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TENSILE STRENGTH AND THERMAL CYCLE ANALYSIS OF AA6061 FRICTION WELD JOINTS WITH DIFFERENT DIAMETERS AND VARIOUS FRICTION TIMES

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The paper reports measurement of tensile strength and the thermal cycle of AA6061 aluminum alloy circular bar friction weld with different diameters and various friction times. A continuous drive friction welding (CDFW) of AA6061 was conducted to weld the AA6061 circular bar with different diameters of 30 mm for the rotating part and 15 mm for the stationary part. The CDFW process was carried out with the revolution speed of 1,600 rpm, the initial compressive force of 2.8 kN during the friction stage for various friction times of 10, 12, and 14 seconds, and an upset force of 28 kN for 60 seconds. The flash temperature was measured using a digital infrared thermometer gun. Computer simulation using the finite element method was also done by coupling transient thermal and static structural methods. The flash temperature becomes higher along with increasing friction time based on the digital infrared thermometer gun measurement and finite element analysis. The results of tensile strength testing show that the specimen with a friction time of 12 seconds has the highest tensile strength. Based on the hardness testing result, it is found that the specimen with a friction time of 10 seconds has higher hardness, but it has an incomplete joint flash so that the tensile strength is lower than that of the specimen with a friction time of 12 seconds. Besides, the hardness of the specimen with a friction time of 12 seconds is higher than that of the specimen with a friction time of 14 seconds. The flash size becomes bigger along with the increase of the friction time based on the macrostructure observation on the longitudinal section of the CDFW specimen. It is confirmed by the temperature measurement and finite element analysis that the specimen with a friction time of 12 seconds has heat input to form the CDFW joint that has a maximum tensile strength in the range of this study

Keywords: Aluminum, Friction Welding, Tensile Strength, Finite Element Analysis, Thermal cycle

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1. Introduction

The friction welding process is solid-state welding to join materials especially metals. There are common methods of friction welding which are rotary friction welding, linear friction welding, friction stir welding, and orbital friction welding. The heat to join the parts in the friction welding is generated from the friction between two contacted surfaces. Rotary friction welding (RFW) has two methods which are inertia friction welding and continuous drive friction welding (CDFW). The RFW is usually conducted for rounded materials. Linear and friction stir welding can be utilized to join sheet metal [1, 2]. The first method of friction welding is rotary friction welding patented in the 1890s [3].

The AA6061 aluminum alloy contains magnesium and silicon as alloys. These alloys are extensively applied in the field as pipelines, marine frames, storage tanks, and aircraft components [4]. Welding of circular bars of aluminum alloys such as AA6061 is challenging because it has a brittle aluminum oxide and high thermal conductivity [5]. A rotary friction welding method such as continuous drive friction welding is usually conducted to weld a circular bar of aluminum. The CDFW process needs a short time and generates a flash that takes out the alumina oxide from the interface that can overcome the problem in aluminum welding [6]. There is also a condition that it is needed to weld a circular bar to the plate or a round bar with a bigger diameter.

As a result, the studies are devoted to improving the tensile strength of friction welding joints of AA6061 circular bar with different diameters by using varied friction time. The friction time is one of the basic parameters of the friction welding process. The studies are expected to obtain friction time that can increase the tensile strength of AA6061 circular bar with various diameters and understanding of the thermal cycle underlying the tensile strength of the CDFW joint from experiment and analysis view.

2. Literature review and problem statement

The papers [7, 8] stated that friction time, friction pressure, upset time, upset pressure, and revolution speed are all important parameters in the CDFW process. These parameters can be varied to obtain maximum strength of CDFW joint, such as tensile strength. However, the effect of the parameters in the CDFW joint with different diameters was not studied yet. The paper [9] studied the effect of varied double chamfer geometry on the friction area of the specimen of AA6061 with the same diameter on the tensile strength of CDFW joints of AA6061. This paper reported that the use of 30 degrees of chamfer angle can yield maximum tensile strength in the range of the study. The use of a one-sided chamfer, and clamping stage in the paper [10], could also improve the tensile strength and reduce fatigue crack growth rate of AA6061 round bar CDFW joints. It could happen as a result of lower initial heat generated from the friction area and additional plastic deformation at the CDFW joint during the clamping state of the CDFW process.

