ANALYSIS OF FRICTION STIR WELDING JOINTS ON HIGH DENSITY POLYETHYLENE (HDPE) DUE TO CHANGE IN MATERIAL TEMPERATURE AND SPINDLE ROTATION

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Friction stir welding (FSW) can be a solution in solving the problem of joining thermoplastic polymers which are difficult to do with fusion welding. Selection of the proper FSW connection parameters can produce optimal connection quality in HDPE material joints. In friction stir welding, the heat of welding is used to raise the temperature of the material from its initial state to the solid state temperature. If the material temperature (T_0) is increased above room temperature (T_{Room}), while the FSW welding parameter is constant, then at a certain increase in T_0 it will produce excess welding heat which results in excessive softening or even melting of the material being welded. Therefore, the material temperature setting (T_0) becomes an important parameter FSW The process of connecting the HDPE plates with friction stir welding was carried out by varying the material temperature (T_0) of T_{Room}, 50 ^{0}C, 75 ^{0}C and 100 ^{0}C. While the spindle rotation varies 2000 rpm and 2500 rpm. Other parameters controlled include the type of square butt joint, 5 mm HDPE plate thickness, 20 mm/min feed rate, 0.1 mm plunge depth, 20 mm tool shoulder diameter, 4.5 mm pin length and 6 mm pin diameter. The result is that the higher the spindle rotation and the material temperature during the welding process causes the FSW peak welding temperature to increase. The highest peak weld temperature was obtained at variations in material temperature (T_0) 100 °C with a spindle rotation of 2500 rpm, which is 123.2 °C or 94% of the melting temperature of HDPE. The hardness of the weld nugged area is still lower than the hardness of the base material. The highest average tensile strength of the research variations was achieved at a spindle rotation speed of 2500 rpm and a material temperature of 75 °C of 16.8 MPa, higher than the average tensile strength of the base material which is 15.1 MPa.

KEYWORDS

HDPE, Friction Stir Welding, Material Temperature, spindle speed

INTRODUCTION

High density polyethylene (HDPE) is a thermoplastic polymer which find application in certain area of engineering [Pirizadeh 2014]. The characteristic of thermoplastic polymers is that they are reversible to heat, so they are easily recycled by heating and reprinted. Polymer materials are widely used in manufactured products because of their light weight, high specific strength, high modulus of elasticity, high design flexibility, and low production costs [Abibe 2011]. The aeronautical industry pays great attention to the weight factor, and the use of thermoplastic materials really helps reduce the total weight of the structure and reduce fuel consumption [Mishra 2019]. The development of automotive products is currently leading to electric-engined vehicles. An important issue in electric vehicles is the weight of the vehicle to reduce electricity consumption. Therefore, polymer and polymer composite materials have an important role in the aircraft industry and electric car industry. The problem is that thermoplastic polymers have low fusion weldability because their melting temperature is low and they easily soften with increasing temperature.

Friction stir welding (FSW) is an alternative solution for joining thermoplastic polymers because in friction stir welding there is no melting and solidification process, so shrinkage or hot cracking will not occur [Tang 1998]. In general, Friction stir welding has many advantages over fusion welding techniques, because the process temperature remains below the melting point of the material being welded therefore low distortion and low residual stress can be achieved easily. Important FSW welding parameters include spindle rotation speed, feed rate (transverse speed), shoulder pressure, material characteristics, and pin and shoulder dimensions [Cook 2002].

In friction stir welding, the heat of welding is used to raise the temperature of the metal from its initial state to the solid state temperature [Dickerson 2005]. The energy (E) required in FSW welding is generated from friction between the tool and specimen which should be proportional to the sensible heat (Q) of the material being welded which give in Eq. 1 :

$$Q = m.c_p.dT \qquad (1)$$

where:

m = mass (kg)

cp = specific heat capacity (J/kg ^{0}C)

dT = change in temperature ($T_{solid\ state} - T_0$) (^{0}C)

If the material temperature (T_0) is increased, the sensible heat will decrease, so the required welding energy should also decrease. However, if the FSW energy remains constant, while T_o is increased far above T_{space}, excess welding heat will be generated which will result in excessive softening or even melting of the metal. Raising the metal temperature above room temperature will accelerate the workpiece to reach a solid state, which means it will reduce the energy requirements in the rotary friction welding process [Bhate 2016]. According to Fratini (2009) and Peng (2018), if the heat generated by friction and plastic deformation is too high it can cause the welded joint to experience a thermal softening effect, which causes the HAZ strength to be lower than that of the base material. Therefore, the material temperature setting becomes an important parameter in addition to other mechanical parameters such as spindle rotation speed, feed rate (transverse speed), shoulder pressure, material characteristics, and pin and shoulder dimensions. Thus, the increase in material temperature (T_0) can also affect the quality of the welding results so that it is interesting to.

