Microjoining developments of ASS316L/AZ31 TLP bonds using Cu and Ni high temperature solid state diffusion

Original Article

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Abstract

Dissimilar joining of austenitic stainless steels to magnesium alloys has recently attained significant attention for the reasons of decreasing the environmental impacts by reducing vehicles emissions and minimizing fuel consumption while maintaining the requireddesign level of mechanical characteristics. This research work is directed toward microscale joining enhancement of the 316 L/(Cu or Ni foils) solid interface through the formation of reaction layers through high temperature solid-state diffusion at 900°C for 15min. Afterward, transient liquid phase bonding (TLP) with AZ31 took place at 530°C and 510°C for 20min using Cu and Ni foils, respectively. The scanning electron microscopy analyses revealed formation of metallurgical micro-reaction films between 316L steel and either Cu or Ni interlayers. Formation of these films enhanced the subsequent TLP bonding with the magnesium alloy AZ31. High temperature solid state interlayer diffusion increases the joint shear strength by 30% when using Cu interlayer and 67% when using Ni interlayer relative to those obtained without the high temperature solid state diffusion stage.

I. INTRODUCTION

The combination of good corrosion resistance, formability, strength, strain hardening sensitivity and crashworthiness madeaustenitic stainless steel alloys suitable for diverse applications particularly for transportation industry[1-3]. When, this grade of austenitic steel is subjected to high strain values, as in the case of crash situations, the work hardening effect increases the strength of the austenitic stainless steel up to 4 times that of its original value [1, 4].

On the other hand, the low density of wrought magnesium alloy AZ31 provides an alternative material to replace heavy structural components with lighter modules in automotive and aerospace industries whereweight reduction and fuel consumptioncost saving can be achieved[5-7]. Recently, many automotive and aerospace components are manufactured using magnesium alloys[7, 8] and austenitic stainless steels[9, 10]. However, joining of these dissimilar alloys still presents a challenge because of thesubstantial distinction in their physical and metallurgical properties[11-13].

Previous research work on joining these dissimilar alloys using direct solid state diffusion bonding revealed limited joint shear resistance of (1.7 KN) when bonding at 550°C for 120 minutes under a bonding pressure of 1.3Mpa. The bond formation was thought to bedue to the formation of Fe-Al intermetallic reaction layer along the steel interface[14]. A meanwhile, the mechanical characteristics of these dissimilar joints were developed by applying thetransient liquid phase (TLP) bonding technique using 20 μm copper interlayers. A record of 57 MPa maximum shear strength was obtained when bonding at 550°C for a bonding time of 30 min. This value represents about 70% of the shear strength of the AZ31 alloy[15]. Furthermore, replacing copper with nickel interlayer when TLP bonding achieved 46 MPa for a bonding time of 20 min at bonding temperature of 510°C[16]. The lower level of shear strength when bonding these dissimilar alloys using TLP bonding techniques is thought to be due to the limited interfacial reaction between the interlayers materials and the stainless steel surface particularly during the early bonding stage as a result of the relatively low bonding temperature. The aim of this study is to enhance the TLP bond characteristics by developing the (Cu or Ni)/316L interface microreaction layers through a direct solid state interlayers diffusion at temperature higher than the melting point of AZ31 prior to TLP bonding to AZ31.

II. EXPERIMENTAL PROCEDURE:

In this research work, samples in form of 5mm thick disks of magnesium alloy AZ31 (3wt%Al, 1wt%Zn

and 96wt %Mg) were cut from a 10mm diameter extruded rod. While, 1 cm³ of the 316L austenitic stainless steel specimens (18wt%Cr, 11wt% Ni, 2wt% Mo, 1.8wt% Mn, 0.03wt%C,1.5wt%Si and 65.7wt%Fe) were cut from a 12 mm thick rolled sheet.The interlayer materials used for the bonding processes were 50μm thick pure copper and nickel foils.

