Article

Brazed Joint Interface Bonding Strength of AR500 Steel and AA7075 Aluminium Alloy

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Abstract. Joining of aluminium alloys to steels has been extensively studied, especially in the automotive sector. However, aluminium alloys are known to be difficult to join with steels when methods involving fusion welding are used because of hot cracking problem. Hence, a high strength joint between these dissimilar metals would be of benefit especially in reducing the weight of products. In this work the torch brazing method was applied to join AR500 steel with AA7075 aluminium alloy using Al-Si-Zn base filler metal at various flame times. The effect of the brazing work on the intermetallic phase formation and the mechanical strength of the joints were investigated. In this work, the maximum shear load obtained was 6460 N and the presence of the intermetallic phases had reduced the shear strength of the brazed joints. However, the torch brazing process using Al-Si-Zn filler metal had successfully facilitated the joining of these dissimilar metals.

Keywords: Dissimilar metal, torch brazing, interface joint, intermetallic compound, shear strength.

1. Introduction

A joint between dissimilar metals provides many advantages, especially in terms of a reduction in the weight and cost of a product. The process of dissimilar metal joining is in great demand in many industries such as automotive, aviation and aerospace. Studies on the joining of aluminium alloys and steels were first conducted many years ago because of the huge potential benefits especially for the automotive industry due to the possibility of reducing the weight vehicle components and structures. More recently, the need to expand the use of lightweight structures in the automotive industry has increased interest in the use of both aluminium and magnesium as structural materials [1-3]. However, the high cost of aluminium compared to steel restricts its usage

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in automobile parts. As a result, aluminium is more economical when it can be used in hybrid structures with steel [4-6]. There has been considerable research on the dissimilar metal joining of aluminium alloys and steel using several joining techniques such as spot welding [7], laser welding [8], brazing [9-11] and friction stir welding [12]. However, a common problem encountered in many approaches is the formation of a brittle aluminium-rich Al-Fe intermetallic compound (IMC) layer at the bonded interface, which causes low strength in the aluminium and steel dissimilar metal joints [13-15]. These IMCs can be grouped into Fe-rich compounds such as FeAl and Fe_3Al, and Al-rich compounds such as $FeAl_2$, Fe_2Al_5 and $FeAl_3$. The Al-rich IMCs are characterized as hard and brittle with low strength while the Fe-rich IMCs are soft with slight ductility and high strength [16-17]. The tough oxide layer on the Al alloy surface and the ability to control the FeAl IMC thickness are issues that have so far hindered the successful joining of Al alloys and steel [18].

The materials AR500 steel and AA7075 aluminium alloy are categorized as high-strength metals in their respective families. However, the joining of AR500 steel and AA7075 aluminium alloy is difficult because of the formation of a brittle intermetallic phase and issues associated with the compatibility of the metallurgical properties of both metals. High-strength aluminium alloys in the 2xxx and 7xxx series are also categorized as unweldable materials due to the difficulty of welding them by using conventional fusion welding [19-20]. In recent years, there have been proposals to use high-strength aluminium alloys from the 7000 series, particularly AA7075, in the fabrication of heavy vehicle shell. However, it has been clearly established that this class of aluminium alloy is generally not recommended for welding by fusion welding processes due to a severe hot cracking problem [21].

In a typical dissimilar metal assembly, there are problems of residual stress and brittle intermetallic phases in the joint because of the two metals' poor physical and metallurgical compatibility, which makes it difficult to join them together by traditional fusion welding techniques. Some methods, such as diffusion bonding, friction stir welding, brazing and fusion brazing can produce joints with no defects. A joint created by diffusion bonding has many advantages including good resistance to high temperature. A joint made by friction stir welding possesses such advantages as a homogeneous and compact microstructure, and lack of gas pole and cracks. A joint formed by using brazing and fusion brazing has advantages such as little IMC, small distortion and high dimensional accuracy. However, the range of application of all the above methods is constrained because of weaknesses such as the nature of the joint format, low production efficiency or poor mechanical properties [22].

The creation of a good joint from dissimilar metals by using brazing methods is also influenced by the choice of filler metal. A filler metal that has a low melting temperature is the most suitable for joining two metals that have a high melting temperature difference. This type of filler is also suitable for joining metals that exhibit a high oxide layer formation, which is caused by a reaction at high temperature. Thus Al-Si-Zn filler metal is suitable for joining dissimilar metals such as aluminium alloy and steel because of its low melting point, but also its cost-effective price. The inclusion of an element such as Zn in the filler metal improves wetting and spreading of the filler into the capillaries to increase the potential for bonding in both base metals [23]. The wetting and fluidity Al-Si-Zn base filler metal also good whereas wetting property of the filler metal is affected by the fluidity of the

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filler metal and the reaction between the filler metal and base metal. When the liquid filler dissolves in the base metal or reacts with the base metal to form the IMC layer, its wetting property is usually better [11].

In light of the above, the purpose of this study is to investigate the mechanical integrity of the AA7075 and AR500 joint interface produced by torch brazing method using a low melting Al-Si-Zn wire as the filler metal. The study focused on the characteristics of the resultant IMC, surface fracture, hardness and shear strength of the brazed joints produced. This work is significant because thus far, there is no reported work in the literature on such dissimilar metals joint interface using this simple torch brazing technique.

2. Materials and experimental studies

The materials used for this study are AA7075 aluminium alloy and AR500 high-strength steel. These materials were selected because they have been widely used in the heavy commercial vehicle industry and they have the best properties in terms of strength and wear resistance. The chemical composition of AA7075 aluminium alloy and AR500 high-strength steel, determined using a spark emission spectrometer (model Spectromaxx), are provided in Table 1 and Table 2, respectively.