LITERATURE REVIEW

Thermoplastic polymers are materials that will soften when heated to a certain temperature and when cooled again will return to their solid form. The characteristic of thermoplastic is that it is reversible to heat, so it is easy to recycle and reprint. Some popular thermoplastic materials include polyethylene (PE), polypropylene (PP), polystyrene (PS), and poly vinyl chloride (PVC) [Pascault 2002]. Thermoplastic polymers are widely used in the automotive industry [Bozkurt 2012] in order to reduce the total load on cars, and reduce carbon emissions. This material has good insulation and is resistant to chemical influences, therefore it is widely used in the piping and tank industry [Hoseinlaghab 2015]. Thermoplastic polymers are also used in the aeronautical industry for several types of components [Bakis 2002] [Kim 2010]. From several publications it is known that there are several thermoplastic polymers that can be welded with the FSW method, namely acrylonitrile butadiene styrene (ABS), polyamide 6 (PA6), high density polyethylene (HDPE), low density polyethylene (LDPE), polytetrafluoroethylene (PTFE), poly methyl mmethacrylate (PMMA), polycarbonate (PC), etc [Besharati Givi 2014].

According to Bhate (2016) friction stir welding is used for joining materials in different ways. A rotating non-consumable tool holder is pressed against the material to be welded. In the center of the tool holder there is a pin or probe. The joint will result from the joining of plastic materials due to the heat generated by the friction between the tool and the interface of the two materials in contact. The rotating tool holder will move along the weld 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 generated in FSW welding is between 80% -90% of the melting point of the material to be welded, so that welding defects can be minimized [Besharati-Givi 2014].

The working principle of FSW consists of several stages, such as preparing and installing the welding tool (chisel) on the chuck shoulder. The tool used in this welding process is selected material with a higher melting point than the connection material where there are shoulders and pins. After the tool is installed on the chuck shoulder, then give a constant rotation to the tool. The rotating tool is then placed in the area to be welded (weld line). The final stage is welding, this stage is carried out after sufficient heat has occurred 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 below.

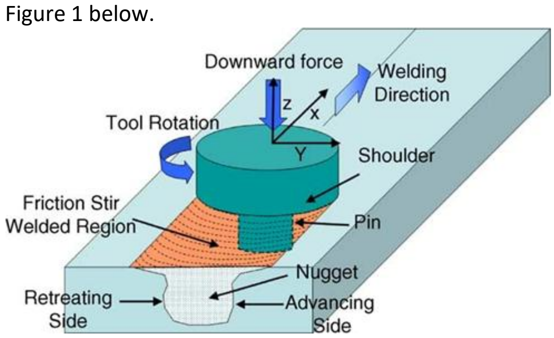

Figure 1. Friction Stir Welding Process [12]

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

According to Rajamanickan (2016), the heat input of FSW welding is influenced by the coefficient of friction, compressive force, pin and shoulder diameter and rotational speed as Eq. 2 as follows:

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

Where :

Q = Heat input FSW (J/m)

μ = Coefficient of friction (Aluminium 0,47)

FN = 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 relationship that is directly proportional to heat input (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 weld heat input and vice versa.

In the friction stir welding process, the energy required in the welding process is the heat required to raise the temperature of the material to be joined from the workpiece temperature (T_0) to the solid state temperature ($T_{solid\ state}$). The energy required in the FSW welding process is $E = \mu.Fn\ (D_i + D_o)\ \omega)\ x\ L$ which should be proportional to the metal's sensible heat, namely E = m.Cp. dT with dT = ($T_{solid\ state} - T_0$), with L = welding length (meters). In order to form good results of welding joints, the right energy is needed in the welding process. The amount of heat input multiplied by the length of the weld must be proportional to the amount of energy required to convert the material into a solid state.

According to Seli (2010), the heat effect due to welding friction has reduced the hardness of the material being welded compared to the base metal. Bozkurt (2012)] conducted research on welding HDPE plates with a thickness of 4 mm, with cylindrical pin and shoulder profiles with a pin diameter of 6 mm. The parameters varied were rotational speeds of 1500, 2100 and 3000 rpm, translation speeds of 45, 75 and 115 mm/min and welding angles of 10, 20 and 30. Optimal results were obtained at a welding speed of 3000 rpm, a translational speed of 115 mm/min, and a welding angle of 30, with a tensile strength of 19.4 Mpa with joint efficiency of 86.2% with base material tensile strength of 22.5 MPa. This study also concluded that the welding angle has the smallest effect on the welding parameters. Furthermore, Mishra (2019) also welded 6 mm thick HDPE plates using cylindrical pin and shoulder profiles with variations in speed of 500, 600 and 800 rpm and translation speeds of 10, 20 and 30 mm/min. The result is that the highest tensile strength is obtained at the combination of a rotational speed of 800 rpm with a translational speed of 10 mm/min, amounting to 14.63 MPa therefore achieving 44.34% joint efficiency with base material tensile strength of 33 MPa.

