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FORMATION OF WELDED JOINTS OF MAGNESIUM ALLOYS IN PULSE MULTIPASS ELECTRON BEAM WELDING

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The work studies the peculiarities of formation of the joints of cast magnesium alloy ML10 of 8 mm thickness in pulse vacuum electron beam welding. The investigations were carried out on specimens of alloy of Mg–Zn-Zr–Nd doping system at optimum pulse repetition frequency and increased welding rate. It is determined that welding in several passes with step increase of electron beam current in the pulse is necessary for providing high quality of formation and strength properties of welded joints. It is shown that strength characteristics of welded joints are at the level not lower than 92 % of similar base metal properties. 11 Ref., 1 Table, 5 Figures.

Keywords: *electron beam welding, magnesium alloys, pulse welding mode, welded joint strength, thermal cycle, weld metal microstructure, HAZ, base metal*

In comparison with known methods of fusion welding, pulse electron beam welding (PEBW) is characterized with high specific energy concentration, low values of heat input, small width of heat-affected zone (HAZ), narrow penetration zone and insignificant deformations of parts being welded [1–4].

PEBW can be easily mechanized and automated, and movement of electron beam employing a deflecting system of electron beam gun on a set trajectory (circle, ellipse, arc, dash, triangle, rectangle etc.) significantly expands capabilities of this process. Keeping the set specific power of the beam and parameters of penetration zone at variation of working distance from electron gun to part surface sets PEBW apart from arc methods of fusion welding, and can promote its wide application in welding of wrought and cast magnesium alloys in critical designation parts.

Investigations of effect of PEBW on formation of welded joints of magnesium alloys were carried out on UL-209M unit with computer control of all parameters and systems, developed at the E.O. Paton Electric Welding Institute of the NAS of Ukraine [5]. UL-209M unit is equipped with power complex based on ELA-60/60 and electron beam gun, which is moved inside the vacuum chamber on linear coordinates X, Y, Z as well as turned about the Y–Y axis through 0–90° angle. At accelerating voltage U_{acc} = 60 kV electron beam gun with metallic tungsten cathode of 3 mm diameter provides current range of electron beam I_{pulse} = = 0–500 mA as well as performance of technological beam scanning in process of electron beam welding. Accuracy of coordinate positioning of the electron beam gun at least 0.1 mm is provided and mating of the electron beam with the joint using RASTR system with at least 0.1 mm accuracy is ensured [6].

Pulse operation mode was realized at connection of pulse generator of HAMEG HM8130 type to the input of power complex ELA-60/60. It provided 100 % modulation of the electron beam on current. Shape and value of welding current pulse was fixed directly before welding of specimens or prototypes of the parts on beam trap (Faraday cup) with the help of electron beam oscillograph TECTRONIX TDS 1002, scheme of connection of which is given in Figure 1.

Works [7] include investigations on formation of welded joints of magnesium alloys of different doping systems by arc welding methods. However, analysis of works on weldability of magnesium alloys showed

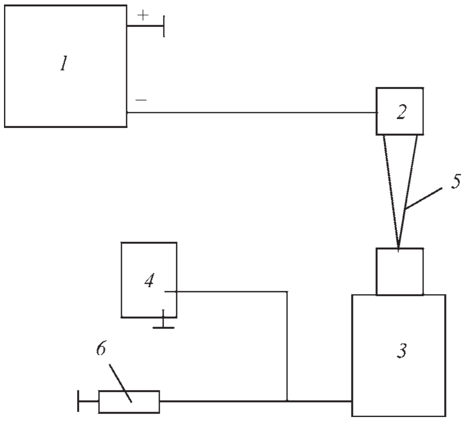

Figure 1. Scheme of registration of parameters of pulse electron beam: *1* — power complex ELA-60/60; *2* — electron beam gun; *3* — massive target of beam trap; *4* — oscillograph; *5* — electron beam; *6* — resistor R = 10 Ohm

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virtually no data on formation of welded joints of magnesium alloys using electron beam in pulse mode.

Earlier carried investigations [7] indicate that cast magnesium alloy of Mg–Zn–Zr–Nd doping system can be satisfactorily welded using arc methods under condition of mandatory preheating of the welded edges from external source to 200–250 °C.

The main problem in welding of magnesium alloys is prevention of hot cracking in welded joints as well as producing the welds without undercuts from face and root part of the weld.

