International Conference on Mechatronics, Electronic, Industrial and Control Engineering (MEIC 2015)

Effects of Cu-Zn alloy additions on microstructure and strength of welded joints between magnesium alloy and mild steel

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Abstract—Experimental investigations on lap welding of magnesium alloy to steel using resistance spot welding with Cu-Zn alloy interlayer are carried out. The effect of welding time, welding current and interlayer thickness on the bonding mode of interface and joint strength has been investigated using mechanical testing and metallurgical examination. The results show that the strength of Mg-steel joints without an interlayer could reach 30 MPa by the optimization of welding current and time. The addition of alloy elements, realized by adjustment of interlayer thickness, has a noticeable effect on mechanical properties and microstructure of the joints. Particularly, with the addition of Cu-Zn interlayer (0.1 mm in thickness), the tensile strength could attain 62 MPa. Owning to the addition of the Cu-Zn alloy interlayer, a metallurgical bonding between Mg alloy and steel is achieved based on the formation of intermetallic compounds of CuMgZn and solid solutions of Cu in Fe. In addition, the formation of pores at the interface of Mg alloy and steel is adverse for the strength improvement of joints.

Keywords-Mg alloy; steel；welding style; interface

I. INTRODUCTION

Resistance spot welding (RSW) is widely used in automobile industry and aircraft industry. Mg alloy, Al alloy and steel have been joined using RSW technology [1-3]. Recently, the welding of dissimilar materials by RSW has attracted vast attention. For example, some studies on RSW of Al to steel have been published [4-7].Studies show that the addition of a Mg-free Al foil or an aluminum clad steel sheet between Al alloy and steel as the transition material is a good method for the improvement of joint strength. RSW of Al-steel supplies a good fabrication technique for the incremental replacement of steel by Al. Mg alloy is the lightest structural material, so the joining of Mg alloy and steel also has an important role in significant reductions in weight. However, the joining of Mg alloy and steel is more difficult than that of Al alloy and steel. Firstly, the melting temperature of the steel is greater than 1773 K, which is much higher than the boiling temperature of Mg (about 1363 K). The tremendous difference in the melting and boiling points between Mg and Fe would cause the difficulty in melting them at the same time during welding. Secondly, there is almost no inter solubility and reaction between Mg element and Fe element, which implies Mg and steel could not mix in the liquid state. Thus, it is very difficult to join directly Mg alloy to steel [8, 9]. Therefore, for the RSW of Mg to steel, only a few studies have been published at present.

Liu et al. studied the joining of Mg alloy AZ31B and zinc-coated DP600 steel sheets using RSW. The result shows that Zn coating on the steel plays a role of brazing filler metal and improves the weldability between Mg and steel [10]. In the studies of other welding technology, additions of metal interlayer could also play a good role in the joining of Mg and steel. For example, the Cu-Zn metal interlayer was inserted between Mg and steel to facilitate the joining of them. Then, Mg alloy AZ31B to bare-steel was realized by laser-TIG hybrid welding technique [11]. Therefore, RSW is a promising welding technology to join Mg alloys and steel by the addition of a Cu-Zn interlayer.

In the current investigation, the Cu-Zn interlayer is made for the first time to improve the weldability and microstructure of Mg alloy and steel in the RSW. Our emphasis in this paper is mainly on the feasibility o f Mg alloy and steel by the addition of a Cu-Zn interlayer using RSW, substantiated by some preliminary microstructural findings.

II. EXPERIMENTAL PROCEDURES

The base materials used were AZ31B Mg alloy and Q235 steel, and the two plates were overlapped with the Mg alloy plate on top. The Cu-Zn interlayer was set between the two plates. The compositions and sizes of them are shown in Table 1. Before welding, they were degreased and ground by acetone and abrasive papers. The specimens were welded using a median-frequency DC RSW machine. RSW process was carried out in an air atmosphere. Flat-ended, round, Cu-1.0%Cr electrodes of 8 mm diameter were used. Welding time is from 0.1 s to 0.8 s and welding current is from 4 kA to 11 kA. The sketch of the experimental setup is shown in Fig .1a.

The samples used for microstructure analyses were abraded by 80#, 400#, 800# and 1000# grit emery papers and then polished by 1.0 μm diamond paste. Afterwards, the samples were etched with picric acid based etchant solution (0.83 mol/L acetic acid, 5.56 mol/L H2O, 0.262 mol/L picric acid and 17.33 mol/L ethanol). Transverse cross-sections were analyzed by scanning electron microscope (SEM) with energy dispersive X-ray spectroscopy (EDS). The phases of joints are analyzed by XRD.