Based on the microstructure and thermal effects, FSW joints are usually divided into four zones: the nugget zone (NZ), the thermo-mechanical affected zone (TMAZ), the heat affected zone (HAZ), and the base material (PM) as shown in Fig. 2 for 7075Al-T651. According to Reddi Prasad (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 that of the parent metal (PM) [Fratini 2009] [Peng 2018]. Other studies also show that forced cooling is beneficial for increasing the mechanical strength of aluminum alloy FSW joints [Zhang 2014] [Sabari 2016] [Sinhmar 2017].

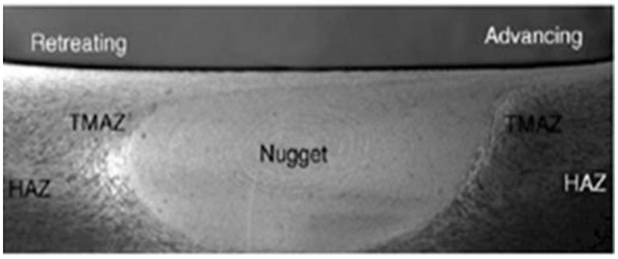

Figure 2. FSW Welding Zone : unaffected material or parent material; heat-affected zone (HAZ); thermomechanically affected zone (TMAZ and weld nuggets for 7075Al-T651 [Mishra 2005]

Hamilton (2012) explains that, as the transverse movement of the tool during the FSW process, the cooler material in front of the tool will flow towards the retreating side (RS). Furthermore, the material that is rotated and heated by the tool is deposited behind the tool towards the advancing side (AS). This material flow effectively increases the temperature on the advancing side (AS) as shown in Figure 3 below.

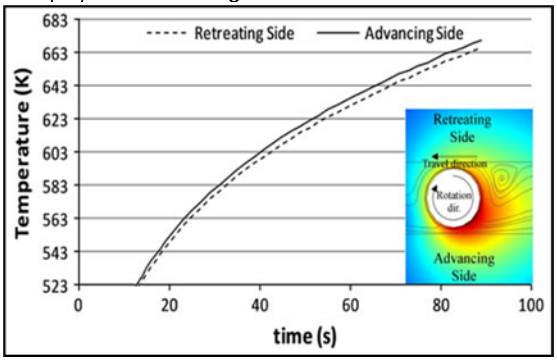

Figure 3. Temperature cpmparison of retreating and advancing sides during FSW [Hamilton 2012]

MATERIALS AND METHODS

This study used a laboratory-scale experimental method for the process of joining 5 mm thick HDPE, with properties is given in Tab. 1, plates using a 3A HAAS VF2 CNC machine. For the process of collecting welding temperature data, a work piece heating device and a thermo gun are used with temperature readings every 10 seconds for 50 seconds.

Properties	Value
Density	940 kg/m3
Melting point	130.8 C.
Temperature of crystallization	111.9 C.
Latent heat of fusion	178.6 kJ/kg.
Thermal conductivity	0.44 W/m.°C. at °C.
Specific heat capacity	1330 to 2400 J/kg-K
Specific heat (solid)	1.9 kJ/kg. °C.
Crystallinity	60%

