STRENGTH AND FEATURES OF FRACTURE OF WELDED JOINTS ON HIGH-STRENGTH ALUMINIUM ALLOYS AT LOW TEMPERATURE

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The regularities of variation in strength values of nonconsumable electrode welded joints on aluminium alloys of different alloying systems at low temperature (down to 20 K) were analyzed. Peculiarities of their fracture in different heat-affected zones are noted.

Keywords: *aluminium alloys, nonconsumable electrode argon-arc welding, welded joints, strength, failure, low testing temperature, fractures*

Owing to their structural capabilities and mechanical properties, aluminium alloys are an attractive material for low-temperature operation. They have high specific strength and are not prone to brittle fracture [1–3]. High-strength alloys of three alloying systems — Al–Mg–Mn (AMg6N), Al–Cu–Mn (1201) and Al–Cu–Li (1460) — became the most widely accepted by designers and technologists for fabrication of welded products for cryogenic engineering (Table). At application of permanent joints of components and structures from such alloys, it is necessary to determine their strength level and establish their fracture features at low temperature. This will allow determination of optimum temperature intervals of operation of aluminium alloy welded structures that is important, as a certain chemical and structural heterogeneity develops in the weld metal and HAZ during welding that determines fracture characteristics.

The subject of this work is establishing the regularities of the change of physico-mechanical properties and features of fracture of welded joints on high-strength aluminium alloys AMg6N, 1201 and 1460 in a broad temperature range (300–20 K). Sheets of the above alloys 4 mm thick were butt welded by mechanized nonconsumable electrode argon-arc welding that is the most widely accepted method of manufacturing products for cryogenic applications. Welding was performed by a pulsed-arc of asymmetrical square-wave current of different polarity [4]. To prevent formation of defects in welded joints the welded edges were scraped to the depth of not less than 0.1 mm. Welding of AMg6N alloy was performed with welding wire of SvAMg63 grade, for 1201 alloy Sv1201 wire was used, and for 1460 — alloy test wire of Al–Cu system (see the Table). Wire diameter was 2 mm in all the cases. Proceeding from the results of X-ray inspection, the quality of the studied welds was recognized to be satisfactory.

Assessment of physico-mechanical properties was performed under the conditions of uniaxial and off-center tension at the rate of $3.3\cdot10^{-5}$ m/s at the temperature of 300, 200, 77 and 20 K. Samples were cooled using dry ice (at 200 K), liquid nitrogen (at 77 K) and hydrogen (at 20 K). At uniaxial tension flat smooth samples with notch radius of 0.25 mm along the weld axis were tested (GOST 227–77). At off-center tension, when tension and bending are applied simultaneously, flat samples of 57 × 36 × 4 mm size with notch of 11 mm depth and 0.1 mm radius at the tip were used [5]. Theoretical coefficient of stress concentration was equal to 10. Notch tips in welded joint samples were located strictly along weld axis, in the fusion zone and HAZ zone located at 5 mm distance from the fusion line, as dissolution of alloying elements occurs at welding heating, and solid solution

Composition (wt.%) of commercial high-strength aluminium alloys and filler wires used in welding

Systems	Alloy and wire grades	Cu	Mg	Mn	Ti	Zr	Fe	Si	Other elements
Al–Mg–Mn	AMg6N	0.1	5.8–6.8	0.5–0.8	0.02–0.10	–	0.40	0.40	–
	SvAMg63	0.1	5.6–6.8	0.5–0.8	0.10	0.15–0.35	0.05	0.05	–
Al–Cu–Mn	1201	5.8–6.8	0.02	0.2–0.4	0.02–0.10	0.10–0.25	0.30	0.20	0.05–0.15 V
	Sv1201	6.0–6.8	0.02	0.2–0.6	0.02–0.10	0.10–0.25	0.15	0.08	0.05–0.15 V
Al–Cu–Li	1460	3.1–3.5	–	–	0.10–0.20	0.08–0.09	0.30	0.20	2.00–2.20 Li 0.07–0.08 Sc
	Test Al–Cu								