Table 1. Composition of AA7075 aluminium alloy (wt.%)

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. Composition of AR500 high-strength steel (wt.%)

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

The materials were supplied as plate and were cut to lengths suitable for shear strength testing. The ends of both the steel and aluminium samples were machined by a wire-cutting machine to 79.5 mm in length, 25.4 mm in width, and 2.5 mm in thickness, as shown in Fig. 1. The surface oxide film on both plates was removed by 180 grit silicon carbide paper. The joint between these two metals were produced by a torch-brazing process using $CsAlF_4$ flux-cored Al-Si-Zn base filler wire with 15-20% flux composition. The melting of the filler materials - at around 425^{o}C . The filler wire was rolled to 0.5 mm thickness (using roller machine) and cut into strips of 3.5 mm x 25 mm as shown in Fig 2 and arranged to fill the surface of the base metal, as shown in Fig. 3(a, b). The chemical composition of the filler metal is shown in Table 3. The AA7075 aluminium alloy overlapped the high-strength steel plate with the filler metal in between, as shown in Fig. 4.

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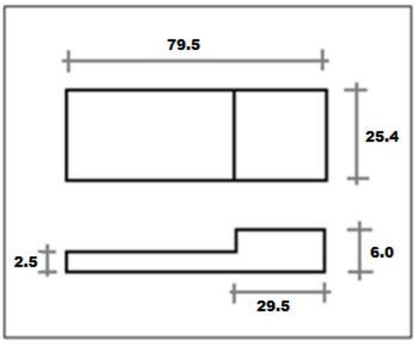

Figure 1. Dimensions of steel and aluminium samples

Figure 2. Filler metal preparation process

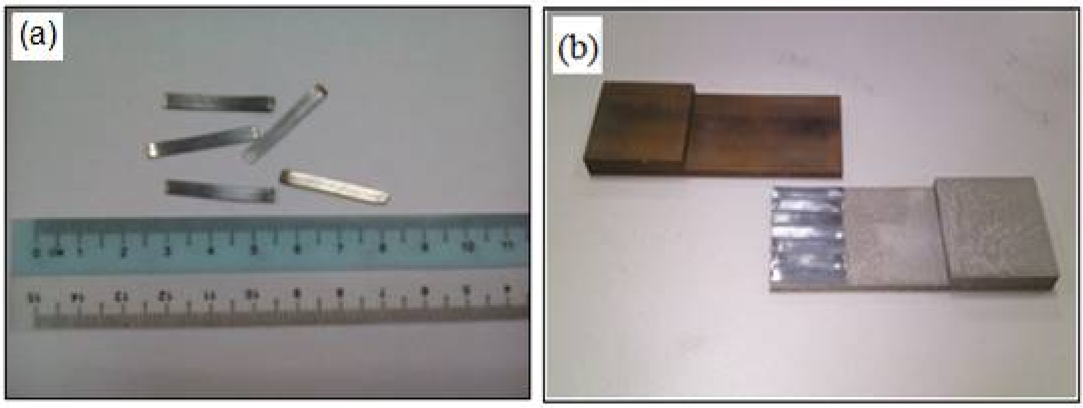

Figure 3. Filler preparation: (a) filler metal, (b) filler metal arrangement in specimen

Table 3. Composition of Al-Si-Zn base filler metal (wt.%)

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Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Ag	Pb	Sn	V	Al
14.84	3.13	0.58	1.42	1.70	0.06	1.49	15.60	2.02	0.1	0.87	3.75	0.13	Balance

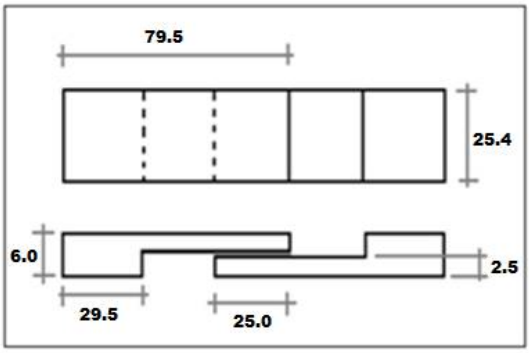

Figure 4. Overlap of steel and aluminium for joining process

The torch-brazing process involved the burning of butane gas whereby the base metal was heated to a temperature within a range where the bonding phase between the molten filler metal and the base metal can occur (see Fig. 5). This brazing was conducted for three different durations of 1, 2 and 5 minutes to see the effect of holding time and temperature variation to surface wetting by the filler. It was also reported that the formation of IMC could be related to brazing temperature [24].

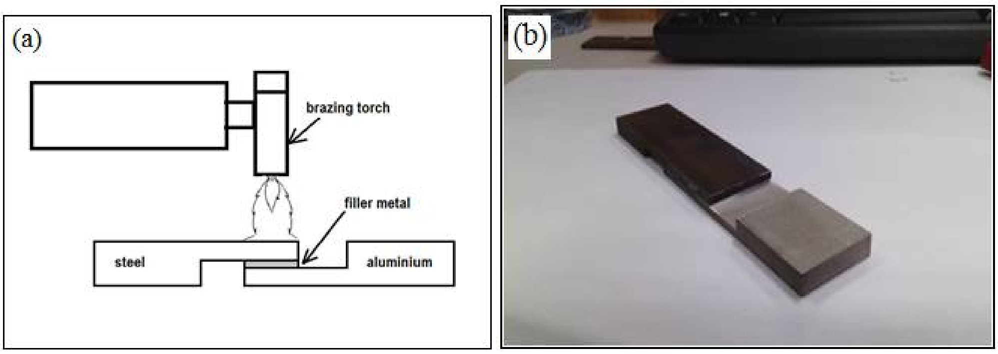

Figure 5. Brazing process: (a) torch brazing process, (b) specimen produced by brazing process

The joint strength was evaluated by shear testing (3 tests for each flame time). Shear tests were carried out in an universal testing machine with a load cell (model Zwick Roell Z100). The cross-section of the brazed joint after shear testing was observed by using a variable pressure scanning electron microscope (VP-SEM) (model Zeiss Evo Ma 10). Specimens for SEM were provided by cutting both metals to the size of 10 mm x 10 mm x 2.5 mm and carried out brazing process. The surface fractures caused by the shear test were observed by using a stereo microscope (model Olympus SZ61) and the hardness test was conducted by using a Rockwell Brinell machine (model Shimadzu DXT). The equipment employed in this study is shown in Fig. 6.

