DEVELOPMENT OF LASER WELDING OF ALUMINIUM ALLOYS AT THE E.O. PATON ELECTRIC WELDING INSTITUTE (Review)

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The works, connected with the development of precision technologies of welding of aluminium alloy structures, allowing minimizing the residual welding deformations, are urgent. They, for example, include the technologies, envisaging the application of a laser welding. The aim of the present article is the review of investigations on welding aluminium and its alloys, applying a laser emission, carried out at the E.O. Paton Electric Welding Institute since the end of the 1960s until now. The stage-by-stage development of these investigations is shown depending on the progress of the laser engineering and growth of level of knowledge of researchers. Three main stages of works on laser welding are distinguished: with application of low-power pulsed lasers (from the end of the 1960s until the end of the 1970s), with application of powerful continuous-wave lasers (from the beginning of the 1980s until the beginning of the 2000s) and with application of hybrid laser-arc and laser-plasma processes (from the beginning of 2000s until now). The offered review illustrates the sufficiently high level of investigations of aluminium alloy welding by applying a laser emission, carried out by the PWI in different years. It is shown that these investigations are continued also at the present time. Their challenges are outlined, including industrial applications of the described methods of welding for manufacture of thin-walled body structures of motor cars, high-speed railway cars, different-purpose ships, aircrafts, rockets and space engineering objects. 16 Ref., 1 Table, 4 Figures.

Keywords: *aluminium alloys, laser emission, hybrid, consumable electrode arc, transferred arc plasma, welding speeds, residual deformations, mechanical properties*

Aluminium and its alloys are widely used in the modern industrial manufacturing. The variety of structures, manufactured of aluminium alloys, required the development of different methods of their welding [1]. Among them a special attention is paid to those, where the laser emission is used. At the E.O. Paton Electric Welding Institute (PWI) the investigations of laser welding of aluminium alloys were carried out since the end of the 1960s. The present paper is devoted to review of these investigations.

At the end of the 1960s–beginning of the 1970s the pulsed solid-body lasers began to be effectively applied for manufacture of products of instrument industry, radio engineering, electrovacuum systems and in other branches of small-object machine building. This promoted the progress of investigations and development of industrial technologies of welding at the PWI, which applied a laser pulsed heating source for heating and braze welding of metallic semi-products.

The technological investigations were headed by O.A. Velichko and V.P. Garashchuk was responsible for the hardware, and the general management of works was realized by V.E. Moravsky. Laser installations of UL-2m, SLS-10 and later Kvant-10 were used in experiments. Due to a comparatively low energies of a pulse (to 10 J) the samples were manufactured mainly of foils of 0.1–0.5 mm thickness. The continuous welds were obtained by overlapping of weld spots, forming per one pulse. The coefficient of overlapping was usually from 50 up to 75 %. Welding was performed in shielding gases, helium was often preferable. The distinguished feature of this stage of works was thorough examination of metallographic peculiarities of joints being produced, and also their effect on mechanical properties of the joints.

The example of these investigations is the work [2], in which the data about mechanical properties of butt joints of dissimilar metals, made by laser welding, were published for the first time. The weldability of commercially pure aluminium with such materials as copper M1, bronze Br.B2, austenite stainless steel 1Kh18N9T and carbon steel 08kp (rimmed) was also investigated. It was found that in all these cases the fracture of welded joint is occurred in weld and is brittle. To join the aluminium with copper M1 the relation of tensile strength σ_t of weld metal to appropriate characteristic of the less stronger metal (σ_t of aluminium) was 40 % at 60° bending angle. To join aluminium with bronze Br.B2 and steel 1Kh18N9T the ratio of tensile strength was

