PROPERTIES OF JOINT REGION IN THE Mg/Al TWO-LAYER MATERIALS AFTER EXPLOSIVE WELDING PROCESS

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Abstract

The paper presents investigation of the properties of joint region in the two-layer Mg/Al material semi-finished product obtained by the explosive welding method. Aluminum 1050A and magnesium alloy AZ31 were used to fabricate the bimetallic material to be analyzed. The Mg/Al materials were made using different technological parameters of explosive welding. In this work an analysis of microstructure changes on the cross-sections of the joint region was conducted. There were also made tests of layers connections quality. The results of the research show a deviation in microstructure in the bonding area. Analysis of the results shows that for all used parameters of the explosive welding method guarantee a permanent connection of the both magnesium and aluminum layers.

Keywords: Explosive welding, two-layer Mg/Al materials, microstructure, bond strength

1. INTRODUCTION

A growing demand of the means of transport manufacturing industry for lightweight constructional materials has been observed in recent years. Therefore, aluminum and magnesium alloys are widely used in the automotive and aircraft industries. A major problem in the use of magnesium alloy parts is their very low corrosion resistance [1]. A promising solution is to manufacture Mg/Al bimetallic products, which may open the path to the expansion of these materials in new areas of applications, because an Mg/Al bimetallic part can combine the advantages of both materials: the low density of the magnesium alloy and the good corrosion resistance of the aluminum alloy. For these reasons, a two-layered Mg/Al material has been selected for investigation within the present study. Multilayered Mg/Al products are most commonly manufactured by a diffusion bonding [2], friction welding [3], rolling [4], extrusion [5] or a casting [6] methods, and increasingly often, by an explosive welding method [7, 8]. Most of the above-mentioned methods cause a poor durability of bonding between individual bimetal layers and involve a high consumption of the cladding layer (e.g. from stock obtained by a metallurgical method). Moreover, they are expensive, as they are produced in specialized equipment, and are also too little efficient to be used on a commercial scale. A competitive method of producing Mg/Al materials is the explosive welding method. It owes its popularity to the fact that it is uncomplicated, relatively inexpensive and provides a durable bond between bimetal layers. Due to the fact that the methods of Mg/Al products manufacturing are primarily "hot" processes, thus a hard and little ductile Mg-Al intermetallic phase layer usually forms at the Mg/Al joint interface, which is from several to a dozen or so micrometers in thickness. Intermetallic phases are characterized by low ductility and brittleness at ambient temperature. Also the use of the explosive welding method for production of Mg/Al bimetals with incorrectly chosen explosive welding parameters may cause intermetallic phases to form at the bond boundary [9]. Thus, it is necessary to determine the effect of explosive welding technological parameters on the possibility of obtaining a durable and resistant Mg/Al bonding without a continuous transient layer of intermetallic phases.

2. EXPERIMENTAL MATERIALS AND PROCEDURES

A series of four sets of 10x70x240 mm specimens taken from rolled AZ31 alloy plates were subjected to cladding. As a clad material, 2 mm-gauge 1050A aluminum plates were used. Cladding was done in a parallel system according to the schematic diagram shown in **Figure 1**. The explosive welding of the Mg/Al materials was made in cooperation with the company Explomet (Poland).

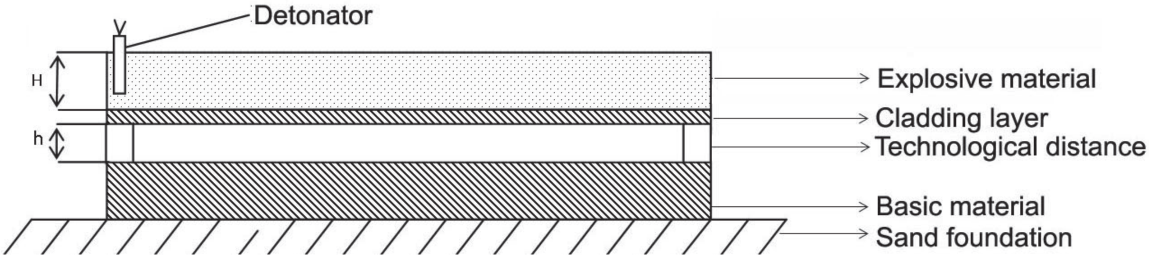

Figure 1 Schematic illustration of the explosive welding process

The explosive welding parameters are given in **Table 1**.