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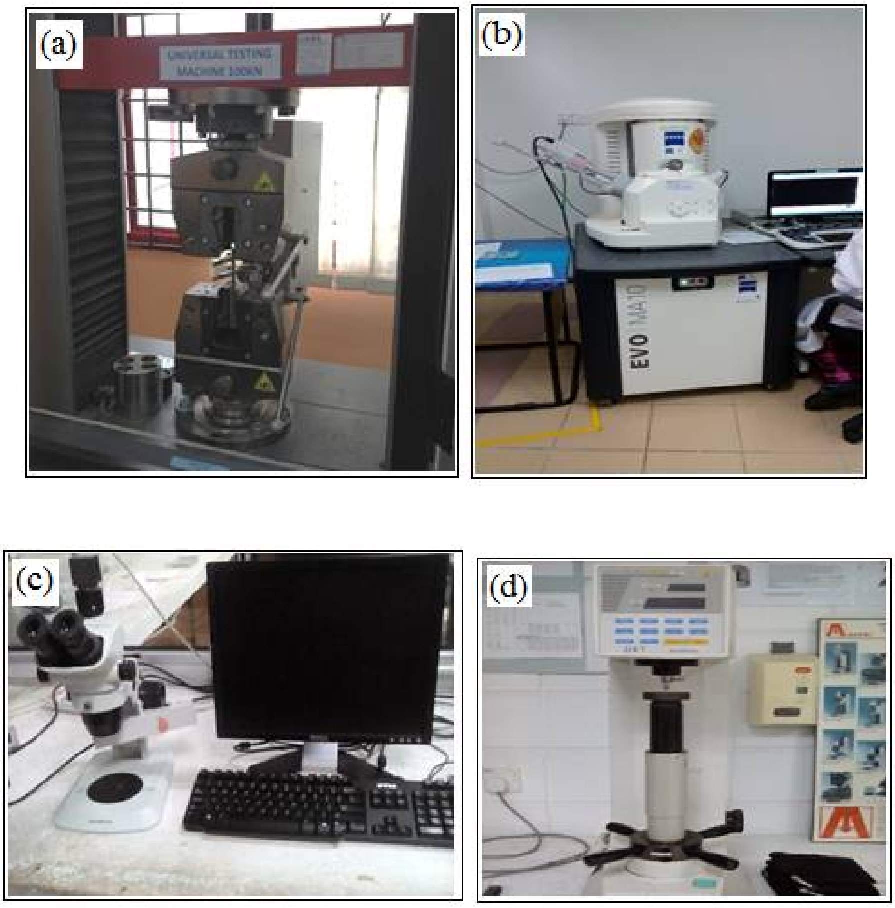

Figure 6. Equipment for testing and analysis: (a) universal testing machine, (b) variable pressure scanning electron microscope (VP-SEM), (c) stereo microscope, (d) hardness testing machine

3. Result and discussion

3.1 Intermetallic compound layer formation

The presence of an IMC is known to affect the crack sensitivity, ductility and strength of a joint. A thicker layer of IMC results in more-brittle joints and reduces strength and hardness [25]. The thickness of the IMC was observed for both the AR500 steel/filler metal and the AA7075 aluminium alloy/filler metal. Figure 7 shows the thickness of the IMCs formed on AR500 and AA7075 with filler metal for three different flame times (1, 2 and 5 minutes). Generally, IMC formation and thickness increases due to an increase in the brazing time and temperature [24]. In the experiment, the brazing temperature was recorded by a thermocouple for the flame times 1, 2 and 5 minutes, the values of which are shown in Table 4. The result of the current study show that the formation and thickness of the IMC on AR500 steel and filler metal increased substantially with increasing flame time, whereas the IMC thickness on AA7075 and filler metal showed a small decrease with increasing flame time. The SEM images of IMC formation on AR500 steel/filler metal and on AA7075 aluminium alloy/filler metal for the three different flame times are shown in Figs. 8–10.

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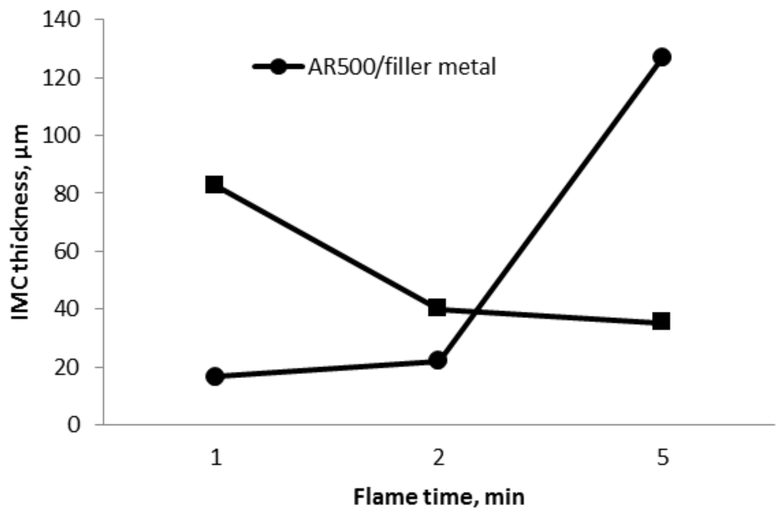

