INCREASED TENSILE STRENGTH OF DISSIMILAR FRICTION WELD JOINT OF ROUND BAR A6061/S15C USING UPSET FORCE AND ONE-SIDE CHAMFER ANGLE

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ABSTRACT

An effort to increase the tensile strength of dissimilar friction weld joint of round bar A6061/S15C was done in this study using upset force and one-side chamfer angle. Commercial round bar aluminum alloy A6061 and carbon steel S15C were used as rotated and a stationary part, respectively in continuous drive friction welding (CDFW) process. Upset force variations of 10.5, 14, and 17.5 kN were used. CDFW process used burn of length of 15 mm for all CDFW specimens. Chamfer angle was machined on friction area of the S15C stationary part with the variation of 0 (without chamfer angle), 30 and 45 degrees. Tensile strength test, macrostructure observation and micro Vickers hardness testing, SEM-EDX analysis were performed. It was found that the smaller chamfer angle (30 degrees) produced maximum tensile strength of A6061/S15C CDFW joint. It occurred due to smaller formed flash, the lower temperature of the flash that indicate lower heat input and caused smaller heat affected zone and higher hardness in the CDFW joint. The higher upset force also yields higher tensile strength of CDFW joint due to the higher degree of plastic deformation during the upset stage of CDFW joint and this state contributes to higher hardness and tensile strength of A6061/S15C CDFW joint. SEM-EDX analysis result also confirmed that more aluminum existed on the fracture surface of the A6061/S15C CDFW specimen with maximum tensile strength.

Keywords: *Continuous drive friction welding, aluminum, carbon steel, upset force, chamfer angle, tensile strength*.

1. INTRODUCTION

Joining two round bars with different metal is interesting to produce a bimetal round bar for application of shaft, axle, or other components. The bi-metal shaft can be made of aluminum and steel. The advantage of this bimetal is lighter shaft compared to usual steel shafts such as S15C or AISI 1015 shaft, which is one of the carbon steel that can be used as a shaft of the machine (Budinski, 1996; Bauccio, 2001). The lighter shaft can be obtained due to the low density of aluminum, which is around one-third of that of steel. One of aluminum alloys that have adequate tensile strength and better corrosion resistance than aluminum A2024 is aluminum A6061. The problem is the difficulty to join these two different metals to form A6061/S15C round bar with metallic bonding due to its different properties such as melting point and thermal conductivity.

Riveting, bolting, adhesive joining, and welding are some techniques to join dissimilar metal to be round bar. Welding is one of the processes that can be applied to join different metal such as aluminum and steel. Continuous drive friction welding (CDFW) is one of solid state joining technique that also possible to join dissimilar metal round bar because CDFW process is friction welding technique for joining metallic round bar, cylinder, or pipe. Using heat generated from the friction of two different metallic round bars, joining can be done in short time with low or nil defects, heat input, no oxidation in the interface, adequate strength. CDFW technique can solve problems in joining dissimilar metals using conventional welding technique such as fusion welding (Olson *et al.*, 1993).

To ensure the safety of CDFW joint, one of the mechanical properties of CDFW joint to be studied is the tensile strength. Researchers have been conducted some efforts to increase the tensile strength of CDFW joint. Lin *et al.* (1999) used chamfer on the friction area of aluminum alloy Al-Mg-Si to obtain CDFW joint of an A6061/Al-SiC composite. They found that using chamfer on Al-Mg-Si part could improve the tensile strength of Al-Mg-Si/Al-SiC composite CDFW joint. Irawan *et.al.* (2012) reported that A6061 specimen using double chamfer angle of 30 degrees on both friction areas had the maximum tensile strength of A6061 CDFW joint. Irawan *et.al.* (2016a) also used double chamfer combined with the surface roughness of the friction area can also affect and increase the tensile strength of A6061 CDFW joint. Irawan *et.al.* (2016b) applied single cone geometry on the stationary part of CDFW specimen to increase torsion strength of CDFW joint of A6061. The strength of CDFW joint using single cone geometry was higher than that of the specimen using double chamfer angle on both friction areas.

