CAPACITOR-DISCHARGE STUD WELDING IN VACUUM

B.E. PATON, D.M. KALEKO, A.R. BULATSEV and **V.F. SHULYM**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Given are the results of investigations into capacitor-discharge welding of studs of aluminium-magnesium alloy AMg3 and stainless steel 10Kh18N9T under conditions of medium and high vacuum. It is shown that a high-current short-time pulsed discharge, at which the major part of evaporated metal remains in the gap between the mating surfaces, can be used for vacuum butt welding of compact-section parts to a sheet material. It is experimentally proved that up to M6 diameter studs can be welded at pressure of 1.33 Pa with a static tensile strength value of the joints being equal to that of the stud material.

Keywords: *capacitor-discharge welding in vacuum, arc discharge, stud welding, aluminium alloy, stainless steel, volt-ampere characteristics, macrostructure, mechanical properties*

Futurological research conducted by many scientists unambiguously shows that survival of the mankind at an accelerated consumption of different kinds of earth resources is possible only on a condition of exit into outer space. Minerals have already been found on the Moon with the help of space vehicles. Moreover, the absence there of atmospheric screening of solar radiation makes it possible to use the inexhaustible (within the historical time limits) energy of the Sun to meet the human demands which grow in geometric progression.

Discussions have been resumed in recent years on the expediency of construction of research laboratories on the Moon and planets of the solar systems. In 2004, the President of the United States presented a new space program, in which much consideration was given to exploration of interplanetary space. According to the Administration plans, American astronauts should create a station on the surface of the Earth satellite for «sustainable course of long-term exploration».

Therefore, it is timely to state [1] that «space vehicles and stations, as well as infrastructure of lunar outposts designed for long-term operation in space, should be fitted with welding hardware systems, allowing performance of mounting and repair operations in construction and operation of facilities, and the vehicle and mission crews should master the basic welding technologies and should have practical skills of performance of the above operations».

The E.O. Paton Electric Welding Institute of the NAS of Ukraine has accumulated a wide experience [2] in welding of metals under vacuum and zero gravity conditions. Also, the Institute initiated experiments on welding of metals in outer space using the hardware and technology it had developed. As established in the course of work on a sheet material [3], compared to electron beam welding all the rest of the welding methods have drawbacks that hamper their use in space.

However, conditions of mounting operations on space facilities and their repair in space require wider ranges of the parts welded by using fastening elements, among which the most extensively used ones are studs of different types and designs.

All the above-said determine interest in verification of the possibility of providing an arc discharge of a millisecond time range in vacuum, as welding of studs with the arc burning at a discharge of capacitors takes place exactly in this time interval.

The authors are aware of only one study [4] on welding of studs under conditions simulating the space environment. The experiments were carried out with M5 diameter studs of aluminium alloys Al5000 (Al–Mg) and Al2319 (Al–Cu), as well as of stainless steel SUS 305 (12Kh18N12). Vacuum conditions were limited by capabilities of the laboratory equipment, i.e. to 10^{-4} torr (13.3 Pa). Substantial differences between welding in low and high (10^{-5} torr) vacuum are shown below. Therefore, the previous experience does not allow reliably estimating the possibility of using capacitor-discharge stud welding in outer space. Moreover, study [4] gives no electrical characteristics of the process or numerical indicators of strength, nor does it describe metallographic examinations of welded specimens.

In our experiments we used unit K747MV developed by the E.O. Paton Electric Welding Institute as an energy source [5]. Instead of a conventional welding gun we employed a welding head mounted on a rack. The head was placed inside a vacuum chamber and was controlled by using a remote control panel, and it performed the same operations as the welding gun.

The experiments were carried out with M4 and M6 diameter studs of the RT type, made from AMg3 and 10Kh18N9T in compliance with ISO 13918 (Figure 1). The choice of the materials corresponded to the space application conditions [6]. According to the standard, sizes of a stud do not depend on the material used to make it. The M4 and M6 diameter studs had the following sizes: l_{stud} = 20 mm, $h_{shoulder}$ = 1.2 mm, $d_{shoulder}$ = 5.5 and 7.5 mm (for M6), d_{boss} = 0.65 (for