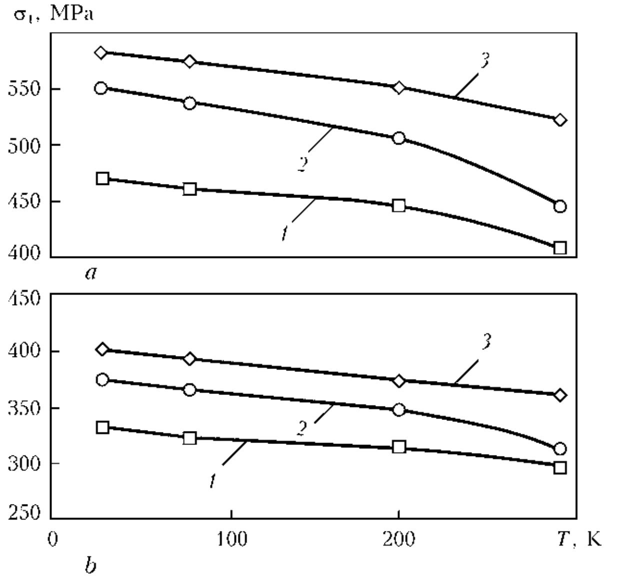

Figure 1. Influence of low-temperatures on ultimate tensile strength σ_t of notched samples of aluminium alloys AMg6N (*1*), 1201 (*2*) and 1460 (*3*) (*a*) and their welded joints (*b*)

decomposition and phase formation depend on heating source and temperature-time parameters of welding [4]. Tested for comparison were similar base metal samples of all the studied aluminium alloys, cut out in the direction transverse relative to rolling direction, the most unfavourable for rolled sheets.

Fracture mode of base metal and welded joints of the above alloys at different temperatures was studied in scanning electron microscope (SEM) JSM-840 with Link-860/500 microanalyzer system at accelerating voltage of 15, 20 and 30 kW. This instrument allows diagnosing the macro- and microstructure of welded joint fractures to study the kinetics and mechanism of crack propagation, as well as revealing the causes for the impact of various factors, in particular, change of their structure in welding, loading conditions and temperature [6–8].

As a result of experimental study, it was established that the values of ultimate tensile strength σ_t of samples of welded joints of AMg6N, 1201 and 1460 alloys at room temperature uniaxial tension were equal to 330, 350 and 400 MPa, respectively. Base metal strength here was by 20–25 % higher than that of welded joints (Figure 1). Lowering of testing temperature to 77 K increases by 10–20 % σ_t values for base metal (of AMg6N, 1201 and 1460 aluminium alloys).

Ultimate tensile strength values of welded joints compared to room temperature increase by only 5–10 %, remaining lower than those of base metal. Of the studied alloys, AMg6N alloy and its welded joints have a lower susceptibility to low-temperature strengthening. A similar dependence of σ_t is found at transition from 77 to 20 K temperature. Ultimate tensile strength of weld metal of 1201 and 1460 alloys here rises by more than 70 and 100 MPa, respectively.

Comparison of strength values of samples of base metal and welded joints shows that they differ from each other in the entire studied temperature range (from 20 up to 300 K), despite an increase of ultimate tensile strength (Figure 1). With lowering of testing temperature the rate of strength increase is 1.5–1.8 times higher for base metal than for welded joints. Among the studied alloys AMg6N alloy has a lower susceptibility (by 10–15 %) to low-temperature strengthening.

A similar tendency of strength variation is noted also under the conditions of off-center tension (Figure 2). At testing temperature of 300–77 K nominal breaking stress σ_{br} of AMg6N alloy rises only slightly (by 3–5 %), and in liquid hydrogen medium at 20 K temperature it decreases to room temperature level. In 1201 and 1460 alloys this strength characteristic rises monotonically in all the studied temperature range reaching σ_{br} = 510 and 630 MPa at 20 K. The physics of this phenomenon is related to the value of atom diameter (0.3120 nm) of magnesium as the main alloying element of AMg6N alloy. Lower value of atom diameter (0.256 nm) of copper contained in 1201 and 1460 alloys, compared to magnesium, promotes a more active movement of dislocations, with achievement of a uniform stress field distribution at lowering of ambient temperature [4, 5].

Welded joints of the studied alloys have lower values (by 100–200 MPa) of breaking stress at all values of testing temperature (Figure 2, *a*, *d*). Level of σ_{br} lowering is determined by alloying system of the alloy, as well as by the degree of inhomogeneity by alloying element and impurity content as a result of their segregation along the grain boundaries and formation of zones with a coarse structure under the impact of welding heating. Minimum level of σ_{br} values is noted in welded joints of AMg6N alloy. Temperature of testing welded joint samples has differing influence on the rate of stress increase in the weld and HAZ metal.

