the commercial 1 and experimental 3 filler metals, respectively.

3. The maximal value of short-time tensile strength equal to 1310 MPa (at T_{test} = 20 °C) was achieved in brazing heat-resistant alloy Inconel 718 with the commercial filler metal based on the Pd–Ni–Cr–Si system. However, the brazed joints tested to long-time tensile strength had an insufficient life time within a range of 29–60 h.

4. The experimental Pd–Ni–Cr–Ge filler metal provides the short-time tensile strength value at a level of that of the base metal equal to 1230–1290 MPa, and ensures the consistent results in long-time tensile strength tests at a temperature of 550 °C and load of 785 MPa. The brazed specimens did not fracture after the tests even for 112 and 132 h, this being more than two times in excess of the required life time.

1. Seams, Ch., Hagel, V. (1976) *Heat-resistant alloys*. Moscow: Metallurgiya.
2. (2003) *Reference book on brazing*. Ed. by I.E. Petrunin. Moscow: Mashinostroenie.
3. (1999) *Constitutional diagrams of binary metal system*: Refer. Book. Vol. 3. Ed. by N.P. Lyakishev. Moscow: Mashinostroenie.

FEATURES OF WELD FORMATION AND PROPERTIES OF ALUMINIUM AND MAGNESIUM ALLOY JOINTS UNDER SIMULATED SPACE CONDITIONS

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Features of weld formation in welded joints of aluminium and magnesium alloys made by electron beam welding under the influence of varying gravity forces and low temperatures are given. Influence of the above factors and content of dissolved hydrogen in the base metal on joint strength, defect formation and loss of alloying elements from the weld metal is shown.

Keywords: *electron beam welding, flying laboratory, aluminium alloys, magnesium alloys, gravity conditions, low temperature, liquid nitrogen, dissolved hydrogen, porosity, strength, alloying element evaporation, X-ray microprobe analysis*

Aluminium and magnesium alloys are the main structural materials for aerospace vehicle construction [1–4]. It is probable that already in the near future a real need may arise for application of welding under the conditions of near-earth space or on the Moon surface [5, 6]. These can be mounting-assembly operations in construction of space complexes or repair-preventive operations, associated with guaranteeing long-term service of operating systems [7]. Analysis of the range of welding operations performed in space shows that it will be most often necessary to join materials from 0.5 up to 4.0 mm thick. In this connection, selection of the welding process is an important factor in obtaining an objective assessment of welded joints of aluminium alloys of the mentioned thickness under these conditions. Here it is necessary to apply such a basic criterion as producing high quality welded joints equivalent to the base metal, without pores or cracks, without lowering the ductility of weld or near-weld zone at minimum losses of alloying elements in the welded joint [8]. Taking the above-said into account, application of EBW is the most effective in construction of space structures requiring a high reliability of joints, minimum weight and volume of the used hardware, complete automation of the welding process and its low energy intensity [5].

In fusion welding of aluminium alloys on the ground, the weld and HAZ develop various macro- and microdefects [9], which lead to lowering of joint strength and ductility, and sometimes also to a loss of their tightness [10, 11]. Development of such defects is also possible in welding of these materials under the space flight conditions (presence of microgravity, low temperature, deep vacuum). In addition, initial composition of the used material has a certain influence [12]. The nature of running of a number of physical processes changes significantly: gravity forces are completely or partially absent, role of thermocapillary and chemical convection rises abruptly, phase separation is practically completely absent because of the difference in density, influence of surface tension forces and adhesion increases greatly [13–15].

The purpose of the conducted research consisted in studying the influence of the enumerated factors on the quality of weld formation and properties of welded joints of AD0, AMg3, AMg6, 1201 aluminium alloys and IMV-2 magnesium alloy. Investigations were performed at the change of gravity in the range of g/g_0 from $1\cdot10^{-2}$ up to 2 (where g_0 is the free fall acceleration, and g is the effective acceleration) and fixed sample temperature of +20, −100, −120 and −196 °C.

During investigations through-thickness penetration beads on plates and welding of butt joints of the above alloys 2.0 and 2.5 mm thick were performed.

Table 1. Composition (wt.%) and tensile strength of the studied alloys

Alloy grade	Mg	Cu	Al	Mn	Zn	Cd	Fe	σ_t, MPa
AMg6	6.2	0.1	Base	0.60	0.2	–	0.40	320
AMg3	3.5	0.1	Same	0.50	0.2	–	0.50	230
AD0	0.3	0.1	»	0.15	0.2	–	0.30	80
1201	–	6.2	»	0.30	–	–	0.10	370
IMV-2*	Base	–	5.0	0.30	1.4	4.2	0.01	250

*This alloy has 2 wt.% Li.

