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A Study on the Wetting Behaviour of Al-Si-Zn Brazing Filler on AA7075 and AR500 Surface

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ABSTRACT

This paper presents the results of an experimental study on wetting and spreading of Al-Si-Zn filler metal on AR500 steel and AA7075 aluminium alloy surface. Wetting and spreading conditions of filler metal onto the surface of the metal were analysed by contact angle and spread ratio with different surface conditions. The contact angle is the measured angle between the tangent to the liquid-vapour interface and the surface of the solid. While, spread ratio measured according to the change in diameter of spread shape geometry of filler metal. The use of the low melting temperature of filler metal is increasingly popular since they are able to reduce the effect of heat on metals. However, the low spreading and de-wetting condition have limited the application of filler metal due to the adverse effect of these conditions on the joint ability. However, overall, this study with different surface conditions of these metals is to identify the wetting and spreading behaviour of filler metal. In this work, Al-Si-Zn filler metal heated by torch brazing was applied to AR500 steel and AA7075 aluminium alloy surface with the different type of surface conditions. Experimental results showed that the higher spreading area of filler metal occurred on a smooth surface compared to the rough surface of metals.

Keywords: Filler metal; brazing; wetting; spreading; contact angle

ABSTRAK

Penyelidikan ini adalah kajian sifat kebasahan dan penyerakan logam pengisi Al-Si-Zn pada keluli AR500 dan AA7075 aluminium aloi. Kesan kebasahan dan penyerakan logam pengisi pada pelbagai keadaan permukaan logam substrat dianalisis melalui sudut sentuh dan nisbah serakan. Sudut sentuh diukur di antara tangen bagi permukaan cecair-wap dengan permukaan pepejal. Manakala, nisbah serakan pula diukur berdasarkan perubahan diameter geometri bentuk serakan logam pengisi. Penggunaan logam pengisi bersuhu lebur rendah semakin popular dan meluas kerana dapat mengurangkan kesan haba terhadap logam. Walau bagaimanapun sifat penyerakan yang rendah dan keupayaan pembasahan yang kecil menghadkan pengunaan sesuatu logam pengisi sebagai bahan cantuman kerana kesan kebolehcantuman yang tidak baik. Pada keseluruhanya kajian yang dijalankan adalah untuk melihat sifat pembasahan dan penyerakan logam pengisi ini di atas keadaan permukaan yang pelbagai Kajian ini dilakukan dengan memanaskan logam pengisi Al-Si-Zn di atas pelbagai keadaan permukaan AR500 dan AA7075 menggunakan kaedah pateri keras tunu. Hasil kajian ini menunjukkan penyerakan logam pengisi yang tinggi dan baik berlaku pada permukaan logam yang halus.

Kata kunci: Logam pengisi; pateri keras; pembasahan; penyerakan; sudut sentuh

INTRODUCTION

Development of joining technologies are important in various industries. The invention of versatile joining methods are very useful in fabrication process and the joining ability in various condition will affect product quality such as semisolid welding joint (Mohammed et al. 2014; Mohammed et al. 2012), laser welding (Kwanwoo et al. 2010), brazing (Feng 2005; Dai et al. 2012) and friction stir welding (Cheng and Lin 2010).

Joining of dissimilar metal steel and aluminium alloys is difficult due to differences in metallurgical, physical properties and also the formation of brittle intermetallic compound (IMC) where the major issues in joint performance of both metals (Ozaki and Kutsuna 2009). The dissimilar metals joint using brazing technology with high-performance brazed joint are highly needed for the manufacturing area in the near future. Brazing is a special and unique joining technology, which offers several advantages to the manufacturing industry especially in low temperature joining process. The ability of joining by brazing method is influenced by several factors especially wetting and spreading of molten brazing filler material (Kogi et al. 2014). Several studies in wetting and spreading of filler metal conducted in various condition such as surface roughness (Kubiak et al. 2011; Takyi & Bernasko, 2015; Zhao et al. 2014; Hay & Dragila, 2008; Zaharinie et al. 2015), brazing time-temperature (Nogi et al. 1992; Cui & Cui, 2015) and alloying element (Dai et al. 2012; Niu et al. 2016). Wettability is defined as the apparent contact angle, where the angle is between the nominal solid surface and the liquid-air interface. Wettability phenomena is often characterized by measuring through the liquid and at the point where the liquid-air interface meets the solid. Several studies defined the contact area provides good indication for the wettability and the low contact angle correspond to greater wettability. (Derrrick et al. 2007; Nogi 1993).