Table 1. Characteristic of HDPE

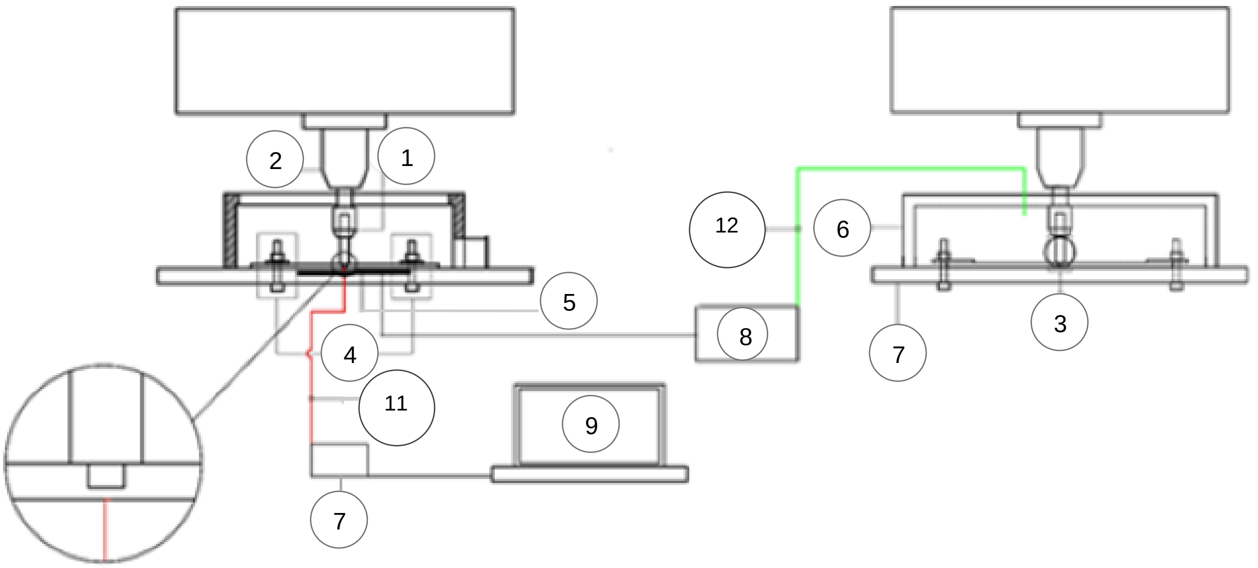

Figure 4 Friction Stir Welding Research Installation

Description:

1. Tool gripper
2. Spindle
3. Welding Tools
4. Workpiece gripper
5. Heater
6. Insulator
7. Milling Table
8. Regulator Circuit (T_0)
9. Laptop to record data from data logger
10. Data logger
11. Thermocouple for measure weld temperature
12. Thermocouple for measure ambient temperature

The independent variables in this study were the material temperature (T_o), which was varied by T_{Room}, 50 ^{0}C, 75 ^{0}C, 100 ^{0}C and the spindle speed was varied by 2000 rpm and 2500 rpm. The controlled variables included: 5 mm thick HDPE material, 20 mm/min square butt joint type, 20 mm/min feed rate, 0.1 mm plunge depth, 20 mm tool shoulder diameter, 4.5 mm pin length and 6 mm pin diameter. For each variation, one experimental runs has been used to weld two separately HDPE. The weld takes place along the gap between two specimens.

RESULTS AND DISCUSSIONS

The results of welding temperature measurements every 10 seconds are displayed in a graph as shown below.

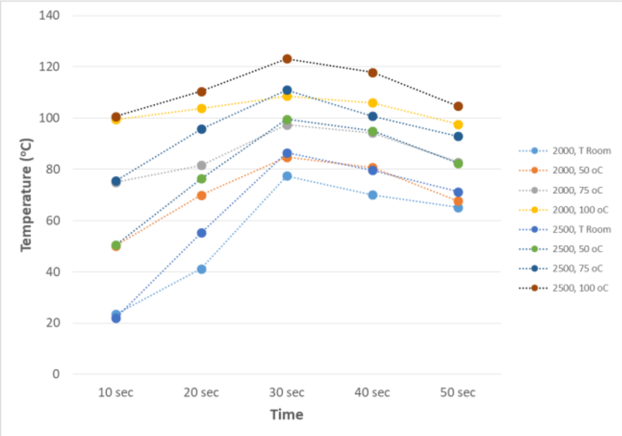

Figure 5. Graph of welding temperature measurement results

From Figure 5 it is known that the higher the material temperature and the higher the spindle rotation, the higher the welding temperature. This is due to the material temperature being higher than room temperature, while the friction welding parameters are kept constant, causing the welding heat that appears to be an accumulation of material heat plus heat due to friction between the material and the pin and shoulder. It appears that in general the variation in material temperature (T_0) of 100 °C with a spindle rotation of 2500 rpm produces the highest trend of welding temperature. The increase in welding temperature can be illustrated as follows: when the material temperature (T_0) is raised above room temperature, the material will receive sensible heat in proportion to E_2 = m Cp (T_0 – T_{space}). The heat required for the FSW welding process without heating is E_1 = m Cp ($T_{solid\ state}$ – T_{Room}) + Sholder and pin pressure energy which is proportional to E = µ.Fn (D_i + D_o) ω) L. If the material temperature is increased above the space, while the FSW parameter is constant, the FSW welding temperature becomes E3 = µ.Fn (D_i + D_o) ω)L + m Cp (T_0 – T_{Room}).

