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Mechanical Properties of Aluminum 5083 Alloy GMA Welds with Different Magnesium and Manganese Content of Filler Wires

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Abstract: Gas metal arc welding of aluminum 5083 alloys was performed using three new welding wires with different magnesium and manganese contents and compared with commercial aluminum 5183 alloy filler wire. To investigate the effect of magnesium and manganese contents on the mechanical properties of welds, mechanical properties were evaluated through tensile strength, bending, and microhardness tests. In addition, the microstructure and chemical composition were analyzed to compare the differences between each weld. The tensile strengths of welds using aluminum alloy filler wires with a magnesium content of 7.33 wt.% (W1) and 6.38 wt.% (W2), respectively, were similar. The tensile strength and hardness of welds using wires with a similar magnesium content, but a different manganese content of 0.004 wt.% (W2) and 0.46 wt.% (W3), respectively, were higher in the wire with a high manganese content. Through various mechanical and microstructural property analyses, when the magnesium content of the filler wire was 6 wt.% or more, the manganese content, rather than the magnesium content, had a dominant effect on the strengthening of the weld.

Keywords: aluminum 5083 alloy; gas metal arc welding; vaporization; magnesium; manganese; solid solution strengthening

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1. Introduction

Aluminum 5XXX alloys have excellent strength, weldability, and corrosion resistance and are widely used in the ship, vehicle, and plant industries [1–3]. In addition, aluminum 5XXX alloys have higher strength than other aluminum alloys due to solid solution strengthening by magnesium, a major additive element [4]. Mukai [5] reported that the magnesium content added to the aluminum alloy and the mechanical properties was proportional. However, Mukai's results were based on sheet materials and did not report the results of welds when arc welding was performed. Kwon et al. [6] performed MIG welding with a high current on aluminum 5083 alloys. The primary variable that changes the mechanical properties of a weld is the content of magnesium, and the magnesium concentration and yield strength in the weld have a linear proportional relationship. Kim et al. [7] reported that, when gas metal arc (GMA) welding was performed on an aluminum 5083 alloy using a commercial filler wire (Mg 5.10 wt.%) and a filler wire manufactured with a higher magnesium content (Mg 5.98 wt.%), the strength of the weld using the filler wire with a high magnesium content was higher. However, there has been no research confirming whether the magnesium content and mechanical properties are proportional when high-current arc welding is performed using a filler wire with higher magnesium content (7 wt.% or more).

During the arc welding of aluminum alloys, magnesium, an additive element, is vaporized by high arc heat and deteriorates the mechanical properties [8–10]. According to Ismail [11]'s study, when GMA welding aluminum alloys, the melting pool temperature of the deposited metal zone is reported to be 2000 K (1727 °C) at the center. Since the boiling point of magnesium is 1090 °C, the vaporization of magnesium will occur. In the study of Wang [12], the volume temperature of the aluminum alloy filler wire was measured when the peak current was 335 A during GMA welding, and it was about 1700–1730 K (1427–1457 °C), which caused the magnesium to vaporize. Studies on the deterioration of the mechanical properties caused by the vaporization of magnesium when welding aluminum alloys have been reported in the gas tungsten arc (GTA) welding process and the laser welding process, but studies of the GMA welding process have not been reported [13–15].

Manganese, one of the elements added to aluminum 5XXX alloys, is used for solid solution strengthening in aluminum alloys, such as magnesium. Still, its strength per atom is higher than that of magnesium [16]. Moreover, the boiling point of manganese is 2090 °C, which is higher than the arc-melting pool temperature and volumetric temperature in the aforementioned studies of Ismail [11] and Wang [12]. The effect of the manganese content on the mechanical properties in aluminum alloy arc welds has not been reported yet.

This study investigates the effect of magnesium and manganese contents on the mechanical properties of GMA welds of aluminum alloys. Double-sided butt V-groove joint welding was performed using three types of aluminum alloy welding wires with different contents of magnesium and manganese than aluminum 5183 alloy wire. The mechanical properties of the welds were evaluated through tensile tests, bending tests, and microhardness tests. In addition, the microstructure and chemical composition were analyzed to compare changes in the welds according to their magnesium and manganese contents.

2. Materials and Methods

2.1. Base Metal and Filler Wires

The base metal used in this study was AA5083-H112, with a thickness of 25 mm; the chemical composition is shown in Table 1. This study designated the filler wires as W1, W2, and W3, according to the magnesium and manganese contents. Table 2 shows the chemical composition of the aluminum 5183 alloy wire and the wires, W1, W2, and W3, used in the experiment. The diameters of the four wires are all the same at 4.8 mm. The reason for selecting the contents of magnesium and manganese, as shown in Table 2, is that the solid solubility and drawing characteristics of the aluminum alloy were taken into consideration when manufacturing the aluminum alloy wire. Magnesium and manganese improve the mechanical properties due to solid solution strengthening, but, if the content is excessive, defects occur when drawing the wire. The aluminum alloy wires used in the experiment were created in several steps. First, aluminum alloy billets were continuously cast using continuous casting equipment. Then, an extruded metal with a diameter of 9.5 mm was produced through a multi-filament wire extrusion process. Lastly, an aluminum alloy wire with a diameter of 4.8 mm was produced by drawing using an extruded metal.