During the brazing process, the increases in temperature cause the melting of the filler metal to occur. The melting of filler usually maintained a little higher than the melting temperature and known as peak temperature. The temperature influencing the molten filler metal to spread over the substrate metal, the action cause of interfacial energies, intermetallic reaction between filler metal alloy and the surface metal is present. The molten filler metal during brazing process dissolves on substrate metal by capillary action. According to Warren et al. (1998), the spreading of molten filler over the substrate metal involves several complex processes such as fluid flow, heat flow and chemical reactions. The formation of intermetallic compound also occurred during the process.

The good joint strength between metals depends on the good wettability of molten filler metal over the metal substrate. Wettability of molten filler on metals surface depends on several factors such as flux, process temperature and surface roughness. Flux was used to protect metals surface from oxides formed during the heating process. The oxide formed will block the molten filler to spread smoothly. The oxide protective layer over the substrate formed by reaction between flux and vapor phase caused the lack of total contact between substrate metal and filler. The improvement of molten metal spreading influenced by reducing the contact angle by flux action. According to Singler et al. (2004), the process temperature is an important factor that affects spreading. The increasing on temperature influences liquid viscosity and liquid surface tension to decrease. These conditions which assist the good spreading of molten filler, in the same time it increases the wetting rate and spread uniformly.

Surface roughness on the substrate surface is an important factor of molten filler flow, but, there is no consensus on how in general it influences wetting (Singler et al. 2004). The wetting on the rough surface is lower than on the smooth surface. This occurs due to the presence of open channel capillaries in the form of grooves on a rough surface and was in line with the study conducted by Chen et al. (2000). Those studies also stated that the asperities present on a rough surface act as barriers needed to be overcome by molten metal while spreading.

Production of low melting temperature aluminium-based filler metal with strengths similar to the aluminum alloys is in high demand. For brazing applications, Al-Si with Si content in the 7-13% range is used for joining purposes due to its good spreading, high strength and high corrosion resistance. This Al-Si filler metal has a melting point of between 575-610 °C and its use is limited because some aluminium alloys have a solidus temperature of around 590 °C which makes it difficult to joint. Therefore, a low melting point is required for this purpose. Various low melting metal fillers have been developed for the purpose of lowering the brazing process temperature by adding alloying elements such as Cu, Zn, Ni and others to Al-Si alloys. According to Dai et al. (2012), the addition of Zn in Al-Si alloys resulted the lower melting filler metal at a temperature of 520 – such as Al-6.5Si-42Zn and Al-6.5Si-42Zn-0.5Sr filler metals. Addition of alloying elements and alteration of element composition on Al-Si-Zn can improve the effectiveness of the filler metal, this addition will affect factors such as lowering melting temperature, improving microstructure, properties of metal fillers and capability of joining.

In depth studies on wetting and filler metal spreading abilities have to be conducted intensively. Moreover, spreading of molten brazing filler material on metal surface is affected by their roughness and conditions of surface, and especially by the interfacial reactions between the filler and base materials. In this study, the effects of the surface roughness and surface conditions on the spreading of Al-Si-Zn filler metal alloys are investigated.

METHODOLOGY

EXPERIMENT DESIGN AND PROCEDURE

Wetting is a property of molten filler metal to spread over a solid surface. Wettability and spreading ability performance described by contact angle and spreading ratio of filler metal on the metal surface. The system is usually described as wetting or non-wetting if the contact angle is smaller or greater than 90°. The contact angles of filler and the base material (θ <90°) resulted the proper wetting occur between this two materials. The factors that determine wettability is contact angle. The lower the contact angle, the greater the wettability (Derrick et al. 2007; Kiyoshi et al. 1993). The contact angle is the measured angle between the tangent to the liquid-vapor interface and the surface of the solid as shown in Figure 1.