Figure 7. Effect of flame time on thickness of intermetallic compound layer formed on AR500 steel and AA7075 aluminium alloy

Table 4. Temperature recorded at flame time

Joining Material	Flame time (min)	Temperature (°C)
	1	477
AR 500 + AA7075	2	580
	5	669

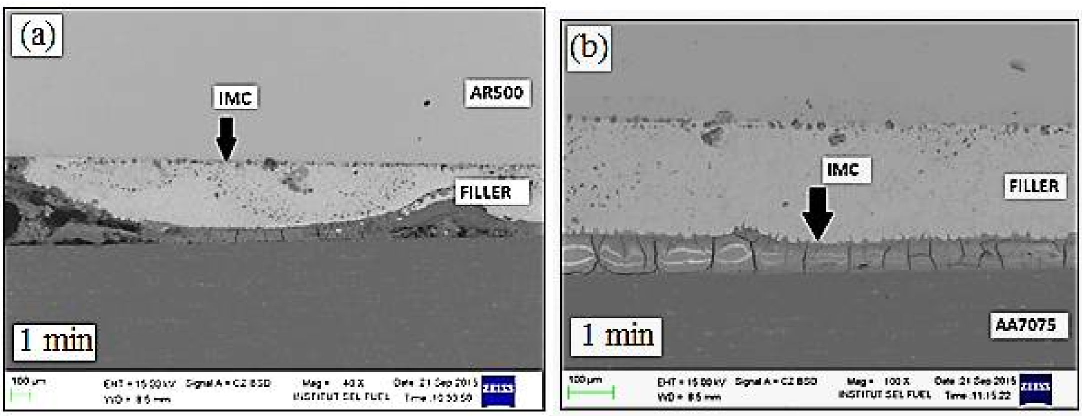

Figure 8. IMC layer formation on torch-brazed joint between AR500 steel and AA7075 aluminium alloy for flame time of 1 minute: (a) IMC layer between AR500 and filler, (b) IMC layer between AA7075 and filler

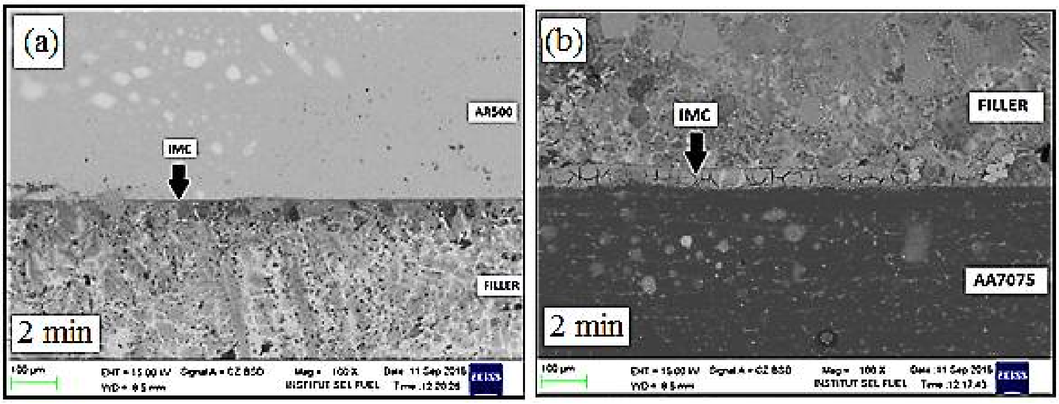

Figure 9. IMC layer formation on torch-brazed joint between AR500 steel and AA7075 aluminium alloy for flame time of 2 minutes: (a) IMC layer between AR500 and filler, (b) IMC layer between AA7075 and filler

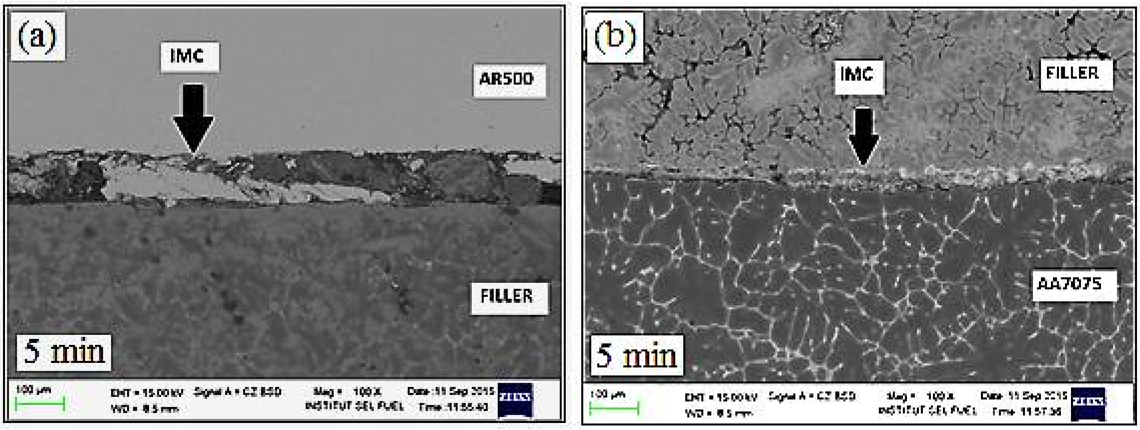

Figure 10. IMC layer formation on torch-brazed joint between AR500 steel and AA7075 aluminium alloy for flame time of 5 minutes: (a) IMC layer between AR500 and filler, (b) IMC layer between AA7075 and filler

