Characterization of a high strength Al-alloy interlayer for mechanical bonding of Ti to AZ31 and associated tri-layered clad

Yasser Fouad 1,*

Faculty of Engineering and Materials Science, German University in Cairo – GUC, Main Entrance Al Tagamoa Al Khames, New Cairo City, Egypt

Received 31 October 2013; revised 24 February 2014; accepted 6 March 2014
Available online 8 April 2014

Abstract The Al 6081 alloy is proposed as a favorable interlayer alloy with satisfactory deformability characteristics; high strength; least reactivity and melting temperature for high temperature joining of pure Ti and AZ 31. Titanium and Magnesium sheets with Al–0.81 Mg–0.9 Si alloy interlayer plate were joined by cold-roll bonding and subsequent annealing treatment. The maximum strength after annealing at 550 °C is due to the combined effect of the precipitation strengthening of Al–Mg–Zn interlayer and static strain aging. The most pronounced increase in the Vickers microhardness (from 49.2 to 74.5 Hv) was observed in the Al 6081 interface with AZ31 and Ti, thus indicating Al 6081 as a sound bonding interlayer with a lower melting temperature, initial excellent deformability and high strength after joining. With the increase in heat-treatment temperature, the tensile strength increased initially up to 550 °C and then decreased with the increase in annealing temperature to levels above 550 °C. The threshold deformation is about 44% of the total rolling reduction in a single rolling pass. The highest mechanical properties were 35 MPa in the composite – which was obtained by 550 °C/2 h annealing treatment.

1. Introduction

With the advancement of technology, the demand for leading-edge materials with enhanced properties and various functions increased [1–6]. It has become more difficult to satisfy the combination of various properties such as superior environmental-resistant characteristics, mechanical and biochemical properties in a single material. To meet such demands, clad materials in which different metals and alloys-with various properties were joined – have been developed and used in various industrial fields [1–3]. The properties of clad materials

* Tel.: +20 2 7589990 8, mobile: +20 1272001133; fax: +20 2 7581041.
E-mail address: yasser.fouad@guc.edu.eg.

1 Associated Professor.

Peer review under responsibility of Faculty of Engineering, Alexandria University.

© 2014 Production and hosting by Elsevier B.V. on behalf of Faculty of Engineering, Alexandria University.
are determined by the selection of component materials to be joined and the stacking structure of different materials with various thicknesses and interface structure [3,5,6]. Several methods such as extrusion, rolling, electro-plating, overlay welding and explosive welding have been used for the clad material production and, among these methods, the rolling is one of the most cost-effective and productive processes [1–3,5]. Titanium has excellent corrosion resistance and stability in gaseous and aqueous environment and excellent specific strength compared to steels. Carbon steel has good strength and excellent cost advantage over titanium, but less environmental stability and corrosion resistance. Recently, the efforts to develop mechanically reliable Ti/steel clad [7] material have increased considerably driven by the need for materials with excellent corrosion resistance, good environmental stability, high specific strength and low production cost. A thin layer of expensive corrosion-resistant Ti alloy provides excellent corrosion protection while the thicker – but less expensive high-strength – carbon steel ensures adequate structural strength in Ti/steel clad. Titanium clad steel plates can be used in a variety of industrial fields including shipbuilding, construction and manufacturing of various chemical tanks. More specifically, roll-bonded Ti/steel clad plates are likely to be the economic solution for corrosion resistant applications in refineries, oil and gas production, chemical industry as well as in desalination plants and marine power plants. Cladding titanium/steel with mechanical reliability – at low temperatures – is difficult because of the high melting temperature and low mutual solubility [2,8–10]; explosive welding and diffusion bonding have been frequently used in the industry. An important challenge in titanium cladding is to obtain an interface with an acceptable bonding strength. During high temperature processing, titanium can react both with iron and with carbon, and forms brittle TiC and Fe–Ti compounds in contact with steel which decreases the interfacial strength [2,15]. Explosive welding with very short process time may yield a limited intermetallic compound, but is known to be an expensive process. In case of diffusion bonding, however, brittle intermetallics are likely to form at high temperatures, which may induce easy delamination and interface fracture. Therefore the optimum condition for diffusion bonding that ensures proper interface bonding – with non-excessive intermetallics at the interface – should be established [9,12–15].

