Friction stir welding of aluminium alloy 6061-t651

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Abstract. One method of metal welding is a solid-state incorporation process, namely friction stir welding (FSW). This technique can be used on materials that are difficult to weld with fusion welding processes. Among the benefits of FSW are reducing distortion, eliminating solidification, saving energy and being environmentally friendly. This research investigates the effect of three different transverse speeds at 1.2, 2.4 and 3.6 (mm / s) on the hardness, tensile and micro structure properties of friction stir welds of AA6061-T651 plates. The research result find that the micro hardness and strength increase when the transverse speeds are increase. The micro structure showed that the grain size more smaller by increase the transverse speeds.

1. Introduction
Friction stir welding (FSW) is a solid-state joining process using frictional heat produced by a rotating cylindrical device and traversing with a profiled pin with a square butt weld connection. FSW was first developed in 1991 by The Welding Institute (TWI) in the UK, and since then, this method has accumulated a great deal of interest in a variety of applications in the automotive, aerospace, and construction industries. FSW can produce high-quality connections compared to other conventional welding processes, and it is also possible to join metals and non-metals, which are not considered to be welded by conventional methods [1]. This process is classified as a solid-state welding process which
means that the temperature of this process is below the melting point of the plates so that the plates remains solid state throughout the entire process [2].

This process can prevent many problems, namely compaction cracks, vacancies and porosity [3]. The advantages of solid-state FSW processes also include better mechanical properties, low residual stress and deformation, weight, and reduced defects [4]. Welding parameters such as rotational speed, transverse speed, tool geometry, strength and slope angle of the FSW device play a major role in mechanical properties [5]. Currently, the FSW study has mainly focused on joining Al alloy plate, which has the greatest demand in various industries compared to conventional welding processes [6, 7]. The interest in combining different steel or metal products, both simple and complex, is also greatly increased. In the friction stir welding process, a tool is in the form of cylindrical shoulder equipped with a rotating pin and immersed between two plates to be welded. The pin must be shorter than the thickness of the plate to be welded so that it does not hit the backing plate. Friction between the tool and the work piece causes heat and softens the surrounding material. With this soft condition, the welding tool can rotates and move so that the welding process occurs [8]. FSW micro-structure can be separated into 4 zones, namely stirring zone, TMAZ, HAZ and basic materials.

2. Material And Method

Milling machines are used to rotate and move FSW tools. The strength of the milling machine spindle is 5HP. FSW tools consist of two parts. The first part is the shoulder and the second part is the probe. The shoulder is used to produce heat with friction between the shoulder and the plates. The probe is used to make stirring action on the plates. The FSW probe is threaded, has a length of 5 mm, a diameter of 6 mm with a thread pitch. Shoulder diameter of 20 mm.

The material is Al6061-T651 where the composition of the chemical alloy can be seen in table 1. Al 6061-T651 plate with dimensions of 250mm x 60mm x 6mm. The mechanical properties of the as received material are ultimate tensile strength of 310 MPa, yield strength of 276 MPa and elongation level % 12 - 17.

| Table 1. Chemical Compositions of Al 6061-T651 Alloys in Weight Percent |
|-----------------|---|---|---|---|---|---|---|---|---|---|
| Element         | Al | Si | Cu | Mg | Fe | Mn | Zn | Cr | Ti | Others |
| Amount (Wt %)   | Balance | 0.4 - | 0.15 - | 0.8 - | Max | Max | Max | 0.04 - | Max | 0.05 |
|                 | 0.8 | 0.40 | 1.2 | 0.7 | 0.15 | 0.25 | 0.35 | 0.15 |

After preparing six plates of Al6061-T651, we took two of six plates and cleaned the plate with ethanol to remove the oxide on the surface of the plate, and then put two plates on the bed of the milling machine by adjusting the edges of the plates to meet and fix the plates with clamp tools to keep the plate in the same position during the FSW process. Than we set the position of the FSW device by adjusting the FSW tool on the contact line between the two plates and setting the parameters
namely transverse speed 1.2, 2.4 and 3.6 mm/s, rotational speed of 100 rpm and tilt angle of 2°. When finished arranging everything turned on the milling machine to make the FSW tool spin and press the FSW tool probe into the plate with a depth of 5.2 mm. Then moved the FSW tool along the connecting lines of two plates to make a weld line and joined plates as shown in figure 1. After the FSW process is complete we can see that the plates have been joined in to one piece as shown in figure 2.

