RESISTANCE OF WELDS ON THIN-SHEET ALUMINIUM ALLOYS TO INITIATION AND PROPAGATION OF SERVICE CRACKS

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Resistance friction stir and TIG welds on ductile low aluminium alloys and high-strength multi-component aluminium alloys 1.8 mm thick to initiation and propagation of cracks was determined by subjecting specimens comprising stress raisers to tension. It was shown that the welds made without metal melting have a higher resistance to service cracks.

Keywords: *friction stir welding, TIG welding, thin-sheet aluminium alloys, service cracks*

Ductile low aluminium alloys and high-strength multi-component aluminium alloys are widely used for fabrication of various-application welded structures. Different fusion welding methods are applied in the majority of cases to produce permanent joints. The welds in this case are formed as a result of melting of a certain volume of the materials joined and filler wire in a common weld pool, as well as their subsequent solidification in a shielding inert gas. The resulting welds have a cast dendritic coarse-crystalline structure, this making them inferior to the base material in mechanical properties [1, 2].

Melting of metal within the weld formation zone can be avoided and properties of base materials can be maintained in weldments by using solid-state friction stir welding (FCW) [3, 4]. The finely dispersed structure is formed in such a weld as a result of heating of an aluminium alloy due to friction within the welding zone to the plastic state, intensive stirring, deformation in a limited volume and compression by the working surfaces of a tool, and the base material in the HAZ weakens less than in fusion welding. This leads to increase in tensile strength of such joints in uniaxial tension of specimens [5–7], their fatigue strength under cyclic loading [8, 9] and resistance to corrosion in aggressive environments [10, 11], as well as to decrease in levels of residual stresses and strains [12, 13]. However, of high importance for estimation of performance of welded structures is resistance of the welds to initiation and propagation of cracks during operation. The purpose of this study was to evaluate resistance of the TIG and friction stir welds on thin-sheet aluminium alloys to initiation and propagation of cracks.

Ductile low aluminium alloys (AMtsN and AMg2M) and high-strength multi-component aluminium alloys (AMg6M, 1201, 1420 and 1460) used for fabrication of various welded structures were studied. Sheets 1.8 mm thick were welded by automatic TIG welding in argon atmosphere at a speed of 20 m/h using machine MW-450 (Fronius, Austria). The welding process was carried out at currents of 130–145 A by using strips of matching alloys (for alloys AMtsN and AMg2M), or welding wires SvAMg6, SvAMg63 (for alloys AMg6M and 1420) and Sv1201 (for alloys 1201 and 1460). The FSW process was performed with a laboratory unit designed by the E.O. Paton Electric Welding Institute.

Butt welded joints were made by using a special tool with a tapered tip and a shoulder 12 mm in diameter. The speed of rotation of the tool was 1420 rpm, and the linear speed of its movement along the joint was 18–14 m/h.

Characteristics of resistance of the base metal and welds of the welded joints to fracture were determined on Kahn specimens [14] with a sharp (R = 0.1 mm) notch 11 mm long (Figure 1), providing initiation of crack at a relatively low energy level using versatile testing machine RU-5. The notch was arranged so that its apex coincided with the weld axis. The cross section area of the specimens was 44.75 mm^2. Tensile strength at off-centre tension and specific crack propagation energy (SCPE) for each specimen were determined by means of the load–strain diagrams plotted during the tests.

As shown by the studies, alloy AMtsN was characterised by the highest ductility. Even the presence of a stress raiser in the form of the sharp with R = = 0.1 mm notch did not always lead to initiation of crack near its apex, and a specimen during tension might fracture outside the critical zone where this notch was located (Figure 2, *a*).

If a crack nevertheless initiated at the stress raiser apex, in tension of a specimen it propagated very slowly (Figure 3, *a*). The value of tensile strength in tension of such specimens of the AMtsN base metal was at a level of 261 MPa.

Tests of specimens of the TIG welded joints showed that the cracks forming near the stress raiser propagated in the weld metal (Figure 2, *b*). The cracks initiated and propagated in such specimens during tension mush faster than in the base metal (Figure 3).