In order to find a way to prevent the formation of brittle intermetallics between Ti and steel during high temperature diffusion bonding, the effects of metal interlayer such as Ni and Cu on the interfacial reaction were studied [9,12]. In this study, the cladding Ti and Al 6081 with magnesium AZ 31 interlayer was carried out at room temperature processing using a high plastic deformation processing. The mechanical properties were, in turn, characterized. The Ti–AZ31 layer was sandwiched by Al plates and the three layers of Ti–Al–AZ31 were clad using “Hot isotatic Press” (HIP). The effects of post-bonding heat treatment at low temperatures on the interfacial properties and the mechanical performance – in the tri-layered clad material – were also studied. In addition the design concept for an Al interlayer used in this study for cladding Ti and AZ31 was thoroughly described.

2. Experimental program

For this experimental program, Tri-layered Ti/Al–0.81 Mg–0.9 Si/AZ31 clad plates were produced by hot isotatic pressing. An Al–0.81 Mg–0.9 Si sheet with a thickness of 1.8 mm was inserted between Ti – with 2 mm thickness – and AZ31 sheets – with a thickness of 2 mm. They consequently exhibited hot isotatic pressing; processed under the pressure of 15 tonnes for 1, 2 and 3 h. Before HIP processing, the surfaces of Ti, Al 6081 and AZ31 sheets were degreased in acetone and the intimate surfaces between these sheets were scratched with #80 abrasive papers before stacking for HIP process. The clad plate after HIP bonding had a total thickness between 3.8 up to 4.2 mm according to temperature and time. Ti plates used in this study are of the commercial purity of 1100 ppm oxygen; Al 6081 plates had the composition of Al–0.81 Mg–0.9 Si; Magnesium alloys with composition of major elements 3.1% Al and 1.05 Zn of commercial as mentioned in Table 1. After HIP processing, composite clad plate was cooled under time control in furnace by a rate of 10 °C/min to examine the effect of cooling rate on the overall mechanical performance. To examine the variation in the hardness across the interface, Vickers microhardness measurements were conducted through a Vickers hardness tester (Zwick/Roell ZHV10). Vickers hardness was obtained at the mid-region of each component plate and at the interface of Ti/Al as well as Al/AZ31. Micro-structures of interfaces were observed by an optical microscope and scanning electron microscopy. To evaluate the mechanical performance of clad materials, tension tests were performed using a Universal Materials Testing Machine (Zwick/Roell Z100). Tensile specimens of standard specimene were elongated at a strain rate of 1 mm/min at room temperature. A scanning electron microscope (SEM) (JEOL 5410) at 293.9 K and 35% humidity equipped with energy dispersive X-ray spectroscopy (EDX) and an X-ray diffractometer (XRD) were used to analyze interface morphology and detect the compositions, and to identify intermetallic formed during the annealing treatment. The purpose is to evaluate the effect of temperature and time on the mechanical properties of Ti, annealed aluminum (6081) and AZ31.

3. Results and discussion

Design architectures as well as ply numbers are being considered for composite processing. The chemical compositions of the alloys sheets are shown in Table 1. As-received samples were

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Chemical composition of investigated alloys (Wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy</td>
<td>Al</td>
</tr>
<tr>
<td>Al 6081</td>
<td>Bal</td>
</tr>
<tr>
<td>Ti (pure)</td>
<td>–</td>
</tr>
<tr>
<td>AZ 31</td>
<td>3.1</td>
</tr>
</tbody>
</table>
3.1. Microstructure

The interface morphology of Tri-layered pure Ti/Al-0.81 Mg-0.9 Si/AZ31 sheets with different heat treatment temperatures is shown in Figs. 1–3. It is clear that the Ti, Al, AZ31 interfaces of as-fabricated HIPping sheets are not smooth, and the Ti, Al, AZ31 are squeezed into each other. The medium heat temperature caused the Al/AZ31 interface to become smooth, as shown in Fig. 1. Such a phenomenon should be attributed to the diffusion between Al and AZ31. With the increase in heat treatment temperature, the transition layer appeared along the Al/AZ31 interface, as shown in Fig. 2. Moreover, the width of the transition layer showed significant increase. The overall composite of the 3 alloys is shown in Fig. 1.