Composition and ultimate tensile strength of the studied alloys are given in Table 1.

AMg6 alloy was taken from different melts with dissolved hydrogen concentration of 0.2, 0.3, 0.5 and 0.6 $cm^3/100$ g. Before loading into the chamber the samples to be welded were scraped to the depth of 0.05 mm. Time of sample soaking in air did not exceed 10 min. Then they were rigidly fixed to a stationary table, which was cooled by liquid nitrogen after chamber pumping down. Absolute pressure in the chamber, which did not exceed $1.33\cdot10^{-3}$ Pa, was maintained by a cryogenic sorption pump. The following parameters were recorded during welding: beam current, focusing current, voltage of powering the power unit from on-board DC system, welding speed, acceleration applied to the weld pool, sample temperature and absolute pressure in the chamber. Welding was performed in the modes given in Table 2 at accelerating voltage of 15 kV and not more than 1.5 mm beam diameter, distance from gun edge to sample surface was 120 mm.

Short-time microgravity conditions were provided by Tu-104A flying laboratory (FL), which carried A-1084M system with high-frequency electron beam power source and small-sized OB 717 gun moving along two coordinates (Figure 1).

During experiments the following accelerations were applied to the weld pool: $-g/g_0 \leq 1\cdot10^2$ (microgravity), 1/6 (free fall acceleration on the Moon surface), 1 (free fall acceleration on the Earth surface), not less than 2 (more than two-fold acceleration).

Table 2. Modes of EBW when making joints of the studied alloys

Sample No.	Alloy grade	Thickness, mm	Sample type	Beam current, mA	Welding speed, m/h
1	AMg6	2.0	Butt joint with penetration	90	36
2	1201	2.0	Same	100	26
3	AMg3	2.5	Deposited bead with penetration	100	36
4	AD0	2.0	Same	100	30
5	IMB-2	2.5	»	70	36

Figure 1. System for EBW of samples at room and low temperatures under the conditions of short-term zero gravity on Tu-104A FL board

Joint quality was assessed by the results of analysis of roentgenograms and macrosections of welds, alloying element distribution and features of weld and HAZ metal structure, as well as by the values of ultimate tensile strength of the joints. With this purpose, small-sized samples were made (Figure 2). Transverse and longitudinal macrosections were revealed by etching in a solution of acids of 72 % NCl, 24 % HNO_3, 4 % HF.

At visual observation of the process of EBW in the entire range of applied accelerations, no cases of liquid metal ejection from the pool or differences in formation of welded joints were registered, compared to the ground conditions. Appearance of welded joints made under the conditions of short-time zero gravity (Figure 3), is indicative of the fact that the nature of their formation does not in any way differ from the ground conditions. It should be noted that in welding under acceleration conditions ($g/g_0 \geq 2$) welds on the studied alloy samples were obtained with a lower technological convexity of the upper part and sagging root (Figure 4). This shows that significant gravity forces have an essential influence on the molten weld pool and, as a consequence, on weld geometry.

Analysis of roentgenograms and layer-by-layer surface sections of welded joint macrosections showed that in all the variants of welding AMg3, AD0, IMV-2

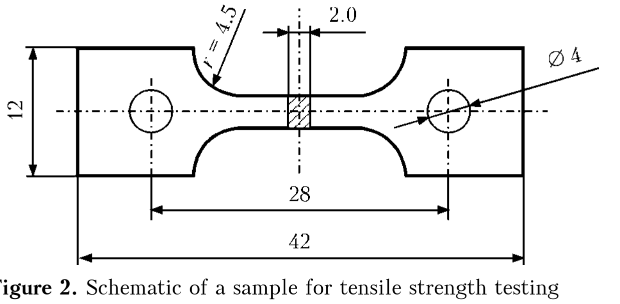

Figure 2. Schematic of a sample for tensile strength testing

Figure 3. Appearance of welded joints of alloys AMg6 (*a*), 1201 (*b*), AMg3 (*c*), AD0 (*d*) and IMV-2 (*e*) made by EBW under the conditions of short-time zero gravity in Tu-104A FL

and AMg6 alloys with dissolved hydrogen concentration of 0.2 $cm^3/100$ g, porosity in weld metal is less than $0.1\cdot10^{-2}$ $cm^3/100$ g or is completely absent. In welding AMg6 alloy with dissolved hydrogen concentration of 0.3 $cm^3/100$ g and higher, an increase of porosity is found in welds, which is manifested particularly at lowering of the level of gravity forces ($g/g_0 = 1/6$ and $\leq 1\cdot10^{-2}$) (Figure 5). Under these conditions, the total volume of pores sometimes reaches 4.42 $cm^3/100$ g. In addition, the size of individual pores increases considerably, and they can reach 2.0–2.5 mm in diameter (Figure 6, *b*).

