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DIFFUSION WELDING OF MAGNESIUM ALLOY MA2-1 THROUGH A ZINC INTERLAYER

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ABSTRACT

The paper gives the results of investigations on vacuum diffusion welding of MA2-1 magnesium alloy. Different technological measures were used in welding: unsupported welding, welding with application of forming matrices, welding without interlayers and with a zinc interlayer. It is found that it is not possible to produce the joint in unsupported welding without an interlayer at 400 °C temperature and process duration less than 60 min. Increase of welding temperature or time leads to considerable grain growth. Application of 250 μm zinc interlayer and of the following welding mode: $T = 320$ °C, $P = 10$ MPa, $t = 30$ min allows producing the joint. Analysis of chemical composition in different areas of the joint zone shows that development of diffusion processes in the butt during welding results in pore formation with magnesium content on the level of 17.8–20.12 wt.% in the zinc interlayer at 2–3 μm distance from magnesium/zinc contact line. In the central part of the joint zone the metal chemical composition is close to pure zinc composition. Application of forming matrices and an interlayer of zinc in the solid-liquid state in welding in the following mode: $T = 340$ °C, $P = 10$ MPa, $t = 30$ min. allows producing sound joints due to localisation of plastic deformation in the butt joint. Results of metallographic investigations showed formation in the butt joint of common grains and remains of the interlayer in the form of dispersed particles of 15–50 μm size, with chemical composition of Mg–4.53Al–0.20Mn–63.49Zn, wt.%, having an irregular elongated shape.

KEYWORDS: vacuum diffusion welding, magnesium alloy, interlayer, microstructure, microhardness

INTRODUCTION

Magnesium is one of the most common elements in the earth's crust. It is the most lightweight material of all the structural metals. Its density of 1.74 g/cm^3 is four times lower than that of steel and by a third lower than that of aluminium. Owing to its low density and high specific mechanical properties, magnesium is becoming ever wider accepted in different industries, such as automotive (steering wheels, seat frames, steering column housing, driver airbag housing, steering wheels, etc.), aerospace (parts of turbofan engine box, engine compressor housing, transmission case, etc.), medicine (implants), electronic equipment (housing for mobile phones, computers, laptops, cameras and portable media players), sport (archery bow handles, tennis rackets, golf clubs, bicycle frames, and roller skate chassis), manual tools (chain saw housings, housings of gears and hand tool motors, handles of hand shears and hand drills) [1, 2].

An essential increase of the production of magnesium and its alloys requires development of effective joining methods. It is known that fusion welding leads to softening of magnesium alloys in the joint zone, formation of welds with a coarse-crystalline structure, and it is accompanied by appearance of pores, microinclusions of oxide films and cracks, formation of which is caused by metal melting and subsequent solidification [3, 4].

Diffusion welding is an attractive technology in this respect, which allows avoiding defects, often appearing at application of fusion welding methods. According to literature sources, in welding without interlayers at a temperature below 420 °C, the diffusion processes in the butt are slowed down, the contact line is clearly visible; and shear strength of such samples is low. Application of a higher temperature (450–490 °C) in combination with a longer welding duration (90–120 min) leads to excess grain growth, and, consequently, to deterioration of the joint mechanical properties [5, 6].

Application of interlayers allows producing sound joints; however, the welding temperature remains high. So, welding through a silver interlayer is performed at 480–500 °C [7, 8], through a copper interlayer — at 480–530 °C [9, 10], through nickel interlayer — at 515–520 °C [11, 12].

Given examples point to the need to apply interlayers, which alongside surface activation, would allow conducting the process at lower temperatures. Pure zinc interlayers can be regarded as one of such promising materials.

The objective of the study was to determine the influence of a zinc interlayer in diffusion welding of MA-1 magnesium alloy on formation of structure and properties of the welded joints.

MATERIALS AND PROCEDURE

Vacuum diffusion welding (VDW) of MA2-1 magnesium alloy (Mg – 3.8–5.0Al – 0.8–1.5Zn –

0.3–0.7Mn, wt.%) [13] was conducted in P-115 unit at the temperature of 250–560 °C, 10 MPa pressure, 15–60 min process duration, and vacuum in the chamber was maintained on the level of $1.33 \cdot 10^{-3}$ Pa. Welding of 15×10×1.5 mm plates was conducted both in an unsupported state and using forming matrices. Welding in unsupported state envisages free deformation of the samples during the welding thermodeformational cycle. With this welding scheme, deformation of the entire sample takes place. In welding using forming matrices (forced deformation) conditions are in place for plastic deformation localization in the sample joint zone. The oxide film was removed from the sample contact surfaces by mechanical scraping, which was followed by degreasing them in ethyl alcohol. Pure zinc foil 250 μm thick was used as an interlayer.

