CHARACTERISTIC OF FRICTION STIR WELDING WELD JOINT OF AA 6061 ON INITIAL TEMPERATURE DIFFERENCE

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Friction stir welding (FSW) is a solution to overcome the problems of AA 6061 welding. When the initial temperature T_0 of the material is increased during the FSW process while the FSW process parameters are kept constant then FSW welding parameter value can be lowered. T_0 was varied by $T_{room\ temperature}$, 50 ^{0}C, 75 ^{0}C, 100 ^{0}C and 125 ^{0}C. The weld joint design form is a square butt joint. By using this approach the higher the T_0, with the FSW parameter being kept constant, produce the higher the welding peak temperature and cooling rate, the smaller and smoother the metal grain structure in the weld nugget, TMAZ and HAZ, the higher the hardness of the weld nugget and the higher the tensile strength eventough welding defects in the form tunneling, kiss bond, and void are still observed.

KEYWORDS

friction stir welding, initial temperature (T_0), AA 6061, weld characteristics

1 INTRODUCTION

Aluminum alloy is a type of non-ferrous metal, widely used in the transportation industry such as aerospace, container, automotive and marine vessels because of its advantages in terms of strength, lightweight, fatigue resistance, and high corrosion resistance [Dusun 2014][Fratini 2009][Hassan 2003]. According to Wiryosumarto (2004), aluminum alloys have low fusion weldability because the specific heat and high heat conductivity of aluminum make it difficult to heat or melt only a small part of the welding area. In addition, the heat in fusion welding is generally high which can cause excessive deformation of the aluminum alloy and can cause heat cracking and embrittlement of the weld area. According to Mishra (2005), conventional fusion welding such as GTAW and GMAW is not recommended for welding aluminum alloys, due to the unavailability of suitable filler metal and prone to cracking due to differences in freezing due to chemical composition. This is corroborated by the statement [Biradar 2012] [Ericsson 2003], that fusion welding is difficult to apply to aluminum alloys, because it tends to produce defects such as porosity, cracks during solidification and brittleness of the weld area.

The solution to this problem is the method of joining aluminum alloys in solid-state conditions. Solid-state welding (SSW) is a welding process carried out below the melting point of the material to be welded. One method of SSW is friction stir welding (FSW), by utilizing the heat generated by friction between the rotating tool and the workpiece to be joined. This splicing occurs due to stirring of the interface area on the two sides of the workpiece which begins to soften. In friction stir welding there is no melting and solidification process, so there will be no shrinkage or hot cracking [Tang 1998]. Fiction welding has many advantages over fusion welding techniques, because the process temperature remains below the melting point of the material being welded, no gas shielding is required, low distortion and low residual stress [Cook 2002]. FSW is an energy efficient process. Which does not produce smoke, arc flash, or spatter. Because the metal joining process occurs without melting (solid-state process), the hydrogen diffusion is low to minimize the occurrence of hydrogen induced cracking. FSW is the most significant development in metal joining. FSW requires lower energy and can be applied to various types of joints such as butt joints, lap joints, T joints, and fillet joints [Mishra 2005].

In particular, FSW is suitable for joining metals that have low molten weldability, such as aluminum alloys. This is because the heat generated in the FSW process is concentrated and does not reach the melting point of the material to reduce the possibility of deformation. Several welding parameters that influence the FSW process are rotational speed (spindle speed), feed rate (transverse speed), the amount of tool pressure on the workpiece, the characteristics of the material to be joined, and the dimensions of the material. Friction welding is an interaction of a series of thermodynamic processes which is the accumulation of several parameters such as heat input, cooling rate, metal flow and deformation, recrystallization and integration of mechanical joints [Sakano 2001]. While the chemical composition of aluminum alloys in friction welding has an important role in determining weld properties [Ravikumar 2013].

In the FSW process, welding energy is used to raise the temperature of the metal from the initial state to the solid-state temperature (preheating). The melting temperature of aluminum A6061-T6 is around 660 ^{0}C [Surdia 2000]. The energy required in the FSW welding process is proportional to the sensible heat of the metal which is depend on of mass, heat capcitancy and temperature difference. FSW heat is obtained from the heat due to friction between the rotating tool and the workpiece and the pressure exerted by the tool on the workpiece. If the T0 of the material is increased, the sensible heat to change the solid material into a solid-state will certainly decrease. If the sensible heat required for the material to go to the solid-state decreases, the energy required in the FSW process should also be lower. However, if the FSW process parameters are kept constant and have reached the solid-state temperature while the initial temperature of the material is increased, excess heat will be generated which will result in excessive softening or even melting of the metal. Raising the room temperature above room temperature will accelerate the workpiece to reach a solid-state condition and reduce dT = ($T_{solid\ state}$ – T_0) which means it will reduce energy requirements in the friction stir welding process [Sugiarto 2021]. The heat generated by friction and plastic deformation that is too high can cause the weld joint to experience a thermal softening effect, which causes the HAZ strength to be lower than that of the base metal [Fratini 2009] [Peng 2018]. Increasing the T_0 of the material in the FSW process can reduce welding energy requirements and can affect the quality of the weld.

