Journal of Engineering and Applied Sciences 11 (6): 1178-1185, 2016
ISSN: 1816-949X

Effect of Surface Roughness and Chamfer Angle on Tensile Strength of Round Aluminum A6061 Produced by Continuous Drive Friction Welding

Yudy Surya Irawan, Bustanul Imawan, Rudy Soenoko and Hery Purnomo
Department of Mechanical Engineering, Faculty of Engineering, Brawijaya University,
65145 Malang, Indonesia

Abstract: This study reveals the effect of surface roughness and chamfer angle on tensile strength of Continuous Drive Friction Weld (CDFW) joint of round aluminum A6061. CDFW specimens had chamfer angle of 15, 30, 45 degree and no chamfer angle. The both chamfered friction area of the specimens had surface roughness of 0.697, 0.9 and 1.067 μm. From the tensile strength test results, it was found that the lower surface roughness and the smaller chamfer angle will give higher tensile strength. The maximum tensile strength of CDFW joint was found in the specimen with surface roughness of 0.697 μm with chamfer angle of 15°. It may occur due to the minimum porosity, the maximum area of fully plasticized zone 1 (ZPl1) which has high hardness, minimum area of fully plasticized zone 2 (Zpl2) that have lower hardness in the CDFW joint. SEM fracture surfaces showed smaller dimple fracture in the specimen with maximum tensile strength compared to that of specimen with lower tensile strength.

Key words: Continuous drive friction welding, aluminum, chamfer angle, tensile strength, macrostructure, hardness

INTRODUCTION

Friction welding method is one of solid state welding process that has many advantages to join metals especially metal that difficult to be join such us aluminum due the high thermal conductivity and the existence of aluminum oxide (Barnes and Pashby, 2000; Charit *et al*., 2002). Continuous Drive Friction Welding (CDFW) is a friction welding method which is able to join round metals using heat generated from friction at the contact surfaces. Principle of this method is by rotating a specimen at constant angular speed and the other specimen in the same alignment under an applied compressive force or pressure. Due to the friction and compressive pressure in the certain time, the process yields adequate heat and mechanical state of the interface region and produces flash in the interface. After the flash is formed, the rotated specimen is stopped then higher compressive pressure applied to forge the specimens together (Nicholas, 2003; Sathiya *et al*., 2007; Uday *et al*., 2010).

Aluminum alloy that main alloys of Mg and Si is called A6061. This aluminum alloy has adequate tensile strength, good weldability, good formability and also good corrosion resistance (Budinski, 1996). The products of this aluminum alloy are usually machine components, heavy vehicles, ships, aircraft and rail transportations (Bauccio, 2001).

Improvement of CDFW joint strength is essential for structural integrity and high quality of mechanical product. Therefore, many researches were performed to increase tensile strength of CDFW joint by finding the effect of CDFW parameters such us friction time, friction pressure, burn of length, upset force and time. Other researches focused on the geometry of faying surfaces. Namely, Lin *et al*. (1999) found that by using 60 degree chamfer angle towards contact surface of aluminum alloy Al-Mg-Si to SiC could increase the tensile strength of CDFW joint. Irawan also found that chamfer angle of 30° on the both side of A6061 contact surface gave maximum tensile strength of CDFW joint produced by CDFW or spinning friction welding.

Surface roughness is also one of parameter that can affect the properties of CDFW joint. Satyanarayana *et al*. (2007) have conducted studies on the effect of surface roughness on the austenitic-ferritic stainless steel dissimilar friction weld joints. They found that the higher

Corresponding Author: Yudy Surya Irawan, Department of Mechanical Engineering, Faculty of Engineering, Brawijaya University, 65145 Malang, Indonesia

surface roughness of the faying surface produced higher interface hardness. Maximum notch tensile strength occurred in the specimen with roughness Ra of 5.0 μm but the strength decrease for the roughness >5.0 μm because of the banded microstructure. However, the effect of surface roughness and chamfer angle on ht both side of faying surfaces on tensile strength are not investigated yet. This study discussed about surface roughness and chamfer angle that affected tensile strength of CDFW joint based on tensile strength test, macrostructure and microstructure and hardness distribution of CDFW joint.

