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# Mechanical and microstructural characterization of single and double pass Aluminum AA6061 friction stir weld joints

**N H Othman[1], L H Shah[1], and M Ishak[1]**
[1]Manufacturing Focus Group, Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600, Pekan, Pahang, Malaysia

E-mail: nurul_hidayah213@yahoo.com

**Abstract.** This study focuses on the effect of single pass (SP), double sided pass (DSP) and normal double pass (NDP) method on friction stir welding of aluminum AA6061. Two pieces of AA6061 alloy with thickness of 6 mm were friction stir welded by using conventional milling machine. The rotational speeds that were used in this study were 800 rpm, 1000 rpm and 1200 rpm, respectively. The welding speed is fixed to 100 mm/min. Microstructure observation of welded area was studied by using optical microscope. Tensile test and Vickers hardness test were used to evaluate the mechanical properties of this specimen. Mechanical property analysis results indicate that at low rotational speeds, defects such as surface lack of fill and tunneling in the welded area can be observed. Vickers hardness of specimens however did not vary much when rotational speed is varied. Welded specimens using single pass method shows higher tensile strength and hardness value compared to both double pass methods up to 180.61 MPa. Moreover, DSP showed better tensile test and hardness test compared to NDP method. The optimum parameters were found to be single pass method with 1200 rpm of rotational speed. Therefore economically sound to only perform SP method to obtain maximum tensile strength for AA6061 FSW with thickness of 6 mm.

## 1. Introduction

Friction stir welding (FSW) is a welding process that involves solid state joining technique. FSW has expended rapidly since its development in 1991 by The Welding Institute (TWI), UK. This application can be found in a wide variety of industries such as automotive, aerospace, maritime and railway. This joining process has been regarded as one of the most significant joining process in recent years due to its many advantages like energy efficiency, environmental friendliness and versatility. As compared to conventional welding process, FSW requires less energy and uses no gas and flux that makes the process environmentally friendly. FSW joining process does not involve any use of filler metals and unlike fusion welding; any aluminum alloy can be joined without concern for the suitability of composition[1-8].

The FSW method that is commonly used in most research is single pass method (SP) where pin tool is inserted into the abutting edge of plate to be joined and transverse along the line of joint, passing only once. Several papers have suggested variations on this approach, namely the number of welding passes for a single joint. An alternative approach to this research is by using double sided pass (DSP) or multiple pass name normal double pass (NDP). Double sided pass (DSP) method is the process when a single pass process is made on both sides of the plate. On the other hand, multiple pass or normal double pass method (NDP) is a process where the pin passes along the same welding path twice or more. The illustrations of passes method are shown as figure 1.

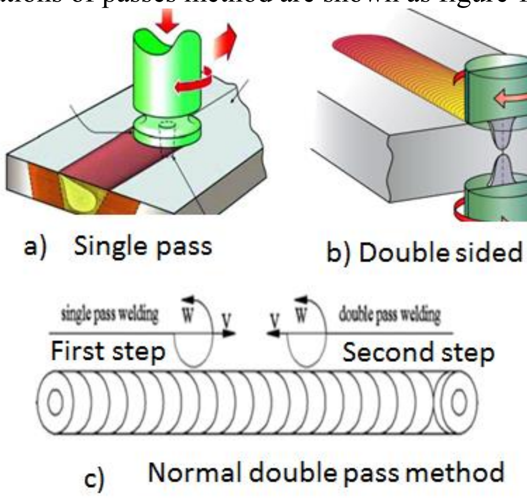


**Figure 1.** Welding passes method. a) Single pass, b) Double sided pass method and c) Normal double pass method [9, 10].