From the results of welding temperature measurements, the highest peak weld temperature was obtained at variations in material temperature (T_0) 100 °C with a spindle rotation of 2500 rpm, which is 123 °C. If seen from the data of HDPE liquid temperature of 130.8 °C and recrystallization temperature of 111.9 °C [Mark 2009], then the FSW welding process at variations in material temperature (T_0) of 100 °C and spindle rotation of 2500 rpm has produced a peak temperature The weld is above the recrystallization temperature and has not yet entered the liquid phase. At the peak welding temperature of 123.2 °C, it shows that the welding heat has reached 94% of the liquid temperature. The peak temperature of the weld at variations in material temperature (T_0) 75 °C and 2500 rpm spindle rotation is 111 °C or about 85% of the liquid temperature of HDPE and has reached its recrystallization temperature. Meanwhile, at variations in material temperature (T_0) of 100 °C and spindle rotation of 2000 rpm, the peak temperature of the weld is 108.6 °C or about 83% of the liquid temperature of HDPE. Furthermore, at variations in material temperature (T_0) 50 °C and 2500 rpm spindle rotation resulted in a peak welding temperature of 100.1 °C or about 76.5% of the liquid temperature of HDPE, which means that HDPE has not reached the recrystallization temperature of HDPE.

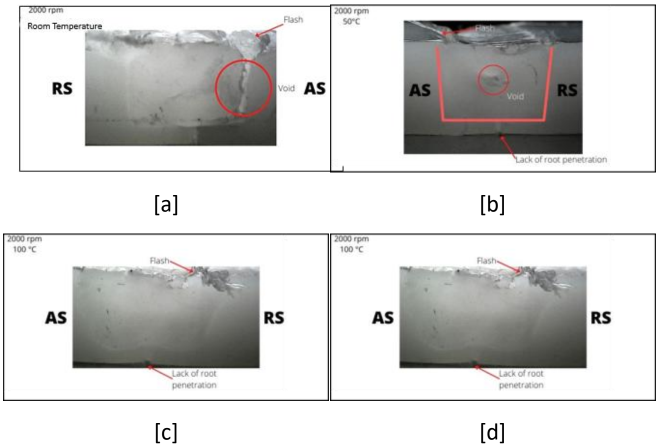

Figure 6. Connection morphology side view of 2000 rpm variations in material temperature [a] T_{Room}, [b] 50 °C, [c] 75 °C, [d] 100 °C

Figure 6 shows the cross-sectional morphology of the 2000 rpm spindle rotation variation. From this figure it is known that in Figure 6[a] TRoom there is an imperfect connection defect in the advancing side (AS) area and a flash defect at the top. In Figure 6[b] 50°C there are void defects on the weld nuggets and lack of root penetration at the bottom. Whereas in Figure 6[c] 75°C and 6[d] 100°C it appears that the joints are smoother and there are no defects in the weld nuggets. This shows that the material mixing process is going well because the material has softened so that the joint results are smoother.

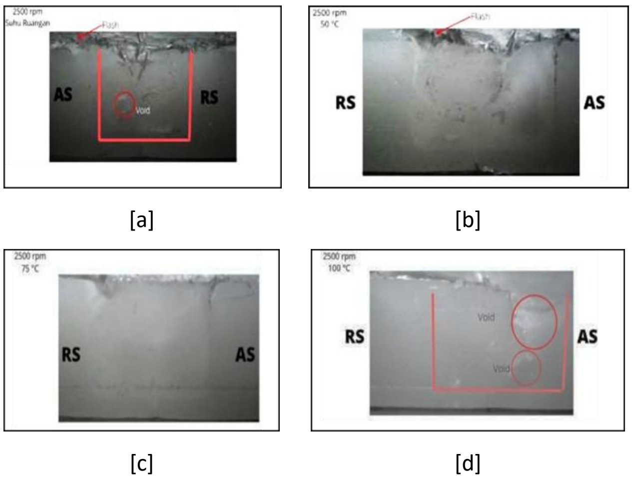

Figure 7. Connection morphology side view of 2500 rpm variations in material temperature [a] T_{Room}, [b] 50 °C, [c] 75 °C, [d] 100 °C

Figure 7 shows the morphology of the transverse joints at 2500 rpm spindle rotation variations. Figure 7[a] TRoom has void defects on the weld nugget and flash defects on the top surface, especially in the weld zone. Figure 7[b] 50°C there are imperfect joints on the weld nugget and flash defects on the joint surfaces. In Figure 7[c] 75 °C it can be seen that the weld nugget has a smooth grout structure and there are no defects in the joint area. Whereas in Figure 7[d] 100 °C it can be seen that there is an imperfect connection on the advancing side (AS) which is caused by the peak temperature of the weld reaching 94% of the liquid temperature of HDPE. This causes excessive softening of the weld nuggets so that the joints are not perfect.