Table 1. Chemical composition of base metal (wt.%).

Base Metal \ Element	Si	Fe	Cu	Mn	Mg	Cr	Ti	Al
AA5083	0.13	0.27	0.04	0.66	4.40	0.05	0.02	Bal.

Table 2. Chemical composition of filler wires (wt.%).

Base Metal \ Element	Si	Fe	Cu	Mn	Mg	Cr	Ti	Be	Ca	Al
W1	0.03	0.09	0.003	0.003	7.33	0	0.03	0	0.07	Bal.
W2	0.02	0.07	0.002	0.004	6.38	0.001	0.03	0	0.06	Bal.
W3	0.08	0.04	0.002	0.46	6.56	0.01	0.03	0	0.05	Bal.
AA5183	0.07	0.17	0	0.66	5.10	0.07	0.07	0	0	Bal.

In this study, the effects of the addition of magnesium and manganese on the aluminum filler wire were analyzed, respectively. First, the mechanical properties were analyzed, according to the difference in magnesium content, by comparing the weld using W1 with the highest magnesium content and the weld using W2 with a relatively low magnesium content. Whether the residual amount of magnesium and the strength of the weld were different after vaporization occurred during welding was analyzed depending on whether the magnesium content of the filler wire was different. Next, the mechanical properties were compared according to the difference in manganese content by comparing the weld using W2 and the weld using W3. Whether the strength of the weld was different due to solid solution strengthening was analyzed depending on whether manganese was added to the filler wire or not. Lastly, welding was performed using a commercial aluminum 5183 alloy wire, and the strengths were compared amongst all welds.

2.2. Welding Conditions

As the welding power source, a constant-current-type GMA welding machine with a capacity of 1500 A was used. The welding power source used in the experiment was a general commercial welding machine without special controls, such as a synergic program. Since the welding power source was a constant-current type, the wire feed rate was slightly variable. Therefore, the welding current was set instead of the wire feed rate. Welding current and voltage were 600 A and 34 V, respectively. Contact tip to work distance (CTWD) was 45 mm, and the travel angle was fixed at 10° push. The welding speed was set to 50 cm/min, which is relatively fast to minimize the welding heat input in the first pass (the upper surface), and 30 cm/min in the second pass (the lower surface). Figure 1 shows a schematic design of a double-shielded GMA welding torch. A double-shielded GMA welding torch was used with an inside shielding gas to reduce turbulence and an outside shielding gas to protect the arc from the atmosphere. The shielding gas was supplied at 110 L/min by mixing 99.9% argon and 99.999% helium in a 5:5 ratio using a gas mixer inside the double torch and 99.9% argon at 80 L/min outside the double torch.

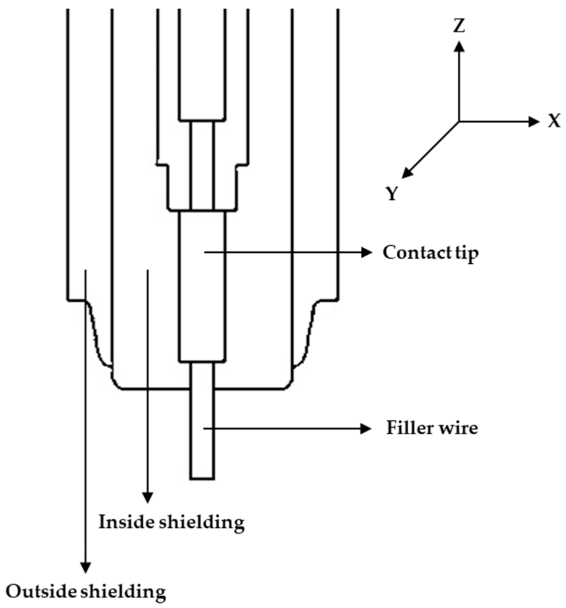

Figure 1. Schematic design of double-shielded GMA welding torch.

2.3. Specimen Conditions

2.3.1. Groove of Weld

Bead on plate (BOP) welding was performed in advance to analyze the amount of deposited metal and the penetration by welding conditions. Based on the analysis results, the welding conditions (Table 3) and the double-sided butt V-groove shape (Figure 2) that satisfy the sufficient penetration of the aluminum 5083 alloy weld were selected. The groove shape was selected to evaluate whether the wire used in the experiment satisfies a high welding current, a high deposited rate, and a high heat input. The first pass was in conditions such that burn-through did not occur during welding without using a backing material. The second pass needed to satisfy sufficient penetration, so the amount of heat input was increased by lowering the welding speed. The thickness of the base metal was 25 mm, the angle of the groove was 120°, and the length of the root face was 14 mm. To minimize the deformation of a specimen that may occur during welding, tack welding was performed at the start and end points of the weld line, and then the main welding was performed.