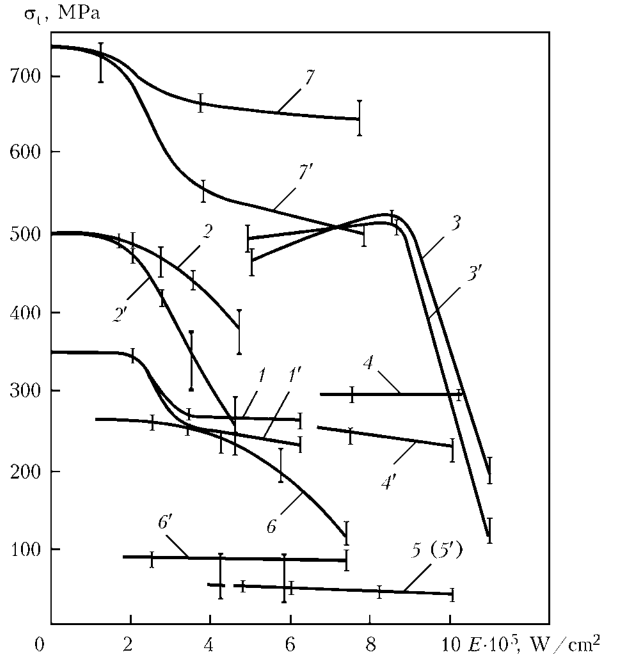


Figure 1. Curves of dependence of weld metal strength on intensity of focused emission, obtained experimentally, in making butt joints [2]: *1* — steel 08kp, δ = 0.3 + 0.3 mm; *2* — titanium, δ = 0.3 + 0.3 mm; *3* — tantalum, δ = 0.3 + + 0.3 mm; *4* — niobium, δ = 0.2 + 0.2 mm; *5* — aluminium, δ = 0.3 + 0.3 mm; *6* — nickel, δ = 0.3 mm, with niobium, δ = 0.2 mm; *7* — niobium, δ = 0.5 + 0.5 mm; *1*–*7* — welding in argon; *1′*–*7′* — welding in air

60 and 10 % at bending angle of 30° and 5°, respectively. For Al–08kp joint it was 66 % at 80°. To increase the mechanical characteristics of dissimilar joints and to improve the weld geometry, such technological procedure of laser welding was suggested in work [2], as shifting of heat spot from butt axis into the side of one of the metals being joined. Thus, the high-quality butt joints were produced with melting only of one of metals, i.e. so-called process of braze welding. Among these joints, the joints of aluminium with tungsten, molybdenum and steel were noted.

Later, the larger attention was paid to the study of technological features of process of a pulsed laser welding of aluminium alloys. Thus, in work [3] the data about laser welding of aluminium were given for the first time. This work considered the problems of initiation of different types of defects connected with change in process conditions: both the defects of joint formation (cavities, pores, undercuts, thinning) and also of metallurgical origin (structural and chemical changes of metal of weld spot and HAZ, cracks). It was found that at the pulsed laser welding in the condition of heat-conductive penetration the mechanical properties of weld spot metal do not almost depend on intensity of emission, and at transition into the condition of a deep penetration the structure and mechanical characteristics of weld spot can be deteriorated with increase in emission intensity. The susceptibility to the formation of cavities, pores, microcracks and other defects is also increased in this case. It was found that aluminium is very low reacted on the change of emission intensity (Figure 1).

At the PWI even at the initial stage of works on laser welding of aluminium D.M. Rabkin showed a great interest to the obtained results. By the end of the 1980s, when the transition to powerful continuous-wave lasers began and the development of technological procedures of laser welding allowed producing long defect-free welds, he highly evaluated this method of welding and predicted its further progress.

Unlike the pulsed laser welding, the laser welding of aluminium alloys by the continuous emission was considered very problematic almost to 1978–1979. At that time the experiments were carried out in installation OB-1617, designed at the PWI under management of V.P. Garashchuk. In welding of alloy AMg6 by emission of this CO_2-laser of 1.4 kW capacity the significant microporosity, oxide films and clusters of products of weld metal interaction with air gases in the form of brittle acicular phases were observed in weld. At weld pool shielding with argon the depth of penetration was decreased to zero [4].

At the end of the 1970s the transition began for powerful CO_2-lasers, generating continuous emission that allowed significant widening of technological capabilities of the laser welding process [5]. For example, at the PWI in 1981 a feasibility of welding of alloy AMg6 (δ = 4 mm) by the continuous-wave laser emission was established in principle [4]. The application of shielding atmosphere of helium at emission power of 5 kW allowed producing at 120 m/h speed the quality keyhole welds, and the microstructure of weld metal by nature and dispersity on alloy AMg6 was identical to weld metal produced in EBW. The attained result was recognized for the first time among the leaders of mastering the laser welding in industrial manufacture of aerospace engineering objects.

