The effect of annealing on the interface microstructure and mechanical characteristics of AZ31B/AA6061 composite plates fabricated by explosive welding

Nan Zhang, Wenxian Wang, Xiaoqing Cao, Jiaqi Wu

PII: S0261-3069(14)00641-4
DOI: http://dx.doi.org/10.1016/j.matdes.2014.08.025
Reference: JMAD 6722

To appear in: *Materials and Design*

Received Date: 19 May 2014
Accepted Date: 8 August 2014

Please cite this article as: Zhang, N., Wang, W., Cao, X., Wu, J., The effect of annealing on the interface microstructure and mechanical characteristics of AZ31B/AA6061 composite plates fabricated by explosive welding, *Materials and Design* (2014), doi: http://dx.doi.org/10.1016/j.matdes.2014.08.025

The effect of annealing on the interface microstructure and mechanical characteristics of AZ31B/AA6061 composite plates fabricated by explosive welding

Nan Zhang[a,b], Wenxian Wang[a,b,]*, Xiaoqing Cao[a,b], Jiaqi Wu[a,b]

a) College of Science and Engineering, Taiyuan University of Technology, 79 West Yingze Street, 030024Taiyuan, Shanxi Province, China

b) Key Laboratory of Interface Science and Engineering in Advanced Materials, Ministry of Education, 79 West Yingze Street, 030024Taiyuan, Shanxi Province, China

Address: College of Materials Science and Engineering, Taiyuan
University of Technology, 79 West Yingze Street, Taiyuan 030024,
Shanxi Province, China.

Tel: +86 0351 601 0076

Fax: +86 0351 601 0076

Email address: wangwenxian@tyut.edu.cn

Abstract: In this investigation Magnesium alloys AZ31B / Aluminium alloys 6061 composite plates were obtained successfully through the method of explosive welding. The effect of annealing on the evolution of interface microstructure and mechanical properties of the composite plates were investigated. The results demonstrated that the AZ31B/AA6061 composite plates were bonding well. On annealing at and above 250˚C, intermetallic compounds of Al_3Mg_2 and $Al_{12}Mg_{17}$ were observed to form at the bonding interface. By increasing the annealing temperature, the tensile strength of the composite plates increased firstly, then it was dramatically decreased, while the elongation increased significantly. This behavior was considered to be due to the diffusion of Mg and Al elements as well as the formation of intermetallic compounds during annealing process. Crack propagation and interface delamination were observed of the composite plates annealed at and above 250˚C. Corresponding fracture mechanisms of the composite plates were also analyzed.

Keywords

Explosive welding; Magnesium alloys; Aluminium alloys; Interface microstructure; Mechanical characteristics

1. Introduction

Magnesium alloys are applied in automotive and aerospace industries due to their low density and high specific strength. Therefore, Magnesium alloys are actively developing to a new type of environmental friendly materials [1]. However, the poor corrosion resistance and room temperature ductility are the main reasons limiting the applications of Magnesium alloys. By contrast, Aluminium alloys express an excellent oxidation resistance by naturally forming dense and protective oxide coatings. Liu et al.[2] reported that the corrosion resistance of Mg could be improved by using Al coating. Thus, Magnesium alloys and Aluminium alloys are fabricated as composite plates can not only improve the corrosion resistance but also utilize the properties of the both metals [3-5]. Currently, various techniques of fabricating Magnesium alloys / Aluminium alloys composite plates have been developed, such as fusion welding [6], diffusion welding [7], hot pressing [8], hot rolling [3-5]. However, under high temperature the bonding interface of Magnesium alloys Aluminium alloys easily react into brittle intermetallic compounds that decrease the mechanical property [8]. Consequently, solid state welding techniques such as explosive welding overcomes the problem of the generation of intermetallic compounds on the welding process [9].

Explosive welding is a very useful technology for metal welding and metal composite production by using explosives as an energy resource [10]. Hence, explosive welding introduces convenience to the bonding of dissimilar materials which are not possible to be bonded by conventional welding methods and it is preferred by the materials in which the formation of brittle phase is unavoidable [11].

However, work hardening is created by the impact of joining plates during explosive welding process, and the microstructures on the interface are deteriorated and distorted by the tremendous force induced by the effect of the explosion. Furthermore, residual stresses are produced due to mismatch in liner expansion coefficients of the constituted base metals in the composites [12]. Sedighi et al.[13] has investigated through-depth residual stress in explosive welded Al-Cu-Al multilayers. The results showed that multilayer surface was subjected to high tensile residual stress. Also, there was an intense gradient of residual stress at the interface of multilayers. Mohammad et al.[14] studied the effect of heat treatment on the bonding interface in explosive welded copper/stainless steel. It showed that the tensile strength and elongation were increased by post heat treatment. Acarer et al.[15] studied mechanical and metallurgical properties of explosive welding aluminum-dual phase steel. Due to the formation of brittle intermetallic compounds at the joining interface, the heat treatment performed on the samples should be controlled carefully, because the formation and growth of the thickness of these compounds will affect the mechanical properties of the plates involved in the process. Akbari Mousavi et al.[16] investigated the effect of post-weld heat treatment on the interface microstructure of explosively welded titanium-stainless steel composites. The results showed that post-heating of the composite layer in different temperatures causes to form different intermetallic phases at the joint interface. In these studies, the effect of annealing on the composite plates made by explosive welding has been investigated.

In order to obtain a good formability for composite plates, and also to research the change of interface morphology or to change the disordered microstructure, it is necessary to perform annealing on the workpieces after explosive welding. Y.B. Yan et al [17] studied that a composite plate of Magnesium alloys and Aluminium alloys was fabricated by explosive welding. The microstructure and properties of the bonding interface after explosive welding were investigated. However, the research about the effect of post-weld annealing for the Magnesium alloys /Aluminium alloys composite plates by explosive welding is significant. Thus, this paper, which had just focused on this aspect, could be seen a supplement in this field. The aim of the present work is to evaluate the evolution of microstructure on the interface and mechanical properties for the explosive welded Magnesium alloys AZ31B/Aluminium alloys 6061 composite plates under different annealing conditions. As a result, it may offer a guide on the formulating of proper annealing technology for explosive welded Magnesium alloys AZ31B /Aluminium alloys 6061 composite plates in the industry.

2. Experimental procedure

2.1. Materials

The dimensions of AZ31B and AA6061 plates used in this study were 300mm×300mm×6mm and 330mm×330mm×3mm, respectively. The chemical compositions of the materials used are given in Table 1.

Table 1

2.2 Preparation of the AZ31B / AA6061 composite plates

Mg alloys and Al alloys plates were degreased in acetone and grinded with 800# SiC paper. Due to the different of mechanical and corrosive properties of AZ31B and AA6061, they were chosen as base plate and flyer plate, respectively. In this study, a parallel layer arrangement was used for experimental setup in the explosive welding process (seen in Fig 1). The explosive in this paper was AMATOL power type in the height of 8mm, for getting a velocity of detonation equal to 2500 m/s. The distance between the flyer plate and the base plate was 3 mm.

Fig.1

2.3 Annealing treatments

In order to investigate the effect of annealing on the interface microstructure and mechanical properties of the AZ31B / AA6061 composite plates, the annealing treatment was performed after the explosive welding process. Annealing temperature and holding time were selected at 200˚C,250˚C,300˚C, and 400˚C for 1h, 2h, 3h, and 4h on the basis of the previous works [3,18].

2.4 Microstructure characterization

The specimens for microstructure analysis were cut parallel to the detonation direction. The cut samples were then prepared by mounting, grinding, then polishing using diamond paste. Microstructural observations were performed, and the presence of the intermetallic phases was characterized using scanning electron microscopy (SEM) equipped with an energy dispersive spectroscope (EDS) that allowed the local elemental composition to be investigated.