In order to enhance the interlayer/316L interface, prior to TLP bonding to AZ31, the 316L surfaces were finished on 1000 grit SiC paper. Surfaces of 316L, Cu and Ni interlayer thenultrasonically cleaned in acetonebath before joining the Cu/316L and Ni/316L using solid-state diffusion bonding at 900ºC for 15 minutes at a bonding pressure of 2 MPa in a vacuum chamber under pressure of 4×10⁻⁷ bar[17-19]. After diffusion bonding stage, the bare surfaces of the interlayers were polished using 1μm diamond paste before TLP bonding with the AZ31 specimens.

For TLP bonding, surfaces of AZ31 specimens were ground down to 1000 grit finish on SiC paper, then cleaned with ethanol. For TLP dissimilar bonding of AZ31/Cu-316L sandwiches were performed at 530ºC for 20 minutes and under a 0.2 MPa bonding pressure. These bonding parameters were selected in accordance with the highest level of bond shear strength revealed by the author previous research finding[15, 16]. However sandwiches of AZ31/Ni-316L were bonded at 510ºC for 20 minutes and under a 0.2 MPa bonding pressure[14, 20]. TLP bonding was performed in a vacuum chamber at a pressure of 4×10⁻⁷ bar and with induction heating rate of 0.8ºCs⁻¹. K-type thermocouples were inserted close to the bond interface in order to monitor bonding temperature. For microstructural examination and compositional analyses, the bonded samples were cut transversely through the joint region, mounted in bakelite and polished using 3μm diamond suspension and then examined using the SEM.

III. RESULTS AND DISCUSSION

- Solid State Diffusion of Interlayer Foil to 316L Interface:

In order to enhance the interfacial reaction between the interlayer materialsand the 316L base metal diffusion bondingfor 15 min under axial pressure of 2 MPa was performedat a bonding temperature of 900ºC which is much higher temperature than the melting one of the AZ31 base metal.

Fig. 1 illustrates SEM micrographs of Cu/316L (a) and Ni/316L (b) interfaces after solid state diffusion bonding, respectively. It can be noticed that, along the Cu/316L interface a discontinuous reaction layer in a form of separate grains within the Cu matrix is formed. However, for Ni/316L the separation line between the Ni foil and the 316L base metal is completely disappeared. The bonded interfaces show intimate contacts between the interlayer surfaces for both Cu and Ni with the 316L base metal.

The AFM scanning micrographs taken across Cu/316L and Ni/316L interfaces after solid state diffusion, shown in Fig. 2, revealed the absence of interfacial microvoids or interlayer delamination marks and confirmed that the applied pressure and surface finish provide high surface/surface contact and facilitates the solid state diffusion at the selected conditions.

The EDS spectrum Fig. 3 (a), and WDS quantitative point analyses of a Cu/316L reaction layer grain confirmed the occurrence of diffusion between the base metal 316L alloying elements and the Cu interlayer where an elemental composition of (7.2%Cr, 25.9%Fe, 63.4%Cu, 2.5Ni and 0.6%Mo) was recorded. Moreover, the line analyses along line segment (I-I), shown by Fig.3 (b) revealed Cu diffusion along the 316L surface and along the subsurface grains forming a heterogeneous reaction layer.

On the other hand, SEM micrograph and WDS line analyses across the of Ni/316L interface after solid state diffusion, shown in Fig. 4, revealed that the 316L/Ni interface witnessed formation of about 10μm homogeneous Ni/Fe reaction layer where Ni and Fe concentrations are gradually changed until reaching the base metal concentration without forming detectable intermetallics compounds.
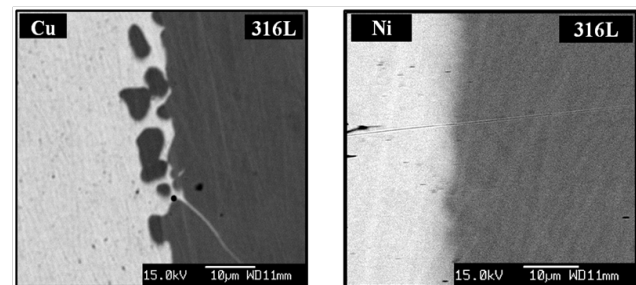

