Study on the Influence of Tool Rotating Speed on the Weld Joint Strength of Friction Stir Welding Method

Sarjito Joko Sisworo and Ahmad Fauzan Zakki
Department of Naval Architecture, Diponegoro University, Semrang, Indonesia

Keywords: Aluminum 6061, Friction Stir Welding, RPM Speed, Tensile, Impact, Micrographic Test.

Abstract: Aluminum 6061 is a lightweight metal and has a corrosion resistance and good conductivity. In the marine industry, aluminum 6061 is widely used for ship construction. Friction Stir Welding (FSW) uses the principle of utilizing friction from a rotating work piece with another stationary work piece so that it is able to melt the stationary work piece and finally connect it together. The focused of this study is to determine the impact strength, tensile strength and micrographic structure of the butt joint of FSW Welding. The feed rate is determined as 10 mm / min with the variations of rpm speed is defined as 1640 rpm, 2620 rpm, and 3820 rpm. Tensile strength, impact strength and micrographic evaluation will be discussed to assess the effect of rotational speed on the strength of the welded joint produced by Friction Stir Welding.

1 INTRODUCTION

In the era of modern technology, humans are required to create an effective and efficient progress and development that can give benefits to the society in all of fields. One of the fields is the field of marine and shipbuilding industry. Technological developments in the shipbuilding industry are the use of various types of materials such as steel, aluminum, fiberglass, etc. All of the types of materials have advantages and disadvantages. One type of material that has good strength against corrosion is aluminum.

Aluminum is a metal that has relatively low strength and soft. Aluminum is a lightweight metal and has good corrosion resistance, good electrical conductivity and other properties. Generally aluminum is mixed with other metals to form aluminum alloys. Aluminum 6061 is a kind of aluminum alloy between magnesium and silicon that has good mechanical properties without reducing electrical conductivity. In the marine industry, aluminum is widely used for construction in piping and tank sections such as fresh water tanks or fuel tanks. Aluminum is a metal that has mechanical properties that are resistant to corrosion and relatively good electrical conductivity. This metal is widely used not only for household appliances, but also for aircraft, automotive, marine and building construction materials, (Surdia et. al., 1999).

FSW (Friction Stir Welding) is a welding method that was discovered and developed by Wayne Thomas for aluminum and aluminum alloy work pieces in 1991 at TWI (The Welding Institute) in the United States (Nandan et. al., 2009). The working principle of FSW is to utilize the friction of a rotating work piece with another stationary work piece so that it is able to melt the stationary work piece and finally connect it together. The welding process with FSW occurs in solid conditions (Solid State Joining). The welding process with FSW occurs at the temperature of the solvus, so there is no decrease in strength due to over aging and the dissolution of coherent deposits. Since the welding temperature is not too high, the residual stresses and the distortion that are formed due to heat are also low (ASM, 2007). The mechanical characteristics of the weld joint in the FSW are determined by the parameters: welding speed, tool rotation, and tool pressure (Jayamaran et. al., 2009).

The application of FSW technique to support the manufacture of marine structures and shipbuilding also can be found in (Maggiolino, 2008; Feistauer, 2014; Farajkhah, 2016; Singh, 2019; Ramesh, 2020).

Previous studies have conducted a study on the effect of rotating tools on micro structures and mechanical properties of friction stir welding

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connections on aluminum alloy 6061 (Wartono et. al., 2015) where in that study using tools rotation speed: 540 rpm, 910 rpm, and 1500 rpm. Tensile test results showed that the average ultimate strength for welding using 540 rpm tool speed was 139 MPa, for 910 rpm tool speed was 157 MPa and at 1500 rpm tool speed was 155 MPa. With these results it can be seen that the highest ultimate strength is to use the 910 rpm tool rotation. Furthermore, in case of the impact strength behaviour, the weld joint impact strength at 540 rpm has magnitude of 0.594 (J/mm^2), for a speed of 910 rpm it has an impact strength of 0.624 (J/mm^2), and at a speed of 1500 rpm has an impact strength of 0.573 (J/mm^2).