Hardness testing was carried out on specimens with a variation of spindle rotation of 2500 rpm with a material temperature of 75°C and 100°C and base material, using the Brinell shore D test method with units of hs hardness values. Tests were carried out at the connection center, advancing side (AS) and retreating side (RS) and the results are shown in Tab. 2. For variation of 2500 rpm – 75⁰C, the hardest part is on centre while the softest one is at RS. Meanwhile for variation of 2500 rpm – 100⁰C, the similar pattern also exist. In general, the later variation give higher values of hardness.

Variations	Hardness (hs)		
	RS	Centre	AS
2500 rpm – 75⁰C	34	35	34,5
2500 rpm – 100⁰C	54	58	57
Base material	65		

Table 2. Hardness testing results of specimens

From these data it is known that the hardness of the weld nugged area is still lower than the hardness of the Base Material. This is due to the softening effect experienced by the material due to the welding process. Violence in the welding center is higher than the retreating side (RS) and advancing side (AS). Meanwhile, hardness in the advancing side (AS) is higher than in the retreating side (RS). According to Hamilton (2012) in Figure 3, that as the transverse movement of the tool during the FSW process, the cooler material in front of the tool will flow towards the retreating side (RS). Furthermore, the material that is rotated and heated by the tool is deposited behind the tool towards the advancing side (AS). This material flow effectively increases the temperature on the advancing side (AS) as shown below. The higher the advancing side (AS) peak temperature will cause the cooling rate to also be faster which results in higher hardness.

Tensile test data for HDPE plate FSW joints resulted in an average tensile strength of the base material of 15.1 MPa. Furthermore, the results of specimen testing based on variations in spindle rotation rate and material temperature are shown in Figure 8 below.

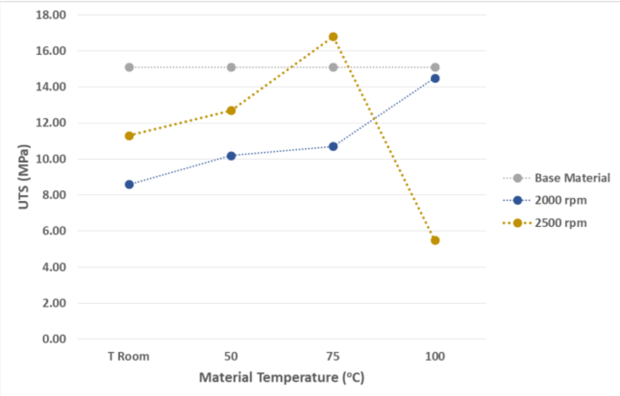

Figure 8. Tensile strength of weld join

From Figure 8, it appears that in general the tensile strength increases with increasing material temperature when welding FSW at both 2000 rpm and 2500 rpm. However, at 2500 rpm and a material temperature of 100 °C, the tensile strength of the FSW joint drops. This is because the peak temperature of the weld at this variation reaches 123.2 °C or 94% of the liquid temperature of HDPE so that the joint area experiences excessive softening. This is also supported by Figure 5(d), that is, in the advancing side (AS) area there are imperfect connections. This is what causes the low tensile strength. The highest average tensile strength of the research variations was achieved at a spindle rotation speed of 2500 rpm and a material temperature of 75 °C which was 16.8 MPa higher than the average tensile strength of the base material which was 15.1 MPa. The average tensile strength for variations in spindle rotation of 2000 rpm and material temperature of 100 °C is 14.59 MPa or slightly lower than the tensile strength of the base material.

This shows that the optimum parameters in this study were achieved at variations of spindle rotation of 2500 rpm and material temperature of 75 °C or variations of spindle rotation of 2000 rpm and material temperature of 100 °C. This is in accordance with the statement of Chao (2003), that the optimal temperature generated in FSW welding is between 80% -90% of the melting point of the material to be welded, so that welding defects can be minimized. In this study the peak FSW temperature achieved by the specimens with a variation of the spindle rotation of 2500 rpm and a material temperature of 75 °C was 111 °C or 85% of the melting point of HDPE. While the peak FSW temperature achieved by the specimen with a variation of the spindle rotation of 2000 rpm and a material temperature of 100 °C is 108.6 °C or 83% of the liquid temperature of HDPE. While the FSW peak temperature achieved at 2500 rpm spindle rotation and 100 °C material temperature is 123 °C or 94% of the HDPE liquid temperature, which means that the FSW peak temperature achieved is too high from the optimum temperature.

