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STRENGTH AND FATIGUE LIFE OF JOINTS OF HIGH-STRENGTH ALLOY AA7056-T351, MADE BY ELECTRON BEAM WELDING

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Application of modern aluminium alloys when designing elements and structures for aircraft and rocket construction, sea vessels and ground transportation, is ensured by high values of their strength and ductility. New welding technologies allow reducing the structure weight and lowering the operating costs, respectively, while providing the required values of strength and fatigue life. Here, producing sound welded joints of heat-hardenable aluminium alloys is an urgent science and technology problem. Application of welding technologies with a small temperature contribution, such as electron beam welding, compared to traditional welding processes, is promising for aircraft and rocket construction. The objective of this work is studying the level of softening, structural features, magnitude of residual postweld stresses, mechanical properties and regularities of fatigue resistance of joints of heat-hardenable aluminium alloy AA7056-T351 with higher zinc content, produced by electron beam welding. 8 Ref., 2 Tables, 5 Figures.

Keywords: *welded joints, fatigue resistance, residual stresses, aluminium alloy, electron beam welding*

Heat-hardenable aluminium alloys, owing to their high specific weight, considerable corrosion resistance, high values of fatigue resistance and fatigue crack growth, are widely applied for manufacturing components of carrier rockets and space vehicles, launch complexes, vessels, air and ground transportation, agricultural machinery, chemical equipment and other welded structures, which, as a rule, are operated under very complex conditions [1, 2].

At the current stage of development of subsonic and supersonic aviation, aluminium alloys are the main structural materials in aircraft construction [3]. Selection of the alloy for the structure is based on differentiated approach to operation of each component, allowing for its life, service loads, possibility of its heating and other requirements to the parts. Heat-hardenable high-strength aluminium alloys of 7xxx series (Al–Zn–Mg–Cu alloying system) are successfully used in aviation industry. They are the structural material for the wing, skin and inner structural elements of the airframe (spars, ribs, frames, etc.). Aluminium alloy AA7056 was developed as an alloy with characteristics of strength, corrosion resistance and fatigue life, improved relative to alloys AA7150 and AA7449. This alloy is used for manufacturing medium- and large-sized parts, such as upper panels of the wing in aircraft construction, which operate under alternating loading conditions. Modern welding technologies allow reducing the structure weight and lowering the operating costs, respectively, while providing the required strength and fatigue life values. The data on fatigue resistance characteristics of welded joints of AA7056 alloy are not available. Therefore, research in this direction is urgent, and producing a sound welded joint with high physico-mechanical properties is an important scientific and technological problem [4, 5].

Owing to high energy concentration in the electron beam, electron beam welding (EBW) allows producing welded joints with minimum dimensions of the HAZ and high weld depth-to-width ratio. EBW enables application of low heat input with small volume of pool molten metal and short-time thermal impact on the metal being welded. Application of a small amount of heat results in a marked reduction of item deformation. Welding in vacuum prevents saturation of the molten and heated metal by gases. As a result, a high quality of welded joints is achieved on such reactive metals and alloys as niobium, zirconium, titanium, molybdenum, etc [6].

The objective of this work is studying the level of softening, structural features, magnitude of residual postweld stresses, mechanical properties and regularities of fatigue resistance of EBW joints of heat-hardenable aluminium alloy AA7056 with higher zinc content.

High-strength aluminium alloy AA7056 (8.5–9.7 % Zn, 1.5–2.3 % Mg, 1.2–1.9 % Cu) was welded in heat-hardened condition T351. Plates of 12 and 30 mm thickness were EB welded in a vacuum chamber.