Table 3. Welding conditions.

Condition	Value
Welding current	600 A
Welding voltage	34 V
Welding speed	30, 50 cm/min
Travel angle	Push 10°
Shielding gas	Inside: 99.9% Argon + 99.999% Helium (Ratio 5:5, flow rate 110 L/min) Outside: 99.9% Argon (flow rate 80 L/min)
CTWD	45 mm

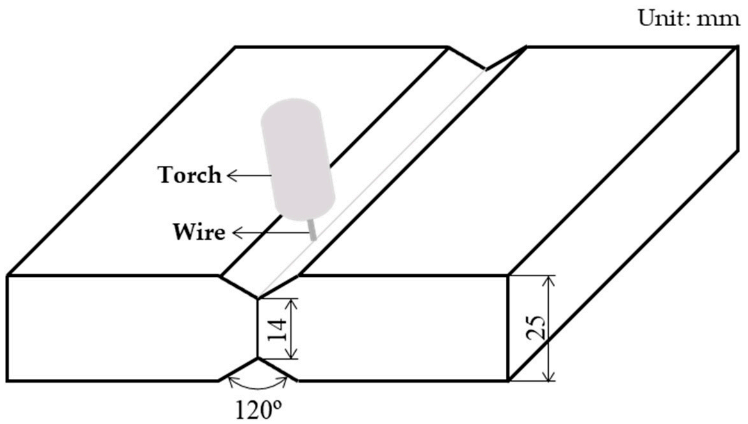

Figure 2. Schematic design of double-sided butt V-groove joint specimen.

2.3.2. Specification of Test Specimen

Figure 3 shows schematic designs of the tensile test specimen and the bending test specimen. To minimize the notch effect, which is prone to fracture due to the generation of concentrated stress when external forces, such as fatigue or impact, are applied to the welded specimen, the tensile test specimen and the bending test specimen were milled 1 mm from the upper surface and 1 mm from the lower surface. The thickness of the tensile test specimen is 23 mm. Three tensile test specimens were machined for each weld, each tensile test was performed, and then the tensile strength was obtained as an average value. The bending test was performed by producing a transverse-sided bending test specimen. The bending test method was a roller-type guided bending. The bending test was repeated three times for each weld zone because the results may vary due to defects, such as pores. After the bending test, defects, such as cracks appearing on the surface of the bent part, were examined by visual inspection. The standards for manufacturing the specimens and the test method standards are in accordance with AWS D1.2.

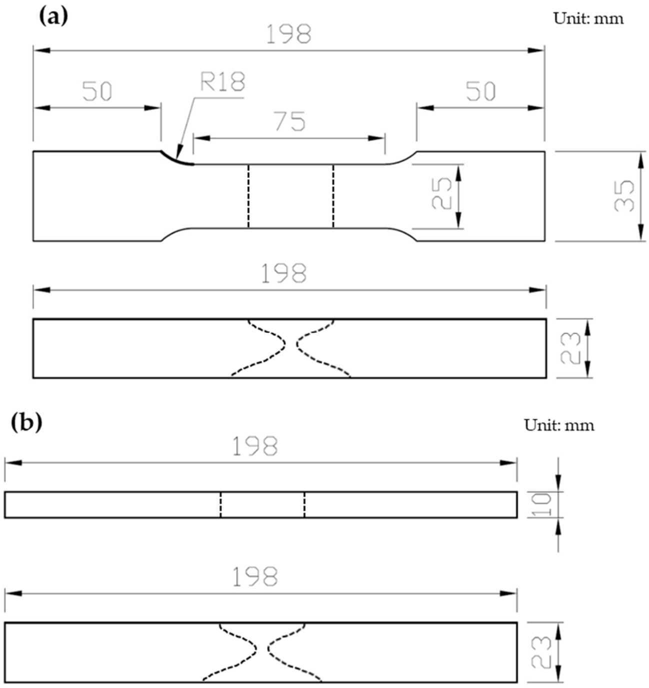

Figure 3. Schematic design of test specimen: (**a**) tensile strength test; (**b**) bending test.

