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Torsion Strength of Dissimilar Metals Friction Weld Joint of A6061-St41 Round Bar with Various One-Sided Chamfer Angle and Burn-Off Length

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ABSTRACT

This paper reports the torsion strength of dissimilar metals friction welded aluminum alloys A6061 and mild steel St41 round bar affected by various one-sided chamfer angle and burn-off length. In this study, cylinder specimens were made of aluminum alloy A6061 and mild steel St41. On the contact area of stationary specimens, chamfer angle of 30, 45, 60, and 90 degrees or no chamfer with chamfer length of 5 mm and 18 mm diameter were machined. Continuous drive friction welding was performed with the revolution speed of 1600 rpm, initial compressive force of 7 kN, and burn-off the length of 10, 15, and 20 mm, then upset compressive force of 14 kN was applied on the specimen for 40 seconds. Torsion strength of the specimens was conducted based on the ASTM standard. Macrostructure observation and microhardness testing were also done on the friction weld joint. From the results, it was found that maximum torsion strength occurred in the specimen of dissimilar metal A6061 & mild steel St41 friction weld with chamfer angle of 30 degrees and burn-off length of 15 mm and fractured in aluminum alloy part. It may occur due to the complete cone geometry, minimum porosity, and adequate total burn-off length in the specimen.

Keywords: Dissimilar metal friction welding, One-sided chamfer angle, Torsion strength, Macrostructure, Microhardness.

1. INTRODUCTION

The welding process is a manufacturing process by performing a joint process that is usually carried out in the engineering product assembly stage [1]. In the manufacturing process of products, welding technology advances rapidly to improve the quality of welded joints, which also increases the level of construction and machine safety. Without a strong weld joint, products that are easily damaged will only result in economic loss and safety for the wearer. The advancement of welding technology is marked by the discovery of new methods to overcome problems faced in the process of joining materials such as friction welding.

Aluminum and its alloys are corrosion resistant materials because they have a very low hydrogen potential, but have a strong protective layer [2]. This protective layer is a barrier oxide that is formed naturally and firmly bonded to its surface and can protect aluminum and its alloys from corrosion [3]. In the aluminum alloys, aluminum alloy A6061 has corrosion resistance, good weldability, and fairly good formability [4]. Some of the uses of this material are mainly for the manufacture of components for machinery, heavy vehicles, shipping, rail vehicles, which allow the friction welding process to be carried out [5]. However, this aluminum also has difficulties in the welding process because it has excellent thermal conductivity. In common welding methods such as arc and gas welding, this high thermal conductivity of aluminum causes heat to rapidly transfer, making it difficult to heat the weld joint area. Besides, the oxide generated during welding has a high melting point and high density, so that a homogeneous joint with good strength is difficult to obtain [6].

Friction welding such us continuous drive friction welding (CDFW) is a method of joining materials that utilize heat arising from the friction between the surfaces of the two materials to be joined [7] [8] [9]. The friction weld joint occurs due to the emergence of heat from the friction between the rotated material and stationary material under a certain compressive force. The friction weld joint will occur with flash in the interface when approaching the melting point of the two materials, so there is no need to melt too much material for the weld joint [10][11]. The energy required for the joining process is less than for other welding processes. This method can be used to overcome the difficulties of welding on aluminum [1][6]. There are parameters of the friction welding process, such as friction time, friction pressure, upset time, upset pressure, and revolution speed

[12]. These parameters and other parameters can be used to produce good quality of the CDFW joint.