Several papers have reported the effect of double or multiple passes on aluminium alloy's mechanical property. Mehra (2012) conducted single and double sided FSW on AL19000 aluminium alloy and stated that higher ultimate tensile strength can be obtained from joints fabricated using double pass method [11]. This is also supported by a recent study by Sathari (2013) using AA1100 aluminium alloy, where the tensile strength have even doubled at a certain rotational speed [12]. In addition to that, Johannes and Mishra (2006) succeeded in creating a larger superplastic region of 7075 aluminium alloy after undergoing multiple FSW process, despite the single pass materials having the largest elongations [13]. Some researchers have even opt for utilizing multiple pass FSW method to improve the mechanical properties of die cast aluminium alloys such as ADC12 and A356 [14, 15]. However, Rebecca Brown (2009) contradicts the above claims and concluded that single pass have higher tensile strength compared to double and triple pass method when investigating multi-pass FSW on 7050-T7451 aluminium alloy [9].

## 2. Experimental method

The base material used in this study is AA6061 aluminium alloy plate with thickness of 6 mm. A pair of plate with dimensions of 100 mm × 50 mm were abutted and clamped rigidly at the backing plate for welding. Table 1 shows the chemical compositions of AA6061 alloy that was check using Foundry Mass Spectrometers machine.

**Table 1.** Chemical compositions of AA6061 (wt.%).

| Element | Al | Si + Fe | Mg | Cu | Mn | Cr | Other |
|---|---|---|---|---|---|---|---|
| AA6061 | 97.8 | 0.80 | 0.84 | 0.22 | 0.096 | 0.1 | 0.144 |

The FSW was carried out by using Milltronics Partner milling machine with square butt joint configuration of samples. The welding tool material is H13 steel with a normal cylindrical pin shape. The tool was processed by using a conventional lathe machine.

Table 2 presents the details of the welding parameters and tool dimensions used for the FSW. For both double passes, the specimen was cooled down after the first pass to ambient temperature before initiating the second pass to eliminate the effect of accumulative heating. For the DSP method, the plates were flipped over about an axis along the weld after the first pass was made, so that the two welding passes start at the same position along the joint interface, and the advancing side of the second pass was over the retreating side of the first pass weld. The tilt angle is kept constant at a $3^{\circ}$ angle.

Mechanical characterizations were conducted using tensile test and Vickers hardness test. The tensile test was prepared according to the ASTM-E8 standard. Figure 2 shows the dimension for tensile specimen. Micro hardness test was done by using Vickers hardness test with 200 gf load for 10 seconds. The results were recorded and analyzed accordingly. The microstructure of the weld specimens was observed using an optical microscope

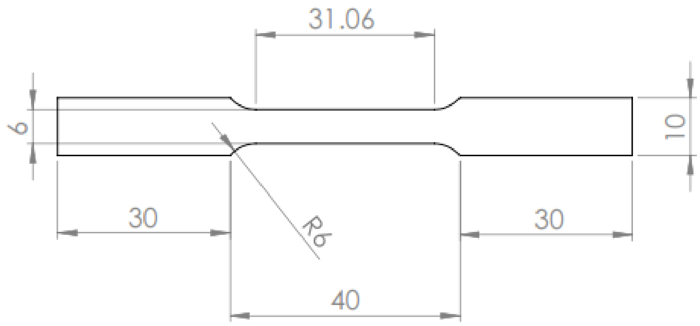


**Figure 2.** Tensile specimen dimensions.

**Table 2.** Welding parameters and tool dimensions for FSW.

| Process parameters | Values |
|---|---|
| Rotational speed(rpm) | 800, 1000, 1200 |
| Welding speed (mm/min) | 100 |
| D/d ratio of tool | 3.0 |
| Pin length, l (mm) | 5.5(single pass (SP), normal double pass (NDP)), 3.0(double sided pass (DSP)) |
| Tool shoulder diameter, D(mm) | 18 |
| Pin diameter, d(mm) | 6 |
| Holder diameter, a(mm) | 10 |
| Holder length, b(mm) | 20 |
| Shoulder length, c(mm) | 24 |

## 3. Result

### *3.1. Microstructure Analysis*

Figure 3 shows the cross section of the FSW joint of SP, NDP and DSP specimen, respectively. The microstructural image was taken by using an optical microscope with ×10 magnifications. The major FSW regions can be observed, namely the base metal (BM), heat affected zone (HAZ), thermo mechanically affected zone (TMAZ) and weld zone (WZ). The DSP specimen cannot be labeled with advancing or retreating side, since both sides experienced the advancing and retreating stir flow. The WZ and HAZ for this specimen show a larger region due to the double sided pass. Moreover, the TMAZ region can be seen in both upper and lower part of the figure 3.