2.3.3. Hardness and Dilution Rate

The hardness test was performed using a Vickers hardness tester. As shown in Figure 4, each specimen was divided into three lines, and hardness was measured along the three lines. Line A was defined as an imaginary line 2 mm below the upper surface of the weld, line B was set in the middle line of the weld, and line C was defined an imaginary line 2 mm above the lower surface of the weld. Then, the hardness was measured at HV 0.1, and, for each line, from the heat-affected zone to the center of the deposited metal zone, 81 points were estimated at 0.5 mm intervals, for a total of 40 mm.

$$\text{Dilution rate} = \frac{\text{Molten metal}}{\text{Deposited metal} + \text{Molten metal}} \times 100\ (\%) \tag{1}$$

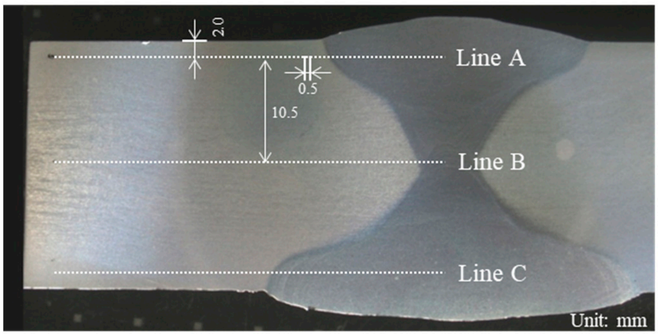

Figure 4. Schematic design showing hardness measurement method of aluminum 5083 alloy welds using a Vickers hardness tester: (**Line A**) an imaginary line 2 mm below the upper surface of the weld; (**Line B**) the middle line of the weld; (**Line C**) an imaginary line 2 mm above the lower surface of the weld.

The dilution rate of the weld was measured by Figure 5 and Equation (1). The dilution rate is calculated by dividing the area of the molten metal by the sum of the areas of the deposited metal and the molten metal.

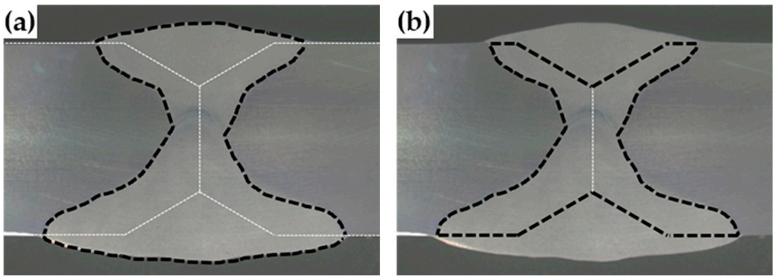

Figure 5. Schematic design of the dilution rate measurement method of weld: (**a**) sum of deposited metal and molten metal; (**b**) molten metal.

2.3.4. Microstructure

The electrolytic etching method was used to analyze the microstructure of the weld according to the difference in the contents of magnesium and manganese in the filler wire. Before etching, it was polished using silicon carbide (SiC) abrasive paper and alumina suspension, and electrolytic etching was performed using Barker's solution (40 mL HBF_4 + 960 mL Dist. H_2O). Immediately after the etching operation, the microstructure was observed with an optical microscope using a polarizing filter.

2.3.5. Chemical Composition

To confirm the residual contents of magnesium and manganese in each weld, the chemical composition was analyzed using an inductively coupled plasma–optical emission spectrometer (ICP-OES). The first pass and the second pass were separated for each weld, three points were measured, and the obtained values were averaged.

3. Results and Discussion

3.1. Appearance and Mechanical Properties

Figure 6 shows a cross-sectional image of a weld using each wire. All welds showed good shape without defects. Figure 7 shows the fracture location of the weld after the tensile test. As a result of observing the fracture location after the tensile test, the W1 and W2 welds with a tensile strength of 292 MPa, lower than the strength of the base metal, were fractured at the center of the weld metal. In contrast, the W3 weld, which had a tensile strength of 305 MPa, similar to that of the base metal, was fractured along the fusion line.

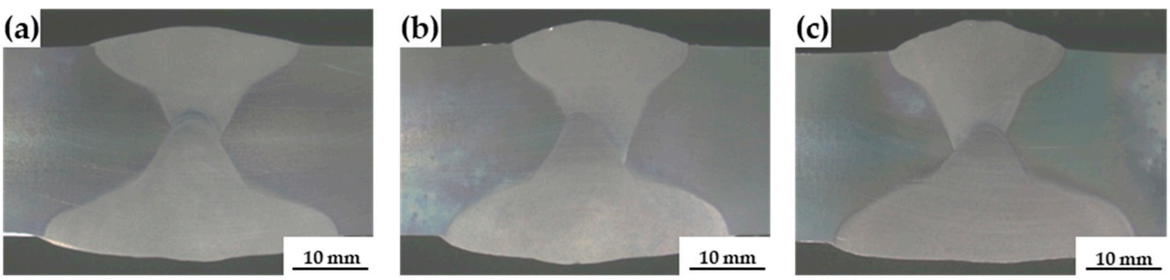

Figure 6. Cross-section of aluminum 5083 alloy gas metal arc welds using filler wires with different magnesium and manganese contents: (**a**) W1; (**b**) W2; (**c**) W3.