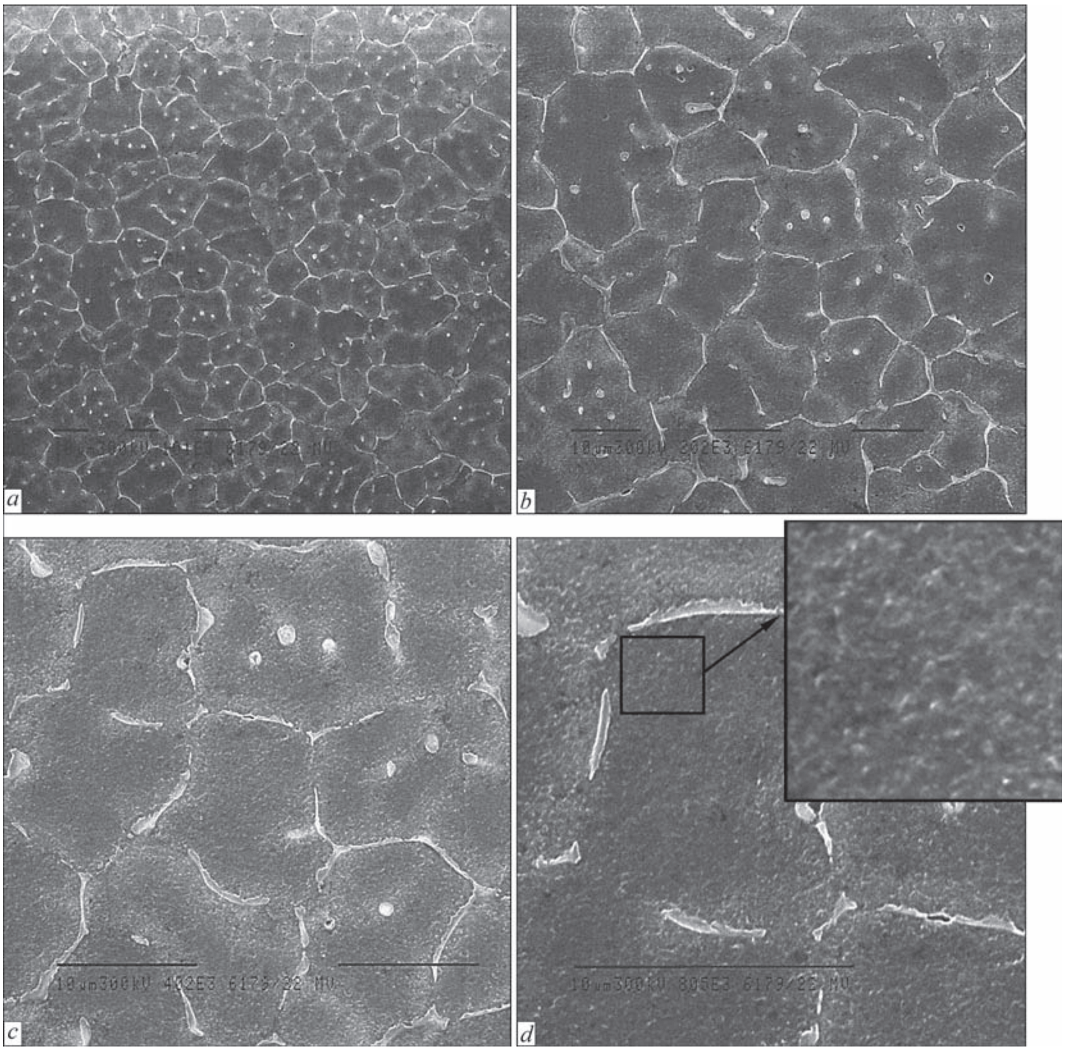

Figure 1. Metal structure of welded joint of alloy 7056-T351: *a* — ×1010; *b* — ×2020; *c* — ×4040; *d* — ×8080

EBW of specially prepared in keeping with the technological requirements plates of aluminium alloy AA7056-T351 12 and 30 mm thick was performed in UL-209M machine in vacuum. Computer-controlled UL-209M machine of PWI design is fitted with power unit based on ELA-60/60 and electron beam gun that moves in a vacuum chamber with internal dimensions of 3850×2500×2500 mm. Working vacuum was $3.54\cdot10^{-2}$ MPa in the chamber and $6.65\cdot10^{-3}$ MPa in the gun and was reached in 30 min. Electron beam gun with metal tungsten cathode together with the high-voltage power source ELA-60/60 provides the range of electron beam current I_b = 0–500 mA at accelerating voltage U_{acc} = 60 kW. The technology of EBW of aluminium alloy 7056-T531 was finalized using local scanning of the electron beam with up to 1000 Hz frequency and up to 4 mm amplitude.

