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FORMATION OF DIFFUSION ZONE IN WELDED JOINTS OF POROUS ALUMINIUM ALLOY WITH MONOLITHIC MAGNESIUM ALLOY AT CHEMICAL ACTIVATION BY GALLIUM

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Comprehensive investigation of mechanical and physical properties of diffusion zone of the produced joints was performed as part of fulfillment of the technological task, namely producing superlight welded structures from porous aluminium alloys of Al–Mg–Zn system and monolithic magnesium alloys (ML4 standard alloy of Mg–Al–Zn system and experimental alloys of Mg–Ga system). The objective of the study was evaluation of the influence of heating cycle, characteristic for different welding processes, on the joints. Welding was performed by two methods with maximum heating temperature up to 300 °C: diffusion welding with long-term cycle of heating in vacuum, and welding with heating by passing current in air, which is characterized by short heating cycle. Gallium was used for forming a monolithic joint and diffusion activation. It is found that a diffusion zone about 10 μm wide forms on porous aluminium side, with slight lowering of micromechanical properties in pore walls, that is typical for aluminium alloys at contact with gallium. In magnesium alloys, an extended (60–100 μm) wavy intermetallic-strengthened diffusion zone forms along the joint line in both the welding processes, mostly of Mg_5Ga_2 composition with melting temperature of 456 °C that is higher than the welding temperature. Thus, the possibility of joining porous alloys to monolithic ones is shown at their slight heating and chemical activation of the joint zone by gallium. 11 Ref., 1 Table, 8 Figures.

Keywords: *magnesium, porous aluminium, gallium, diffusion welding, welding with heating by passing current*

Application of superlight porous alloys enables fabrication of structures with high specific strength, i.e. rational strength-to-weight ratio. Depending on density and type of porosity, such materials are 50 to 80 % lighter than monolithic ones [1]. Despite the diversity of commercially produced porous metals, their broad application is still difficult for the reason of high cost and complexity of production, but it is quite justified for engineering solutions aimed at creation of housing or multilayer protective elements of aerospace microelectronics, where minimizing the structure mass is a priority [2]. Porous metals are in the top ten of «Materials of the Future» ranking, as are magnesium alloys, the mass of which is by 30 % less than that of the traditionally applied aluminium alloys.

Figure 1. Porous aluminium panels produced by MetalFoam Company with and without monolithic walls

New porous materials based on porous aluminium (PA) of «MetalFoam» Company (Germany) (Figure 1), available for experiment performance, as well as experience of producing welded joints at temperatures of about 300 °C [3–6], developed for manufacturing bimetal blocks for encapsulating microelectronics, allowed us actualizing and carrying on investigations, aimed at creation of superlight multilayer bimetal sandwich panels, using porous and monolithic alloys, in different sequences and combinations.

The objective of the study was producing bimetal joints of sandwich panels of PA with magnesium alloys based on mechano-chemical activation by gallium, limiting welding temperature to 300 °C, and application of two welding processes with different rate and duration of heating. A comprehensive investigation of the features of formation of microstructure, chemical and phase composition, micromechanical properties of diffusion zone in the produced samples was performed for technological evaluation of optimality of application of short or prolonged heating.

Joined pairs of alloys were PA (Al–Mg–Zn system) with standard magnesium alloy ML4 (Mg–Al–Zn system) and PA with experimental doped alloy (Mg–Ga system).

PA contains a large number of gas-filled pores of 1–2 mm diameter with voids making about 80 % of total material volume. At deformation PA demonstrates non-linear behaviour, characteristic for porous structures so that the material has a high shock absorption coefficient (it is capable of adsorbing kinetic energy of the shock). PA is characterized by low hygroscopicity (1–3 %), is non-toxic, heat-resistant, and does not fail at exposure to fuels and lubricants, solvents, ultraviolet and radiation. When exposed to open flame, it gradually softens, if temperature in the heating zone reaches the melting temperature of 650 °C. Microhardness (Mayers) of PA pore walls is equal to 1.5 GPa, and Young's modulus of elasticity is 69 GPa.

