Fracture Toughness and Microstructure of Gas Metal Arc Welded Plates of Aluminium Alloy 5083 Using Different Filler Wires and Heat Inputs

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Abstract. Aluminum alloys AA5083 is alloys which mostly used in the hull components of the ship and high-speed craft. Commonly gas metal arc welding (GMAW) is used for joining the construction. Welding strength especially cracks toughness, is very important on this welding due to the regular operation of the ship or high-speed craft. In this research, welding of aluminum alloys AA5083 with dimension 150 mm x 350 mm and thickness 15 mm and 20 mm, were carried out by gas metal arc welding using two difference filler metal ER5183 and ER5356, and 99% argon is used as shielding gas. The result of the experiment that the maximum value of excellent toughness was shown on welding with thickness plate 15 mm using filler metal ER5356 and heat input 7.8 kJ/cm.

Keywords: Aluminium Alloy AA5083 Welding, Filler Metal, Mechanical Properties, Microstructure, Crack tip Opening Displacement

1. Introduction
The Republic of Indonesia is the largest archipelagic country in the world, consisting of 17,508 islands, including 9,638 unnamed islands and 6,000 uninhabited islands. As an archipelagic country often referred to as the emerald of the equator, Indonesia has a unique and challenging configuration; besides, it has a strategic archipelago position between two continents and two oceans. This position has a high level of vulnerability to the influences of neighbour countries due to the opening and spread of Indonesian territories, which have caused disruption to the security stability and can destabilize the Indonesian integrity as NKRI. Therefore, sea transportation (ships & speed boats) is needed to support all trades and security activities [1]. Aluminum is the right choice of engineering material to be used for the hull of sea transportation because Aluminium has a lightweight and a good strength that is almost the same as the strength of low carbon steel [2]. One type of aluminum that is widely used in shipbuilding fabrication is Aluminium Alloy 5083, an aluminum that can be annealed with an alloy composition of 4.5% Mg, has good strength, and is easily welded, and also has high corrosion resistance [3]. In addition to the necessary materials used must also take into account the development process so that the quality of the product can meet the design plan.

Fabrication is one of the processes or stages that are important in shipbuilding, where the connection process between parts or components is carried out using welding at this stage [4]. The AA5083 aluminum welding process using the GTAW welding method is more reliable than the GMAW method, from the results of research conducted by Liu, et al. Found that the mechanical properties of
the welding results using the GTAW method are better than using the GMAW method. Besides, no welding defects were found in the microstructure of welds using the GTAW method [5]. However, welding of aluminum alloy AA5083 especially in shipyards uses the GMAW method and generally uses multi-pass, the results of research that have been done show that after a long time and after experiencing improvements due to the age of the weld, the mechanical properties of the weld may have decreased and the microstructure has changed [6, 7]. Welding with GTAW is a welding method that uses protective gas. Commonly used protective gases are argon and helium with varying protective gas flows. Based on the results of the investigation showed that welding GTAW for aluminum AA5083 using argon shielding gas would produce a smaller grain size compared to using helium gas. Small grain size may produce better mechanical properties, so the use of argon gas as a protective gas is better than using helium [8, 9].

The welding procedure is essential and has a significant influence on the quality of the welds, mechanical properties, and microstructure of the welding results. For aluminum alloy material A5083, which is generally used for the maritime industry, testing and analysis have been carried out using aluminum alloy A5083-O and A5083-H321 with numerical simulations. From the results of the investigation found that there are differences in resistance behaviour to crack growth and the validity of simulation figures from fatigue crack growth based on the RPG stress criteria [10, 11].

Another thing that influences welding is the heat treatment process before welding. The pre-heat treatment influences the mechanical properties of aluminum welding. The Aluminium alloys 6061-T6 and 7075-T651 were welded using the MIG method before welding samples were preheated (preheating aging heat treatment), the results of the investigation showed that the welds that were subjected to heat treatment before welded had better mechanical properties compared to samples without heat treatment [12]. The effect of Butt-joint connection design, with variations in the distance of the magnesium alloy welding joint using the GTAW, has been carried out to determine the mechanical properties and microstructure. From the results of the investigation found no porosity in the microstructure and other types of weld joint found porosity [13].

The purpose of this research was to determine the toughness of aluminum material in its application as a body-hull of fast patrol boats. Right now, the toughness measurement of welding results using CTOD for Aluminum material is uncommonly done. So it is necessary to know the mechanical properties, microstructure, and CTOD value generated from the welding process using existing procedures in order to obtain an analysis of whether the welding procedures used in the construction of fast patrol boats using aluminum currently meet the technical requirements or standards.