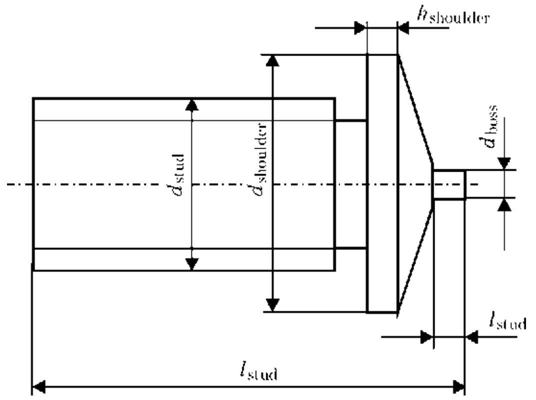


Figure 1. Design sizes of stud RT for capacitor-discharge welding

Parameters of welding of alloy AMg3 and steel 10Kh18N9T

Material	Stud diameter	Charging voltage, V	Length of initial gap, mm	Compression force, N
AMg3	M4	100	2.5	104.6
	M6	180	3.0	104.3
10Kh18N9T	M4	120	2.2	104.9
	M6	140	2.0	105.0

Note. Capacitance of capacitor bank was 96 mF in all experiments.

M4) and 0.75 mm (for M6), and l_{boss} = 0.55 (for M4) and 0.80 mm (for M6).

Welding in forevacuum (10^{-2} torr) and in high vacuum was performed at the parameters providing a strong joint under atmospheric conditions. According to ISO 14555:2006, the joint is considered strong when it withstands bending of a stud to 60°. If standard tests confirmed the preservation of strength of the joint, the welding parameters were regarded as satisfactory, the process was subjected to oscillography (Textronic TDS2000B), and photoregistration of the bend test results was carried out.

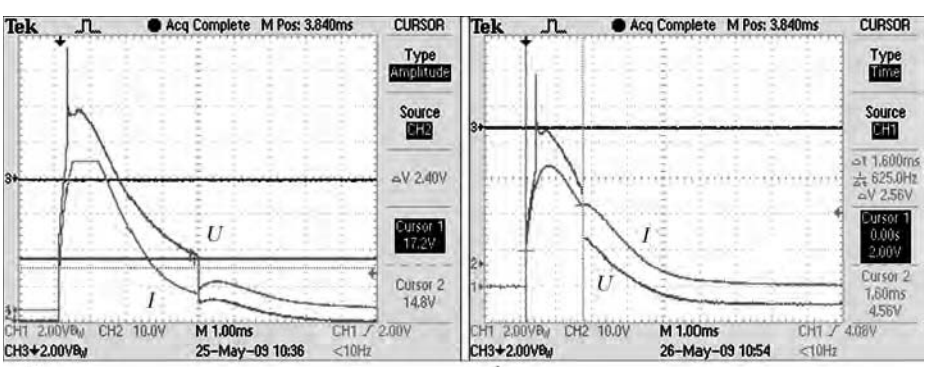
Two main methods for capacitor-discharge stud welding are available: with preliminary gap and with preliminary contact [7]. Both methods can be used for welding of stainless steel, but aluminium alloys can be well welded only with the preliminary gap. However, even the first experiments in the vacuum chamber showed that the method with the preliminary contact even in forevacuum failed to provide the consistently strong joints on the M4 studs made from steel 10Kh18N9T. Analysis of oscillograms (Figure 2) indicated that in welding with the preliminary contact the time of the arc discharge phase was more than twice as long as burning of the arc in welding with the preliminary gap. Moreover, the discharge current with the first method was also higher than with the second method. As a result, metal intensively evaporated from the welding zone in welding with the preliminary contact, and the remaining amount of metal was insufficient to provide a strong joint. Undercuts along the perimeter of the joint also indicated to this character of the process.

Proceeding from this fact, all further experiments were carried out by the method of capacitor-discharge stud welding with the preliminary gap.

Parameters of welding of the investigated joints are given in the Table. They were kept constant for welding under atmospheric and low pressures in order to further compare characteristics of the arc and welded joints.

In welding of the aluminium alloy studs the values of current (Figure 3) and voltage (Figure 4) hardly depend on the air pressure. In welding of the steel studs in high vacuum there is an increase in the «incubation» time between the initial contact of the pieces welded and «explosion» of a thin boss made at the stud end and designed for ignition of the arc (the time moment of the «explosion» is marked by a decrease of the current). As the capacitor-discharge loop is closed even at a slight touch of the mating surfaces, the initial contact causes explosion of the microrelief and excitation of the arc between the tip of a thin boss and surface of a sheet which the stud should be welded to. The presence of the arc is evidenced by increase in voltage above 10 V, this being characteristic of the arc discharge.