Several attempts have been made to increase the strength of the friction welding joint between aluminum and steel, especially in the variation of friction welding parameters such as initial friction, forging stage, friction time and rotation speed. Kawai et al. [13] have performed friction welding on solid shafts of various aluminum alloys and low carbon steels with various presses and presses of forgings as well as 3000 rpm rotational speed with flat specimens without chamfer. They found that the higher the upset pressure and the shorter the friction time, the higher the strength of the weld joints for Aluminum A6061 and S25C carbon steel. Taban et al. [14] conducted the CDFW process of dissimilar metal friction weld joint of A6061-T6/AISI 1018. They found that it needed upset pressure in the level of 60 MPa to have the higher tensile strength of the weld joint. Irawan et al. [15] also performed a friction weld process to join dissimilar metal A6061 and mild steel S15C using parameters of upset pressure and a one-sided chamfer angle. They found that the use of a one-sided chamfer angle and upset pressure can improve the tensile strength of the weld joint.

In the research of friction welding joints, different materials between aluminum alloys and Al-SiC metal composites, Lin et al. [16] have used a chamfer angle on one side of the aluminum alloy material in friction welding between aluminum alloy (Al-Mg-Si) and Al-SiC metal matrix composites. It was found that the friction welded joint with the specimen using a chamfer angle has a higher tensile strength than the specimen without a chamfer angle.

Irawan et al. [17] have also investigated the effect of variations in chamfer angles on both sides of the contact area on the tensile strength of friction weld joints in aluminum alloy A6061. It was found that the specimen with a 30-degree chamfer angle on both contact sides provides the maximum tensile strength of the weld joint. It is due to a maximum weld joint area, high hardness, and a narrow area of Heat Affected Zone (HAZ). Irawan et al. [18] have also found that the use of a one-sided chamfer angle can increase torsion strength and minimize porosity in the A6061 friction weld joint. However, it is still unknown the impact of the burn-off length and one-sided chamfer angle on the friction weld joints of A6061 and mild steel St41.

Then Ashfaq et al. [19] also used various kinds of contours of the friction area of friction welding specimens with the rotational speed at 1500 rpm aluminum, which was friction welded to stainless steel AISI 304. From the research, it was found that specimens using an external taper with an angle of 15 had the maximum strength of a friction weld joint of aluminum A6061 and stainless steel AISI 304.

From previous studies on aluminum and carbon steel friction welding, it is known that the CDFW welding process uses a high rotational speed of around 3000 rpm and above, except for Ashfaq et al., which uses a lower rotational speed of 1500 rpm. Then from the research of Ashfaq et al.[19], it is still not known about the effect of various contours of the friction area on the steel side with the same taper height but different taper or chamfer angles and unknown torsion strength properties of friction weld joints. Therefore, it is necessary to investigate the above matter and the chamfer angle, which can increase the torsion strength of the dissimilar-metal friction weld joint between A6061 and St41 steel to the maximum. Torsion strength and porosity of the weld joint are one of the main concerns because the components or materials that are porous are more susceptible to static loads, especially torsion loads.

This paper discloses the enhancement of the torsion strength of dissimilar metal friction weld joint of A6061-St41 round bar. The discussion is carried out based on the results of the torsion strength test, porosity test, macrostructure test, and hardness test.

2. EXPERIMENTAL METHOD

The materials used were a solid round bar of aluminum alloy A6061 and low carbon steel St41 with tensile strengths of about 341 MPa and 410 MPa, respectively. Tables 1 and 2 show the chemical composition of A6061 and St41 steel, respectively, tested by the Spark spectrometry method.

Friction welding specimens were made of solid round bar A6061 and mild steel St41 by turning them up to a diameter of 18 mm. Figure 1 shows the geometry of the friction weld

Table 1: Chemical Composition of A6061

Elements	Weight %
Al	97.38
Mg	0.91
Si	0.69
Fe	0.44
Cu	0.21
Zn	0.19
Mn	0.09
Cr	0.04
Pb	0.02
Ti	0.01
Ni	0.01

Table 2: Chemical Composition of Mild Steel St41

Elements	Weight %
Fe	98.76
C	0.17
Cr	0.05
Al	0.02
Nb	0.04
W	0.09
Sn	0.01
Si	0.19
Mn	0.45
Mo	0.03
S	0.01
P	0.08
Cu	0.07
V	0.04