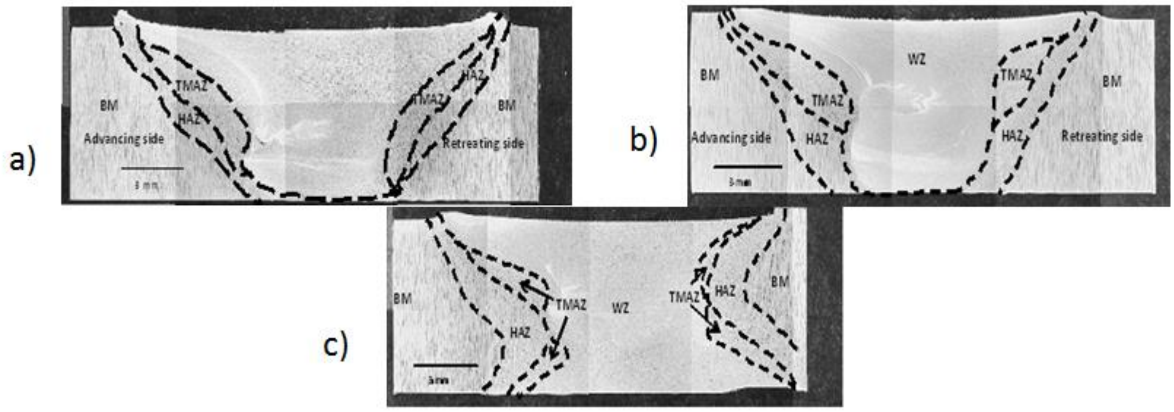


**Figure 3.** Cross section area for FSW joint. a) SP joint, b) NDP joint and c) DSP joint.

Figure 4, 5 and 6 show the grain structures of each FSW region for NDP and DSP, respectively. Figure 4(a), figure 5(a) and figure 6(a) shows similar elongated grain structure for BM that involved negligible heat input. Grain structures at the WZ for both groups (figure 4(b), 5(b) and figure 6(b)) show fully recrystallization, where the heat generated from the interaction of the pin tool deformed the grain boundaries [16]. In other words, the recrystallization nuclei can be created more easily at the high speed welding and it will get more refinement grain structure that lead to the higher tensile strength [10].