In this study a similar study was made, however the rotational speed was significantly increased by: 1640 rpm, 2620 rpm, and 3820 rpm. The experimental studies was conducted to assess the strength of the connection consist of tensile test, impact test and micrographic test.

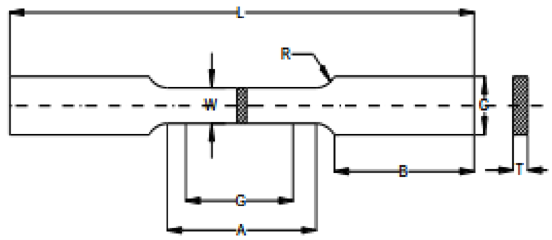
2 PREPARATION AND TESTING METHOD OF THE WELD JOINT

The Aluminum 6061 was produced by the local steel industry that was used in the ship production process with the thickness 10 mm. The material properties of the Aluminum 6061 can be seen in the Table 1.

Table 1: Mechanical properties of Aluminum 6061.

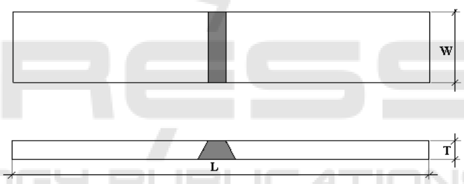
Aluminum 6061	
Poisson's Ratio	0,33
Modulus Of Elasticity	68,9 GPa
Density	2700 kg/m^3
Yield stress	276 MPa
Fatigue Strength	633 MPa
Failure Strain	0,39
Tensile Strength	324 MPa

The specimens are made for the purposes of tensile testing, impact testing and micrographic testing. In making specimens for test experiments not used the standard ASTM E8 / E8M-09. Illustration of dimensions and shape of tensile test specimens can be seen in Fig. 1. In impact test experiments, specimen preparation is carried out using the ASTM E23 standard. Illustration of dimensions and shape of the impact test specimens can be seen in Fig 2. The existing welded joints on the specimens were made using the friction stir welding method with the rotating pin tool with variations in the pin tool speed of 1640 rpm, 2620 rpm, and 3820 rpm. Illustration of pin tool dimensions can be seen in Fig. 3. The numbers of specimens in the tensile test and impact test are 3 specimens, while for the micrographic test are 1 specimen.



Gage length (G) : 50.0 mm
Length of reduced section (A) : 57 mm
Width (W) : 12.5 mm
Thickness (T) : 10 mm
Radius of fillet (R) : 12.5 mm
Overall length (L) : 200 mm
Width of grip section (C) : 20 mm
Length of grip section (B) : 50 mm

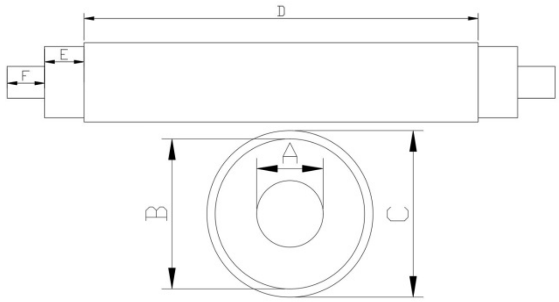
Figure 1: Tensile test specimen (ASTM E8/E8M-09).



Overall length (L) : 55 mm
Width (W) : 10 mm
Thickness (T) : 10 mm
Notched Charpy : 45°

Figure 2: Impact test specimen (ASTM E23).

The weld joint specimens were prepared by friction stir welding method. The universal milling machine was used to create the weld joint. Rotational speed of universal milling machine can be arranged with the maximum rotational speed of 4000 rpm. In this study the rotational speed was determined on 1640 rpm, 2620 rpm, and 3820 rpm. The universal milling machine has been equipped with an automatic moving table. Therefore the friction stir welding process can be accomplished with the steady travel speed. The travel speed of the rotating tool of the welding process was determined as 30 mm/min. The rotating pin tool has the main function to generate the heat and to mix the work piece material. Therefore the material of the rotating tool should have a higher melting point compare with the weld material. The K-110 KNL EXTRA steel was selected as the material of the rotating tool.