Some researchers conducted the study to increase the strength of CDFW joint of dissimilar metal of aluminum and steel. Taban *et al.* (2010) conducted characterization of dissimilar metal friction weld joint of A6061-T6/AISI 1018 using CDFW process. They found that to obtain the higher tensile strength of CDFW joint, upset pressure in level 60 MPa is needed. Ochi *et al.* (1998) reported about friction weldability of A6061 toward steel, especially carbon steel with a flat friction surface. They also found that higher upset pressure could increase the tensile strength of dissimilar A6061 and carbon steel. Ashfaq *et. al.* (2012) stated that using external taper could improve the tensile strength of A6061/stainless steel CDFW joint. However, the study on an effort to increase the tensile strength of dissimilar metal using the combination of upset force and one-side chamfer angle has not been reported. Therefore, this paper discusses the result of an effort to increase the tensile strength of A6061/S15C CDFW joint based on the results of tensile strength test, macrostructure, and flash geometry, flash temperature measurement, micro Vickers hardness testing on CDFW joint and SEM-EDX analysis on the fracture surface.

2. MATERIALS AND METHODS

Commercial round aluminum alloy A6061 and carbon steel S15C were used in this study. A6061 alloy has magnesium and silicon as main alloying elements. S15C is carbon steel that has carbon content around 0.15% of weight. Table 1 and 2 show chemical composition of A6061 and carbon steel S15C

Table 1. Chemical Composition of A6061 (weight %).

Element	%	Element	%
Al	97.8	Pb	0.0021
Mg	0.795	Ni	0.0103
Si	0.529	P	<0.0005
Fe	0.344	Sn	0.0013
Cu	0.299	Sb	<0.0004
Mn	0.125	Sr	<0.0001
Cr	0.49	Be	0.00006
Zn	0.0372	Zr	0.00067
Ti	0.0249	Bi	<0.0003
Na	0.00032	Cd	0.00063
Ca	0.00016		

Table 2. Chemical composition of S15C steel (weight %).

Element	%	Element	%
Fe	98.68	B	0
C	0.162	Co	0
Cu	0.071	Nb	0.043
Mn	0.448	P	0.008
Si	0.185	Sn	0.006
Ni	0	W	0.086
Cr	0.055	V	0.019
Pb	0.0036	Al	0.016
Sn	0.006	Mo	0.025
Ti	0	S	0.011

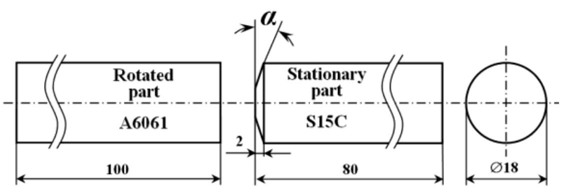

Figure 1. Shape and dimension of CDFW specimen with one-side chamfer angle, α = 0, 30 and 45 degrees (left side is rotated A6061 part and the right side is the stationary S15C part).

used in this study as the result of chemical composition measurement using Spark spectrometry method. The tensile strengths of A6061 and S15C before welding were 287 MPa and 571 MPa, respectively. Round bars of A6061 and S15C were cut using a saw machine with water coolant to make CDFW specimens. The geometry of CDFW specimen that machined by turning process is illustrated in Figure 1. The A6061/S15C CDFW specimen has two parts, which are A6061 as rotated part and S15C as stationary part. In this study, rotated part is the left side which has flat friction area and stationary part is the right part that has chamfer angle, α =0, 30, 45 degrees. Chamfer angle of 60 degrees was not set up, due to the low tensile strength of CDFW joint as reported by on Irawan *et.al.* (2012) and Santoso *et.al.*(2012).