2. Experimental method

2.1. Materials
The material used for base metal is Aluminium AA5083, while the filler metal used is based on the AWS A5.10 classifications, Blue Mig 5183 and Blue Mig 5356 with diameter size 1.20 mm and using argon 99% shielding gas. The material composition can be seen in Table 1 and Table 2. The thickness of the base metal used in this research is 15 mm and 20 mm. The material width is 300 mm, and the length is 350 mm.

| Material | Material Composition of Base Metal (%) |
|----------|----------------------------------------|
| Base Metal Al AA5083 | Si | 0.4 | Fe | 0.4 | Cu | 0.1 | Mn | 0.4-1 | Mg | 4.0-4.9 | Cr | 0.05-0.25 | Zn | 0.25 | Ti | 0.15 |

| Materials | Material Composition of Electrode Wire (%) |
|-----------|-------------------------------------------|
| Electrode 5183 | Si | 0.40 | Cu | 0.1 | Fe | 0.4 | Mn | 0.75 | Mg | 4.75 | Cr | 0.15 | Ti | 0.15 | Al | Rem |
| Electrode 5356 | Si | 0.25 | Cu | 0.1 | Fe | 0.4 | Mn | 0.12 | Mg | 5.0 | Cr | 0.12 | Ti | 0.13 | Al | Rem |
2.2. Sample preparation
The type of connection used in welding is a butt joint welding, with a single V-groove. The distance from the connection is 2 ~ 3 mm, with a bevel angle of 60°, the surface of the joint in fine grinding, and cleaned before the welding process, the connection details such as Figure 1.

The welding process is using the gas metal arc welding and carried out by certified welders in the shipyard using two kinds of welding machines. The MIG Welding brand welding machine for material thickness of 15 mm and OTC type CPVE 400 for materials with a thickness of 20 mm. The voltage is set at 20-26 V and using the welding current between 180-200 A on the first pass and 200-270 A for the next pass.

![Figure 1. Detail of Weld Join.](image)

Visual testing is done to determine the results of welding in general, especially in the surface area; the other test is a radiography examination to determine the results of the welding process in the weld metal. The observation of the microstructure was taken using the Nikon Model Epiphot 200 optical microscope, with a magnification of 500 times on weld metal and HAZ. For mechanical testing, there is three kinds of testing: Tensile Testing, Impact Testing, and Hardness Testing. Tensile testing is carried out with specimen preparation standards and testing using AWS D1.2 or ISO 4136 standards. While impact testing is carried out with sample preparation and testing using the standard of AWS D1.1 or ISO 9016 standards, each welding sample is taken three impact test specimens on weld metal, and the test is carried out at room temperature and the Hardness testing using the Vickers. Each welding sample is tested hardness on the base metal, weld metal, and HAZ (heat affected zone) area. Crack Tip Opening Displacement (CTOD) testing is one part of mechanical fracture testing conducted to determine and measure the resistance of a material to crack growth [14]. Sample preparation and testing is carried out using the BS 7448 standard or ASTM E1290, and each welding sample is taken 1 CTOD test specimen on a weld metal, and the test is carried out at room temperature. The fractographic observation was carried out with SEM on the weld test specimen with magnification up to 50 times. SEM-EDS testing aims to analyze the chemical composition by scanning methods.

3. Results and discussion
The welding parameters used in the welding process in this study are the heat input and filler metals or electrode of the welding process. The heat input required in the welding process can be seen in Figure 2, in general, it can be seen that the heat input required for welding with the metal arc welding (GMAW) method using ER5183 and ER5356 fillers for materials with a thickness of 20 mm require more significant heat input than materials with a thickness of 15 mm.

Welding results from the entire sample can be seen in Figure 2, both 15 mm and 20 mm thickness, and based on the electrodes used, showed no defects on the surface either surface porosity or undercut from the results of radiographic testing conducted by PT. Gong Samudra International in Batam, shows that all welding results are quite good and meet the requirements of existing standards. However, welding defects obtained in the form of inclusions in the sample 20-5356, where the maximum inclusion length of 2.0 mm that still meets the requirements of existing standards.
From the results of macro and micro metallographic observations in Figure 3, it can be seen that the weld has been wholly integrated (homogeneous) between the base metal and the filler metal. Moreover, the results of metallographic microstructure observations made using an optical microscopy outline can be seen in the grain structure formed in the HAZ region and weld metal produced in the welding process of AA5083 aluminum alloy material using the gas metal arc welding and two metals different fillers.

