Ultrasonic Brazing of Aluminum to Stainless Steel

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Abstract

Joining of aluminum to the 304-type stainless steel was performed at 673 K for different ultrasonic application times. Different reaction layers could be observed at the interface, containing Fe-Al, Fe-Zn, and Fe-Al solid solutions. The maximum bond strength of 146 MPa was obtained for Al / 304 joint brazed at 673 K for 3 seconds UAT. A critical remained thickness of the filler alloy after ultrasonic application is believed to improve the interfacial joining. Extending the ultrasonic application time beyond 3 seconds causes a bulk escape of the brazing alloy from the interface which decreases the bond strength.

KEY WORDS "Ultrasonic Brazing", Aluminum, "304 Stainless steel"

Introduction

Joining of stainless steel with aluminum is required for anticorrosion and high strength applications for not only large specimens but also for small electronic parts [1]. Due to differences in their melting points and their thermal expansion coefficients, as well as their poor solubility in each other (especially iron in aluminum), stainless steel and aluminum are not compatible metals and their joining is still a big point of challenge. Gibbesch et.al indicated that plastic deformation of the metal was a dominant mechanism of pore closure at the interface [2]. Also, Korn, et.al, have indicated that the fracture generated interfacially due to high concentrations of segregates at the interface [3]. Naka et.al, indicated that ultrasonic application during brazing accelerates the interfacial reaction between the dissimilar material, and increases the joining strength [4, 5, 6]. The present study aims to study the effect of ultrasonic application during Al – stainless steel brazing. It is also aimed at studying the interface structure and bonding mechanism, as well as the bond strength for the Al-304 joints.

2. Experimental work

Solid cylinders of aluminum and 304-stainless steel of 6 mm. diameter and 4 mm. lengths were used as dissimilar joining sets. An ultrasonic brazing method using (Zn-5 mass % Al) brazing alloy was used for joining. Joining temperature was kept at 673 K.; the ultrasonic wave was applied for a time range from 1 second till 10 seconds and was applied after reaching the joining temperature. After joining, Al/304 couples were prepared for SEM observation and EPMA was used to perform spot and line analysis at the interface between aluminum and 304 stainless. Bond strength measurements were conducted using a fracture shear test with a 1.67 X10^{-2} mm/sec cross head speed.

3. Results and discussion

3.1 Interfacial structures

Figure 1 shows a SEM micrograph and EPMA analysis for a joint brazed using a 1 second ultrasonic time, the first reaction layer (I) within a 14 μm in thickness of gray color was formed just in contact with the Al side, beside which a white colored layer (II) of a 8-μm existed. A 34- μm layer (III) was observed next to the first two layers and is believed to contain a wide mixing range of the brazing alloy. Beside the stainless, the fourth layer (IV) 12 μm in thickness existed. The EPMA analysis for this joint showed that the first reaction layer containing diffused Zn atoms an the Al side (up to 7 at. %) which might occur during the first stages of heating or upon cooling from the melting point of the brazing alloy and resulted in a formation of Zn-Al solid solution (layer I). At the earlier stages of cooling while there is still a high temperature or even upon heating before the ultrasonic application on the joint, diffusion of the Zn increases toward the Al side therefore its content in the aluminum was increased in the second zone (from 16 at. % up to 32 at. %). Therefore some Zn-Al solid solution existed beside a mixture of the brazing alloy composition (layer II). The third zone (III) of 34-μm thickness represents an area containing a mixture of the nominal composition of the filler alloy with (Fe-Al) solid solution. Upon reaction progress at 673 K the diffusion of Al atoms towards the stainless steel side starts to take place while the brazing alloy is in its liquid state and with aid of the ultrasonic

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application, which is believed to accelerate diffusion of Al as well as that of the Zn. Diffusion of Al and Zn towards the stainless causes the formation of (Fe-Zn) solid solution layer (IV) containing a mixture of a five elements, which are Al, Fe, Cr, Ni, and Zn as can be seen from the EPMA.