Both friction surfaces were cleaned using acetone before CDFW process started. During the process of CDFW, the A6061 rotated part of CDFW specimen was set in the lathe machine chuck. The S15C stationary part of specimen was gripped in the chuck that can give compression force of 17.5 kN using the hydraulic cylinder with 50 kN capacity. The A6061 rotated specimen was rotated in the speed of 1600 rpm, then the stationary part of specimen was engaged to the rotated specimen by applying compression force of 7 kN. After 15 mm burn off length was reached, the lathe machine was turned off and the A6061/S15C CDFW specimen that has A6061 flash wrapped S15C part was compressed by upset force of 10.5, 14, and 17.5 kN for 40 seconds and then the CDFW joint specimens were cooled in the air.

CDFW specimens were machined to prepare the tensile strength test specimens according to American Welding Society (AWS) standard (2007) and illustrated in Figure 2. Friction weld joint is located in the center of the specimen. Tensile strength test was conducted using the universal testing machine. Tensile strength test was conducted with cross head speed of 2 mm/minute. Three replications of CDFW specimens were done for each variation of up set force and chamfer angle.

Macrostructure observation was performed on CDFW joint. Area of flash in the

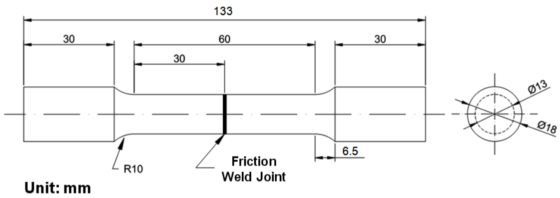

Figure 2. Shape and dimension of tensile strength testing (American Welding Society, 2007).

CDFW joint was measured using ImageJ software. Observation and analysis focused in the A6061 part since the A6061 part endured a bigger portion of plastic deformation; meanwhile, S15C was not plastically deformed due to its higher melt temperature and yield strength compared to those of the A6061. The hardness distribution of CDFW specimen with high and low tensile strength was also conducted using micro-Vickers hardness method with 50 gf force indentation load for 6 seconds. Fracture surface analysis was performed using a Scanning Electron Microscope (SEM-EDX) to analyze the aluminum content that formed metallic bonding with carbon steel fracture surface.

3. RESULT AND DISCUSSION

Figure 3 shows the relationship of chamfer angle, upset force and mean tensile strength of CDFW joint. It is found that chamfer angle and upset force influenced the tensile strength of CDFW joint. Specimen with flat friction area or without chamfer angle (chamfer angle of 0 degree) has lower tensile

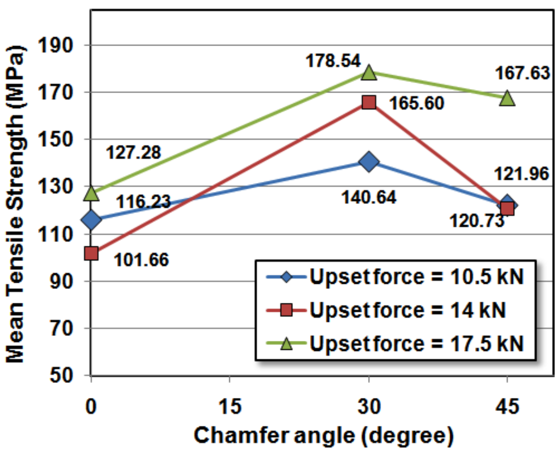

Figure 3. Relationship of mean tensile strength, chamfer angle and upset force of A6061/S15C CDFW specimen.

strength compared to that of the chamfered specimen. There is the variation of data in the specimen with the upset force of 14 kN with chamfer angle of 0 degrees (without chamfer angle) and 45 degrees so that it has lower or almost the same result with the specimen which has the upset force of 10.5 kN, namely specimen with chamfer angle 0 and 45 degree. It supposed the upset force did not take account to influence the tensile strength of CDFW joint, although there is some data show the higher tensile strength of specimen with the upset force of 14 kN compared to that of the specimen with 10.5 kN.