Table 1 Technological parameters used for explosive welding of Mg/Al bimetallic specimens

No. of Sets/ sample	**Explosive material**	**H** (mm)	**h** (mm)	**D** (m/s)	V_p (m/s)	**γ** (°)
1, 2	Saletrol	25	5	2215	589	15
3, 4	Amonit	25	3	1800	453	16

where: H - explosive thickness, h - stand-off distance, D - detonation velocity of explosive material, V_p - calculated flyer plate velocity, γ - calculated collision angle.

For the explosive welding process, two types of explosive were used, namely: Saletrol (Sets nos. 1 and 2) and Amonit (Sets nos. 3 and 4). Moreover, for Sets 3 and 4, the height of the propulsion path was changed. The employed different technological parameters and two explosive types (differing in detonation velocity) influenced the speed of the cladding layer hitting the base layer and the welding angle.

The microstructure of the Mg/Al material was observed using a Nikon ECLIPSE MA 200 optical microscope and a JEOL JSM-5400 scanning electron microscope (SEM). A chemical composition analysis of the joint region was conducted using an Oxford Instruments ISIS 300 X-ray energy dispersive spectrometer (EDS) attached to the SEM. In order to examine the quality of bonding between the base layer and the cladding layer, mechanical tests of the obtained Mg/Al materials were carried out. A tensile test was performed on specimens of a shape and dimensions as shown in **Figure 2**. The tests were carried out on a Zwick Z100 testing machine. Test specimens were taken from individual Mg/Al plates in a direction consistent with the direction of detonation wave propagation and in the transverse direction.

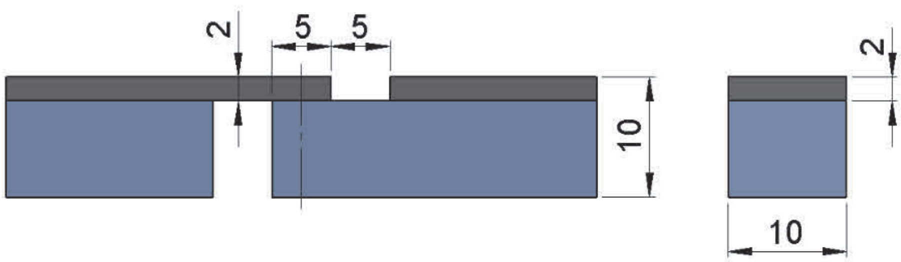

Figure 2 The shape and dimensions of Mg/Al specimens for the examination of bonding quality

3. RESULTS AND DISCUSSION

The welding parameters assured the obtaining of Mg/Al bimetallic specimens in the correct shape and without a longitudinal bend. A sample shape of the welded Mg/Al material produced from Set no. 3 is shown in **Figure 3**.

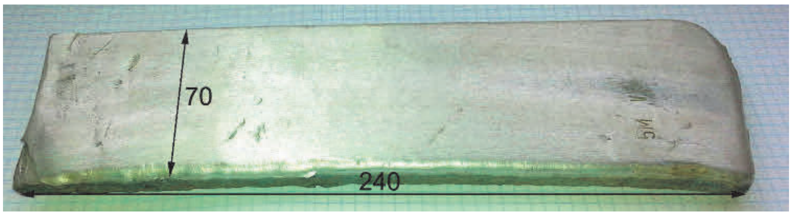

Figure 3 An example view of an Mg/Al bimetallic specimen obtained from Set no. 3

At the first stage of the investigation, metallographic examinations of bond regions were made. The examinations were done on specimens taken, respectively, along and across the propagation of the detonation wave. **Figure 4** illustrates the bond region on the longitudinal section of Specimen 1 and Specimen 3.