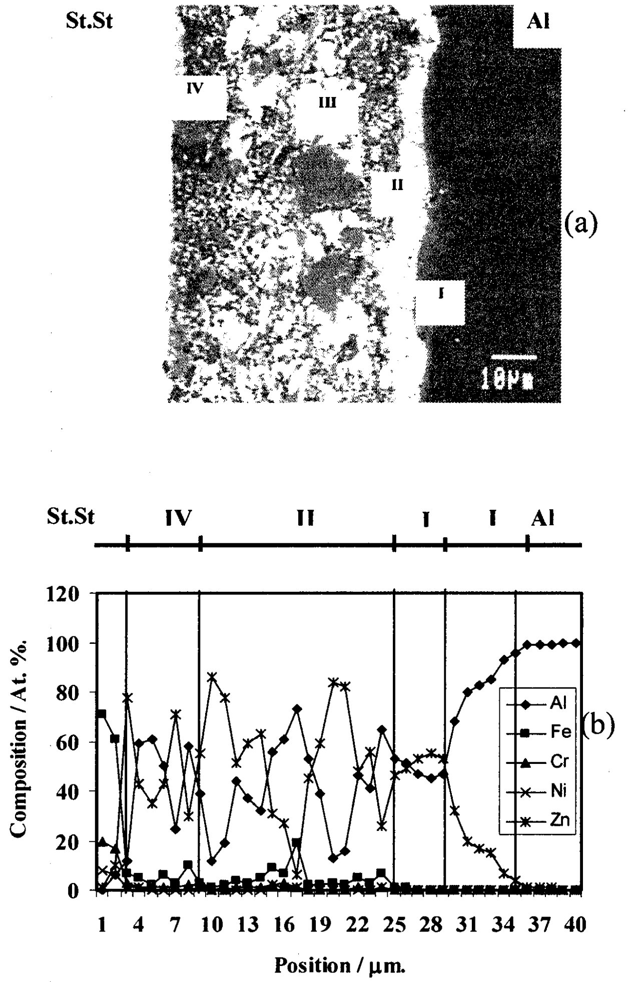

Fig. 1 SEM (a) and EPMA (b) for a joint brazed at 673 K for 1 second ultrasonic time.

When using a 2 seconds ultrasonic application time a more homogenous distribution for the Zn particles could be observed due to increasing ability for diffusion. Also the layers (III and IV) beside the stainless become more rich in both Al and Zn atoms which leads to the formation of (Fe-Al) and (Fe-Zn) solid solutions. This can be observed from the SEM micrograph of Fig. 3 and the EPMA of Fig. 4. Upon increasing the ultrasonic application time to 3 seconds, further diffusion of Zn and Al towards the stainless steel side occurs and this causes more interlocking and chemical reaction to take place to form a solid solution of Zn in Fe (α-Fe), which is a dominate phase beside the other Fe-Al solid solution. The SEM micrograph of Fig. 2(a) indicates the existence of three main layers. The first layer (I) with a 10-μm thickness contains a mixture of (Zn-Al) solid solution and the brazing alloy. The second layer (II) of about 7 μm in thickness is believed to contain a mixture of (Fe-Al) and (Fe-Zn) solid solutions beside the brazing alloy. While the third layer (III) of around 2 μm thickness, contains (Fe-Al) solid solution. The three mentioned layers can also be seen from the EPMA analysis of Fig. 2(b).

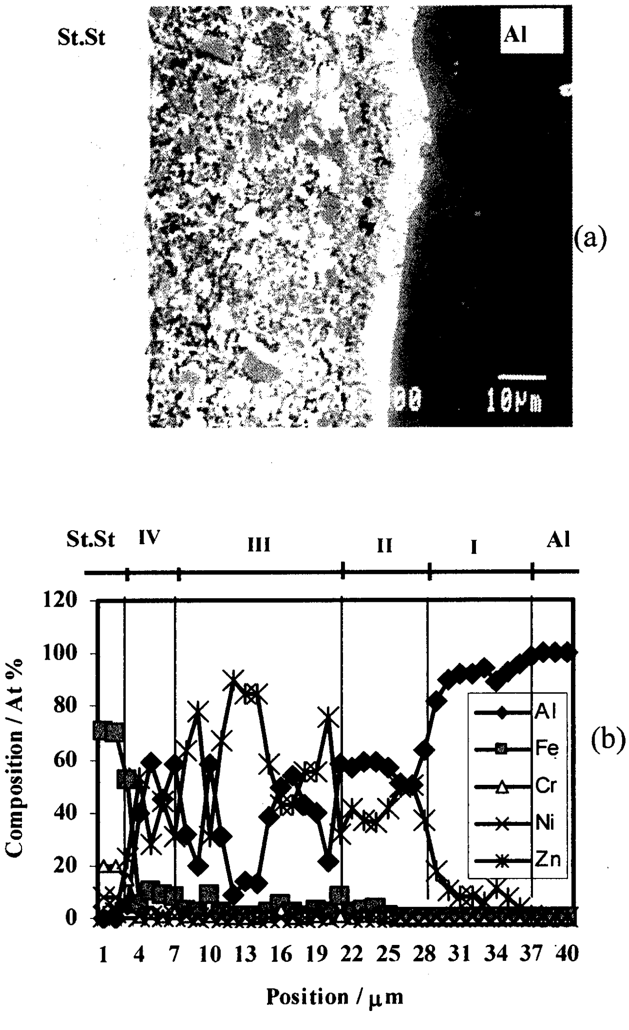

Fig. 2 SEM (a) and EPMA (b) for a joint brazed at 673 K for 2 second ultrasonic time.