CONCLUSIONS

Based on data analysis and discussion of research results, it can be concluded that the higher the spindle rotation and the temperature of the material during the welding process causes the peak temperature of the FSW welding to increase.

From the results of welding temperature measurements, the highest peak weld temperature was obtained at variations in material temperature (T_0) 100 °C with a spindle rotation of 2500 rpm, which is 123.2 °C or 94% of the liquid temperature of HDPE. The peak welding temperature at material temperature variation (T_0) of 75 °C with a spindle rotation of 2500 rpm is 111 °C or about 85% of the liquid temperature of HDPE. While the peak temperature of the weld at variations in material temperature (T_0) of 100 °C with a spindle rotation of 2000 rpm is 108.6 °C or about 83% of the liquid temperature of HDPE.

Based on the morphological images of the joints at variations of spindle rotation of 2500 rpm and material temperature of 75 °C, it can be seen that the weld nuggets have a smooth mixed structure and there are no defects in the joint area. While the morphology of the connection at the variation of the spindle rotation of 2500 rpm and material temperature of 100 °C shows that there is an imperfection of the connection on the advancing side (AS) due to excessive softening.

The hardness of the weld nugged area is still lower than the hardness of the base material. In the center of the weld nugged hardness is higher than the retreating side (RS) and advancing side (AS). And the violence of the advancing side (AS) is higher than the retreating side (RS).

At 2500 rpm spindle rotation and 100 °C material temperature, the tensile strength of the FSW joint is low, namely 5.54 MPa. This is because the peak temperature of the weld at this variation reaches 123.2 °C or 94% of the liquid temperature of HDPE so that the joint area experiences excessive softening. The highest average tensile strength of the research variations was achieved at a spindle rotation speed of 2500 rpm and a material temperature of 75 °C of 16.8 MPa, higher than the average tensile strength of the base material which is 15.1 MPa. The average tensile strength for variations in spindle rotation of 2000 rpm and material temperature of 100 °C is

14.59 MPa or slightly lower than the tensile strength of the base material.

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REFERENCES

[Abibe 2011] A.B. Abibe, A.B., Amancio Filho, S.T., Dos Santos, J.F. and Hage Jr, E. Development And Analysis Of A New Joining Method For Polymer-Metal Hybrid Structures. Journal Of Thermoplastic Composite Materials, 2011, Vol 24, Issue 2, 233-249

[Bakis 2002] Bakis, C.E., Bank, L.C., Brown, V.L., Cosenza, E., Davalos, J.F., Lesko, J.J., Machida, A., Rizkalla, S.H. and Triantafillou, T.C. Fiber-Reinforced Polymer Composites for Construction, State-of-the-Art Review. Journal of Composites for Construction, 2002, Vol. 6, Issue. 2, 73-87

[Bathe 2016] Bhate, S.S., and Bhatwadekar, S.G., A Literature Review Of Research On Rotary Friction Welding, International Journal Of Innovative Technology And Research (IJITR), January 2016, Vol. 4, Issue No.1, 2601 – 2604.

[Besharati-Givi 2014] Besharati-Givi, M.K. and Asadi, P., Advances in friction-stir welding and processing. 1st edition, Sawston: Woodhead Publishing, 2014. ISBN: 9780857094551

[Bozkurt 2012] Bozkurt, Y. The optimization of friction stir welding pro-cess parameters to achieve maximum tensile strength in poly-ethylene sheets, Materials & Design, March 2012, Volume 35, 440-445

[Chao 2003] Chao, Y.J., Qi, X., and Tang, W. Heat Transfer in Friction Stir Welding-Experimental and Numerical Studies. ASME. J. Manuf. Sci. Eng. February 2003, Vol. 125, Issue 1, 138-145

[Cook 2002] Cook, G.E., Crawford, R., Clark, D.E., and Strauss, A.M. Robotic friction stir welding. Industrial Robot: An International Journal, 2002, Vol. 31, issue 1, 55-63

[Dickerson 2005] Dickerson, T., Friction Stir Welding. Cambridge: University of Cambridge, 2005.