Microstructural studies of the welded joints were conducted on transverse microsections in metallographic optical microscope Neophot-32 and scanning electron microscope JEOL JSM-840 in secondary-electron imaging mode (SEI). Electron microscope is fitted with a combined system for energy dispersive microanalysis INCA PentaFet-x3. Microsections were prepared by a standard procedure on high-speed polishing grinders, using diamond pastes of different dispersion. Sample polishing was conducted to 14th class of surface cleanliness. Grain size was determined by a linear method with application of a micrometer eyepiece, using from 10 to 20 fields of vision. Hardness of phase components was measured by Vickers in M-400 hardness meter of Leco Company. The load was 1N (100 gr), load application time was 10 s.

RESULTS AND THEIR DISCUSSION

MA2-1 alloy in the initial state has a fibrous structure with a uniform size distribution of grains. Grains of 22–25 μm size prevail in the metal structure, but individual regions with grain size of 10–15 μm are observed (Figure 1). In keeping with the scientific sources, the grain structure is α-solid solution [14]. Grain boundaries are thicker, secondary phase ($Mg_{32}(Al, Zn)_{49}$ or Mg_4Al_3), probably, evolves along them [15]. Traces of rolling texture are preserved in the sample central part. As a result of chemical heterogeneity of the material, a small region with dark precipitates is observed in the sample center. Hardness distribution over the microsection plane is rather nonuniform: it is 501–591 MPa in the area of chemical heterogeneity, 451–453 MPa in the center without precipitates, and 473–507 MPa along the sample ends at 100–150 μm distance from the edge.

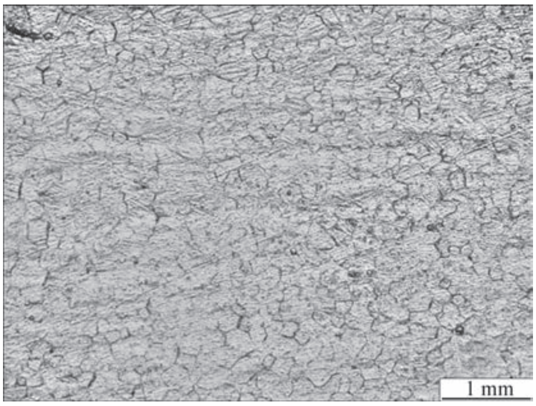


Figure 1. Microstructure of MA2-1 alloy in the initial state

Experiments were conducted on vacuum diffusion welding of MA2-1 alloy in an unsupported state without interlayer application. It is shown that the joint cannot be produced at welding duration of less than 60 min at 400 °C temperature: samples break at the microsection preparation stage. Note that at process duration of 15 min, interaction between the sample contact surfaces was absent. With increase of holding time individual adhesion areas began to be observed between the surfaces being welded (Figure 2, *a*). Grain size here is predominantly equal to 35–100 μm, and individual grains of 200–320 μm size are present. Material microhardness varies in the range of 438–566 MPa, its value being 502 MPa on the joint line.

Welding temperature rise even to 560 °C does not allow producing sound welded joints (Figure 2, *b*). After the welding thermodeformational cycle 150–350 μm is the predominant grain size for MA2-