MATERIALS AND METHODS

Experimental method: Round aluminum alloy A6061 was used in this study. Table 1 shows the chemical composition of the aluminum used. Tensile strength of bulk A6061 is 287.39 MPa

CDFW specimens were set by cutting using a saw machines with cooling media of water as a coolant. The friction surfaces were polished and machined by a lathe machine to shape a CDFW specimen as illustrated in Fig. 1. The variation of the surface roughness of the faying surface are 0.697, 0.9 and 1.0667 μm as the result of emery polishing with grade of #600, #1000 and #1500, respectively. The specimens had various chamfer angles of 15, 30, 45 and without chamfer angle (0 degree) to vertical line or faying surface. Figure 1 illustrates two parts of CDFW specimens.

During CDFW process, the left side of the rod was rotated part and set in the chuck of the lathe machine that connected to an electrical motor. The right part of specimen was stationary part and attached in a gripping tools that can give compression force by a spring mechanism. Before friction welding started, both contact surface of specimens were cleaned by acetone. The rotated specimen has rotation speed of 1600 rpm, then the right part of specimen was engaged to the rotated part of specimen by giving compression force of 1230 N for 2 min. Subsequently, the machine was shut down, the right specimen continued to be applied by compression force of 1570 N for 2 minutes before cooled in air.

Tensile strength testing of friction welding joints were machined with the coolant as shown in Fig. 2. CDFW joint was located in the center of tensile strength specimen.

Tensile strength test were performed using a universal testing machine with cross head speed of 2 mm min^{-1}. Three specimens of each variation of surface roughness and chamfer angle were tested to find tensile strength of CDFW joints.

Macrostructures and microstructures observation of the weld joint were also conducted. Weld joint contains fully plasticized Zone (Zpl) in the center and partly deformed Zone (Zpd) located beside the Zpl and undeformed Zone (Zud) (Ozdemir, 2005). In this study, Zpl contains two zone which are fully plasticized zone 1 and 2, (Zpl1 and Zpl2) (Table). Using a graphic analysis software, the area of these zones porosity were measured to explain behavior of tensile strength of the CDFW joints. Besides, the hardness on the area of Zpl1 and Zpl2 and Zud also measured using micro-Vickers hardness testing machine. Indentation time is 6 sec and 50 g load.

Table 1: Chemical composition of aluminum A6061

Components	Weight (%)	Components	Weight (%)
Al	97.90	Zn	0.0512
Mg	0.806	Mn	0.0314
Si	0.536	Cr	0.0679
Fe	0.333	Ti	0.0145
Cu	0.216	Others	0.0220

Table 2: Area of zone in the middle of CDFW joint in the section of tensile strength specimen with diameter of 14mm, Zpr: Zone of porosity, Zpl1: Zone of fully plasticized 1, Zpl2: Zone of fully plasticized 2

Chamfer angle	Surface Roughness (μm)	Zpr (mm^2)	Zpl1 (mm^2)	Zpl2 (mm^2)
0°	1.0667	0.617	37.58	20.897
15°	1.0667	0.0	29.013	15.337
0°	0.697	0.719	28.706	22.858
15°	0.697	0.0	21.748	11.702

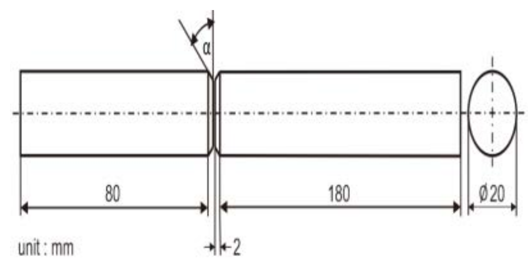


Fig. 1: Geometry of CDFW specimen (dimensions in mm). Left side is rotated part and the right side is stationary part that subjected with compression force