2.5 Mechanical properties

To evaluate the effect of annealing treatment on the mechanical properties of AZ31B / AA6061 composite plates, tensile test was carried out for the composite plates annealed at different temperature. The tensile test specimens were machined by a wire cut machine according to the ASTM:E8/E8M sub-sized tensile specimens, oriented along the explosive direction. The dimensions of tensile test specimens are given in Fig.2 in details. The tensile test at ambient temperature was carried out at a nominal strain rate of $1\times10^{-3}s^{-1}$ by using a fully computerized united tensile testing machine. Tensile properties were estimated from stress-strain plots. The tensile fracture samples were analyzed using SEM as well in order to observe the interface microstructure after failure.

Fig.2

3 Results and discussion

3.1. Characterization of explosive welded composite plates

Fig.3a shows a SEM micrograph of the AZ31B/AA6061 composite plate interface after explosive welding. Experimental results demonstrate that cladding of

AA6061 to AZ31B was achieved by the explosive welding technique. Wavy morphology has appeared on the bonding interface due to the effect of variations in the velocity distribution at collision point and periodic disturbances of materials [19]. Akbaria Mousavi and Farhadi Sartangi [20] have explained the wavy interface and the mechanism of its formation under explosive welding. Kacar and Acarer [21] showed that the bonding interface of clad metals has a wavy morphology. Also, Yakup and Nizamettin [22] have reported that straight and wavy interfaces can be formed between explosively welded materials and wavy interface is preferred due to better mechanical properties. Moreover, no pores and flaws were observed at AZ31B/AA6061 interface. Furthermore, it was reported in the literature [16] that in the explosive welding, a hard and brittle intermetallic is formed and this affects the bonding quality and the mechanical properties with a negative manner. It is clearly seen that no intermetallic layer was observed at the interface of the composite plates after explosive welding. This indicates that the initial combination made by explosive welding yielded a sound joint of AZ31B/AA6061 interface.

Fig.3

An element line scan of Al and Mg elements was conducted by using EDS to determine elements distribution across the bonding interface after explosive welding. Fig 3b shows the EDS line analysis across the interface of the AZ31B/AA6061 composite plates. The element distribution line was X-shaped and no strictly steep line, thereby indicating the occurrence of atomic diffusion at the interface. Evidently, there was a thin diffusion layer on the AZ31B/AA6061 bonding interface after explosive welding. Akbari Mousavi [23] reported that the collision created a circumstance of high temperature and high pressure instantaneously during explosive welding process, and the circumstance promoted the diffusion of elements to form the thin diffusion layer. The result was in agreement with the previous studies [17,24] about element diffusion on the Al/Mg interface after explosive welding. The diffusion layer attributed to a metallurgical bonding between the AZ31B and AA6061.

3.2. Microstructure of constituent AZ31B on composite plates

Optical micrographs in Fig.4a show the structure of the AZ31B based plate. The general characteristic of the AZ31B structure is the grain elongated into streamlined-style along the direction of explosive. It also shows that the deformation degree of each area is not homogenous, which could be divided into three different areas: small equiaxed grain area, coarse grain area, base plate grain area, as shown in Fig.4b-d. For the bonding interface, the temperature of the explosive welding process was fiercely raised during the collision and then would keep for a while [25]. Though the time was extremely short, it had created an annealing effect. After that, the small equiaxed grains were obtained due to the effect of recrystallization as shown in Fig.4b. Besides, the coarse grain area is found on the AZ31B side near the interface as seen in Fig.4c. The existence of the coarse grain area is treated as the severe plastic deformation during the welding [24]. The morphology of prolonged grains was created by the enormous pressure caused by the explosive of detonator.

Fig. 4

Another important phenomenon in the explosive welding interface is adiabatic shear bands (ASB). Fig.4 b-c shows the appearance of ABS in the AZ31B as indicated by arrows. They appear inclined at about 45° to the explosive direction and near the interface. Yan et al. [17] reported that the ASB consists of fine and small equiaxed grains is due to the deformation caused by the large number of twins. Under the explosive welding conditions, the high velocity oblique collision produces high strain rate deformation process under collision loading can lead to a large amount of twins. Also, Yang et al. [26] reported that the observations of ASBs assemblages on the explosive cladding Ti plate interface. Song et al.[27] reported that ASBs occur in the vicinity of the bonding interface of steel after explosive welding.

3.3. Microstructure evolution of constituent AZ31B on annealed composite plates

Fig. 5a-d exhibits the optical micrographs of the AZ31B near the interface from the explosive welding composite plates annealed at 200˚C, 250˚C, 300˚C and 400˚C for 2h. As can be seen from Fig.5, annealing temperature has a significant influence on the interface microstructure in the case of the same holding time. From Fig.5a, the adiabatic shear bands were disappeared completely due to static recrystallization, the grains still keep the same morphology as explosively welded. As shown in Fig.5b and c, the nonuniform grains grew and became equiaxed, and consequently the microstructure was somewhat homogenized. It is evident that the fine grain was obtained upon the process of recrystallization. At a higher annealing temperature, the grains began to grow again. In addition, the width of interfacial layer formed at the interface increased with annealing temperature. Unlike some previous researches, in this work, we firstly researched the evolution of interface microstructure of Mg constituent for explosive welded Mg/Al composite plates under different annealing condition.

Fig.5

3.4. Microstructure evolution of interface on annealed composite plates

Fig.6 shows SEM micrographs of the AZ31B/AA6061 interface from the explosive welding composite plates annealed under various temperature in the unetched conditions. There was no evident change on the AZ31B/AA6061 interface after annealing at 200˚C for 2h compared to that of as explosive welding. The continuous intermetallic phase was obvious in the interface when the annealing temperature is over 200˚C as shown in Fig. 6(b-d). The thickness of the intermetallic phase formed on the AZ31B/AA6061 interfacte was increased with increasing the annealing temperature. The diffusion coefficient in solids increases with increasing the annealing temperature, which results in a considerable increase of the thickness of the intermetallic layer [5,29]. This phenomenon can also be proved by the spectrums about the element line-scanning across the AZ31B/AA6061 interface from the samples annealed at 250˚C, 300˚C, and 400˚C for 2h shown in Fig.7.

Fig. 6

Fig. 7

The concentration of the Mg elements decreased from the AZ31B Mg alloy side to the AA6061 Al alloy side while the concentration distribution of the Al elements was on the contrary. Fig. 6 showed that there are two different diffusion layers observed distinctly at the AZ31B/AA6061 interface. To identify these layers, EDS point analysis was performed on four points in the vicinity of the AZ31B/AA6061 interface after annealing at 400˚C for 2h as show in Fig. 6d and Fig. 8. According to Mg-Al binary phase diagram and the chemical composition measured (Table 2), it can be indicated that region B and C consist of $Mg_{17}Al_{12}$ and Al_3Mg_2 intermetallic compounds according to the Al-Mg binary phase diagram [28], and the $Mg_{17}Al_{12}$ phase was adjacent to the parent Mg side, and Al_3Mg_2 phase close to the parent Al side. Lee et.al [5] have reported the same phenomenon in their work. The intermetallic compound phases were generated at the interface between the constituent Mg and Al of a roll-bonded STS-Al-Mg 3-ply clad sheet after heat treatment. Macwan et.al [18] also found the phenomenon of the thickness of interface intermetallic compounds increased markedly with increasing annealing temperature of rolled Al/Mg/Al tri-layer clad sheets, the results were in agreeing with of our investigation.

Fig. 8

Table 2

Fig.9 shows the thickness of an intermetallic compound layer as a function of annealing time under different annealing temperature. It is seen that the growth of intermetallic compound layers accelerated with increasing annealing temperature and annealing time. The annealing temperature plays a major role to increase the thickness of intermetallic compound layers by comparing the lines as shown in Fig.9. It can be proved by the fact that the interdiffusion coefficient could be determined by the Arrhenius equation [29],

$$K = K_0 \, exp\left(-\frac{E}{RT}\right) \tag{1}$$

Where K_0 and E are the frequency factor (m^2/s) and activation energy (J/mol) for interdiffusion, respectively, R (8.314J/mol·K) is the gas constant, and T is the absolute temperature in Kelvin (K). The thickness of intermetallic compound layers as a function of annealing time for a multiphase diffusion system can be described as,

$$y^2 = Kt \tag{2}$$

Where y is the diffusion layer thickness, K is the interdiffusion coefficient, *it* is the annealing time.