The described investigations gave an opportunity to perform nowadays the welding of T-joints of alloy AMg6 by filler wire SvAMg6 (1.2–3.0 mm diameter) in manufacture of stringer panels. In this case, the stiffeners of 5 mm thickness were welded-on to the sheet of 8 mm thickness by double-sided fillet welds using emission of CO_2-laser of up to 5 kW capacity [5]. To prevent residual welding stresses and deformations the preliminary tension of elements being welded was applied at maximum force of up to 750 kN. It was found that optimum power of emission was 3.8–3.9 kW to produce the quality welds under conditions of carried out experiments. It was also determined that the most effective is the uniform preliminary tension of sheet and stiffeners at force, whose value was at the level of residual stresses in weld, which was made without preliminary tension of elements being welded [6].

The carried out technological investigations proved the effectiveness and actuality of application of powerful CO_2-lasers with a continuous emission for welding of aluminium alloys. In this connection the CO_2-laser LT104 with HF-pumping of emission power of up to 10 kW was designed under supervision of V.P. Garashchuk in the PWI at the beginning of the 1990s [7]. The power source of this laser was designed at the Department, headed by V.D. Shelyagin.

The further experiments on welding of aluminium alloys became to be conducted by using this equipment. Thus, at the end of the 1990s the peculiar features of laser welding of aluminium-lithium alloys 1410, 1420, 1460, and also alloys 1201, AMg6 and D16 were investigated [8]. The interest to the welding of high-strength aluminium-lithium alloys was caused by the fact that their application in structures makes it possible to decrease the mass of latter by 10–15 % that is especially important in design of aerospace engineering objects. Investigations, carried out at the PWI by the staff members of Welding of Aluminium Alloys and Laser Welding Departments showed that in laser welding of semi-products of the above-mentioned alloys at 2–5 mm thickness of edges the width of the HAZ is 3–4 times decreased as compared with welding by arc methods and by 10–20 % as compared with EBW [8]. In application of laser welding the smaller changes in chemical composition of weld metal are observed [9, 10].

The most significant achievements in the field of welding of aluminium alloys, applying laser emission, were obtained as a result of combination of laser and arc power sources [11]. Thus, it was shown that increase in arc current leads to the increase in welding speed (Figure 2). Here, the transition from comparatively low currents (about 100 A) to the threshold value of 130–150 A is important, after which a very small increase in current leads to the high increase in welding speed. In the opinion of the authors of work [11] it is connected with a threshold value of absorption of laser emission requiring the reaching of a definite level of power density. At exceeding the threshold value the stable welding of aluminium alloys becomes possible. For emission of CO_2-laser this threshold corresponds to the power close to $3\cdot10^6$ W/cm^2. It is evident that the arc source at currents of above 150 A creates conditions for the better absorption of the laser emission by the weld pool.

Experiments on hybrid laser-arc welding of alloys AMg5, AMg6, 1915 and commercially pure aluminium with the range of thicknesses δ = 2–

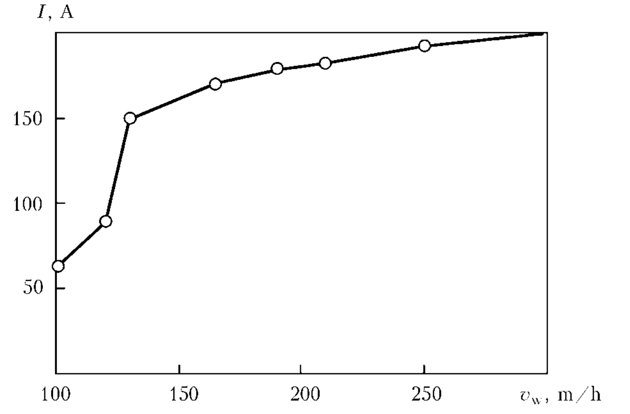


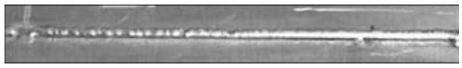
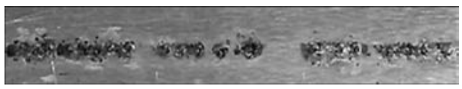
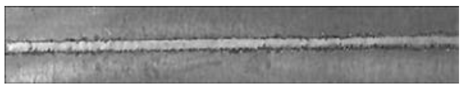
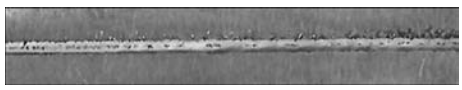
Figure 2. Dependence of speed of hybrid welding of alloy AMg6 2 mm thick on arc current at input of emission power of CO_2-laser of 2.8 kW into metal [10]

