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STRUCTURE AND MECHANICAL PROPERTIES OF EXPLOSIVE WELDED Mg/Al BIMETAL

STRUKTURA I WŁAŚCIWOŚCI MECHANICZNE POŁĄCZENIA UZYSKANEGO METODĄ ZGRZEWANIA WYBUCHOWEGO BIMETALU Mg/Al

In the article we analyzed shape, local mechanical properties, chemical and phase composition of Magnesium/Aluminium cladded material prepared by explosion welding. In particular we focus our investigation on Mg/Al interface and areas close to the joint. Hardness of the joined materials measured far from their interface is similar for both materials, however in the region of interface the hardness drops down by 40%. Phase transformations in the interface was examined by a hard X-ray micro-diffraction experiment performed at beamline P07 at PETRA III at the energy of 99 keV which helped us identify in Al: fcc-Al, Al_2Cu tetragonal and Al_7Cu_2Fe tetragonal and in Mg: hcp-Mg, Mg_2Si cubic phases. In the interface we haven't observed any new intermetallics, but computation of lattice parameters and profiles of Al and Mg peaks proved an existence of solid solution with different gradient of chemical composition.
Keywords: explosive welding, Mg/Al bimetal, micro-hardness, micro-diffraction, PETRA III

W pracy analizowano kształt, lokalne właściwości mechaniczne, chemiczne oraz składników fazowych Mg/Al materiałów platerowanych otrzymanych metodą zgrzewania wybuchowego. W szczególności, skupiono się na badaniach połączenia fazy Mg/Al oraz obszarów znajdujących się w pobliżu połączenia. Twardość połączonych materiałów badano w znacznej odległości od warstwy samego połączenia, i zauważono, iż jest ona podobna do twardości materiałów wyjściowych, jednakże twardość w regionie warstwy połączenia spada o 40%. Przemiana fazowa w warstwie połączenia została poddana badaniom mikrodyfrakcyjnym, na urządzeniu P07, PETRA III o energii 99 keV, dzięki której zidentyfikowano w Al fazy tetragonalne: fcc-Al, Al_2Cu oraz Al_7Cu_2Fe i w Mg: heksagonalną Mg oraz kubiczną Mg_2Si. W warstwie połączenia nie zaobserwowano żadnych innych nowych faz międzymetalicznych. Obliczone parametry sieci komórki elementarnej i profile pików Al i Mg potwierdzają występowanie roztworu stałego z różnym gardientem składu chemicznego.

1. Introduction

One of the major importance regarding to the environment protection and economical energy sources is high strength to weight ratio of the materials used in industry. Aluminium alloys are extensively used in aerospace and automobile industry because of good formability, corrosion resistance and high strength to weight ratio. Magnesium is the lightest among metallic materials utilized in industry, it's density is about 2/3 of that of aluminium, magnesium alloys exhibit good machinability, thermal conductivity, electromagnetic interference shielding, vibration absorption and can be recycled without any degradation in physical properties. Composite laminates of Mg and Al alloys could be a promising structural material combining properties of both of materials and explosive welding seems to be a good welding method how to join it together without creation of any brittle intermetallics causing decreasing the ductility [1-3].

Explosive welding is technique used to join similar or different / highly incompatible materials (e.g. due high melting point) where usage of any other (conventional) technique would be from the technological and economical point of view not suitable. The explosion welding phenomenon was first observed during the World War II (bomb fragments welded to metal objects). Since then the process has been patented (DuPont) and continuously developed and even today it is attaching a great interest due to growing number of potential applications in many industry areas [4-6].

By explosion, almost all metals can be welded. There are no restraints of thickness to the base layer, just to the cladding metal, but clads as thin as 0.13 mm and as thick as 50 mm have been bonded without problems [7]. All the materials meant to be welded can be divided into 8 groups [8] from common bonded materials to unknown system with high probability of direct bonding.