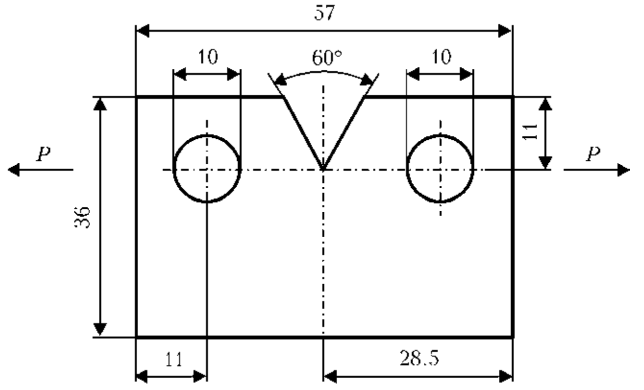

Figure 1. Schematic of Kahn specimen for evaluation of tensile strength of metal and SCPE under tension and bending conditions

The value of tensile strength of the weld metal was at a level of 191 MPa, which is substantially lower than that of the base metal.

The cracks that initiated at the stress raiser apex in specimens produced by the solid-state FSW method shifted to the thermomechanically affected zone (Figure 2, *c*). Tensile strength of metal in this zone was approximately identical to that of the fusion weld metal and equalled 192 MPa, and the diagram describing the character of initiation and propagation of the cracks was very similar to that plotted in tests of the specimens made by the TIG welding (Figure 3, *a*).

Initiation of cracks in the weld metal occurred easier than in the base metal, but resistance of the welds to propagation of the cracks that initiated at the stress raiser apex was higher compared to the base metal. This is evidenced by the SCPE values, which for the FS- and TIG-welded specimens were 7.0 and 6.9 J/cm^2, respectively, whereas for the base metal this value was only 4.5 J/cm^2.

Low aluminium alloy AMg2M was also characterised by a sufficiently high ductility. Therefore, a stress raiser in the form of the sharp notch did not cause instantaneous initiation and propagation of cracks (Figure 3, *b*). The value of tensile strength of such specimens was at a level of 256 MPa.

In specimens produced by the TIG welding method the cracks propagated in the weld metal, while their tensile strength was 214 MPa. In tests of the FSW specimens the cracks propagated from the central part of the weld to a zone where it interfaced the base metal. The value of tensile strength of such welds was at a level of 270 MPa.

Initiation and propagation of cracks in tension of specimens occurred easier in the TIG welds. For instance, the value of SCPE in tests of such specimens amounted to 4.9 J/cm^2, which is 68 % of the corresponding value of the FSW specimens, although the base metal of alloy AMg2M had a higher resistance to initiation and propagation of cracks compared to the weld metal.