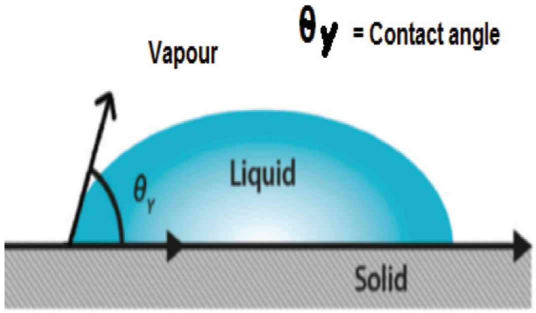

FIGURE 1. Contact angle

The measurement of spread performance was accomplished by measuring the spread ratio according to the change in spread shape and geometry. The spread ratio is used to evaluate and quantify the degree of wetting (Kozlova et al. 2009; Protsenko et al. 2008). The ratio measured by the instantaneous base diameter of the spreading wetting ball (D) to the initial diameter of the wetting ball (D_o) used for the experimental test as shown in Equation 1.1.

$$Spread\ ratio = \frac{D}{D_0} \quad (1.1)$$

The high spread ratio shows the better spreading of filler metal on the substrate. The high spread ratio also describes the molten filler metal flow smoothly and uniformly. This condition also shows the molten filler metal has enough energy to overcome the barrier on the metal surface.

The materials used in this experiment are AR500 steel and AA7075 aluminum alloy as a substrate material, while Al-Si-Zn alloys as filler metal. The chemical composition of AA7075 aluminium alloy, AR500 steel, and filler metal, determined using a spark emission spectrometer (model Spectromaxx), are provided in Table 1, 2 and 3 respectively. The AR500 steel and AA7075 aluminium alloy were cut to 25 mm x 25 mm x 6 mm, while, Al-Si-Zn filler metal wire were rolled and cut into strip with dimension 25 mm x 3.5 mm x 0.5 mm (filler folded half to become 12.5 mm in length).

In the initial stage, the substrate material is grounded using SiC sandpaper with different grit (40, 180 and 600), The surface roughness was measured using Mitutoyo Formtracer – SV C310000 machine. The result of surface roughness on various surfaces of substrate metal is shown in Table 4.

TABLE 4. Surface roughness measurement

Spesimen	Surface preparation	Surface roughness
1	Ground by SiC sandpaper grit 600	AR500 – 0.111µm AA7075 – 0.223µm (Fine surface)
2	Ground by SiC sandpaper grit 180	AR500 – 0.322µm AA7075 – 0.633µm (Medium surface)
3	Ground by SiC sandpaper grit 40	AR500 – 1.427µm AA7075 – 3.047µm (Rough surface)

In the next stage, the wetting ball was produced by heating the stripe filler metal with flame using torch over the surface of the substrate material up to 120ºC as shown in figure 2. The diameter of the wetting ball and contact angle

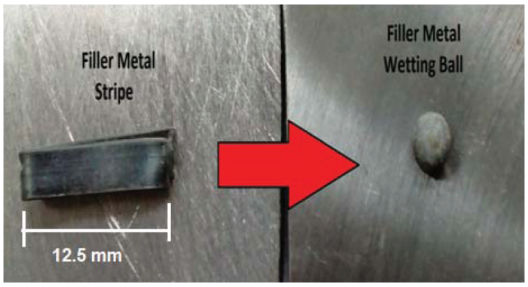

FIGURE 2. Producing wetting ball

TABLE 1. Chemical 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. Chemical 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

TABLE 3. Chemical composition of Al-Si-Zn base filler metal (wt.%)

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

was measured. The wetting ball was continually heated to a temperature of 500 ºC (above of filler metal melting temperature, 425 ºC), where at this stage the spreading of molten filler metal on the substrate metal surfaces was observed. After this process, the diameter of spreading area and contact angle was measured once again.