Using the above equations, the thickness of the intermetallic compound layer was calculated at 300°C and 400°C for different annealing time using the K_0=1. 98×10^6(m^2/s) and the E=83418(J/mol) mentioned on previous studies [18,29], and the obtained results in comparison with the experimental values are shown in Fig.10. A good agreement between the predicted values and experiment values was observed.

Fig.9

Fig.10

3.5. Mechanical properties of composite plates

To study the effect of annealing temperature on the mechanical properties of explosive welding AZ31B/AA6061 composite plates, the tensile tests were conducted and the engineering stress-strain curves were presented in Fig.11. The tensile properties were also summarized in Fig.12. It is seen that the tensile strength of the as explosive welded was 158MPa. There was no sign of macroscopic delamination on the bonding interface shown in Fig. 11(□). The sample annealed at 200˚C showed a higher strength equal to 189MPa. This suggested an increasing bonding strength at the interface as a result of the increasing diffusion layer in annealing process. The other reason to explain the increase in tensile strength was the elimination of dislocations and residual stresses as a result of the annealing process [6,29]. It can be seen obviously from Fig.12 that the strength decreased drastically when the annealing temperature was at or above 250˚C, which was mainly associated with the formation of high brittle and hard Mg-Al intermetallic compounds on the interface. This fact has been observed by other researchers [3,4,5,18]. Macwan et.al [20] reported that with increasing annealing temperature, the ultimate tensile strength of the Al/Mg/Al clad sheets first increased from 200˚C to 250˚C, reached its maximum value at 250 ˚C, followed by the decrease up to 400 ˚C.

From the stress-strain curves of the AZ31B/AA6061 composite plates annealed at 300˚Cand 400˚C, it can be seen that there were two abrupt turns in the curve which correspond to the delamination and fracture of the composite plates. According to the fractured macrostructure shown in Fig. 11(Ⅰ-Ⅴ), partial delamination occurred at interface between AZ31B and AA6061 when stress increased. The initial stress-turn phenomena were obviously caused by the initiation of fracture from the AZ31B side, whereas the second stage of tensile process at a dropped stress value corresponding to fracture from the AA6061 side, which implied that the brittle Mg-Al intermetallic compounds at interfaces by annealing have an important effect on the overall mechanical bonding at the interface. A similar effect of Mg-Al intermetallic compound interlayer on the tensile strength was also reported in a roll-bonded three-ply Al/Mg/Al sheet [29]. Mohammad [14] also reported that the tensile strength of explosive welded copper/stainless steel were decreased by post heat treatment result from the formation of intermetallic compound.

It is well known that the mechanical properties can be improved by proper annealing due to the recovery and recrystallization of the microstructure of Mg and Al alloys metal [4]. The elongation to fracture for composite plates significantly increased with increasing annealing temperature from 200˚C to 400˚C. From Fig.12, it can be seen that the maximum elongation is up to 22.7%, which is strongly related to the generation of intermetallic compound layers at the interface, as shown in Fig. 6 (d). The intermetallic compound layers can transfer enough loads to bear additional plastic deformation of the cracked or partially delamination for the fracture of the overall composite plates. Then, it can be concluded that appropriate annealing can improve the mechanical properties of the AZ31B/AA6061 composite plates after explosive welding, with controlling the thickness of the intermetallic compound layers at the AZ31B/AA6061 bonding interface. Lee et.al [5] concluded that the Mg-Al joint lost its mechanical integrity when the total thickness of the intermetallic compound layers exceed more than 5μm.

Fig.11

Fig.12

Fig.13 shows SEM images of cross-section perpendicular to the composite surface and parallel to the tensile direction after tensile tests. An overall view of the fracture of the as-annealed at 200°C and 250°C of composite plates is shown Fig.13. It is seen that no interface debonding occurred for the composite plates as shown in Fig.13 (a), indicating the well bonding property and thus giving rise to the high tensile strength. The phenomenon of debonding along with the interface took place in the composite plates annealed at 250°C (Fig.13 (b)) , which was not distinct at the fractured macrostructure as shown in Fig.11 (Ⅲ). This debonding leads to the decrease of the strength of the composite plate, which result from the generation of intermetallic compound layers at the interface as shown in Fig.6 (b).

Fig.13

4. Conclusions

In this study, the AZ31B/AA6061 composite plates were obtained successfully through explosive welding method. The interface microstructure and mechanical properties of the AZ31B/AA6061 composite plates during different annealing conditions were evaluated. The conclusions can be summarized as follows:

1) The explosive welding process was a suitable method to produce the AZ31B/AA6061 composite plates and a good bonding quality between AZ31B and AA6061 is achieved.

2) The Mg and Al elements diffused across the interface of the composite plates as explosive welded and annealed. On annealing at and above 250°C for 2h, intermetallic compound layers were observed distinctly to generate. The intermetallic compound layers were identified to be Al_3Mg_2 on the Al side and $Mg_{17}Al_{12}$ on the Mg side.

3) With increasing the annealing temperature and time, the thickness of the intermetallic compound layers increased significantly. A good agreement between the values of the thickness of the intermetallic compound layers obtained by calculation and experiment was achieved.

4) The tensile strength of the composite plates increased after annealing at 200˚C. After annealing at and above 250˚C, due to the formation of the intermetallic compound layers, the strength was dramatically decreased, the phenomenon of debonding along with the interface was took place. Moreover, by increasing the annealing temperature, the elongation of the composite plates increased significantly.

Acknowledgments

This work was supported by the Natural Science Foundation Project of China (Grant No. 51375328).

References:

[1] Hirsch J, Al-Samman T. Superior light metals by texture engineering: Optimized aluminum and magnesium alloys for automotive applications. Acta Mater. 2013;61:818-843.

[2] Liu FC, Liang W, Li XR, Zhao XG, Zhang Y, Wang HX. Improvement of corrosion resistance of pure magnesium via vacuum pack treatment. J. Alloys Compd. 2008;461:399-403.

[3] Lee KS, Kim JS, Jo YM, Lee Se, Heo J, Chang YW, Lee YS. Interface-correlated deformation behavior of a stainless steel-Al-Mg 3-ply composite. Mater. Charact. 2013;75 :138-149.

[4] Zhang XP, Yang TH, Castagne S, Wang JT. Microstructure; bonding strength and thickness ratio of Al/Mg/Al alloy laminated composites prepared by hot rolling. Mater. Sci. Eng. A. 2011;528:1954-1960.

[5] Lee KS, Yoon DH, Kim HK, Kwon YN, Lee YS. Effect of annealing on the interface microstructure and mechanical properties of a STS-Al-Mg 3-ply clad sheet. Mater. Sci. Eng.A. 2012 ; 556:319-330.

[6] Liu F, Ren DX , Liu LM. Effect of Al foils interlayer on microstructures and mechanical properties of Mg-Al butt joints welded by gas tungsten arc welding filling with Zn filler metal. Mater. Des. 2013;46 :419-425.

[7] Joseph Fernandus M, Senthilkumar T, Balasubramanian V, Rajakumar S. Optimising diffusion bonding parameters to maximize the strength of AAAA6061 aluminium and AZ31B magnesium alloy joints. Mater. Des. 2012;33 :31-41.

[8] Zhu B, Liang W, Li XR. Interfacial microstructure, bonding strength and

fracture of magnesium-aluminum laminated composite plates fabricated by direct hot pressing. Mater. Sci. Eng. A. 2011;528:6584-6488.

[9] Findik F. Recent developments in explosive welding. Mater.Des. 2011;32: 1081-1093.

[10] Mousawi SAA, Al Hassani STS, Atkins AG. Bond strength of explosively welded specimens. Mater. Des. 2008;29; 1334-1352.