Studying the structural features of butt welded joints of aluminium alloy 7056-T351 12 and 30 mm thick showed that the weld is characterized by uniform structure in absence of pores or cracks, the grains have an equiaxed shape with the size of 4–15 μm (Figure 1, *a*, *b*). Rather thin interlayers of phase formations (FF) 0.1–0.4 μm wide are observed on grain boundaries (Figure 1, *c*, *d*). Uniformly distributed disperse FF particles of 0.1–0.2 μm size are found in inner volumes of the grain structure and individual FF of larger size of 0.7–1.0 μm are also formed. Here, appearance of a substructural component is characteristic, the size of subgrains being 0.4–0.8 μm (Figure 1, *d*). At transition to the fusion line from the weld side, the grain structure practically does not change, and from the HAZ side — a banded structure with the same orientation forms, which is characteristic for base metal. Band width is 10–30 μm at FF increase to 2–3 μm (Figure 1). Thin FF interlayers up to 0.5 μm wide form on the boundaries of band component. Base metal is characterized by a structure with grain size of 6–10 μm at uniform orientation along the banded structure (up to 15 μm width) that forms under the conditions of directed deformation (rolling). Here, formation of a more fine-grained structure is also observed in the base metal. Thus, at EBW a uniform structure forms in the weld metal, fusion line and HAZ of welded