In the last stage, the joining process completed with the AA7075 aluminium alloy overlapped the high-strength steel plate and the filler metal is between the two metals, as shown in Figure 3 and then torch-brazing process involved the burning of butane gas was heated to the surface of base metal (AR500 steel). The joint specimen was evaluated by shear testing.

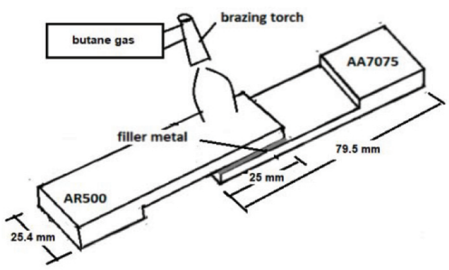

FIGURE 3. Torch brazing joining process

RESULTS AND DISCUSSION

WETTING AND SPREADING FILLER METAL ON AA7075 AND AR500

The result of experiments on wetting and spreading of Al-Si-Zn filler metal on AA7075 and AR500 was recorded and analysed. The spread ratio decreased with increasing of surface roughness as shown in Figure 4.

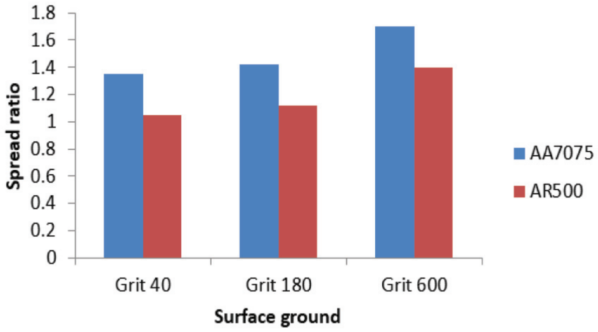

FIGURE 4. Spread ratio of filler metal on the various surface roughness of substrate metal

The fine and clean surfaces generally produce surfaces that contain low oxides and this situation reduced the influence of oxide in wetting. Therefore, the reaction between molten filler metal and substrate was not intense and affected molten filler metals to spread smoothly. In rough surface, the grinding lines may be considered as randomly distributed micro-grooves. The asperities (micro-grooves) present in the rough surface acts as series of barriers as molten filler spreads on the surface (Wu et al. 2016; Cui & Cui, 2015; Kubiak et al. 2011). The micro-grooves on the substrate surface slow down the flow of molten filler on it's surface. It occurred because, during the flame process, the molten filler flow on the substrate need to climb along the micro-grooves and drawn into these grooves by capillary action.

The ability of the molten metal to overcome those barriers and spread depends upon the relative size of the barriers. In some circumstances, the grooves provide passes for molten filler metal flowing away or entrapped in grooves. According to Zhao et al. (2014), the uncontrolled flow and entrapped filler metal can lead to serious consequences such as base metal erosion, not uniform spreading and microchannel blockage.

In this study, as shown in Figure 5(a) and 6(a), spreading of molten filler on a fine surface occurred uniformly surrounding the wetting ball as a result of the absence of barrier on the surface of substrate metal (no large grooves). The absence of barriers on this surface will lead towards smoother spread of filler. The case of the medium surface, spreading of molten filler metal is still uniform but the spread ratio decreases as shown in Figure 5(b) and 6(b). In this case, the micro-groove has begun to appear and it acts as a barrier for the filler molten metal to spread more smoothly. In rough ground surface, filler spread in an irregular shape, indicating a non-uniform spreading as shown in Figure 5(c) and 6(c). This non-uniformity can be attributed to the presence of clear micro-groove lines in the surface. In Figure 5(c) and 6(c) shown, the molten filler moves well along the direction of groove lines when compared to moving in the direction perpendicular to them. Molten filler moving along the groove lines has low energy barriers and should have more of the energy to move overcome the valleys. This situation results in the molten filler spreading in irregular shape and caused improper spreading of molten filler on