Marked differences between the studied aluminium alloys are found at determination of specific work of crack propagation (SWCP). All the alloys demonstrate a general regularity of lowering of SWCP at the change of testing temperature (Figure 2, *b*, *e*). This is related to the fact that at testing temperature below 77 K strong energy barriers are created in the path of dislocation motion [9–11] that reduce the probability of manifestation of thermal fluctuations required for dislocation mobility and, thus, limit plastic deformation, the degree of lowering of which is indicated by SWCP values. AMg6N alloy has a minimum level of fracture energy in the entire temperature range that is, possibly, due to insufficient purity of initial metal as to interstitial impurities or features of their crystalline, dislocation or electronic structure [2, 3].

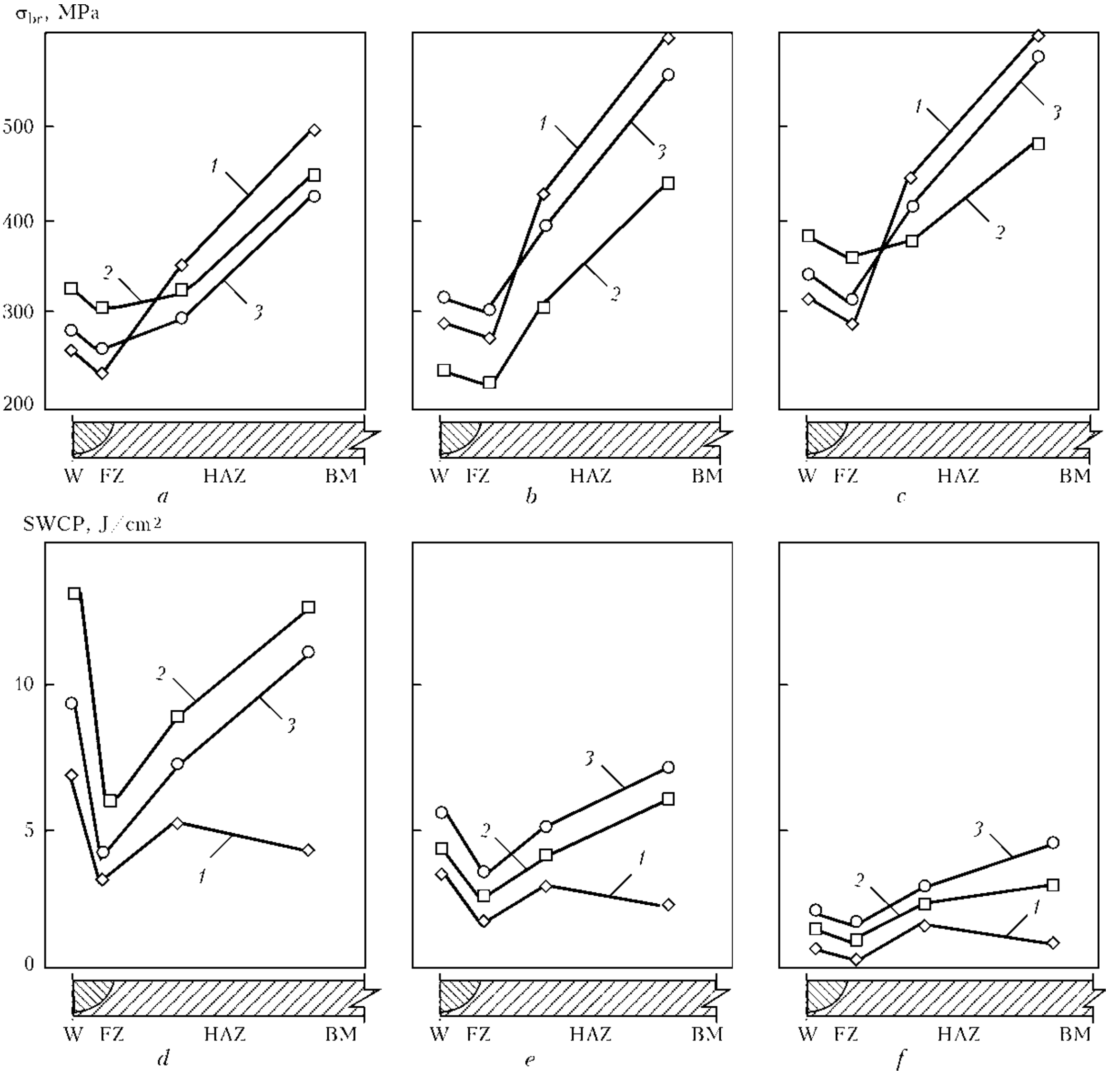

Figure 2. Dependence of nominal breaking stress σ_{br} (*a*–*c*) and SWCP (*d*–*f*) in different zones of welded joints of high-strength aluminium alloys 1460 (*1*), AMg6N (*2*) and 1201 (*3*) on testing temperature of 293 (*a*, *d*), 77 (*b*, *e*) and 20 (*c*, *f*) K: W — weld; FZ — fusion zone; BM — base metal