[11] Durgutlu A, Gulenc B, Findik F. Examination of copper/stainless steel joints formed by explosive welding. Mater. Des. 2005;26: 497-507.

[12] Honarpisheh M, Asemabadi M, Sedighi M. Investigation of annealing treatment on the interfacial properties of explosive-welded Al/Cu/Al multilayer. Mater. Des. 2012;37:122-127.

[13] Sedighi M, Honarpisheh M. Experimental study of through-depth residual stress in explosive welded Al-Cu-Al multilayer. J Mater Des 2012;37: 577-581.

[14] Bina MH, Dehghani F, Salimi M. Effect of heat treatment on bonding interface in explosive welded copper/stainless steel. Mater. Des. 2013;45:504-509.

[15] Acarer M, Demir B. An investigation of mechanical and metallurgical properties of explosive welded aluminium-dual phase steel. Mater. Lett. 2008;62(25):4158.

[16] Mousavi SAA, Sartangi PF. Effect of post-weld heat treatment on the interface microstructure of explosively welded titanium-stainless steel composite. Mater. Sci. Eng.A. 2008;494:329-336.

[17] Yan YB, Zhang ZW, Shen W, Wang JH, Zhang LK, Chin BA. Microstructure and properties of magnesium AZ31B-aluminum7075 explosively welded composite

plate. Mater. Sci. Eng.A. 2010;527:2241-2245.

[18] Macwan A, Jiang XQ, Li C, Che DL. Effect of annealing on interface microstructures and tensile properties of rolled Al/Mg/Al tri-layer clad sheets. Mater. Sci. Eng.,A. 2013;587:344–351.

[19] Akbari Mousavi SAA, Al-Hassani STS. Finite element simulation of explosively- driven plate impact with application to explosive welding. Mater. Des. 2008;29:1-19.

[20] Akbari Mousavi SAA, Farhadi Sartangi P. Experimental investigation of explosive welding of cp-titanium/AISI 304 stainless steel. Mater. Des. 2009;30:459-468.

[21] Kacar R, Acarer M. An investigation on the explosive cladding of 316L stainless steel-din-P355GH steel. J.Mater.Process.Technol.2004;152:91-96.

[22] Kaya Y , Kahraman N. An investigation into the explosive welding/cladding of Grade A ship steel/AISI 316L austenitic stainless steel. Mater. Des. 2013;52 :367-372.

[23] Akbari Mousavi SAA, Barrett LM, Al-Hassanib STS. Explosive welding of metal plates. J.Mater.Process.Technol.2008;202:224-239.

[24] Xia HB, Wang SG, Ben HF. Microstructure and mechanical properties of Ti/Al explosive cladding. Mater. Des. 2014;56:1014-1019.

[25] Wronka .B. Testing of explosive welding and welded joints: joint mechanism and properties of explosive welded joints. J. Mater. Sci. 2010;45:4078-4083.

[26] Yang Y, Wang BF, Hu B, Hu K, Li ZG. The collective behavior and spacing of

adiabatic shear bands in the explosive cladding plate interface. Mater. Sci. Eng. A. 2005;398:291-296.

[27] Song J, Kostkaa A, Veehmayerb M, Raabea D. Hierarchical microstructure of explosive joints: Example of titanium to steel cladding. Mater. Sci. Eng. A. 2011;528:2641-2647.

[28] Brennan S , Bermudez K. Interdiffusion in the Mg-Al System and Intrinsic Diffusion in β-Mg2Al3. Metall. Mater. Trans. A . 2012;43A :4043-4052.

[29] Luo CZ, Liang W, Chen ZQ, Zhang JJ, Chi CZ, Yang FQ. Effect of high temperature annealing and subsequent hot rolling on microstructural evolution at the bond-interface of Al/Mg/Al alloy laminated composites. Mater. Charact. 2013;84:34-40.

Legends of Tables

Table 1 Chemical composition of experiment materials used in this study (mass%).

Table 2 Chemical composition of different regions of Fig.6d via EDS point analysis.

Legends of Figures

Fig.1 Experimental setup of explosive welding process.

Fig.2 The dimension and orientations of tensile test specimens prepared.

Fig.3 (a) SEM images of the composite interface after explosive welding (b) EDS line scan across the composite interface as indicated by line.

Fig.4 Optical micrographs showing the structure of the AZ31B based plate (a) and corresponding high magnification micrographs (b),(c) and (d) on three different areas (B,C,D) shown in (a).

Fig.5 Optical micrographs of the AZ31B near the interface from the explosive welding composite plates annealed at 200˚C,250˚C,300˚C and 400˚C for2h.

Fig.6 SEM images of the composite interface after annealing at different temperature (a)200˚C (b)250˚C (c)300˚C (d)400˚C.

Fig.7 EDS line scan across the composite interface after annealing at different temperatures (a) 200˚C (b) 250˚C (c) 300˚C (d) 400˚C.

Fig.8 EDS spectra from layers marked by letters A (a), B (b), C (c) and D (d) on Fig.6d.

Fig.9 Thickness of intermetallic compounds after annealing at different temperature and holding time.

Fig.10 The comparison of thickness value of intermetallic compounds between experiment and calculation.

Fig.11 Engineering stress-strain curves and macroscopic morphology of the composite plates under various conditions.

Fig.12 Tensile properties summarization of the composite plates under various conditions.

Fig.13 SEM images of tensile fracture interfaces of composite plates annealed at different temperature (a) 200˚C (b) 250˚C.

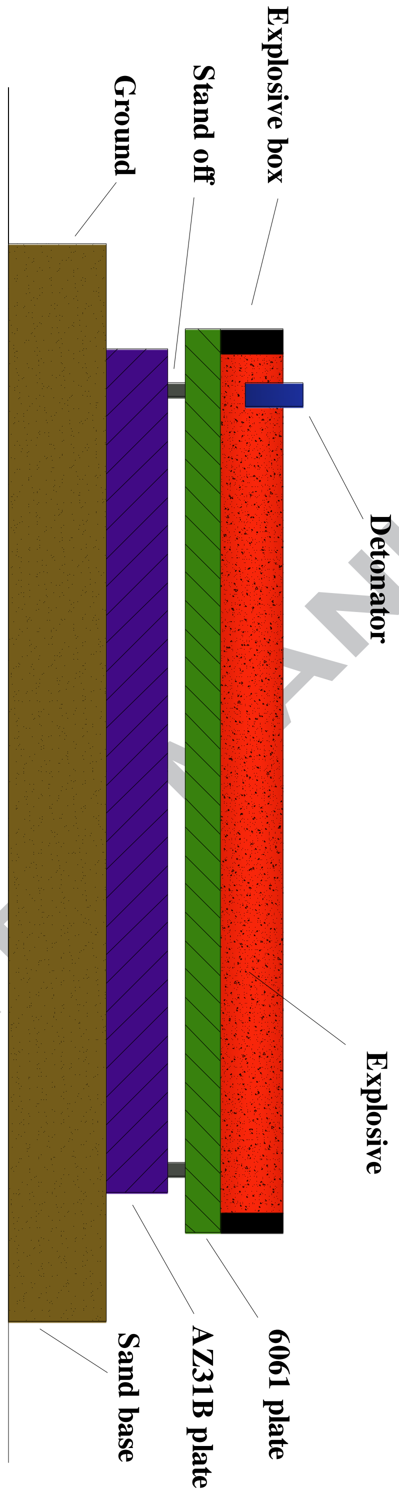

Fig.1. Experimental setup of explosive welding process

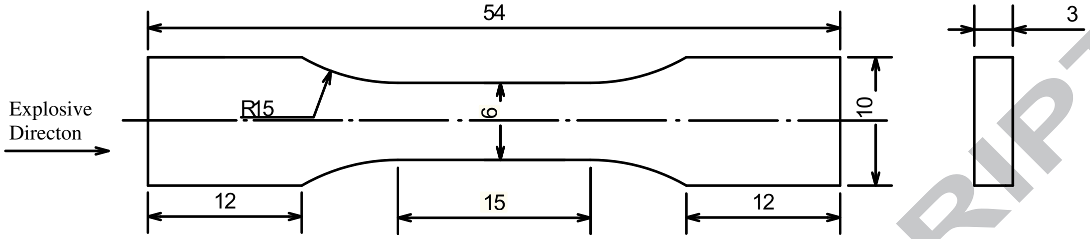

Fig.2. The dimension and orientations of tensile test specimens prepared.