Cast magnesium alloy ML4 is applied for manufacture of parts of engines and other units exposed to static and dynamic loads in service. Limit working temperature is 150 at long-term and 250 °C at short-term operation. Melting temperature is 720–750 °C. Mayers microhardness is 1.2 GPa and Young's modulus of elasticity is 43 GPa.

Experimental magnesium alloy of Mg–Ga system (64Mg + 32 Mg_5Ga_2 wt.%) based on standard ML4, alloyed with gallium and modified by fine particles of zirconia (of 20 nm diameter), was produced at induction remelting in argon [7] without subsequent treatment. Melting temperature was 750 °C. The alloy was dispersion strengthened by Mg_5Ga_2 intermetallics and modifiers, so that it has higher values of microhardness (Mayers) of 4–16 GPa, and Young's modulus of elasticity of 129–250 GPa.

Content of the main chemical elements in the joined materials is given in the Table.

Joints of 10 mm PA panels and 6 mm ML4 sheets (Figure 2) were produced by two different processes: diffusion welding for 3 h in vacuum and welding with heating by low-voltage passing current for 2 min in

Content of the main chemical elements of joined materials, wt.%

Material	Al	Mg	Zn	Ca
PA	83.2	6.7	5.9	–
ML4	5–7	88.4–92.9	2.0–3.5	–
ML4 + Ga	5	80	2.5	10

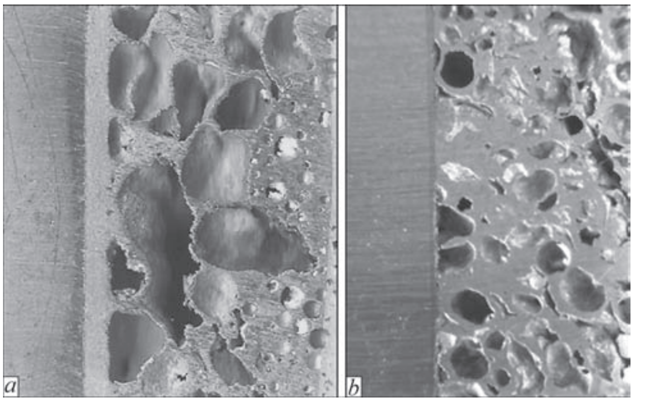

Figure 2. Welded joints of monolithic magnesium alloy ML4 with PA panels: with monolithic walls (*a*) and without them (*b*)

room environment. P-115 unit was used for diffusion welding (Figure 3, *a*) and laboratory unit was applied for welding by passing current (Figure 3, *b*).

Wetting of pre-ground surfaces to be joined by commercial gallium melted at 27.75 °C, was performed to remove oxide films and activate the surfaces being welded.

Microstructural studies of diffusion zone of samples and chemical element distribution were performed in scanning electron microscope JSM-35CF JEOL, fitted with INCA Energy-350 spectrometer of Oxford Instruments (SEM).

Coefficient of diffusion was assessed by simplified formula $D = x^2/T$, where x is the maximum depth of gallium penetration, T is the welding duration.

Gallium diffusion in PA is characterized by a depth range of about 10 μm and absence of a clear-cut zone, its concentration being 5–20 wt.%. Experimental coefficient of diffusion at prolonged heating (at the rate of 5 °C/min) in vacuum is $0.0092 \cdot 10^{-12}$ m^2/s and at short heating (at the rate of 150 °C/min) by passing current it is $0.5555 \cdot 10^{-12}$ m^2/s.

Wavy diffusion front on ML4 side was observed with both the welding processes (Figure 4). At prolonged heating a diffusion zone 85 to 100 μm wide

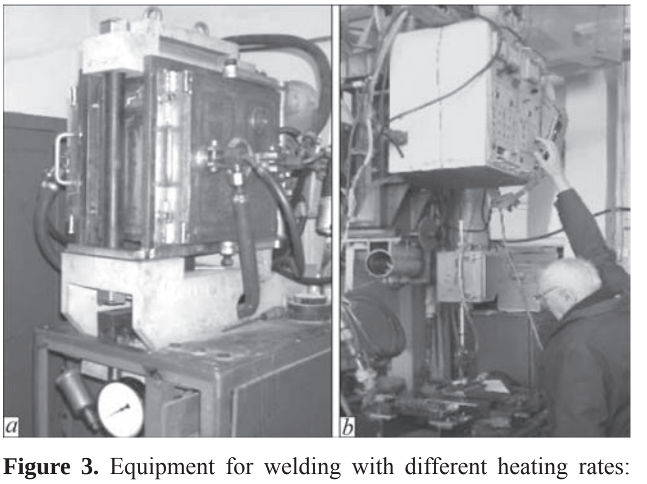

Figure 3. Equipment for welding with different heating rates: *a* — P-115 unit; *b* — laboratory unit