The metals to be bonded are: cladding metal / cladder – thinner plate in direct contact with the explosive or shielded by a flyer plate, and base plate / backer – plate that the cladder is being joined to [9]. The first step in material preparation is to clean the surfaces to be joined from various oxides, nitrides

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and adsorbed gases. Once the plates has been prepared, they are fixed close to each other with a small separation – standoff distance unique for each combination of materials (typically between 0.5 – 2 times the thickness of the cladding metal [9]) by a shims from various materials (depending on the type of welding operation). The main function of this separation distance is ensuring to reach enough specific collision velocity of the cladding metal plate before impacting the backer – the distance on which the velocity of the cladding metal can reach a critical value – the critical velocity – equals approximately 1 to 2 times the thickness of the cladding metal [7]. The width of the cladding metal should exceed the width of the backer minimum for the thickness of the explosive due to unequal acceleration of borders of the cladding metal compared to the rest of the plate (combustion products escaping the plate in the vicinity of the border causing lower velocity of these parts of the cladding metal) [10]. But this procedure is not mandatory.

The explosive is placed in explosive containment box around the edges of the cladding metal and spread over it, it's weight should be approximately equal to the weight of the cladding plate. After initiation of an explosive (detonation velocity typically between 1200 – 3800 m/s [9]), pressure generated by expanding gasses accelerates the cladding plate to the critical velocity and collision of cladding plate with backer (typical collision velocity at the impact point is about 200-500 m/s) causes a jet formed from both of the materials effacing unwanted oxides and other surface films. Upon explosion, kinetic energy of the cladding plate is transformed into heat and locally metals begin to flow creating wavy interface – characteristic feature of explosive welded materials. However, detonation takes few hundred microseconds so there is just very little heat transferred to the metal – no bulk diffusion occurs and the solidification of the melt is immediate (values of cooling rates in the molten zone are of order 10^5-10^7 K/s [11]) so creation of intermetallics is suppressed. The combination of surface cleaning, extreme pressure of several GPa and an extremely narrow local flow of metals causes very tight joint. In the wavy zone one can notice vortexes in which occur stirring, diffusion and solving of solid fragments, alloying of both liquid metals [12]. Typical is inhomogeneous chemical composition. Welded joint shows strength at least as great as the weaker of two base metals [8]. Sometimes weld quality can by improved by inserting a next material between the cladding metal and base material – interlayer.

Regarding to the Mg – Al explosive welding alloys, Findik [3] is reviewing the work of Yan et al. [2] where microstructure and properties of the bonding interface after explosive welding were investigated. Magnesium alloy was used as base and aluminium alloy was used as the flyer plate. Results showed wavy appearance of interface with solidified melts in regularly spaced pattern of discrete regions. Adiabatic shear bands and twin structure were found on the AZ31B Mg alloy side. No intermetallics were observed. Shear strength across the bonding interface and maximum bending stress were evaluated. Appearance of pockets under the curls of the bimetal waves connected Rao et al. [13] and Cowan [14] with collision velocities and for Mg and Al it was 2500 m.s^{-1}. Production of Al -Ti composites bimetal with intermetallic layer was presented by Bataev et al. [15]. Hokamoto et al. [16] showed some microstructural parameters of A5052/AZ31 bimetal including intermetallic phases formed in vortices under higher collision velocity. Magnesium alloys are gaining attention due to their low density and favourable mechanical properties [17].

Generally, to the pure Al and Mg bimetal has not been paid an important attention and it is why the presented work is focused on mentioned sandwich where computation of lattice parameters in the vicinity of welded bond has been performed in order to prove an existence of solid solution with gradually changed chemical composition from the centre of weld to the material.

2. Experimental work

In the article we present our observations on explosively welded commercially available Mg on Al. We analyzed shape, local mechanical properties, chemical and phase composition of interface line as well as inhomogeneities in the vicinity of the wave joint by means of optical light microscopy (Olympus GX 71), optical profilometry (SENSOFAR PLu neox) and electron scanning microscopy coupled with energy-dispersive spectrometer (Jeol JSM-7000 F). In order to investigate phase composition of the interface, microdiffraction experiment has been performed at synchrotron beamline P07 at PETRA III accelerator at HASYLAB, DESY, Germany.