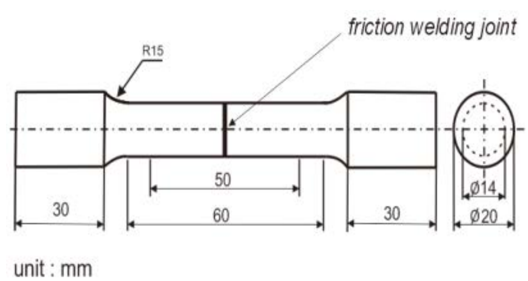


Fig. 2: Geometry of tensile strength test spesimen (in mm) (Japanese, 1980)

Macrostructures and microstructures observation of the weld joint were also conducted. Weld joint contains fully plasticized zone (Zpl) in the center and partly deformed zone (Zpd) located beside the Zpl and undeformed zone (Zud) (Ozdemir, 2005). In this study, Zpl contains two zone which are fully plasticized zone 1 and 2, (Zpl1 and Zpl2). Using a graphic analysis software, the area of these zones and porosity were measured to explain behavior of tensile strength of the CDFW joints. Besides, the hardness on the area of Zpl1 and Zpl2 and Zud also measured using micro-Vickers hardness testing machine. Indentation time is 6 seconds and 50 g load.

RESULTS AND DISCUSSION

Figure 3-6 shows the representative photographs of CDFW joints for specimen without chamfer angle or chamfer angle of 0° and chamfer angle of 15° with surface roughness of 1.0667 and 0.697 μm on the millimeter block paper. Figure 7-10 shows macrostructures of longitudinal sections of CDFW joints. The flash was formed and located at the center of the specimen or at the outer interface side of two rods of the specimens.

Based on the Fig. 3-6, it is found that chamfer angle influenced the flash geometry formation of the CFDW flash. Namely, the specimen without chamfer angle has the largest friction area than that of specimen with chamfer angle of 15°, so that, the largest friction area during CDFW process produced higher heat input and yields bigger flash geometry at the CDFW joint. Meanwhile, surface roughness had no significant effect on flash geometry from macro observation based on the photographs.

In Fig. 7-10, the difference of flash geometry among the CDFW joints could be seen more clearly. In case of specimen without chamfer angle, surface roughness had no significant effect on flash geometry. However, in case of specimen with chamfer angle of 15°, specimen with lower surface roughness has smaller flash geometry (Fig. 10) compared to that of specimen with higher surface roughness (Fig. 9). It might occur related to the generated heat during CDFW process.

Figure 11 illustrate maximum temperature occurred during CDFW process measured by a infra-red thermo-gun on the center of outer flash. It is found that the higher chamfer angle, including specimen without chamfer angle has broader friction area that produced higher heat represented by maximum temperature. Specimen with the smallest chamfer angle (15°) has the lowest maximum temperature in each surface roughness value. Meanwhile, in the higher chamfer angle or broader friction area, surface roughness had no significant effect to maximum temperature, except in the specimen with smaller chamfer angle (15°). Namely, the lower value of surface roughness has the smaller friction coefficient. In