σ_{br} values in different zones of welded joints of AMg6N, 1201 and 1460 alloys decrease with lowering of testing temperature to 20 K, as a result of low-temperature strengthening characteristic for base metal (see Figure 2, *a*, *d*). However, σ_{br} values for different aluminium alloys differ from each other and from the base metal. In the latter case they are lower by 150–200 MPa that is close to the change of strength of welded joints at uniaxial tension. Rate of stress increase is determined by the alloy chemical composition and thermal impact of welding heating. Joints of 1201 and 1460 alloys were found to have a higher susceptibility to low-temperature strengthening than AMg6N alloy joints.

SWCP values of welded joints are more than 1.5 times higher compared to base metal in the entire studied temperature range (see Figure 2, *b*, *e*). Degree of SWCP lowering is also determined by alloy composition and depends on the change of structure in the joint zone under the impact of the welding cycle. Joints of 1201 and 1460 alloys are characterized by higher values compared to AMg6N alloy that may be due to magnesium atom dimensions.

Fusion zone metal has minimum values of fracture resistance at all the values of testing temperatures. Their level depends on the composition of welded alloys (see Figure 2). For an alloy with magnesium, σ_{br} is equal to 310 MPa, SWCP is 6 J/cm^2, and for an alloy with copper they are 260 MPa and 4 J/cm^2, respectively. Lower σ_{br} values of fusion zone metal are indicative of the susceptibility to fast localisation of deformation, and, as a consequence, to low capability of uniform deformation under the conditions of off-center tension. At lowering of testing temperature σ_{br} values increase by 10 %, whereas SWCP values decrease by 30–40 %, that is related to formation of the least favourable metal structure in welding under the impact of welding heat [4]. The greatest lowering of values (by 180–220 MPa) is noted in joints of 1460 alloy containing lithium. Welded joints of 1201 alloy

