Al-Si-Zn Behaviour on Interface of AR500 Steel and AA7075 Aluminium Alloy Brazed Joint

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Abstract. The brazing of steel and aluminium alloy using low melting point aluminium based fillers has been extensively studied and the technique has been used in many industries, especially the automotive industry. The strength and failure mode of AR500 steel and AA7075 aluminium alloy brazing joint using the Al-Si-Zn filler metal will be measured and calculated in this paper. However, the adverse effect of intermetallic phases formation on the joint strength has limited the application of this joining method. These dissimilar metals possessing a high strength joint would be of benefit to industry especially in reducing the weight of products. The torch brazing method using Al-Si-Zn base filler metal was used to join AR500 steel and AA7075 aluminium alloy in this study. The intermetallic phase formation of the brazing was investigated by scanning electron microscopy and the mechanical strength of the joints was evaluated by shear testing, flexural testing and low velocity impact testing. A maximum shear load of 6460 N was obtained. The presence of intermetallic phases was found to have some effect on the strength of the brazed joint. However, overall, this brazing process using Al-Si-Zn filler metal facilitates the joining of these dissimilar metals to improve the mechanical properties of the joint.

1. Introduction
The increased demand in automotive industry on light and tough metal was an attraction to industry and researchers to develop light weight panel metal. Joining of dissimilar metal steel and aluminium alloys high challenges due to extreme differences in metallurgical and physical properties [1]. Several study was conducted to produce the best joint of steel and aluminium alloy such as laser welding [2], diffusion bonding [3], resistance spot welding [4], friction stir welding [5] and laser brazing [6]. Overall the results show that bonding through a solid phase method (non-fusion method) is more practical to be used for joining two different metals. However, continuous studies should be carried out to produce more comprehensive application in terms of productivity, joining strength and flexibility. Brazing has seen as a potential methods to join these metals because their joint process does not involve base metal melting. However, a common problem will reduce the achievement of the join is the formation of a brittle intermetallic compound (IMC) layer or reaction layer at the bonded interface, which causes low strength in the aluminium and steel dissimilar metal joints [7-9]. Some studies have shown that the strength of joining is better if IMC formation is below than 10 µm [10]. The formation of high oxide layer on surface cause by high temperature brazing process also needs to be resolved. The presence of oxides will limit molten filler metal from flowing into capillaries and this condition will lower the joint strength. The ability of joint to be brazed are also influenced by wetting and spreading of molten brazing filler material [11]. The interaction between a liquid phase and solid phase when surrounded by a gas phase is generally called wetting. The spreading of a liquid over a surface is the most widely known examples of wetting phenomena. Wettability of liquid can be
define by the geometry of a sessile drop [12]. Wettability measured by the contact angle (θ) from the side of liquid and solid substrate (angle at the line of contact between the surfaces of the liquid and the solid substrate). The previous researcher found that high wettability is shown by low contact angle between the liquid surfaces and the solid substrate, while poor wettability shows the opposite [13]. The low brazing temperature and low melting temperature filler metal is the best solution to avoid this problem. Due to its low melting point, Al-Si-Zn base filler metal is suitable to joint dissimilar metals such as aluminium alloy and steel. Filler metal added with an element such as Zn enhances wetting and spreading of the filler into the capillaries and increasing the potential for bonding in both base metals [14]. This study is conducted to investigate the capabilities of low melting Al-Si-Zn filler metal in joining steel and aluminium alloy. The focus of this study is concentrated on the characteristics of filler metal, the resultant IMC and mechanical strength of the brazed joints produced. This work seems very significant due to the fact that there is no research work found in the literature on study the interface joint of dissimilar metals joint using this simple torch brazing method up to this point.

2. Materials and experimental studies
The joining of metals in this study were produced by torch brazing process. The materials used for joining are AR500 high-strength steel and AA7075 aluminium alloy as a substrate metal. These materials were selected because they have been widely used various industry such as heavy vehicle and aerospace. The strength and wear resistance properties of this material is the main choice for this purpose. The CsAlF₄ flux-cored Al-Si-Zn base filler wire with 15-20% flux composition was selected as a join agent base on their capability to join steel and aluminium, besides that it is also categorized as low temperature filler metal. Spark emission spectrometer has been used to determine the chemical composition of the metals. The chemical composition of metals are provided in Table 1, 2 and 3 respectively.