Fig. 3: Without chamfer angle (0°), surface roughness of 1.0667 μm

Fig. 4: Chamfer angle of 0°, surface roughness of 0.697 μm

Fig. 5: Chamfer angle of 15°, surface roughness of 1.0667 μm

Fig. 6: Chamfer angle of 15°, surface roughness of 0.697 μm

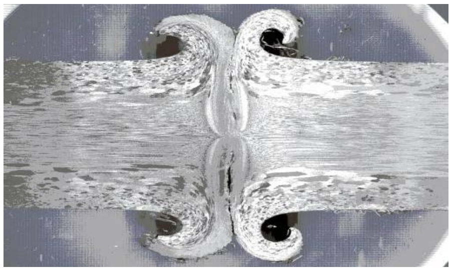


Fig. 7: Without chamfer angle (0°), surface roughness of 1.0667 μm

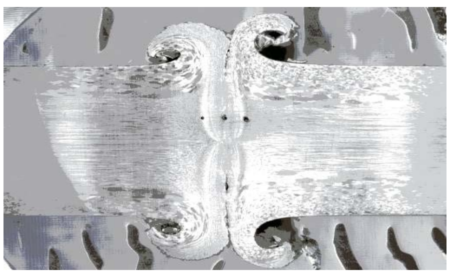


Fig. 8: Without chamfer angle (0°), surface roughness of 0.697 μm

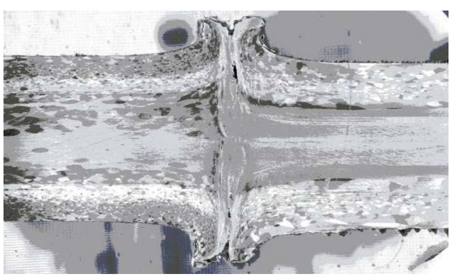


Fig. 9: Chamfer angle of 15°, surface roughness of 1.0667 μm

Fig. 10: Chamfer angle of 15°, surface roughness of 0.697 μm

this state, it produced smaller heat input same condition of revolution speed and compressive force in CDFW process. Smaller heat input yields smaller flash geometry happened in specimen chamfer angle of 15° (Fig. 10-12).

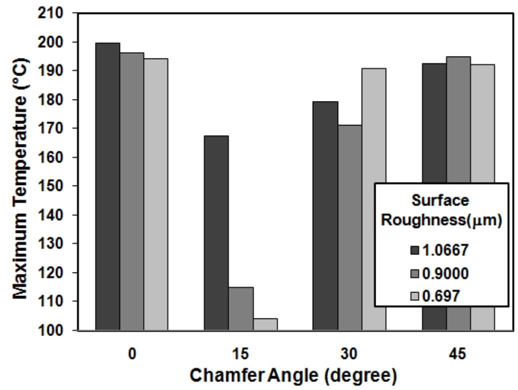


Fig. 11: Maximum temperature on the middle-outer flash of CDFW joints with various chamfer angle and surface roughness

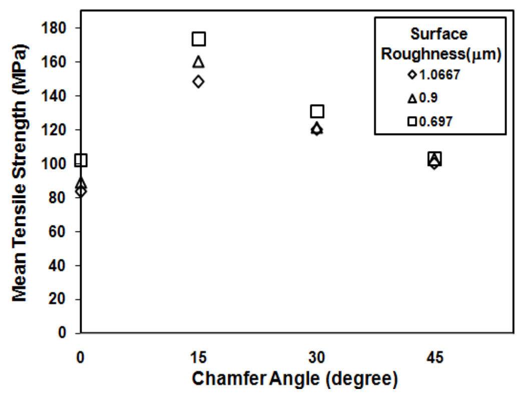


Fig. 12: Relationship of surface roughness, chamfer angle and tensile strength of A6061 CDFW joint

Figure 12 shows relationship of surface roughness, chamfer angle and tensile strength of CDFW joint. It can be seen that chamfer angle of friction area affected the tensile strength of CDFW joint. For each surface roughness condition of faying surface, specimen with chamfer angle of 15 degree has the maximum tensile strength. The surface roughness has significant effect on the tensile strength for specimen with chamfer angle of 15, 30° and no chamfer angle (chamfer angle of 0°). The lower surface roughness of faying surface, the higher tensile strength occurs in the CDFW joint. The highest tensile strength of 173.49 MPa was found in the specimen with chamfer angle of 15° with surface roughness of 0.697 μm. By comparing to the bulk A6061 tensile strength, the maximum welding efficient of the CDFW joint was 60.4%.

To find the cause of the results, macrostructures observation was performed. Figure 13-17 shows some photograph of macrostructures of CDFW joint with the maximum and minimum tensile strength. It can be seen

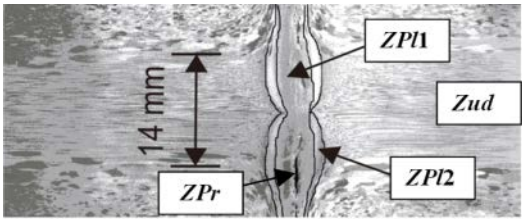


Fig. 13: Chamfer angle of 0° (without chamfer) with surface roughness, Ra of 1.0667 μm