E.O. Paton Electric Welding Institute of the NAS of Ukraine carried the investigations on formation of defect-free joints of cast magnesium alloy ML10 (0.1–0.7 % Zn, 0.4–1.0 % Zr, 2.2–2.8 % Nd, Mg — the rest), made by PEBW and performance in a single technological cycle of additional cleaning of near-weld surfaces with a fine focused low power electron beam, preheating of abutting edges to temperature around 200–250 °C and concurrent heating by the beam in process of multipass welding. Formation of face and root beads of the weld without undercuts and depression is reached through application of local technological scanning of the electron beam on ellipse, at that larger semi-axis is oriented along the welding direction. Alloy ML10 of Mg–Zn–Zr–Nd doping system differs by increased corrosion resistance, good cast properties, small susceptibility to microporosity, can be satisfactorily welded using arc methods, thermally hardened by quenching and artificial aging. The alloy has long operation period at temperatures to 250 °C. Specimens of 150×150×8 mm size were used for adjustment of modes and PEBW procedure using a scheme with vertical electron beam in flat position.

During the investigations the specimens were welded without filler materials, and assembly of specimens for welding was carried out with the minimum possible gaps. Preparation of welded edges for welding was performed by means of degreasing with organic solvents and scrapping to 0.1 mm depth directly before specimen loading in a unit vacuum chamber. Cleaning and preheating of the surfaces with the fine focused electron beam having circular or sawtool scanning was performed after specimen loading in the vacuum chamber and reaching working vacuum.

In PEBW significant effect on welded joint quality together with time parameters of the electron beam (duration of pulse and duration of pause) has a welding rate, choice of which determines the level of overlapping of separate penetration areas. In other words, known diameter of the electron beam on the part and amplitude of its local scanning makes its pass in the pause between the pulses a decisive factor for formation of quality welded joint. Expression for welding rate at seam PEBW can be written as:

$$V_{\text{PEBW}} = \frac{(1-K)\, f_{\text{pulse}} S (A_{\text{loc}} + d_{\text{b}})}{S-1},$$

where K is the coefficient of overlapping of welding spots; f_{pulse} is the pulse frequency, Hz; $S = \tau_{\text{pulse}} + \tau_{\text{pause}}/\tau_{\text{pulse}}$ is the relative pulse duration; τ_{pause} is the pause duration; τ_{pulse} is the pulse duration; d_{b} is the diameter of electron beam on the part, mm; A_{loc} is the amplitude of local scanning of electron beam (for example, if you choose $K = 0.8$; $\tau_{\text{pulse}} = 5$ ms, $\tau_{\text{pause}} = 5$ ms; $f_{\text{pulse}} = 100$ Hz; $d_{\text{b}} = 0.5$ mm; $A_{\text{loc}} = 1$ mm, $V_{\text{PEBW}} = 60$ mm/s is gotten).

It is known fact that pre- and concurrent heating of the part reduce possibility of appearance of solidification cracks, since this decreases intensity of growth of elasto-plastic deformations in weld metal solidification. Reduction of difference between the maximum temperature in welding and initial part temperature provokes decrease of cooling rate at different areas of welded joint, improve their structure and increase elasticity. In heating to 200–250 °C drop of tensile longitudinal stresses can reach 50 % [8].

Investigations using modulated electron beam and its local oscillations on different trajectories and with different amplitudes were carried out for solving a quality problem in welded joints of magnesium alloys of up to $\delta_{\text{m}} = 15$ mm thickness, changing shape of weld penetration and its solidification during welding through forced variation of parameters of oscillation of liquid metal in a vapor-gas channel. A range of frequency of electron beam current pulses on the part $f_{\text{pulse}} = 20$–250 Hz at relative duration of modulation of current beam $S = 1.2$–5.0 was studied. It is determined that beam modulation frequency $f_{\text{pulse}} = 70$–120 Hz eliminates weld expansion in the root part, namely the place of appearance of the formation defects, and improves weld shape, i.e. side penetration walls become virtually parallel. The most favorable penetration shape was received at modulation frequency $f_{\text{pulse}} = 100$–120 Hz. Decrease of modulation frequency below $f_{\text{pulse}} = 60$ Hz results in increase of penetration depth, however, shape of weld approaches to shape of the welds made without beam modulation.

