Anisotropic Torsion Strength of Round Bar A6061 Friction Weld Joint with Various Upset Pressures

Yudy Surya Irawan, David Febri Alfian, Endi Sutikno
Mechanical Engineering Department, Brawijaya University, Malang, Indonesia

Email: yudysir@ub.ac.id

Abstract. This paper revealed anisotropic torsion strength of round bar aluminium alloys A6061 friction weld joint affected by upset force. Round bar A6061 was used for friction welding specimen with two different geometries which were the specimen with flat friction surface (without chamfer angle) and the specimen with chamfer angle of 15 degree. Continuous Drive Friction welding (CDFW) was done by applying initial friction pressure of 39 MPa and upset pressure variation of 39 MPa, 79 MPa and 119 MPa. Torsion test was done according to ASTM standard in which torsion direction was applied in the same and in the opposite direction of friction welding revolution. It was found that the higher upset pressure can give the higher torsion strength of the specimen. The specimen without chamfer angle that applied by 119 MPa of upset pressure has the maximum torsion strength of 165 MPa, with torsion loading direction is the opposite to revolution direction of friction welding process. The anisotropy of torsion strength was found in the specimen, where the torsion strength of the specimen in the opposite direction of friction welding revolution is higher than in that of specimen with the same direction as revolution direction of friction welding process. The maximum difference between torsion strength in the opposite direction of revolution of friction welding and that of specimen with the same direction of friction welding revolution is around 6% that occurred in the specimen without chamfer angle and applied by the highest upset pressure. It was thought that interaction between torsion loading direction and the microstructure of the weld joint as the result of plastic deformation due to upset pressure and revolution during CDFW process affects the existence of the anisotropic torsion strength.

Keywords: Continuous drive friction welding, A6061, anisotropy, torsion strength.

1. Introduction
Welding process is one of joining process in manufacturing technology to produce structure or product by joining materials. Welding of aluminium is essential in product manufacturing because aluminium has about one third of steel density. Aluminium has interesting point to be used due to its light weight and its corrosion resistant beside its adequate strength, depends on the purpose of the products. Aluminum alloys A6061 is one type of aluminum alloy that widely used for light structures, rail transportations, machine component and aircraft structure or machine in the forms of plate or round bar or pipe [1]. However, there is difficulty in welding of aluminium using fusion method due to the high thermal conductivity and oxide of aluminum during fusion welding [2]. This problem can be solved with solid state welding technique such as friction welding than can reduce the negative effect of high thermal conductivity and the existance of aluminum oxide during welding of aluminum [3].
Friction welding is a solid state welding that using heat generating from the rubbing of friction surface of specimen to be joined. Friction welding process that usually used to join a round bar metal is continuous drive friction welding (CDFW), spinning or rotary friction welding or inertia friction welding. Besides, there is friction stir welding and liner welding that used for joining plates. The friction welding process is usually short and produces flash on the specimen. The CDFW process is usually used for welding of metals that difficult to be joined such us aluminium. In this process, there are two part of metals to be joined. The first part is rotated and the other is in the stationary state. During the friction, the stationary part is applied by compression force to contact and rubb the rotated part so the heat generated and compressive force is maintained until adequate flash occurs in the interface. As the flash formed the welding stopped and higher additional compressive force is applied to strengthen the weld joint [4].

Mechanical properties of friction weld joint of round bar Aluminium alloys are important to be studied in order to be useful in application or in designing the product with sustainable strength. Torsion strength is one of mechanical properties that is essential for the component that endures torsion load such as the shaft of the machine. Therefore, some efforts were done to increase the torsion strength of aluminium alloy friction weld joint. Irawan et.al. studied the application of the cone geometry and friction time to increase the torsion strength of A6061 friction weld joint [5], the using of double chamfer angle to increase tensile strength [6] and torsion strength of round bar A6061 friction weld joint [7][8]. However, there is no information about anisotropic torsion strength of round bar A6061 friction weld joint. Previous researchers [5][7][8] applied torsion load with momen direction the same as the revolution direction. Therefore, it is essential to find the torsion strength of round bar A6061 friction weld in the opposite of the revolution direction of friction welding joint. This paper describes the anisotropic torsion strength of round bar A6061 friction weld based on the torsion test result, macro and microstructures, and the fracture surface observation. By knowing the lowest torsion strength of the friction welding joint, it will be useful for product design in order to make safe products that endures torsion load such us the shaft.