Moreover, there is also an essential condition that components shall be joined into larger dimensions using friction welding, such as a circular bar to a bigger diameter round bar of metal. The study on the friction welding of stainless steel and structural steel circular bars with different diameters was conducted in the paper [11]. The paper reported that during friction welding with different diameters, there was transfer metal that exists between the bigger diameter specimen and the flash of smaller diameter specimen. This phenomenon was called rotational plane transfer and occurred in the central zone of the rotational plane. The decrease of the area of the rotational contact plane was influenced by increasing rotational speed and friction pressure and diameter. The study focused on material transfer and rotational plane transfer. However, the study did not discuss the thermal or temperature cycling that occurred at the CDFW joints. The paper [12] conducted the friction welding of AISI 1040 circular bar with the variation of diameter on the rotated and stationary specimens. The study found that the tensile strength of the CFDW joints with the same and different diameters is affected by the ratio of diameter and the parameter of the CDFW process such as friction time. The tensile strength of the AISI 1040 CDFW joints reduced in the case of the CDFW joints with big diameter and small diameter ratio was 2 or above. As a result, increasing the tensile strength of CDFW joints of different diameters is important. Besides, the thermal cycle was not discussed in the paper [12]. A study on thermal evaluation and modeling of friction welding with different diameters of AISI 1040 was performed and reported in the paper [13]. The study using Quick Field finite element analysis which was a free software with limited mesh that can be used was 200 meshes. The paper reported the analysis of total heat energy, the heat loss, and the field of temperature in joints that depends on the friction time. The paper [13] also discussed the temperature cycle at the friction surface from the center to the outer but did not compare with experimental results, especially near the interface which should be measured using the digital infrared thermometer gun or a thermocouple. Comparisons are needed to measure the accuracy of the analytical method against experimental results. The paper [14] reported the simulation of the friction welding process using the coding of Microsoft Visual Basic^{TM} 6.0, 3D Studio Max for 3D modeling, and Paint Shop Pro^{TM} for some coating of the model. The simulation was not based on the finite element method but on the coded program that has two windows. The first window is an input window for inputting friction welding parameters and specimen geometry. Then, the program examines the condition and determined the torque, the total energy, the useful energy, and the lost energy by using the analogy. The second window showed the result of flash simulation based on the behavior of cylindrical specimen 3D model divided into polygons which has deformation behavior based on the experimental result reported in the paper [15, 16]. The program was coded based on the experimental data to predict the flash of the CDFW joint with the same and different diameters, however, the program can simulate the flash of the CDFW joint. The paper [14] should use basic information of material properties and the CDFW process to simulate the CDFW process to yield thermal cycle and deformation prediction close to the experimental result. It is needed to shorten prediction process time by not doing the experimental CDFW process first.

As mentioned in previous research, there are no reports on the friction welding and thermal cycle analysis of AA6061 circular bar with different diameters. Since there is also a situation that needs to join AA6061 circular bar to a bigger-diameter object or component such as a round bar to the plate or disc of mechanical components. Besides, it is still difficult to measure temperature distribution in the surface and the axis of the specimen, especially in the rotated specimen. All of this means that a study of tensile strength and thermal cycle analysis friction welding of AA6061 circular bar with various diameters should be conducted using both experiments and computer simulation. Computer simulation using finite element analysis is needed to uncover the thermal cycle and deformation that occur during friction welding. The finite element analysis can reveal the temperature distribution on the longitudinal axis of the CDFW specimen that has correspondence with the hardness and strength of the CDFW joint. This paper discusses the effect of friction time on the tensile strength of the AA6061 CDFW joints with different diameters, based on the tensile strength test, finite element analysis on a thermal cycle during friction welding, microhardness testing on the CDFW specimens.

3. The aim and objectives of the study

The study aims to get higher tensile strength and the thermal cycle of friction weld joints with different diameters.

In order to achieve the aim, the following objectives were accomplished:

– to conduct the tensile test on the specimen with the variation of friction time;

– to measure the temperature near the interface of the CDFW joint with different diameters;

– to perform finite element analysis to find a thermal cycle to make a correlation among the results of tensile strength test, friction time, and thermal cycle.