**Figure 2.** Welding Result of Al5083 with each parameter (Thickness – Electrode).

**Figure 3.** Heat Input on Welding Process.

**Figure 4.** Microstructures of HAZ and Weld Metal of every specimen (Material thickness – Electrode).
From Figure 4 which is a photograph of observations of microstructure analysis, it can be seen that the grain structure in the HAZ region varies in the form of lanes and reasonable grain structure with sizes varying from 40 µm to 60 µm, this occurs due to changes in heat cycles that occur in the area HAZ during the welding process. While in Figure 5, the microstructure of the weld metal area shows some reasonable round granules with grain sizes varying from 20 µm to 40 µm.

From the tensile test result in Figure 6 results, showed that the most significant yield strength is 172.82 N / mm², which is the result of welding plates with a thickness of 20 mm using ER5183 filler metal and heat input of 10 kJ/cm while the welding results that produce the highest tensile strength is welding on 15 mm material using ER5356 filler metal and heat input 7-8 kJ/cm that is 272.59 N/mm². It can happen because this process creates the finest/smallest grains compare to the other after the welding (Figure 5).
The result of the Impact test can be seen in Table 3. From this Table can be seen that welding of materials with a thickness of 15 mm produces higher impact energy compared to materials with a thickness of 20 mm. The highest average impact energy is obtained at 15 mm welding using ER5356 filler metal, which is 31.67 J, while the lowest is produced by welding 20 mm material using ER5356 filler metal that is 21.67 J.

Table 3. Result of Impact Test in every sample.

| No. | Sample (Thickness – Electrode) | Impact Energy (J) |
|-----|--------------------------------|------------------|
| 1   | 15-5183                        | 30.00            |
| 2   | 15-5356                        | 31.67            |
| 3   | 20-5183                        | 30.33            |
| 4   | 20-5356                        | 21.67            |

From the results of hardness testing conducted both in the base metal area, HAZ and weld metal. Based on the hardness result of all welding samples showed that the highest hardness is in the base metal, and the lowest hardness value is in the weld metal. The hardness value is higher for the welds with high heat input and ER-5183 filler wire and with a low heat input using ER-5356 filler wire. In general, the results of a hardness test can be seen in Figure 7.

![Figure 7. Hardness Distribution of AA5083 Welding.](image)

Table 4. CTOD Test Result.

| No. | Sample  | $K_t$ (Pre cracking) (N/mm$^{3/2}$) | $K_f$ (Fracture) (N/mm$^{3/2}$) | CTOD (mm) |
|-----|---------|-----------------------------------|-------------------------------|----------|
| 1   | 15-5183 | 288                               | 1333                          | 0.26     |
| 2   | 15-5356 | 288                               | 1439                          | 0.31     |
| 3   | 20-5183 | 394                               | 1037                          | 0.23     |
| 4   | 20-5356 | 394                               | 1052                          | 0.28     |

CTOD test results on aluminum welding AA5083 by using plates with a thickness of 15 mm and 20 mm, and by using filler metal ER5183 and ER5356 are shown in Table 4. The Table shows that the CTOD values produced by welding using ER5356 filler metal are higher compared to welding using ER5183 filler metal both for welding materials with a thickness of 15 mm or 20 mm. In welding materials with a thickness of 15 mm, a CTOD value of 0.31 was obtained when using filler metal ER5356 and a CTOD value of 0.26 when welded using filler metal ER5183. As for materials with a thickness of 20 mm, the resulting CTOD value is 0.28 with the fill metal ER5356 and only 0.23 if the fill metal used is ER5183. For welding carried out using the same filler metal and different plate, thicknesses show that the CTOD value on the 15 mm material welding results in a higher CTOD value when compared to welding on a 20 mm thick material.
Figure 8 shows a graph of the relationship between CTOD values and the heat input generated on welding using two different filler metals and different plate thicknesses. Welding results using ER5183 filler metal may result in higher CTOD values and lower tensile strength, but CTOD values may be lower if the tensile strength produced is higher. In contrast to welding with ER5356 filler metals where the CTOD value may be higher if the tensile strength is also high.