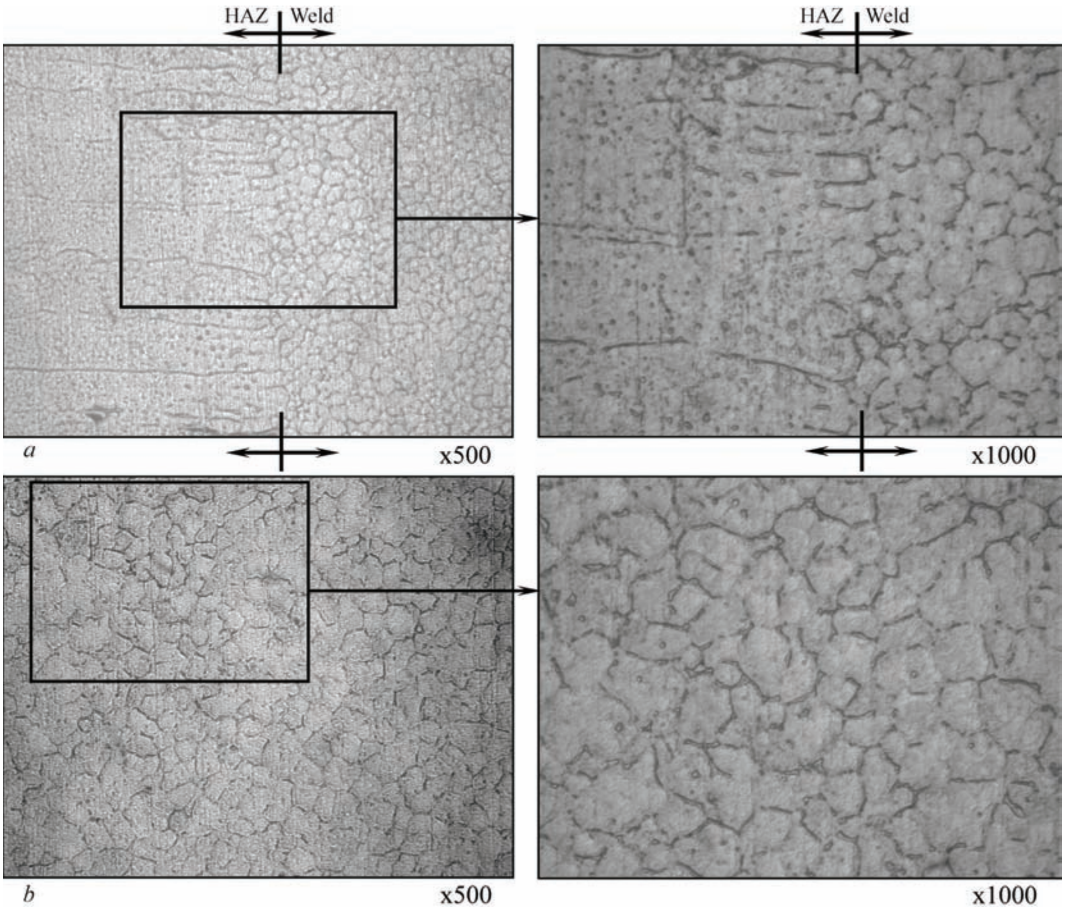

Figure 2. Microstructure of characteristic regions of the joint of alloy 7056-T351 in the fusion zone (*a*) and weld metal (*b*)

joints of aluminium alloy 7056-T351 at significant dispersion of both the grain structure and the phase formations. Pores or cracks are absent (Figure 2). In welding at nonoptimized modes considerable technological problems may develop, which are related to its increased proneness to formation of solidification cracks in the weld and partial melting of base metal grains. All these defects are due to structural and phase transformations, which proceed under the impact of thermal cycle in welding.

Degree of metal softening in the welding zone was assessed by the results of measurement of its hardness to GOST 9013–59 in Rockwell instrument with a steel ball of 1/16″ diameter and 600 N load. Figure 3 shows ball distribution in the welded joint of 7056-T351 alloy. Hardness of base metal of alloy AA7056-T351

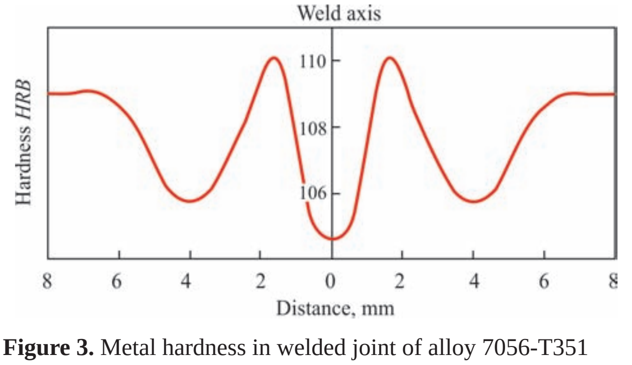

Figure 3. Metal hardness in welded joint of alloy 7056-T351

is on the level of *HRB* 108–109. In the welded joint the width of the softening zone is 15 mm, weld metal hardness being *HRB* 105–110.

Considering the small size of the weld, additional Vickers microhardness measurements were performed to GOST 2999–75. Weld metal microhardness values are 13 % lower than those of base metal, whereas in the fusion zone the microhardness is 9–13 % higher. Table 1 gives the generalized results of microhardness measurements.

The nature of distribution and levels of residual stresses, due to the welding process in the samples, were determined by the destructive method of unloading using resistance strain gauges and ISD-3 instrument [7], as well as nondestructive ultrasonic method, using UPKN instrument [8].

Measurements of residual stresses show that their maximum values reach their maximum in the longitudinal direction relative to the weld, and are almost two times smaller in the transverse direction. Here, maximum residual tensile stresses are in place in the sample center. Figure 4 shows the curves of residual stresses, obtained by ultrasonic method, in the welded plate ($\delta = 12$ mm) of alloy 7056-T351 of 500×240 mm size. Owing to smaller temperature input, the maximum values of longitudinal (σ_x) residual stresses are

Table 1. Microhardness of alloy 7056-T351 in the joint zones

Joint zone	Weld	Fusion line		HAZ	Base metal
		Weld	HAZ		
HV, MPa	1360	1600–1870	1690–1760	1700	1560

equal to just 90–95 MPa, and those of the transverse ones (σ_y) are 40–45 MPa.