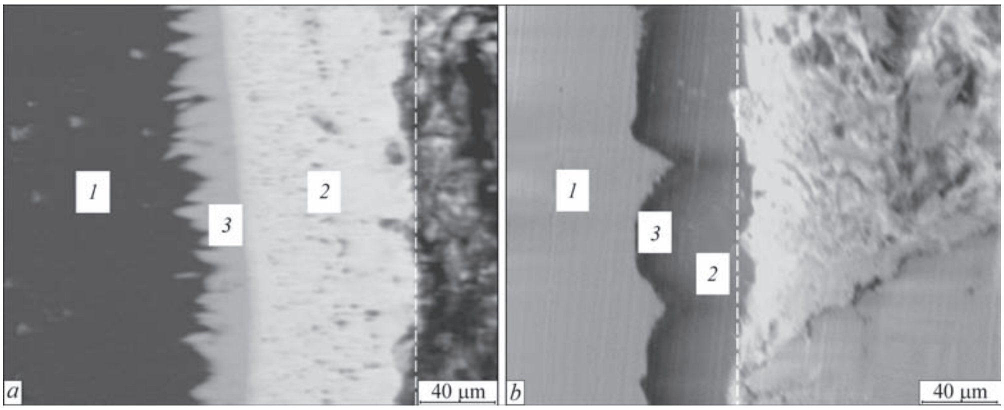

Figure 4. Microstructure of the joint zone produced at prolonged heating under VDW conditions (*a*) and short heating by passing current (*b*) (dashed line shows the limit of gallium application, PA is to the right of the line, and ML4 magnesium alloy is to the left; for designations *1–3* see the text)

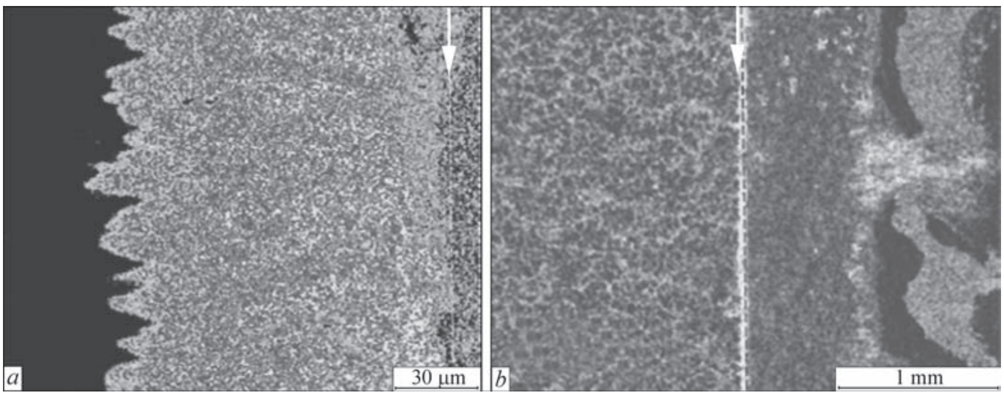

Figure 5. Element map of gallium distribution in ML4 base alloy (*a*) and in doped alloy (*b*). Dashed line shows the zone of gallium application, PA is to the right of the line, and magnesium alloys are to the left

is formed, and at short heating with current passage its width is up to 35–60 μm. Experimental coefficient of diffusion is equal to $0.92 \cdot 10^{-12}$ and $20 \cdot 10^{-12}$ m^2/s, respectively.