| Table 1. Chemical composition in (wt.% ) of AA7075 aluminium alloy |
|-------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Si                | Fe              | Cu              | Mn              | Mg              | Cr              | Zn              | Ti              | Zr              | Al              |
| 0.16              | 0.22            | 1.13            | 0.09            | 2.03            | 0.21            | 6.13            | 0.027           | 0.026           | Bal             |

| Table 2. Chemical composition in (wt.% ) of AR500 high-strength steel |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| C               | Si              | Mn              | P               | S               | Ni              | Cr              | Mo              | B               | Fe              |
| 0.39            | 0.63            | 0.87            | 0.01            | 0.01            | 0.02            | 0.53            | 0.003           | 0.002           | Bal             |

| Table 3. Chemical composition in (wt.% ) of Al-Si-Zn base filler metal |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Si              | Fe              | Cu              | Mn              | Mg              | Cr              | Ni              | Zn              | Ti              | Ag              |
| 14.84           | 3.13            | 0.58            | 1.42            | 1.70            | 0.06            | 1.49            | 15.60           | 2.02            | 0.1             |

| Pb              | Sn              | V               | Al              |
| 0.87            | 3.75            | 0.13            | Balance         |
The plate of metals were cut to lengths suitable for the testing. The steel and aluminium samples were machined to desire measurement (length = 79.5 mm, width = 25.4 mm, and thickness = 2.5 mm) by a wire-cutting machine for shear test. Specimen for flexural and low velocity impact test were machined according to measurement required (length = 80 mm, width = 12 mm, and thickness = 1.5 mm), the dimension of sample as shown in figure 1. Silicon carbide paper (180 grit) used to remove the oxide film in both plates.

![Figure 1. Dimensions of steel and aluminium samples (a) shear test (b) flexural and low velocity impact test](image1)

The joining process of the metals was done by torch brazing method. The CsAlF$_4$ flux-cored Al-Si-Zn base as a filler wire used in this brazing process, the filler is contains about 15-20% flux composition. The filler wire was rolled and cut into strips with dimension 3.5 mm x 25 mm and 0.5mm thickness and arranged to fill the surface of the base metal, as shown in figure 2(a, b).

![Figure 2. Filler preparation: (a) filler metal, (b) filler metal arrangement in specimen](image2)

The joint process done by overlapped the high-strength steel plate on the AA7075 aluminium alloy with the filler metal in the middle. The torch brazing process carried out in this study involves heating the steel surface using butane gas, bonding occurs between the filler metal and the base metals is when the heating of the surface of base metal (AR500) has reached the appropriate temperature. (see figure 3).
The joint strength was evaluated by shear, flexural and low velocity impact testing. An universal testing machine with a load cell (model ZwickRoell Z100) used for shear tests and flexural tests, while low velocity impact tests (drop test) was performed by using Instron 9250HV machine with capacity of maximum force is up to 10kN and capable to performance until velocity of 20 m/s. In this study, a total of 20 J energy was at used at impact velocity 2.3 m/s. The observation on the brazed joint cross-section was done by using a variable pressure scanning electron microscope (VP-SEM) (model Zeiss Evo Ma 10). The SEM specimens (10 mm x 10 mm x 2.5 mm) were cut and joint using brazing technique. The surface fractures caused by the mechanical tests were observed by using a stereo microscope (model Olympus SZ61). The equipment used is shown in figure 4.
3. Result and discussion

3.1 Analysis on filler metal

a) Melting Temperature of filler metal

The filler metal melting temperature were analysed by Thermogravimetric analysis methods (TGA). The Thermogravimetric analysis (TGA) curve result for the filler wire in figure 5 showed three main reactions; the first was the removal of oxide denoted by ‘a’, followed by the melting of the coating material (tin alloy) at point ‘b’, and lastly the melting of the filler materials at around 425°C at point ‘c’ (this is in agreement with the filler melting temperature from supplier datasheet of 420-480°C).

![Figure 5: Thermogravimetric analysis (TGA) for the filler wire](image)

b) Wetting angle of filler metal on substract metal

Contact area gives good indication for the wettability and the low contact angle correspond to greater wettability and good joint strength [15,16]. From the figures 6, it can be concluded that the filler metal exhibits better wettability on AR500 steel than AA7075 aluminium alloy. Liquid flow better on joints if the filler metal wets the base metals. The average wetting angle for AR500 steel are 76°, while the average wetting angle for AA7075 aluminium alloy are 90°. Study conducted by MiklósBerczeli and ZoltánWeltsch (2018) stated that the joint quality is better in the site with low wetting angle between filler metal and substract metal [17].