6 mm were carried out by using electrode wire SvAMg6 of 1.0–1.2 mm diameter in argon shielding [11]. It was found that the effect of mutual influence of laser and arc heat sources is manifested in the first turn in a possibility of significant (2–4 times) increase in the process speed. The important aspect was also the determination of the fact that in case of hybrid welding 1 kW of arc power is capable to replace from 0.5 to 1.0 kW of laser emission power. Moreover, the quality of produced welds can be close to laser one.

The further investigations in the field of laser-arc welding showed that in comparison with conventional MIG welding the hybrid welding of butt joints of thin-sheet alloy AMg6 (δ = = 1.9 mm) contributes to significant decrease in transverse residual deformations and stresses due to six-fold increase in welding speed (up to 250–300 m/h), 40 % decrease in its energy input and two-fold decrease in weld section [12]. It was found that the values of transverse residual stresses in near-weld zone in hybrid welding do not exceed ±20 MPa, that is 4–5 times lower than stresses formed in MIG welding. Secondary transverse residual stresses from residual bending of the sample are in the ranges of ±40 MPa, that is 2–2.5 times lower of values corresponding to MIG welding. Zone with longitudinal tensile residual stresses is 1.5 times narrowed as compared with MIG welding.

For the case of hybrid welding of aluminium alloys by combining the effect of laser emission with transferred arc plasma the investigations of laser-plasma welding of alloys AMts, AMg3, AMg5m, AMg6 of 0.5–3.0 mm thickness using filler wire SvAMg6 of 1.2 mm diameter and without it were carried out at the PWI. In addition, the emission was used from the Rofin-Sinar diode laser DF020HQ of up to 2 kW capacity with wave lengths of 0.808/0.940 μm and CO_2 laser LT-104 with wave length of 10.6 μm [7] (Table). It was found that the application of hybrid laser-plasma welding of aluminium allows 2–4

Welding conditions, appearance of face part of weld and transverse macrosections of butt and overlap joints of alloy AMg3 1.5 mm thick made by laser, plasma and hybrid welding [12]

Welding conditions		Appearance of weld on face side	Transverse macrosection
P_L, W	I_{SP}/I_{RP}, A		
Welding speed of 108 m/h; diode laser DF020HQ; focused spot diameter of 1.2 mm; focus deepening of 1.0 mm; plasma arc voltage of 20 V			
2000	–		
–	100/50		
1000	50/50		
1500	100/50		
Welding speed of 130 m/h; CO_2-laser LT-104; focused spot diameter of 0.5 mm; focus deepening of 1.0 mm; plasma arc voltage of 20 V			
1500	–		–
–	100/50		
1000	60/50		

times increasing the depth of penetration as compared to laser welding, and almost the same increasing the welding speed as compared with plasma welding [13]. Here, the important factor is the use of phenomenon of cathode cleaning of surface from oxide film. Tensile strength for produced joints was $(0.85–0.90)\sigma_t$ of base metal, that exceeds their properties of similar joints, made by arc methods of welding. Structures of welded joints, made by laser-plasma method, are characterized by a fine dispersity of weld metal and narrow fusion zone as compared to those, made by arc methods of welding, thus approaching them to joints made by a laser method.

Except the experiments on welding, the investigations of laser-arc surfacing of aluminium alloys were carried out [14]. The possibility was found for attaining the quality filling of narrow cavities in aluminium products without their mechanical grooving by fixation of electric arc on the cavity bottom using a focused laser emission. The laser-arc surfacing allowed eliminating such drawbacks typical of arc process as the presence of pores and lack of fusion in the lower part of the cavities being filled, as well as reducing the overheating of samples being surfaced.