In the present study the threshold reduction is about 44%. Moreover, the AZ31 and Al layers experience compressive and tensile deformations during the HIPping process; thus beneficial to the microstructure refinement. However, such a great deformation can lead to an abundance of crystal defects, such as twinned crystal, stacking faults and dislocations. The concentration profiles of Ti, Al, and AZ31 elements across the interface at 823 K are shown in Fig. 2A–C. SEM and

![Figure 1](image1.png)

Figure 1  SEM for the Ti–Al–AZ31 3ply at 823 K, at 2 h, showing the interface and transition layers at 50x magnification.

![Figure 2](image2.png)

Figure 2  SEM and EDX represent the Al/AZ31 layers and interface at 823 K, at 2 h, by HIP process.
Figure 3  SEM and EDX represent the Al/Ti layers and interface at 823 K, at 2 h, by HIP process.

Figure 4  (A) % Elongation for position value through SEM and EDX represents the Al/Ti layers and interface at 823 K, at 2 h, by HIP process. (B) Hardness Vickers for different composite zones. (C) Ultimate tensile strength for individual composite layer and composite. (D) Comparison for interface hardness at different HIP temperatures.
EDX analysis are shown in Fig. 2 for composite at 823 K, 2 h. SEM and EDX analysis are shown in Fig. 3 condition for aluminum–magnesium (AZ31) and aluminum–Ti Interface respectively. The structure reveals clear bonding with interface/interphase and no delamination at 823 K, both 2 h composite between Ti, Al, and AZ31. The long time and high temperature heat treatment promotes the elements’ diffusion. Due to the low interfacial energy of the Al/Ti phase interface, the fine Al2O3 particles precipitate along the interface. However the segregation of Al2O3 along the Al/Ti phase interface is harmful to the bond strength of the Ti, Al, AZ31 sheets. LMP induced the delocalized melting phase structures enriched with Al phase and AZ31 phase. Alloy segregation during solidification in a semisolid state processing induced directional solidification with fibrous and bulk whiskers structural interphase. Bond strength was considered a crucial factor in evaluating the effect of heat on the strength of Ti, Al, AZ31 sheets, and thus the tensile test was instrumental.

3.2. Mechanical properties

The variation in mechanical properties is shown in Fig. 4. It is obvious that the temperature of heat treatment can control the bond strength. Elongation-increase for composite was higher compared to Al layers – almost equal to AZ31 – as shown in Fig. 4A. Hardness values were also increased at the interface regions. As for the Al/AZ31 interface, it was higher than Al and almost equal to the AZ31 alloy. While for the Ti/Al interface value, its increase exceeded than of Al by a significantly higher difference compared to pure Ti (see Fig. 4B). The strength values followed the same trend as that of hardness in Fig. 4C. In the latter, the increase in ultimate tensile strength for the composite compare is proximate to base Al AZ31 but less than pure Ti. The HIP process sheet was found to have the highest hardness value at 823 K, 2 h if compared to other cases at 673 and 773 K bearing the same holding time Fig. 4D. According to former efforts [10,11,9,12,13], the intermetallic compound has high strength but low ductility. In addition, the intermetallic compounds have a significant lattice difference with crystals; leading to high stresses along the interface. Such changes are all detrimental to the bond strength. Therefore, it is unlikely to accept that relative low temperature and short time heat treatment is helpful to improve the bond strength of the pure Ti/Al 6081/AZ31 composite.

4. Conclusions

Three ply plate alloy tests of (Ti/Al/AZ31) processed through the HIP ping process were carried out and following conclusions were obtained;

1. The most pronounced increase in the hardness (from 49.2 to 74.5 HV) was observed in Ti/Al/AZ31 interlayer with an initial excellent deformability and high strength after joining.
2. Intermetallic layer with a maximum thickness of 10 µm was observed to be formed at the Al–AZ31 interface. The presence of an Al2O3 interface was confirmed by XRD analyses.
3. No intermetallic compounds were observed at the Ti/Al interface, so low temperature leads to the absence of intermetallic compounds in the Ti/Al.
4. The mechanical properties exhibited step-wise resistance of composites. At 823 K, plate fractured and improvement of ultimate tensile strength manifested; compared to one of the composite layers (Al) and near the (AZ31).
5. A lamellar composite structure with symmetrically arranged plies is introduced with control interface/interphase. Chemical and mechanical bonding between Ti/Al/AZ31 is the main interest for successful composite.

References