Obvious effect was observed in the specimen with the upset force of 10.5 kN and 17.5 kN. It can be seen that the smaller chamfer angle (30 degrees) can give the maximum tensile strength of CDFW joint for each of upset force. The tensile strength of chamfered specimen is higher than that of the specimen without chamfer angle (0-degree chamfer angle). The maximum tensile strength of CDFW specimen occurred in the specimen with chamfer angle of 30 degrees with the upset force of 17.5 kN, which is 178.54 MPa, and 44% higher than the tensile strength of CDFW joint reported by Irawan *et.al* (2012) using double chamfer. It has around 62 percent of welding joint efficiency based on the tensile strength of the specimen before friction welded.

It might be happened due to lower heat input resulted by A6061/S15C CDFW specimen with small chamfer angle of 30 degree and high upset force of 17.5 kN. Lower heat input will affect less to change or to recrystallize the micro/macrostructure in the heat-affected zone so that the CDFW joint will have the higher hardness that contributes to the high tensile strength of the CDFW joint.

Figure 4 and 5 show macrostructure and flash of the specimen without chamfer angle (upset force of 10.5 kN) and specimen with chamfer angle of 30 degrees, (upset force of 17.5 kN) which has low and high tensile strength of CDFW joint, respectively. Formed flash was marked by yellow line and measurement was done on the area of formed flash on both specimens. The result was written in Table 2. It can be seen that the area of flash in the specimen without chamfer angle (0-degree chamfer angle) which has low tensile strength is bigger than that of the specimen with 30 degrees chamfer angle which has high tensile strength. The bigger area of formed flash means that bigger volume of aluminum

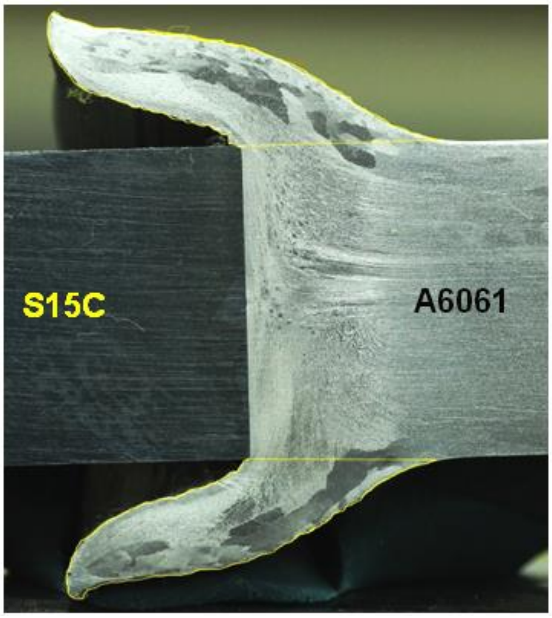

Figure 4. Macrostructure and flash of S15C/A6061 CDFW joint with chamfer angle of 0-degree and upset force of 10.5 kN which has the low tensile strength (116.23 MPa).

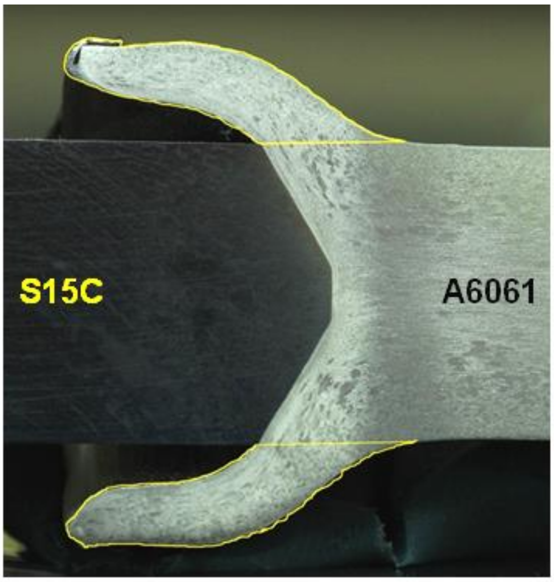

Figure 5. Macrostructure and flash of S15C/A6061 CDFW joint with chamfer angle of 30 degrees and upset force of 17.5 kN, which has high tensile strength (178.54 MPa).

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Table 3. Area of flash on A6061/S15C CDFW joint with high and low tensile strength.