Our bimetal sample with a length of approximately 6 mm and width of 4.8 mm was made by explosive welding of commercially available magnesium and aluminium (Fig. 1). Chemical compositions of cladded materials are listed in Table 1.

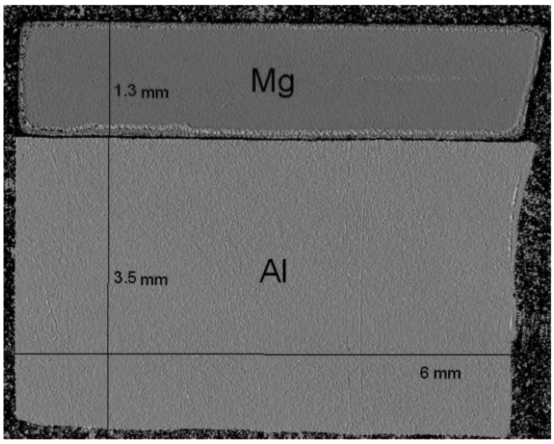

Fig. 1. Image of Mg/Al explosive welded bimetal from 3D Optical Profiler

TABLE 1
Chemical composition of materials at random points outside of the bond interface

Element	Mg [wt. %]	Al [wt. %]
Mg	89,9	93,3
Al	3,8	–
O	2,3	1,7
Cu	–	0,7
C	2,1	4,3
Mn	1,9	–

The thickness of Mg plate is 1.3 mm, Al has 3.5 mm in width. For metallographic analysis the specimen were embedded in IsoFast thermosetting resin (Struers GmbH) at a pressure of 28 MPa and a temperature of 170°C in a SimpliMet 1000 automatic mounting press. The sample has been in the next step grounded and polished with colloidal silica suspension with a grain size of 0.05 microns (Sommer Präzisionstechnik).

3. Results and discussion

The microstructure of the bimetal components consist of elongated and spheric grains of various phases, which can be well distinguishable from the Fig. 2. Elongation of grains appeared to be more evident in the vicinity of welded wavy bond likely caused by local plastic deformation pronounced in the join region. We made in total 10 optical micrographs from the interface region with aim to evaluate average thickness of the interface (bond) we found it in all micrographs almost the same ~45 microns wide.

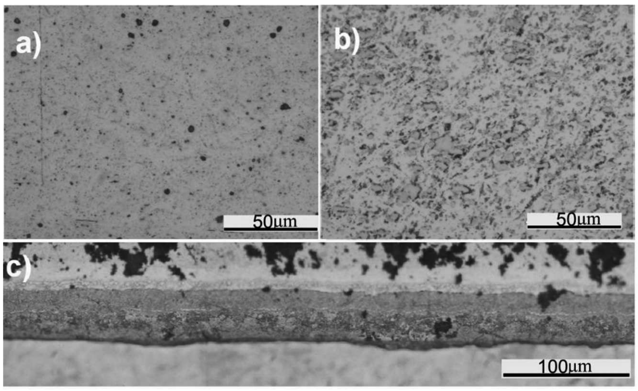

Fig. 2. Microstructure of Mg/Al explosive welded bimetal with well distinguishable elongated and spheric grains of various phases: a) Mg b) Al c) interface of magnesium (top) and aluminium (bottom) with wavy appearance. Magnification 1000x (a and b) and 500x (c)

One interesting observation from our light optical microscopy was we were not able to focus image simultaneously on both materials on one micrograph. The reason is difference between height of the Mg- (lower) and Al- (higher) planes revealed by 3D Optical Profiler SENSOFAR PLu neox. The difference is approximately 8 microns (Fig. 3). We made several efforts to change the procedure of sample preparation (various grinding papers, polishing clothes and suspensions) but the result was always same. One of the explanations can be different hardness of the investigated materials.