Material of Pin : KNL 110 Extra
Hardness : 61 HRC
Diameter of Pin (A) : 8 mm
Diameter of Probe (B) : 18 mm
Diameter of Tools (C) : 20 mm
Length of Tools (D) : 70 mm
Length of Probe (E) : 10 mm
Length of Pin (F) : 9.5 mm

Figure 3: Illustration of the rotating pin tool design.

3 RESULTS AND DISCUSSIONS

3.1 Tensile Strength Test Results

From the tests that have been done, the results obtained in Table 2, tensile testing show that the value of the maximum tensile strength resulting from the FSW (Friction Stir Welding) welding carried out in this research is 88.13 MPa at a speed of 1640 rpm (specimen 2), and the result of the smallest tensile strength is 16.80 MPa at a speed of 2620 rpm (specimen 3).

Table 2: Tensile stress of Aluminum 6061.

Specimen	Thick. (mm)	Width (mm)	Area (mm^2)	P Max (N)	σ Max (MPa)	σ aver. (MPa)
X1	10.09	12.76	128.75	10630	82.56	
X2	10.08	12.72	128.22	11300	88.13	83.34
X3	10.10	12.93	130.59	10360	79.33	
Y1	10.55	12.57	132.61	2750	20.74	
Y2	10.58	12.30	130.13	2640	20.29	19.27
Y3	10.35	12.94	133.93	2250	16.80	
Z1	10.26	12.82	131.53	7440	56.56	
Z2	10.36	12.97	134.37	4970	36.99	45.02
Z3	10.38	13.02	135.15	5610	41.51	

The average magnitude of the tensile strength of the aluminum 6061 weld joint using FSW (Friction Stir Welding) welding with variations in the tool rotation speed carried out in this research was 83.34 MPa at 1640 rpm, 45.02 MPa at 3820 rpm, and 19.27 MPa at 2620 rpm. Before the tensile test is carried out, a visual inspection of the welding surface is carried out first, and the speed of 2620 rpm has the worst weld results. There are worm holes after welding is the main reason that reduces the tensile strength test results on the specimen with a speed of 2620 rpm.

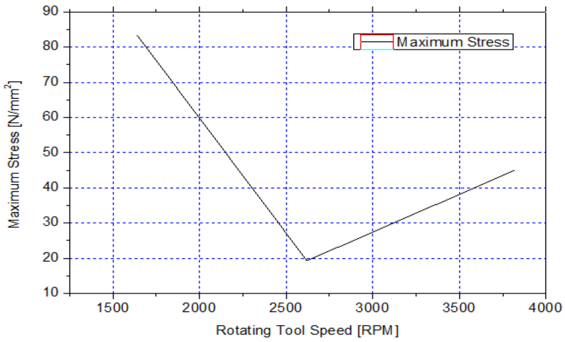


Figure 4: Tensile stress of Aluminum 6061 at the defined rotating tool speed.

Table 3: Tensile strain of Aluminum 6061.

Specimen	L0 (mm)	L1 (mm)	ΔL (mm)	Strain ε (%)	ε aver. (MPa)
X1	50	52.11	2.11	4.21	
X2	50	53.86	3.86	7.71	5.93
X3	50	52.93	2.93	5.87	
Y1	50	51.92	1.92	3.84	
Y2	50	51.66	1.66	3.31	3.41
Y3	50	51.53	1.53	3.07	
Z1	50	52.03	2.03	4.06	
Z2	50	51.92	1.92	3.83	3.65
Z3	50	51.53	1.53	3.06	

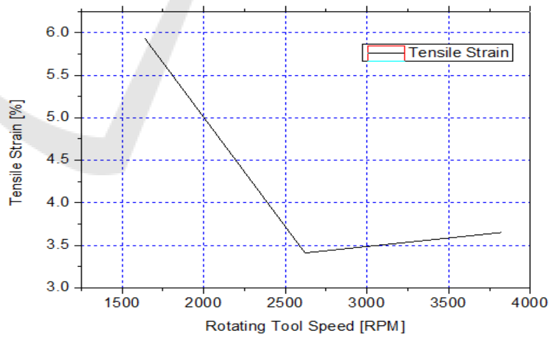


Figure 5: Tensile strain of Aluminum 6061 at the defined rotating tool speed.

