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Original Article

Investigation of low-velocity impact and flexural loading on AR500 steel/AA7075 aluminum alloy brazed joint

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Abstract

This paper presents the results of an experimental study to evaluate the damage and failure mode of AR500 steel/AA7075 aluminum alloy brazed joint panels caused by an impact load. Drop weight tests were conducted on AR500 steel/AA7075 aluminum alloy brazing joint panels to study their response and performance under impact loading. The use of steel and aluminum joints is becoming increasingly popular since they are well known for excellent weight, strength, and stiffness properties and this condition makes them the material of choice for lightweight applications in the automotive industry. In this work, AR500 steel/AA7075 aluminum alloy plates were fabricated by the torch brazing method with Al-Si-Zn base as the filler metal and evaluated for their impact performance and flexural strength by conducting drop weight tests under low velocity impacts and a three point bend test. Experimental results showed that the AR500 steel/AA7075 aluminum alloy brazed joint panel flexural strength was 615 N and the low velocity impact strength was 1569 N. The experiment caused delamination of the joint at the aluminum and filler metal region. The Al-Si-Zn filler bonding capability on the AA7075 aluminum was low compared to the AR500 steel. However, it is capable of joining these dissimilar metals. The data obtained from this study should assist researchers and designers to better understand damage and failure behaviour of panels made of dissimilar metals which will result in components with a better design. This is particularly so in the aspect of the crashworthiness properties of structural components, especially in static, quasi-static, and dynamic loadings.

Keywords: brazing, metal joining, impact strength, dissimilar metals

1. Introduction

The growing demands of weight saving, energy efficient, and bigger loading capacity of vehicles in the transportation industries have led to an increase in studies conducted on joining dissimilar metals. At the same time, the demands on improving strength, stiffness, and crashworthiness of structural components have also increased to fulfil the requirement of safety factors of transport vehicles. A significant proportion of this effort is currently being carried out toward the substitution of light metals, especially aluminum, for steel in the body-in-white stage of production (Choi *et al.*, 2010). The most usual approach is to use light weight materials such as aluminum alloy or high strength steel. Aluminum alloy has been proven to be the most acceptable material for weight reduction for an automotive body. A process to join aluminum alloy to low carbon steel or high strength steel needs to be developed in vehicle body assembly (Lin *et al.,* 2011). The overlap and interface joint of steel and aluminum, also considered as the sandwich joint, was reported in numerous different research studies such as friction stir

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welding by Kimapong *et al.* (2005) and Emel *et al.* (2010), MIG Arc brazing by Murakami *et al.* (2003), vacuum furnace brazing by Huijie *et al.* (2002), resistance spot welding by Choi *et al.* (2010), diffusion bonding by Ogura *et al.* (2011), friction bonding by Yamamoto *et al.* (2004), and laser brazing by Liedla *et al.* (2011).

The main benefit of using the sandwich concept in structural components is its high bending stiffness and high strength to weight ratios (Belouettar *et al.,* 2009). However, the sandwich plates used in space vehicles, aircraft, modern vehicles, and light weight structures are very susceptible to low velocity transverse impact damage such as matrix cracking, delamination, and fiber breakage. The interface or sandwich joint of aluminum and steel is difficult and cannot be joined successfully with current industrial welding techniques. The difficulties faced in this dissimilar metal joining process are the issues of compatibility of filler metal to react with both metals, suitable temperature of brazing, and formation of a reaction layer (i.e. oxide or entrapped flux). These problems are due to the high differences in melting temperature and poor compatibility of properties of both metals. During the solidification process into the liquid state, there is no miscibility between the iron and aluminum elements; therefore, brittle intermetallic phases are formed (Mathiue *et al.,* 2006). In order to prevent the dissolution between both metals, the application of the brazing process using a filler metal with a low melting temperature should be highly considered, as it would allow continuous joints by depositing the molten filler metal onto the capillary without causing the base metal to melt. The joining process by brazing with a low joining temperature has many advantages, especially the possibility of joining complex structures (Wei *et al.,* 2012). There are three critical regions in the brazed joint structure: the filler metal, the interfaces between the filler metal and the base material, and the base materials. The mechanical performance of any brazed joint depends on the capillary absorption of the filler metal into the base material, wetting of filler metal, and the surface conditions of the joining materials.

One of the main concerns in the application of sandwich or interface structures is the load carrying ability that may be significantly reduced by the presence of local damage or delamination between the base metal and joining mechanism. Interface delamination of the contact elements is referred to as debonding. The phenomenon of delamination is prevalent when the residual compression is large and the interface has low delamination toughness (Freund *et al.,* 2004). The damage caused by a low-velocity impact and quasi-static loading may reduce significantly the stiffness and residual strength of the interface structure. For this reason, a significant amount of studies have been done by different researchers to address the problem of interface structures. The mechanical response of a low-velocity impact and quasi-static loading on sandwich structures has been extensively studied using experimental, numerical, and analytical methods. The studies were conducted by Jilin *et al.* (2008) and Jan *et al.* (2015) on various areas such as impact response, flexural effect, and damage characterization. The mechanical response of the panels was recorded and analyzed in terms of the peak load, absorbed energy, and deflection at peak load.