2 LITERATURE REVIEW

Friction welding is a metal joining process without melting (solid-state process). Solid-state welding is a welding process that produces coalescence at temperatures below the melting point of the base metal being joined. This process involves limited diffusion and deformation to produce joints between like and dissimilar metals [ASM 1995]. Friction welding has several advantages over fusion welding, such as the process is done mechanically so it does not require electrical energy or energy from gas combustion. Because the metal joining process occurs without melting (solid-state process), then the hydrogen diffusion becomes low to minimize the occurrence of hydrogen cracking (hydrogen induce cracking). And more importantly, this welding is effective for joining metals that have low weldabilities such as non-ferrous metals, non-ferrous alloys, sulfurized stainless steel type 416, martensitic stainless steels, and others.

Friction stir welding (FSW) is a friction welding method that utilizes heat generated by friction between a rotating tool and the workpiece to be joined. This joint occurs due to the stirring of the two sides of the workpiece (interface area) which has begun to soften. Tang (1998) explains that in friction stir welding there is no melting and solidification process, so there will be no shrinkage or hot cracking. According to Messler (2004), FSW is a friction welding technique, in which the object to be welded is held until heat is formed from the friction of the workpiece with a rotating tool and also from the pressure applied.

According to Bhate and Bhatwadekar (2016), friction stir welding is used for joining plastic materials in different ways. The rotating non-consumable tool holder is pressed against the material to be welded. In the center of the tool holder is a pin or probe. The joint will result from the joining of plastic materials due to the heat generated from the friction between the tool and the parts of the two materials that are in contact. The rotating tool holder will move along the joint line. One of the keys in FSW is the amount of heat created due to friction between the workpiece and the rotating tool. The heat generated must be high enough to soften the material so that it can be stirred by the pin. The optimal temperature produced in FSW welding is between 80-90% of the melting point of the material to be welded, so that welding defects can be minimized [Chao 2003].

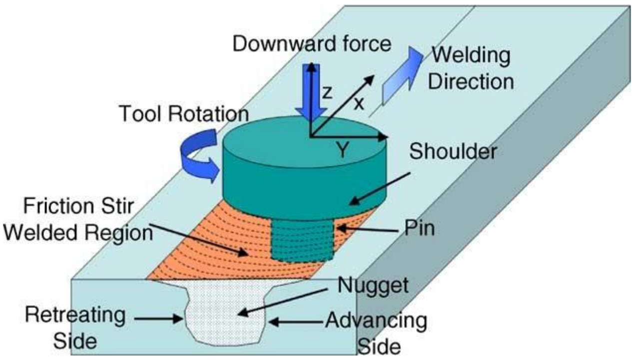


Figure 1. Friction Stir Welding Process [Mishra 2005]

The working principle of FSW consists of several stages, such as the preparation and installation of the welding tool (chisel) on the gripping shoulder. The tool used in this welding process is selected from a material with a higher melting point than the joint material where there are shoulders and pins. After the tool is mounted on the gripping shoulder, then give a steady rotation of the tool. The rotating tool is then placed in the area to be welded (weld line). The last stage is welding, this stage is carried out after there is sufficient heat to reach a temperature of around 0.8-0.9 Tc (melting point) of the base metal and then the tool or workpiece is moved to follow the welding line. The friction stir welding process can be seen in Figure 1 above.

In friction stir welding, the terms retreating side and advancing side are known. According to Colligan quoted by Terry (2005), the advancing side is an area where the movement of the material stirred by the tool is in the direction of the welding direction while the retreating side is the opposite. According to Mishra (2005) the movement of the tool will dredge and deform the advancing side area intensely and the material will be plastically deformed and then flow on the retreating side in the opposite direction.

According to Mishra (2005), the greatest heat in the friction stir welding process arises from surface friction between the shoulder and the workpiece. While the friction between the pin and the workpiece does not generate significant heat. Rajamanickan (2016) said that the heat input is also influenced by the coefficient of friction, compressive force, pin and shoulder diameter and rotational speed as follows:

$$Q = \frac{1}{2}\mu F_N \left(D_i + D_0\omega\right) \qquad (1)$$

Where :

Q = Heat input FSW (J/m)
μ = Coefficient of friction (Aluminium 0,47)
F_N = Compressive force (N)
Di = Pin diameter (m)
Do = Shoulder diameter (m)
ω = Rotational speed (radian/det)

From the above formula, it can be seen that the compressive force (F_N), pin diameter (D_i), shoulder diameter (D_o), and rotational speed of the spindle (ω) have a directly proportional relationship with the heat generated (Q). When the value of the compressive force, pin diameter, shoulder diameter, and rotational speed of the spindle is increased, it will cause an increase in the resulting calorific value and vice versa.