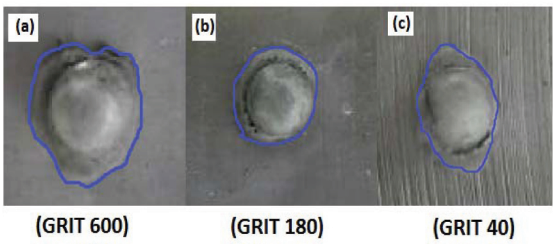

FIGURE 5. Spreading of filler metal on the various surface roughness of AA7075 aluminum alloy (a) Fine surface, (b) Medium surface, (c) Rough surface

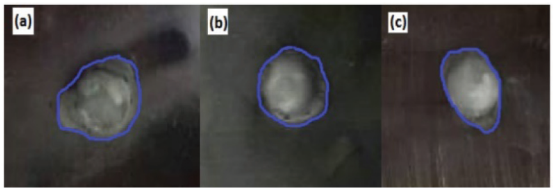

FIGURE 6. Spreading of filler metal on the various surface roughness of AR500 steel (a) Fine surface, (b) Medium surface, (c) Rough surface

a medium and rough surface (40 and 180 grit SiC paper ground surface), when compared to spreading on a fine surface (600 grit SiC paper ground surface.

The study also observed in contact angle behaviour of filler metal on various surface roughness of substrate metals. The Figure 7 shows the relation of contact angle between filler metal and substrate metals. The contact angle shows decreased with increasing of surface roughness. This condition in line with several studies done by previous researchers. The contact angles of filler and the base material (θ <90°) resulted in the proper wetting occur between filler metal and substrate metal. The lower the contact angle, resulted good wettability (Derrick et al. 2007; Kiyoshi et al. 1993).

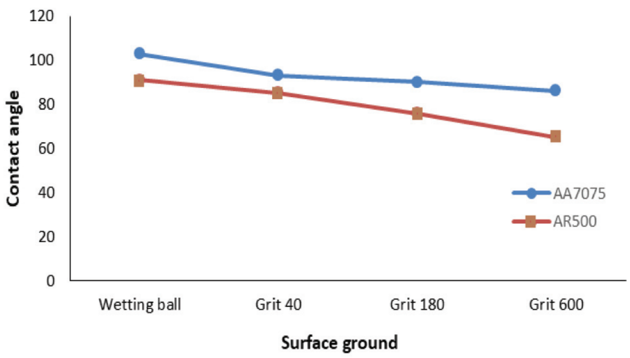

FIGURE 7. The relation of contact angle between filler metal and substrate metal on the various surface roughness

Figure 8 and 9 showed the contact angle of wetting ball on AA7075 and AR500 in various surface roughness. From the figure, Al-Si-Zn filler metal has a lower contact angle on the AR500 surface compared to AA7075. This shows that the wettability and spreading of this filler metal is better on the AR500 surface and can produce the better joining quality on this part.

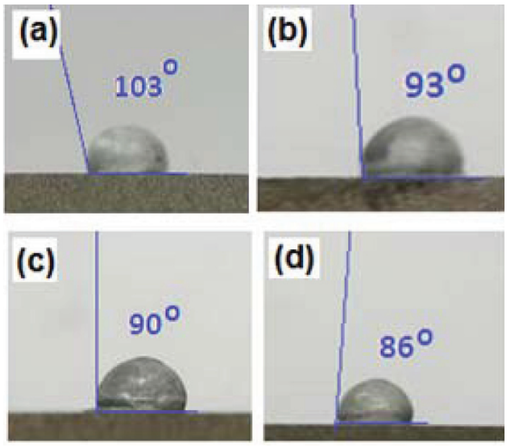

FIGURE 8. Contact angle of filler metal spread on various AA7075 surface roughness (a) wetting ball (b) rough (c) medium (d) fine

