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INFLUENCE OF IRREGULAR CYCLIC LOAD ON FATIGUE RESISTANCE OF THIN-SHEET WELDED JOINTS OF HEAT-STRENGTHENED ALUMINIUM ALLOYS

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The influence of irregular narrow band cyclic load on fatigue resistance of welded joints of heat-strengthened aluminium alloys with a thickness of 1.8–2.0 mm produced by argon arc welding using nonconsumable electrode (AAWNCE) and friction stir welding (FSW) was studied. The basic mechanical properties of the produced welded joints of aluminium D16, 1420 and 1460 alloys were determined. The fatigue curves of the investigated welded joints at narrow band cyclic block-program load with close to normal (Gaussian) and exponential distribution of stress amplitude value were plotted. It is shown that strength and fatigue resistance of welded joints of the investigated aluminium alloys produced by FSW exceed the corresponding values for the joints produced by AAWNCE in the whole range of service life of 10^5–$2\cdot10^6$ cycles of stress variation. 15 Ref., 3 Tables, 8 Figures.

Keywords: aluminium alloys, argon arc welding using nonconsumable electrode, friction stir welding, mechanical properties, fatigue resistance, irregular cyclic loads

Reducing metal consumption of products with high service characteristics and life is an important and challenging direction in development of modern engineering. The solution of this problem is closely connected with the use of aluminium alloys of different alloying systems [1, 2]. Aluminium alloys are widely used for manufacture of units of carrier rockets and spacecrafts, launching sites, air and water vessels, land transport, agricultural machinery, chemical equipment and other welded structures, which are usually operated in the conditions of variable loads [3, 4]. Depending on the peculiarities of variable load of products or structures, aluminium alloys are used, welded joints of which have the required values of fatigue resistance. Designing innovative aerospace products provides mainly for the use of aluminium alloys with a low specific weight, for example, high-strength heat-strengthened alloys of Al–Cu–Mg, Al–Su–Li and Al–Mg–Li systems [4–6]. In most cases, to produce permanent joints during manufacture of different structures from aluminium alloys, fusion welding technologies and also modern welding technologies with a lower heat input, such as solid-phase friction stir welding are used [7, 8].

The vast majority of welded metal structures of long-term use are operated under the action of variable irregular load [9]. Such loads arise, for example, during transportation or movement of loads of different sizes, under the impact of wind and waves, which are constantly changing by their nature and as a result of different types of oscillations and vibrations that appear during operation of structures. In most cases, such a loading process is random and can be described by a certain law of distribution of the random stress amplitude value (e.g., normal Gaussian distribution, Rayleigh distribution, exponential or lognormal distribution) with set parameters of mathematical expectation and mean square deviation [10]. At the same time, the modes of random load differ by a wide variety. For example, in the elements of high-speed vehicles, light metal structures, antenna-mast structures, in the structures of marine deep-water stationary platforms, etc., which can be considered as weakly damping mechanical systems, the change of operating stresses represents a narrow band random process. Therefore, taking into account the features of variable load in designing and calculation of welded element of aluminium metal structure or product for fatigue in the conditions, where they will be operated, is an urgent and important task to provide their reliability and safe operation [11]. That is why the main purpose of the work consists in studying the effect of irregular cyclic load on fatigue resistance of thin-sheet butt welded joints of heat-strengthened aluminium-lithium 1420T1, 1460T1 and duralumin D16T alloys, produced applying the technology of argon arc welding using nonconsumable electrode (AAWNCE) and friction stir welding (FSW).

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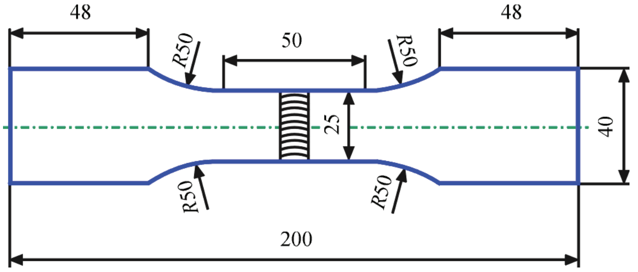

Figure 1. Appearance and geometric sizes of specimen for fatigue tests of butt welded joints