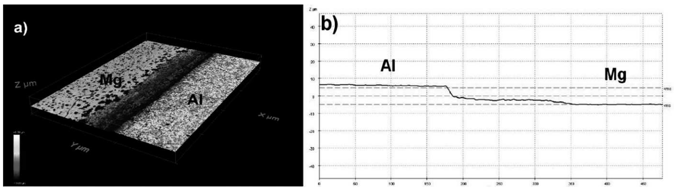

Fig. 3. a) Interface of explosive welded Mg/Al observed at magnification of 20× by 3D Optical Profiler SENSOFAR PLu neox. Average thickness of the bond is 45 μm b) height difference between Mg- (lower) and Al- (higher) plane is approximately 8 μm

Chemical composition of welded materials were determined by point SEM/EDX microanalysis measured far away the interface region, the results are listed in Table 2. Chemical composition is varying with the majority of elements corresponding to Mg and Al. Chemical analysis of the interface were determined by 5 measurements (Fig. 4) placed randomly on the interface line. The welded interface exhibit chemical heterogeneity, results of the analysis are summarised in Table 2.

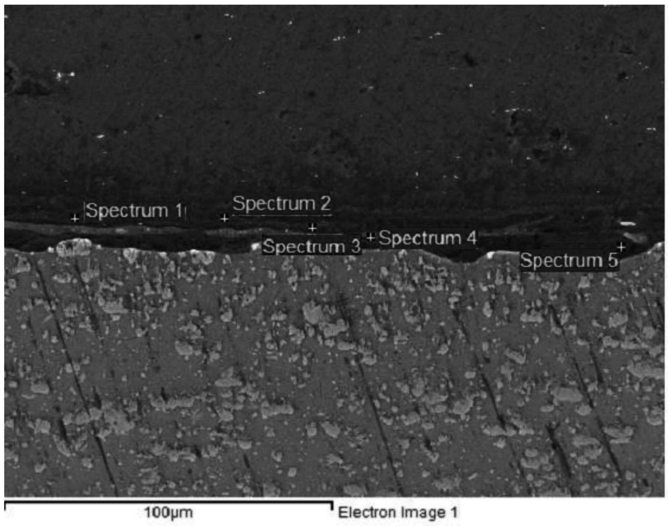

Fig. 4. Random 5 points used for EDX analysis near by the interface of welded Mg/Al

TABLE 2

Results of EDX analysis at random 5 points near by the interface of welded Mg/Al showing chemical heterogeneity of the wavy bond

Element POINT	Mg [wt. %]	Al [wt. %]	Si [wt. %]	Fe [wt. %]	Cu [wt. %]	O [wt. %]
1	6	27.3	0.4	34.1	32.2	–
2	3.7	81.7	–	1.6	10.5	2.5
3	85.4	11.7	0.2	–	–	2.7
4	88.9	–	0.7	–	1.2	9.2
5	95.4	–	–	–	–	4.6

Micro-hardness of the wavy bond and joined materials itself was tested by LECO Microhardness test machine with step of 120 μm. Hardness of the joined materials measured far from their interface is similar for both materials, for Mg it is about 80 HV0.1, and for Al ~75 HV0.1 (Fig. 5). However in the region of interface the hardness drops down by 40% to about 50 HV0.1 indicating some kind of thermal induced microstructure relaxation. These results confirm our assumption that most important changes of materials are taking place at the clad materials interface. Similar observation has been reported by Yan [2] on AZ31B Magnesium on 7075 Aluminium explosive welded clad material.