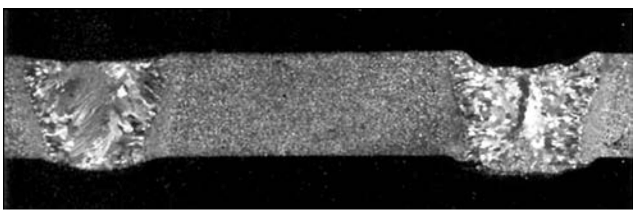

Figure 4. Macrosections of welded joints of AMg6 alloy made by EBW in the same mode at $g/g_0 \leq 1\cdot10^{-2}$ (*left*) and ≥ 2 (*right*)

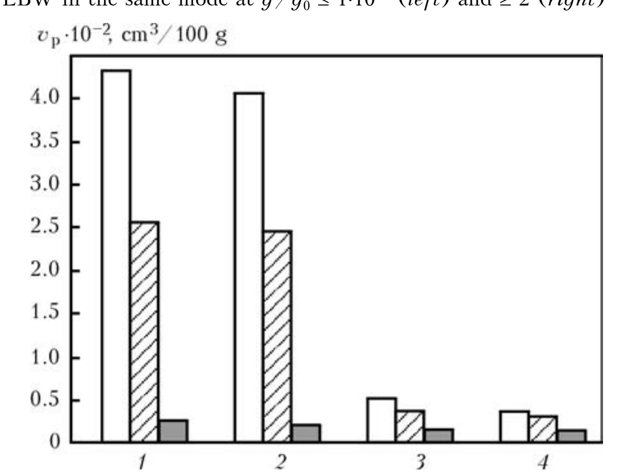

Figure 5. Diagram of susceptibility to porosity, v_p, of welded joints of AMg6 alloy with hydrogen concentration of 0.6 (white bar), 0.4 (hatched) and 0.2 $cm^3/100$ g (gray) at different accelerations: *1* — $g/g_0 \leq 1\cdot10^{-2}$; *2* — 1/6; *3* — 1; *4* — ≥ 2

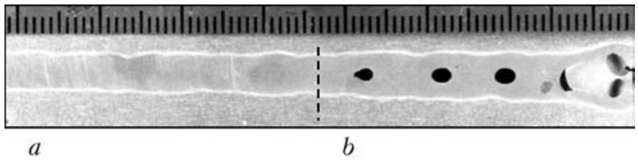

Figure 6. Surface longitudinal section on a joint of AMg6 alloy with hydrogen concentration of 0.4 $cm^3/100$ g made by EBW at $g/g_0 \geq$ ≥ 2 and $\leq 1\cdot10^{-2}$ at acceleration forces (*a*) and zero gravity (*b*)

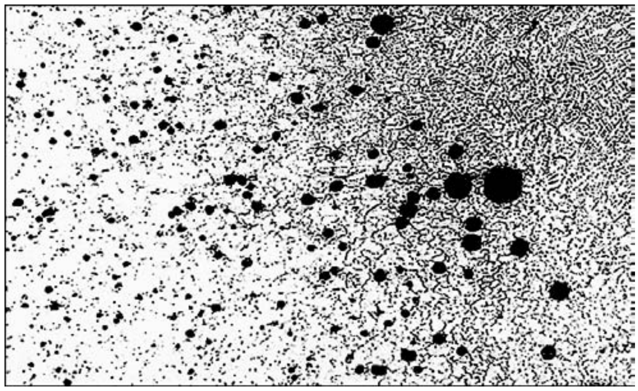

Figure 7. Microstructure (×150) with characteristic porosity in partial melting zone of welded joint of 1201 alloy made by EBW at $g/g_0 \leq 1\cdot10^{-2}$

Welded joints of heat-hardenable alloy 1201 made under the conditions close to zero gravity ($g/g_0 \leq$ $\leq 1\cdot10^{-2}$) feature an increased number of micropores compared to welded joints made on the ground. These