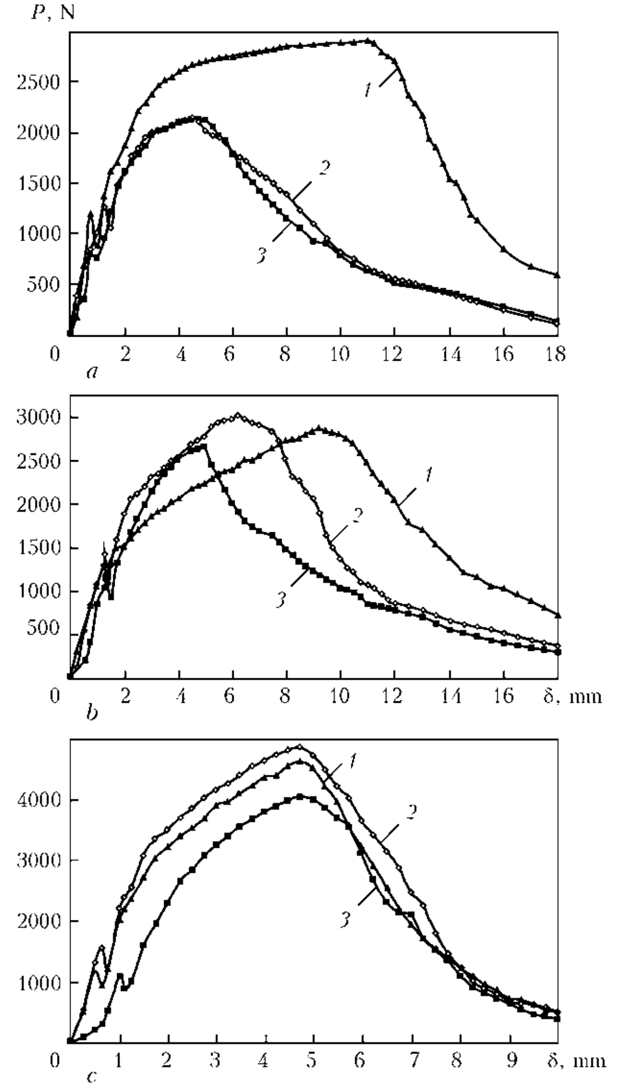

Figure 3. Load–strain diagram plotted during tests of the base metal (*1*) and metal of the FS- (*2*) and TIG- (*3*) welded joints on alloys AMtsN (*a*), AMg2M (*b*) and AMg6M (*c*)

Alloy AMg6M was also characterised by a sufficiently high ductility. The process of initiation of a crack at the stress raiser apex occurred smoothly, but it propagated much faster than in low alloys (Figure 3, *c*). Tensile strength of specimens of this alloy base metal was at a level of 415 MPa.

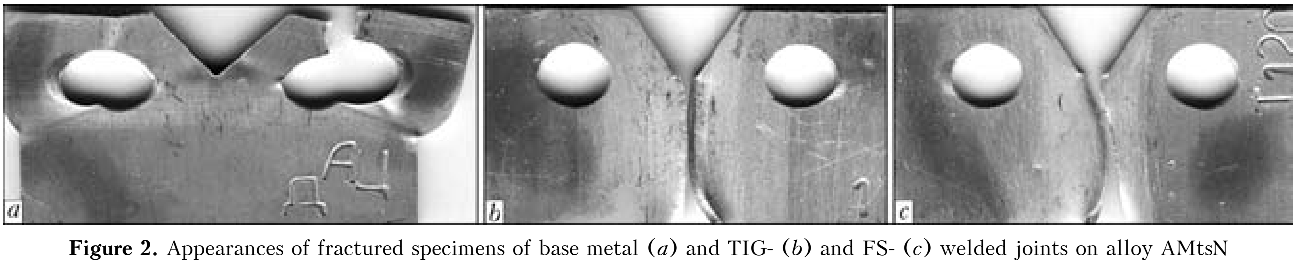

Figure 2. Appearances of fractured specimens of base metal (*a*) and TIG- (*b*) and FS- (*c*) welded joints on alloy AMtsN

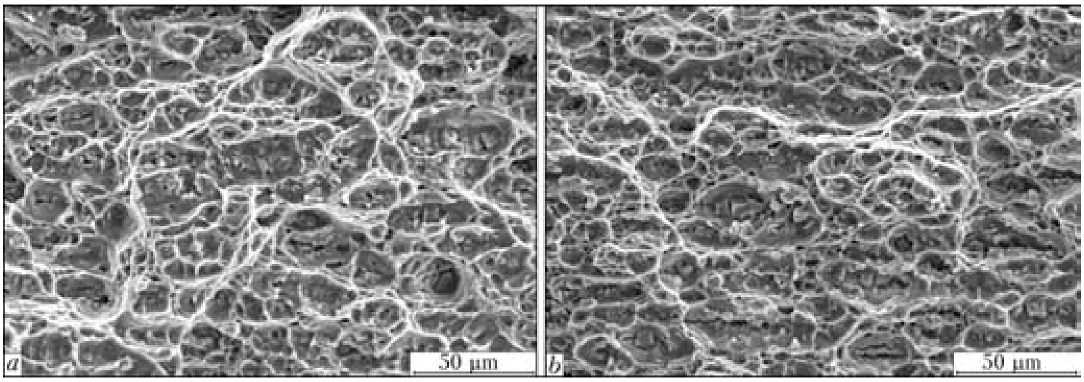

Figure 4. Fractography patterns (×500) of fracture surfaces of the weld (*a*) and weld to base metal interface zone (*b*) obtained in tests of FSW specimens on alloy AMg6M

The cracks that initiated at the sharp notch apex in specimens produced by the TIG welding method propagated in the weld metal. Tensile strength of metal of such welds was lower compared to the base metal and equalled 361 MPa. In tension of the FSW specimens the cracks shifted to the weld to base metal interface zone, and their tensile strength value was at a level of 436 MPa.