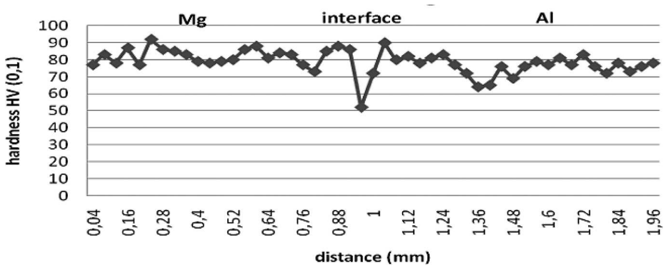

Fig. 5. Comparison of micro-hardness in the vicinity of the interface and in the welded materials itself

Possible phase transformations in the interface was examined by a hard X-ray micro-diffraction experiment performed at beamline P07 [18] at PETRA III (electron storage ring operating at energy 6 GeV with beam current 100 mA) [19]. In this quite unique experiment, monochromatic synchrotron radiation of energy 99 keV was used. The beam of photons was focused by compound refractive lenses down to a spot size of 2.2 μm × 34 μm. Schematic illustration of micro-diffraction experiment is shown in <**Fig. 6.**>. The specimen was scanned shot-by-shot along a straight path passing from Mg to Al across their interface. In total we collected 251 2D XRD patterns recorded from individual places separated by 4 μm distance. The intensity was integrated to 2Θ by using the Fit2D software. From the diffraction patterns we identified phases using the CMPR [20] toolkit. In aluminium part far from the interface we found phase composition consisting of fcc-Al, Al2Cu tetragonal and Al7Cu2Fe tetragonal, phases. In magnesium part we found hcp-Mg and Mg2Si cubic phases.

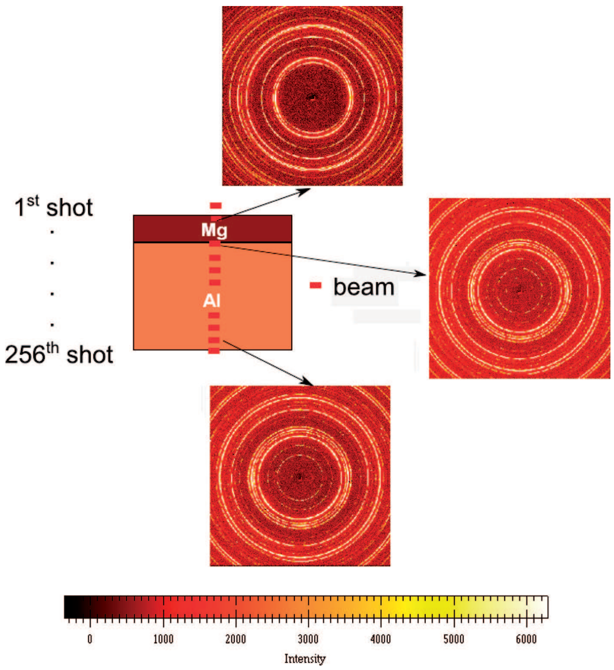

Fig. 6. Schematic illustration together with some 2D XRD patterns from micro-diffraction experiment performed at beamline P07 at PETRA III, DESY, Hamburg by a monochromatic synchrotron radiation of energy 99 keV (λ = 0,14620 Å), spot size 2.2 μm × 34 μm, vertical shot separation 4 μm

Phase analysis from interface region is shown in Fig. 7. At the interface we haven't observed any new intermetallics, but computation of lattice parameters and profiles of Al and Mg peaks proved existence of solid solution with different chemical composition. As it can be seen in Fig. 8a, lattice parameter of Al measured from the interface is significantly bigger (0.2%) compared to the pure Al phase.

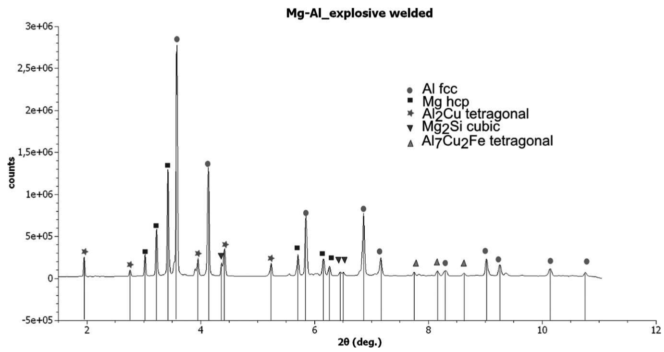

Fig. 7. The phase composition identified at the interface of explosive welded Mg on Al using CMPR toolkit [5]