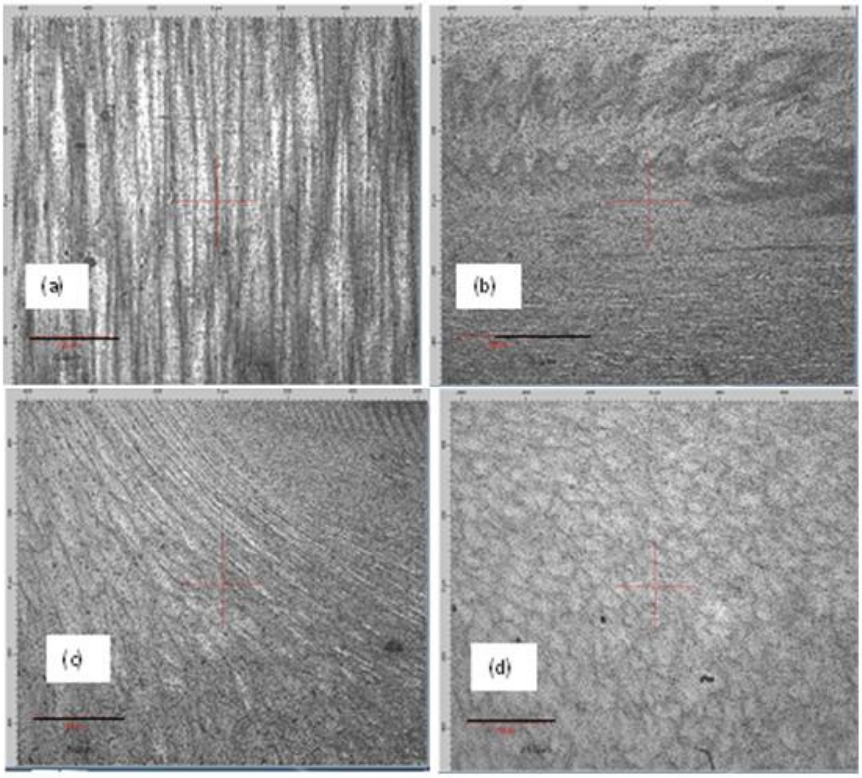


**Figure 4.** Microstructure for SP sample (a) BM, (b) WZ, (c) TMAZ and (d) HAZ.

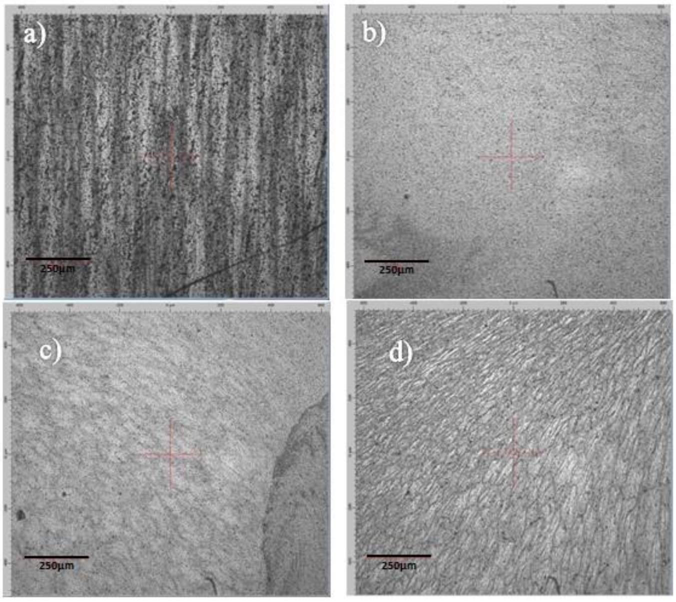


**Figure 5.** Microstructure for NDP sample (a) BM, (b) WZ, (c) TMAZ and (d) HAZ.

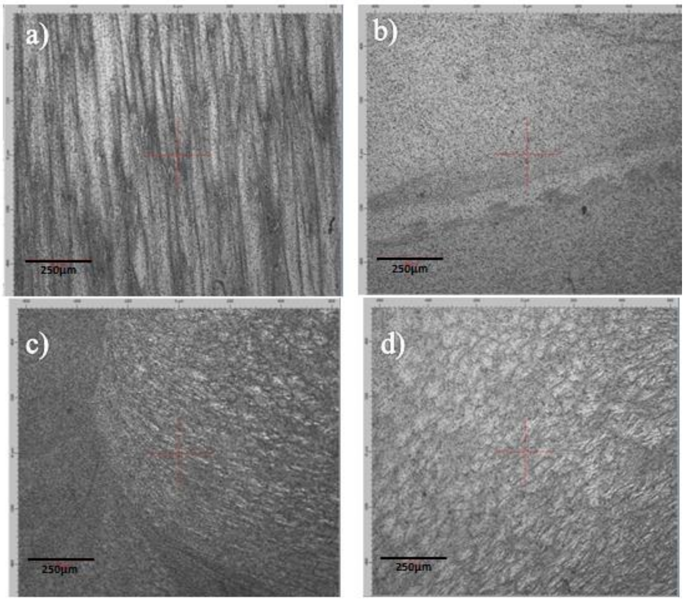


**Figure 6.** Microstructure for DSP sample (a) BM, (b) WZ, (c) TMAZ and (d) HAZ.

In the TMAZ, it can be observed that the grain size was slightly bigger than the weld nugget. Grain structure at TMAZ as shown in figure 5(c) and figure 6(c) have slightly changed in grain structure due to the heat input that is sufficiently heated to undergo deformation from its original grain boundaries. While TMAZ for figure 4(c) shows smaller grain size compare to others. TMAZ region undergo plastic deformation but recrystallization did not take place in this region due to inadequate deformation strain. Grain structure in figure 5(c) shows coarser grain structure compared to grain structure in figure 6(c).