In the friction stir welding process, the energy required in the welding process is the energy used to raise the temperature of the metal to be joined so that there is a change from solid-state to solid-state. This welding heat will be able to raise the temperature of the metal from the initial condition (T_0) to the solid-state temperature ($T_{solid\ state}$). For the softening process to occur, pressure is added to the frictional area. The energy required in the FSW welding process is proportional to the sensible heat of the metal, namely E = m.Cp. dT with dT = ($T_{solid\ state} - T_0$). This energy is obtained from the heat due to friction between the rotating tool and the workpiece and the pressure exerted by the tool to the workpiece. Sensible heat to raise the temperature from the initial temperature to the solid-state temperature is formulated as follows:

$$E = mC_p dT \qquad (2)$$

Where:

E = Sensible heat (J)
m = Mass of material to be converted to solid state (kg)
C_p = The specific heat of the material to be joined (J/kg^{0}C)
dT = Welding temperature change = $T_{solid\ state} - T_0$ (^{0}C)

Meanwhile, in the FSW process itself, heat arises from the friction and pressure process during welding whose magnitude is proportional to the heat input times the welding length. So the energy balance in the FSW is:

$$QL = mC_p dT \tag{3}$$

or

$$Heatinput \times L = mC_p dT \tag{4}$$

and

$$\left[\frac{1}{2}\mu_k\, F_N\left(D_i + D_o\right)\omega\right] \times L = mC_p\left(T_{ss} - T_0\right) \tag{5}$$

Where :

L = Welding length (m)

To form a good welding joint results, it requires the sufficient energy in the welding process. The amount of heat input times the length of the weld must be proportional to the amount of energy required to convert the material into a solid state.

According to Mumin and Akata (2003), friction welding parameters that can be optimized to get good joint results include friction pressure, friction time, forging pressure, forging time, and rotational speed. Satyanarayana et al, (2005), stated that the quality of friction welding results can be improved by optimizing welding parameters, using interlayers, changing geometric shapes and treatment before or after the welding process.

According to Seli et al. (2010), the heat effect due to welding friction has reduced the hardness of the welded material compared to the base metal. Furthermore, according to the research results of Ambroziak (2014), that a long time and high welding temperature can cause the formation of an intermetallic phase which tends to cause joint brittleness. Furthermore, the alloying elements in aluminum alloys, especially magnesium, can worsen the metallurgical bond of aluminum, which will cause an acceleration of the formation of the intermetallic phase at the joint boundary, due to an increase in the diffusion coefficient.

Ravikumar et al. (2013), stated that the chemical composition of aluminum in friction welding has an important role in determining the properties of the weld. Based on the microstructure and thermal effects, FSW joints are usually divided into four zones: nugget zone (NZ), thermo-mechanical affected zone (TMAZ), heat affected zone (HAZ), and base metal (BM). According to Prasad et al. (2017), the microstructure in the weld zone and HAZ in the AA 6061-T6 friction welding joint has a uniform fine grain structure which makes the hardness and tensile strength higher than the base metal. However, if the heat generated by friction and plastic deformation is too high, it can cause the weld joint to experience a thermal softening effect, which causes the HAZ strength to be lower than BM [Fratini 2009] [Peng 2018]. Another study also showed that forced cooling is beneficial for increasing the mechanical strength of aluminum alloy FSW joints [Mofid 2012] [Sabari 2016] [Sinhmar 2017] [Zhang 2014]. Furthermore, according to Peng et al. (2019), the HAZ at the AA6061 joint is the weakest area and failure is common in this area during tensile tests. The tensile strength of the FSW joint becomes weak due to hardening which causes brittleness, precipitation damage and due to coarse grain caused by the increase in temperature during FSW.

Shukla and Shah, (2010), have connected AA6061 with copper using friction stir welding (FSW). The results showed that the tensile strength of AA 6061 aluminum connection joint with copper was low due to the presence of intermetallic compounds. Increasing the rotational speed decreases the tensile strength, because it increases the amount of intermetallic compounds formed between the aluminum-copper junction surfaces. While the higher hardness in the friction zone (stir zone) compared to the base metal due to the formation of hard and brittle compounds such as $CuAl_2$, CuAl, and Cu_9Al_4.