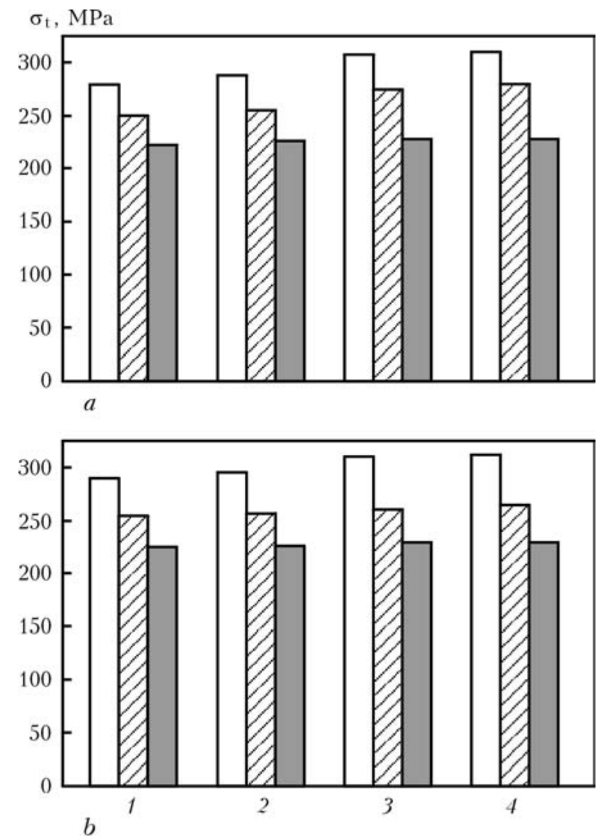

Figure 8. Diagram of ultimate tensile strength σ_t of welded joint of alloys AMg6 (with hydrogen concentration of 0.3 $cm^3/100$ g) (white bar), IMV-2 (hatched) and AMg3 (gray) made at $T = 20$ (*a*) and −196 (*b*) °C depending on gravity level: *1* — $g/g_0 \leq$ $\leq 1\cdot10^{-2}$; *2* — 1/6; *3* — 1; *4* — ≥ 2