Investigation of quantitative chemical composition of the diffusion zone from magnesium alloy side (Figure 4, zone *1* — base metal) showed the presence of two regions of excellent chemical composition. Zone *2* (closer to the point of activator application) contains, wt.%: 35Mg and 64Ga, zone *3* — 73Mg and 24Ga. Proceeding from simplified schematic of analysis of magnesium alloying at gallium diffusion into it [8] and according to binary diagram of this chemical system, MgGa, Mg_2Ga and Mg_3Ga_2 intermetallic compounds form, having melting temperature of 373–456 °C that is higher than the welding temperature.

In experimental magnesium alloy pre-alloyed with gallium, which is based on standard ML4, homoge-

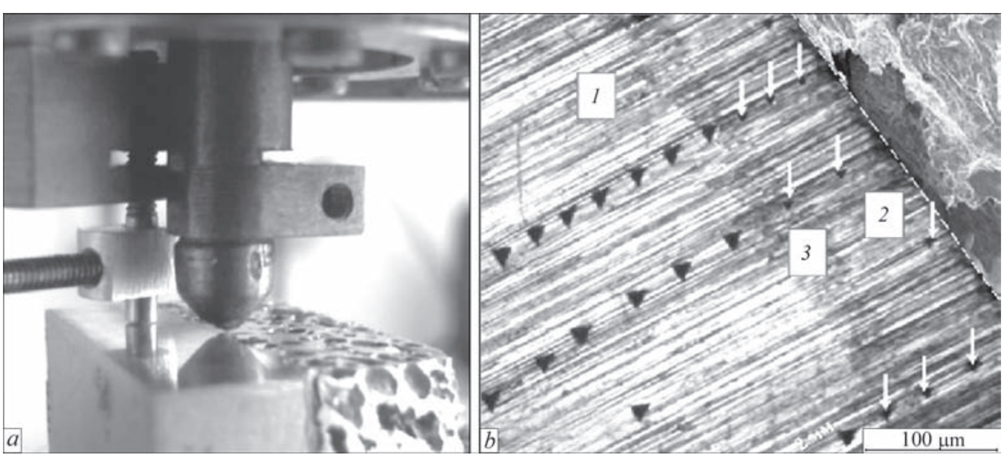

Figure 6. Micromechanical testing of ML4 + PA joint in Micron-gamma instrument (*a*) and indenter imprints in the diffusion zone on the side of magnesium alloy ML4 (*b*) (arrows show imprints of smaller area, characterizing strengthening; dashed line shows the zone of gallium application)

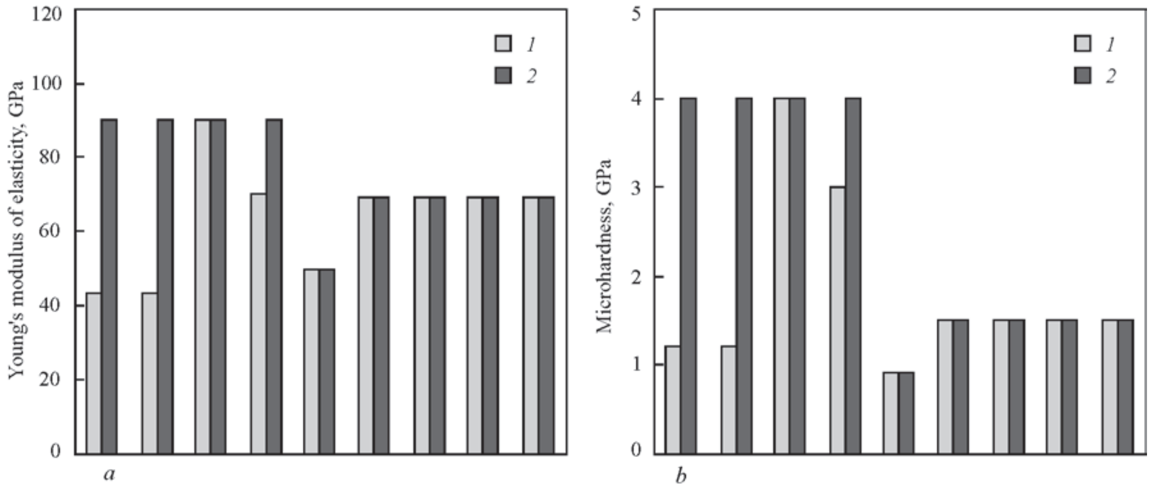

Figure 7. Diagram of tendencies of distribution of Young's modulus of elasticity (*a*) and hardness (*b*) across the diffusion zone of the joint of: *1* — ML4/PA; *2* — Mg + Ga/PA

