardness in the zone of welded joint formation, increases, but the nature of its distribution practically does not change — regions of minimum metal hardness remain after artificial ageing in the same locations as immediately after welding.

Samples of welded joints of alloy 1201 produced by FSW, fail under static tension in TMIZ in the region of weld transition to base material. Here, their ultimate strength is on the level of 310 MPa, directly after welding and on the level of 320 MPa after artificial ageing. Fracture of samples with weld reinforcement produced by automatic TIG welding with filler wire Sv1201Sc and arc oscillations, runs in the zone of weld fusion with base material. Their ultimate strength directly after welding is equal to 290 MPa, and after heat treatment it is 315 MPa. After removal of weld reinforcement the site of sample fracture at their tension becomes the weld metal, the ultimate strength of which is on the level of 245 MPa after welding and 270 MPa after artificial ageing.

Conclusions

1. Application of welding wire Sv1201Sc, containing 0.2 % Zr and 0.5 % Sc, in nonconsumable electrode argon-arc welding of aluminium alloys 1460 and 1201 with arc oscillations, due to its deviations from the vertical position as a result of electric current passage through the filler section, ensures formation of fine equiaxed crystals over the entire section of the weld. However, at FSW, intensive plastic deformation of metal in the zone of permanent joint formation results in development of the finest (3–5 μm) structure in the weld.

2. Formation of a permanent joint in the solid phase without melting of the edges being welded and of fine structure of welds at FSW allows achieving higher values of ultimate strength of the metal of welds and welded joints of aluminium alloys 1460 and 1201, than at automatic TIG welding with welding pool oscillations, even with application of welding wire containing zirconium and scandium.

3. Artificial ageing of welded joints, when phase transformations and processes of stabilization of the structure of metal subjected to thermal impact take place, promotes their strengthening. Here, the maximum level of strength (75 % for alloy 1201 and 86 % for 1460 alloy), compared to base material, is achieved after such heat treatment of FSW samples.

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