Based on the conducted test results of tests in this study, the maximum tensile strain value resulting from friction stir welding joints which was occurred on aluminum 6061 is 7.71% at a speed of 1640 rpm specimen 2, and the smallest tensile strain yield is 3 .07% at a speed of 2620 rpm specimen 3.

The average tensile strain value from highest to lowest resulting from the aluminum 6061 weld joints using FSW (Friction Stir Welding) welding with variations in the tool rotation speed carried out in this research was 5.93% at 1640 rpm, 3.65% at 3820 rpm, and 3.41% at 2620 rpm.

Table 4: Modulus of elasticity of Aluminum 6061.

Specimen	σ Max (MPa)	Strain ε (%)	E (GPa)	E aver. (GPa)
X1	82.56	4.21	19.61	14.85
X2	88.13	7.71	11.42	
X3	79.33	5.87	13.52	
Y1	20.74	3.84	5.40	5.67
Y2	20.29	3.31	6.13	
Y3	16.80	3.07	5.47	
Z1	56.56	4.06	13.93	12.38
Z2	36.99	3.83	9.65	
Z3	41.51	3.06	13.57	

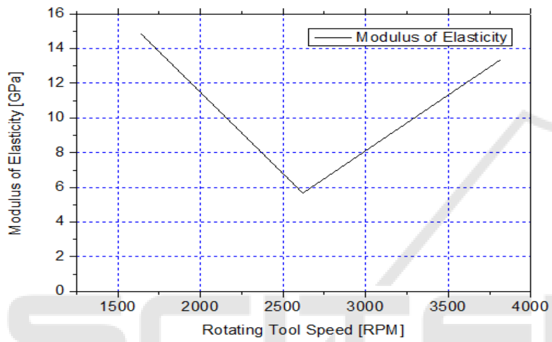


Figure 6: Modulus of elasticity of Aluminum 6061 at the defined rotating tool speed.

From the diagram of the test results that have been carried out, the highest elastic modulus value at the aluminium 6061 weld joint using FSW (Friction Stir Welding) welding is 19.61 GPa at a speed of 1640 rpm specimen 1. While the lowest elastic modulus value of the specimen of aluminum 6061 weld joint using FSW (Friction Stir Welding) at a speed of 2620 rpm specimen 1 has shown a modulus of elasticity of 5.4 GPa. From the highest to lowest, the average modulus of elasticity of the aluminum 6061 welding connection using FSW (Friction Stir Welding) welding is 14.85 GPa at 1640 rpm; 13.81 Gpa at a speed of 3820 rpm; and 5.67 Gpa at a speed of 2620 rpm.

3.2 Impact Strength Test Results

From the diagram of the results of the tests that have been done, the impact strength on the aluminum 6061 weld joint using FSW (Friction Stir Welding) welding is 0.27 J/mm^2 at 3820 rpm of specimen 1. While the lowest impact strength on the aluminum 6061 weld joint using FSW welding (Friction Stir Welding) is produced at a rotating speed of 2620 rpm specimen 2 with an elastic modulus value of 0.10 J/mm^2. The highest to lowest average impact value generated at the aluminum 6061 weld joint using FSW (Friction Stir Welding) welding is 0.23 J/mm^2 at 1640 rpm; 0.20 J/mm^2 at a rotating speed of 3820 rpm; and 0.13 J/mm^2 at a rotating speed of 2620 rpm.

Table 5: Impact strength of Aluminum 6061.

Specimen	Width (mm)	Height (mm)	Absorbed Energy (J)	Impact Strength (J/mm^2)	Impact Strgh. aver. (J/mm^2)
X1	10.16	8.88	22.18	0.25	0.23
X2	10.28	9.00	17.08	0.18	
X3	10.20	8.88	23.95	0.26	
Y1	10.21	9.29	10.78	0.11	0.13
Y2	10.16	8.77	8.65	0.10	
Y3	10.16	8.66	15.45	0.18	
Z1	10.23	9.24	25.75	0.27	0.20
Z2	10.26	9.31	16.18	0.17	
Z3	10.32	8.67	14.45	0.16	