Then the thin boss is heated by two sources, i.e. by the arc at the tip and by the flowing current. Dispersion of the initial microarc vapours in vacuum leads to decrease in the effective power of the arc. As



a *b*

Figure 2. Oscillograms of current and arc voltage at discharge of capacitors in low (10^{-2} torr) vacuum in welding of M4 diameter studs of steel 10Kh18N9T with preliminary contact (*a*) and preliminary gap (*b*) (capacitor charging voltage — 120 V, capacitance — 96 mF)

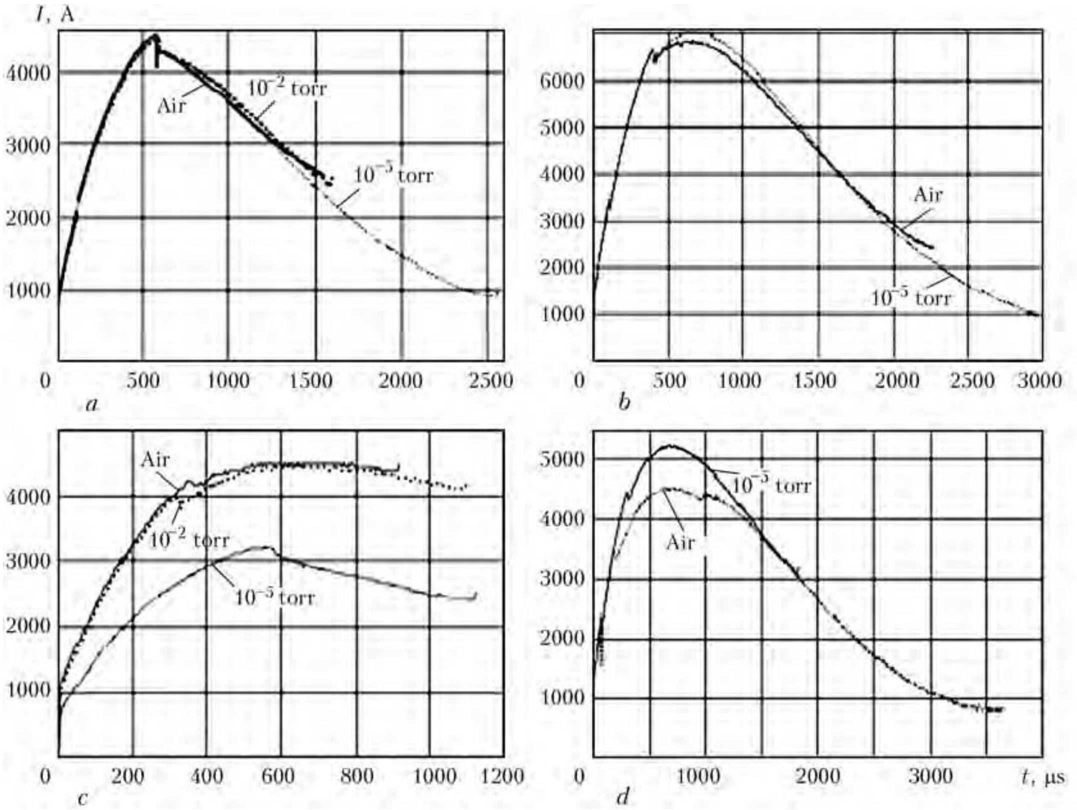


Figure 3. Current in capacitor-discharge stud welding under different air pressures: *a*, *b* — alloy AMg3; *c*, *d* — steel 10Kh18N9T; *a*, *c* — M4; *b*, *d* — M6

proved by the calculations based on the oscillography data, despite extension of the «incubation» time in welding in vacuum compared to welding under atmospheric pressure (M4 stud — 588 and 366 μs, respectively), the energies released on the pieces welded become approximately identical by the moment when the discharge transforms from the microarc to arc one (49.2 and 50.9 J, respectively).

In welding of the M6 diameter stud, because of a 1.5 times increase in length of the boss compared to