To evaluate the tensile strength and study the effect of irregular cyclic load on fatigue resistance of thin-sheet butt welded joints of aluminium 1420T1 1460T1 and D16T alloys the sheets with a thickness of 1.8–2.0 mm were used, mechanical properties of which are given in Table 1. Friction stir welding was carried out in the laboratory installation designed at the PWI, using a special tool with a conical tip and a clamp of 12 mm diameter [12], the rotation speed of which was 1420 rpm. Aluminium alloys with lithium were welded at a speed of 14 m/h, and D16T alloy at a speed of 10 m/h. For comparison, the same butt joints were produced by non-consumable electrode argon arc welding with the use of MW-450 installation (Fronius, Austria) at a welding speed of 20 m/h. As the filler material for AAWNCE of 1420T1 and D16T alloys the filler wire SvAMg63 was used, and to weld 1460T1 alloy, the filler wire Sv1201 of 1.6 mm diameter. The value of welding current for aluminium alloys with lithium was 145 A, and for D16T alloy — 160 A. The width of the welds produced by AAWNCE was at the level of 6.5 mm, and those produced by friction stir welding was 3.5 mm (at a width of a zone of thermomechanical influence on the facial side of the weld was about 12 mm).

Table 1. Mechanical properties of studied aluminium alloys

Alloy grade	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %
1420T1	459	322	11
1460T1	565	523	9
D16T	484	347	15

From the produced welded plates in accordance with DSTU ISO 4136, the specimens were made to determine the tensile strength of joints at a uniaxial tension. The width of the working part of the specimens was 15 mm. In this case, in the specimens produced by fusion welding, mechanical cleaning of the reinforcement of the root part of the weld on the level of base material was also performed, as it is common during manufacture of most structures of a critical purpose. The values of tensile strength of the investigated welded joints produced by AAWNCE and FSW technologies are given in Table 2.

Fatigue tests of joint specimens were performed in the universal servo-hydraulic complex MTS 318.25 with a maximum force of 250 kN. The specimens were tested at an axial sinusoidal load at a constant cycle asymmetry and a loading frequency of 10–15 Hz until a complete fracture. Fatigue curves were plotted for a multicycle region of life of 10^5–$2 \cdot 10^6$ cycles of stress variation.

Tests under irregular load were performed at a narrow band load spectrum with the stress amplitude close to normal (Gaussian) and to exponential distribution of the stress amplitude value (Table 3). The asymmetry of the stress cycle of the load spectra was accepted $R_\sigma = 0.1$, as far as this asymmetry is the most damaging for aircraft and rocket structures.

Specimens for fatigue tests of the base metal and welded joints (Figure 1) of 1420T1, 1460T1 and D16T alloys, produced by AAWNCE and FSW, were manufactured in accordance with acting national and international standards [13, 14].

Table 2. Tensile strength of welded joints of studied aluminium alloys produced by AAWNCE and FSW

Alloy grade	AAWNCE				FSW	
	Specimens with reinforcement		Specimens without reinforcement			
	σ_t, MPa	Location of fracture	σ_t, MPa	Location of fracture	σ_t, MPa	Location of fracture
1420T1	373	FZ	320	Weld	342	FZ
1460T1	311	FZ	257	Weld	309	TMAZ
D16T	330	FZ	295	Weld	425	TMAZ

Table 3. Equivalent load blocks for a narrow band random stresses spectrum

Block degree number	Spectrum No.1 (close to the normal Gaussian distribution)		Spectrum No.2 (close to the exponential distribution	
	Number of cycles	$\sigma_{a.i}/\sigma_{a.max}$	Number of cycles	$\sigma_{a.i}/\sigma_{a.max}$
1	18	1	13	1
2	170	0.96	78	0.9
3	1250	0.92	403	0.8
4	5750	0.88	2028	0.7
5	17500	0.84	10153	0.6
6	37812	0.80	50778	0.5

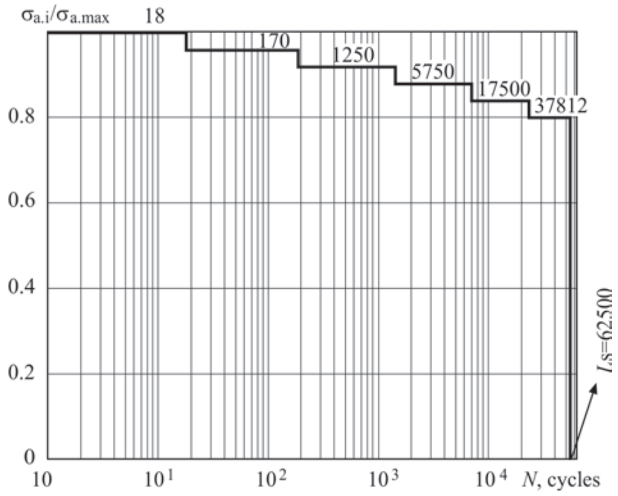

Figure 2. Block No.1 of loading specimens of D16T1 and 1420T1 alloys with the stress amplitude value close to the normal Gaussian distribution