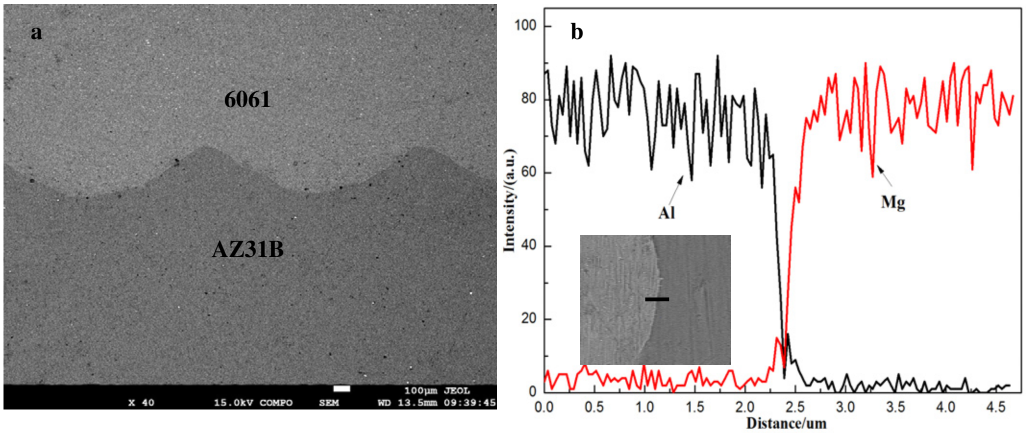

Fig.3. (a) SEM images of composites interface after explosive welding

(b) EDS line scan across the composite interface as indicated by line.

1

31B

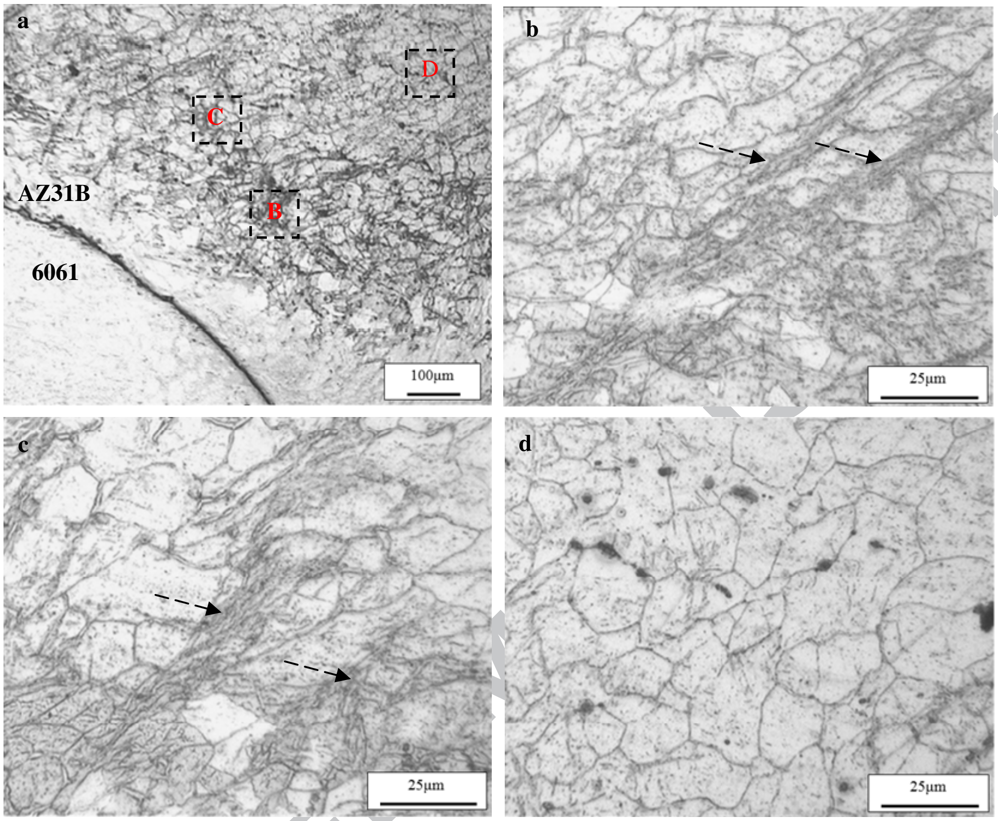

Fig.4. Optical micrographs showing the structure of the AZ31B based plate (a) and corresponding high magnification micrographs (b),(c) and (d) on three different areas (B,C,D) shown in (a).

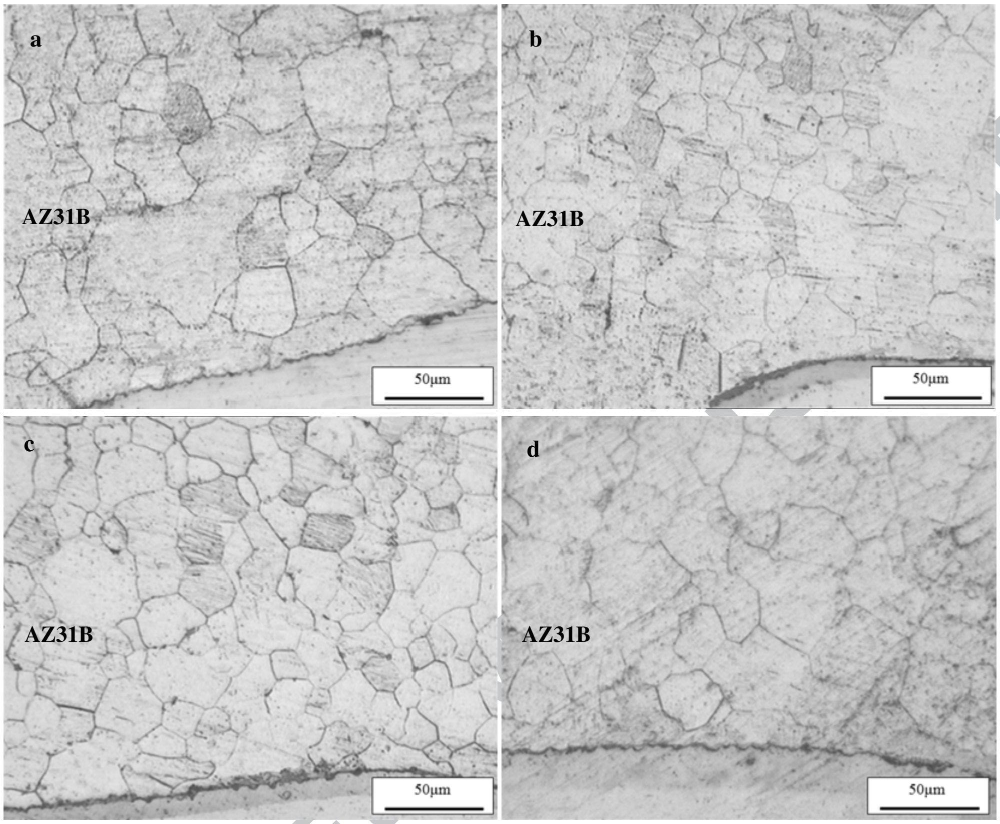

Fig.5. Optical micrographs of the AZ31B near the interface from the explosive welding composite plates annealed at 200˚C,250˚C,300˚C and 400˚C for2h.