The weld joints were machined into the specimens for the shear testing. Supporting plates were added to both ends of the specimen to maintain the joint interface parallel to the load direction, and to reduce the bending effect of the specimen. Gaps of 2 mm are reserved to avoid friction between the specimen and the supporting plate in oval regions as shown in Fig .1b. The tensile shear strength was calculated as follows:

$\sigma b = F/S$，

where, F and σb_are the load and the ultimate shear strength, respectively. S is a rectangular bonding area of the joint, which could be evaluated according to the size of the fracture surface. The average value of strengths for at least 3 specimens was taken as the shear strength of the lap joint.

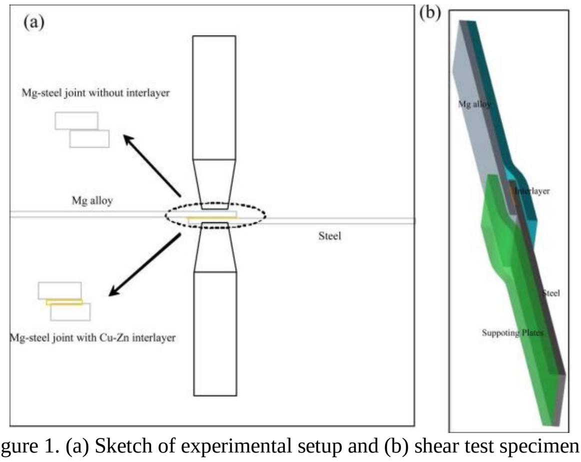

Figure 1. (a) Sketch of experimental setup and (b) shear test specimen.

III. RESULTS AND DISCUSSIONS

A. *Mg-steel joints without a Cu-Zn interlayer*

Fig .2a shows the variation of tensile-shear strength against the welding current (0.5 s of welding time) in the Mg-steel joint without a Cu-Zn interlayer. The joint strength increases first and then decreases with the rise of the current. Fig .2b shows the effect of the welding time (7 kA of current) on the joint strength. The strength also increases first and decreases afterward. For the Mg-steel direct RSW, the higher joint strength can be obtained under the specific conditions of our experiments is about 30MPa. The wettability of Mg alloy on steel is poor, so the lower heat input is adverse for the bonding of Mg alloy and steel. But the higher heat input easily induces the formation of a large number of pores at the Mg-steel interface as shown in Fig .3.

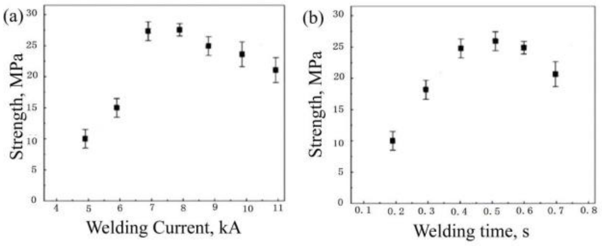

Figure 2. The variation of tensile-shear strength against the (a) welding current and (b) welding time.

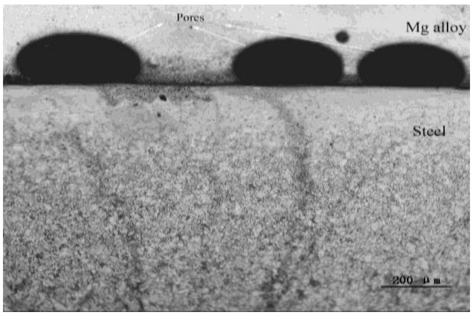

Figure 3. Cross-section morphology of Mg-steel joints with 0.5 s of welding time and 9 kA of welding current.

Fig .4 shows the cross-section view of the joint with 0.5 s of welding time and 7 kA of current. It is found that melting of Mg alloy side plays a dominant role in the Mg-steel RSW because of the lower melting points of Mg alloy.

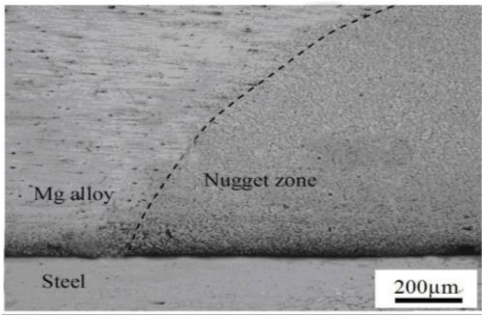

Figure 4. The cross-section view of the joint with 0.5 s of welding time and 7 kA of current.

Fig .5a shows the microstructure of Mg-steel interface. It is found that Mg alloy and steel form a mechanical bonding with some pores. Fig .5b shows the line analysis of Fe and Mg elements from top of the scanning line to bottom in the Fig .5a. Little diffusion between steel and Mg alloy is detected, which coincides with the micro-structural variation of interface zone. It is apparent from the Mg-Fe binary equilibrium phase diagram that the solid solubility of Mg in Fe is 0.00043at.%, furthermore, there are not any types of intermetallic compounds between them. After welding, Mg alloy and steel form a mechanical bonding. In addition, the low wettability between Mg and steel results in the formation of interface defects, which is adverse for the strength improvement of the joint [9].