Whereas welding with 15 mm thick material may produce a low CTOD value if the tensile strength produced is also low and the CTOD value may be high if the tensile strength produced is also high, and the CTOD value may be very high when welding using a material with a thickness of 20 mm as shown in Figure 8, which shows the relationship between the CTOD value and the tensile strength of the AA5083 aluminum welding using two different filler metals and plate thicknesses [15].

![Graph showing CTOD value vs Heat Input](image1)

**Figure 8.** Comparison between CTOD value and heat input based on filler metal (a) and plate thickness (b).

![Graph showing CTOD value vs Tensile Strength](image2)

**Figure 9.** Comparison between CTOD value and Tensile Strength on filler metal (a) and plate thickness (b).

Furthermore, the relationship between CTOD value and the impact energy absorbed in aluminum AA5083 welding using two filler metals and different plate thickness can be seen in Figure 10, for welding with ER5183 filler metal, the CTOD value may decrease significantly if the impact energy produced increases, whereas for ER5356 filler metal CTOD values may increase according to the increase in impact energy produced, whereas for welding with 15 mm thick material CTOD values may increase if the impact energy also produced increases, but decreases when welding with 20 mm thick material.
Figure 11 is the microstructure of the SEM test results in the HAZ and weld metal regions. Based on photographs with a magnification of 2000 times, it can be seen that the grains formed in the HAZ region are more significant than the grains in the weld area. From these pictures, it can also be concluded that the 5183 electrode has a smaller size of grains compare to 5356 electrodes. SEM photos also show that solid magnesium deposits formed in the HAZ region with a larger size compared to deposits in the weld metal area. This conclusion from the research done by Jakobsen that the increasing of the Silicon may reduce the grain size [16].

Figure 11. SEM with magnification 2000 times for HAZ (above) and Metal Region (below).

The results of the EDS examination conducted in the weld area showed the chemical composition formed from the filler metal after smelting due to the welding process. Welding with filler metal ER5183 on a 15 mm plate resulted in a 4.92% Mg element and 95.08% Mg element, while welding with ER5356 filler metal showed maximum Mg elements 5.37% and Al 94.63%. Welding of materials with a thickness of 20 mm with ER5183 shows a maximum of 4.82% Mg element and 95.18% Mg element, while welding with ER5356 filler metal shows a maximum of 5.19% Mg and 94.81% Al. This EDS result is related to the effect of heat number and the material properties. From the results of tests conducted by Vargas et al., one of the factors that influence the welding results of aluminum with the GMAW method is heat input. The heat input may affect the mechanical properties of 6061-T6 aluminum.
welding. It was concluded that heat input would affect the temperature of the welding process, but the amount of energy absorbed by the material depends on the alloy contained in the aluminum. So the maximum temperature of this process may affect the cooling process, which may affect the resulting microstructure changes [17].

SEM testing is also carried out on the surface of the fracture results from the CTOD test to determine the type of fault that occurs, the results of SEM testing on the surface of the fracture can be seen in Figure 12. That figure shows a dimple type surface fracture. Thus it can be concluded that the type of fracture that occurs for the welding results of AA5083 aluminum alloy material with two different filler metals is elastic (ductile). Moreover, from two types of filler metals used welding with ER5183 shows dimple surface fractures, compared to welding with filler metals ER5356.

![Figure 12. SEM photos of CTOD fracture surfaces of welding area for different filler metal (a) ER5183 and (b) ER5356.](image)

4. Conclusion

From the results of the research and discussion that has been carried out, it can be concluded that the results of welding in general, both visual, NDT, and other tests can be accepted according to the classification rule standards (classification rule and regulation). It also found that the influence of plate thickness on the heat input indicates that the thicker plate used may require a higher heat input. Based on the results of the tensile test, the higher the heat input may produce a high tensile strength for welding with ER5183 filler metal, but the high heat input for welding with ER5356 produced a smaller tensile strength. While the higher hardness value happens on the welding with high heat input and ER5183 filler metals and with low heat input when using ER5356. Otherwise, impact energy is higher if the heat input on welding is lower for welding with ER5356 filler metal, but not much different when welding with ER5183 filler metal. The higher heat input on welding may produce a lower CTOD value, and with the same heat input, the CTOD value may be higher on welding with ER5356 filler metal compared to ER5183. The shape of the surface fracture in the CTOD test that occurs from the SEM results shows the simplified form of welding with ER5183 and ER5356 filler metals with a larger surface fracture diameter for ER5183. Optimization of research results obtained by welding results with a 15 mm thick plate with ER5356 and 7.8 kJ/ cm heat input obtained the highest value of fracture toughness.

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