3 MATERIALS AND METHODS

This study uses a laboratory scale experimental method in the process of joining aluminum plate AA 6061 with a thickness of 6 mm using a friction stir welding (FSW) process. The FSW process uses a Universal Milling Machine and for measuring the welding temperature, a K-type thermocouple is used with a data logger and a computer for reading temperature data. T_0 is set using a heating plate affixed to the bottom of the workpiece. The shape of the welded joint is a square butt joint. The FSW process parameters are set at 921 rpm spindle rotation, 24 mm/min feed rate, 12 mm tool shoulder diameter, 6 mm pin diameter, 5 mm pin depth, and 0.2 mm depth of plunge. The initial temperature of the material (T_0) was varied by $T_{\text{room temperature}}$, 50 ^{0}C, 75 ^{0}C, 100 ^{0}C, and 125 ^{0}C. All parameters for welding are determined based on the experience during conducting the previous research which produce sound weld join.

The research installation of friction stir welding (FSW) AA 6061 is shown in the following figure.

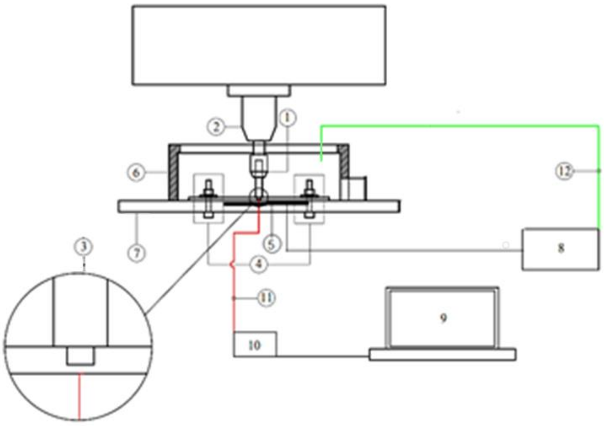


Figure 2. Friction Stir Welding Research Installation

Description :

1 = Tool gripper
2 = Spindle
3 = Welding tool
4 = Workpiece gripper
5 = Heater
6 = Insulator
7 = Milling table
8 = Regulator Circuit (T0)
9 = Laptop to record data from data logger
10 = Data logger
11 = Thermocouple for measure welding temperature
12 = Thermocouple for measure room temperature

Elements	Percentage	Elements	Percentage
Al	96.3 %	Mn	0.32%
Si	0.68%	Ni	0.029%
Mg	0.871%	Zn	0.091%
Cu	0.648%	Ga	0.077%
Ca	0.48%	Ba	0.05%
Ti	0.053%	Yb	0.03%
V	0.027%	Re	0.009%
Cr	0.288%	Os	0.02%

Table 1. Composition of AA6061

Aluminum with the main alloying elements Mg and Si is an aluminum alloy series 6, and more specifically known as AA 6061 aluminum which the composition is presented in Table 1. The values in Table 1 were obtained by testing the material using XRF spectrometry.

4 RESULTS AND DISCUSSIONS

From Figure 3, it is known that the increase in T0 while the friction welding parameters (spindle speed, feed rate, pin dimensions, and tool shoulder) is kept constant, is causing the peak welding temperature to increase. Welding with T_0 = 125 ^{0}C reaches the highest welding peak temperature, which is 376 ^{0}C. For T_0 = 100 ^{0}C the peak welding temperature is 311 ^{0}C. For variations of T_0 = 75 ^{0}C it reaches the peak welding temperature of 309 ^{0}C. For the variation of T_0 = 50 ^{0}C it reaches the welding peak temperature of 292 ^{0}C. As for the variation of T_0 = $T_{room\ temperature}$ (28 ^{0}C) the peak welding temperature is 278 ^{0}C. In other words, the higher the welding T_0 with the FSW parameter kept constant, the higher the welding peak temperature. This is because the heat of friction stir welding (FSW) is influenced by the friction and pressure that occurs between the pin and the workpiece which is equal to the heat input times the length of the weld or Heat Input x Lweld. This FSW welding heat should be equivalent to the sensible heat used to make the weld metal to a solid-state (just before melting) or Heat input x L_{weld} = m. Cp. dT. If the T_0 of the weld is increased, dT will decrease and the sensible heat will decrease, which means that the required Heat input x Lweld must also be decreased. However, if T_0 is increased while the Heat input x Lweld is constant, then the peak temperature of the FSW weld will certainly increase as well.