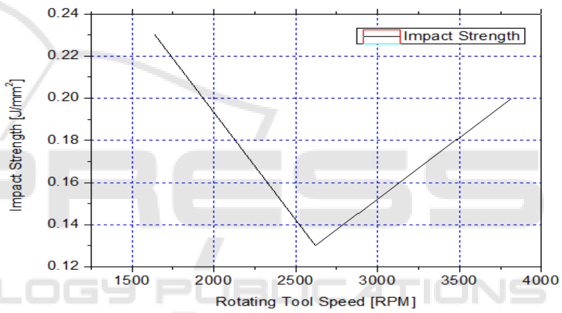
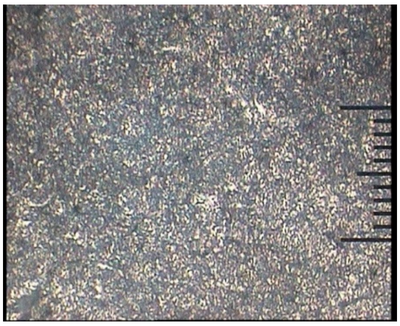


Figure 7: Impact strength of Aluminum 6061 at the defined rotating tool speed.

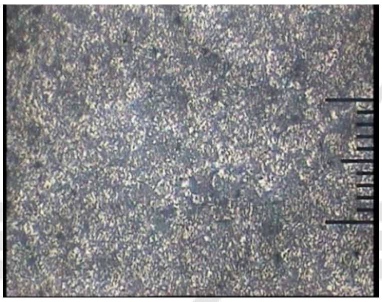
3.3 Micrographics Test Results

The specimens used for micrographic testing are impact specimens with a size of 55 mm × 10 mm × 10 mm as many as 3 specimens of FSW weld joint. The shape of the microstructure at the aluminum 6061 weld joint can be seen through the surface treatment which is carried out on the test specimen so that the micro structure of the aluminum weld joint can be clearly observed using a microscope. Firstly, the specimens are smoothly grinded using 4 sequences of sandpaper layers, namely sandpaper numbers 100, 200, 400, 600 and 1000. After being smooth, then the specimen is smeared with the autosol until glossy. After that, the surface of the specimen that has been smeared with autosol is then given a 50% NaOH etching solution so that when viewed using a microscope, the microstructure of the aluminium 6061 welded joint can be clearly seen. Furthermore, micrographic testing is performed to see the microstructure shape of the aluminum 6061 weld joint using a microscope with a magnification of 200 times.

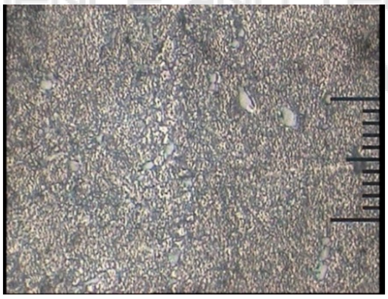
From micrographic testing on aluminum 6061 welding (Base Metal, HAZ, and Weld Joint) using FSW (Friction Stir Welding) welding, the following results were obtained, see Fig. 8 – Fig. 10:



[a] Weld Joint Region



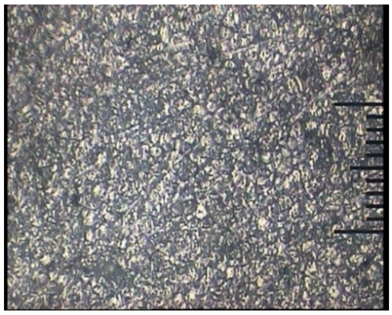
[b] HAZ Region



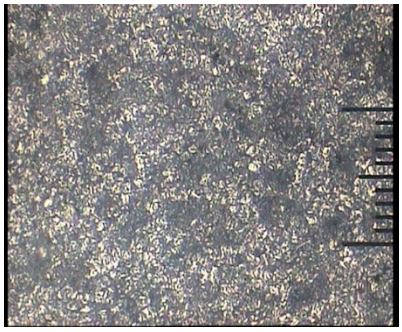
[c] Base Metal Region

Figure 8: Microstructure of the aluminium 6061 weld joint at 1640 RPM.