The cracks in the FSW specimens propagated during tension even slower than in the base metal. For example, the SCPE value of the weld metal in such specimens was at a level of 8.8 J/cm^2, whereas for alloy AMg6M this value was 5.7 J/cm^2, and for the fusion weld metal it was 4.7 J/cm^2.

Fractography of fracture surfaces of specimens of the FS-welded joints indicated to a tough character of fracture of the welds (Figure 4). Shallow pits with thin ridges can be clearly seen in the central part of the weld near the apex of a stress raiser in the form of the sharp notch. Fine structure of the welds provided a large total length of the grain boundaries, which hampered an abrupt increase of stress concentration and suppressed propagation of an avalanche crack in the weld metal.

Values of fracture resistance of Kahn tensile test specimens of aluminium alloys and their FS- and TIG-welded joints

Alloy welded	Welding method	Filler metal	σ_t, MPa	SCPE, J/cm^2
AMtsN	–	–	261	4.5
	FSW	–	192	7.0
	TIG	AMtsN	191	6.9
AMg2M	–	–	256	9.5
	FSW	–	270	7.2
	TIG	AMg2M	214	4.9
AMg6M	–	–	415	5.7
	FSW	–	436	8.8
	TIG	SvAMg6	361	4.7
1201	–	–	479	2.7
	FSW	–	449	3.8
	TIG	Sv1201	335	3.7
1420	–	–	458	2.6
	FSW	–	385	4.3
	TIG	SvAMg63	421	5.3
1460	–	–	571	8.5
	FSW	–	410	4.5
	TIG	Sv1201	366	2.7

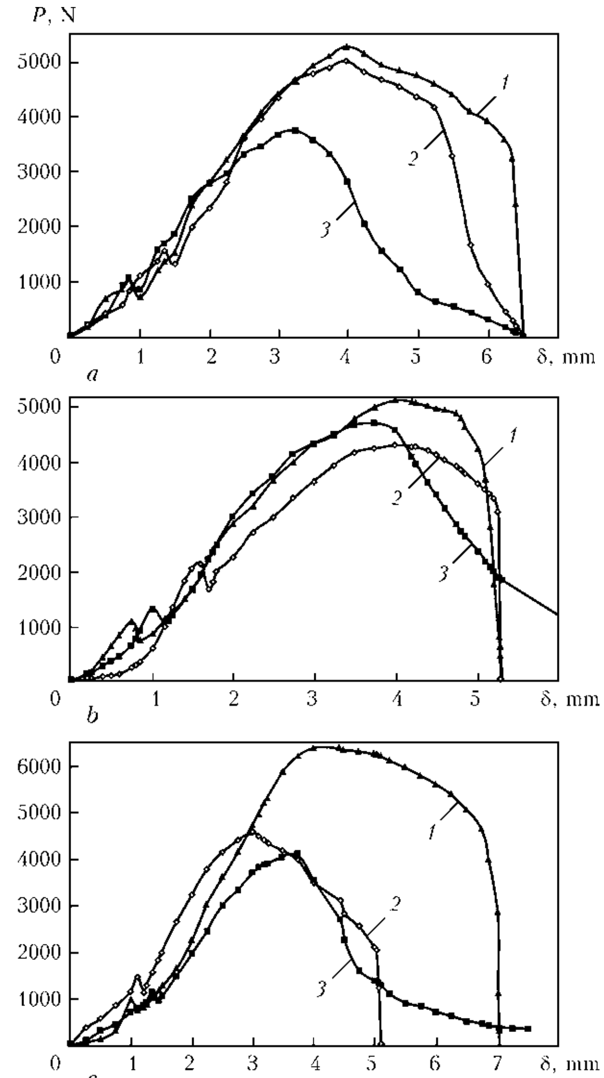

Figure 5. Load–strain diagram plotted in tests of specimens of the base metal (*1*) and FS- (*2*) and TIG- (*3*) welded joints on alloys 1201 (*a*), 1420 (*b*) and 1460 (*c*)

