Influence the Filler Metal Containing Zirconium on the Weld Metal Porosity of The MIG Welded Aluminum Alloy 5083

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Abstract. The aluminum alloy series 5083 has high corrosion resistance and high specific strength properties; hence, it is widely used for ship structures, marine components, cryogenics of LNG tanks, and unfired pressure vessels. This study was undertaken to investigate the effect of zirconium on weld metal porosity and hardness of MIG welded aluminum Alloy 5083. Zirconium is one of the alloying elements that are mostly used for grain refining in the aluminum casting process. Zirconium element was previously added in the electrode wire as a filler metal. The experiments were carried out by MIG welding for several aluminum alloy plates to produce the full penetration weldments. Two different filler wires used in the welding: one is containing zirconium, and another is no containing zirconium. The grain size of weld microstructures was measured using a Linear Intercept Method (ASTM E 112), and the hardness measurement is conducted using micro-Vickers along the cross section of AA-5083 weldment. Results showed that the grain size of AA-5083 weldment using the filler metal containing zirconium was considerably finer size than that of using the filler metal without zirconium. Moreover, the hardness of AA-5083 weldment using the filler metal containing zirconium is generally higher than that of using the filler metal without zirconium.

Keywords: Aluminium Alloys 5083; Zirconium, Weld Metal Porosity, Grain Size, and Hardness.

1. Introduction
Aluminum alloy 5083 is one of the groups of aluminum-magnesium (5XXX series) that are strengthened by alloying elements in solid solution, a fine dispersion as well as by strain hardening and grain size control [1]. They are work hardenable, have quite high strength, excellent corrosion resistance even in seawater, and very high cryogenic toughness. This alloy contains magnesium as a major alloying element with 4.5 wt. % magnesium, and also often includes small addition of transition elements such as chromium and manganese to control the grain and subgrain structure and the small impurities such as iron and silicon that are present in the form of intermetallic particles [2,3].

Aluminum Alloy - 5083 plates is generally welded by Metal Inert Gas (MIG) welding process, due to this process is more efficient and suitable for welding in industries. However, a significant hindrance in the weakness of the heat-affected zone (HAZ) and a presence of porosity in the weld fusion zone have been potential for degradation of mechanical properties as a result of welding. Peasura and Watanapa carried out MIG welding shielded by argon and helium gas on aluminum alloy AA 5083. They found that shielding gas argon provided smaller grain size, resulting in higher hardness both in the weld metal and HAZ, while helium, which has high thermal conductivity, provided larger grain size due to a large amount of heat [4]. One of the solutions for avoiding the welding degradation in the aluminum...
alloy is the use of micro alloying which has proven to be one of the effective mechanisms in enhancing mechanical properties of aluminum alloys through its microstructure improvement [5-7].

Seshagiri et al. [8] conducted intensive research on the effect of Zircon (Zr) addition to the mechanical properties of Al-Cu alloys welded with Gas Tungsten Arc Welding (GTAW). They found that better mechanical properties were achieved by adding zirconium to the molten zone during welding due to the finer grain size. Zhao et al. [9] examined characteristics of the Al-Mg-Sc alloy resulted from Tungsten Inert Gas (TIG) and Friction Stir Welding (FSW). They found that the A13(Sc, Zr) particles refine the weld metals of both joints effectively. Yang Dongxia et al. [10] showed that the small alloying of zirconium give the small grain size in the weld metal structure, due to the existence of Al1Zr. Micro-hardness of the center of the fusion zone goes up from 74 HV0.1 to 84 HV0.1 since the reduction of grain size by small alloying of Zr.

Moreover, the small alloying of Zr gave improvement on the tensile strength. Yin Deng et al. [11] also found that the microalloying of Zr and longer the aging period at 120 °C, both can reduce the corrosion of Al-Zn-Mg alloys. This effect is due to the grain size refiner of Zr and limiting the formation of precipitates.

This work aimed to examine the grain size, weld porosity, and mechanical properties in two types of welded plates after applying different filler wires (ER5556A and ER5087) on the mechanized MIG weldments of aluminum alloy 5083.