2. Materials and Method
Material used in this research was the round bar of aluminum alloy A6061. The chemical composition in % of weight of A6061 was 97.385% Al, 0.907% Mg, 0.695% Si, 0.436%Fe, 0.210 Cu, 0.190%Zn, 0.094%Mn, 0.036%Cr, 0.021%Pb, 0.014%Ti, 0.008%Ni, and 0.004%Sn. The round bars of A6061 were cut by a saw machine with water coolant and machined by a lathe machine to form CDFW specimen as shown in figure 1. There are two parts which are the rotated part and stationary part. The stationary part has friction area that has chamfer angle of 0 degree and 15 degrees. The chamfer angle of 15 degrees was selected because it can produce the maximum tensile strength as reported in Irawan et.al. [5].

During CDFW process, the rotated part of the specimen (figure 1a) was set in the chuck of the lathe machine. The stationary part of the specimen (figure 1b and 1c) was gripped in the chuck that connected with a hydraulic cylinder with capacity of 50 kN. Before the CDFW process, the both contact surfaces of the specimen were cleaned using acetone. The rotated specimen was rotated with revolution speed of 1600 rpm, then the initial friction pressure of 39 MPa was applied on the stationary specimen to contact with the rotated specimen. The initial friction pressured was applied until 3 mm burn of length reached. After the lathe machine was shut down, the stationary specimen continued to be given by varied upset pressure of 39, 79, and 119 MPa for 10 seconds before the welded specimens were cooled in the air.
Figure 1. Geometry of CDFW specimen of A6061, (a) the rotated part of the specimen, (b) the stationary part of the specimen without chamfer angle, (c) the stationary part of the specimen with chamfer angle of 15 degree.

The friction welded specimens were machined with the coolant to make torsion strength testing specimen as illustrated in figure 2 based on ASTM standard [9]. The friction weld joint was located in the center of the torsion strength test specimen. The torsion strength test was conducted using a torsion strength test machine and the testing procedure was done based on ASTM standard [9]. Three specimens of each variation of chamfer angle and upset pressure were prepared. In order to find anisotropy of torsion strength of the CDFW joint, two specimens were prepared with the same condition of chamfer angle and upset pressure and applied by two different torsion loading as shown in figure 3. Two torsion loading directions are the same as friction welding revolution direction (FWRD) and counter friction welding revolution direction (CFWRD). The data of torsion strength test of each torsion loading direction was obtained in order to be compared and to find the anisotropy of torsion strength of CDFW joint.

Temperature of the flash of CDFW joint during CDFW process was measured by an infra-red thermogun. Macro and microstructure of the CDFW specimens with maximum and minimum torsion strength were also observed. The grain size of microstructures was measured using a planimetric method based on ASTM standard [10].
3. Results and Discussion

Torsion strength of each specimen was measured in torsion loading direction of FWRD and CFWRD and the mean value of torsion strength of the specimens were calculated from 3 replications data of each combination of variables. Figure 4 shows the relationship of mean torsion strength (in FWRD and Counter FWRD) and upset pressure for the specimens without chamfer and chamfer angle of 15 degrees.
strength of the specimens in FWRD and Counter FWRD (CFWRD) and upset pressure. It can be seen that the increasing of upset pressure increased the mean torsion strength of the CDFW specimens. It is thought that the higher upset pressure causes higher degree of plastic deformation that can yield atomic slips to make smaller grains or increasing dislocation density. Therefore, the higher upset pressure yields higher torsion strength of the A6061 CDFW joint.

It also shows that there is difference magnitude of mean torsion strength for the CDFW specimens that endured torsion loading in FWRD and CFWRD, namely the mean torsion strength of the CDFW specimens is higher when the specimen was applied by torsion loading in CFWRD. It means that the anisotropy or the dissimilar properties of the materials in different direction was found in the torsion strength of the CDFW specimen whether without or with chamfer angle of 15 degrees. Meanwhile, it was also found that in the same 3 mm burn of length, the specimen without chamfer angle has higher torsion strength compared to that of the specimen with chamfer angle of 15 degrees. Maximum difference of torsion strength occurs in the specimen without chamfer under upset pressure of 119 MPa. Namely, the torsion strength of the specimen without chamfer angle in CFWRD is 165.12 MPa which is higher than that of the specimen in FWRD that has 154.94 MPa. The difference of these torsion strength values or its anisotropy is 6.57 percent. In the case of the specimen with chamfer angle of 15 degrees, the difference of torsion strength in FWRD and CFWRD is almost the same as shown in figure 4. The torsion strength is still higher in the CFWRD. Even the anisotropy of torsion strength is around 6 percent, it must be considered in designing the torsion strength of the shaft to use the lower torsion strength of CDFW joint which is in FWRD strength to ensure the safety of the shaft or the structures that using a round bar that endures the static torsion loading.