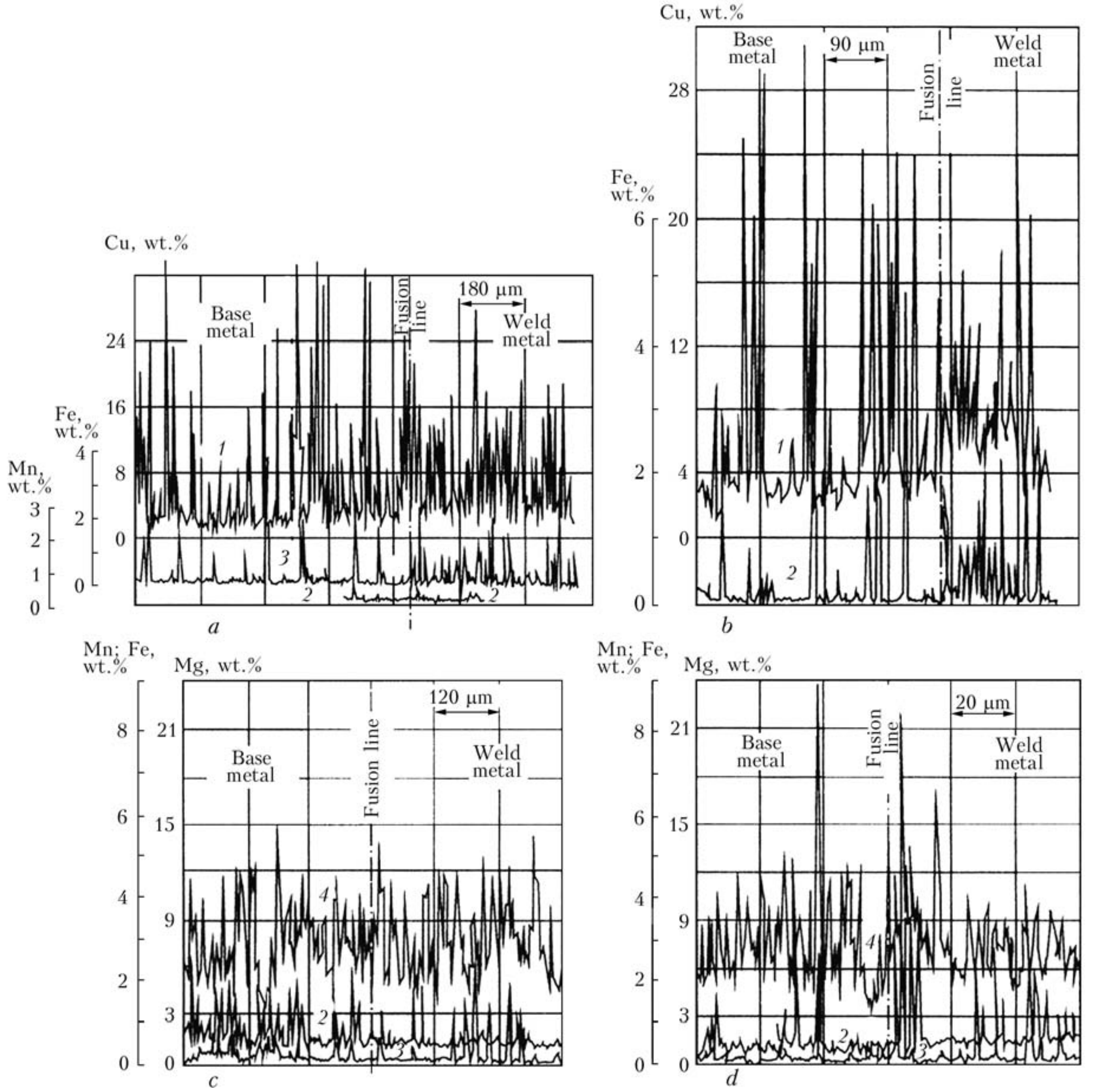

Figure 9. Distribution of alloying and impurity elements in welded joints of alloys 1201 (*a*, *b*) and AMg6 (*c*, *d*) made by EBW on the ground (*a*, *c*) and at zero gravity (*b*, *d*): *1* — copper; *2* — manganese; *3* — iron, *4* — magnesium

micropores are located predominantly in the partial melting section (Figure 7).

It is determined that the density of metal of welded joints made on the studied materials does not depend on temperature conditions of welding. Comparing strength values of welded joints of alloys AMg6 (with hydrogen concentration 0.3 $cm^3/100$ g) and IMV-2 made at the temperature of 20 °C and various values of g/g_0 (Figure 8, *a*), a tendency to lowering of strength at $g/g_0 = 1/6$ and $\leq 1\cdot10^{-2}$ should be noted, while these values remained unchanged for AMg3 alloy. In welding under the conditions of low temperature and different g/g_0 values (Figure 8, *b*) a regularity of strength rise with increase of gravity level is also observed. Here, similar strength values are preserved.

Testing for ultimate tensile strength of base metal of heat-hardenable alloy 1201 was performed in as-delivered condition (without heat treatment). Welded joints were tested with heat treatment (T = 180 °C for 12 h) and without it. Values of ultimate tensile strength of 1201 alloy joints are given in Table 3.

Analysis of the results of mechanical testing of 1201 alloy shows that welded joints made under the conditions close to zero gravity ($g/g_0 \leq 1\cdot10^{-2}$) are characterized by the lowest strength values (see Table 3). With increase of acceleration the strength of welded joints obtained at the temperature of 20 °C rises from 230 up to 250 MPa, and after artificial ageing — from 240 to 300 MPa. In welding with sample cooling to the temperature of −196 °C strength of joints made at $g/g_0 \leq 1\cdot10^{-2}$ also rises up to 270 MPa, and at $g/g_0 \geq 2$ it rises considerably (up to 320 MPa). Thus, increase of gravity and presence of low temperatures promote an increase of the level of ultimate tensile strength of 1201 alloy joints after welding up to 315 MPa, and as a result of artificial ageing — up to 330 MPa.

Table 3. Tensile strength, MPa, at 20 °C of 1201 alloy joints made under different technological conditions

Treatment temperature, °C	Acceleration g/g_0 applied to weld pool			
	$\leq 1\cdot10^{-2}$	1/6	1	≥ 2
+20	$\frac{237}{243}$	$\frac{228}{261}$	$\frac{245}{292}$	$\frac{248}{301}$
−100	$\frac{259}{264}$	$\frac{254}{281}$	$\frac{269}{297}$	$\frac{303}{308}$
−120	$\frac{271}{273}$	$\frac{279}{289}$	$\frac{282}{291}$	$\frac{307}{312}$
−196	$\frac{266}{275}$	$\frac{291}{296}$	$\frac{310}{328}$	$\frac{314}{329}$

Note. 1. Numerator gives the data for welded joint without heat treatment, denominator — those with artificial ageing. 2. Tensile strength of base metal tested in initial condition (quenching + artificial ageing) is equal to σ_t = 454 MPa. 3. Sections without any defects visible at X-ray inspection were selected for testing. 4. Presented data were obtained by averaging the results of five tests.