Figure 7. Fracture appearance of aluminum 5083 alloy gas metal arc welds using filler wires with different magnesium and manganese contents: (**a**) W1; (**b**) W2; (**c**) W3.

Figure 8 shows the tensile test results using the filler wires with different magnesium and manganese contents. In the case of the weld using W1 and W2, the average tensile strengths were 292 MPa and 293 MPa, respectively. An attempt was made to compare the strengths of the W1 and W2 welds to the difference in the magnesium content of the filler wire, but the tensile strengths of W1 weld and W2 weld did not show significant differences. However, the W3 weld showed an average tensile strength of 305 MPa, despite the lower magnesium content than the W1 weld, and its highest tensile strength was 310 MPa. In the results of Kwon [6], the magnesium concentration and strength of the filler wire were said to be linearly proportional, but the above experimental results showed non-linear results. The weld using commercial aluminum 5183 alloy wire had an average of 283 MPa and showed the lowest strength compared to the welds of the three types of manufactured wires, W1, W2, and W3.

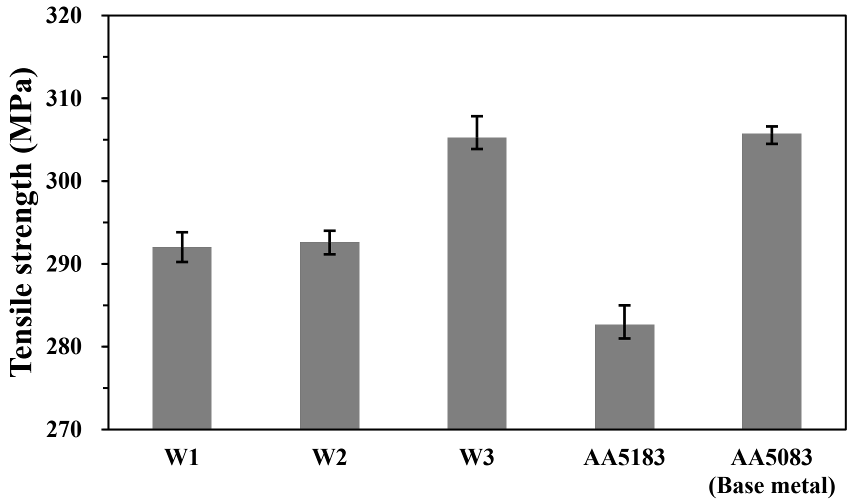

Figure 8. Tensile strength of aluminum 5083 alloy gas metal arc welds using filler wires with different magnesium and manganese contents.

Figure 9 shows the appearance of the specimen after a bending test of each weld. All specimens showed good welding quality as the bending angle could reach up to 180° without defects, such as cracks on the weld surface.

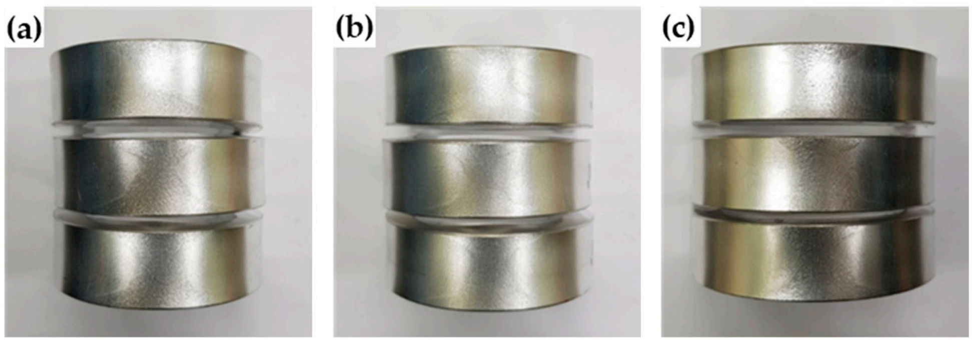

Figure 9. Appearance of aluminum 5083 alloy GMA weld bending test specimen using filler wires with different magnesium and manganese contents: (**a**) W1; (**b**) W2; (**c**) W3.

Figure 10 shows the hardness measured for each line of all welds. In the W1 weld, the hardness decreased by about 9 HV on average from the heat-affected zone to the deposited metal zone. In the W2 weld, the hardness decreased by about 14 HV on average from the heat-affected zone to the deposited metal zone, and, in particular, the hardness decreased relatively sharply in the deposited metal zone. In the W3 weld, the hardness of the heat-affected zone and the deposited metal zone was similar in line A and line B, and the hardness was slightly decreased in line C (the second pass) due to high heat input. The maximum hardness of the W1 weld was similar to that of the W3 weld, but the minimum hardness was relatively low. At the same arc heat input, the magnesium vaporized, and the hardness decreased in the W1 weld, but, in W3 weld, the magnesium was also vaporized, but the manganese remained in the deposited metal zone without vaporizing, so the hardness value did not decrease and was relatively high. As a result, the W2 weld showed the lowest hardness value compared to the other welds. The difference between the maximum and minimum hardness at the W1 weld and the W2 weld was relatively more significant than the W3 weld due to the magnesium vaporization in the weld metal. In the W3 weld, the hardness did not decrease moderately, and the deviation was slight because the manganese remained without vaporization.