Pertaining to the explanation above, the purpose of this study is to investigate the torch brazed joint of an AR500 steel/AA7075 aluminum alloy using an Al-Si-Zn filler metal that has a low melting temperature. The characteristics of low-velocity impact strength, flexural strength, and delamination of the brazed joints were investigated in this present research. This work is significant because it provides further guidance on the interfacial bonding characteristic between steel and aluminum when a filler metal with low melting point temperature is used in a torch brazing process.

2. Materials and Methods

The materials used in this study were AA7075 aluminum alloy and AR500 high-strength steel. The mechanical properties of the materials are shown in Table 1. The steel and aluminum samples were fashioned by a wire-cutting machine to 80 mm in length, 12 mm in width, and 1.5 mm in thickness. The plate surfaces were polished with 180 grit silicon carbide paper to remove the oxide layer. The joints between these two metals were produced using the torch brazing process with the Al-Si-Zn base filler metal as the joining mechanism. The filler metal was cut into strips measuring 3.5x80x0.5 mm and arranged to fill the surface of the base metal. The filler metal was sandwiched between the AR500 steel and AA7075 aluminum alloy. The torch brazing process involved the burning of butane gas. The surface of the steel was heated by flame from the butane gas and this process was conducted until the interface temperature reached 538 ^{0}C (Figure 1). The specimens were then selected to three point bend and drop tests. The three point test experiments were performed according to the composite flexural test following the ISO-14125 standard using Class 1 type specimen. The same specimen standard was used for the drop test.

Table 1. Mechanical properties of AR500 steel and AA7075 aluminum alloy.

Material	Density (kg/m^3)	Hardness	Tensile strength (MPa)	Yield stress (MPa)	Elongation at break (%)
AR500	7850	115 HRB	1740	1370	12.5
AA7075-T6	84 HRB	2804	536	480	10.0

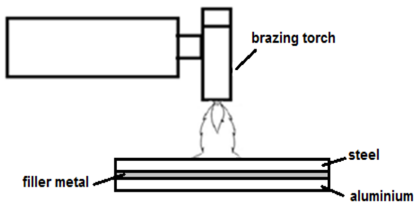

Figure 1. Torch brazing process.

Three point bending tests were conducted on a Zwick/Roell Z100 universal testing machine with a 100kN load cell. The tests were carried out at a crosshead speed of 1 mm/min with preload applied at the value of 5 N. The drop test was performed using an Instron 9250HV machine with the ability to receive a maximum force up to 10kN and a maximum velocity of 20 m/s. The energy level used was 20 J with an impact velocity of 2.3 m/s. The equipment employed in this study is shown in Figure 2.

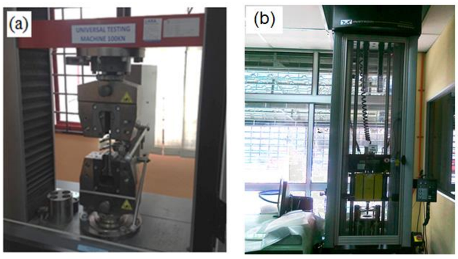

Figure 2. Equipment for testing and analysis: (a) universal testing machine; (b) drop test machine.

3. Results and Discussion

In the low velocity impact test, specimens were tested under an energy level of 21.47 J. It was observed that the peak load of the specimens was 1569 N at 19.44 J (Figure 3). Overall, the load showed a decrease after peak load because of bending of the specimen. The specimen was bent and it delaminated at the joint layer by the impact test. The bending of the specimen can be divided into four stages (Figure 3). In stage 1 or the stable stage, the fluctuating force indicated that the energy was sufficiently absorbed to break the elastic energy in the specimen. In this stage, bending resistance was in control and the stable stage continued to a load value of 500 N. In stage 2, resistance of bending exceeded the elastic limit and the specimen was in the plasticity region where the initial bending started. The third stage showed the load fluctuated and reached the peak load at 1569N with the impact energy at 19.44 J and the deflection of specimen was 23.29 mm. In this stage the energy was absorbed and rebounded because some of it was used to continue the bending of the specimen. In stage 4, the load decreased while the energy kept on increasing. This condition occurred because the absorbed energy was used to continue the deflection and the bending process until it reached the maximum total energy applied (Ahn *et al.*, 2011, Rajkumar *et al.*, 2011, Farhood *et al.*, 2016).