![Figure 6: Wetting angle of filler metal and substract metal (a) AA7075 (b) AR500](image)
3.2 Mechanical properties

Mechanical properties of the join measured with evaluated shear strength, flexural strength and low velocity impact strength of the brazed joint specimen. The joint produced by torch brazing technique using Al-Si-Zn filler metal. From the figure 7 it can be seen that the joint plates can withstand a shear load at 6460 N, low velocity impact at 1569 N and flexural load at 615 N.

![Mechanical Properties](image)

Figure 7. Mechanical properties of AR500 steel and AA7075 aluminium alloy brazed joint

The observation from the test shows that this joint is able to withstand the shear load better than the low velocity impact and flexural load. This is because the low velocity impact and flexural load will produce high force and applied directly to specimens rather than the shear load. The energy absorbed by the specimen causes the deformation and the absorbed energy will cause the strength of the joint fails to overcome it. This causes the joint fail at a lower load on flexural and low velocity impact test than the shear test.

3.3 Fracture failure observation

In all the test conducted on AR500 steel and AA7075 aluminium alloy joint, the fractures occurred in the joint interface between the filler and AA7075 aluminium alloy. The joint fractures between metals joint that shows that the filler metal is detached from the AA7075 aluminium alloy base metal. Figure 9 shows stereo microscope images of the fractures surface of the brazed joint after the tests. The joint do not show any warning of failure because it occurred as a brittle failure where the failure surface does not show a significant plastic deformation. From the observation, the brittle failure along the AA7075/filler metal interface is dominant, as shown in figure 8(a, b and c). These interfaces is the weak area for the joint, this coincide with the study conducted by other researcher were found that interfaces joint isthe weak positions under high strain rate loading [18].
Figure 8. Fracture surfaces of test: (a) shear test fracture (b) flexural test fracture (c) low velocity impact test fracture
3.4 Formation of intermetallic compound layer (IMC)

The formation of an IMC is main factor to affect the joining strength of metals. The intermetallic compound of Fe-Al is most predominantly formed in joint between steel and aluminium alloy. The IMC formed between AR500 steel and AA7075 aluminium alloy joint was observed on both base metals with filler. The analysis show the thickness of IMC for AR500 steel/filler metal is 16.7µm and the AA7075 aluminium alloy/filler metal is 82.7µm. A thicker layer of IMC tend to form brittle joint and reduces strength of the joining [19]. The high resolution microscope images of IMC formation on AR500 steel/filler metal and on AA7075 aluminium alloy/filler metal are shown in figure 9.

![Image of IMC layer on AR500 and AA7075](image)

Figure 9. IMC layer on AR500 / filler and AA7075 / filler

The SEM-EDX analysis result of IMC on the joint are shown in figure 10. On the side of AR500/filler joint, the reaction layer or the IMC formed consisted of an Al, Zn and O element, whereas on the AA7075/filler side, IMC consisted of an Fe, Al, Zn and O element. The previous research shows, the intermetallic compound of Fe-Al is most predominantly formed in joint between steel and aluminium alloy [7,9,20,21]. Analysis shows that IMC on the joint between AA7075 and filler metal contains a high zinc element and the Fe-Al component with Al-rich also exists in this part. According to several studies, the intermetallic compound containing low zinc will affect the shear strength whether increase or decrease [22,23] and the existed the Fe-Al with Al-rich IMCs will forming a brittle and hard compound and causing a low joint strength [6,24]. This analysis on thickness and element of IMC is in line with the failure of the shear, flexural and low velocity impact test where the failure of the joint occurred between AA7075 and the filler metal.
Figure 10. EDX analysis on AR500 steel and AA7075 aluminium alloy joint: (a) SEM image of spot areas, (b) spot area 1 (analysis on IMC of AR500/filler), (c) spot area 2 (analysis on IMC of AA7075/filler)

4. Conclusions
In this study, the joining by using torch brazing method on AR500 steel and AA7075 aluminium alloy was successfully carried out. Result and analysis can be conclude as below:

(1) The study shows that the IMC plays an important role in the brazed joint failure. This occurred in the region of the filler and base metal. A thicker layer of IMC results in more brittle joints and reduces strength and hardness. The greatest thickness of IMC formed in the AA7075/filler region of the joint.

(2) The result shows, joint quality is better in the site with low wetting angle between filler metal and substrate metal.

(3) Fractures occurred on the surface of the base metal and filler metal joint. The failures occurred on joints with a high thickness of IMC. From visual observation, it would seem that the failure of the joint can be considered as brittle failure.

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