In our case PEBW of magnesium alloy ML10 of $\delta_{\text{m}} = 8$ mm thickness was carried out in several passes by step-by-step rise of beam current in the pulse and preheating during cleaning of near-weld zone using the fine focused electron beam. In parallel welding thermal cycle was measured with the help of thermal couple of K type (chromel-alumel, GOST 6615–94) of 0.5 mm diameter, caulked at 2 mm distance from weld axis. Figure 2 shows that preheating temperature of specimen during cleaning using electron beam in

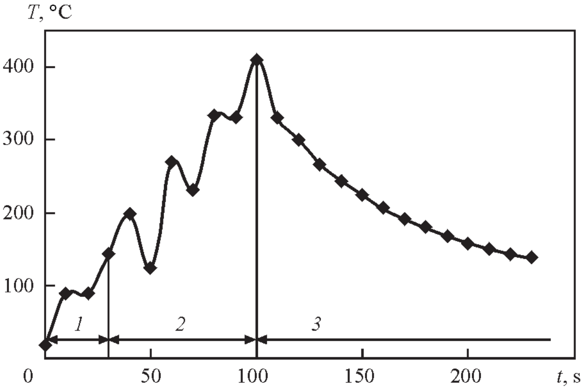

Figure 2. Thermal cycle of near-weld zone in PEBW of specimen of magnesium alloy ML10 of 150×50×8 mm size: *1* — cleaning using fine focused electron beam in two passes; *2* — welding in four passes with step-by-step increase of beam current in pulse; *3* — cooling after welding

two passes (U_{acc} = 60 kV, I_b = 10 mA, V_f = 10 mm/s, ΔI_f = 0 mA, A_{circ} = 10 mm, l_{work} = 200 мм) made approximately 140 °C and can be regulated by variation of beam power and number of passes. A mode of pulse welding in four passes with concurrent preheating made:

the first pass: U_{acc} = 60 kV, I_{pulse} = 15 mA; v_w = 10 mm/s, ΔI_f = 0 mA, $A_{ellipse}$ = 1.5/0.5, l_{work} = = 200 mm, τ_{pulse} = 5 ms, τ_{pause} = 5 ms, f_{pulse} = 100 Hz. The larger semi-axis of ellipse is oriented along the welding direction, the second pass: I_{pulse} = 25; the third — 35 and the fourth — 45 mA. Other parameters in the second, third and fourth passes are preserved.

Detection of structure of welded joints on cast magnesium alloy ML10 was performed using chemical etching in 10 % solution of citric acid. The examinations were carried out on optical microscope Neophot-32, hardness was measured on hardness gage M-400 of LECO Company, digital image of structures was taken with the help of Olympus camera. The welded joint of magnesium alloy ML10 of δ_m = 8 mm thickness (Figure 3) was made in a mode of multipass PEBW using the flat position scheme by vertical electron beam on substrate of the same material. It can be seen on its macrosection that weld side walls are virtually parallel in all penetration depth, no expansion is present in the root part, undercuts and depression on the weld face are absent as well as cracks.

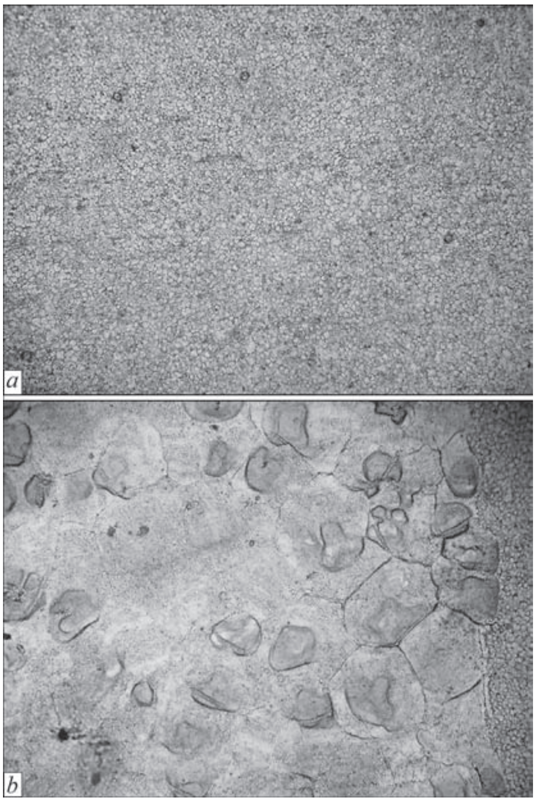

Figure 4. Microstructure (×200) of welded joint of magnesium alloy ML10, made in PEBW mode: *a* — weld seam; *b* — weld, HAZ, base metal

Structure of weld metal on ML10 alloy is fine disperse (cell size 10–12 μm) at all weld height (Figure 4, *a*) and consists of α-solid solution with located along the boundaries grains of eutectic and intermetallic phase $(MgZr)_{12}Nd$. Weld metal hardness makes *HV*0.5-394–490 MPa, that agrees with the results of investigations, given in work [9].