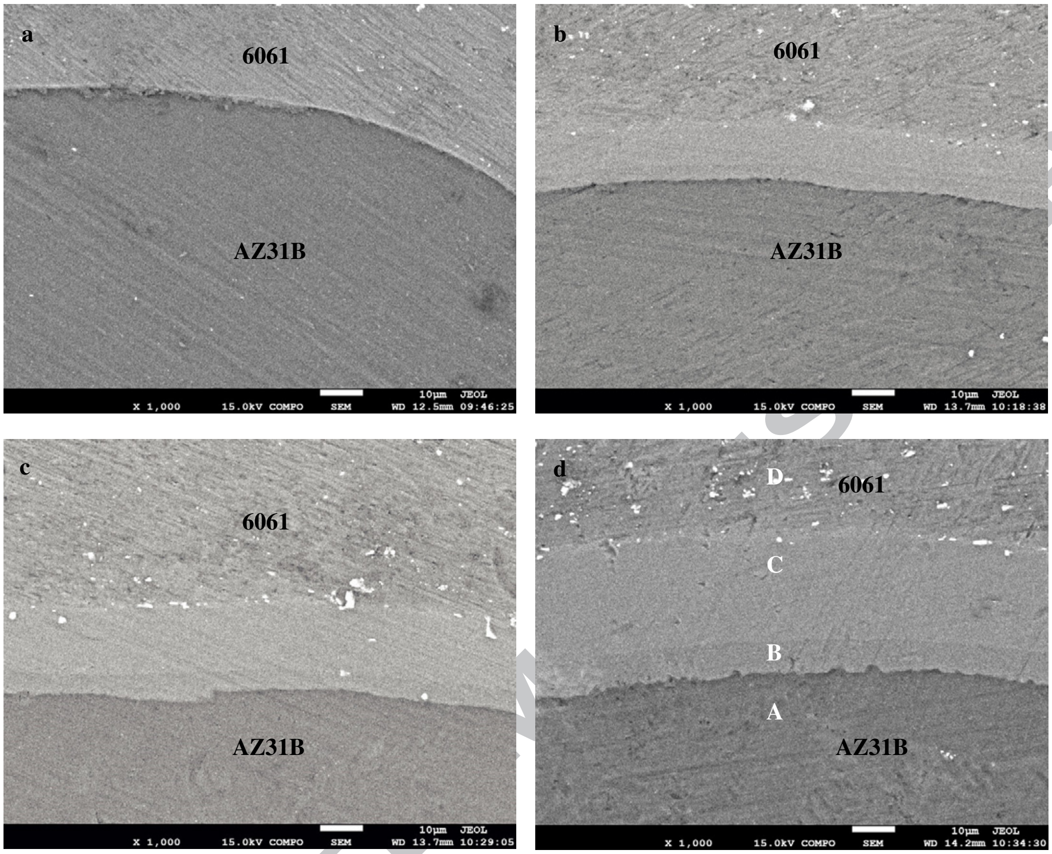

Fig.6. SEM images of composites interface after annealing at different temperature

(a)200˚C (b)250˚C (c)300˚C (d)400˚C

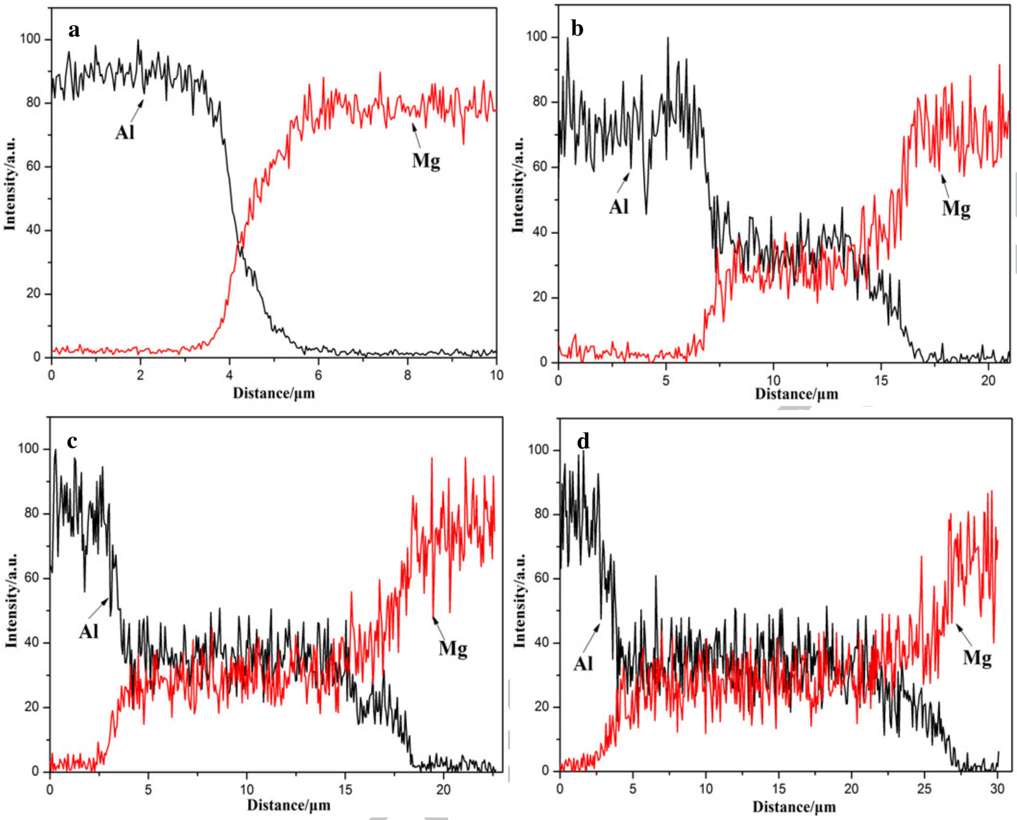

Fig.7. EDS line scan across the composite interface after annealing at different temperature (a)200˚C (b)250˚C (c)300˚C (d)400˚C.