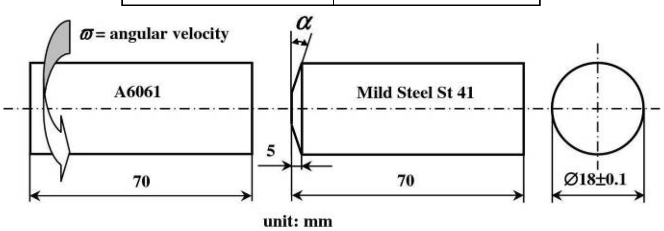

Figure 1: Geometry of Specimen for Continuous Drive Friction Welding (CDFW) with chamfer angle, α of 30, 45, 60, and 90 degrees (no chamfer)

specimen. The aluminum A6061 is a rotating part, and the steel St41 is a specimen at rest with a chamfer angle, α with variations of 30, 45, 60, and 90 degrees (no chamfer).

The friction welding process was carried out using a lathe machine. The rotated aluminum specimen was attached to the chuck. Meanwhile, the stationary steel specimen was held in the chuck placed in the tailstock. The chuck was moved linearly by a hydraulic cylinder powered by a hydraulic pump with a pressure gauge.

Before the two specimens were attached to the chuck, the surface of the specimens to be rubbed was polished using water-resistant sandpaper No. # 1000 and then cleaned using acetone. The A6061 friction welding specimen was mounted on a lathe chuck, while the steel friction welding specimen was mounted on a stationary chuck.

Continuous drive friction welding (CDFW) was performed at a rotational speed of 1600 rpm. An initial compressive force of 7 kN was applied to the steel specimen to rub against the A6061 specimen with various burn-off lengths (BOL) of 10, 15, and 20 mm. After the burn-off length was reached, the lathe machine was turned off and given a final compressive force of 14 kN for 20 seconds. After that, the final compressive force was removed, and the friction weld joint was cooled in the air for 10 minutes before removing it from the stationary chuck.

In this study, torsion strength and porosity were tested with the specimen shape, as shown in Figure 2. Porosity testing used the Archimedes method and tested on the specimen before torsion testing.

The torsion strength test was conducted using a torsion testing machine following the ASTM standard [20]. The test was carried out by providing a torsional moment for every 2 degrees of torsion angle increase. The additional torsional moment was added until the friction weld joint specimen was broken. The maximum torque that the specimen can hold was used to calculate the torsion strength of the friction weld joint. Macrostructure observation was also carried out on the part of the friction weld joint to observe the macrostructure and flash

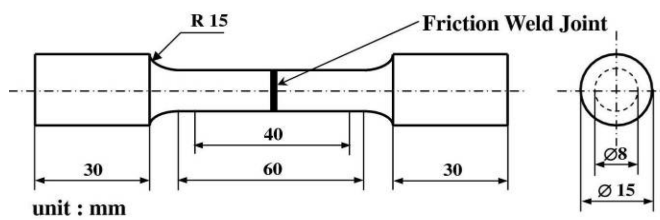

Figure 2: Geometry of Torsion Strength Test Specimen [14]

forms. Hardness testing was also carried out on the friction weld joint using the micro Vickers method with an indentation load of 50 gf for 6 seconds.

3. RESULT AND DISCUSSION

The results of this torsion strength test are illustrated by a graph of the relationship between the chamfer angle and the burn-off length and the mean torsion strength, as shown in Figure 3. It can be seen that the one-sided chamfer angle of low carbon steel and the burn-off length affect the torsion strength of dissimilar metal CDFW joint of A6061-St41. At burn-off lengths of 10 and 15 mm, the highest torsion strength was found in specimens with a chamfer angle of 30 degrees followed by specimens with a chamfer angle of 45 degrees. Meanwhile, specimens with chamfer angle 60 and without chamfer angle have a lower torsion strength. Then at the 20 mm burn-off length, it appears that the torsion strength of the weld joints at all chamfer angles has decreased.