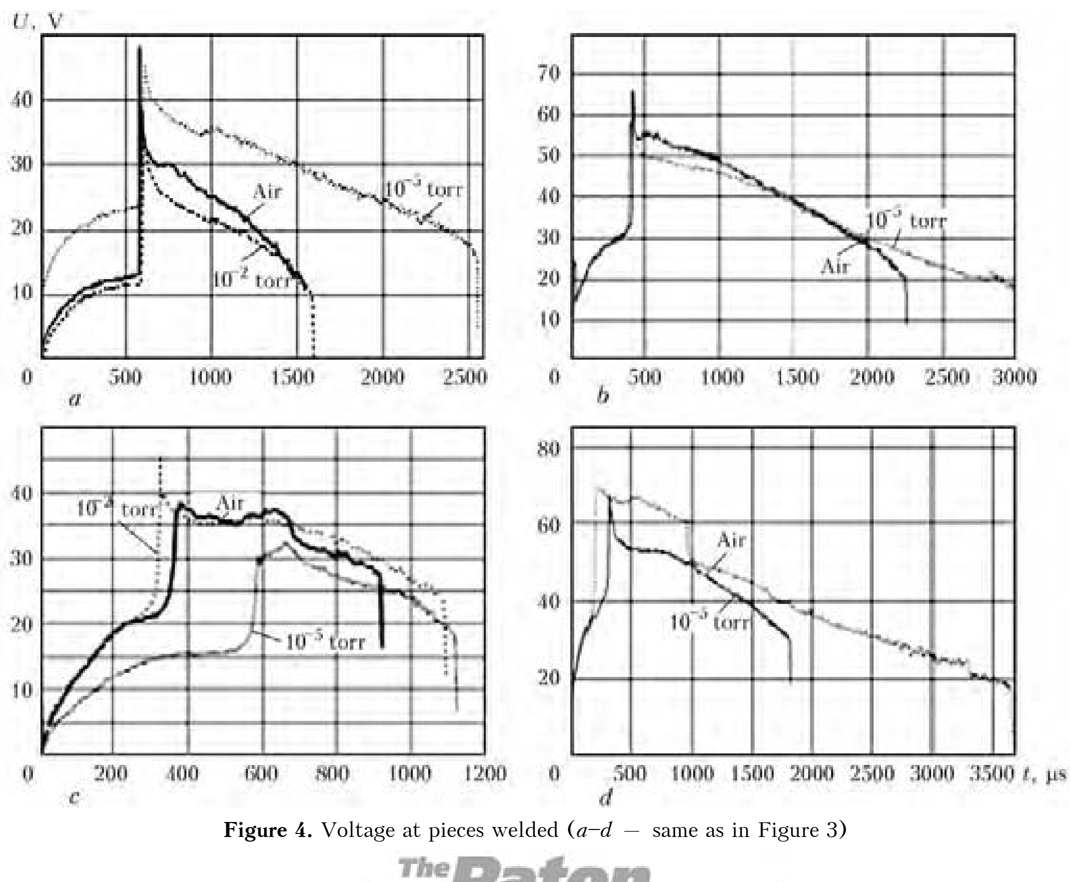


Figure 4. Voltage at pieces welded (*a*–*d* — same as in Figure 3)