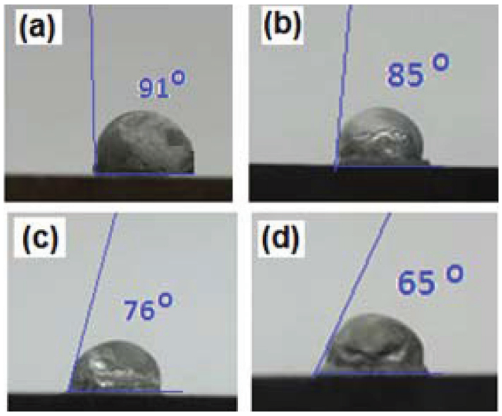

FIGURE 9. Contact angle of filler metal spread on various AR500 surface roughness (a) wetting ball (b) rough (c) medium (d) fine

SHEAR STRENGTH OF AR500 AND AA7075 JOINT

Shear test conducted to AR500 and AA7075 joint with two different surface ground medium fine (grit 180) and coarse (grit 40) as shows in Figure 10. Shear test result shown the smooth and fine surface has resulted better joining strength than the rough surface. This is in line with experimental results showed that low contact angles and high spread ratio occur on fine metal surfaces. This condition has also been acknowledged by previous researcher states that low contact angle and high spread ratio will result in better joining (Berczeli and Weltsch 2018; Protsenko et al. 2008).

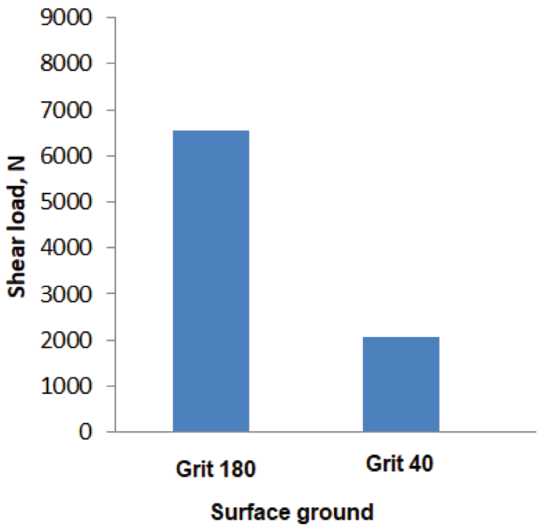

FIGURE 10. Shear strength of AR500 and AA7075 joint

Observation of joint failure shown in Figure 11. The amount of dark reaction layer was high and covered the aluminium surface on coarse surface as shown in Figure 11(b) compare to on medium fine surface in Figure 11(a). This situation caused some flux and filler metal to be entrapped and prevented from spreading to whole joint area and reacting with aluminium surface. This situation also mentioned by Chen & Duh (2000) and Zhao et al. (2014)

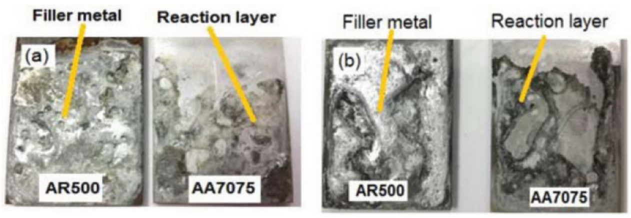

FIGURE 11: Fractured surfaces of AR500 steel and AA7075 brazed joint: (a) joint fracture surface for medium fine surface (grit 180), (b) joint fracture surface for coarse surface (grit 40)

CONCLUSION

1. The surface roughness of substrate material (AA7075 and AR500) had an influence on the spreading behavior of the Al-Si-Zn filler metal.
2. The existence of barriers/grooves in the surface influenced the filler metal to spread non-uniformly.
3. The contact angle between filler metal and AA7075 is high compared to AR500.
4. With the decrease in contact angle between filler metal and substrate metals, the spreadability of Al-Si-Zn filler metal improves.
5. When compared to the two different metal (AA7075 and AR500), the spreading of filler metal on the surface of substrates do not show major different on spreading performance.
6. Finally, Al-Si-Zn filler metal spreads well over the fine surface as opposed to the rough one.

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