4. Material and method of experiment

AA6061 circular bar was used in this experiment. It has a tensile strength of 264 MPa. The chemical composition of AA6061 is shown in Table 1.

A power hacksaw and coolant were used to cut the bulk circular bars of AA6061 with diameters of 30 mm and 22 mm.

The CDFW specimens were machined using a CNC TU-2A machine according to Fig. 1. Fig. 1 shows that the rotated specimen has a 30 mm diameter on the left side and the stationary specimen of friction welding is shown on the right side.

Table 1

Chemical composition of AA6061 aluminum alloys

Components	Weight %	Components	Weight %	Components	Weight %
Al	97.396	Fe	0.436	Mn	0.094
Mg	0.907	Cu	0.210	Cr	0.036
Si	0.695	Zn	0.196	Others	0.035

The CDFW process was conducted using a modified lathe machine with a hydraulic cylinder for applying a compressive force to the stationary specimen. The first step was to rotate the specimen with a diameter of 30 mm at 1,600 rpm while applying a compressive force of 2.8 kN to the stationary specimen. After a friction time of 10, 12, 14 seconds, the lathe machine was stopped. At the final stage, a compressive force of 28 kN was applied to the stationary specimen for 60 seconds. After the CDFW process, the specimens were cooled at room temperature before the specimens were removed from the chuck. During the CDFW process, the digital infrared thermometer gun with a sampling rate of 5 Hz was used to measure the temperature on the flash of the CDFW joint. After the welding of the specimen finished, the specimens were machined for tensile strength testing with the geometry shown in Fig. 2, based on the AWS standard [17]. The CDFW process was carried out twice at each variation of the friction time to provide the tensile strength test specimen and the macrostructure observation including the hardness testing specimen.

Fig. 3 shows the model used in the finite element analysis. The model has 141,977 elements and 95,484 nodes. The dense mesh in the friction and the deformed zone has an element size of 1 mm and the coarse element size for the undeformed zone is 3 mm. The analysis was conducted using Academic Ansys 18.1 [18]. The model was a model with bilinear isotropic hardening. Table 2 shows the temperature-dependent properties of AA6061 used in the finite element analysis [19]. The boundary condition was set as experimental procedures. The heat generation was defined at the interface of 30 mm diameter and 15 mm of CDFW specimen. The finite element analysis used a couple of transient thermal and static structural methods.

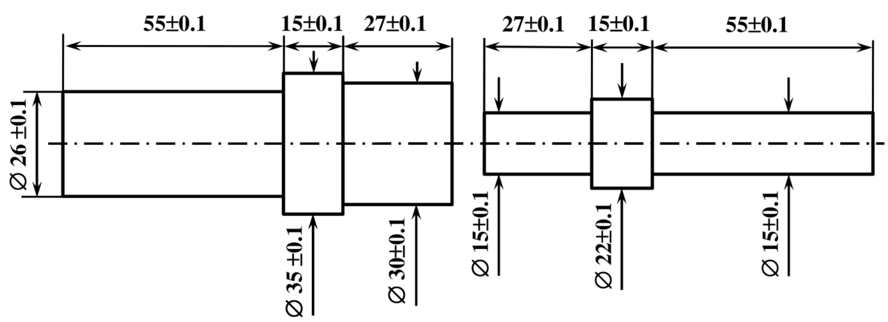

Fig. 1. Geometry of friction welding specimens, the left side is rotating part and the right side is the stationary part of the friction welding specimen (unit: mm)

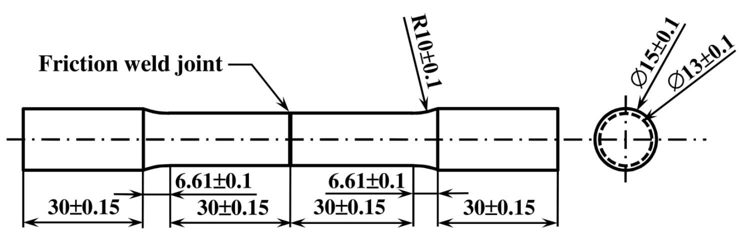

Fig. 2. Specimen for the tensile strength testing of the friction weld joint [17]