It can happen that with the number of parts that are reduced during friction welding; in other words, the increased burn-off length indicates a higher heat input at the weld joint. Therefore, it makes the aluminum part, which has a lower liquid temperature (about 660 degrees Celsius) than steel (around 1580 degrees Celsius), was experiencing softening due to changes in the micro-grain structure which is getting bigger so that the strength of the weld joint decreases. The torsion strength test results show that the twisted part was fractured in the aluminum part, not at the interface between A6061 and St41, as shown in Figure 4. This state also shows that the friction weld joint is stronger against torsional loads than the A6061 section. This condition also indicates that friction welding has succeeded in making friction welding joints with maximum torsion strength. In this study, it was found that the burn-off length of 15 mm was a sufficient heat input to make the maximum torsion strength in the dissimilar metal A6061-St41 friction welding joints.

In the case of the effect of the chamfer angle on torsion strength, it was found that the specimen with a chamfer angle of 30 degrees has the maximum torsion strength. This state can happen because of the perfect cone shape of the steel specimen with a chamfer angle of 30 degrees, as shown in Figure 5. With this condition, the friction area is smaller and made heat input smaller and at the end of the friction welding

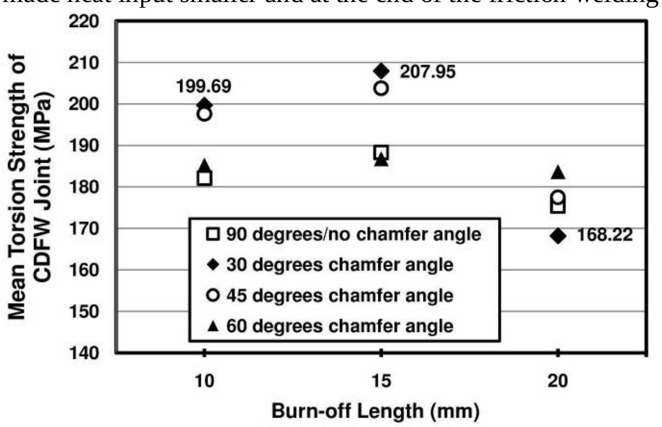

Figure 3: Relationship of the Mean Torsion Strength, Chamfer Angle, and Burn-off Length

(a)

(b)

Figure 4: (a) Photograph of Fractured CDFW Joint of A6061-St41 with 30 Degrees Chamfer Angle and 15 mm Burn-off Length with Maximum Torsion Strength, (b) Photograph of Fractured CDFW Joint of A6061-St41 with 90 Degrees Chamfer Angle (no chamfer) and 20 mm Burn-off Length with Minimum Torsion Strength

where the aluminum metal is subjected to forging stress. The joint profile that forms a perfect cone makes the plastic deformation groove smooth and compresses the interface, which results in the A6061-St41 friction weld joint with

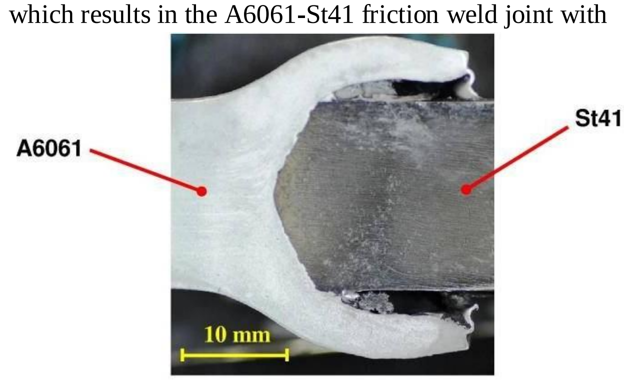

Figure 5: Macrostructure Photograph of Longitudinal Section of CDFW Joint of A6061-St41 with 30 Degrees Chamfer Angle and 15 mm Burn-off Length