After completed the FSW process, then prepared specimens for hardness and tensile testing by cutting the plates. Before hardness test, we grinding the specimens to remove surface roughness by pressing specimens on rotating sand paper numbers 120, 280, 400, 800, 1200, 2500 and 4000 to remove material from the specimen surface until the desired surface quality were achieved. The specimens polished by rubbing on a polishing disk with a 1 μm aluminum polishing solution. To etch the polished surface, chemical solutions are used to create contrast between micro-elements. The etching solution is Keller solution. First, put the specimen into the jar about 62 seconds, and cleaned the specimen with deionized water. Then clean the specimen again with an ultrasonic cleaner. After etching, use an optical microscope to see the micro-structure of the plates before hardness test. Start the hardness test using a hardness test machine with a preload of 200g (1.96N) and 10 seconds to make the indentation on the specimen. The Vickers hardness formula is shown in the following equation:

\[HV = 0.1891 \times \frac{F}{d^2}\]  

(1)

For the tensile test, prepare the specimens according to ASTM E8-08 standard. The specimen dimensions are shown in figure 3.

Performed a tensile test on the tensile testing machine by loading the specimen until the specimen was broken. Finally, measured the length of the center of the specimen piece to calculate the
longation with the formula: \[ e = \frac{1 - l_0}{l_0} \] \hspace{1cm} (2)

3. Results and Discussion

3.1. Hardness test

According to figure 4, the highest hardness in each weld was still in BM, followed by HAZ and NZ and the lowest hardness was in TMAZ. But if we look at the graph again, it is difficult to know and analyze the hardness test on each specimen, so we use average hardness to find out the hardness test results and which one is the hardest. We produce average hardness in the FSW shoulder tool diameter range from 10 mm to 10 mm. The average hardness values for specimens with 1.2, 2.4 and 3.6 mm/s transverse speeds are 70.98, 76.42 and 79.10 HV, respectively. We can see that the average hardness value increase with the increasing of transverse speeds [9], and it can be proven by the grain size of micro structure.

The result from hardness test of the specimen is shown in figure 4.

![Hardness distribution at different transverse speeds](image)

**Figure 4.** Hardness distribution at different transverse speeds

3.2. Micro-structure

After finish etching, we can investigate the micro-structure of the specimen using an optical microscope. Figure 5 shows the division of positions from each zone in the micro-structure of materials, namely BM, HAZ, TMAZ, and NZ. When viewed in micro-structure image with a transverse speed of 1.2 mm/s, it is clear the difference from the HAZ with other zones, where the HAZ
structure looks darker and rough. This is due to the low transverse speed resulting in longer heat input. The micro-structure of the weld with transverse speed of 3.6 mm/s reveals finer grains and less darker followed by weld with a transverse speed of 2.4 and 1.2 mm/s. If the grain size is finer, the hardness and strength of the weld will be higher. Figure 6 shows clear difference between NZ, TMAZ, HAZ in welds with a transverse speed of 1.2 mm/s. In the NZ zone, the traces of stir pin are clear to be revealed. In TMAZ, the grain is finer and brighter. In the HAZ the grain looks darker and coarser.

![Figure 5. Macro structure of three different FSW transverse speeds](image1)

![Figure 6. Micro-structure of flow arm at stir zone for transverse speed 1.2 mm/s](image2)

Micro-structure of stirring zones for different transverse speeds with magnification 50x (figure 7).
3.3. Tensile test

The result of the tensile test is shown in the table 2.

| Transverse Speed (mm/s) | Tensile Load (N) | Ultimate Tensile Strength (MPa) | Yield Strength (MPa) | Elongation (%) | Breaking Position |
|-------------------------|-----------------|---------------------------------|----------------------|---------------|------------------|
| 1.2                     | 4526            | 63.036                          | 59.218               | 15.63%        | HAZ              |
| 2.4                     | 5013            | 69.444                          | 65.588               | 18.75%        | HAZ              |
| 3.6                     | 5055            | 70.030                          | 66.140               | 20.31%        | HAZ              |

After obtaining the results of each tensile properties as shown in table 2, the graph can be made as shown in Figure 8. The breaking position is shown in figure 9.

From figure 9 it can be seen that the highest ultimate tensile strength at transverse speeds 3.6 mm/s followed by 2.4 mm/s and 1.2 mm/s. Similar to ultimate tensile strength, the highest yield strength is also found at the transverse speed 3.6 and the lowest at 1.2 mm/s. The strengths are inversely proportional to the elongation, where the longest elongation occurred at transverse speed 3.6
mm/s and the smallest occurred at 1.2 mm/s.

Figure 9. The fractured specimen

4. Conclusion

1. Increasing transverse speed will increase the average hardness and tensile properties.
2. Increasing transverse speed will decrease the grain size microstructure of specimens.
3. It means that the effect of FSW will improve better the properties of Al 6061-T651.

5. References

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