Fig. 1: Interlayer and steel base metal interface after solid state diffusion (a) Cu/316L and (b) Ni/316L.
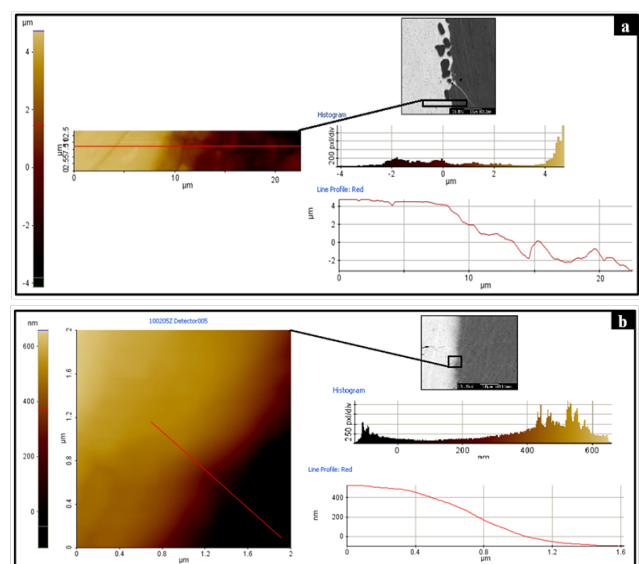

Fig. 2: AFM scanning results for interlayer/316L diffusion bonded interface (a) Cu/316L and (b) Ni/316L.
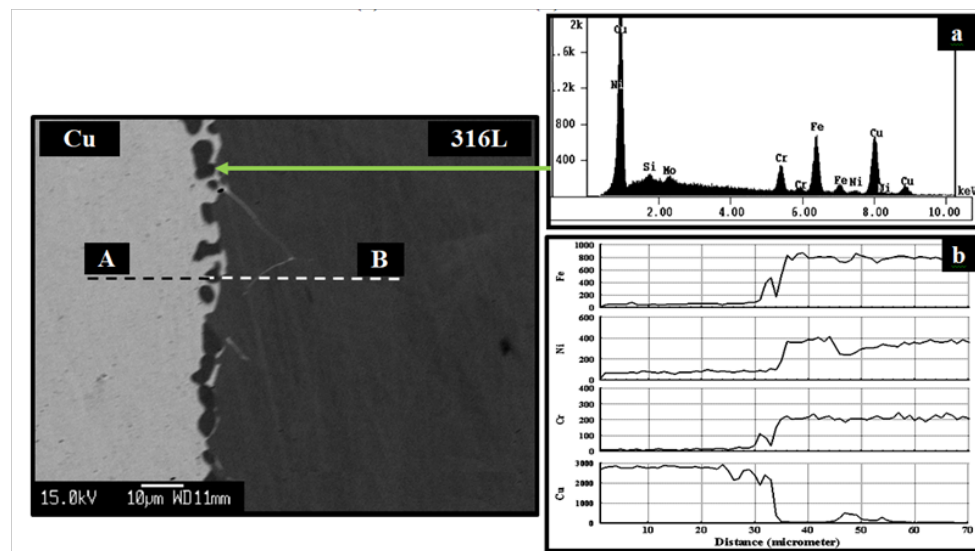
Fig. 3: Elemental analyses along the Cu/316L interface (a) EDS point analyses, (b) WDS line analyses across the diffusion bonded interface.
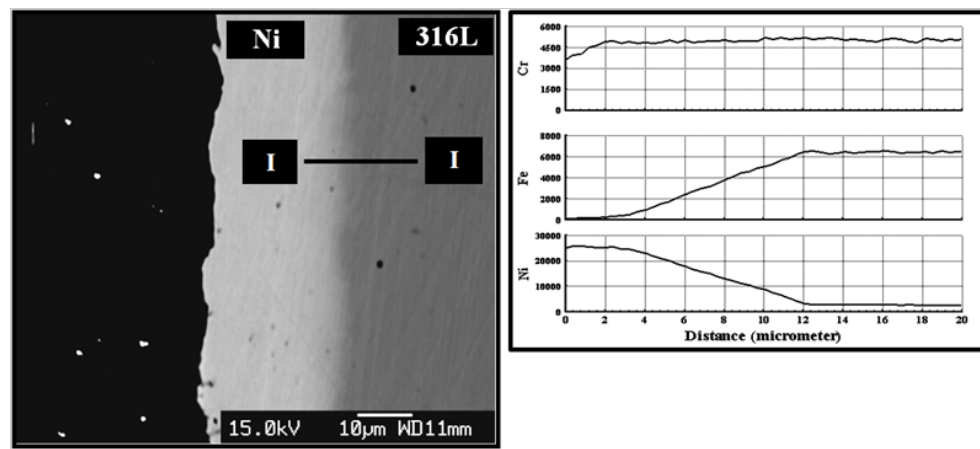