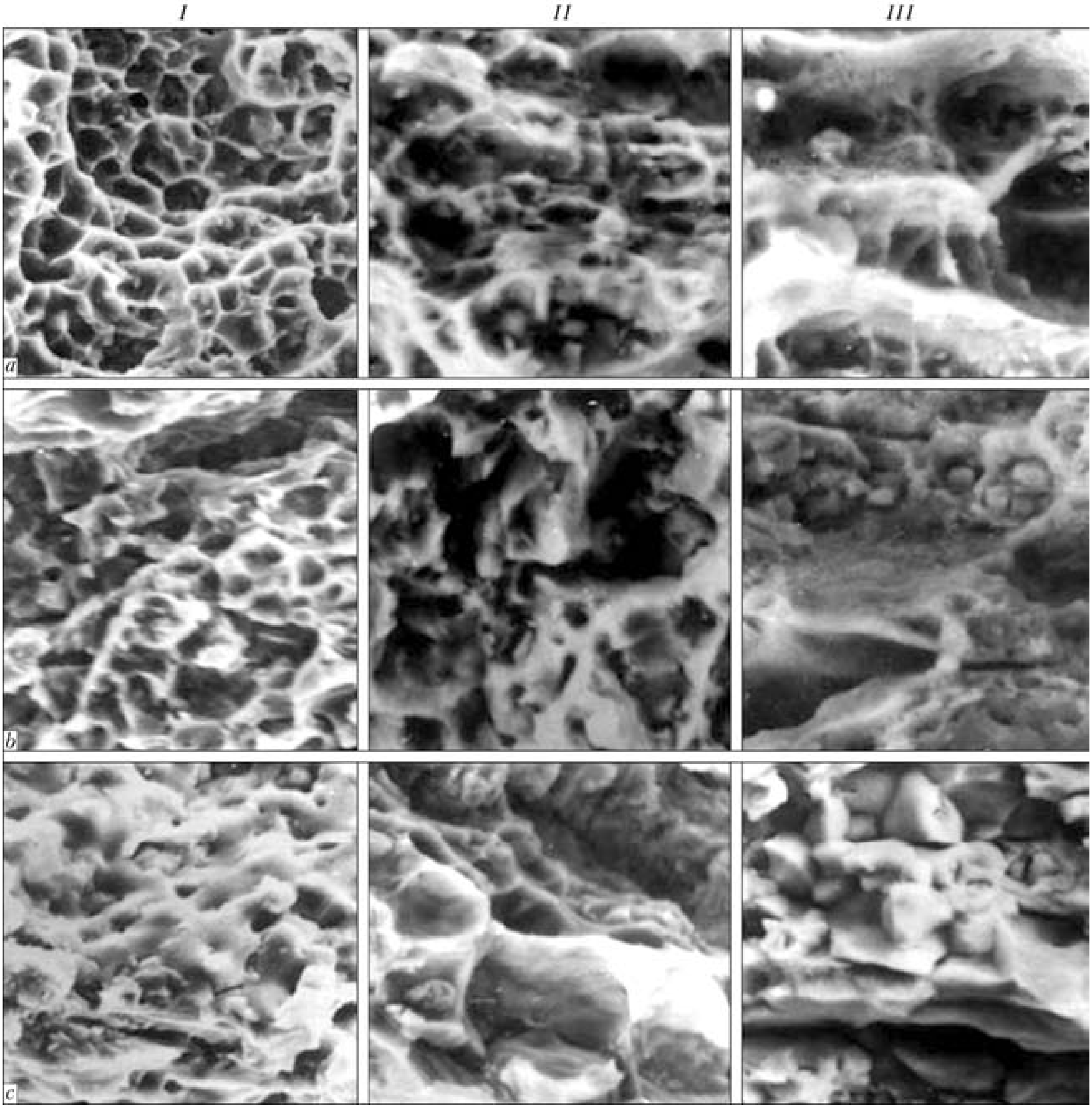

Figure 3. Fractograms of fracture surface of individual zones of welded joint of AMg6N alloy tested at the temperature of 293 (*a*), 77 (*b*) and 20 (*c*) K: *I* — W; *II* — FZ; *III* — HAZ

in the temperature range of 77–20 K have higher values of fracture resistance characteristics (σ_{br} and SWCP). Even in the dangerous fusion zone where a coarse structure forms, promoting the inevitable formation of technological defects, at testing temperatures of 20 K values of these properties are higher than for other studied alloys.

Fractographic studies of fracture surfaces of welded joints revealed that fractures of samples tested at room temperature have pit-like structure (Figures 3–5). Fracture surfaces were found to have micropores, presence of which is indicative of crack development by the mechanism of microvoid initiation, growth and coalescence, characteristic for aluminium alloys. Spherical shape of the pits, decorated by developed ridges along the edges, indicates the ability of welded joint metal to deform intensively, resisting crack initiation under the impact of nominal tensile stresses. This is manifested particularly in AMg6N alloy, having the highest values of pit diameter and depth (Figure 3). Crack initiation sites are inclusions of intermetallics of 0.1–10.0 μm size, which form during alloy manufacture, as well as secondary phase particles of the type of dispersed particles of intermediate inclusions of 0.05–0.50 μm size and phase precipitates of 0.01–0.50 μm size. Pit formation, mode of fracture of brittle intermetallic particles or their delamination on the interface depend on the alloy composition, determining the properties of welded joints, pit shape, volume coefficient and state of structural component interface.