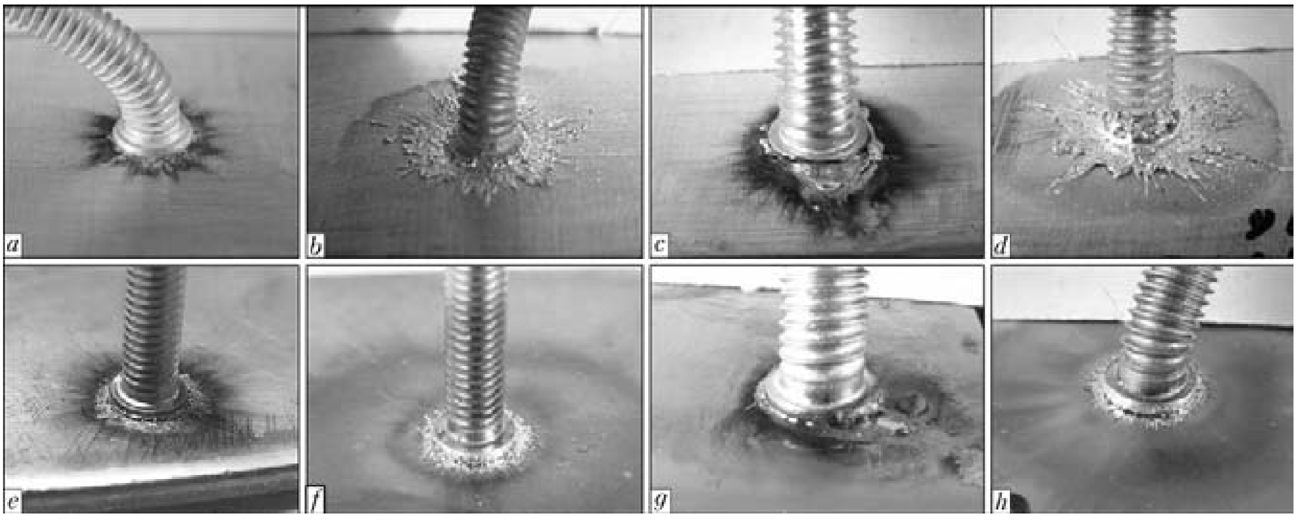


Figure 5. Appearances of the welded joints on M4 (*a*, *b*) and M6 (*c*, *d*) studs of alloy AMg3, and M4 (*e*, *f*) and M6 (*g*, *h*) studs of steel 10Kh18N9T made under atmospheric pressure (*a*, *c*, *e*, *g*) and in vacuum of 10^{-5} torr (*b*, *d*, *f*, *h*)

the M4 diameter stud (see Figure 1), an insignificant increase in diameter causes a substantial growth of the role of the internal source of heating by the flowing current. To add to it, there is a decrease in heat removal from the boss into the bulk of the stud, which leads to shortening of the time of heating of the boss to evaporation, compared to the M4 diameter stud (316 μs in vacuum and 192 μs under atmospheric pressure).

However, the ratios of the «incubation» time in welding of the M4 and M6 diameter studs in air and in vacuum being approximately the same, the energy released during this time on the pieces welded is much lower in welding of the M6 diameter studs in air (15.2 J) than in welding in vacuum (35.3 J), at which decrease in the effective power of the microarc is compensated for by extension of the time during which the current flows through the thin boss.