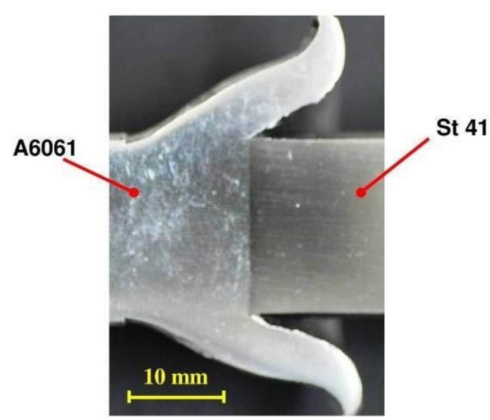

Figure 6: Macrostructure Photograph of Longitudinal Section of CDFW Joint of A6061-St41 with 90 Degrees Chamfer Angle (No Chamfer) and 20 mm Burn-off Length

maximum torsion strength. It is different from specimens of friction welded joints with other chamfer angles that form a sharpened cone, as shown in Figure 6. It shows that the welded joint profile can inhibit the flow of metal as pressing forging applied at the end of the metal welding process. There is still less plastic and atomic displacement and is expected to have less dislocation than the specimen with an angle of 30 degrees, resulting in lower torsion strength of the friction weld joint.

The porosity test shows the results, as shown in Figure 7. It appears that in the case of the smaller the chamfer angle (30-degree angle), the porosity at the weld joint tends to be the smallest so that it can support the maximum torsion strength. The minimal porosity can occur presumably due to a straighter groove in the steel specimen with a solid cone or a 30-degree chamfer angle. Therefore, the metal flow of aluminum material when pressed in the friction welding process becomes more smoothly pushing out air, oxides, or impurities, which can cause porosity in the interface.

Figure 8 shows the distribution of hardness in the aluminum

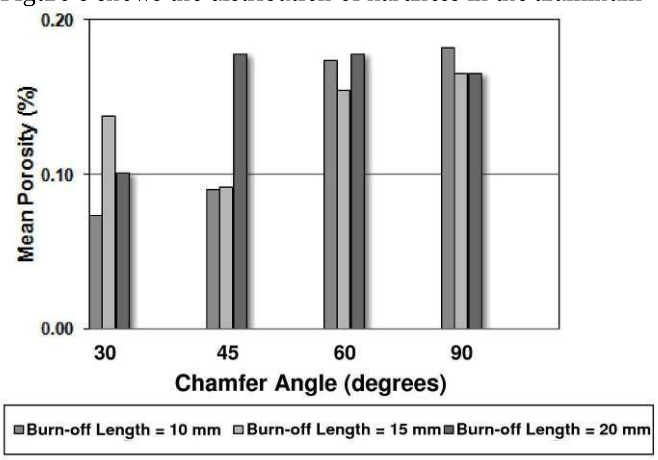

Figure 7: Relationship between Chamfer Angle and Mean Porosity of CDFW Joint Specimens

section of the friction weld joint, which has fractured with the highest torsion strength (specimen with a chamfer angle of 30 degrees, BOL = 15 mm) and the lowest torsion strength (specimen with a chamfer angle of 0 degrees, BOL = 20 mm). Hardness measurements were carried out from the interface between aluminum alloy and low carbon steel. It appears that at the aluminum part away from the interface, there was a decrease in hardness, presumably because the closer the interface was, the plastic deformation due to the final compression was greater than the initial friction stage. Meanwhile, the aluminum part away from the interface endure less plastic deformation but is still affected by heat from the interface. Due to this condition, the hardness becomes lower, and the torsion test specimen was fractured the aluminum section with lower hardness, not on the interface.