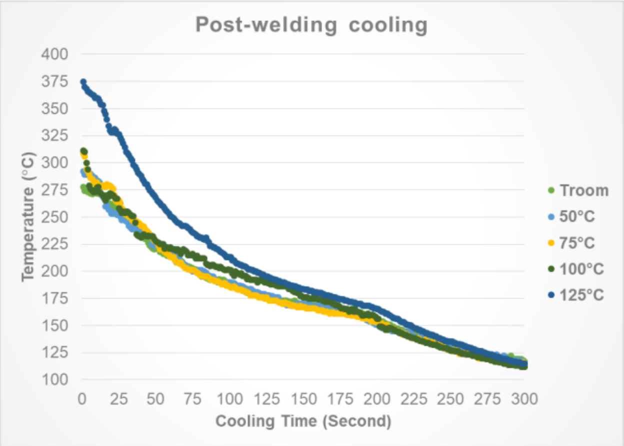
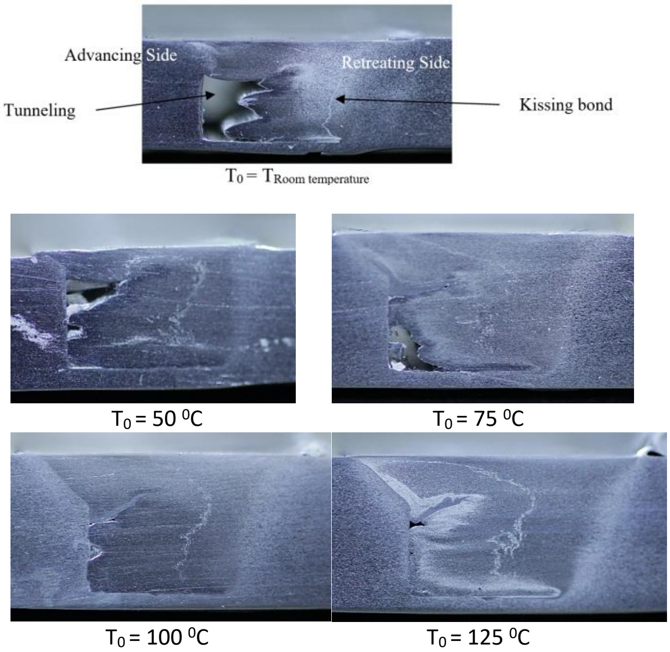


Figure 3. Graph of peak temperature and post-welding cooling rate of each variation of the initial welding temperature

Figure 3 also shows the effect of welding T_0 on the post-welding cooling rate. The higher the T_0 of welding, the higher the peak welding temperature and the faster post-welding cooling rate, which is indicated by the steeper cooling graph. The difference in post-welding cooling rate will have an impact on the microstructure and mechanical properties.

Figure 4 shows the FSW joint profile of AA 6061 Aluminum plate based on the difference in welding T_0. From the profile picture of the joint, it can be seen that there are defects in all the test specimens. In general, the defects that arise are incomplete connections joint or known as tunnel defects or wormholes which occured at advancing side (AS) of joint. Kissing bond also occured at retreating side (RS) which is caused by defficiency of both heat input and material flow.



$T_0 = T_{Room\ temperature}$

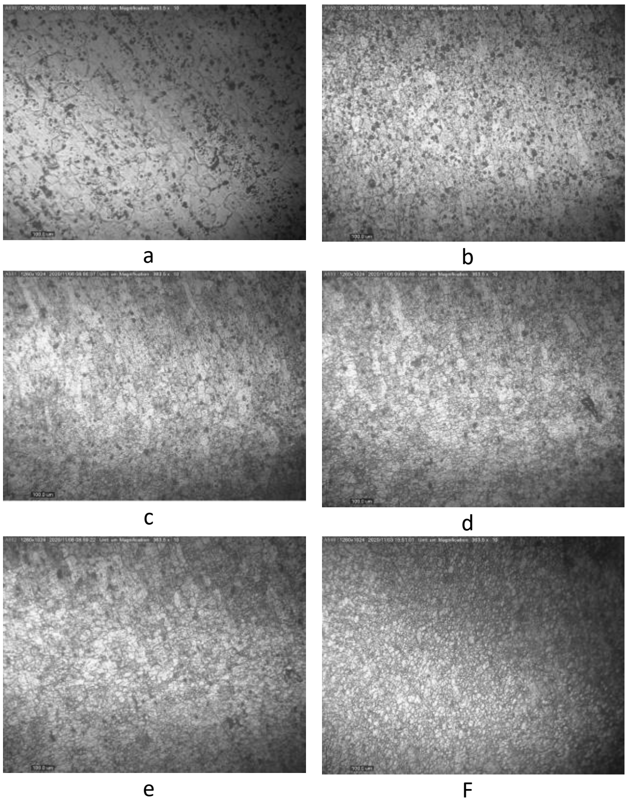
T_0 = 50 ^{0}C

T_0 = 75 ^{0}C

T_0 = 100 ^{0}C

T_0 = 125 ^{0}C

Figure 4. Macro photo of FSW welding results for each variation of the initial welding temperature



a

b

c

d

e

F

Figure 5. Microstructure Photograph (a) *Base Metal* Aluminium AA 6061, (b) *Weld Nugget* specimen with $T_{room\ temperature}$, (c) T_0 = 50^{0}C, (d) T_0 = 75^{0}C, (e) T_0 = 100 ^{0}C and (f) T_0 = 125^{0}C

These defects occur because the temperature generated during the welding process does not reach the optimal temperature in the joint or has not reached the solid-state condition so that insuffiecent material flow and poor mixing occur. If it is seen from the peak welding temperature data achieved, it appears that the largest defects are produced by welding with $T_0 = T_{room}$

$_{\text{temperature}}$ or without heating. While the least defects are produced in the specimen with T_0 = 125 ^{0}C. It can be said that the welding defects are reduced by providing preheat of 50 ^{0}C to 125 ^{0}C.