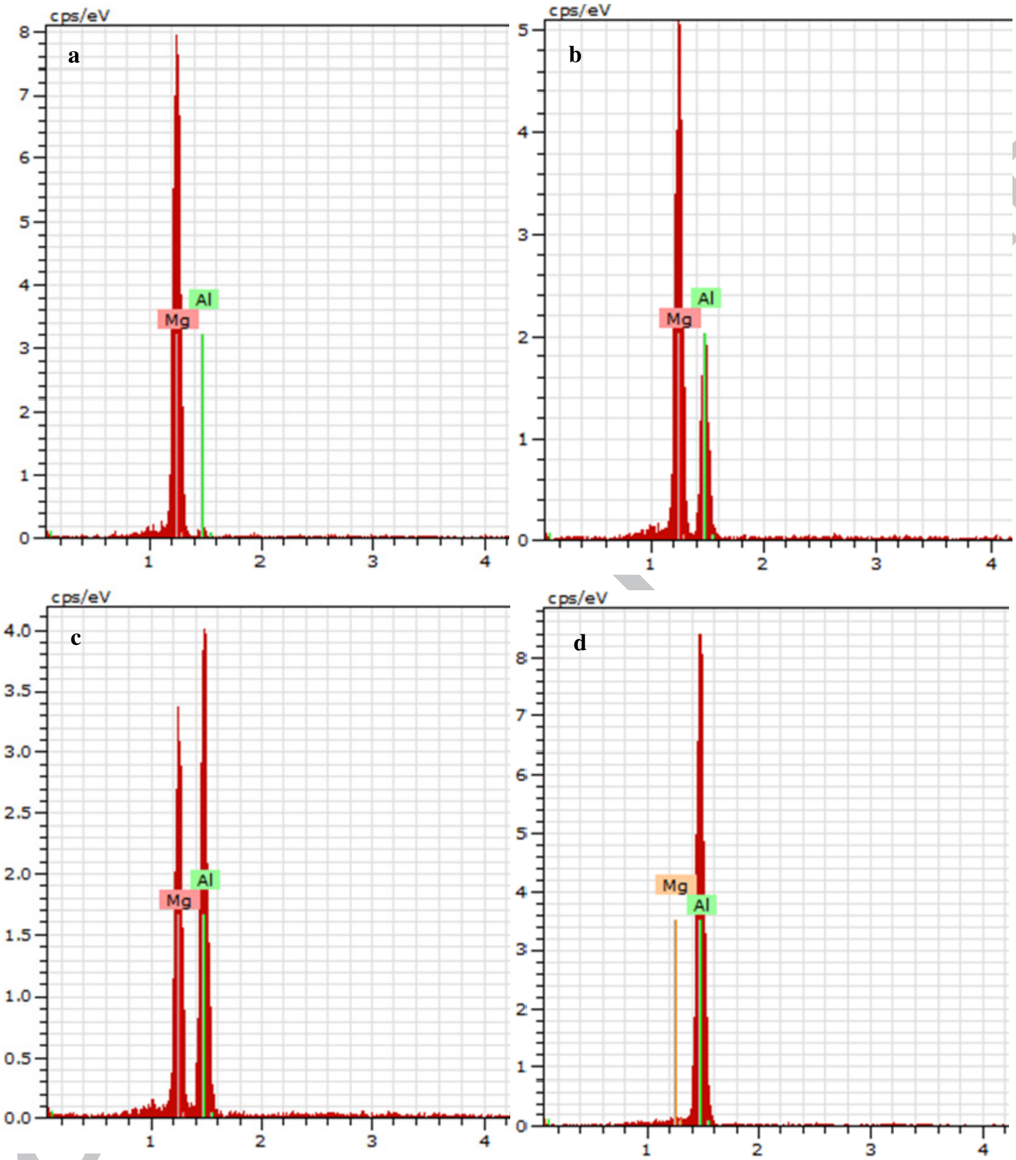

Fig.8. EDS spectra from layers marked by letters A (a),B (b),C (c) and D (d) on Fig.6d

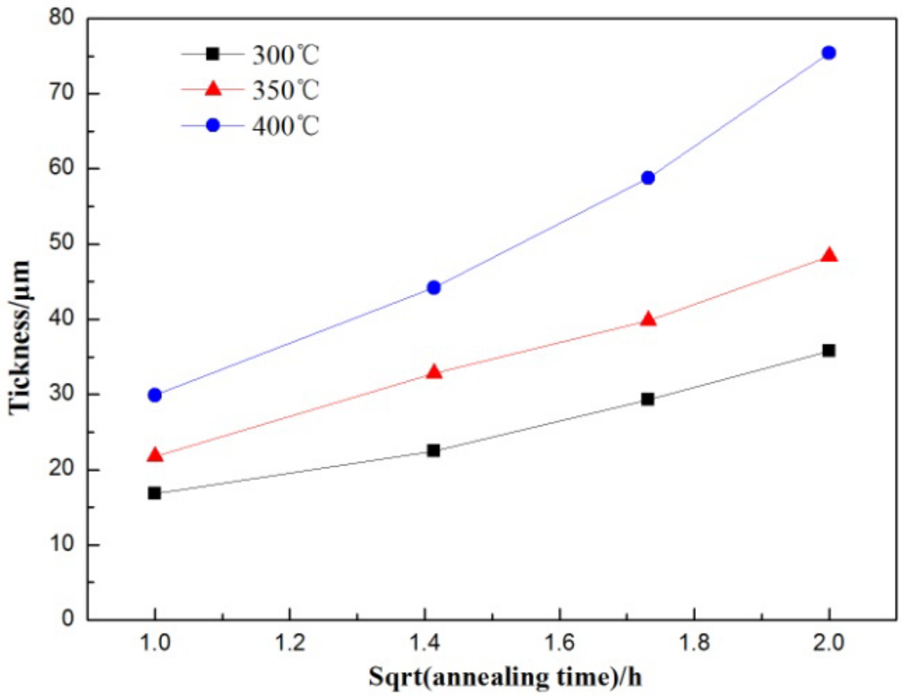

Fig.9. Thickness of intermetallic compounds after annealing at different temperature and holding time.

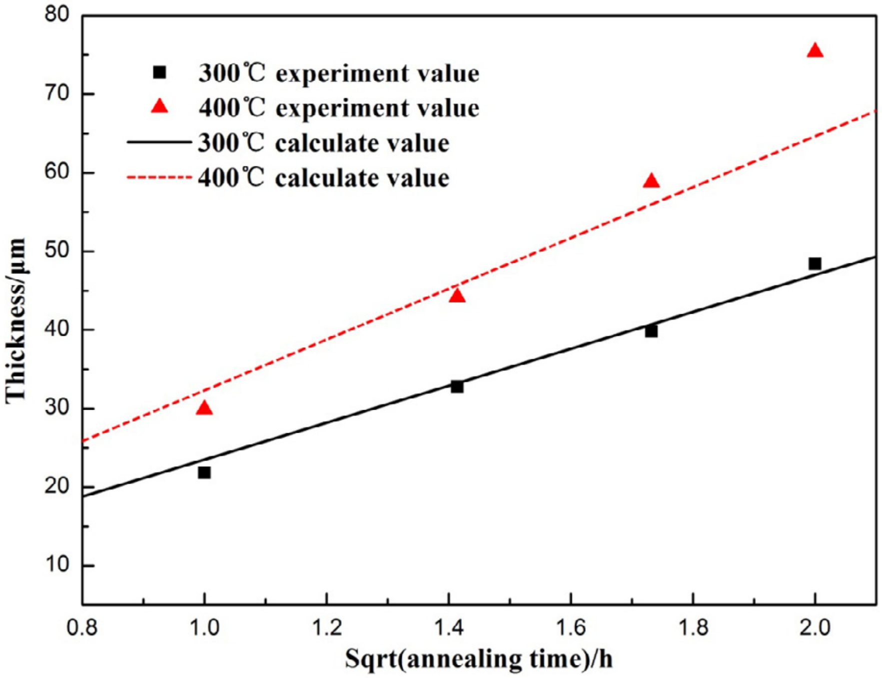

Fig.10. The comparison of thickness value of intermetallic compounds between experiment and calculation.