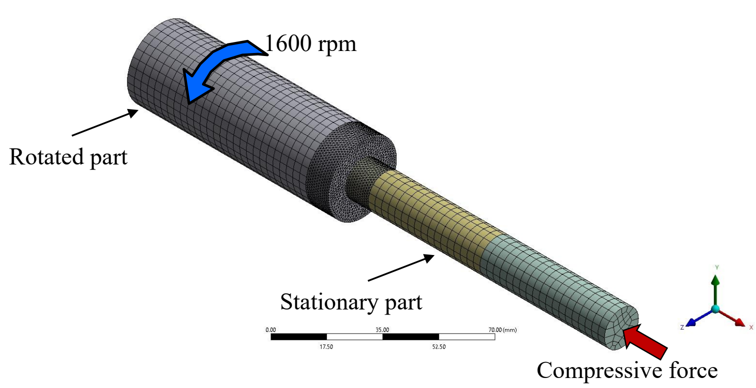

Fig. 3. Finite element model for thermal transient coupled with static structural analysis

Table 2

Temperature-dependent properties of AA6061 aluminum alloys [19]

Material Properties		Density (kg/m^3)	Young Modulus (GPa)	Poisson's Ratio	Thermal Conductivity (W/m·°C)	Specific Heat (J/kg·°C)
Temperature (°C)	37.8	2,690	68.5	0.33	162	945
	93.3	2,690	66.2	0.33	177	978
	149	2,670	63.1	0.33	184	1,000
	204	2,660	59.2	0.33	192	1,030
	260	2,660	54	0.33	201	1,052
	316	2,630	47.5	0.33	207	1,080
	371	2,630	40.3	0.33	217	1,100
	427	2,600	31.7	0.33	223	1,130

Macrostructure observation was conducted on the longitudinal section of CDFW joints. Vickers hardness testing was also performed with 50 gf load and 6 seconds of indentation time.

5. Results of the experiment

5. 1. Tensile strength test result

Fig. 4 shows the longitudinal section of the CDFW joint with friction times of 10, 12, and 14, respectively. In the case of the specimen with a friction time of 10 seconds, the flash formed at the interface. However, for the specimen with a friction time of 12 and 14 seconds, the flash formed away from the interface. All specimens have the flash formed only in the smaller diameter specimen.

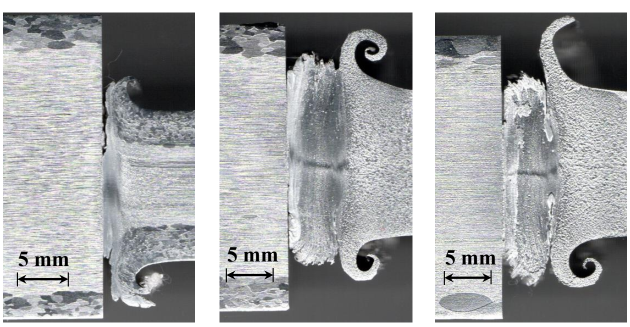

Fig. 4. Macrostructures of the longitudinal section of friction weld joint of AA6061: *a* – friction time of 10 seconds; *b* – friction time of 12 seconds; *c* – friction time of 14 seconds

The tensile strength test result is shown in Fig. 5. It can be seen that the larger friction time did not yield higher tensile strength but at a certain friction time of 12 seconds, the CDFW process can produce maximum tensile strength. It is thought that the longer friction time can generate higher heat and temperature that can increase grain size when the temperature is above crystallization temperature. The increase of flash temperature is also confirmed with the digital infrared thermometer gun as shown in Fig. 6, where the longer friction time, the higher generated heat along with the temperature.