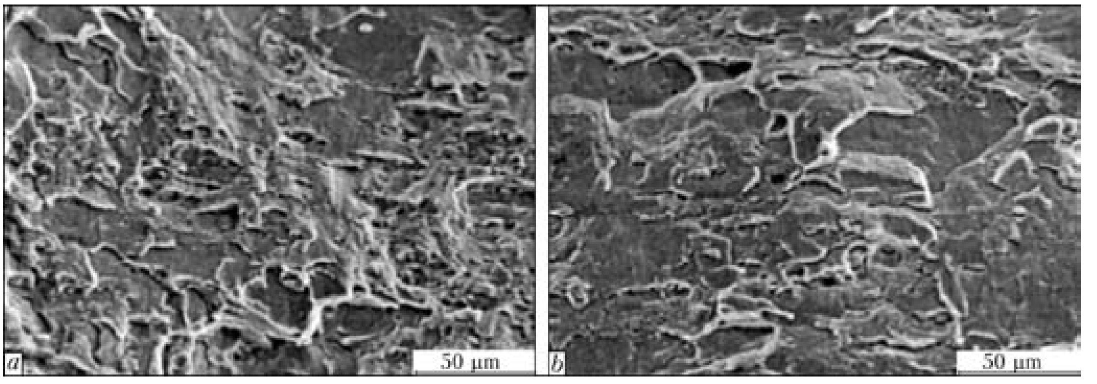

Figure 6. Fractograsphy patterns (×500) of fracture surfaces of the weld (*a*) and weld to base metal interface zone (*b*) obtained in tests of FSW specimens on alloy 1460

Tension of such specimens of alloy 1201 with a stress raiser in the form of the sharp notch led to a quick initiation and propagation of cracks in them (Figure 5, *a*). Tensile strength of the base metal was about 479 MPa.

In specimens of the TIG-welded joints on alloy 1201 the crack that initiated at the sharp notch apex propagated in the weld metal. Tensile strength of the weld metal was approximately 335 MPa. In tests of the FSW specimens the crack shifted to the weld to base metal interface zone. Tensile strength of metal in this zone amounted to 449 MPa. The minimal value of SCPE in the base metal (2.7 J/cm^2) is indicative of the fact that the crack propagation process in it occurred easier than in metal of the solid-state and fusion welds.

High-strength aluminium-lithium alloy 1420 is more brittle than alloy AMg6M. Hence, a crack initiated at the sharp notch apex much quicker in the base metal (Figure 5, *b*), and it propagated almost instantaneously. The value of tensile strength of the base metal was at a level of 458 MPa.

The crack that initiated at the sharp notch apex in the fusion welded specimens propagated in the base metal, whereas in the FS-welded specimens it shifted to the weld to base metal interface zone. Tensile strength of such specimens was 421 and 385 MPa, respectively. The character of initiation and propagation of cracks in the solid-state weld metal was almost identical to that in the base metal (Figure 5, *b*).

The crack that initiated at the sharp notch apex propagated most easily in the base metal having a minimal SCPE value equal to 2.6 J/cm^2. For the welds produced both by the solid-state and fusion methods this value was considerably higher, i.e. 5.3 and 4.3 J/cm^2, respectively.

Alloy 1460 is characterised by a low ductility. Hence, initiation of cracks in tension of the base metal specimens occurred almost as quickly as in tension of alloy 1420, while propagation of cracks was a bit slower, approximately like in alloy 1201 (Figure 5, *c*). The tensile strength value of specimens of the 1460 base metal was about 571 MPa.

The cracks in the fusion welded specimens propagated in the base metal, while tensile strength of metal of such welds was approximately 366 MPa. In the FSW specimens the crack shifted to the weld to base metal interface zone, the tensile strength value of this metal being 410 MPa.