A fusion line with the base metal is virtually equal and well expressed. In some places, coarse HAZ grains displace the fusion line into the weld metal

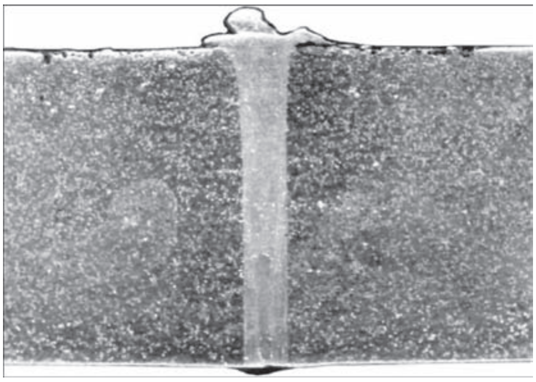

Figure 3. Macrostructure (×10) of welded joint of magnesium alloy ML10 of δ_m = 8 mm thickness

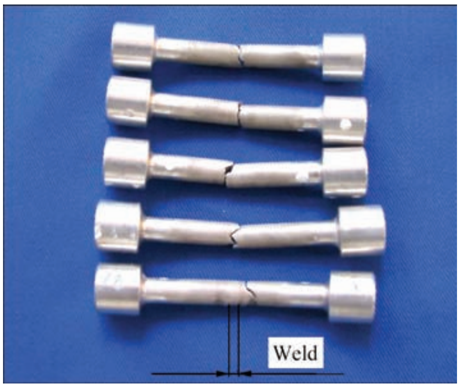

Figure 5. Specimens after mechanical breaking tests of welded joints of ML10 magnesium alloy

Mechanical properties of cast magnesium alloy ML10 after pulse EBW

Object for examination	Mechanical properties						Fracture place
	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	ψ, %	$\sigma_{t\,w}/\sigma_{t\,BM}$	$a_н$, kJ/m^2	
Base metal	220	140	5.0	11	–	62.7	–
Welded joint	202	135	6.5	12	0.92	82.0	Along fusion line, HAZ

(Figure 4, *b*). HAZ metal structure is coarse grain, eutectics is uniformly located, metal hardness makes *HV*0.5-409–539 MPa.

Base metal structure is the same as in HAZ metal. It differs by coarser grain size (70–80 μm) and number of spherical eutectic formations (Figure 4, *b*).

The mechanical tests were used for quality control of welded joints of magnesium alloy ML10. In addition to σ_t value, other parameters of welded joint strength, namely $\sigma_{0.2}$, δ and Y were determined as a result of breaking tests.

Specimens of the base metal ML10 in as-delivered condition and of welded joints produced by PEBW method were manufactured for performance of strength tests. Breaking tests of welded joints were carried out on cylinder specimens of gauge length diameter $d_s = 3$ mm.

It follows from Figure 5 that breaking of the specimens of magnesium alloy ML10 after PEBW takes place mainly on fusion line and HAZ. Ductility of welded joints ψ rises insignificantly in comparison with the base metal ductility and toughness $a_н$ increases approximately per 30 %. Coefficient of strength of the welded joints, produced in PEBW mode with preheating in cleaning with the fine focused electron beam and further welding in four passes by means of step-by-step enlargement of beam current in pulse, reaches the value $\sigma_{t\,w}/\sigma_{t\,bm} = 0.92$ % (Table).

Analysis of microstructure in different zones of welded joint of magnesium alloy ML10 shows that the weld metal structure in PEBW virtually does not differ from that which occurs for alloys in as-cast condition. Lower value of grain and thickness of intercrystalline layers in comparison with the weld structure, which occurs in arc methods of welding [10, 11], are observed taking into account high solidification rates in PEBW.

Conclusions

1. It is determined that high quality of formation and strength properties of welded joints of magnesium alloy ML10 is reached by application of multipass pulse EBW with step-by-step rise of beam current in each pass.

2. It is determined that the side penetration walls become virtually parallel in PEBW with application of local beam scanning on ellipse.

3. It is shown that strength characteristics of welded joints of cast magnesium alloy ML10 are at the level not lower that 92 % of the same base metal properties.

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