In HAZ, the aluminum alloy experienced thermal cycle but only little plastic deformation occurred. It can be seen that the average grain size of SP result as shown in figure 4(d) give small grain size compare to other passes and HAZ for NDP (Figure 5(d)) slightly increased compared to DSP grain structure (Figure 6(d)). Grain size for NDP shows coarsening grain that will degrade the mechanical property. The increase in grain size consequently decreased the tensile strength [17].

### *3.2. Microhardness Evaluation*

Figure 7 shows the Vickers hardness profile of the cross section welded area for the SP, NDP and DSP method with distinctive welding regions. All groups showed relatively similar results, indicating that the welding methods have little affect the specimen's Vickers hardness. The based metal hardness for AA6061 is 70.5 HV. It can be seen from the figure that the hardness decreases from base metal to the HAZ region, followed by a slight increase at the WZ. The highest hardness at the WZ is 50.6 HZ from the SP group. The lowest value for SP, NDP and DSP is 39.3 HV, 40.8 HV and 35.5 HV, respectively. All the lowest values are typically located in the HAZ due to recrystallization. The HAZ regions have coarsening of the grain size due to the plastic deformation and fracture occur at HAZ region [18].

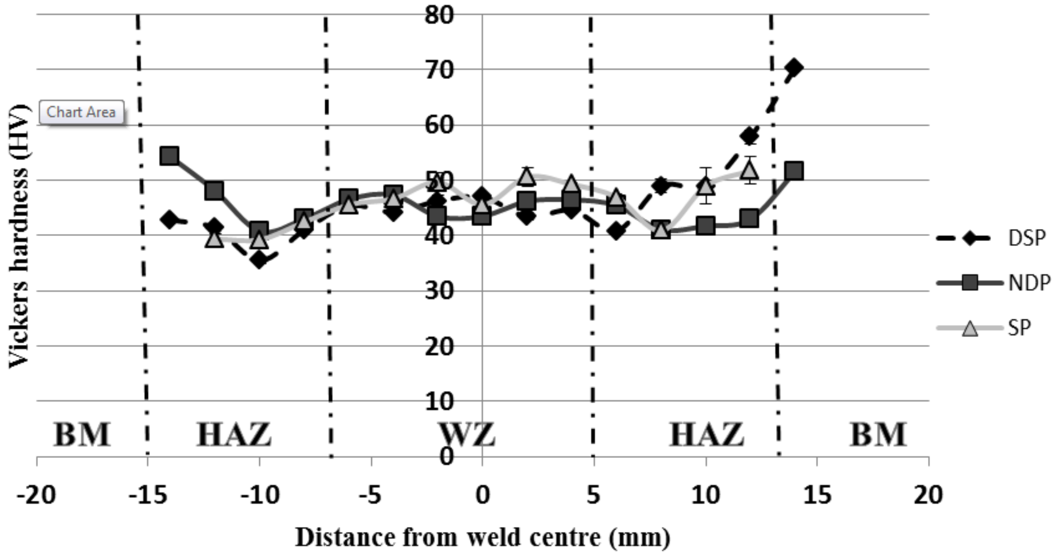


**Figure 7.** Vickers hardness profile for single pass (SP), normal double pass (NDP) and double sided pass (DSP) method.