Meanwhile, to determine the amount of heat input experienced by the friction welding specimen, the total burn-off length or total shortening of the specimen during the friction welding process was measured by calculating the difference between as

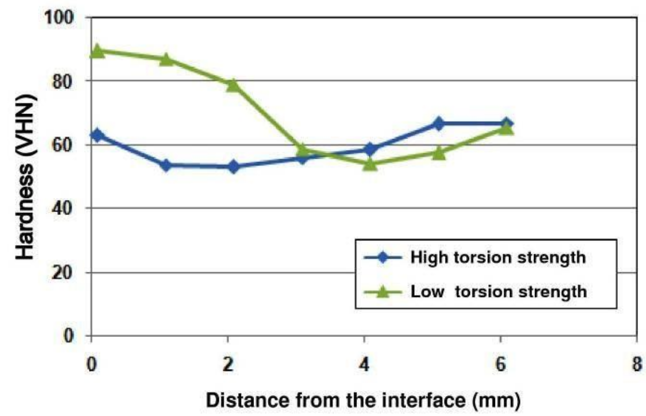

Figure 8: Hardness Distribution on the Aluminum Side for Specimen with High Torsion Strength (BOL: 15 mm, 30 degrees Chamfer Angle) and Low Torsion Strength (BOL: 20 mm, 90 degrees Chamfer Angle)

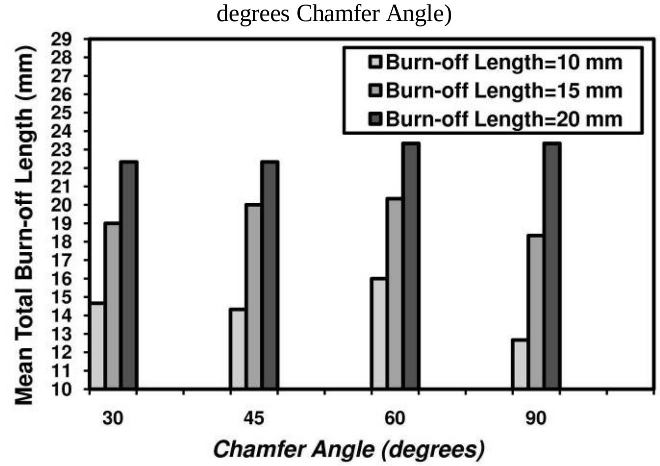

Figure 9: Relationship of Chamfer Angle and Mean Total Burn-off Length of CDFW Specimens

the final length before welding and the length after welding called total BOL. Figure 9 shows the measurement results. It appears that specimens with intact cone dimensions or a chamfer angle of 30 degrees have the second smallest total shortening after specimens with a 90-degree angle or without a chamfer for BOL 10, 15, and 20 mm. The larger the BOL, the more flash was formed, and the greater the heat input received by the friction weld joint. It shows that the heat input that occurred in the specimen with a chamfer angle of 30 degrees was sufficient to make the joint torsion strength maximum. If the total BOL were less than required, such as in the specimen with a chamfer angle of 90 degrees, the joint formed would not have maximum strength. Meanwhile, if the total BOL was too large, it will provide a greater heat input so that the friction welded joints on the aluminum part will soften, and the torsion strength decrease.

3. CONCLUSION

From the research on the torsion strength of dissimilar metal friction weld joint of A6061-St41 with variations of one-sided chamfer angle and burn-off length, it was found that the one-sided chamfer angle and burn-off length affect the torsion strength of Al-Mg-Si friction welding joints.

Dissimilar metal fiction weld joint of A6061 and St41 were fractured in the aluminum section due to torsional moments. It might happen because the interface area underwent plastic deformation so that the hardness increased, while in the aluminum part, there was softening due to the heating effect during welding so that fractures occurred in the aluminum section.

Specimens with a chamfer angle of 30 degrees with a burn-off length of 15 mm forming a perfect cone provide the greatest torsion strength. It might happen due to the wide area of the interface and the amount of plastic deformation when pressing forging at the end of friction welding. It yields high hardness in the friction weld joint area, as well as minimal porosity and sufficient total burn-off length during the welding process.

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