2. Experimental method

2.1. Materials

2.1.1. Base Material and Specification. AA 5083 was used as the base material in the present investigation. This alloy is in the annealed condition or can be written as AA5083-0 and was supplied in plate form with a 5mm thickness, 300mm long, and 100 mm wide. The chemical composition of this alloy is shown in Table 1.

| Table 1. Chemical composition of base metal AA-5083. |
|-----------------------------------------------|
| AA-5083 | %Si | %Fe | %Cu | %Mn | %Mg | %Cr | %Zn | %Ti | Other | %Al |
| Standard | 0.40 | 0.40 | 0.10 | 0.40-1.00 | 4.00-4.90 | 0.05-0.25 | 0.25 | 0.15 | 15 | Rem |
| Tested | 0.90 | 0.24 | 0.01 | 0.60 | 4.70 | 0.10 | 0.02 | 0.01 | 15 | Rem |

| Table 2. Chemical composition of filler wire. |
|-----------------------------------------------|
| ER-5556A | %Si | %Fe | %Cu | %Mn | %Mg | %Cr | %Zn | %Ti | %Be | Other | %Al |
| Standard | 0.25 | 0.40 | 0.100 | 0.6-1.0 | 5.0-5.5 | 0.05-0.20 | 0.20 | 0.05-0.20 | 0.0008 | 0.15 | Rem |
| Tested | 0.07 | 0.19 | 0.002 | 0.72 | 5.40 | 0.093 | 0.001 | 0.118 | 0.0007 | 0.0042 | Rem |
| ER-5087 | %Si | %Fe | %Cu | %Mn | %Mg | %Cr | %Zn | %Ti | %Be | %Zr | %Al |
| Standard | 0.25 | 0.40 | 0.05 | 0.7-1.1 | 4.5-5.2 | 0.05-0.25 | 0.25 | 0.15 | 0.0008 | 0.1-0.2 | Rem |
| Tested | 0.08 | 0.20 | 0.015 | 0.68 | 4.61 | 0.096 | 0.011 | 0.128 | 0.0004 | 0.12 | Rem |

2.1.2. Filler Wire. The recommended filler alloys for welding AA 5083 are ER5356, ER5183, and ER5556 (ASM, 1993). Two filler alloys used in this investigation were ER5556A and ER5087. The last one, ER5087, is a new development of filler alloy that contains zirconium as a grain refiner. The certificate analysis for the chemical composition of filler wires can be seen in Table 2.

2.2. Weldment Preparation.

There were 12 pieces of full-penetration aluminum alloy 5083 weldments produced using a mechanized MIG welding with the following welding parameters, as presented in Table 3.
Table 3. Welding parameter of AA-5083 plate using two types of filler wires.

| CODE | Filler Wires | Voltage (U) (Volt) | Current (I) (Ampere) | W.Speed (S) (mm/s) | Power (P) (kW) | Linear Energy (Q) (J/mm) |
|------|--------------|--------------------|----------------------|-------------------|---------------|------------------------|
| SU-01 | ER 5556A     | 22.3               | 250                  | 8.33              | 5.6           | 673                    |
| SU-02 | ER 5556A     | 22.5               | 256                  | 9.46              | 5.8           | 610                    |
| SU-03 | ER 5556A     | 23.7               | 260                  | 9.32              | 6.2           | 653                    |
| SU-04 | ER 5556A     | 22.8               | 266                  | 9.43              | 6.1           | 640                    |
| SU-05 | ER 5556A     | 23.4               | 270                  | 10.49             | 6.3           | 600                    |
| SU-06 | ER 5556A     | 24.0               | 281                  | 11.24             | 6.7           | 596                    |
| SU-07 | ER 5556A     | 23.1               | 252                  | 8.22              | 5.8           | 703                    |
| SU-08 | ER 5556A     | 23.5               | 257                  | 9.49              | 6.0           | 633                    |
| SU-09 | ER 5556A     | 24.2               | 261                  | 9.32              | 6.3           | 673                    |
| SU-10 | ER 5556A     | 24.5               | 267                  | 9.55              | 6.5           | 683                    |
| SU-11 | ER 5556A     | 24.0               | 271                  | 10.68             | 6.5           | 603                    |
| SU-12 | ER 5556A     | 25.8               | 281                  | 10.60             | 7.2           | 686                    |

2.3. Material Characterization.
The microstructure of weldments was investigated under an optical microscope to reveal their microstructure of grains, phases, and precipitates. The measurement of weldment grain size was carried out using the optical microscope. The grain size was determined by the Linear Intercept Method (ASTM E 112) [11]. Micro-hardness tests were conducted on a cross-section of weldment specimens with a Vickers micro-hardness tester of the 100-gr load. Hardness measurements were made across the weld interface parallel and 1.5 mm below the face surface of the sample. The indentations were made with increments of 1 mm from the middle of weld metal. The process of calculating the percentage of porosity of welds performed on the cross-sectional area of the weld of AA 5083 by using Image Analysis.