It was shown in work [15] that increase in depth of penetration in laser welding is directly proportional to decrease in length of emission wavis Monotonous decrease in depth of penetration with increase in process speed is observed both for laser and also for plasma welding in the range of 18–330 m/h speeds. Comparison of arithmetic sum of depths of penetration for laser and also for plasma processes with depths of penetration, obtained in hybrid laser-plasma process, showed the presence of synergic effect at simultaneous welding into a common pool by laser and plasma components (Figure 3). This effect consists in non-adequate growth of penetration depth and demonstrates the advantage of hybrid welding as compared to welding performed separately by laser and plasma processes.

The investigations of hybrid laser-arc welding of aluminium alloys, where the arc on consumable electrode was used, showed that intensity of evaporation of separate elements of base metal and electrode wire, and also the composition of shielding gas influence greatly the laser emission passing to the metal being welded [16]. Application of arc in argon or at high welding current led to the screening of emission and, consequently, to significant decrease in depth of penetration. To prevent this effect, it occurred to be rational to apply the mixtures of argon with helium or pure helium for the weld pool shielding and also to use the pulsed modulation of laser emission. In this case the hybrid welding in the

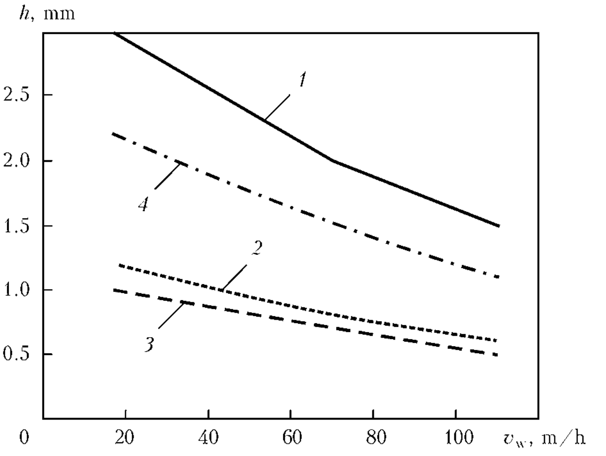


Figure 3. Dependence of penetration depth on speed of welding the aluminium alloy AMg6 (δ = 1–3 mm): *1* — hybrid laser-plasma welding; *2* — laser welding; *3* — plasma welding; *4* — sum of depths of penetrations obtained by laser and plasma welding (P_L = 1.2 kW; I_{SP}/I_{RP} = = 50/50 A; U_a = 18 V)

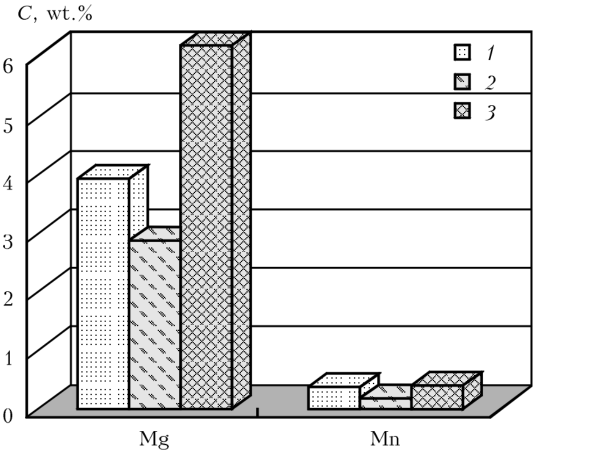


Figure 4. Effect of energy input *E* of laser welding of alloy AMg6 (δ = 1.2 mm) at density of emission power *W* = = $2\cdot10^7$ W/cm^2 on content of alloying elements *C* in weld cast metal: *1* — laser welding, *E* = 50; *2* — laser welding, *E* = 120 J/mm; *3* — base metal

range of 30–60 m/h speeds allowed, as compared with a pulsed-arc consumable electrode welding, 1.8–2.6 times increasing the speed of welding the metal of 6 mm thickness, 1.3–1.6 times decreasing the heat input into metal being welded and reducing significantly the deformations of joints of 4 mm thickness. The investigation of nature of formation of welded joints allowed making conclusion that it is rational to apply the laser emission of more than 4 kW power at hybrid welding of aluminium alloys of 6 mm thickness.