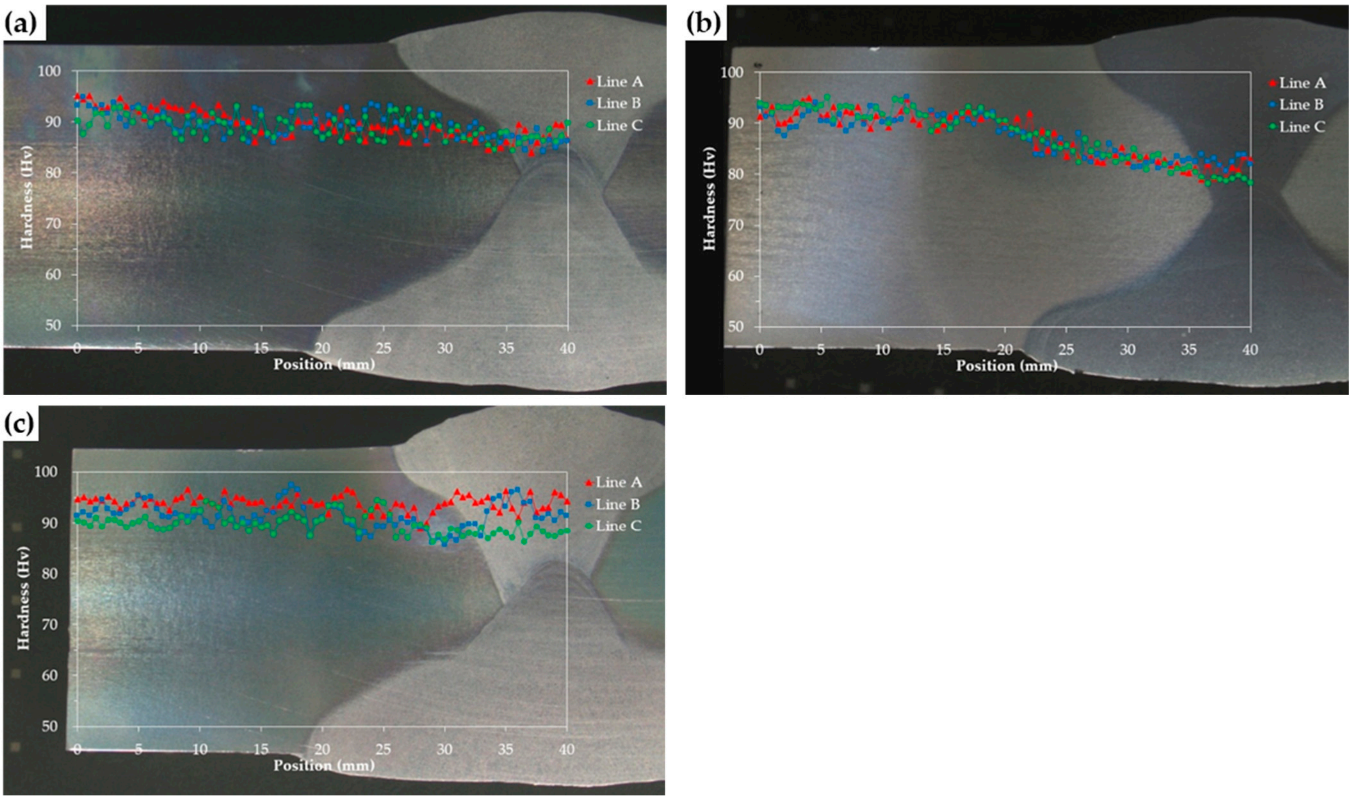

Figure 10. Vickers micro-hardness of aluminum 5083 alloy GMA weld: (**a**) W1; (**b**) W2; (**c**) W3.

The dilution rate of the aluminum 5083 alloy welds was analyzed in relation to their mechanical properties. The dilution value was similar to 55–57%, and there was no significant result.

3.2. Microstructure and Chemical Composition

Figure 11 shows the microstructure observed for each welding pass of every weld. The average grain sizes of the first pass (Figure 11a) and the second pass (Figure 11b) were 39.0 µm and 39.7 µm in the W1 weld, respectively. The average grain sizes of the first pass (Figure 11c) and the second pass (Figure 11d) were 40.1 µm and 40.8 µm in the W2 weld, respectively. The average grain sizes of the first pass (Figure 11e) and the second pass (Figure 11f) were 35.7 µm and 36.3 µm in the W3 weld, respectively. Thus, the grain sizes of the W1 weld and the W2 weld were almost at the same level within the error range, and the W3 weld had the smallest grain size, which was about 10% lower than that of the W1 weld and the W2 weld. According to the Hall–Petch relation [17,18], the smaller the grain size, the more grain boundaries that interfere with the dislocation movement, so greater stress is required for deformation.