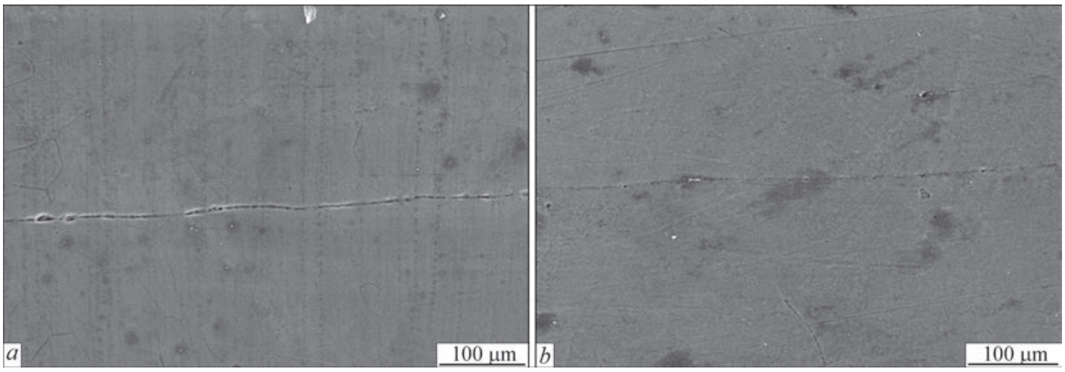
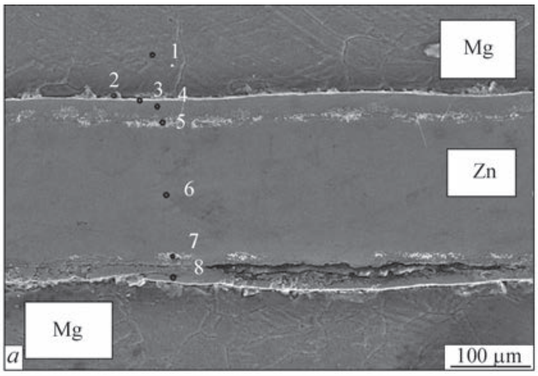


Figure 2. Microstructure of the zone of MA2-1 + MA2-1 joint, produced by VDW in the following mode: *a* – $T = 400$ °C, $P = 10$ MPa, $t = 60$ min; *b* - $T = 560$ °C, $P = 10$ MPa, $t = 15$ min



Spectrum number	Element content, wt.%			
	Mg	Al	Mn	Zn
1	99.39	–	0.09	0.52
2	66.41	0.91	0.21	32.47
3	62.06	1.14	0.28	36.52
4	20.12	–	–	79.88
5	3.27	0.15	0.31	96.27
6	2.26	–	–	97.74
7	–	–	0.10	99.90
8	17.80	–	–	82.13

b

Figure 3. Microstructure (*a*) and chemical composition (*b*) of the zone of MA2-1 + Zn + MA2-1 joint produced by VDW in the following mode: $T = 320$ °C, $P = 10$ MPa, $t = 30$ min

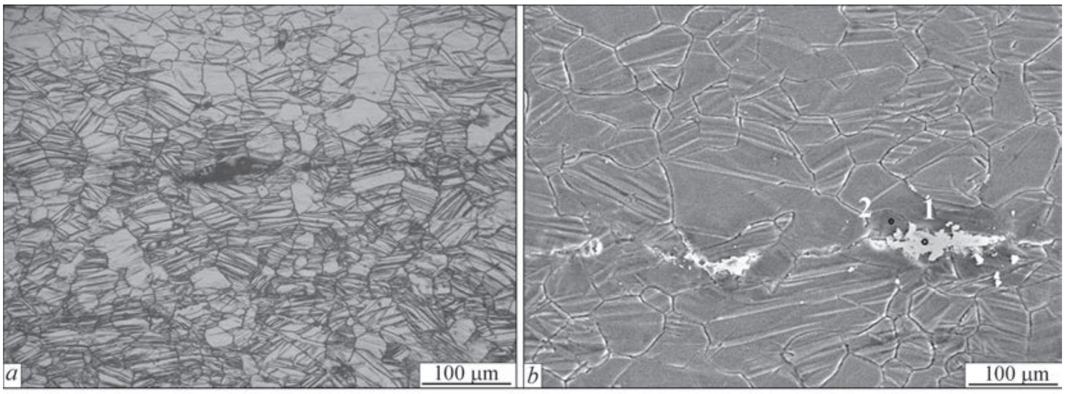
1 alloy, individual clusters of 60–100 μm grains and separate grains, growing through the entire sample thickness, are observed. Note a marked degradation of the joint metal: after high-temperature impact of the welding mode, brittle fracture of the magnesium alloy is in place, as a result of intensive grain growth. Microhardness of such joints is more uniform, and it varies from 371 MPa in the joint zone to 458 MPa closer to the sample outer boundaries. It is attributable to complete development of the recrystallization process and disappearance of texture traces with simultaneous homogenization of the chemical composition.

It is known that interlayer application in diffusion welding allows localizing plastic deformation in the butt joint [16]. That is why interlayers in the form of foil were used in further studies.