The highest welding peak temperature achieved by several variations of T_0 welding is 376 ^{0}C, which is produced by the specimen with T_0 = 125 ^{0}C. When compared with the melting temperature of Aluminum AA 6061 of 660 ^{0}C the highest temperature achieved is only 57% of the melting point of AA 6061. This shows that the main parameters used in the FSW process are spindle rotation speed of 921 rpm, feed rate of 24 mm/min, tool shoulder diameter of 12 mm, and pin diameter of 6 mm is still not able to produce the optimum temperature for sound joint. For this reason, the value of the FSW process parameter needs to be increase so that the welding heat input is higher and can produce the optimal welding temperature, for example 80-90% of the liquid temperature of AA 6061. Apart from temperature problem, using different desain of tool which offer better material flow and mixing may also give the better result.

Figure 5 shows the photos of the microstructure of A6061-T6 aluminum base metal and weld nuggets from the T_0 variation of the welding carried out. From the photo of the microstructure, it appears that the microstructure of the base metal has a flat, elongated grain structure that is characteristic of the microstructure of metal grains in the form of plates or strips due to continuous rolling during the plate and strip production process (Figure 5. a).

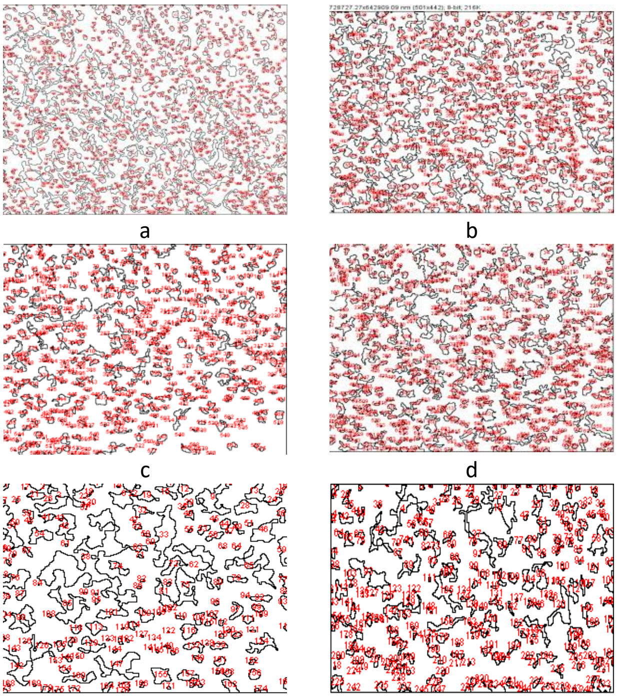
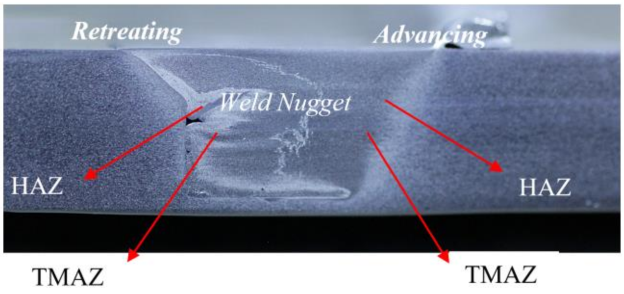
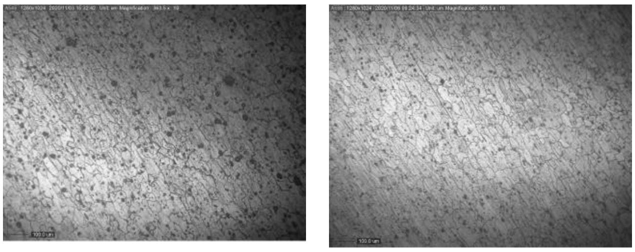