The results of the EDX analysis for flame times of 1 and 5 minutes are shown in Figs. 11 and 12, respectively. They show that at 1-minute flame time the reaction layer or the IMC formed on the AR500/filler consisted of an AlZnO compound, whereas on the AA7075/filler metal the IMC consisted of an FeAlZnO compound. When the flame time and temperature increased (5 minutes), the IMC was primarily composed of an FeAl compound, whereas an FeAl compound formed on AR500/filler metal and Fe_3Al IMCs formed on the AA7075/filler metal. It should be mentioned that just the relative composition of Al and Fe was evaluated in the present investigation base on atomic percentage from the EDX results [26-27]. These are shown in Table 5. EDX analysis was carried out at various spots at and around the interface layer (some typical spots were shown in Fig. 11(a)). The different elemental ratios indicate the presence of different IMCs in this region.

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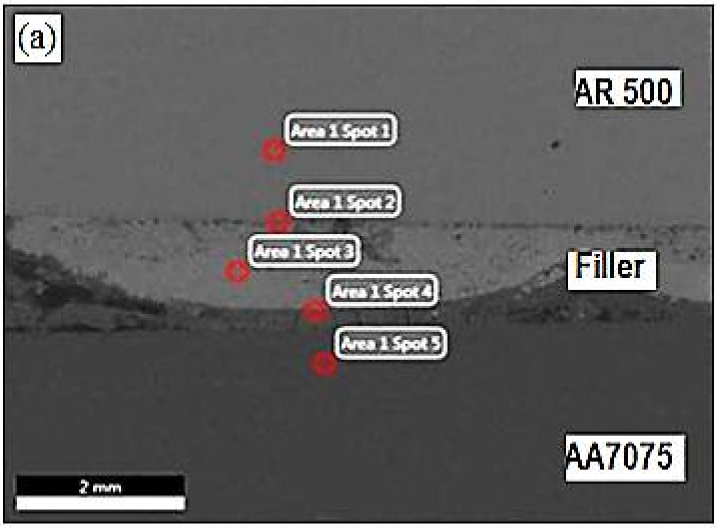
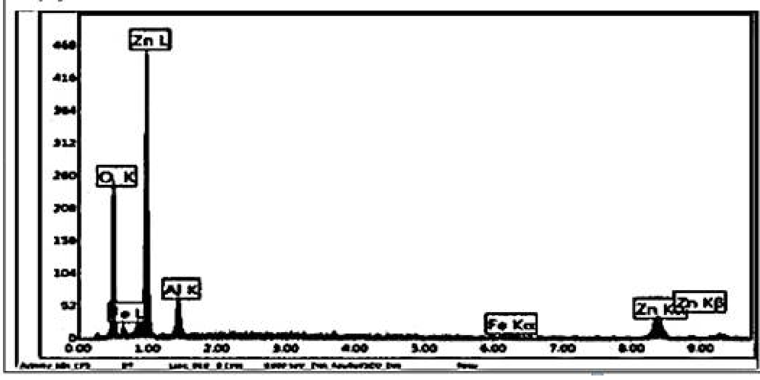


(b) **Spot 2**

Element	Weight %	Atomic %
C	12.35	25.53
O	36.39	56.47
Al	1.61	1.49
Cs	12.08	2.26
Zn	37.56	14.26

(c) **Spot 4**



Element	Weight %	Atomic %
O	30.3	61.14
Al	6.22	7.44
Fe	0.87	0.5
Zn	62.61	30.92

Figure 11. EDX analysis of torch-brazed joint between AR500 steel and AA7075 aluminium alloy for flame time of 1 minute: (a) SEM image of spot areas, (b) analysis of spot area 2 (IMC of AA7075/filler), (c) analysis of spot area 4 (IMC of AR500/filler)