[Fratini 2009] Fratini, L.; Buffa, G.; and Shivpuri, R., In-process heat treatments to improve FS-welded butt joints. Int. J. Adv. Manuf. Technol., 2009, 43, 664–670

[Hamilton 2012] Hamilton, C., Kopyscianski, M., Senkov, O., Dymek, S. A Coupled Thermal/Material Flow Model of Friction Stir Welding Applied to Sc-Modified Aluminum Alloys. Metallurgical And Materials Transactions A., April 2012, Vol. 44, Issue A, 1730-1740

[Hoseinlaghab 2015] Hoseinlaghab, S., Mirjavadi, S.S., Sadeghian, N., Jalili, I., Azarbarmas, M., and Besharati-Givi, M.K. Influences of welding parameters on the quality and creep properties of friction stir welded polyethylene plates. Materials and Design, 2015, Vol. 67, 369-378

[Kim 2010] Kim, W.S., Yun, I.H., Lee, J.J. and Jung, H.T. Evaluation of mechanical interlock effect on adhesion strength of polymer–metal interfaces using micro-patterned surface topography. International Journal of Adhesion and Adhesives, 2010, Volume 30, Issue 6, 408-417

[Mark 2009] Mark, J.E., Polymer Data Handbook. Oxford: Oxford University Press, 2005

[Mishra 2005] Mishra, R.S. and Ma, Z.Y., Friction Stir Welding and Processing. Materials Science and Engineering R, 2005, Vol. 50, 1-78

[Mishra 2014] Mishra R.S., De, P.S., Kumar, N. Friction Stir Welding And Processing. Heidelberg: Springer, 2014. ISBN: 978-3-319-07043-8

[Mishra 2019] Mishra, D., Sahu, S.K., Mahto, R.P., Pal, S.K., and Pal, K., Friction Stir Welding for Joining of Polymers. Singapore: Springer, 2019. ISBN: 978-981-13-0378-4

[Pascault 2002] Pascault, J.P., Sautereau, H., Verdu, J., and Williams, R.J.J. Thermosetting Polymers, Boca Raton: CRC Press, 2002. ISBN 9780429208072

[Peng 2018] Peng, G., Ma, Y., Hu, J., Jiang, W., Huan, Y., Chen, Z. and Zhang, T. Nanoindentation Hardness Distribution and Strain Field and Fracture Evolution in Dissimilar Friction Stir-Welded AA 6061-AA 5A06 Aluminum Alloy Joints. Adv. Mater. Sci. Eng., 2018, 1–11

[Pirizadeh 2014] Pirizadeh, M. et al. 2014, Friction Stir Welding of Thermoplastics Using a Newly Designed Tool, Materials and Design, 2014, Vol. 54, 342–347.

[Rajamanickan 2009] Rajamanickan, N. et al. Effect of Process Parameters on Thermal History and Mechanical Properties of Friction Stir Welds. Materials & Design, 2009, Vol 30, Issue 7, 2726-2731

[Reddi Prasad 2017] Reddi Prasad, K. And Sridhar, V.G. Experimental Investigation On Mechanical Characterization Of Aa6061-T6 Pipe Joints By Continuous Drive Friction Welding. International Journal of Mechanical Engineering and Technology (IJMET), 2017, Vol. 8, Issue 9, 264–273

[Sabari 2016] Sabari, S.S.; Malarvizhi, S.; and Balasubramanian, V. Influences of tool traverse speed on tensile properties of air cooled and water cooled friction stir welded AA2519-T87 aluminium alloy joints. J. Mater. Process. Technology, November 2016, Vol. 237, 286–300

[Seli 2010] Seli, H., Md. Ismail, A.I., Rachman, E., and Ahmad, Z.A. Mechanical evaluation and thermal modelling of friction welding of mild steel and alluminium. Journal of Materials Processing Technology, 2010, Vol. 210, Issue 9, 1209-1216.

[Sinhmar 2017] Sinhmar, S. and Dwivedi, D.K. Enhancement of mechanical properties and corrosion resistance of friction stir welded joint of AA2014 using water cooling. Mater. Sci. Eng., 2017, Vol. 684, 413–422

[Sugiarto 2021] Sugiarto, Ma'arif, M.S., Darmadi, D.B., Kido, M.I. Characteristic of friction welding weld joint of AA6061 on elevated environmental temperature, IOP Conf. Series: Materials Science and Engineering, Vol. 1034 No.1 012178, doi:10.1088/1757-899X/1034/1/012178.

[Tang 1998] Tang, W., Guo, X., McClure, J.C., Murr, L.E., and Nunes, A. Heat Input and Temperature Distribution in Friction Stir Welding. Journal of Materials Processing and Manufacturing Science, October 1998, Vol. 7, 163-172

[Zhang 2014] Zhang, Z. Xiao, B.L. and Ma, Z.Y. Influence of water cooling on microstructure and mechanical properties of friction stir welded Al-T6 joints. Mater. Sci. Eng., 2014, Volume 614, 6–15

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