Variation of		Area of Flash (mm^2)
Upset force (kN)	Chamfer angle	
10,5	0°	80,56
17,5	30°	64.76

was plastically deformed which also a correlation with higher heat input has occurred in the specimen with low tensile strength. It can be seen that area of heat affected zone for the specimen with bigger flash or low tensile strength is broader than that of the specimen with smaller flash or high tensile strength.

Figure 6 is the thermal cycles graph of the specimen without chamfer angle (0-degree chamfer angle, the upset force of 10.5 kN) with low tensile strength and specimen with chamfer angle of 30 degree (upset force of 17.5 kN), which has high tensile strength. The temperature was measured on the surface of the formed flash in the interface using an Infrared thermometer gun. It is found that maximum temperature of the specimen without chamfer angle that has low chamfer angle is around 15 percent higher than that of the specimen with chamfer angle of 30 degrees, the upset force of 17.5 kN. It is confirmed that higher heat input during CDFW process occurred in the specimen without chamfer angle with low tensile strength compared to that of the specimen with high tensile strength.

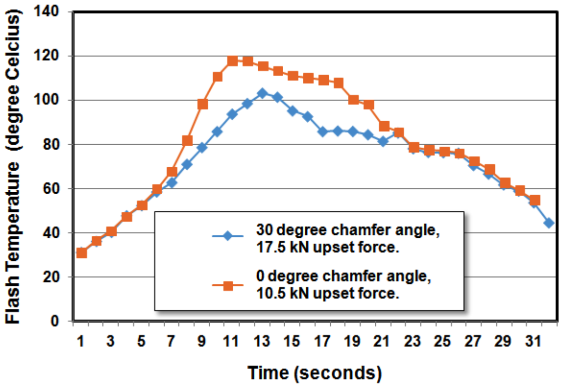

Figure 6. Thermal cycle during friction welding for specimens with high tensile strength of 178.54 MPa (30 degrees chamfer angle, 17.5 kN upset force) and low tensile strength of 116.23 MPa (0-degree chamfer angle, 10.5 kN upset force).

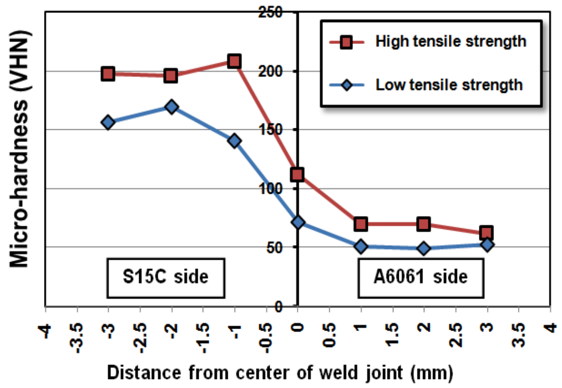

Figure 7. Hardness distribution for the specimens with high tensile strength (30 degrees chamfer angle, 17.5 kN upset force) and low tensile strength (0-degree chamfer angle, 10,5 kN upset force).

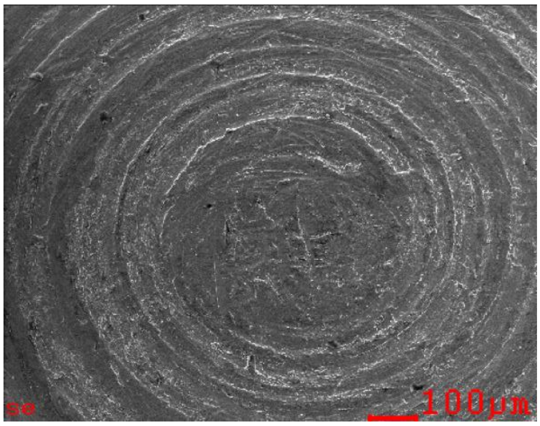

Figure 8. Fracture surface at the center of tensile strength test specimen with chamfer angle of 0 degree and 10.5 kN upset force that has the low tensile strength of 116.23 MPa.