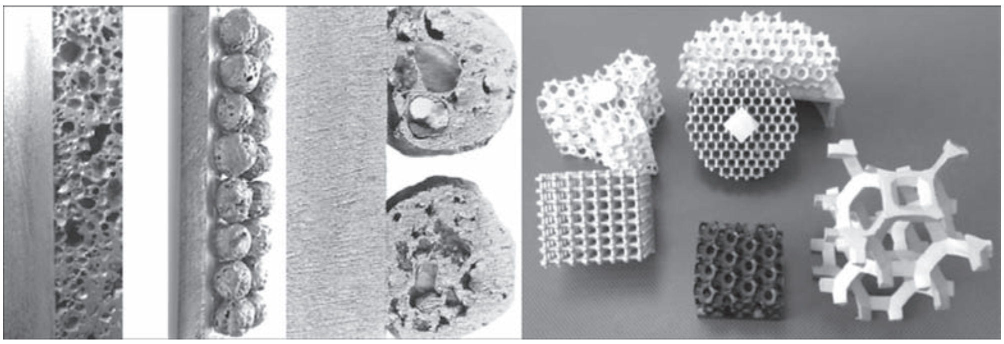

Figure 8. Fastening of diverse commercial cellular-porous materials to a monolithic base

nizing of chemical composition of near-contact zone and base material proceeds at joint activation by gallium (Figure 5). A clearly defined diffusion zone is absent.

Micromechanical testing of the diffusion zone of the joints was conducted by standard procedures [9, 10] according to ISO/FDIS 14577-1:2002 standard with Berkovich 3-face diamond pyramid [11] and application of Micron-gamma instrument. The instrument records Mayers microhardness and Young's modulus of elasticity at automatic recording of Berkovich indenter displacement, depending on the load applied to it. Maximum load was 500 g, load value error was 0.001; error of indenter penetration depth was 5 nm; maximum depth of indentation was 200 μm. Results are presented in the form of indentation diagrams at 20 g load with 50 μm increment. Preparation of samples for indentation was performed in keeping with the standard procedure of light alloy polishing to mirror surface and without etching.

From PA side, diffusion zone width is characterized by lowering of hardness from 1.5 to 1.0 GPa, of Young's modulus from 70 to 50 GPa. In the diffusion zone from ML4 alloy side (Figure 6), a considerable increase of Young's modulus from 42 to 73–110 GPa and of microhardness from 1.2 to 4.5 GPa is observed.

Magnesium alloy pre-alloying with gallium leads to a uniform level of Young's modulus and microhardness of base material and near-contact zone (Figure 7).

Welding with application of chemical activation by gallium enables fastening diverse commercial cellular-porous materials to a monolithic base (Figure 8).

Conclusions

1. Shown is the possibility of producing joints at 300 °C by two welding processes, differing essentially by heating duration and rates, for the case of manufacturing superlight multilayer bimetal sandwich panels, using porous and monolithic alloys based on aluminium and magnesium, in different sequence and combinations with application of chemical activation by gallium.

2. Investigation of microstructure and maps of chemical element distribution in the diffusion zone of the joint showed that the wavy front of gallium diffusion in monolithic magnesium alloy is typical as to its chemical composition for both the welding processes. Micromechanical studies of the joint diffusion zone showed a significant increase of microhardness and Young's modulus of elasticity from the side of monolithic magnesium alloy ML4, homogenizing of these

values in the diffusion zone and in the base metal in ML4 alloy alloyed with gallium, as well as a slight lowering of micromechanical properties in the walls of aluminium alloy pores. Thus, duration and rate of heating, depending on the applied welding technology and equipment, affects only the diffusion zone width.

Investigation results were obtained during performance of departamental program of the NAS of Ukraine «Investigation of structural transformations in welds and development of technologies of welding sheet hull and satellite structures from aluminium and dissimilar materials for fairings and adapters for rocket and space engineering» and Youth Basic Research Program of the NAS of Ukraine for young scientists «Optimization of the method of solid-phase joining of monolithic magnesium alloys to foamed aluminium».

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