3. Results and discussion

3.1. Microstructure of Weldments

Photographs of the HAZ structure of AA-5083 weldment, as seen in Figure 1, show that the grain morphology of weldment is irregularly shaped grains and the HAZ grain size of weldment in SU-06 is coarser than the HAZ grain size of weldments in SU-09. Also, some of the precipitates are distributed in the matrix with the black cluster.

![Figure 1](image1.png)

Figure 1. The microstructure of HAZ in weldments of (a) SU-06 using the filler wire of ER-5556A, (b) SU-09 using the filler wire of ER-5087, etched with Keller's Reagent.
3.2. Grain Size Measurement

The result of grain size measurement can be shown in Figure 1 (a) and (b). The grain size of both weldments, as in Figure 2, shows that the grain size for weldments using ER-5556A (Figure 2-a) is different value compared to the weldments using ER-5087 (Figure 2-b), especially at HAZ and at the interface (fusion line) area. The HAZ grain size of weldments using ER-5556A is in the range of 6.0 to 6.3 (ASTM Grain Size). This value is coarser than the grain size of weldments using ER-5087 which is the value between 7.1 and 7.4 (ASTM Grain Size). Besides, the interface grain size of weldments using ER-5556A seems to be the same trend-line with the HAZ grain size. The interface grain size in the weldments using ER 5556A is quite coarser than the interface grain size of weldments using ER-5087. Those grain refinement would affect not only the mechanical properties improvement but also hot crack susceptibility reduction of the weldments. Grain refiner element able to provide many efficient heterogeneous nucleation sites in the weldment [12].

![Figure 2](image-url)

**Figure 2.** The result of grain size measurement for weldments using filler wire (a) ER-5556A and (b) ER-5087.

3.3. Microhardness Distribution of Weldments

Analysis of the hardness profiles was performed for both weldments. Hardness values in the weld metal, HAZ, and the base metal are plotted as a function of the distance (D) from the middle of weld metal, as shown in Figures 3 and 4. An average hardness value in the base metal ($H_{BM\ ave}$) equals 76 HV, with maximum fluctuations from average being approximately 3%. These fluctuations may be a result of the uneven distribution of the second phase particles in the base metal microstructure.

Figure 3(a) shows a hardness distribution of a weld produced using filler wire ER-5556A. There is a flat trend line in weld metal hardness from about 66 to 74 HV in the location between 0 mm to 4 mm from the middle of weld metal. Following that between 4 to 5 mm weld interfaces, the hardness increases slightly from 74 HV to 76 HV. After that decrease in HAZ hardness occurs in the distance between 5 mm to 9 mm from 76 HV to between 40 HV and 60 HV. This hardness is significantly the lowest value across the weldments. Subsequently, from 9 mm to 15 mm, the HAZ hardness increases sharply to approximately 76 HV, and this value remains constant at the base metal of 76 HV.

Figure 3(b) shows a hardness distribution of a weld produced using filler wire ER-5087. There is a flat trend line in weld metal hardness from about 66 to 75 HV in the location between 0 mm to 4 mm from the middle of weld metal. Then between 4 to 5 mm weld interfaces, the hardness decreases slightly from 75 HV to 70 HV. After that, the decreasing in HAZ hardness occurs in the distance between 5 mm to 9 mm from 59 HV to between 66 HV and 60 HV. This value is slightly decreasing in HAZ. Subsequently, from 9 mm to 15 mm, the base metal hardness is approximately constant at 76 HV on average.
Figure 3. Hardness distribution of weldments using filler wires: (a) ER-5556A and (b) ER-5087.

From Figure 3, it shows that the HAZ hardness distribution for welds using ER-5087 is more flat-distributed compared to the weldments using ER-5556A which is the HAZ hardness dropping very steeply to about 40 HV at the distance of 6 mm from the middle of weld metal. This is the minimum hardness for all welds produced.