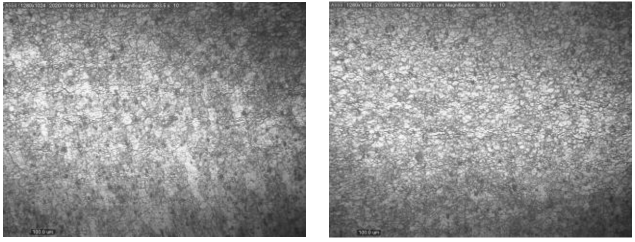
Figure 6. Grain size determination using ImageJ (a) *Base Metal* Aluminium AA 6061, (b) *Weld Nugget* specimen with $T_{\text{room temperature}}$, (c) T_0 = 50^{0}C, (d) T_0 = 75^{0}C, (e) T_0 = 100 ^{0}C and (f) T_0 = 125^{0}C

Meanwhile, the microstructure in Figures (b) to (f) shows the microstructure of the weld nugget from FSW welding with an increasing T_0 variation of welding from $T_{\text{room temperature}}$ to 125 ^{0}C. From the photo of the microstructure (b) to (f), it appears that the grain size is getting smaller or finer due to the increasing T_0 of welding from $T_{\text{room temperature}}$ to 125 ^{0}C. The smallest and finer grain structure of weld nuggets was produced by T_0 = 125 ^{0}C. This is related to the faster cooling rate due to the higher welding peak temperature as explained in Figure 2. The grain size average of join as depicted in Figure 5 from a to f are 193,406,661.4 nm^2, 172,307,920.9 nm^2, 88,485,161.47 nm^2, 128,631,474.6 nm^2, 228,243,195.2 nm^2, 93,029,286.12 nm^2 respectively. The grain sizes were acquired using Planimetry method using ImageJ as shown in Figure 6.





HAZ Retreating HAZ Advancing



TMAZ Retreating TMAZ Advancing

Figure 7. Photograph of the microstructure of the specimen welded area with T_0 = 125 ^{0}C

Figure 7 shows the presence of several welded areas, namely the heat affected zone (HAZ), the thermo-mechanically affected zone (TMAZ), and the weld nugget area. The weld nugget area is the area that is subjected to stirring and pressure by the pin and holder to form a small and fine grain structure as shown in Figure 5 (f). The thermo-mechanically affected zone (TMAZ), is the area affected by the heat of welding which causes the structure to be plastically deformed. The grain structure of TMAZ is also small as a result of the plastic deformation and recrystallization process during welding although it is not as fine as the grain structure of weld nuggets. The HAZ region undergoes thermal cycling but does not undergo plastic deformation and significant microstructural changes so that the grain structure is large, similar to that of the parent metal.

From Figure 7 it can also be seen that the grain structure formed on the advancing side is smaller and smoother than the microstructure of the retreating side area in both TMAZ and HAZ. This occurs due to the difference in heat generated on both sides of the workpiece. The heat generated on the advancing side is greater than the retreating side according to the explanation of Hamilton in his 2012 research results. From Hamilton's simulations using ANSYS, the results show that the advancing side is 5–10 K hotter than the retreating side as shown in Fig. 8.

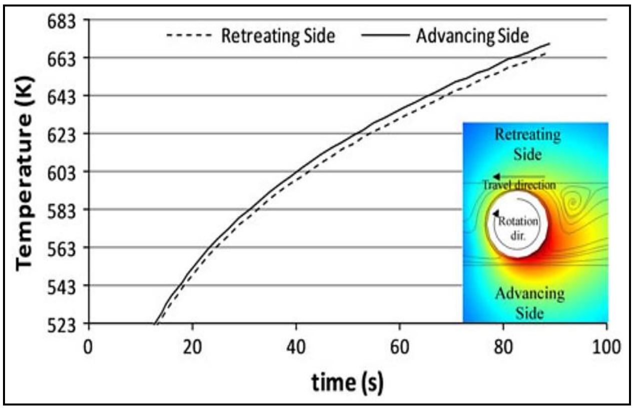


Figure 8. Temperature plotting of retreating side and advancing side of friction stir welded specimen

From Figure 8 Hamilton explains that with the transverse movement of the tool during the FSW process, the cooler material in front of the tool will flow towards the retreating side. Furthermore, the material that is rotated and heated by the tool is deposited behind the tool towards the advancing side. This material flow effectively increases the temperature on the advancing side.

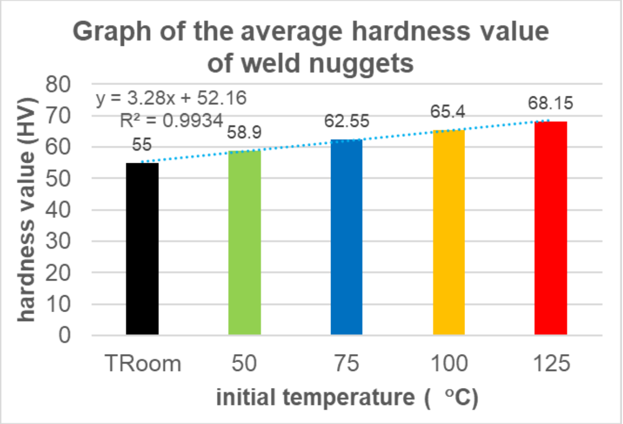


Figure 9. Graph of the average hardness value of weld nuggets AA 6061 FSW welding results based on T0 variation.