When studying the weldability of the above alloys by X-ray microprobe structural analysis (SX-50 microanalyzer of Cameca) the influence of the above factors on alloying element evaporation was investigated (Figure 9). Composition of metal of the studied welds made with different technological variants of welding is practically independent on sample temperature and pressure in the chamber and is close to that of base metal. Having analyzed the nature of alloying element distribution in joints of AMg6 alloy made on the ground, it can be noted that the maximum content of magnesium in the base metal and weld metal is equal to about 15 wt.%, and at $g/g_0 \leq 1\cdot10^{-2}$ it is above 21 wt.% in the base metal and more than 15 wt.% in the weld metal. In joints of 1201 alloy made on the ground an abrupt increase of copper content (above 28 wt.%) is found both in the base metal, and in the weld metal. A similar increase of copper content occurs also in the welded joint of 1201 alloy made at $g/g_0 \leq 1\cdot10^{-2}$. It demonstrates a tendency to increase of copper content in the weld metal by 1.5–2.0 wt.% compared to base metal.

CONCLUSIONS

1. It is established that the adverse influence of zero gravity and accelerative forces on formation of aluminium and magnesium alloy welded joints is not manifested. No ejection of liquid metal from the weld pool was recorded, either.

2. Aluminium alloys AD0, AMg6 and magnesium alloy IMV-2 are readily weldable by EBW under the conditions of low gravity forces and low temperature (down to −196 °C), when concentration of hydrogen dissolved in the base metal does not exceed 0.2 $cm^3/100$ g. Conditions close to zero gravity promote an increase of porosity in the metal of welds made on aluminium alloys with hydrogen concentration of 0.3 $cm^3/100$ g and higher.

3. Increase of values of ultimate tensile strength of welded joints of alloys AMg6, AMg3, AD0 and 1201 by 10–15 % is promoted by increased gravity conditions and low temperature −(100–196) °C.

4. Artificial ageing of welded joints of 1201 alloy made at 20 °C and low temperature at all the accelerations applied to the weld pool, further increases the value of ultimate tensile strength of the joints by 10–15 %.

1. Nikolaev, G.A., Fridlyander, I.N., Arbuzov, Yu.P. (1990) *Weldable aluminium alloys*. Moscow: Metallurgiya.
2. Rabkin, D.M. (1986) *Metallurgy of fusion welding of aluminium and its alloys*. Kiev: Naukova Dumka.
3. Drits, M.E., Sviderskaya, Z.A., Elkin, F.M. (1972) *Superlight structural alloys*. Moscow: Nauka.
4. Osokina, T.N., Karan, A.B., Yakushin, B.F. (1978) Welding of magnesium alloys with lithium. *Avtomatich. Svarka*, **1**, 48–50.
5. Paton, B.E., Lapchinsky, V.F. (1998) *Welding and related technologies in space*. Kiev: Naukova Dumka.
6. Paton, B.E., Dudko, D.A., Lapchinsky, V.F. (1985) *Prospects for applied problems of space technology of metals*. Kiev: Naukova Dumka.
7. Suezava, E. (1989) Space stations and colonies. Welding in space. *Tekhnika Sborki i Soedineniya*, **9**, 66–75.
8. (1974) *Technology of fusion electric welding of metals and alloys*. Ed. by B.E. Paton. Moscow: Mashinostroenie.
9. Nikiforov, G.D. (1972) *Metallurgy of fusion welding of aluminium alloys*. Moscow: Mashinostroenie.
10. Soete, W. (1971) De problematiek van de lasfouten en de moelijkheden van de breukmechanica. *Rev. Soudure*, 27(**3**), 198–203.
11. Ishii, Yu., Iida, K. (1969) Low and intermediate cycle fatigue strength of butt welds containing weld defects. *J. NDI*, 18(**10**), 443–476.
12. (2000) *Space: technologies, materials, strucrures*. Ed. by B.E. Paton. Kiev: PWI.
13. Belyakov, I.T., Borisov, Yu.D. (1974) *Technology in space*. Moscow: Mashinostroenie.
14. Ganiev, R.F., Lapchinsky, V.F. (1978) *Problems of mechanics in space technology*. Moscow: Mashinostroenie.
15. (1989) *Space materials science*. Ed. by V.S. Avduevsky. Moscow: Mir.