Mechanical testing of samples was conducted in a universal servohydraulic machine MTS 318.25 with maximum force of 250 kN, in keeping with the adopted state standards. Base metal plates of alloy AA7056-T351 12 and 30 mm thick were used to prepare cylindrical samples of the IIIrd type of 8 and 10 mm diameter to GOST 1497–84 for determination of the main mechanical characteristics. Welded plates of rolled metal were used to prepare, in keeping with GOST 6996–66, proportional samples (of 6×28 mm cross-section and 270 mm length) for determination of strength limit at uniaxial tension. Average value of strength limit for the sample series was equal to 412–426 MPa that is equal to approximately 70 % of the respective base metal values (Table 2).

Flat samples of 30×6 mm cross-section with a weld in the sample center were cut out of 500×250×30 mm plates with a central weld of 500 mm length, in order to study the fatigue resistance of the joints of alloy 7056-T351. Corset-type samples of 250×30 mm size (20 mm in the test zone) were used for fatigue testing in keeping with GOST 25.502–79. Testing was conducted under the conditions of uniaxial cyclic tension with 8 Hz frequency at the value of the stress asymmetry coefficient of 0.1 and 0.4. Results of the conducted fatigue testing for each sample series, based on the established values of limited endurance limits, were used to plot the fatigue curves — regression lines in $2\sigma_a$–lg$N$ coordinates. Fatigue curves were plotted for high-cycle fatigue region of 10^4–$2 \cdot 10^6$ stress alternation cycles.

Table 2. Mechanical properties of base metal and welded joints of alloy 7056-T351*

Properties	Base metal	EBW
Proof stress $\sigma_{0.2}$, MPa	540–560	–
Strength limit σ_t, MPa	610–625	412–426
Relative elongation δ_5, %	14–16	2–5

*T351 — condition of heat-hardening, which consists of hardening, specified deformation and natural ageing.

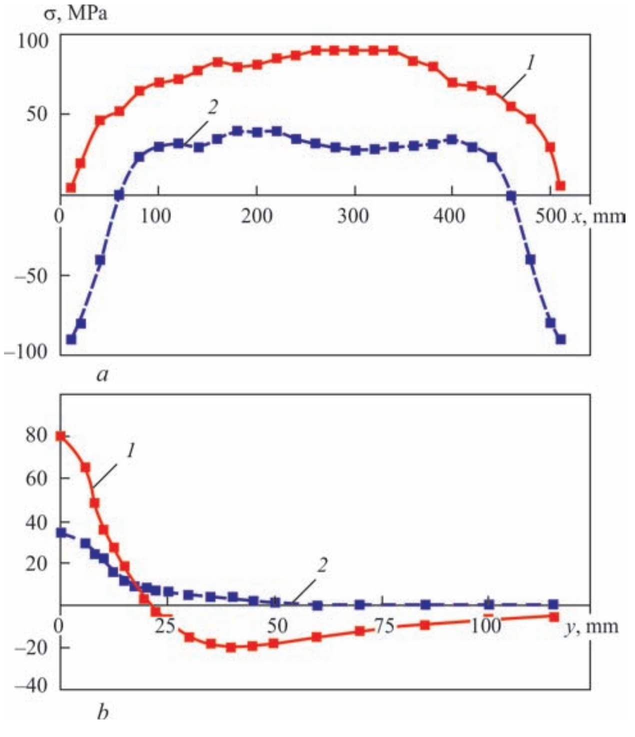

Figure 4. Distribution of maximum longitudinal and transverse residual stresses along the weld (*a*) and normal to the weld (*b*) of welded joint of alloy 7056-T351 12 mm thick: *1* — σ_y; *2* — σ_y