Propagation of the cracks that initiated at the notch apex occurred easier in the TIG weld metal, whose SCPE value was only 2.7 J/cm^2. This value of the solid-state weld metal was much higher (4.5 J/cm^2) and constituted 53 % of the base metal level.

Fractography of fracture surfaces of the welds made on alloy 1460 by the FSW method (Figure 6) showed that they had the form typical of ductile materials, which are characterised by a high energy-consuming fracture by the tough mechanism. The groove-type relief formed as a result of plastic displacement of material in tension of the specimens. The weld to base metal interface zone featured a substantial increase in length of plane relief regions, which are indicative of a higher brittleness of the material with such a structure. Therefore, the crack initiated by the sharp notch in the central part of the weld shifted in tension of the specimen to the weld to base metal interface zone, where it propagated at lower levels of stress concentration and required much lower energy consumption.

Therefore, fracture resistance of the solid-state FS welds on aluminium alloys AMg2M, AMg6M, 1201 and 1460 was higher than that of the fusion welds. This confirms their higher resistance to initiation and propagation of cracks. The welds on low alloy AMtsN characterised by a super high ductility, made both by the solid-state and fusion welding methods, had identical values of tensile strength and SCPE. The higher values of fracture resistance of the welds on alloy 1420 were provided in fusion welding using filler metal than in friction stir welding.

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METHODS FOR ASSESSMENT OF STRENGTHENING OF HSLA STEEL WELD METAL

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Possibilities of application of strengthening mechanisms and structural approach to evaluation of strengthening of weld metal of high-strength low-alloyed (HSLA) steels were analyzed. It is shown that brittle fracture resistance of welds is mainly influenced by solid solution and grain-boundary strengthening.

Keywords: *arc welding, HSLA steels, weld metal, strengthening mechanisms, structure, forecasting mechanical properties*

At present HSLA steels are one of the most promising materials in welded structure fabrication. Starting from 1970s a lot of attention was given to investigations of the problems of metallurgy and technology of welding these steels. The accumulated extensive material on the properties of welded structures from this steel class allows forecasting the ways and the background technologies of further improvement of the entire set of mechanical properties of welds on HSLA steels. Analysis and generalization of the data of various researchers allowed defining several postulates aimed at producing reliable welded joints of HSLA steels with a high level of service properties [1, 2]. In particular, it is believed that in order to ensure an optimum combination of the values of strength, toughness and ductility of the metal of welds, made on HSLA with up to 560 MPa yield point, it is necessary to form wells with a high content of acicular ferrite structure [3, 4]. Investigations performed recently [5, 6] showed that an increased content of acicular ferrite in the weld structure in itself does not guarantee producing metal with high strength and toughness values. The process of brittle fracture, on the one hand, is influenced by solid solution alloying, and on the other hand — by the characteristics of non-metallic inclusions.

At evaluation of the influence of alloying on solid solution strengthening many authors used three main approaches: by metal composition, strengthening mechanisms and content of microstructural components.

In the first case, regression equations are used, which are based on the results of experiments on determination of metal mechanical properties, depending on the change of its alloying element content within certain limits. Such dependencies are valid only for that part of the compositions, for which they were established. So, the results of investigation of weldability of HSLA steels with C–Mn–Si alloying system [7] generalized in the equations

$$\sigma_t = 268 + 450[C + 0.33Si + Mn(1.6C - 0.145)], \quad (1)$$

$$a_I^{+20} = 144 - 387C + 330C^2 \quad (2)$$

cannot be used for low-alloyed steels with C–Mn–Si–Mo–Ni–Ti alloying system.

In the second case proceeding from the physical processes influencing the weld metal strengthening, an evaluation is proposed which is based on analysis of strengthening mechanisms, in keeping with which it is necessary to take into account the mechanism of solid solution, dislocation, dispersion and grain-boundary strengthening [8]. For instance, yield point $\Delta\sigma_y^F$ and temperature of transition from the brittle to tough fracture mode of ferritic-pearlitic steel T_{br}^{FP} can be determined as