The fracture surface of the specimen with the maximum and the minimum torsion strength is shown in figure 5. It can be seen that the specimen with the maximum torsion strength has slightly more flat fracture surface compare to that of the specimen with minimum torsion strength. Flat fracture surface means that the specimen with the maximum torsion strength was fractured due to pure shear stress. It also shows that both specimens were fractured in ductile manner. Slightly not flat fracture surface that occurred in the specimen with chamfer angle of 15 degrees might happened due to non uniform microstructure as the result of collision of non uniform friction area which is between flat friction area and chamfered friction area (figure 1b and 1c).

Figure 4 shows that the mean torsion strength of the specimen with chamfer angle of 15 degrees is lower than that of specimen without chamfer angle at various upset pressures. It is thought that in the period of 3 mm burn of length, the time that needed for the specimen with chamfer angle to form flash is longer due to small initial friction area compared to that of the specimen without chamfer angle that has wide initial friction area (figure 1). It was confirmed with the result of flash temperature measurement as shown in figure 6. It can be seen that the flash temperature for the specimen with chamfer angle at various upset pressures are higher than that of the specimens without chamfer angle. Meanwhile, the effect of upset pressure on the flash temperature was not significant, since the curves are not different in the specimen with or without chamfer angle. The higher temperature of flash has correlation with higher heat input during CDFW process that causes re-crystallization of the grains and yields bigger grains in the interface of welded zone. Figure 7 shows this state that the grains of microstructures in the interface area of CDFW joint without chamfer angle is smaller than that of the specimen with chamfer angles. The grains size measurement using planimetric method [10] in the black circle shows the grain size of the specimen without chamfer angle and chamfer angle of 15 degrees are 18.9 µm and 22.5 µm,
Figure 5. Fracture surface of torsion strength testing specimen with (a) maximum torsion strength (specimen without chamfer angle and upset pressure of 119 MPa) and (b) minimum torsion strength (specimen with chamfer angle of 15 degrees and upset pressure of 39 MPa).

Figure 6. Flash temperature of the CDFW specimens with various upset pressures.

respectively. Moreover, the CDFW joint state is also confirmed by the VHN hardness measurement result on the interface of CDFW joint for the specimen without chamfer which has maximum torsion strength and chamfer angle of 15 degrees are 77.83 and 53.62, respectively.

The anisotropy of mean torsion strength of the CDFW joint in FWRD and CFWRD is the result of interaction between torsion loading direction on micro and macrostructures of the interface. Figure 8 shows macrostructures of the interface of the specimen with maximum torsion strength and the vector of torsion loading during torsion strength testing. The macrostructures has spinning-like mark in counter clock wise or the same as friction welding revolution or FWRD. This spinning-like macrostructures are the result of plastic deformation caused by shear stress as the result of the CDFW process. It can be thought that atomic slips occurs easily in the direction of FWRD, so when the torsion loading is applied in the direction that the same as FWRD the atomic slips easier than in the counter FWRD. The easier the atomic slip occurs, the easier plastic deformation occurs until fracture due to torsion. Therefore, the mean torsion strength of the CDFW joint in CFWRD is higher than that of the specimen in FWRD.
Figure 7. Microstructures of CDFW joint interface: a) for the specimen without chamfer angle and upset pressure of 119 MPa which has maximum torsion strength, VHN hardness of 77.83 and grain size of 18.9 \( \mu \text{m} \), b) the specimen with chamfer angle of 15 degrees and upset pressure of 39 MPa which has minimum torsion strength, VHN hardness of 53.62 and grain size of 22.5 \( \mu \text{m} \).

Figure 8. Directions of torsion loading during torsion strength testing: a) the same as friction welding revolution direction (FWRD), b) Counter Friction Welding Revolution Direction (CFWRD).
4. Conclusions

This study about investigation on the anisotropy of torsion strength in the A6061 CDFW joint without and with chamfer angle of 15 degrees at various upset pressures has been done and the prominent findings of this study are:

1. Anisotropy of torsion strength of A6061 CDFW joint was found in the specimens at various upset pressures. The torsion strength of the CDFW joint in the direction of opposite of CDFW revolution direction is higher than that of the specimen in the direction of CDFW revolution.

2. Upset pressure during CDFW process affected the magnitude and anisotropy of torsion strength of CDFW joint. The higher upset pressure increase higher torsion strength and the anisotropy of the torsion strength of the CDFW joint. Higher upset pressure caused higher degree of plastic deformation and atomic slips to produces smaller grains that can increase the torsion strength of the CDFW joint.

3. Anisotropic torsion strength might occur due to the different interaction between atomic slips of  microstructures and direction of shear stress as the result of the torsion loading during the test. Namely, atomic slips occurs easily in the direction of FWRD, so that when the torsion loading is applied in the direction that the same as FWRD the atomic slips easier than in the counter FWRD. Therefore, the mean torsion strength of the CDFW joint in CFWRD is higher than that of the specimen in FWRD.

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