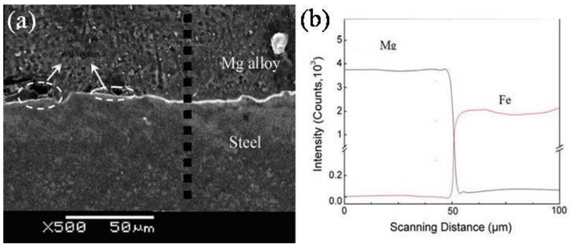

Figure 5. (a) The microstructure of Mg-steel interface and (b) line scan.

In a word, the optimization of the welding parameters has little effect on the improvement of the strength of welded joints.

B. *Mg-steel joints with a Cu-Zn interlayer*

To improve strength of the joint, Cu-Zn interlayer was selected as a transition layer. The influence of its content on the joint strength was investigated by the change of the interlayer thickness. Fig .6 shows the effect of interlayer thickness on the strength of Mg-steel joints. It can be seen that the joint strength increases first and then decreases to a lower value. As the interlayer thickness increases from 0.05 to 0.1 mm, the average tensile strength increases from 44 MPa to 62 MPa. Then it decreases to 27 MPa with the interlayer thickness varying from 0.2 mm to 0.3 mm. It can be noticed in Fig 6. that the tensile strength of the joints with a 0.1 mm interlayer attains a maximum value of 62 MPa, about twice than that of the Mg-steel joint without an interlayer. The addition of interlayer could improve significantly the strength of Mg-steel joints, while the addition of a 0.3 mm thick interlayer is unfavorable for improving the strength. The thermal conductance of Cu-Zn interlayer is high, so it must enhance the thermal input in order to melt the Cu-Zn inter layer when its thickness increases to a higher value in the experiment. Moreover, further increasing heat input would increase the volatilization of Mg alloy and lead to the formation of large pores, which could result in the decrease of strength as shown in Fig .7.

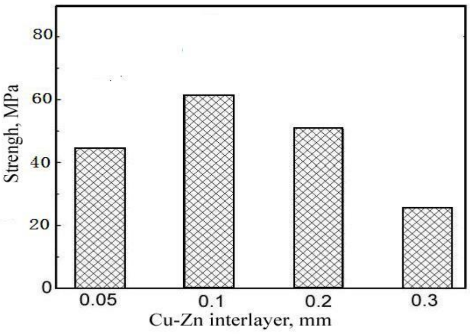

Figure 6. The effect of interlayer thickness on the strength of Mg-steel joints.

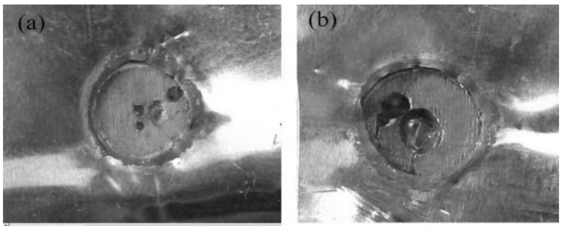

Figure 7. Fracture morphologies of Mg alloy side in the Mg-steel joint with the addition of a Cu-Zn interlayer: (a) 0.2 mm in thickness and (b) 0.3 mm in thickness.

The joint with a 0.1 mm interlayer in thickness are further investigated. Fig .8a shows the macrostructure characteristic of right side of a cross-sectioned joint. Two regions are defined according to the reaction content between Cu-Zn interlayer and substrate. The difference in the degree of reaction is determined mainly by the characteristics of the heat source in the RSW [12].

Fig .8b shows the microstructure of Zone A of Mg-steel interface in Region Ⅰ. It is found that the Ni interlayer almost disappears and dissolves into the Mg substrate. In order to investigate the element diffusion of Mg-steel interface zone (Region Ⅰ), line scan along the scanning line shown in Fig .8b was analyzed, and the results are in shown in Fig .9. It can be seen that Cu element diffuses into the steel substrate, resulting in the formation of transitional layers between the weld seam and steel, and the width of the transition layer is very small. In addition, no interaction occurs between Zn or Mg and Fe at the interface. EDS analysis shows that the position D in Fig .8b contains mainly Fe with a little Cu, indicating that the observations in this region are mainly supersaturated solid solutions of Cu in Fe in terms of the Fe-Cu binary phase diagrams. For the Cu element in the layer, it is visible that it could facilitate the reliable and sound bonding of the Mg alloy and steel. For the Zn element in the interlayer, on one hand, it could lower the melting point of interlayer and reduce the heat input during the welding process. On the other hand, the boiling temperature of Zn is lower than that Mg, so it is easy to appear gasification at the interface in the welding process, which leads to the formation of weld defects, such as pores (shown in Fig .8a).