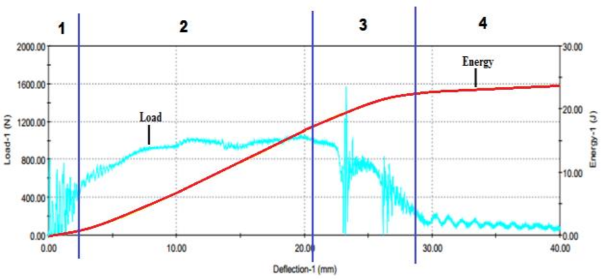

Figure 3. Load and energy deflection characteristics.

The results of flexural testing showed that the flexural strength of the samples was 615 N with a deflection of 11.5 mm. The typical load displacement relationship of the specimen is shown in Figure 4. The results showed that the load capacity of the specimen increased linearly with deflection to a load of 400 N. After reaching this load, a decrease in stiffness was observed due to the bend initiation in the specimen. The specimen then continued to carry the load until failure of the specimen at maximum load. The load of the sample decreased after reaching the maximum load and a significant drop in load was observed due to the compressive failure of the AR500 followed by shearing failure of the joint between the filler and AA7075.

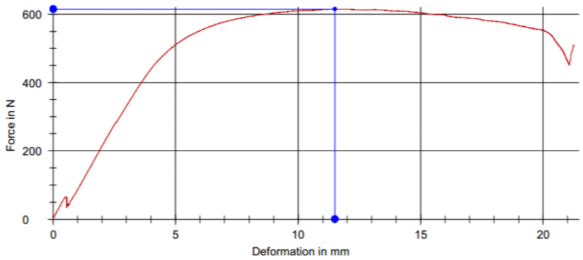

Figure 4. Force-deformation curve.

The failure pattern observations of the specimens subjected to flexural and low velocity impact loading are shown in Figures 5 and 6. Both samples failed and delaminated; however, observation did not show any visual cracks on either of the base metals. During the test, the sample did not show signs of clear interface joint failure or delamination. However, in the mode flexure and impact sample, delamination of the interlayer joint AR500 steel and AA7075 aluminum alloy occurred before the metals cracked. The sample showed that the joint of the material delaminated in the aluminum and filler metal region. According to Wisnom (2012), Li *et al.* (2008), Jilin *et al.* (2008) and Krzysztof *et al.* (2016), delamination happened because at that moment, shear stress occurred on the back surface in line with the shear crack on the filler (Figure 7) and compressive stress occurred on the front surface. At this layer of the specimen (back surface), between the filler and aluminum, the bonding force is lower than the front surface causing the specimen to be delaminated at this region. The experiment showed that the buckling delamination occurred at impact loading and flexural loading of the specimen.

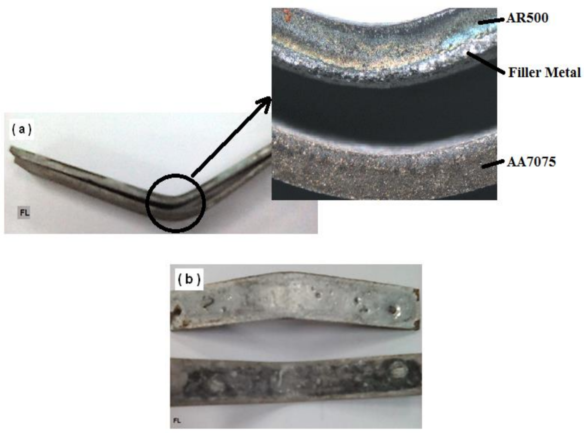

Figure 5. Failure of flexural loading: a) failure pattern; b) delamination of specimen.

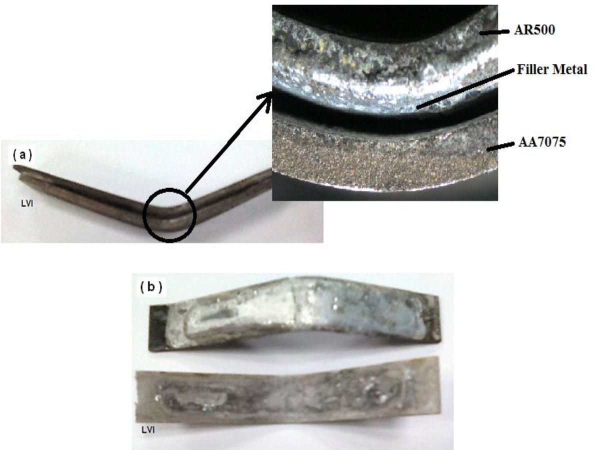

Figure 6. Failure of low velocity impact: a) failure pattern; b) delamination of the specimen.