Fig. 4: Elemental analyses along the Ni/316L diffusion bonded interface.

- TLP Bonding of AZ31 Alloy to Cu-316L Joint:

After successful solid state diffusion bonding between the copper foil and AZ31 base metal, AZ31/Cu-316L sandwich combinations are TLP bonded at 530°C for 20 minutes under 0.2 MPa of bonding pressure. The SEM micrograph of the TLP bond interface shown by Fig. 5, illustrates generation of (Mg-Cu) lamellar eutectic liquid phase along the 316L base metal interface. Formation of the eutectic bond takes place through (Mg-Cu) solid state diffusion until reaching the eutectic composition, eutectic liquid phase generation, spreading and wetting of bonded interfaces followed by isothermal solidification as a result of further Mg diffusion towards the liquid layer[16, 21]. The SEM micrograph declared also that, along the bond interface (Mg-Cu-Al) intermetallic phase was performed[22]. In addition, a discontinuous fine intermetallic layer is continuously observed along the 316L bond interface. Point spectra at various locations along this layer, as shown in Fig. 6, indicated that it is multi-elements interfacial intermetallics that consist mainly of (Mg-Al-Cu-Fe-Cr). Furthermore, quantitative analyses of this layer revealed a composition of (35.38%Mg, 2.64%Al, 51.57%Cu, 8.8%Fe and 1.53%Cr). The formation of this layer can be attributed to the diffusion taking place between the eutectic liquid phase that formed between Cu/AZ31 during the TLP bonding process and the