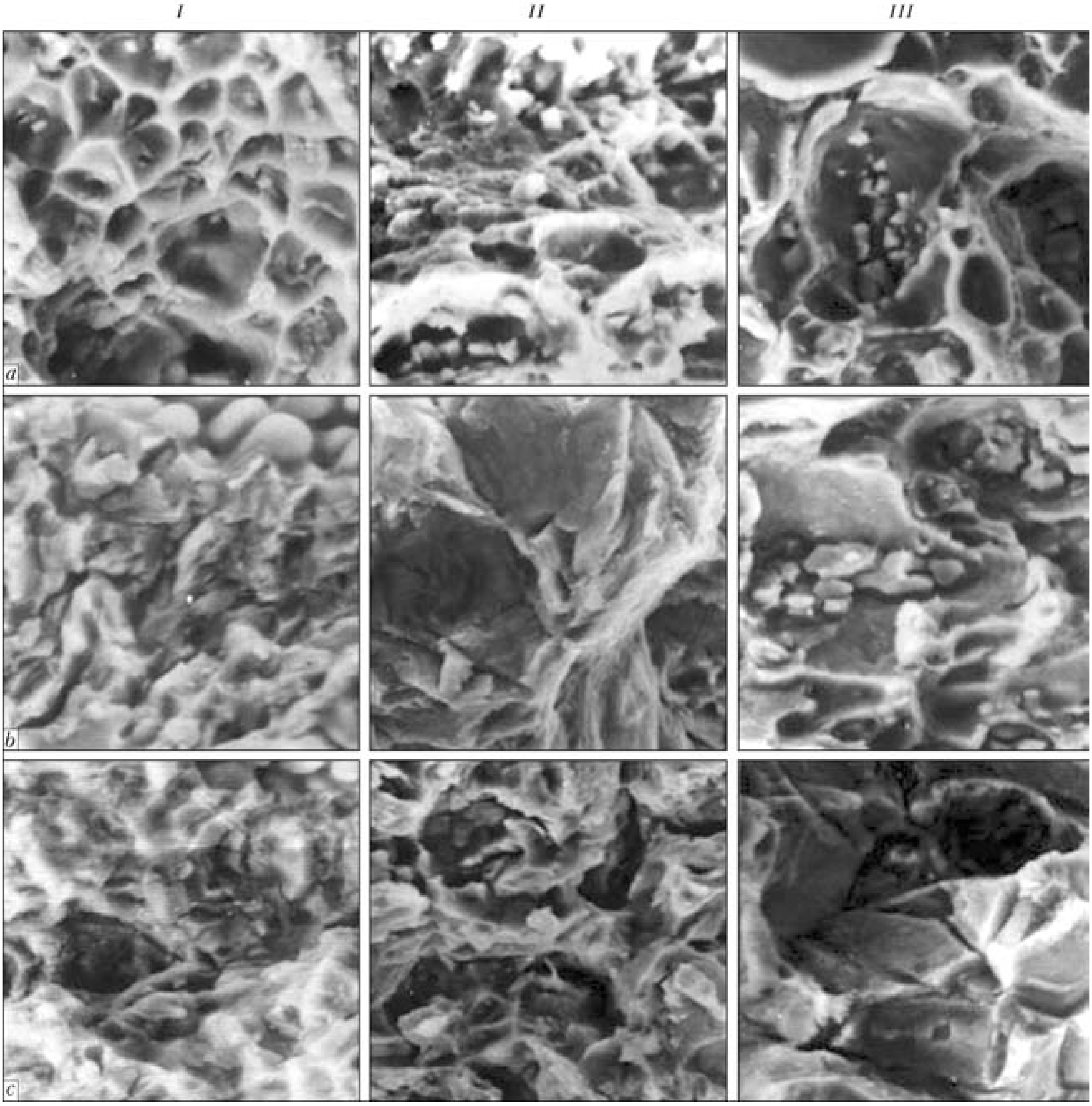

Figure 4. Fractograms of fracture surface of individual zones of 1201 alloy welded joint at low testing temperature (*a*–*c* and *I*–*III* — see Figure 3)

Relief topography of the weld and HAZ has certain differences. Weld metal is characterized by deep equiaxed pits with traces of particles initiating microcracks, observed on their bottom (see Figures 3–5). Such particles are coarse precipitates of excess phase formed under the conditions of welding cycle, as well as insoluble intermetallic inclusions. They are usually non-coherent to the matrix and lead to porosity on the interphases at plastic deformation of the metal [3]. Found features of the relief are indicative of the fact that the leading mechanism of microvoid formation in the structure of aluminium alloys and their welded joints is non-uniformity of plastic deformation and its localizing in the metal microvolume near the particles.

Structural inhomogeneity (difference in particle size and their spacing) in the fusion zone is reflected in non-uniformity of pits on fracture surface. Regions are observed, where a multitude of finer pits are found on the large pit surface that is indicative of stage-by-stage nature of void formation and is the result of gradual fracture of finer inclusion particles. Individual microcracks are visible on grain boundaries. Their presence points to a high sensitivity of metal of this welded joint region to the impact of a complex stressed state at simultaneous tension and bending. HAZ metal relief preserves the orientation of pit sequences characteristic for wrought semi-finished products that was acquired during cold rolling. It is the most pronounced in AMg6N alloy with work hardening equal to approximately 20 %.