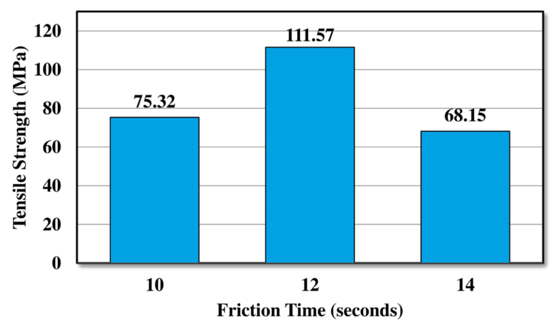

Fig. 5. Tensile strength of CDFW specimens with various friction times

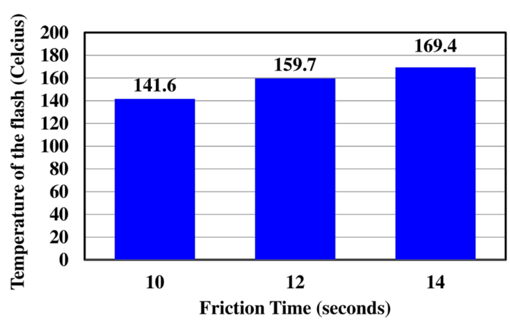

Fig. 6. Maximum temperature of the flash of CDFW joints

5. 2. Thermal cycle measurement of the CDFW joint

Fig. 7 shows the thermal cycle of the CDFW joint with different diameters which is obtained from temperature measurement on the flash of the joint using the digital infrared thermometer gun. It can be seen that the longer friction time the higher the temperature that occurs in the interface of the CDFW joint with different diameters. The higher temperature can affect the hardness and strength of the CDFW joint.

Fig. 8 is the graph between Vickers hardness and the distance from the interface (noted as zero). It can be seen that the rotated specimen has higher hardness since the rotating part has a larger mass and volume so that the generated heat from the interface is absorbed by the part. Meanwhile, the stationary part has a lower mass and volume so that the temperature in this section is higher than that of the rotating specimen and the hardness is lower.

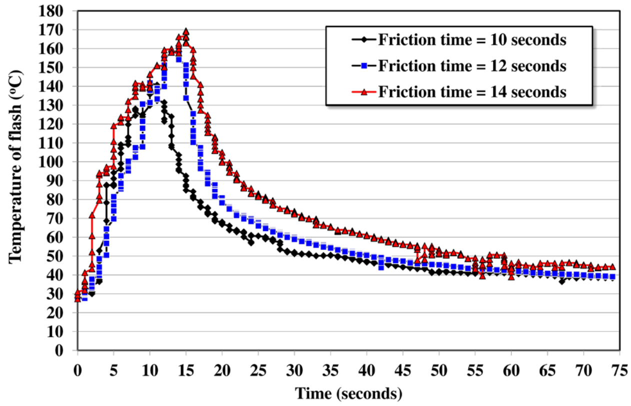

Fig. 7. Experimental thermal cycles at the flash of CDFW joints

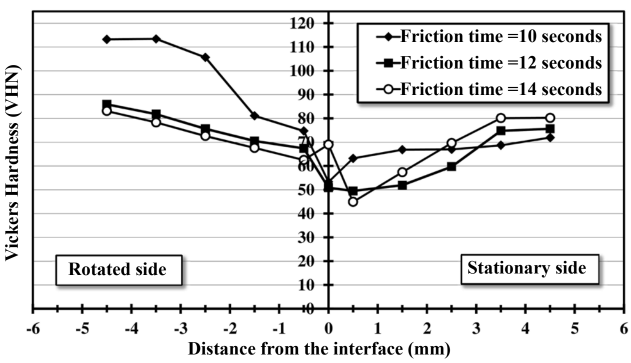

Fig. 8. Vickers hardness distribution on the longitudinal section of the CDFW joint. The left side is rotated specimen and the right is the stationary specimen

5. 3. Finite element analysis results on thermal cycles

Fig. 9 shows the comparison of the experimental thermal cycle and finite element analysis results. It can be found that finite element analysis can simulate the friction welding process. The difference between the experimental value and finite element analysis is around 5.3 percentage which is the value of finite element analysis is higher than the experimental result.

Fig. 10 is the graph of the temperature distribution on the longitudinal axis of the CDFW specimen as the result of FEM analysis. It can be seen that the temperature of the rotated specimen with a bigger diameter has a lower temperature and the maximum temperature occurs at the interface which is shown as 0 mm. It also shows that the longer the friction time the higher the peak temperature at the interface of the CDFW specimen.

Fig. 11 shows the flash formation that was analyzed using finite element analysis. It can be seen that the result has the same trend that the larger the friction time the larger the diameter size of the flash. Meanwhile, due to the final compressive force at the CDFW specimen, the longer friction time, the higher temperature at the flash so that the flash contracted becoming shorter from 2.61 mm to 2.41 mm.