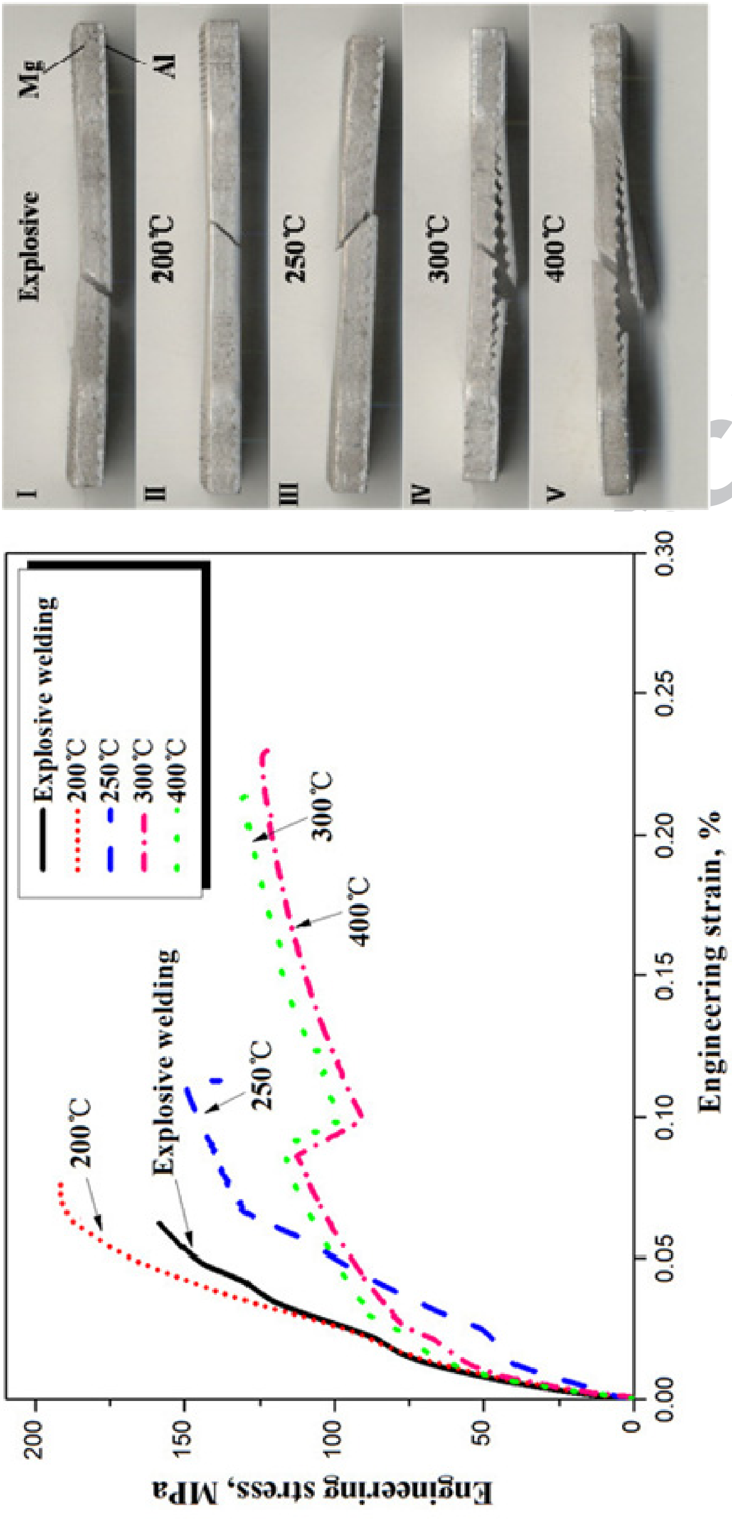

Fig.11. Engineering stress-strain curves and macroscopic morphology of the composite plates under various conditions.

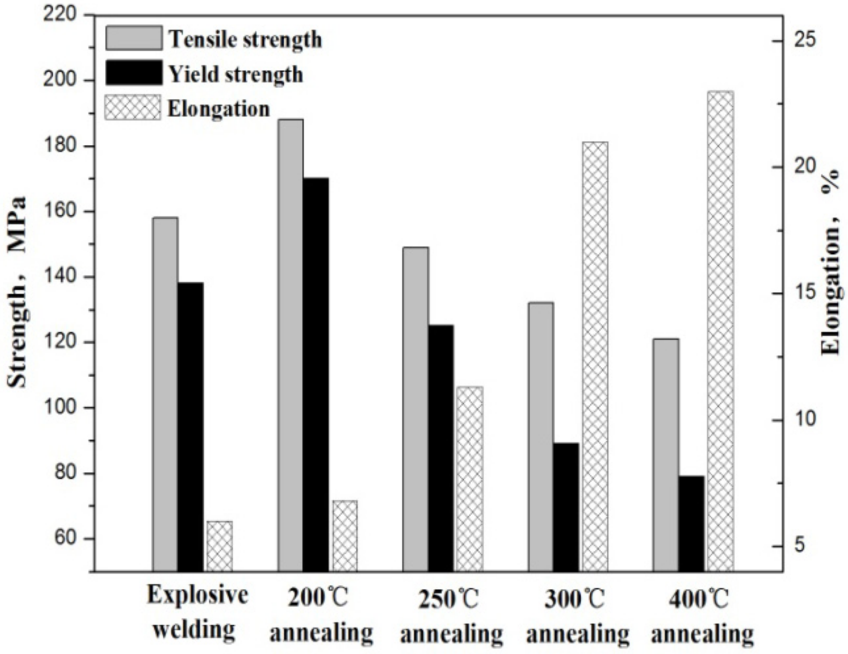

Fig.12. Tensile properties summarization of the composite plates

under various conditions.

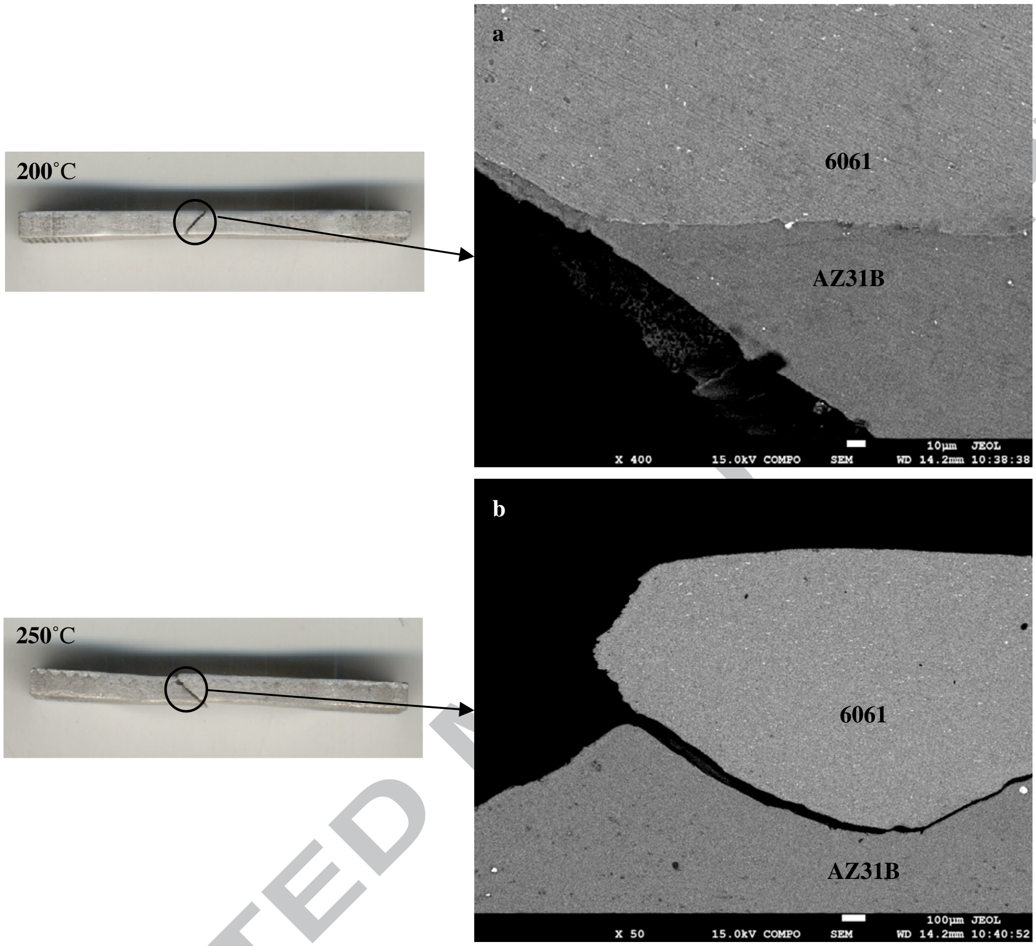

Fig.13. SEM images of tensile fracture interfaces of composites plates annealed at different temperature (a)200˚C (b)250˚C.

Highlights

- Mg/Al composite plates were successfully obtained through explosive welding.
- The evolution of interface microstructure after explosive welding and annealing were firstly investigated.
- The tensile strength first increased and then decreased with increasing annealing temperature.
- Intermetallic compound layers at the interface resulted in the interface delamination.

Table 1 Chemical composition of experiment materials used in this study (mass%).

Materials	Mn	Mg	Zn	Ti	Si	Fe	Al
AZ31B	0.63	Rest	1.10	-	0.10	0.005	3.02
6061	0.15	0.8~1.2	0.25	0.15	0.4~0.8	0.7	Rest

Table 2 Chemical composition at different regions of Fig.6d via EDS point analysis.

	Al（at.%）	Mg（at.%）	Compound
Point A	3.55	96.45	-
Point B	39.73	60.27	$Al_{12}Mg_{17}$
Point C	59.19	40.81	Al_3Mg_2
Point D	95.32	4.68	-