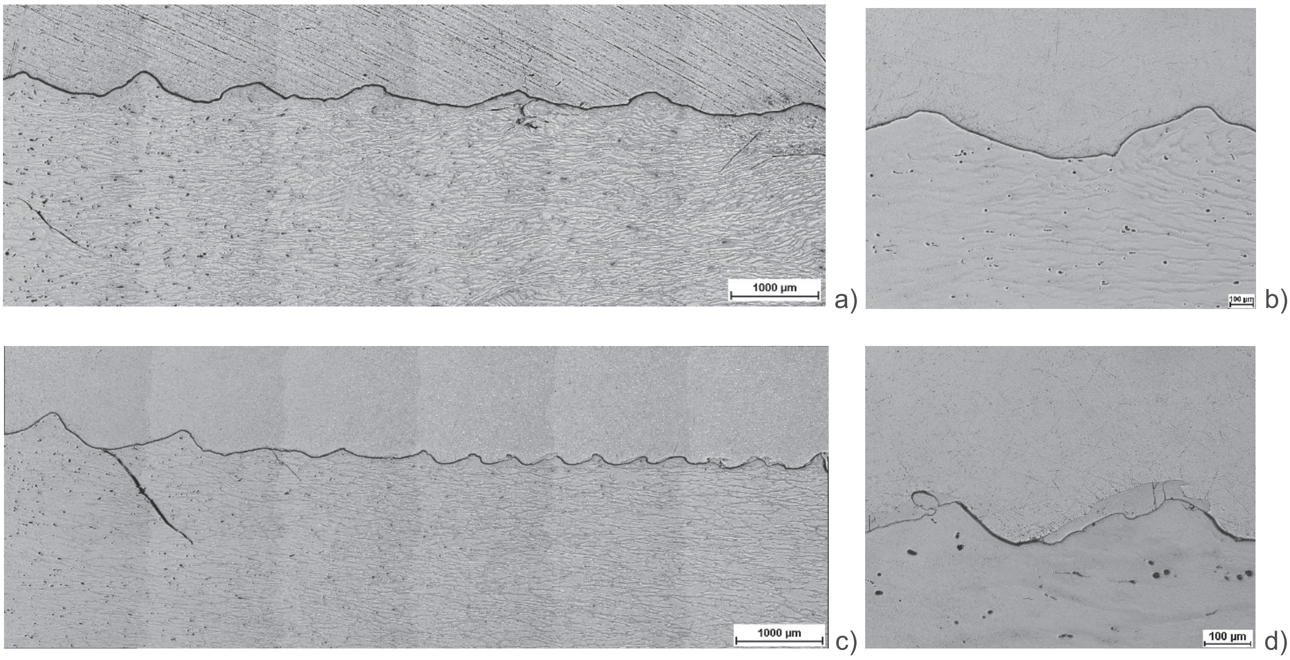

Figure 4 The microstructure of the bond region on the longitudinal section: a) Specimen 1, low magn., b) Specimen 1, high magn., c) Specimen 3, low magn., d) Specimen 3, high magn.

When analyzing the microstructure observed at a low magnification in specimens obtained with different welding process parameters (Specimen 1 - **Figure 4a**, Specimen 3 - **Figure 4c**) it can be found that the shape of the bond region is typical of products obtained by the explosive welding method. A characteristic wavy bond was obtained. It was observed that change in welding parameters influenced the shape and amplitude of waves formed. For Specimen 1 (**Figure 4a**), the frequency and height of waves occurring across the entire bond are more uniform compared to Specimen 3 (**Figure 4c**). When examining the shape of waves occurring in Specimen 3, a varying frequency of their occurrence along the region under analysis can be found. In the specimen region on the detonation wave propagation side, the shape and frequency correspond to those for Specimen 1. By contrast, in a farther region, a considerable increase in the frequency of the occurrence of waves takes place and their height decreases. When examining the microstructure of Specimen 1 (**Figure 4b**) on an optical microscope at a larger magnification, no transient zone was observed between the Al layer and the AZ31 alloy. By contrast, in the bond in Specimen 3 (**Figure 4d)** at the Al/AZ31 contact, regions irregular in shape were observed in some places, which suggests that diffusion had taken place, resulting in the formation of new phases at the Al/AZ31 boundary.

Figure 5 depicts the bond region of Specimen 1 and Specimen 3, as observed on the cross-section. For Specimen 1, the bond region is approximately flat (**Figure 5a**), whereas for Specimen 3 (**Figure 5c**) the bond shape is very irregular and wavy. When examining the bond zone in those specimens at a larger magnification, no transient zone was found to occur at the material boundary for Specimen 1 (**Figure 5b**), while for Specimen 3, just like on the longitudinal section, irregular regions were observed in the bond zone (**Figure 5d**).