preformed Cu-Fe-Ni-Cr discontinuous reaction layer which formed during the direct Cu/316L solid state diffusion. Furthermore, the line analyses across the bond interface, shown in Fig. 5, revealed limited iron dissolution within the bond interface while copper was able to maintain its existence through the 316L base metal after bonding. This development of the elemental diffusion across the 316L base metal interface as a result of earlier Cu-316L solid state diffusion enhanced the bond shear strength where it can reach up to 74MPa. Previous research work recorded that one step AZ31/Cu/316L TLP bonding achieved shear strength of about 57MPa[15]. Therefore, earlier Cu-316L solid state diffusion enhanced the bond strength with an increase of about 30%.
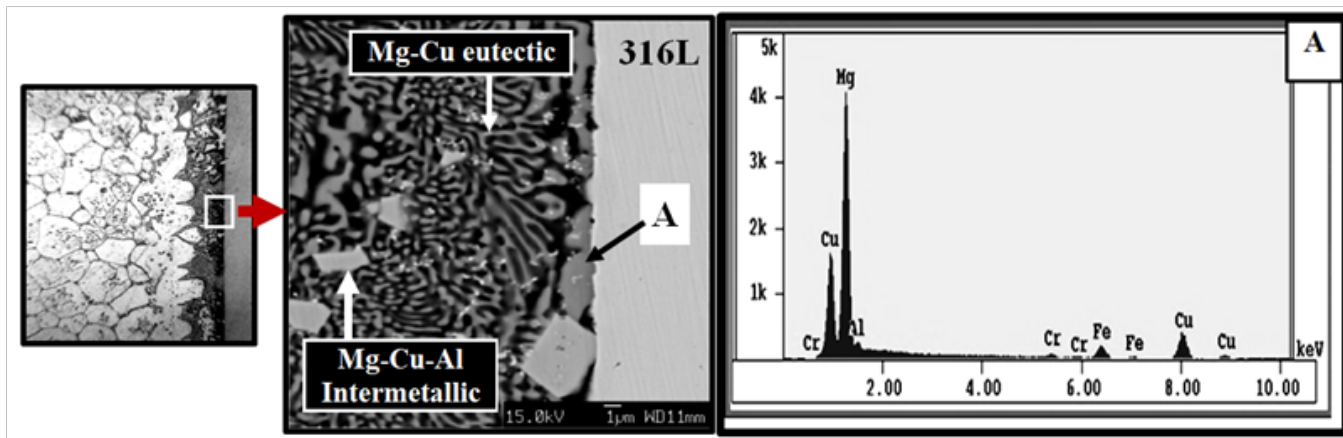
Fig. 5: Micrographs and microstructural analyses of AZ31/Cu-316L TLP joint.
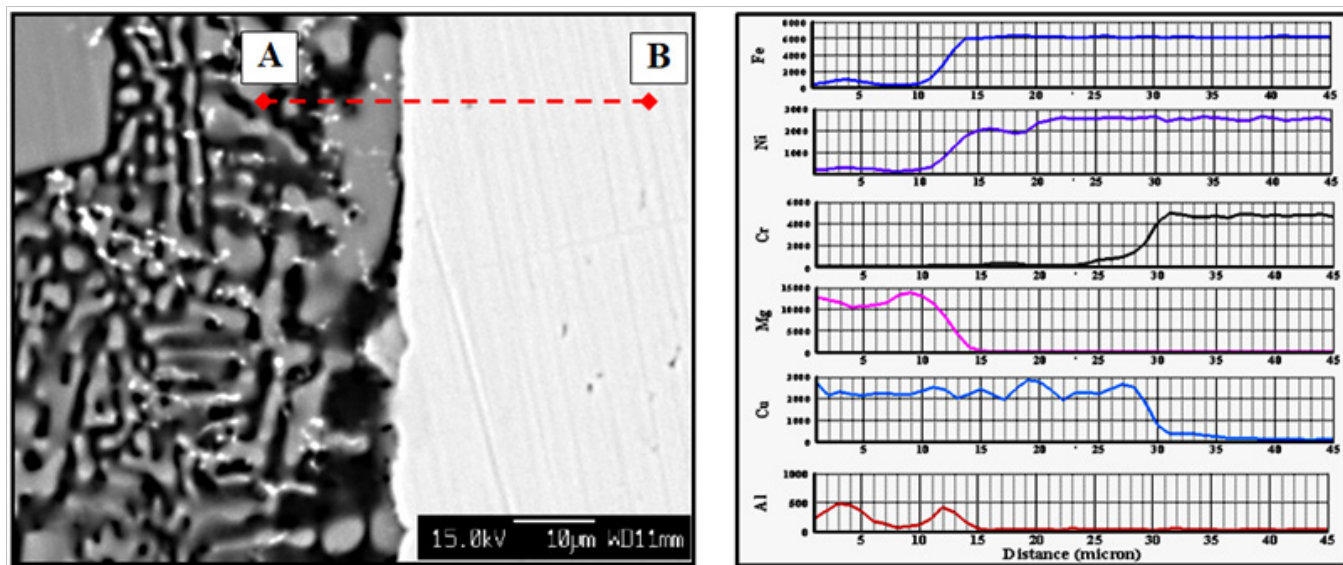

Fig. 6: The line analyses across the AZ31/Cu-316L TLP bonded interface.

- TLP Bonding of AZ31 Alloy to Ni-316L Joint

In a similar way, the Ni-316L solid state diffusion bonded interlayers were TLP joined to the AZ31 magnesium base alloy at 510°C for 20 minutes[14]. The SEM micrograph taken for the 316L-Ni/AZ31 joint interface shown in Fig. 7 revealed a remarkable continuous reaction layer along the 316L after TLP bonding. In addition, lamellar Mg-Ni eutectic phase was generated according the TLP bonding mechanism while Mg-Ni-Al rich intermetallics canbe detected[16].