At the present time the investigations of intensities of losses of alloying elements in aluminium alloys at their melting during welding with applying of laser or laser-arc heat sources are carried out. The limits of conditions of laser and hybrid welding are established, at which these losses from evaporation influence negatively the mechanical properties of the joints (Figure 4). It was suggested to eliminate this drawback by control heat input value, including also the application of a pulsed modulation of emission and its scanning, application of hybrid laser-arc processes, gas-dynamic or plasma-chemical processes inside the penetration channel (for example, by development and application of shielding systems with a differential gas supply directly into a vapor-gas channel) as well as processes of weld metal alloying by feeding of filler materials.

The offered review outlines the sufficiently high level of investigations of welding of aluminium alloys using a laser emission at the PWI over the various years. Nowadays these investigations are continued. They include development of the more effective methods of welding for manufacture of thin-walled body structures of motor cars, high-speed railway cars, different-purpose ships, aircrafts, rockets and space engineering objects.

1. Rabkin, D.M. (1986) *Metallurgy of fusion welding of aluminium and its alloys*. Kiev: Naukova Dumka.
2. Velichko, O.A., Garashchuk, V.P., Moravsky, V.E. (1972) Laser welding of butt joints of dissimilar metal. *Avtomatich. Svarka*, **3**, 71–73.
3. Velichko, O.A., Garashchuk, V.P., Moravsky, V.E. (1973) Relation between joint quality and laser welding parameters. *Ibid*., **3**, 24–27.
4. Nazarenko, O.K., Velichko, O.A., Avramchenko, P.F. et al. (1979) *Technological possibilities of welding unit LT1-5*: Information letter. Kiev: PWI.
5. Avramchenko, P.F., Molchan, I.V. (1983) Continuous laser beam welding of AMg6 alloy. *Avtomatich. Svarka*, **3**, 68–69.
6. Velichko, O.A., Avramchenko, P.F., Molchan, I.V. et al. (1987) CO_2-laser welding of T-joints of aluminium-magnesium alloy AMg6. *Ibid*., **6**, 34–37.
7. Garashchuk, V.P., Shelyagin, V.D., Nazarenko, O.K. et al. (1997) Technologicac 10 kW CO_2-laser LT104. *Ibid*., **1**, 36–39.
8. Bondarev, A.A., Boldin, A.A., Shelyagin, V.D. et al. (1998) Peculiarities of laser welding of high strength aluminium-lithium alloys. In: *Abstr. of Int. Conf. on Welding and Related Technologies into 21st Century* (Kiev, Nov. 1998). Kiev: PWI.
9. Bondarev, A.A., Bondarev, Andr.A. (2001) Laser welding of aluminium alloys (Review). *The Paton Welding J*., **12**, 19–25.
10. Bondarev, A.A., Bondarev, Andr.A. (2001) Device for a focusing lens protection from sprays and heating in laser welding. *Ibid*., **12**, 58–60.
11. Shelyagin, V.D., Khaskin, V.Yu., Nabok, T.N. et al. (2005) Hybrid laser-arc welding of carbon steels and aluminium alloys. *Dopovidi NAN Ukrainy*, **7**, 97–102.
12. Shonin, V.A., Mashin, V.S., Khaskin, V.Yu. et al. (2006) Residual stresses in butt joints of thin sheets from alloy AMg6 after arc and laser-arc welding. *The Paton Welding J*., **9**, 20–24.
13. Krivtsun, I.V., Shelyagin, V.D., Khaskin, V.Yu. et al. (2007) Hybrid laser-plasma welding of aluminium alloys. *Ibid*., **5**, 36–40.
14. Khaskin, V.Yu. (2009) Application of laser-arc cladding for filling up narrow cavities in aluminium alloy items. *Ibid*., **2**, 31–34.
15. Krivtsun, I.V., Shelyagin, V.D., Khaskin, V.Yu. et al. (2009) Hybrid laser-plasma and laser-arc welding of various aluminium alloys. In: *Laser technologies in welding and materials processing*. Kiev: PWI, 47–49.
16. Shelyagin, V.D., Khaskin, V.Yu., Mashin, V.S. et al. (2009) Features of laser-MIG welding of high-strength aluminium alloys. *The Paton Welding J*., **12**, 21–27.

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