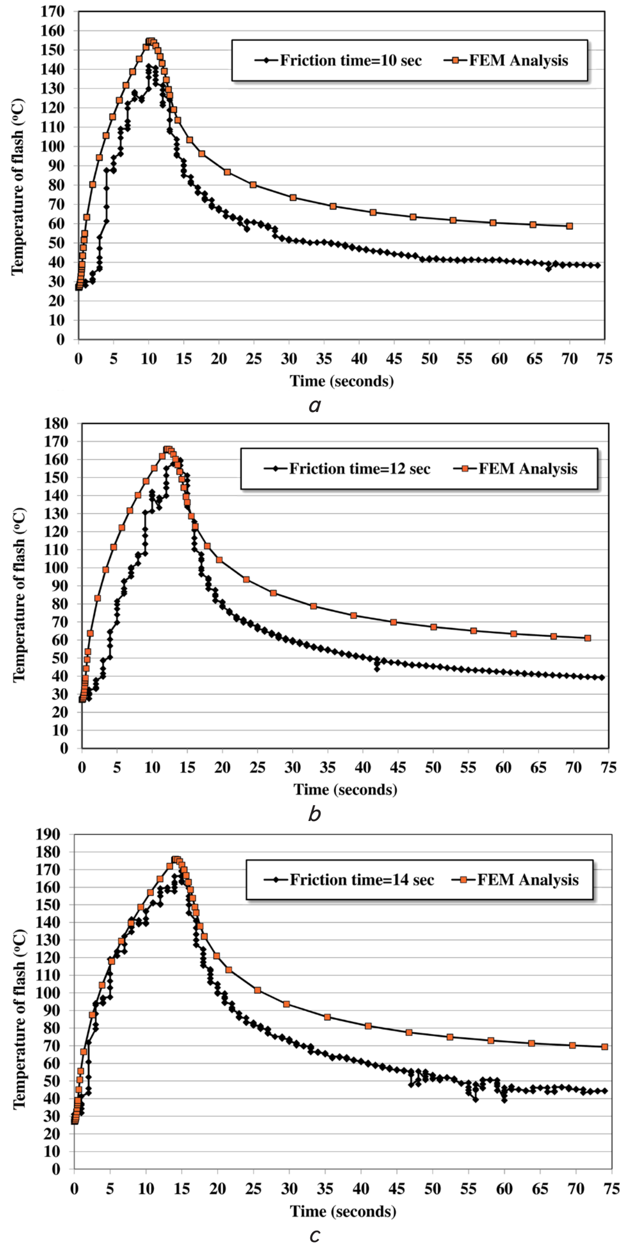

Fig. 9. Comparison of thermal cycles between experimental result and finite element analysis: *a* – friction time of 10 seconds, *b* – friction time of 12 seconds, *c* – friction time of 14 seconds

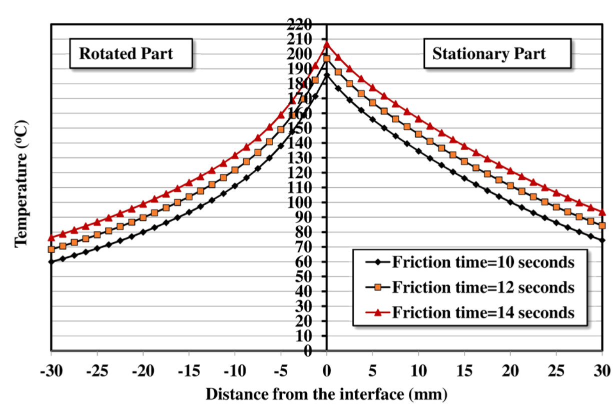

Fig. 10. FEM analysis result of temperature distribution at the longitudinal axis of the CDFW specimens with friction time of 10, 12, and 14 seconds