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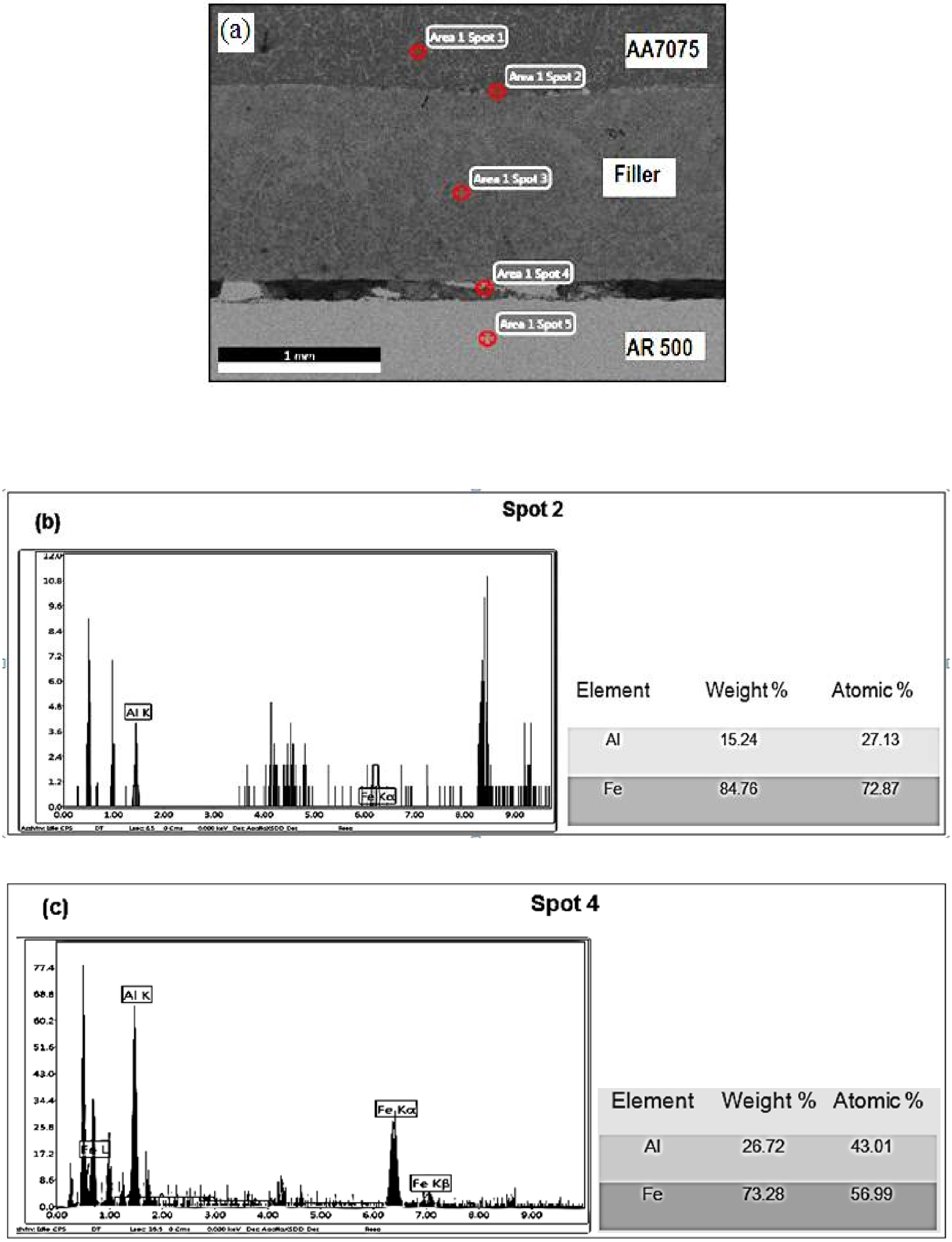

Figure 12. EDX analysis of torch-brazed joint between AR500 steel and AA7075 aluminium alloy for flame time of 5 minutes: (a) SEM image of spot areas, (b) analysis of spot area 2, (IMC of AR500/filler), (c) analysis of spot area 4 (IMC of AA7075 /filler)

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Table 5. SEM-EDX analysis results on FeAl compound of torch-brazed joint between AR500 steel and AA7075 aluminium alloy for flame time of 5 minutes

Point	Al (at%)	Fe (at%)	Al : Fe	IMC
spot 2	27.13	72.87	1 : 3	Fe_3Al
spot 4	43.01	56.99	1 : 1	FeAL

3.2 Mechanical properties

Nippon Steel conducted a study on the strength of steel and aluminium joints for automotive body parts that were made by using various methods of joining such as spot welding, self-piercing riveting, blind riveting, friction stir welding, adhesive bonding and laser brazing, and reported that the highest shear load that could be achieved is below 6000 N [28]. Figure 13 shows the average shear load (of three tests) of the brazed joint produced in the current study by using Al-Si-Zn filler metal. From the figure it can be seen that a shear strength was achieved in the range of 1340–6460 N. The results show that the shear load decreased with increasing flame time and temperature. For the joint formed by brazing for 2 and 5 minutes of flame time the joint shear load decreased significantly compared to that produced by the 1-minute flame time. The poor shear load of the joints produced by 2-minute and 5-minute flame times is due to the increased amount of brittle IMCs in the interface. In other words, the brazing temperature in an oxidizing atmosphere plays a critical role in the formation of the reaction layer. An increase in the brazing temperature produces high oxidation on the surface. A higher formation of oxide can give rise to a higher amount and variety of brittle IMCs. The higher brittleness of the IMCs results in lower joint shear strength [25].

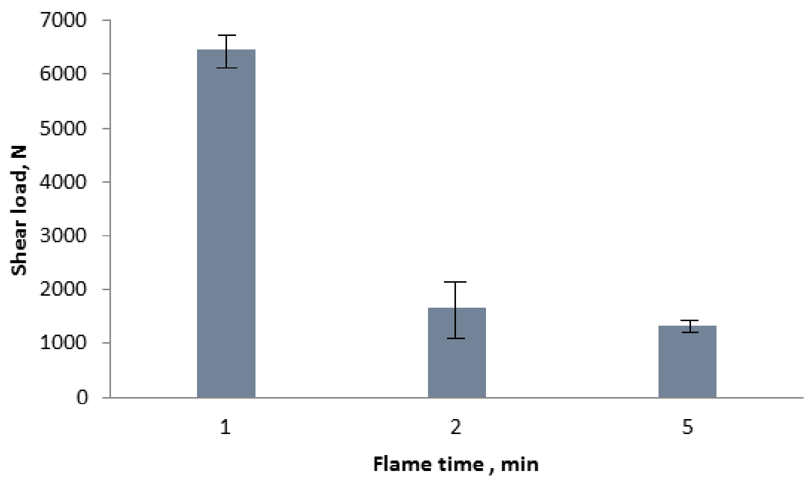

Figure 13. Shear load vs flame time for torch brazing of joint between AR500 steel and AA7075 aluminium alloy