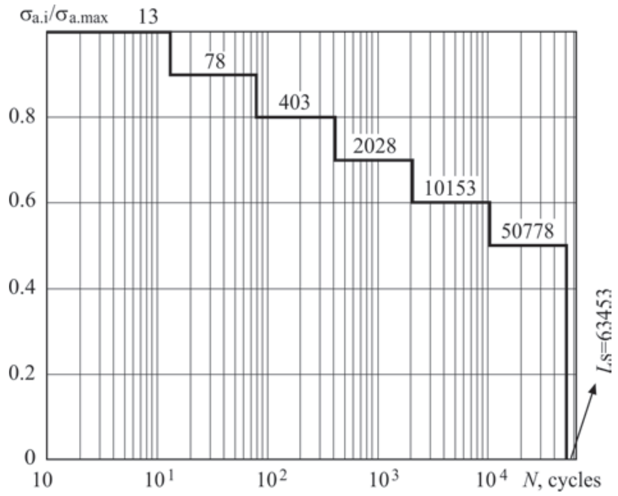

Figure 3. Block of loading specimens of joints of 1460T1 alloy with distribution of stress amplitude value close to the exponential distribution law

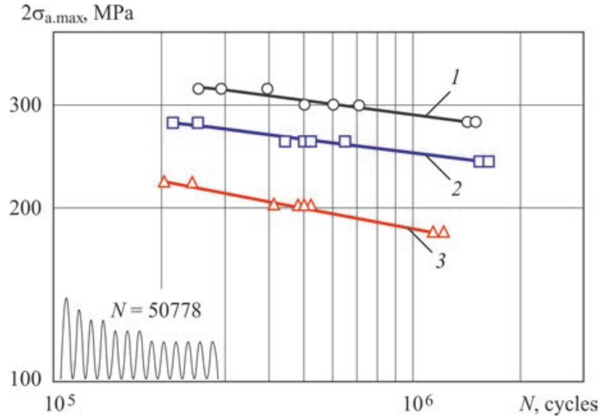

Figure 5. Gassner fatigue curves of base metal and welded joints of aluminium 1460T1 alloy with a thickness of 2 mm at block-program load No.2: *1* — base metal; *2* — welded joints produced by FSW; *3* — welded joints produced by AAWNCE

Under the same conditions, a series of 5–8 specimens of the same type was tested. The experimental data of fatigue tests were processed by the methods of linear regression analysis, generally accepted for this type of investigations [15]. According to the results of fatigue tests for each series of specimens on the basis of the established values of the limits of fatigue strength the corresponding fatigue curves — regression lines in the coordinates $\lg(2\sigma_a^{max})$ were plotted [11].

Specimens of welded joints of 1420T1 and D16T alloy were tested at a block-program load No.1, typical for airframe structures. The length of the load block was 62500 cycles of stress variation (Figure 2).

Specimens of welded joints of 1460T1 alloy were tested at a block-program load No.2, typical for the structures operated under the action of inner pressure, for example, such as cryogenic fuel tanks. Figure 3 presents the block of program load No.2, typical for pressure vessels, the length of which is 63453 cycles of stress variation.

Figure 4 shows the Gassner fatigue curves of the base metal and welded joints of aluminium 1420T1 and D16 alloys welded by AAWNCE and FSW, ob-