Lowering of testing temperature changes fracture topography (see Figures 3–5). Increase of the sections

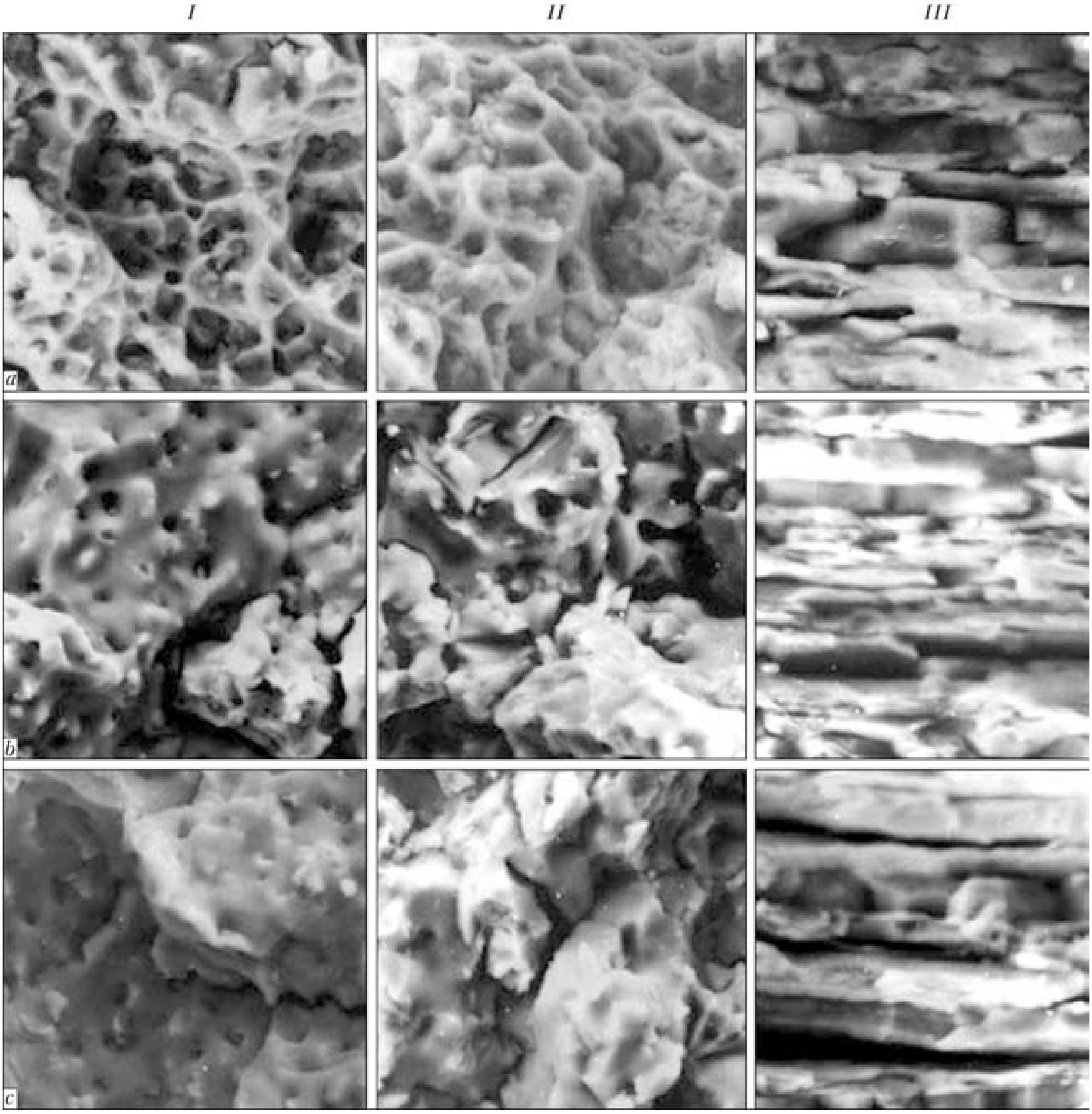

Figure 5. Fractography of fracture surface of individual zones of 1460 alloy welded joint at low testing temperature (*a–c* and *I–III* — see Figure 3)

of intergranular fracture by the tearing mechanism should be regarded as one of the main fractographic indications, even though individual fragments of tough relief are also observed, particularly in AMg6N and 1460 alloys. Further lowering of testing temperature to 20 K causes an increase of the number and extent of sections with microcracks located along grain boundaries, as well as area of fragments with metal delamination. This was less pronounced in fractures of weld metal, where a large number of tough ridges are located around the pits (see Figure 3). Increase of the fraction of intergranular and intercrystalline failures on fractures of welded joints of AMg6N alloy at lowering of testing temperature is accompanied by development of a net of fine and shallow pits that points to a lowering of its fracture resistance. Their formation can be caused by lowering of cohesion forces of structural components and embrittlement of intermetallic phases [1].