Zinc of 250 μm thickness was selected as an interlayer. Zinc application allows an essential lowering of process temperature to 320 °C. In keeping with the equilibrium state diagram, several eutectic reactions are observed in magnesium-zinc system at 340 and 368 °C temperatures. Increase of welding temperature up to a value higher than the eutectic reaction temperature leads to component melting and zinc penetration throughout the entire thickness of the sample, resulting in further brittle fracture of the sample. Welding at lower temperatures of 250–300 °C does not provide the conditions for joint formation.

Figure 3 shows the microstructure (*a*) and chemical composition (*b*) of the joint zone of samples produced in the following mode: $T = 320$ °C, $P = 10$ MPa, $t = 30$ min.

After welding the interlayer thickness is ~200 μm. The results of metallographic investigations lead to the conclusion that welding magnesium to magnesium with zinc interlayer application is quite promising, as it allows the joints to be produced at relatively low temperatures. It should be noted, however, that a chain of longitudinal pores forms in joint zone from both sides as a result unbalanced diffusion flows. Analysis of the chemical composition of different regions of the joint zone shows that pores form in the zinc interlayer at 2–3 μm distance from magnesium/zinc contact line with magnesium content on the level of 17.8–20.12 wt.%, which corresponds to



Spectrum number	Element content, wt.%			
	Mg	Al	Mn	Zn
1	31.77	4.53	0.20	63.49
2	98.71	2.51	0.06	1.72

c

Figure 4. Microstructure (*a*) and chemical composition (*b*) of the zone of MA2-1 + Zn + MA2-1 joint produced by VDW in forming matrices in the following mode: $T = 340$ °C, $P = 10$ MPa, $t = 30$ min

$MgZn_2$ phase [17]. In the central part of the joint zone (point 6), the metal chemical composition is close to that of pure zinc (Zn – 2.26Mg, wt.%).

Variation in grain size was detected in the metal structure with a large number of twins located at 500 μm distance from the weld deeper in the metal with finer grain of 30–100 μm. At greater depth the grains are of 100–200 μm size with isolated twins. Joint microhardness is rather uniform, except for 20 regions, where $MgZn_2$ phase formed. Here, microhardness is increased to 580 MPa, compared to 330–458 MPa for other sample regions.

Further studies were conducted in welding in forming matrices, which ensure plastic deformation localizing in the sample joint zone during the thermodeformational cycle of welding. Figure 4 shows the microstructure (*a*, *b*) and chemical composition (*c*) of the joint zone of samples produced in forming matrices in the following mode: $T = 340$ °C, $P = 10$ MPa, $t = 30$ min.

In this case, zinc is practically completely removed from the butt joint. The cause for that is the welding process proceeding in the solid-liquid state. As shown by microstructural analysis, growing of common grains through the joint zone takes place in the butt joint, which is indicative of active running of the diffusion processes. Isolated dispersed inclusions of an irregular shape, oriented in the direction of the metal flow, are observed in the butt joint. Inclusion size is 15–50 μm. White inclusions in Figure 4, *b* are $Mg_{51}Zn_{20}$ phase, according to [17]. Mean grain size in the magnesium alloy is mostly equal to 15–60 μm, with separate grains of up to 200 μm. Microhardness along the joint zone is nonuniform, varying in the range of 594–660 and 330–479 MPa for regions with $Mg_{51}Zn_{20}$ phase inclusions and without it, respectively. It can be assumed that such a microhardness distribution will not have a negative impact on the joint mechanical properties, as intermetallic inclusions are of a dispersed nature. Microhardness in the base metal is 371–526 MPa. Evaluation of the joint bending strength was performed, which showed that the bend angle of samples with a zinc interlayer, produced by diffusion welding in forming matrices, is equal to 180°, unlike samples produced without using the interlayer, which fail at microsection preparation stage.

CONCLUSIONS

Proceeding from the derived results, we can conclude that it is difficult to produce sound welded joints in vacuum diffusion welding of MA2-1 alloy without using interlayers.

Welding performance in the mode of $T = 340$ °C, $P = 10$ MPa, $t = 30$ min, with application of forming matrices and zinc interlayer which is in the solid-liquid state, allows producing sound joints. Based on the results of metallographic studies, formation of common grains and practically complete removal of the interlayer are observed in the butt joint with appearance of dispersed particles of 15–50 μm size elongated along the joint line with chemical composition of Mg–4.53Al–0.20Mn–63.49Zn, wt.%. The nature and detailed explanation of the mechanism of joint formation through an interlayer which is in a solid-liquid state, under the impact of local plastic deformation in the butt joint, requires further studies.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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