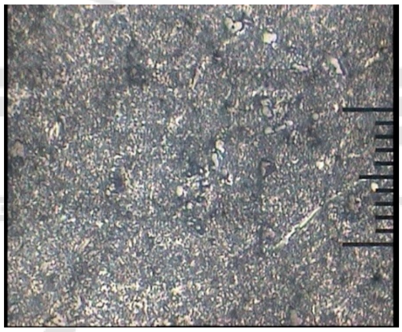
From the micrographics test, the results of the aluminium 6061 weld joint using FSW (Friction Stir Welding) welding with variations in the rotational speed of the tool was presented in the form of particle size and shape at the regions of the HAZ (Heat Affected Zone), the base metal and the weld joint. In the base metal area has a small grain size, because the base metal region is not affected by the effects of heat due to welding. Otherwise, in the



[a] Weld Joint Region



[b] HAZ Region

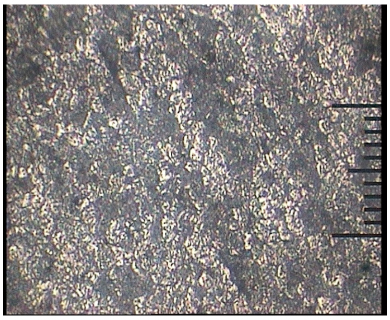


[c] Base Metal Region

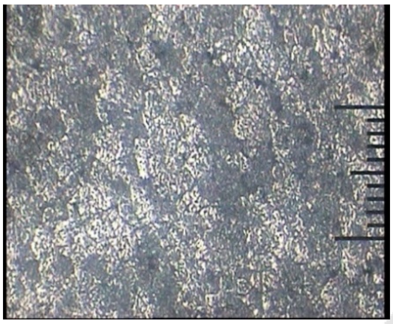
Figure 9: Microstructure of the aluminium 6061 weld joint at 2620 RPM.

HAZ region, particle granules change in the shape and grain size larger and coarser, and the density of particles is more tenuous when compared to the base metal region. This is because the HAZ is only affected by heat caused by friction when welding process occurred.

In the area of the steering zone changes in the shape and particle size looks rough and larger than the particle size in the HAZ and base metal. This is caused by the temperature and rotational movement of the tool when welding around the stir zone. In Fig. 8[a], Fig. 9[a] and Fig. 10[a], the weld joint region (stir zone) will have soft granules which are caused by recrystallization.



[a] Weld Joint Region



[b] HAZ Region

[c] Base Metal Region

Figure 10: Microstructure of the aluminium 6061 weld joint at 3820 RPM.

Based on the results of micrographic testing, the higher of the rotation speed, the grain size of the particles produced is greater, it is caused by several factors such as heat input, welding rate and magnitude of cooling rate. Therefore the weld joint at a speed of 1640 rpm has a good density level compared to the weld joint that is produced on the speed of 2620, and 3820 rpm. It can be seen on the results of the micrographics photo in the HAZ region.

4 CONCLUSIONS

The tensile test results of the weld joint with FSW (Friction Stir Welding) welding have an average stress of 83.34 MPa and an average strain of 5.93% at a rotational speed of 1640 rpm. At a rotation speed of 2620 rpm it has an average stress of 19.27 MPa and an average strain of 3.41%. An average stress of 45.02 MPa and an average strain of 3.65% are held at the 3820 rpm. Prior to the tensile test, visual inspection of the welding surface should be carried out, and the speed of 2620 rpm has the worst weld results. There are hot cracks and worm holes after welding is the main reason that reduces the tensile strength test results on the specimen with a speed of 2620 rpm.

The impact test results on the results of welding joints with FSW welding have the average impact strength of 0.23 J at the rotating speed of 1640 rpm. The average impact of 0.13 J was appeared at 2620 rpm rotation speed, and at the rotating speed of 3820 rpm of the tool has the average impact strength of 0.20 J.

Micrographic structure test results which is obtained in the HAZ region, and weld joint (nugget zone) at each tool rotation has a grain size larger than the base metal, it is caused by the influence of the tool rotation speed. The larger of the tool rotation, the greater the grain size produced in the welding results.

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