Fig .8c shows the microstructure of Mg-steel interface of Zone B between Region Ⅰand Ⅱ. Incompact phases accumulate on the top of the Cu-Zn inter layer. Zone B includes 54 pct Mg, 34 pct Cu, and 12 pct Zn (wt) by EDS analysis, which indicates that the formation of metallurgical bonding between Mg alloy and residual Cu-Zn interlayer.

Fig .8d shows the microstructure of Mg-steel interface of Zone C in RegionⅡ. For the interface of Mg alloy and Cu-Zn interlayer, the new ribbon-shaped phase layer is generated indicting that Mg and interlayer form a good metallurgical combination. However, for interlayer-steel interface, little inter-diffusion between interlayer and steel is detected, which indicates that there are no reactions between them.

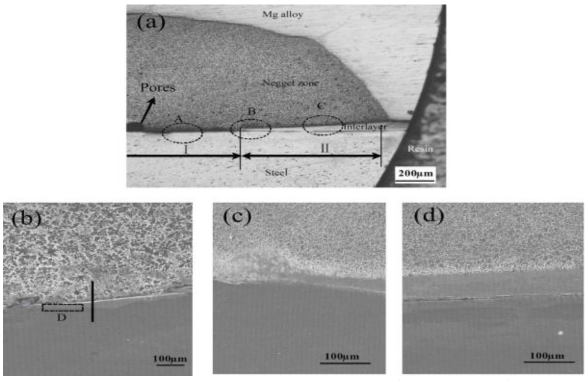

Figure 8. (a) The macrostructure characteristic of right side of a cross-sectioned joint with the addition of a Cu-Zn interlayer: (b) the microstructure of Zone A of Mg-steel interface in Region , (c) the microstructure of Mg-steel interface of Zone B between Region Ⅰand Ⅱ, and (d) microstructure of Mg-steel interface of Zone C in Region Ⅱ.

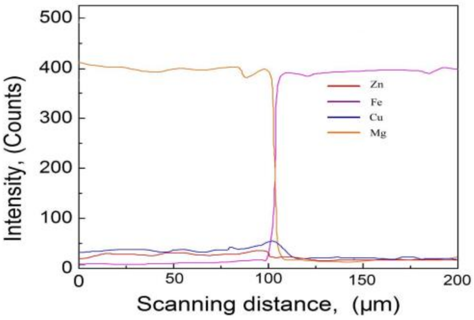

Figure 9. Line analysis along the scanning line of Fig 8b.

In a word, the effect of microstructure of Mg-steel interface in Region I on the strength of joints is the most important, which determines the strength of Mg-steel joints.

Fig .10a shows the microstructure of nugget zone on Mg alloy side. It is found that a large number of white particulates are distributed uniformly along the boundaries of darker grains in the whole weld seam. EDS analysis at position E of Fig .9 shows that the main composition of darker grains is Mg and the white particulates at position F contain elements of Mg, Cu and Zn with a little Al. Fig .10b shows the XRD results of nugget zone, which further proves that the white structures are mainly ternary intermetallic compounds of CuMgZn.

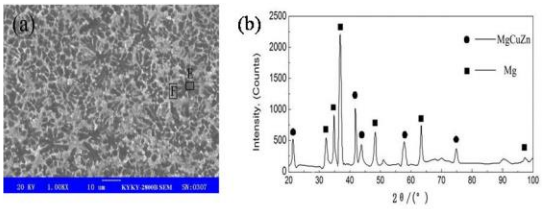

Figure 10. (a) The microstructure of nugget zone on Mg alloy side and (b) XRD result.

IV. CONCLUSIONS

The welding of Mg alloy to steel with the addition of the Cu-Zn alloy interlayer using RSW is successfully realized and the conclusions are as follows:

(1) The strength of the Mg-steel joints could be improved significantly by the addition of a Cu-Zn interlayer. The tensile strength of the joints with a 0.1 mm interlayer attains a maximum value of 62 MPa, about twice than that of the Mg-steel joint without an interlayer.

(2) Contrary to the direct joining of Mg alloy to steel, with the addition of Cu-Zn interlayer, a metallurgical bonding between Mg alloy and steel is achieved based on the formation of intermetallic compounds of CuMgZn and solid solutions of Cu in Fe. In addition, the formation of weld defects is inevitable due to the large difference between Mg alloy and Q235 steel, which is adverse for the strength improvement of the joint.

(3) Owning to the addition of the Cu-Zn interlayer, the compounds of CuMgZn are formed in the whole nugget zone of Mg alloy side.

ACKNOWLEDGMENT

The authors gratefully acknowledge the sponsorship from University Students' innovative training program (DCX140805), Liaoning Province Doctor Startup Fund Program Funded by Liaoning Province Education Administration (20131087) and Doctor Starting Foundation for Shenyang Aerospace University (12YB09).

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