3.4. Weld Porosity
The purpose of this calculation is to compare the use of filler metal at different welding AA5083 plates against the formation of porosity in the area of weld metal. Total percentage of porosity calculated on the weld metal for all weld parameters by using an optical microscope. Further images are recorded and the percentage using the image analysis software. Results can be seen in Table 4 and the macrostructure of porosity distribution, as shown in Figure 4. The porosity of weldment ER5087 containing zirconium is lower than the ER5556A containing no-zirconium. The rate of hydrogen absorption and solubility primarily determined by weldment composition. Pure aluminum is more prone to porosity formation, while Al-Mg alloys are much less due to the degassing effect from the evaporation of magnesium [13]. Furthermore, the addition of Mg, Ti, or Zr will tend to increase hydrogen solubility and have higher hydrogen concentration threshold values of porosity formation and thus more challenging to form porosity [14,15].

Table 4. Welding parameter of AA-5083 plate using two types of filler wires.

| No. | Filler Metal | Linear Energy (J/mm) | Porosity (%) |
|-----|--------------|----------------------|--------------|
| 1   | ER 5556A     | 669                  | 3.36         |
| 2   | ER 5556A     | 643                  | 1.11         |
| 3   | ER 5556A     | 602                  | 0.77         |
| 1   | ER 5087      | 708                  | 0.74         |
| 2   | ER 5087      | 685                  | 0.29         |
| 3   | ER 5087      | 609                  | 0.52         |
3.5. Relationship between the Grain Size and Zirconium Content in the Filler Wires

The level of grain refiner in the welding filler wire of ER5087 affects the solidification mode in the weld metal. Kou and co-workers [16] using the G/R ratio, showed that the effect of heat input and welding travel speed on the grain structure of weld metal. G denotes the temperature gradient in the solidification in the center of the weld pool, while R indicates the growth rate of the solidification. The stage of nucleation is influenced remarkably by the addition of grain refiner. Since ER5087 filler metal has a content of zirconium, some researchers investigated that low concentrations of zirconium aid grain refinement in Al alloys [5-11]. Their finding has shown that the second phase particles Al$_3$Zr may act as nucleating agents (sites) for aluminum alloy. Work by Kou et al. [16] who studied the parameters of welding and the weld metal grain has found that increased welding speed (TS) may enhance not only the G but also the S while increasing heat input (HI) is likely to lower the G. Thus, the reduction of G/R ratio when both the HI and the TS are increased. The decline of the G/R ratio can promote the constitutional supercooling [17,18]. The larger the constitutional supercooling, the higher the tendency for pore and the solid phase to nucleate and grow upon nucleating agent or site (Al$_3$Zr) in the super cooled liquid and a hence higher degree of grain refining. This super cooling, together with the presence of heterogeneous nucleation provided by zirconium in the filler wire, explains the reduction of grain size in weldment using ER5087 filler wire.

It is interesting to note that the grain size in the interface area (fusion line) and HAZ was smaller (finer) in the weldment of using 5087 filler wire than that of using ER-5556A. The possible explanation for this case is that the effects of grain refiner site of Al$_3$Zr may increase with decreasing the total of base metal melted (i.e., lower dilution) or high heat input (P) and high welding speed (S). This argument is supported by the research work on the effect of zirconium in aluminum [18] that zirconium was found to be a potential grain refiner of aluminum alloy.

4. Conclusion

This investigation has been primarily concerned with the influence of filler wire containing zirconium on MIG welded aluminum alloy 5083. The grain size of HAZ structure with the ER5087 containing zirconium was considerably finer than that of HAZ structure with the ER5556A containing no-zirconium. The grain size of the HAZ structure is coarser with increasing the linear energy (Q), ranging from 600 to 680 J/mm, this yields the decreasing in HAZ hardness. The hardness values in all welds vary with welding parameters employed. The HAZ hardness distribution of a weld produced using ER-5087 filler wire is more flat distributed compared to the weldments using ER-5556A, which is the HAZ hardness dropping very steeply to about 40 HV at a distance 6 mm from the middle of weld metal. Percentage porosity AA-5083 welds that use welding wire ER5087 has a smaller percentage than the weld using welding wire ER5556A.

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