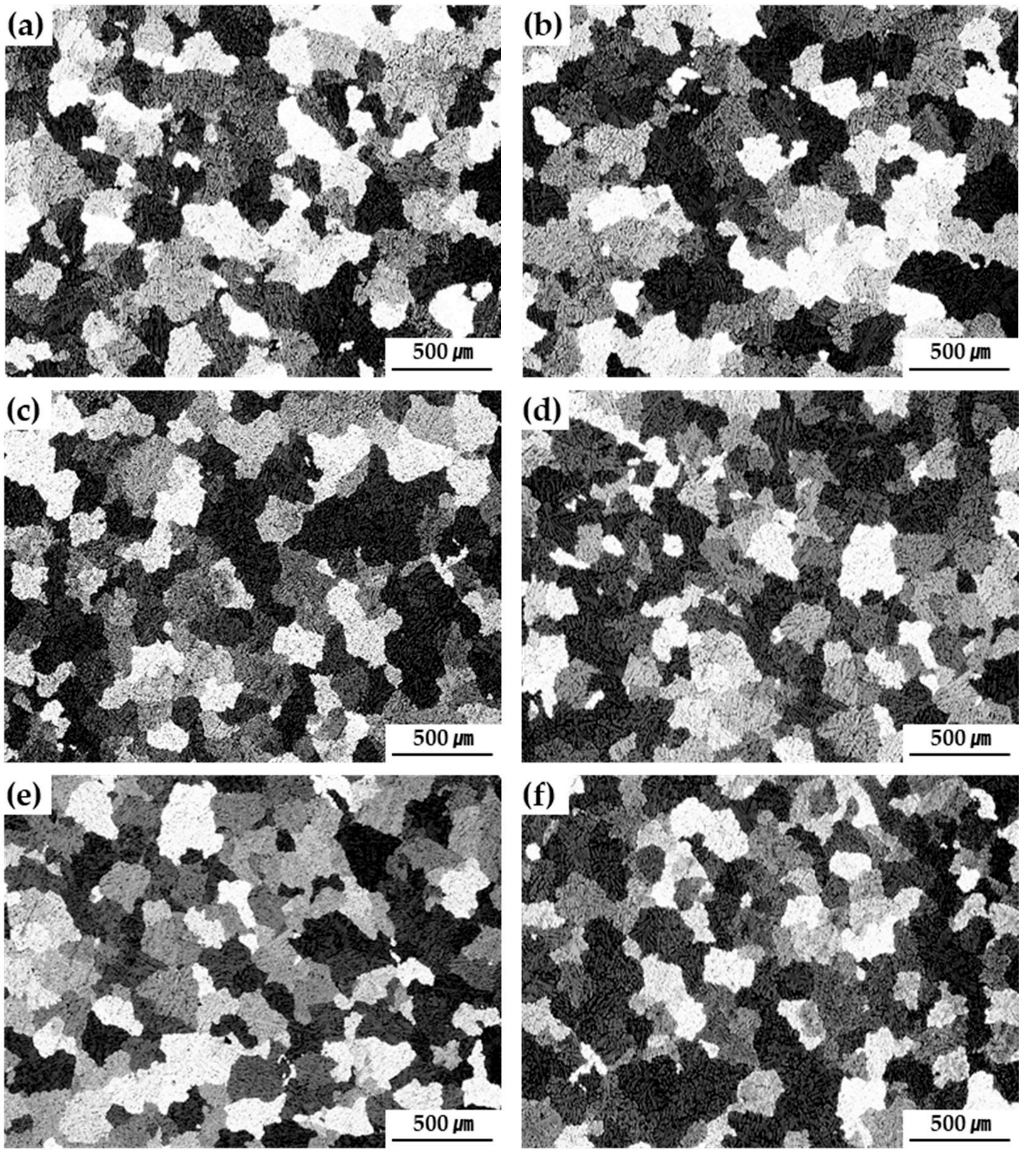

Figure 11. Microstructure by electrolytic etching of aluminum 5083 alloy GMA welds: (**a**) W1-first pass; (**b**) W1-second pass; (**c**) W2-first pass; (**d**) W2-second pass; (**e**) W3-first pass; (**f**) W3-second pass.