A considerable number of tough fracture regions in fractures of 1201 alloy and its welded joints at all the testing temperatures compared to AMgN and 1460 alloys, determines on the whole its high performance under low temperature conditions (see Figure 4). Weld metal fracture remains tough in the entire temperature range. Fracture mode in HAZ zones is practically identical to that in the base metal. At lowering of testing temperature, however, the fusion zone preserves the tendency to formation of microcracks along the grain boundaries, that is related to the presence of a coarse structural heterogeneity which develops during welding. Non-uniform dimensions of microvoids, formed at cracking of coarse phase inclusions, are indicative of their stage-by-stage fracture during matrix deformation up to the moment, when the crack length has reached critical dimensions.

In welded joints of aluminium-lithium alloy 1460 susceptibility to intergranular fracture is manifested at temperatures of 77 and 20 K (see Figure 5). This is related not only to the presence of coarse intermetallic inclusions in the structure, but also to formation of zones free from precipitates on the boundary between solid solution grains, hindering development of plastic deformation of the metal [3]. Their formation is due to alloy composition and welding heating conditions, which promote intensive development of structural heterogeneity by alloying element and impurity content as a result of their segregation along grain boundaries. With increase of volume fraction of such zones in the welded joint structure an increase of stress concentration level is found that is indicated by formation of flat sections of the relief along the boundaries of crystallites and grains on broken sample fractures. On the other hand, no such significant lowering of fracture resistance characteristics values is found in welded joint samples at low temperatures, as is observed in the base metal (see Figure 2). Slant fracture of samples is indicative of shear fracture under the impact of tangential stresses with formation of a tough pit structure. Their small dimensions and presence of cleavage sections decorated by slip lines, point to a local nature of deformation that runs along the slip planes. Increased resistance of metal of 1460 alloy welded joints to crack propagation at low temperature is attributable to presence of copper in its composition, as well as dispersed precipitates of scandium phase, uniformly distributed across all the structural sections of welded joints [3]. Refinement of weld metal structure and absence of recrystallization in the HAZ in welding provide fracture resistance of welded joint metal, despite presence of intergranular fracture regions in the fusion zone (Figure 5). It should be noted that this fact is confirmed by industrial testing of aluminium-lithium alloys of 1460 type and their welded joints. Obtained results enabled application of these alloys in pilot production of welded structures for aerospace engineering [2].

Proceeding from the results of investigations of aluminium alloy welded joints at low temperature, it can be stated that the condition of grain boundaries in structural zones of welded joints on AMg6N, 1201 and 1460 aluminium alloys affects their strength level and fracture mode. Negative impact of welding heating is manifested only in the presence of extended sections with unfavourable structure in the base metal, which form in connection with excess content of alloying elements, impurities and phase clusters located along the rolling line. To prevent structural component embrittlement, it is necessary, using advanced technologies, to strictly specify the content of impurities and volume of welding heat input, when making joints of the above alloys.

CONCLUSIONS

1. Strength σ_t of welded joints of AMg6N, 1201 and 1460 aluminium alloys at uniaxial tension and nominal breaking stress σ_{br} at off-center tension increase by 10–20 % at lowering of testing temperature from 300 to 20 K. AMg6N alloy features a lower susceptibility to low-temperature strengthening. Here, SWCP of welded joints decreases, depending on alloy composition and testing temperature. Crack initiation sites are intermetallic inclusions, particles of secondary phases and phase precipitates, which become brittle at low temperature.

2. Minimum values of fracture resistance properties at all values of testing temperature are characteristic for the zone of weld fusion with base metal, which depends on welded alloy composition. This is due to inhomogeneity of structure, namely difference in particles dimensions and distance between them in this welded joint zone that is expressed in non-uniformity of the depth and dimensions of tough pits on fracture surface.

3. It is established that crack propagation in welded joints of aluminium alloys AMg6N, 1201 and 1460 at room temperature runs by the mechanism of initiation, growth and coalescence of microvoids, characteristic for ductile materials. Lowering of testing temperature to 20 K leads to a change of fracture mechanism from the tough to quasi-tough. Here, an increase of the number and extent of regions with microcracks and fragments of structure delamination along the grain boundaries formed by the tearing mechanism is found on the fracture surface. This was manifested to a smaller degree on weld metal fractures, where a considerable number of tough ridges are located around the pits.

4. It is rational to apply welded joints of AMg6N alloy containing magnesium in structures operating in the temperature range of 300–77 K. High strength and low susceptibility to brittle fracture in the fusion zone of welded joints of 1201 and 1460 alloys containing copper, allows these materials to be applied in cryogenic engineering structures.

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