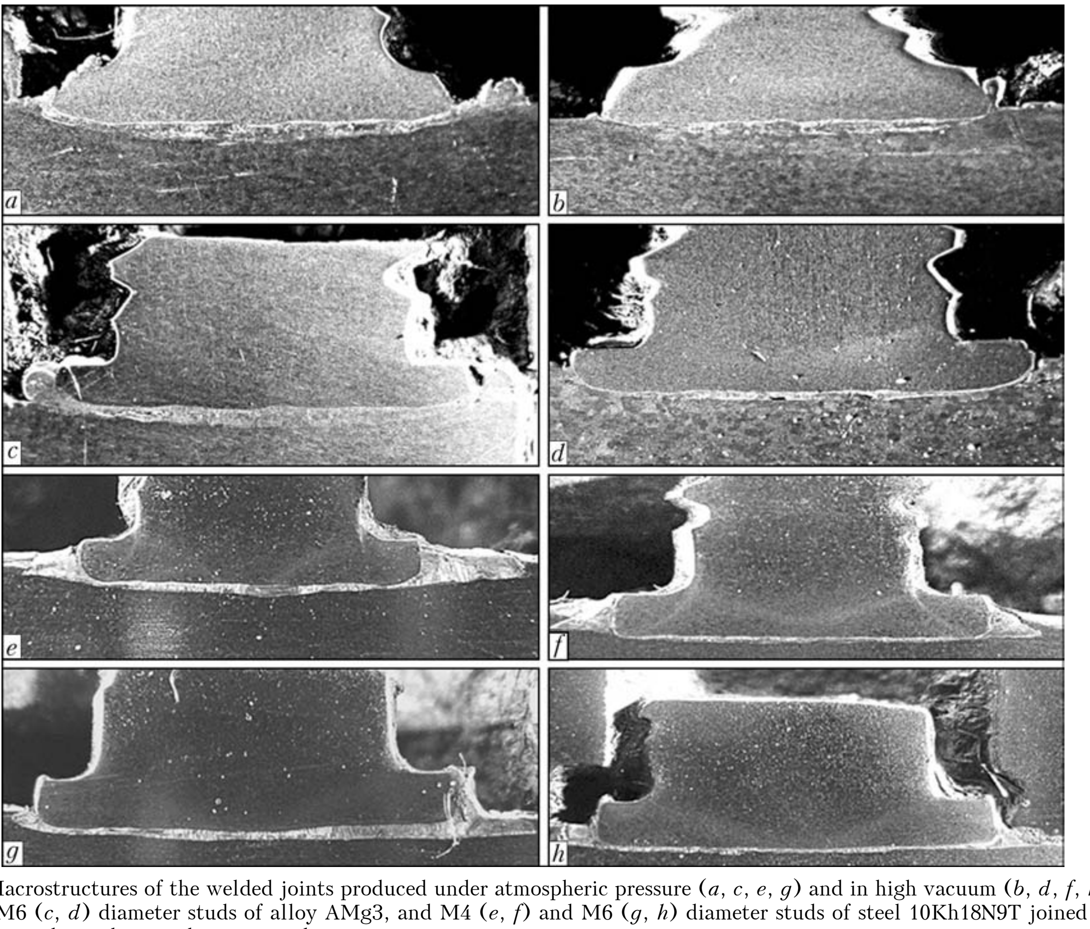


Figure 6. Macrostructures of the welded joints produced under atmospheric pressure (*a*, *c*, *e*, *g*) and in high vacuum (*b*, *d*, *f*, *h*) on M4 (*a*, *b*) and M6 (*c*, *d*) diameter studs of alloy AMg3, and M4 (*e*, *f*) and M6 (*g*, *h*) diameter studs of steel 10Kh18N9T joined to sheets of aluminium and stainless steel, respectively

Resistance of the arc under all the conditions investigated, except for welding of the M6 diameter steel studs, grows with decrease in the air pressure, this corresponding to the classical concepts of the arc discharge burning in gas environment [8]. In welding of the M6 diameter steel studs intensive evaporation of the boss causes a short-time local growth of pressure and dispersion of the vapours at a high initial rate, this leading to a shorter time of arcing determined by the time of levelling of the pressures in the arc gap and of a spring of upsetting of the welding head (when they are equal, the stud is lowered onto the sheet).

In the rest of the variants investigated the duration of the welding process in vacuum is longer than in air. This is related to the fact that evacuation in welding of the aluminium studs causes increase in the arc voltage, which at a constant current leads to intensification of evaporation. Extension of the process duration (Figure 4) in the experiment with the M4 diameter steel studs was caused by a lag of the main arc excitation phase due to a drop of the initial arc current (see Figure 3).

According to ISO 14555:2006, the joints with the studs welded are visually examined to check the absence of undercuts, breaks in the weld beads and other types of discontinuities. All the joints met requirements of the standard. As seen from Figure 5, the main difference between the joints produced under atmospheric pressure and in vacuum lies in increase in the area of splashing of molten metal from the welding zone taking place in vacuum. This can be explained by the fact that the counteraction of metal vapours that damp the impact of a stud onto the molten metal pool on the sheet surface under the effect of the welding head spring decreases under the vacuum conditions. Also, this is evidenced by a halo of the metal vapours in the form of a dense oxide layer on the surface of a joint welded under atmospheric pressure, and in the form of a transparent but large-diameter layer of soot in welding in vacuum.

As noted above, all the joints welded at the optimal parameters withstood bending to an angle of not less than 60°. Static tensile tests of the welded joints showed that they all fractured in the base metal of a stud, far from the joining zone.

It can be seen from photos of the sections (Figure 6) that thickness of the molten metal solidified in the joint decreased with transition from the atmospheric pressure to the high vacuum, despite an increased duration of the discharge, which takes place in the majority of cases, at an almost unchanged current. This confirms the conclusions made from analysis of specimen appearances.

Therefore, the experiments proved the possibility of welding the up to M6 diameter studs from aluminium alloy AMg3 and stainless steel 10Kh18N9T by the capacitor-discharge method in vacuum, the resulting welded joints having strength equal to that of the stud material.

1. Paton, B.E. (2009) 25 years of welding in open space. *The Paton Welding J.*, **7**, 2–6.
2. (2003) *Space: Technology, Materials, Structures*. Ed. by B.E. Paton. London: Taylor & Francis.
3. Shulym, V.F., Lapchinsky, V.F., Demidov, D.L. et al. (2003) Peculiarities and further development of welding in space. In: *Ibid*., 42–49.
4. Masubuchi, K., Imakita, A., Miyake, M. (1988) An initial study of remotely manipulated stud welding for space applications. *Welding J.*, **4**, 25–34.
5. Kaleko, D.M., Kononets, B.I., Oseledko, N.N. et al. (1991) Unit K747MV for capacitor-discharge stud welding. *Svarochn. Proizvodstvo*, **6**, 25–27.
6. Paton, B.E., Kubasov, V.N. (1970) Experiment on welding of metals in space. *Avtomatich. Svarka*, **5**, 7–12.
7. Kaleko, D.M., Lebedev, V.K., Chvertko, N.A. (1999) Processes of welding using the arc discharge of the capacitors. *Welding and Surf. Rev.*, Vol. 13. Amsterdam: Harwood Acad. Publ., 1–148.
8. Kaptsov, N.A. (1950) *Electric phenomena in gases and in vacuum*. Moscow; Leningrad: Gostekhteorizdat.