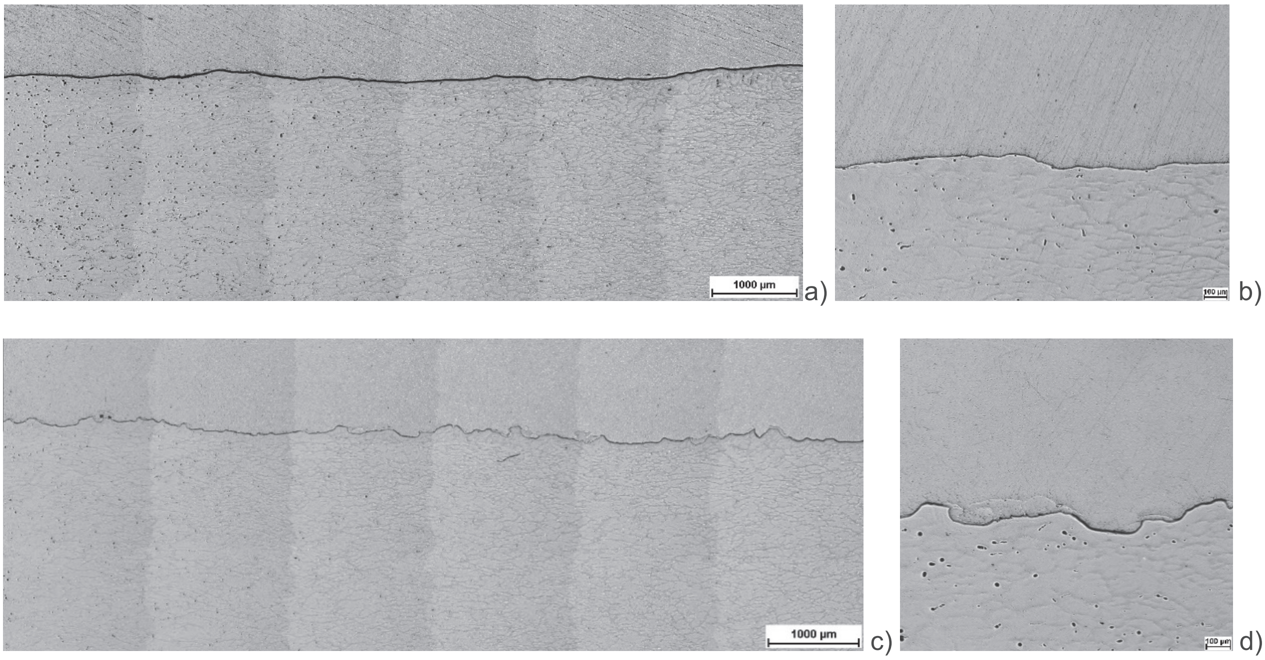

Figure 5 The microstructure of the bond region on the transverse section: a) Specimen 1, low magn., b) Specimen 1, high magn., c) Specimen 3, low magn., d) Specimen 3, high magn.

Because of the transient zone occurring locally between Al and AZ31 in Specimen 3, a detailed analysis of those bond regions was made. **Figure 6** shows the microstructure of the transient bond zone along with the distribution of Mg and Al along the indicated line. The results of quantitative analyses at the points indicated in this figure are given in **Table 2**. As can be noticed, the transient zone of variable thickness is distinguished by an inhomogeneous structure. The results of the quantitative analysis in this zone on the Al side (Point 1) suggest the intermetallic phase Al_3Mg_2. Chemical composition of the transient zone on the AZ31 alloy side (Point 2) corresponds to that of the $Mg_{17}Al_{12}$ phase. In the transient zone, bright regions can also be observed (Point 3), whose composition corresponds to that of the solid solution of Mg in Al.