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The hardness of AR500 steel, AA7075 aluminium alloy and filler metal (brazing seam) after brazing was also investigated in this study. The hardness of base metal was tested on the outer surface of the joint metals. Figure 14 shows the hardness of AR500 steel, AA7075 aluminium alloy and filler metal before and after brazing (average hardness values of 6 readings for each condition). The results show that the hardness of both AR500 and AA7075 after brazing decreased. The hardness of AR500 and AA7075 decreased at 1 and 2 minutes of flame time. The recorded temperatures during those flame times were 477°C and 580°C, respectively. The hardness of aluminium decreased as a result of annealing. Coarse grains of the $MgZn_2$ phase were formed during the annealing process and non-uniformly distributed in the aluminium matrix. However, at 5-minutes flame time, the hardness increased and the temperature recorded for that flame time was 669°C, which is above the solvus temperature of the aluminium alloy. At this temperature, the formation of a small and finely uniform dispersed precipitate of the $MgZn_2$ phase occurs in the aluminium matrix which serves as a foreign atom or inclusion in the lattice of the host crystal in the solid solution; this causes more lattice distortions which makes the alloy harder [29]. Figure 14 also shows that there was no significant change in the hardness of the steel base metal. Base on the Fe-C phase diagram, the temperature has an effect on the microstructure and properties of steel at around 738°C [30]. The maximum temperature used in the brazing process in the current study was 669°C, therefore no significant change in the hardness value of the steel took place. The hardness of brazing seam was tested on the surface of the delaminated joint. The results in Figure 15 showed that the hardness of brazing seam had increased when the flame time and temperature were increased. This happened because of the solid solution strengthening effect in filler metal during flaming process [31].

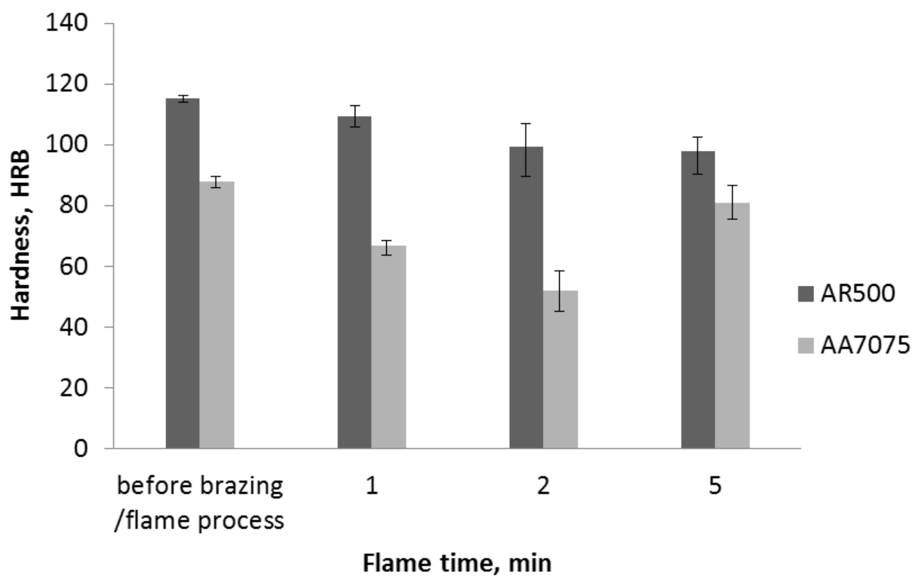

Figure 14. Hardness vs flame time for AR500 and AA7075 specimen plates

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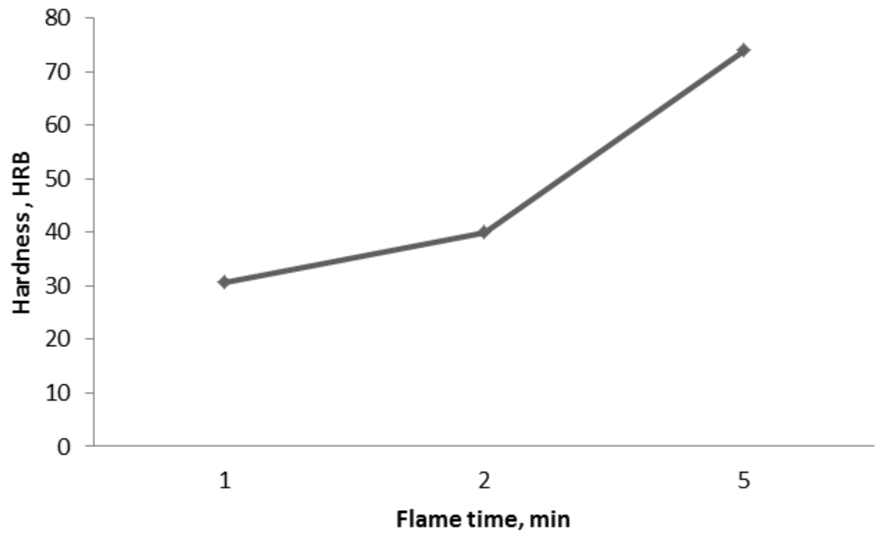

Figure 15. Hardness vs flame time for brazing seam

3.3 Fracture surface observation

Figure 13 shows stereo microscope images of the fractured surface of the brazed joint after the shear test. In all the joint specimens of AR500 steel and AA7075 aluminium alloy, the IMCs formed in the bonding of the AR500/filler and of the AA7075/filler. The fractures caused by the shear test occurred in the joint interface between the filler and base metal. The images in Fig. 16(a, b) of the joint fracture between AR500 steel and AA7075 aluminium alloy that occurred after flame times of 1 and 2 minutes shows that the filler metal is detached from the AA7075 aluminium alloy base metal. The EDX analysis in Fig. 11 shows that the IMC formed in the joint brazed for 1 minute consists of a Zn-rich compound. The side containing low zinc compound causes the IMC to decrease and increase the shear strength [32-33]. This condition causes the surface to fracture in the region of the AA7075 aluminium alloy and filler where the IMC consists of a high zinc compound. For the joint prepared under the condition of a 5-minute flame time, the joint was fractured between the filler metal and AR500 steel (the interface that is rich in FeAl, as also observed by previous other researchers) [13,14,34]. In Figure 16(c) it can be seen that the filler metal attached at AA7075 aluminium alloy is detached from the AR500 steel surface. As mentioned above, the EDX analysis in Fig. 12 shows these interfaces, AA7075/filler and AR500/filler, contained Fe_3Al and FeAl IMCs respectively. Thus the results show that the Fe-rich IMC on the AA7075 and filler bonding gives better strength than the AR500 and filler bonding. Hence, in line with previous results, it is clear that the fracture mode changes by increasing the brazing temperature and time [35]. At the same time, it was observed that a reaction layer also formed between the base metal and filler metal joint. This layer can be considered an oxide layer that forms during the heating or flame process [36]. The formation of an oxide reaction layer reduces the diffusion of the filler metal into the base metal and also reduces the strength of the joint [37].