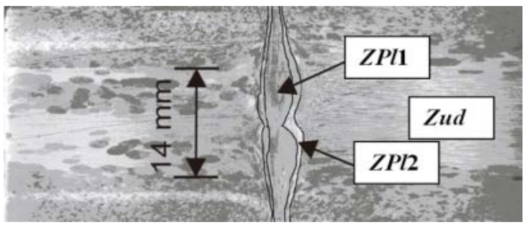


Fig. 14: Chamfer angle of 15° with Ra = 1.0667 μm

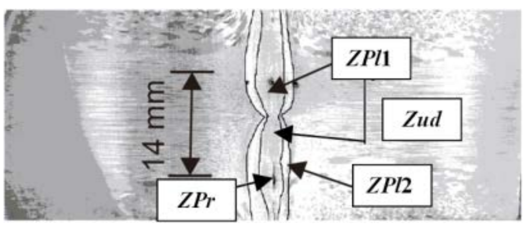


Fig. 15: Chamfer angle of 0° with Ra = 0.697 μm

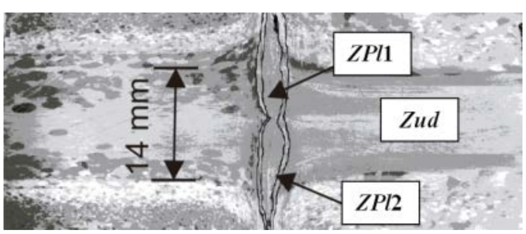
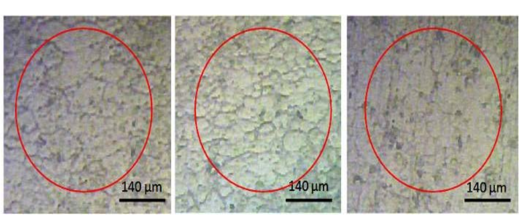


Fig. 16: Chamfer angle of 15° with Ra = 0.697 μm



(a) Zpl1 (b) Zpl2 (c) Zud

Fig. 17: Microstructures of CDFW joint with chamfer angle of 0° and surface roughness of 1.0667 μm

Table 3: Mean hardness in the zone of Zpl1, Zpl2 and Zud. Each zone has three indentation locations

Chamfer angle	Surface roughness (μm)	Zpl (VHN)	Zpl2 (VHN)	Zud (VHN)
0°	1.0667	62.74	61.233	58.646
15°	1.0667	70.283	66.703	62.930
0°	0.697	67.023	64.313	58.350
15°	0.697	71.733	66.130	63.183

that CDFW joint contains of fully plasticized zone 1 (Zpl1), fully plasticized zone 2 (Zpl2), undeformed zone (Zud) and also porosity zone (Zpr). The zone of partly deformed (Zpd) did not clearly appear in the macrostructures, so that it does not take account for the range of this study.

Using a graphic analyzer software (ImageJ), the area of Zpl1, ZPl2 and Zpr were measured in the range of tensile specimen diameter of 14 mm as shown in Fig. 9. The result can be seen in the Table 2. It was found that the porosity for specimen with chamfer angle of 15° with surface roughness of 1.0667 and 0.697 μm is nil with greater ratio of Zpl1/Zpl2≈2 compared to other specimen. It is known that the hardness of ZPl1 usually higher than Zpl2 (Sathiya *et al*., 2007; Uday *et al*., 2010; Lin *et al*., 1999; Sahin *et al*., 2007; Kimura *et al*., 2006; Irawan *et al*., 2016) as the result of CDFW process and upset deformation in the end of the process. Therefore, these conditions were thought to yields maximum tensile strength of CDFW joints in the specimen with surface roughness of 1.0667 and especially 0.697 μm.

Table 3 shows the mean value of micro-Vickers hardness testing on the CDFW joint zones with 3 indentations locations at each zone. It was found that the hardness of Zpl1 is higher than Zpl2. Meanwhile, the hardness of Zpl1 for specimen with chamfer angle of 15 degree and surface roughness of 0.697 μm is higher than that of specimen with chamfer angle of 15 degree and surface roughness of 1.0667 μm.