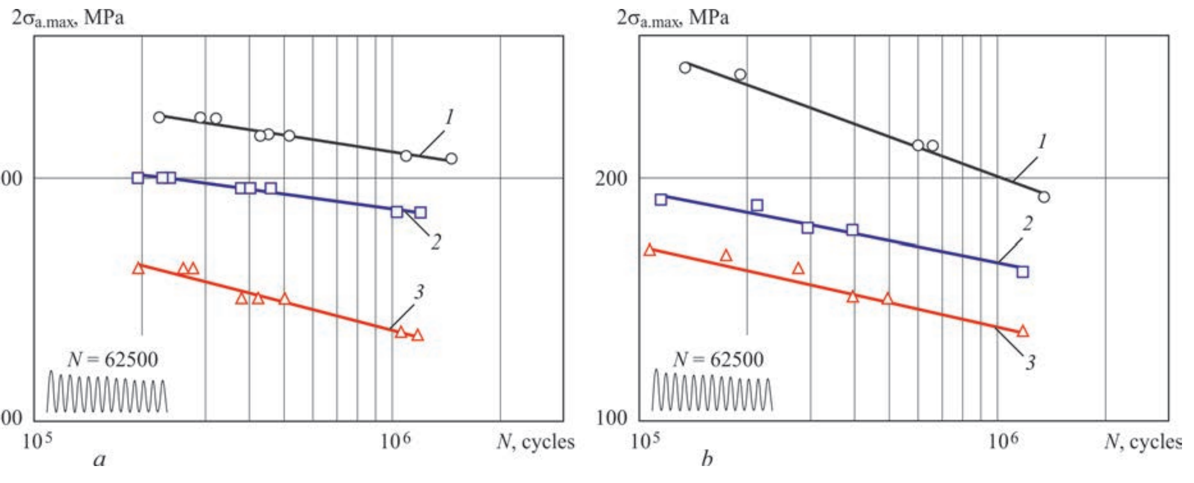

Figure 4. Gassner fatigue curves of base metal and welded joints of aluminium D16T1 (*a*) and 1420T1 (*b*) alloy with a thickness of 1.8 mm at block-program load No.1: *1* — base metal; *2* — welded joints produced by FSW; *3* — welded joints produced by AAWNCE

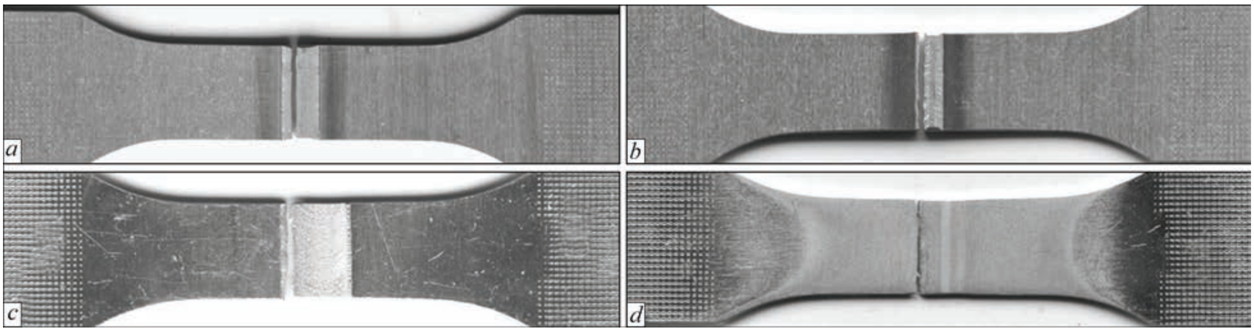

Figure 6. Appearance of facial (*a*, *c*) and lower (*b*, *d*) sides of specimens of butt joints of D16T alloy of 1.8 mm, produced by AAWNCE (*a*, *b*) and by FSW (*c*, *d*) and fractured after cyclic tests

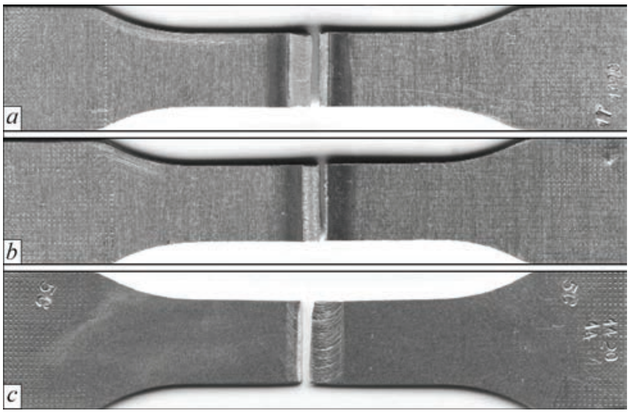

Figure 7. Appearance of facial (*a*, *c*) and lower (*b*) sides of specimens of butt joints of 1420T1 alloy of 1.8 mm, produced by AAWNCE (*a*, *b*) and by FSW (*c*) and fractured after cyclic tests

tained at a block-program load No.1. The obtained results show that the fatigue strength based on 10^6 cycles of stress variation for the welded joints of 1420T1 and D16T1 alloys, produced by FSW is by 25 and 18 % higher than the corresponding values for the joints produced by AAWNCE, and by 83 and 79 % of the corresponding values of the base metal.