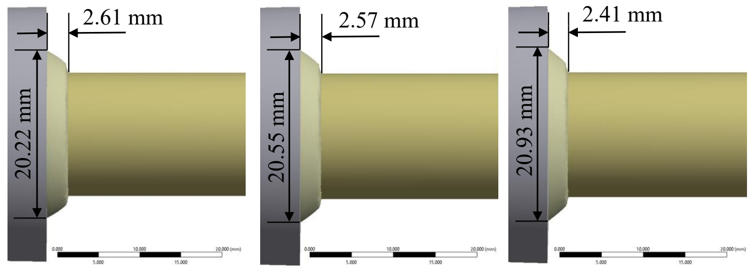

Fig. 11. FEM simulation result of the flash of friction weld joint of AA6061:
a – friction time of 10 seconds; *b* – friction time of 12 seconds; *c* – friction time of 14 seconds

6. Discussion of experimental results

The results of the experiments show that the tensile strength of the AA6061 circular bar CDFW joint was achieved in the specimen with a friction time of 12 seconds. It has a maximum tensile strength of 111 MPa. It is thought that in this CDFW process and the condition of the specimen with different diameters, a friction time of 12 seconds gives adequate heat input to form a metallic joint in the interface of the CDFW joint. It was confirmed by the digital infrared thermometer gun and finite element analysis on the thermal cycle that the longer friction time can increase heat input along with the increase of temperature. When the temperature is above the recrystallization temperature of AA6061, the grain of microstructure will increase which can reduce the tensile strength of the CDFW joint as shown in Fig. 6. It shows that the CDFW joint with a friction time of 14 seconds has lower tensile strength. However, there is a limitation of this study that there is a lack of penetration in the interface of the CDFW joint that causes porosity shown in Fig. 5. Therefore, in the forthcoming study, another parameter of friction welding, such as upset pressure at the final stage of the CDFW process will be applied to remove the porosity of the CDFW joint.

In the case of hardness distribution on the longitudinal section of the CDFW joint as shown in Fig. 8. The hardness of the specimen with a friction time of 10 seconds has higher hardness than that of the specimen with a longer friction time. It shows that friction time of 10 seconds still does not affect the larger volume of the CDFW joint so that the grain size of the specimen is not significantly affected by the heat generated at the interface. However, due to the short friction time, the area of metallic bond in the weld zone is still smaller compared to that of the specimen with a longer friction time as shown in Fig. 4, *a*. In this condition, the joint still cannot endure tensile load so that the tensile strength of the CDFW joint with a friction time of 10 seconds is still lower than that of the specimen with a friction time of 12 seconds. Meanwhile, in the case of the specimen with a friction time of 14 seconds, due to longer friction time, the generated heat is higher than that of the specimen with a shorter friction time. Therefore, the aluminum circular bar will be more softened that yields lower tensile strength. Moreover, the rotating specimen with higher diameters which has a larger mass has higher hardness; because the temperature at the rotated specimen is lower that has the lower softening effect on the rotated specimen as shown in Fig. 10. It shows that the rotated specimen with a higher diameter has a lower temperature than that of the stationary specimen.

The finite element analysis can simulate a thermal cycle that is close to the experimental thermal cycle with a different value of 5.3 percentages as shown in Fig. 9. However, the study has a limitation that the size and shape simulation of the flash is still different from the experimental result. It might happen because of the limitation of the finite element model using bilinear isotropic hardening. In the near future, finite element modeling using another material model is needed to improve the simulation results that are close to the experimental results.

7. Conclusions

1. In the range of this study, the CDFW joint of AA6061 round bar with different diameters has a maximum tensile strength at the friction time of 12 seconds. At this friction time, there was adequate heat input to form strong metallic bonding at the interface of the CDFW joint. It is confirmed by the experimental result and finite element analysis on the thermal cycle of the CDFW joint.

2. The longer the friction time, the higher the peak of temperature on the flash of the CDFW joint. The longer the friction time, the flash formed away from the interface. It might occur due to higher temperatures to make smaller diameter specimens more plasticized. And since the counterpart specimen has a higher diameter which has a larger volume so that the rotating part is not plastically deformed so that the fully plasticized part of the smaller part cannot form the flash at the interface except the specimen with a friction time of 10 seconds.

3. The finite element analysis on thermal cycle, deformation, and the result of hardness testing can confirm that the longer friction time the larger the peak of the thermal cycle and the size of the flash. Besides, the CDFW joint has a higher temperature and larger flash at the small diameter of the friction welding specimen. Therefore, at a friction time of 12 seconds, the CDFW joint with different diameters has maximum tensile strength.

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