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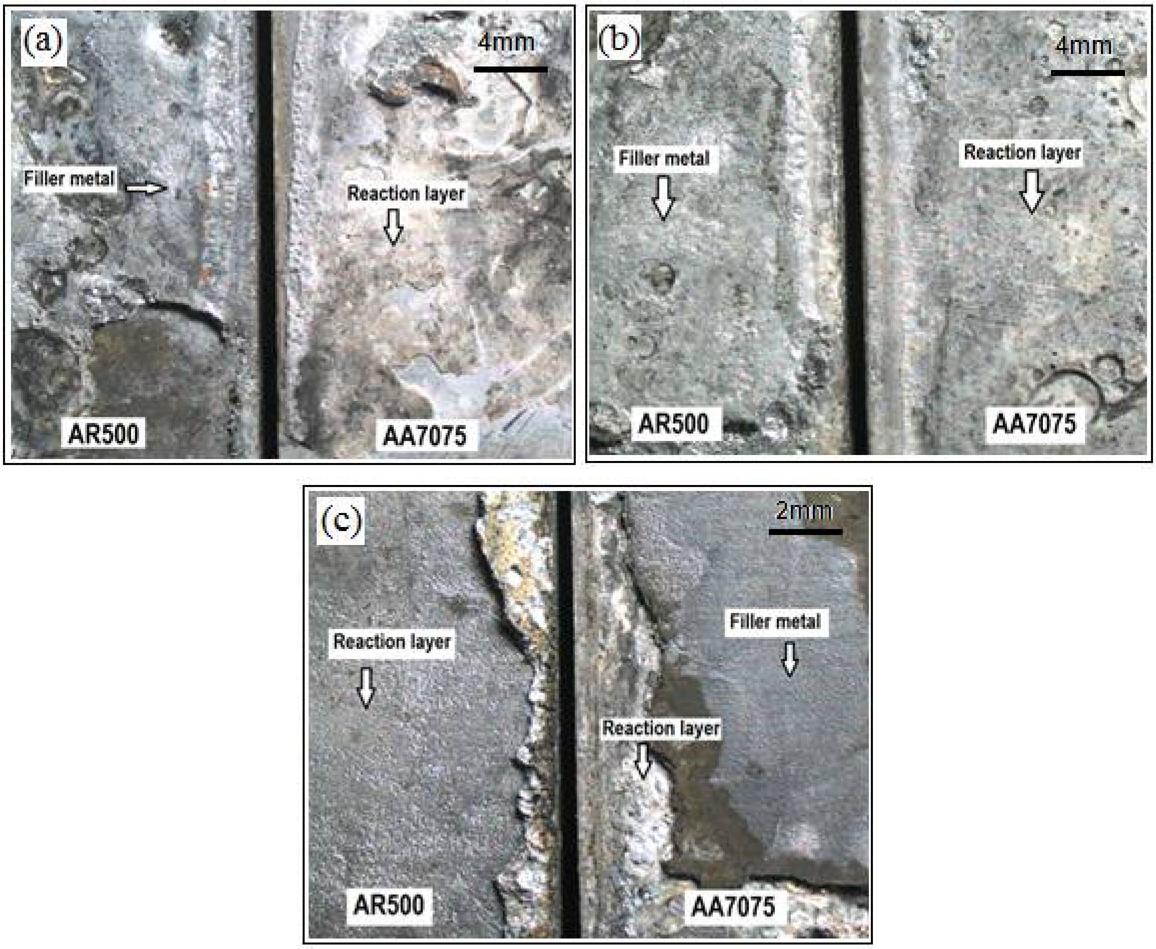

Figure 16. Fractured surfaces of AR500 steel and AA7075 brazed joint: (a) joint fracture surface for flame time of 1 minute, (b) joint fracture surface for flame time of 2 minutes, (c) joint fracture surface for flame time of 5 minutes

4. Conclusions

In this study, the joining of AR500 steel and AA7075 aluminium alloy by using torch brazing was successfully carried out. The effect of brazing time was investigated and the results obtained can be summarized as follows:

1. The study shows that in all cases presented, fracture will always occurred at the metal/filler interface containing FeAl intermetallic compound. It signifies that the interface containing IMC with higher Fe ratio, e.g. Fe_3Al, is stronger than the interface containing IMC with relatively lower Fe ratio, e.g. FeAl.
2. The shear strength of the interface of the joint decreased with increasing flame or brazing temperature. The highest shear load was 6460 N, which was obtained at brazing temperature of 477^0C.
3. The hardness of the aluminium base metal was reduced by about 30%-40% when brazing below its solvus temperature. It was due to the increasing grain size of the aluminium base metal.

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4. Fractures occurred on the surface of the base metal and filler metal joint. The presence of a passive oxide layer between the base metal and filler metal would have affected the diffusion of the filler metal into base metal and significantly reduced the strength of the joint.

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