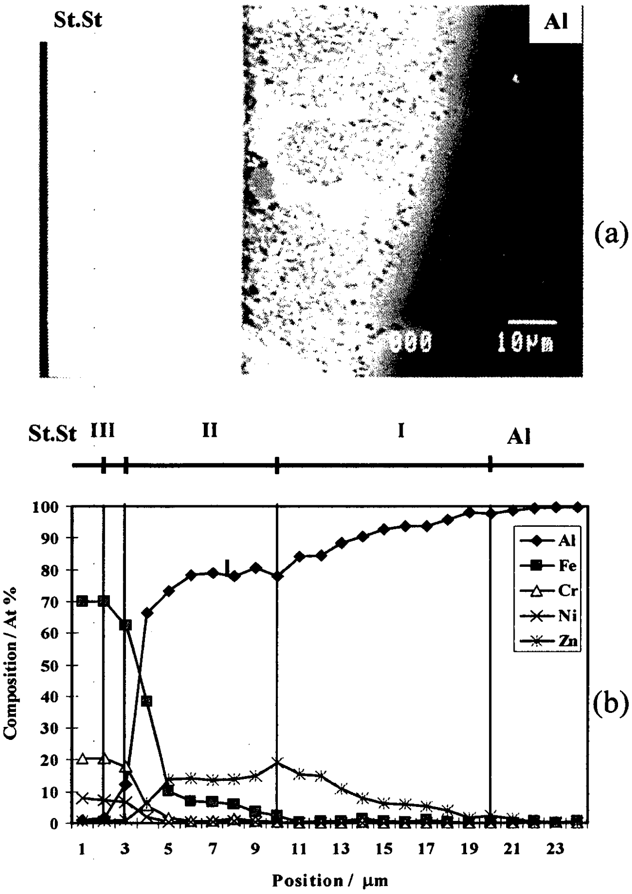

Fig. 3 SEM (a) and EPMA (b) for a joint brazed at 673 K for 3 second ultrasonic time

The formation of those solid solutions especially the (Fe-Al) solid solution is believed to improve the interfacial condition create a stronger joint. It is obvious to say that the remaining amount of filler alloy is smaller than before due to the ultrasonic action at the interface. The EPMA line analysis of Fig. 3(b) indicates a considerable penetration of both Zn and Al towards the stainless steel side. Extending the ultrasonic application times up to 4, 6 and 10 seconds causes a gradual bulk escape of the brazing alloy from the interface.

3.2 Bond strength

The reaction of one or more elements from the brazing alloy with the two starting materials may promote wetting, providing a chemical bonding and minimizing stresses arising from thermal expansion mismatch between Al and stainless steel. Fig. 4 shows the variation of bond strength of the Al-304 joints brazed at 763 K for different ultrasonic application times. It can be observed that the bond strength increased with increasing the ultrasonic application time up to a maximum after 3 seconds, and then a gradual decrease in the bond strength occurred. As the reaction proceeds at the interface, more diffusion from the elements (Al and Zn) of the brazing alloy takes place towards the Al and stainless steel, and consequently more interaction occurs. As the amount of the Al-Zn, Fe- Zn, and Fe- Al solid solutions increases at the interface, there is a gradual improvement in the bond strength. The 3 seconds ultrasonic application time provides an optimum condition for elemental diffusion at the interface to form solid solutions between Al, Zn, and Fe. The formation of such solid solutions especially the (Fe-Al) solid solution is thought to improve the joining bond strength between Al and the 304-type stainless steel. On the other hand, a thinner brazing alloy at the interface is beneficial for better interaction with the Al and stainless steel to increase the joining strength; this is accepted up to a limit as will be discussed later. Increasing the ultrasonic application time over 3 seconds causes an escape of the brazing alloy while it is in a liquid state, which results in a poor wetting condition at the interface and brings Al and stainless steel into direct contact. This increases the possibility to form inter-metallic compounds between Al and Fe and consequently impairs the interfacial bond strength.

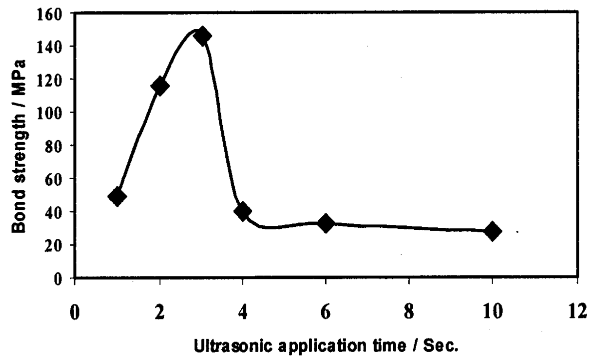

Fig. 4 Bond strength of the joints

4. Conclusions

Brazing of aluminum to the 304-type stainless steel was performed at 673 K for different ultrasonic application times and the following conclusions could be obtained;

1. As the amount of the Fe-Al, Fe-Zn, and Al-Zn solid solutions increases at the interface, there is a gradual improvement in the joining bond strength.
2. Maximum bond strength of 146 MPa was obtained for Al / 304 joint welded at 673 K with 3 seconds UAT.
3. Excessive ultrasonic application causes a decrease in the bond strength.

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