Microstructure observation was also conducted on the center of zones in the CDFW joints. Figure 17-20 show microstructures of CDFW joint with chamfer angle of 0 and 15° with surface roughness of 1.0667 and 0.697 μm, respectively. Morphology of grains were mostly equiaxed grains with unhomogeneous size due to the deformation during CDFW process. Grain sizes were estimated using Planimetric method (ASTM, 2004). The circle in Fig. 17 shows analyzed grains in each photograph. Table 4 and 5 show grain sizes at the Zpl1, ZPl2 and Zud of the CDFW joints with surface roughness of 1.0667 and 0.697 μm, respectively. It is confirmed that zone with smaller grain size such us ZPl1 has the higher hardness that may contribute to yield higher tensile strength of CDFW joint. This condition also reported by other researchers (Sathiya *et al*., 2007; Uday *et al*., 2010; Irawan *et al*., 2012;

Table 4: Grains size in the zone of Zpl1, Zpl2 and Zud for specimen with surface roughness of 1.0667 µm

Chamfer angle	Zone	D (µm)
0°	Zpl1	16.74
	Zpl2	19.39
	Zud	22.16
15°	Zpl1	15.75
	Zpl2	16.16
	Zud	20.45

Table 5: Grains size in the zone of Zpl1, Zpl2 and Zud for specimen with surface roughness of 0.697 µm

Chamfer angle	Zone	D (µm)
0°	Zpl1	16.16
	Zpl2	18.61
	Zud	21.66
15°	Zpl1	14.28
	Zpl2	17.05
	Zud	20.1

(a) Zpl1 (b) Zpl2 (c) Zud

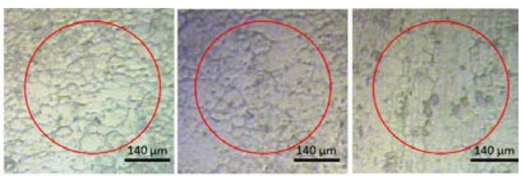


Fig. 18: Microstructures of CDFW joint with chamfer angle of 15° and surface roughness of 1.0667 µm

(a) Zpl1 (b) Zpl2 (c) Zud

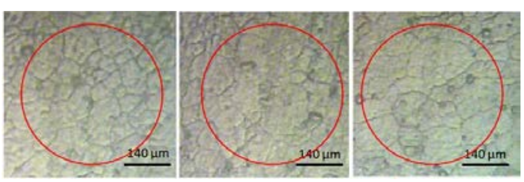


Fig. 19: Microstructures of CDFW joint with chamfer angle of 0° and surface roughness of 0.697 µm

(a) Zpl1 (b) Zpl2 (c) Zud

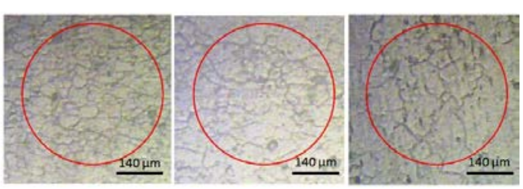


Fig. 20: Microstructures of CDFW joint with chamfer angle of 15° and surface roughness of 0.697 µm

Sahin *et al*., 2007; Kimura *et al*., 2006; Irawan *et al*., 2016). It is thought that it may occur due to the upset loading in the final stage of CDFW process that produced plastic deformation that increased density of dislocation to form smaller grain size.

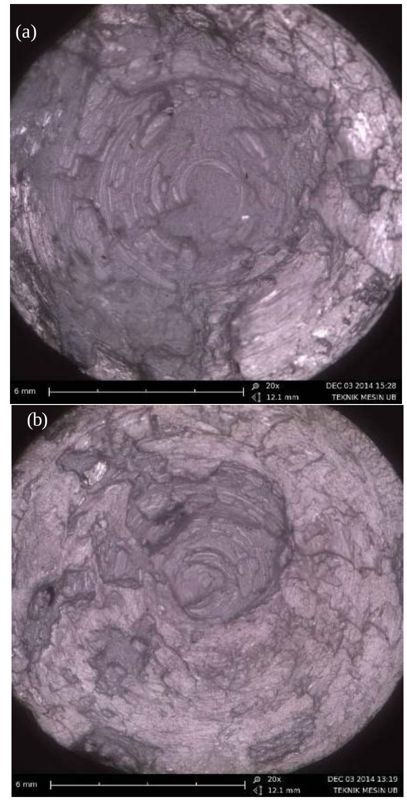


Fig. 21: Macro fracture surface of tensile test specimen: a) No chamfer (0°) and surface roughness of 0.697 µm with tensile strength of 102.16 MPa; b) Chamfer angle of 15° and surface roughness of 0.697 µm with the highest tensile strength = 173.49 MPa