Table 4. The result of chemical composition analysis using SEM-EDX on the analyzed fracture surface as shown in Figure 8.

Element	*Wt%*	*At%*
CK	05.01	16.63
OK	01.96	04.88
MgK	0.77	01.26
AlK	**14.99**	**22.13**
FeK	77.27	55.11
Matrix	Correction	ZAF

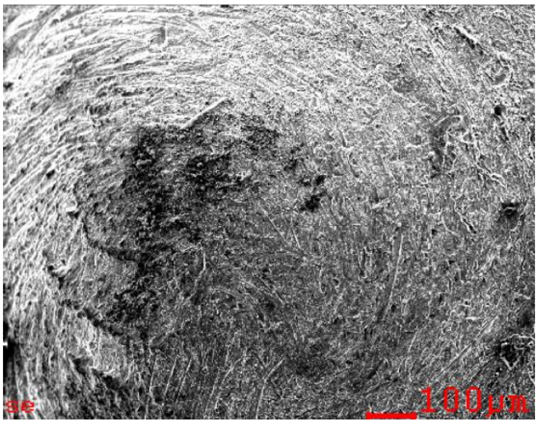

Figure 9. Analyzed fracture surface at the center of tensile strength test specimen with chamfer angle of 30 degree and upset force of 17.5 kN that has the high tensile strength of 178.54 MPa.

Table 5. The result of chemical composition analysis using SEM-EDX on the fracture surface as shown in Figure 9.

Element	***Wt%***	***At%***
CK	04.28	13.31
OK	03.88	09.05
MgK	0.62	00.95
AlK	**21.48**	**29.71**
SiK	00.56	00.74
FeK	69.18	46.24
Matrix	Correction	ZAF

Figure 7 shows hardness distribution of CDFW joint with high and low tensile strength. Specimen with 30 degrees chamfer angle and upset force of 17.5 kN and high tensile strength has the higher hardness in CDFW zone than that of the specimen with low tensile strength. Higher hardness is the result of lower heat input during CDFW process in the specimen with chamfer angle of 30 degrees and the higher upset force that makes the larger portion that plastically deformed which has more slips occur and higher density of dislocation.

Figure 8 and 9 are photographs of fracture surface and the chemical composition analysis results of SEM-EDX observation on the center of the fracture surface of the tensile strength test of CDFW specimen without chamfer angle with low tensile strength and specimen with chamfer angle of 30 degree that has high tensile strength. It can be seen that fracture occurred in the interface of A6061 and S15C, which has the lowest strength. The fracture surface of the specimen with high tensile strength is covered more by aluminum with brighter surface compared with that of the specimen with low tensile strength. It is also confirmed by the result of chemical element analysis result that the content of aluminum is higher on the observed fracture surface with the same magnification of the specimen with high tensile strength compared to that of the specimen with low tensile strength. It is thought that more aluminum remains in the fracture surface means more metallic bond occurred in the interface between A6061 and S15C. Moreover, the specimen with chamfer angle has broader interface area where metallic bond occurred to give a positive effect to increase tensile strength. This condition could contribute to yield higher tensile strength of A6061/S15C CDFW joint.

4. CONCLUSION

The effort to increase the tensile strength of A6061/S15C using upset force and chamfer angle on the S15C stationary part was achieved to give the maximum tensile strength of the specimen with chamfer angle of 30 degree and high upset force of 17.5 kN. It is confirmed that smaller chamfer angle on the S15C stationary part produced smaller formed flash, the lower temperature of the flash that indicates lower heat input and caused smaller heat affected zone and higher hardness in the CDFW joint.

In addition, the higher upset force also made the larger portion of plastic deformation during the upset stage of CDFW process that makes more slips and dislocation to give higher hardness. SEM-EDX analysis result also confirmed that more aluminum detected on the fracture surface of the A6061/S15C CDFW specimen with high or maximum tensile strength. It means more metallic bonding occurred in the interface of the A6061/S15C CDFW specimen that has high tensile strength affected by the smallest chamfer angle and maximum upset force.

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