The graph of the hardness test results in the weld nugget area (welding center) is shown in Figure 8.

From Figure 9, it is known that the higher T_0 of FSW welding causes the average value of the hardness of the weld nugget area (welding center) to also be greater. Based on the explanation in Figure 3, it is known that the higher the welding T0 causes the temperature of the weld nugget area to be higher and the post-welding cooling rate to be faster which is indicated by a steeper cooling graph. The faster the cooling rate will produce a smaller grain structure (explanation of Figure 5) with a greater hardness value [Ravikumar 2013].

In this study, a tensile test was also carried out with the shape of the specimen following the ASTM E8 standard, the results are shown in Figure 10.

From the graph in Figure 9, it is known that the higher T_0 of FSW welding causes the average tensile strength of the AA 6061 aluminum FSW joint to increase. In the specimen with $T_0 = T_{\text{room temperature}}$ the tensile strength value is 38,066 MPa. Furthermore, based on an increase in welding 50 ^{0}C, 75 ^{0}C, 100 ^{0}C and 125 ^{0}C the tensile strength was 52,139 MPa, 55,8065 MPa, 59,180 MPa and 68,009 MPa which showed an increase. This is because the welding defects on the test specimens are getting smaller with the increase in welding T^0 as described in Figure 4. The larger the defects, the lower the tensile strength of the specimens. The larger the joint imperfections will reduce the area of the connected area, which means the smaller the resistance of the specimen to withstand tensile loads from the outside.

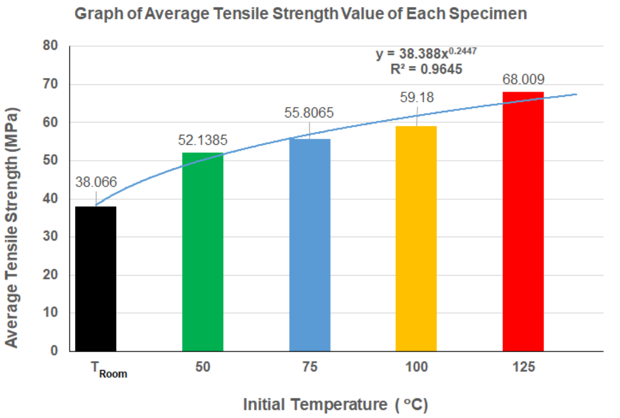


Figure 10. Graph of the average tensile strength of Friction Stir Welding Aluminum AA 6061 based on variations of T0

Meanwhile, based on the graph of the cooling rate, the microstructure of the weld nugget and TMAZ areas as well as the graph of the hardness of the weld nugget shows that the higher the welding T_0 causes the post-welding cooling rate to be faster, the grain structure formed is smaller and smoother and the value of the weld nugget hardness is higher. The higher the hardness value, the higher the tensile strength will be. So the higher the welding T_0 with the FSW welding parameter being kept constant, the higher the tensile strength of the weld, as long as the joint is still in a solid-state. However, the highest tensile strength resulting from this variation of T_0 welding is still far below the tensile strength of the base metal (12,6 kgf/mm^2 equivalent to 123,606 MPa), which is only about 55.02% of the tensile strength of the base metal. This is due to the achievement of the highest welding temperature which is only 57% of the molten temperature of aluminum AA 6061, which means the joint is not perfect. To overcome this problem, it can be done by increasing the welding parameter so that the FSW heat input increases and the welding temperature can reach the solid-state temperature or in the range of 80-90% of the molten temperature of AA 6061 aluminum.

5 CONCLUSIONS

From the results of the research on the joint of FSW joints on AA 6061 aluminum plates with a thickness of 6 mm with variations in welding T_0, it can be concluded that the higher the welding T_0 causes the welding peak temperature to increase and the post-welding cooling rate to be faster. From the profile picture of the weld area, it is known that in all specimens there are defects in the form of imperfect connections joint, known as tunnel defects or wormholes. The results of imperfect joints due to the welding temperature have not reached solid-state conditions, where the highest temperature has only reached 57% of the molten temperature of aluminum AA 6061. The higher the welding T_0 causes the post-welding cooling rate to be faster, the grain structure of the weld nugget area is getting smaller and smoother, the higher the hardness of the weld nugget and the greater the tensile strength of the joint. The highest tensile strength is only 55.02% of the strength of the base metal which indicates the connection joint is not perfect or the welding heat has not reached the solid-state condition.

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