Table 2 EDS results (at.%) for points marked 1-3 in **Figure 6**

Point	Mg	Al	Zn
1	41.67	58.33	-
2	55.29	43.85	0.36
3	7.29	92.71	-

To sum up the structural examinations of the bond zone in bimetallic specimens produced by the explosive welding method it can be stated that the microstructure of the bond zone depends on the process parameters applied. At higher detonation velocity (Specimen 1), no intermetallic phases were found to occur at the Al/AZ31 boundary. In contrast, at a lower detonation velocity (Specimen 3), regions of an inhomogeneous structure were observed in some places at the Al/AZ31 boundary, in which the occurrence of Mg-Al phases was found. No continuous brittle Mg-Al intermetallic phases were found to occur in the bond zone of any of the examined specimens, which could result in a high strength of the bond zone in the bimetallic specimens.

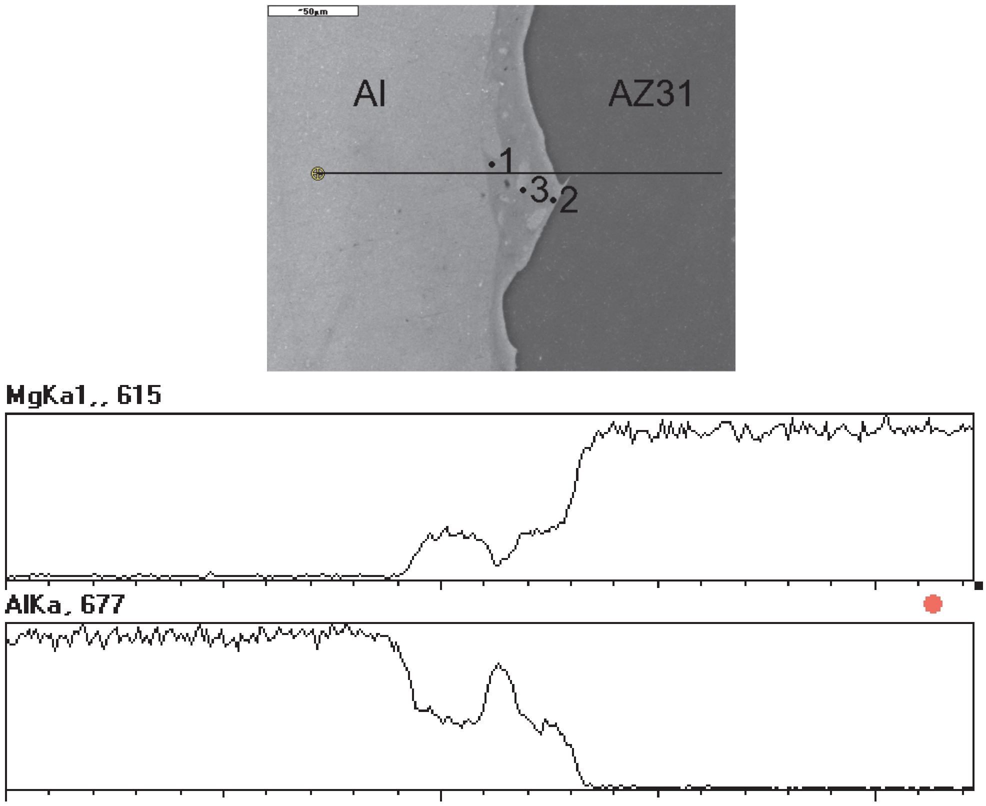

Figure 6 The microstructure of the transient zone of the bond of Specimen 3 along with linear analysis made by the EDS method

The next step was to determine the strength of the bond. **Figure 7** shows sample Mg/Al specimens after bond strength testing.

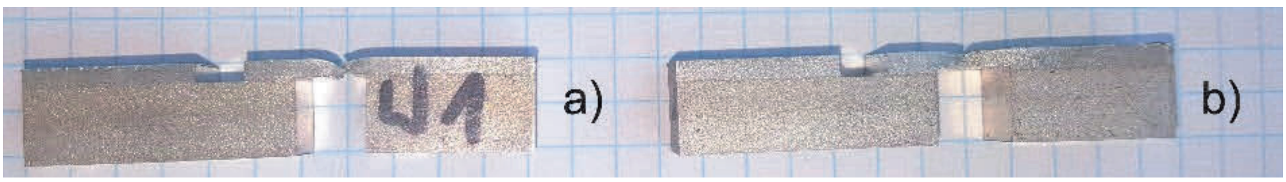

Figure 7 The shape of Mg/Al bimetallic specimens after bond strength testing:
a) Specimen 1, b) Specimen 3

The examination of bond quality found that no bond shear had occurred in any bonding region. In each of the examined specimens, regardless of the sampling direction (longitudinal or transverse), a break occurred within the aluminum layer (**Figure 7**).