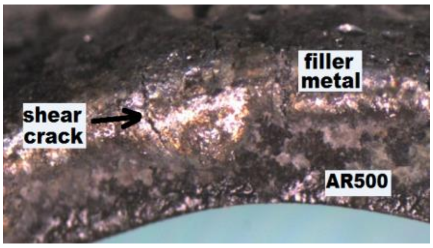

Figure 7. Failure on filler metal observed in impact test.

Figure 8 shows the loading relationship between the impact and flexural tests. In the stage of the low loading condition between 0 to 400N, the deflection on impact (low velocity impact) and flexural (three point bend) tests showed small differences in relation to the load increment. After the load value reached 400 N, more force was required by impact test to deform the specimen compared to the flexural test. It was observed that the AR500/AA7075 joint specimen had as much as twice the strength under low velocity impact loading condition compared with the flexural loading condition of the specimen. Similar behaviour was also observed by Jilin *et al.* (2008) (for aluminum sandwich) and Gencoglu *et al.* (2007) (fabric reinforced cement composite). However, the strength of the joints cannot be compared directly due to the differences in stress concentration induced by the two measuring methods and the elastic mismatch around the steel/aluminum interfaces.

Scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX) analyses were conducted in the area of the joint failure. The results of SEM and EDX analysis showed the formation of a reaction layer at the area (spot 1) between the filler and AA7075 (Figure 9). From the analysis, it was observed that the reaction layer and intermetallic compounds (IMCs) formed on the AA7075/filler metal. The IMCs consisted of Fe, Al, Zn, and O elements. The reaction layer formed on the aluminum surface and filler metal was considered to be oxides and IMCs. The formation of a brittle IMC (FeAl) and the limited capillary action between the filler metal and base metal by the oxide layer had caused the joint strength to reduce (Scwartz, 2009; Zaharinie *et al.*, 2014).

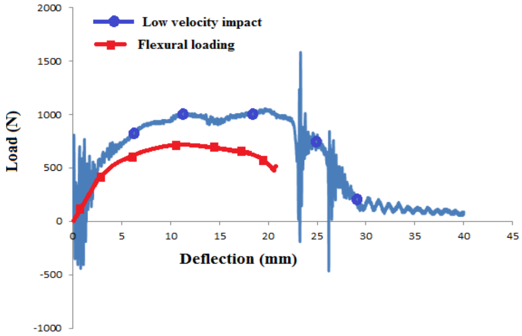

Figure 8. Load-deflection relationship of low velocity impact and flexural loading.

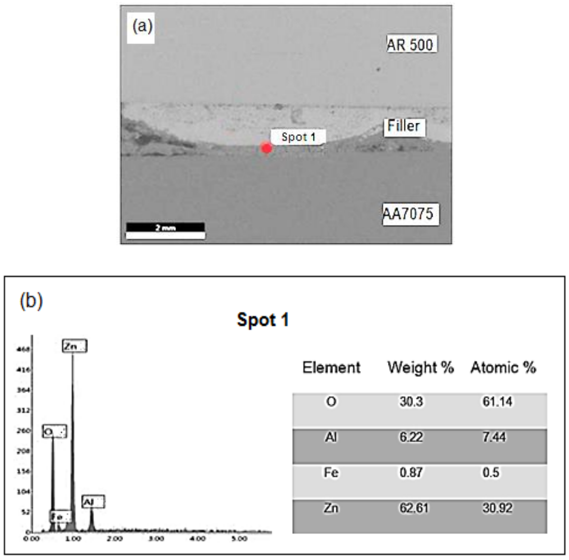

Figure 9. Scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX) analyses of torch brazed joint between AR500 steel/AA7075 aluminum alloy: (a) SEM image of spot 1 area, (b) EDX analysis of spot 1 area (reaction layer of AA7075/filler).

4. Conclusions

In this study, an experiment was conducted to investigate the behaviour of joint strength on the dissimilar metals of AR500 steel and AA7075 aluminum alloy in flexural and impact conditions. The flexural and impact loading at the joint caused the bonding between the metals to delaminate. The investigation showed that buckling of the delamination occurred at low velocity impact loading and quasi-static loading of the specimen. Observation showed that the delamination of the joint occurred at the aluminum and filler metal region. This condition occurred because the bonding strength between the aluminum and filler metal was lower than between the steel and filler metal. The existence of low strength and failure of the joint at the aluminum alloy and filler metal region were influenced by formation of oxides in the base metal surface and this limited the capillary absorption of the filler metal, and a thick brittle IMC layer formed at the metal and filler metal. This situation led to a decrease in the strength of the joint between the metals. The results showed that the AR500/AA7075 joint specimen had as much as twice the strength under impact conditions compared to a static condition.

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