### *3.3. Tensile Test*

Figure 8 shows the tensile test results for all the groups with varying rotational speed. All specimens fractured at the HAZ. The highest tensile strength is 180.61 MPa which occurred at rotational speed of 1200 rpm using the single pass method. The highest tensile strength for NDP and DSP is 164.37 MPa at 800 rpm and 166.13 MPa at 1000 rpm, respectively.

From the graph observation, it can be seen that SP collectively has higher tensile value compared to other groups due to the smaller grain size compare to other passes method. This finding is in line with a previous report that states that the tensile value will decrease slightly at the second pass, increasing again at the fourth pass [9].Furthermore, no conclusive pattern can be seen linking the rotational speed to tensile value, since each group yielded different results.

The DSP has a slightly higher tensile value compared to NDP. It is probably due to the DSP having both advancing and retreating side at either specimen sides, while NDP only have advancing or retreating at either side of the plate. Since it is proven from the results that SP method shows highest tensile strength compared to both double passes, it is therefore economically sound to only perform SP method to obtain maximum tensile strength for AA6061 FSW with thickness of 6 mm.

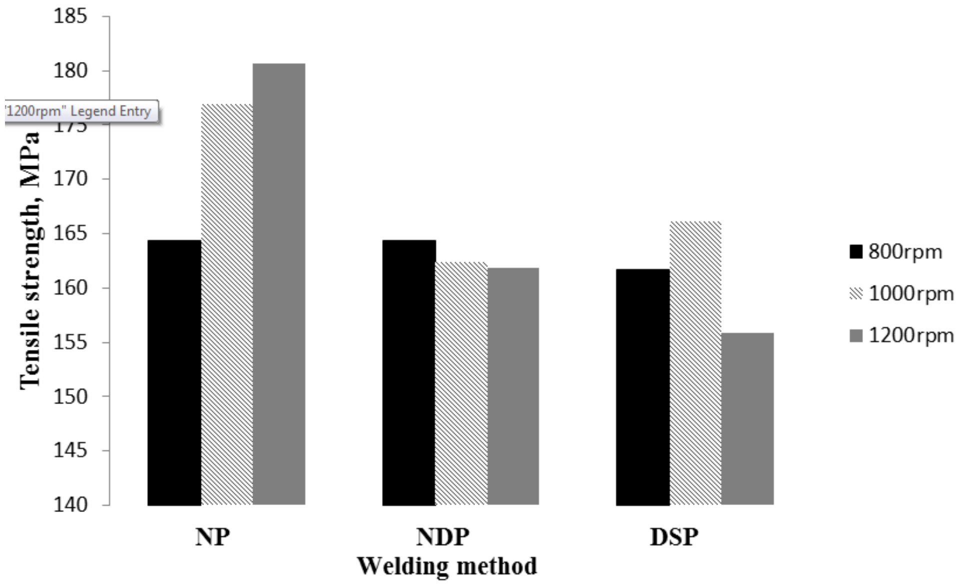


**Figure 8.** Tensile test results for group 1, group 2 and group 3.

## 4. Conclusion

6 mm thick aluminum 6061 plates were successfully welded by using friction stir welding process with varying welding method and rotational speed. The conclusions are as follows:
All specimens resulted in sound quality joints with minimal defects. The best weld appearance from single pass, normal double pass and double sided passes, is by using rotational speeds of 1000 rpm, 800 rpm and 800 rpm, respectively. The best weld appearance can be observed in lower rotational speeds. The specimen microstructure shows similar result for all groups. Fine grain size can be seen in WZ and TMAZ and coarser grain size can be seen in the HAZ. The WZ and HAZ for the double sided pass show a larger region due to the stirring of both sides. Moreover, a distinguished TMAZ region can be seen in both upper and lower part of the sample.

No distinct change can be seen from the Vickers hardness of all groups. The highest value of the WZ is 50.6 HV from the SP group. All groups show lowest value at the HAZ. The SP method yielded the highest tensile value of 180.61 MPa compared to NDP and DSP method with ultimate tensile values of 164.37 MPa and 166.13 MPa, respectively. No conclusive pattern can be observed from the tensile test results connecting the rotational speed and strength value.

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