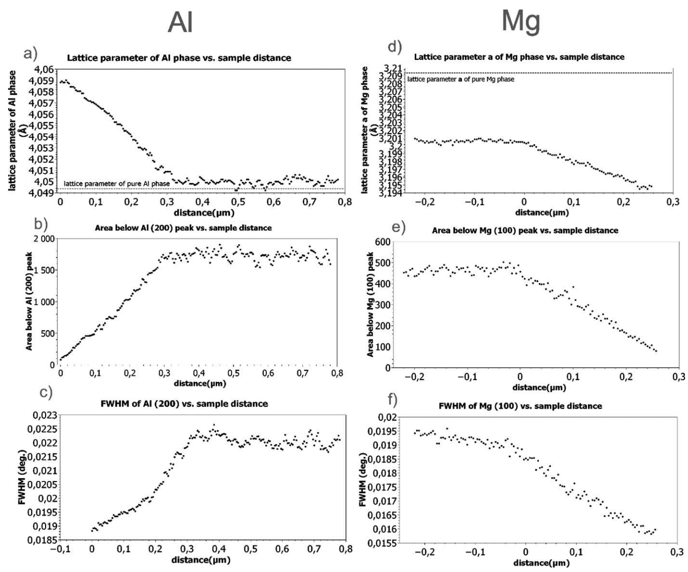

Fig. 8. Calculated a) lattice parameter of Al phase b) area below Al peak c) Full width at half maximum (FWHM) of Al d) lattice parameter of Mg phase e) area below Mg peak f) FWHM of Mg. Point "0" on the x-axis (distance) represents beginning of the interface evaluated by Octave computation toolkit by depicting the total dispersion of the obtained diffraction patterns. Patterns 1-54 represent Mg, 54-142 belong to interface, 143-251 are part of Al. Depicted parameters of Al and Mg are taken from the interface

This is due to the diffusion of larger Mg phase to the lattice of Al. With increased distance from the interface the lattice parameter gradually decreases to the value of pure Al phase. Presence of the solid solution with gradually decreased Mg concentration is visible up to 0.33 μm from the interface. Similar result we obtain by measuring area bellow the Al (200) Bragg's peak, <**Fig. 8b**>**.** The increased distance, the fcc lattice becomes more and more enriched by Al atoms what is nicely demonstrated by increased Al (200) peak area. Full width at half maximum (FWHM) of the peak increases testifying progressive crystalline size reduction and increased lattice deformation by going from the interface to aluminium (Fig. 8c)). For the case of Mg, Al is penetrating to the lattice of Mg (Fig. 8d) manifested by lattice parameter decrease. With more Al atoms in the Mg lattice area bellow Mg (100) peak decrease, what is shown on **Fig. 8e**. There is less failures incorporated at Mg matrix measured closer to the boundary, likely caused by the effect of thermal induced material relaxation (FWHM parameter by going closer to Mg/Al boundary decreases, see **Fig. 8f**).

4. Conclusions

In this article we present our observations on explosively welded commercially available Mg on Al. The results of metallographic and microchemical analysis showed that a wavy Al/Mg explosive welded interface is molten in a very thin (45 μm wide) region. In the welded bond, there is substantial chemical inhomogeneity. Hardness in the middle of the Al/Mg interface region drops down by 40% from ~80HV0.1 to ~50 HV0.1 indicating some kind of thermal induced microstructure relaxation. From the diffraction patterns we identified phases: in aluminium – fcc-Al, Al_2Cu tetragonal and Al_7Cu_2Fe tetragonal, in magnesium we found hcp-Mg and Mg_2Si cubic phases. In the interface no intermetallics were observed, but we proved an existence of solid solution with gradually changed chemical composition from the centre of weld to the material.

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