Figure 21 shows macro fracture surface of the specimen with typical fracture surface with lower tensile strength and the maximum tensile strength of CDFW joint with chamfer angle of 15° and surface roughness of 0.697 µm. It can be seen that specimen fractured in the weld joint with spinning mark as result of friction process.

Specimen with maximum tensile strength fractured in the location away from Zpl zone with less spinning mark on the macro-fracture surface.

Figure 22 shows SEM photograph of fracture surface. It is found that all specimen fractured in ductile fracture pattern with equiaxed dimple formation as the result of tensile stress during tensile strength test. The specimen with the highest tensile strength (Fig. 22b) has smaller dimple size of ductile fracture compared to that of specimen with lower tensile strength of CDFW as the result of higher hardness and smaller grain size in the CDFW joint. This fracture condition also reported in Tialloy by Kanamori *et al.* (2007) and in Inconel sheet by

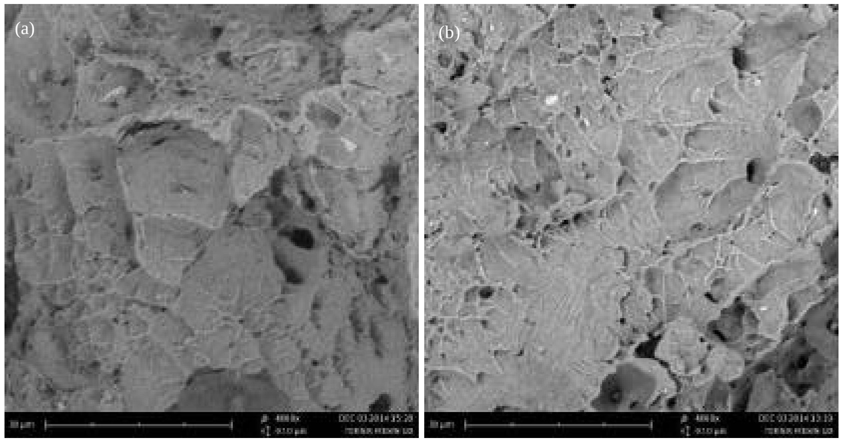


Fig. 22: SEM photographs of fracture surface of tensile test specimen: a) No chamfer (0°) and surface roughness of 0.697 μm with tensile strength of 102.16 MPa; b) Chamfer angle of 15° and surface roughness of 0.697 μm with the highest tensile strength = 173.49 Mpa

Liu *et al.* (2016). This result also confirmed that smaller grain size in the Zpl zone might influenced smaller dimple formation during fracture in tensile strength test. It is thought that the result affected by smaller chamfer angle and smaller surface roughness that lead to smaller heat input due to smaller friction area and lower friction coefficient but adequate to make metallic bonding in the interface of CDFW joint to yield maximum tensile strength.

CONCLUSION

The conclusions from this study can be obtained as follows:

- Surface roughness and chamfer angle affected maximum temperature, flash geometry and tensile strength of Aluminum alloys A6061 CDFW joints
- The lower surface roughness and the smaller chamfer angle could produce higher tensile strength of the CDFW joint, due to smaller heat input but it is sufficient to yield CDFW joint
- The maximum tensile strength of CDFW joint was found in the specimen with surface roughness of 0.697 μm with chamfer angle of 15 degree. It may occur due to the minimum porosity, the maximum area of fully plasticized zone 1 (ZPl1) which has high hardness, the minimum area of fully plasticized zone 2 (Zpl2) that have lower hardness in the CDFW joint

ACKNOWLEDGEMENTS

This research was supported in part by Directorate Higher Education of Indonesian Ministry of Education and Faculty of Engineering, Brawijaya University, Indonesia.

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