The compositional analyses of these microstructural features can be declared through the line analysis across the 316L-Ni/AZ31 joint interface shown in Fig. 8. The line spectrum showed that the reaction layer along the 316L interface consists of two regions with remarkable difference in composition. The region located close to the AZ31/Ni eutectic reaction consisted of the elements Fe-Cr-Ni-Mg-Al while the one located towards the Ni-316L interface was still reach with Ni in level higher than that originally exist within the 316L steel. Considering the earlier Ni-316L solid state bonding, it can be concluded that during the TLP bonding process, surface wetting by the eutectic liquid phase facilitates Mg diffusion and interaction with the Fe-Ni reaction layer causing Ni depletion within this region and developedametallurgical bondinterface along the steel side.

The shear test ofAZ31/Ni-316L bonded sandwichat 510°C for 20 minutes showed shear strengthof about 53.5MPa. The previous research work on direct AZ31/Ni/316L TLP bonding recorded a maximum level of bond shear strength of about 32MPa[16]. It can be noticed

that earlier solid state interlayer diffusion successfully achieved a 21.5MPa increase of the bond shear strength which represent about 67% increase with respect to the reported value. However, existence (Mg-Ni-Al) intermetallics along the bond interface still weakening the joint mechanical properties relative to the shear strength of the AZ31 base metal alloy (82.4MPa).
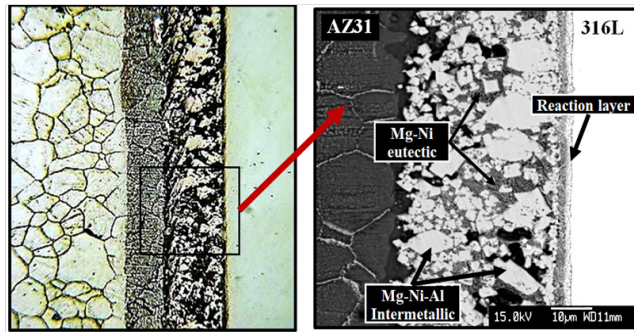

Fig. 7: Optical and SEM Micrographs of AZ31/Ni-316L TLP joint.
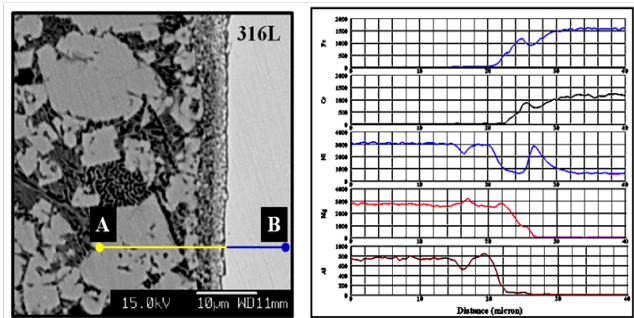

Fig. 8: The line analyses across the AZ31/Ni-316L TLP joint interface.

IV. CONCLUSION

Direct TLP bonding between AZ31 and 316L using Cu foil interlayer at 530°C for 20min achieved bond shear strength of about 57MPa while using Ni using foils at 510°C for 20min achieved bond shear strength of about 32MPa. The low level of bond strength relative to AZ31 alloy can be related to the lower metallurgical interaction along the steel interfaces as a result of the low bonding temperatures.

Applying earlier solid state diffusion between 316L base metal and interlayer foils (Cu or Ni) at 900°C for 15min developed remarkable reaction layers along the steel side that were discontinuous when using Cu foils while it was uniform and continuous when using Ni foils.

Further TLP bonding with AZ31 at the recorded optimum conditions promote formation of metallurgical bonds along the steel side and resulted in an average bond shear strength of about 74MPa with an increase of about

30% when using Cu interlayer and about 53.5MPa with an increase of about 67% when using Ni interlayer foils.

V. REFERENCES

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