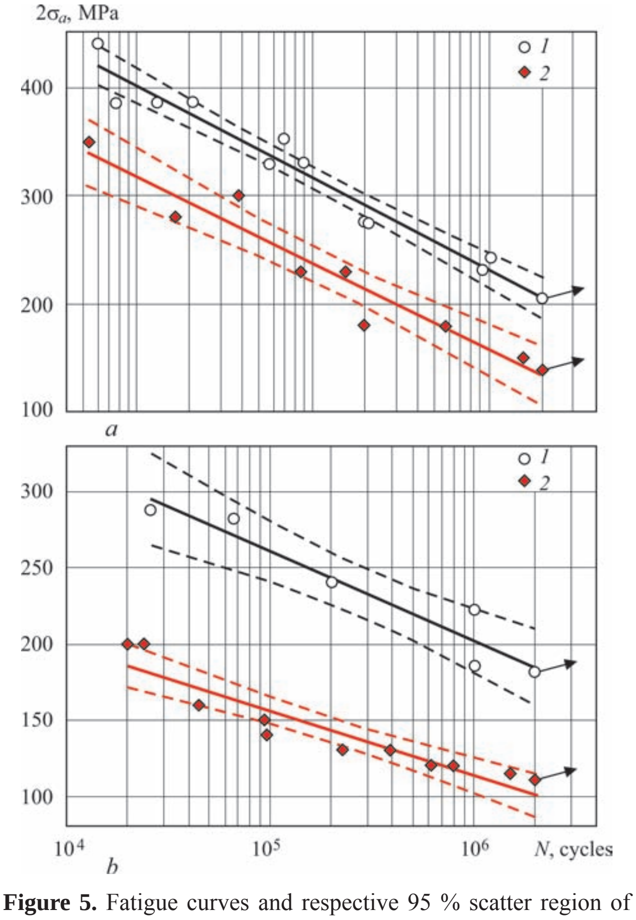

Figure 5. Fatigue curves and respective 95 % scatter region of these samples of base metal and welded joints of aluminium alloy 7056-T351 6 mm thick at loading cycle asymmetry of 0.1 (*a*) and 0.4 (*b*): *1* — base metal; *2* — welded joints

Limited endurance limit on the base of $2{\cdot}10^6$ cycles at loading cycle asymmetry of 0.1 and 0.4, is equal to 150 and 110 MPa, respectively, for the joints that makes up approximately 70 % of the respective base metal values (Figure 5). Slope of fatigue curves obtained at loading cycle asymmetry of 0.1 and 0.4 in the double logarithmic system of coordinates for the joints is equal to $m_{0.1} = 5.36$ and $m_{0.4} = 6.99$, whereas for base metal this value is $m_{0.1} = 6.92$ and $m_{0.4} = 8.5$, respectively. Here, sample fatigue life at the stage of fatigue crack propagation up to complete fracture is much smaller than the fatigue life of the stage before crack initiation that is attributable to low ductility of weld and HAZ metal.

Derived results are indicative of the good prospects for application of electron beam welding for producing quality joints of high-strength aluminium alloy 7056-T351 with higher zinc content.

Conclusions

1. Physico-mechanical properties of welded joints of high-strength heat-hardenable aluminium alloy 7056-T531 (δ = 12 and 30 mm) with higher zinc content (8.7–9.8 %) produced by optimized EBW technology, were studied. It is found that the strength limit of such joints is equal to approximately 70 % of the respective base metal values ($\sigma_{t\,bm}$ = 620 MPa).

2. Maximum values of residual longitudinal stresses in the welded plate of 500×240×30 mm size, produced by EBW technology, are equal to 90–95 MPa, and those of transverse ones are 40–45 MPa.

3. It is found that the limited $2{\cdot}10^6$ endurance limit of EBW joints at loading cycle asymmetry of 0.1 and 0.4 is equal to 150 and 110 MPa, respectively that makes up approximately 70 % of the respective base metal values.

4. At EBW a defect-free uniform structure forms in metal of welds, fusion line and HAZ, at dispersion of the grain structure and phase formations that ensures a high level of strength and fatigue life of welded joints of aluminium alloy 7056-T351.

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