Figure 5 shows the Gassner fatigue curves at a block load No.2 of the welded joints of 1460T1 alloy, produced by AAWNCE and FSW. It is shown that the value of fatigue strength based on 10^6 cycles amounts to 85 % for the joints produced by FSW, and 63 % for the joints produced by AAWNCE, relative to the corresponding value of the base metal.

Initiation and propagation of fatigue crack in the specimens with the weld reinforcement of the welded joints of aluminium D16T alloy, produced by AAWNCE, occurred in the zone of fusion of the weld with the base metal (Figure 6). This is explained by a substantial concentration of stresses and a significant softening of the metal in the weld and heat-affected-zone. Fracture of the specimens produced by FSW occurred at the boundary of the thermomechanical and heat-affected-zones on the side of the run-on tool, where a significant softening of metal is observed and a structural and slight geometric heterogeneity is formed.

Fracture of the specimens of welded joints of 1420T1 alloy with the reinforcement of the weld, produced by AAWNCE, also occurred in the area of fusion of the weld with the base metal, where a significant concentration of stresses arises during fusion welding (Figure 7). Fracture of the joints produced by FSW occurred in the thermomechanical-affected zone.

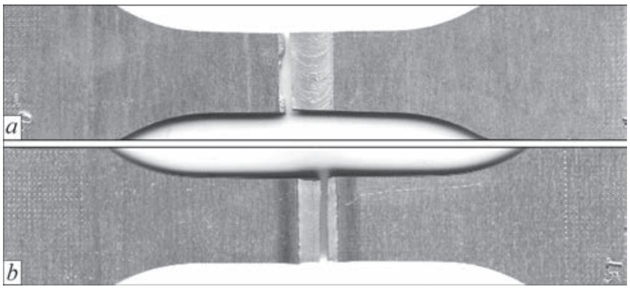

Figure 8. Appearance of facial side of specimens of butt joints of 1420T1 alloy with a thickness of 2.0 mm, produced by FSW (*a*) and by AAWNCE (*b*)

The welded joints of 1460 alloy produced by FSW were also fractured at the boundary of thermomechanical and heat-affected zones on the side of the tool, which is predetermined by softening of the metal alloyed by lithium located in the weld and in the zone of thermomechanical affect and the formation of some geometric heterogeneity (Figure 8). The specimens of welded joints with the weld reinforcement, produced by AAWNCE were fractured in the area of fusion of the weld with the base metal, where a significant concentration of stresses and a significant softening of metal arise.

Conclusions

1. Gassner fatigue curves under irregular load of butt welded joints of heat-strengthened aluminium 1420T1 and 1460T1 alloys, produced by FSW and AAWNCE technologies, were experimentally established. It was shown that the value of fatigue strength of such joints in the whole range of life 10^5–$2\cdot10^6$ amounts to 70–85 % of the corresponding indices of the base metal.

2. Gassner fatigue curves for a narrow band random load process with a stress amplitude value close to the normal Gaussian distribution for the joints of 1420T1 and D16T alloy produced by AAWNCE and FSW were obtained. It was shown that at such a load the fatigue strength on the basis of 10^6 cycles

for the welded joints produced by FSW, exceeds the corresponding values from the joints produced by AAWNCE by 18–25 %, and amounts to 79–83 % from the fatigue strength of the base metal.

3. It was established that for 1460T1 alloy produced by FSW and AAWNCE, the value of the fatigue strength based on 10^6 cycles in narrow band random loading process with the value of stress amplitude, approximate to the exponential law of distribution, amounts to 85 and 63 % of the corresponding value of the base metal.

4. Initiation and propagation of fatigue crack in the specimens of welded joints of the investigated aluminium alloys produced by AAWNCE occurred in the area of fusion of the weld with the base metal, where in the process of fusion welding a substantial concentration of stresses and a significant softening of metal arise. Fracture of the specimens produced by FSW during cyclic tests occurred at the boundary of thermomechanical and heat-affected zones on the side of the run-on tool, which is predetermined by softening of metal and the formation of structural and slight geometric heterogeneity in this area of the welded joint.

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