The results of the examination of the quality of bonding between individual Mg/Al layers as explosively welded are shown in **Figure 8**. The specimen numbering is as per **Table 1**. The presented results are averaged values for individual specimens.

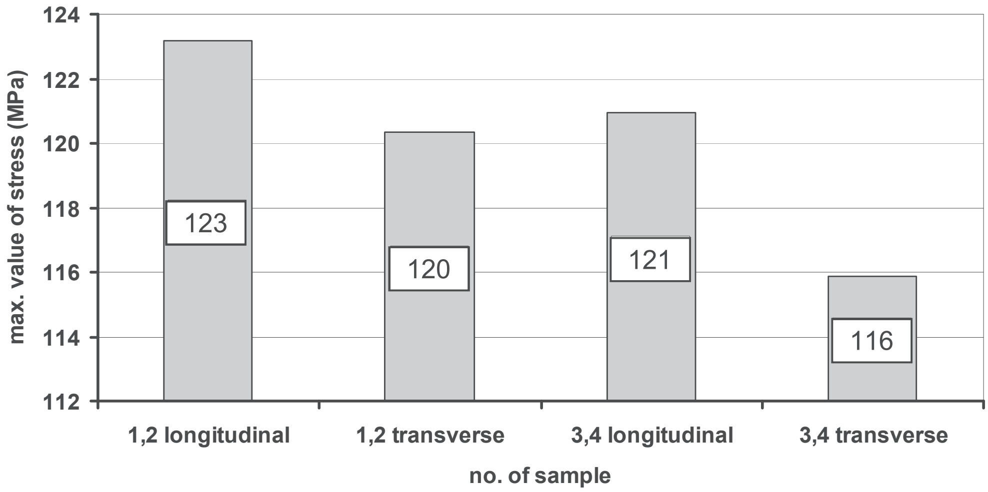

Figure 8 The bond strength of Mg/Al bimetallic specimens

The data in **Figure 8** indicates that the obtained results correspond to the tensile strength of the aluminum layer. The applied explosive welding parameters did not significantly influence the obtained results. It should be noted, at the same time, that slightly greater hardening of the cladding layer has occurred in the detonation wave propagation direction, compared to the transverse direction. The obtained stress values show that the strength of the bond, amounting to over 120 MPa, has surpassed that of the cladding layer. For comparison, the shear strength of the bond, as obtained in laser-welded two-layered AZ31B/A5052-O plates, has amounted to 48 MPa [10], which corresponds to a tensile strength of approx. 84 MPa. In contrast, the bond tensile strength achieved in friction-welded two-layered AZ31B/1050A plates is 90 MPa [3], while for AZ31/1050A plates produced by the diffusion bonding method it is 80 MPa [2]. Study [7] determined the shear strength of the bond for two-layered AZ31B/7075 specimens obtained by the explosive welding method. The bond shear strength for that case was 70 MPa, which corresponds to a tensile strength of approx. 123 MPa. Whereas, in study [8], the strength of the bond in AZ31/1100A specimens, as obtained by the explosive welding method, was contained in the range from 69 to 78 MPa, which corresponds to a tensile strength from 121 to 136 MPa.

Considering the above, it can be stated that the achieved bond strength of above 120 MPa is much higher than that of two-layered Mg/Al materials produced by the laser welding or friction welding method. It can also be stated that the obtained values are consistent with the results for two-layered Mg/Al materials produced by the explosive welding method.

4. CONCLUSION

From the obtained investigation results it can be concluded that the adopted parameters influenced the shape of the bond, and although a characteristic wavy bond was obtained in both cases, localized, very scarce regions of the occurrence of Mg-Al phases were observed for Specimen 3. The assumed explosive welding technological parameters provided in both cases a durable, high-strength Mg/Al bond. The achieved bond strength exceeds that of the Al layer, as evidenced by the rupture of the Al layer, instead of the bond region, in mechanical tests.

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