Table 4 shows the results of analyzing the chemical composition of the welds. As a result of measuring the chemical composition of the welds, the W1 weld and the W2 weld showed that the magnesium content of the filler wire was different, but the amount of magnesium remaining in the deposited metal zone after welding was not significantly dissimilar. In the filler wire, the magnesium contents of W1 and W2 were different by about 1 wt.%. Still, the content of the deposited metal zone after welding was significantly reduced by about 0.16 wt.% in the first pass and about 0.19 wt.% in the second pass. In the GMA welding process with a high current, the magnesium in the aluminum alloy filler wire is vaporized more than the amount diluted in the deposited metal zone. The added magnesium of the filler wire is vaporized in a large amount during welding, and the magnesium of the base metal is diluted in the deposited metal zone. Similarly, in the W1 weld and the W2 weld, which have almost no manganese content, the measured manganese in the deposited metal zone was diluted from the base metal. The W3 weld had a magnesium content similar to that of the other welds, but the manganese content was over 60% higher. When the tensile strength results (Figure 8) and chemical composition results are analyzed together, it can be seen that the manganese in the filler wire has a positive effect on the improvement of the weld strength after GMA welding and the results of the best tensile strength are shown.

Table 4. Chemical composition of aluminum 5083 alloy GMA welds measured by ICP-OES (wt.%).

	Base Metal		First Pass		Second Pass	
Element	**Mg**	**Mn**	**Mg**	**Mn**	**Mg**	**Mn**
W1	4.271	0.631	4.952	0.363	5.257	0.354
W2	4.264	0.639	4.793	0.360	5.070	0.355
W3	4.232	0.620	4.944	0.606	5.110	0.597

Figure 12 shows the regression analysis results on the magnesium content of filler wire and tensile strength of welds in aluminum 5083 alloy GMA welding. The W1 weld, with almost no manganese (0.003 wt.% or less) and 7.33 wt.% of magnesium, was compared with the W2 weld, with almost no manganese (0.004 wt.%) and 6.38 wt.% of magnesium, and analyzed. The coefficient of determination (R-squared) of the regression formula was 0.05. When the magnesium content of the aluminum alloy filler wire was 6 wt.% or more, the tensile strength and the magnesium content were not linearly proportional. However, as shown in the results of the W2 weld and the W3 weld of Figure 8, when the magnesium content of the aluminum alloy filler wire is higher than that of commercial products (6 wt.% or more), the strength of the weld is improved according to the addition of manganese.

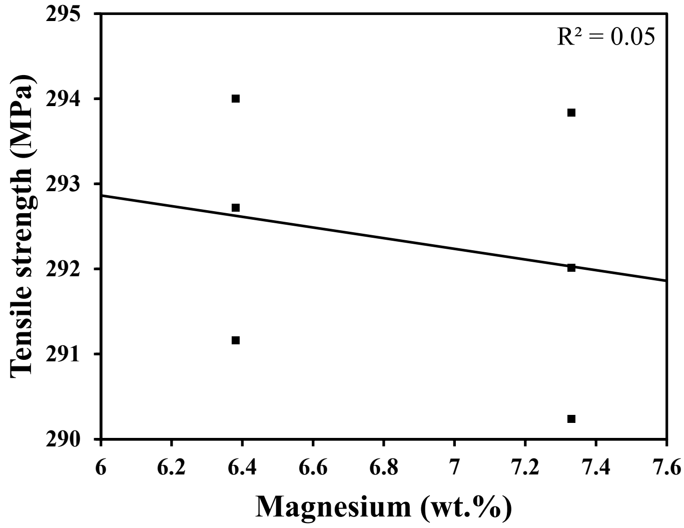

Figure 12. Regression analysis of tensile strength and magnesium content of filler wire in aluminum 5083 alloy GMA welds.

4. Conclusions

In this study, welding was performed using different magnesium and manganese contents of filler wire used for GMA welding of an aluminum 5083 alloy, and the mechanical properties of the weld were analyzed. The detailed conclusion is as follows:

- When an aluminum alloy filler wire (W1) with a magnesium content of 7.33 wt.% and a wire (W2) with a magnesium content of 6.38 wt.% were used, respectively, the tensile strength was similar. As a result of the chemical composition analysis of the two welds, a similar amount of magnesium remained. When the two filler wires are melted during arc welding, the magnesium is vaporized by the high arc heat, and the amount remaining in the deposited metal zone is similar.
- When W2 and W3 were used with similar magnesium contents and different manganese contents of 0.004 wt.% and 0.46 wt.%, respectively, the tensile strength and hardness of the W3 weld were higher. This is for the reason that manganese, like magnesium, has a solid-solution strengthening effect in aluminum alloys because the

boiling point of manganese is relatively high; therefore, vaporization hardly occurs and it remains in the weld.

- As a result of microstructure analysis, the grain size of the W3 weld was the smallest. Since the weld zone, having fine grains, has a larger grain boundary area that hinders the movement of dislocations than the weld zone with coarse grains, the strength of the weld zone of W3 with the finest grains is excellent.
- When the magnesium content of the filler wire used for aluminum alloy GMA welding is high (6 wt.% or more), the manganese content, rather than the magnesium content, had a dominant effect on the strength improvement of the weld.

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