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Effect of shielding gas on microstructure and mechanical properties in AA6061-T6 alloy MIG welding

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ABSTRACT

Due to its properties such as high strength/weight ratio, enhanced corrosion resistance, low density, AA6061-T6 aluminum alloy welding is widely used in structural, automotive and rail industry. In this study, AA6061-T6 alloy was welded with robotic metal inert gas technique using ER5356 filler wire. The effects of different shielding gas composition ratios (argon/helyum) on the macro / microstructre, mechanical properties (hardness, tensile strength) of the weld joint were investigated. Welding porosity decreased with the addition of helium gas to argon gas. Accordingly, the tensile strength of welded joints increased from 190 MPa to 221 MPa with the addition of helium gas. The strength of the welded joints (190-221 MPa) was obtained lower than that of the base material (290 MPa) due to the changes in the microstructure as a result of the weld thermal cycle and grain coarsening in the heat affected zone. Dentritic, columnar and coarse shaped grains were observed along the weld section, respectively in the weld bead, partially melted zone and heat affected zone. The differentiation of the shielding gas composition did not cause these regions to change, but the heat affected zone expanded with the increase in the helium content. The change in hardness of the cross section of welded joint has increased from around 60 HV to 90 HV from the welding area to the base material. 25% Argon-75% Helium gas mixtures provided optimum combination in terms of microstructure, mechanical properties and cost.

Keywords: 6061-T6 Aluminum alloy, MIG welding, Shielding gas, Porosity, ER5356

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1. Introduction

Aluminum alloys are widely used in industry (automotive, aviation, military, transportation, marine, etc.) due to their properties such as high strength / density ratios, lightness and low cost [1,2]. The 6XXX series aluminum alloys that make up the Al-Mg-Si alloy system are increasingly preferred due to their weldability, extrudability, heat treatment capability, corrosion resistance and medium strength values. Excellent mechanical properties can be given to these alloys by forming precipitates containing Mg and Si as a result of T6 heat treatment. Therefore, AA6061-T6 alloy is one of the most widely used alloys in this group [3–5].

Aluminum alloys, especially the 6XXX series alloys, are welded more frequently than non-ferrous metal types due to their good weldability [6]. Friction stir welding, tungsten inert gas welding (TIG), metal inert gas (MIG) welding and plasma welding can be used for aluminum alloy welding [7]. TIG and MIG welding methods, which provide high quality welded joints without the need for any flux and contain inert shielding gases, have made great progress in welding aluminum alloys. MIG welding is more common than TIG welding because it is faster and easier to learn, it is also very popular in non-ferrous metal welding field. In MIG welding, heat is generated by the electric arc between the base material and the consumable electrode, the solid wire electrode is continuously fed into the weld pool [8]. In recent years, MIG welding has been developed for use in hazardous locations with the use of robots. With the robotic MIG welding process, welding parameters (heat input, gas flow rate, welding speed, etc.) can be adjusted more easily and better quality, fast and economical welding can be done [9].

There are various difficulties in welding aluminum and its alloys. Aluminum has a high affinity for oxygen, so the surface is covered with an oxide layer. This can cause oxide residues and porosity during the welding process. Argon (Ar) / Helium (He) mixture is used as shielding gas, the shielding gas must not contain oxygen and hydrogen. The weld pool should be free of oxygen and hydrogen. In addition, the pore problem in aluminum welding is common due to its high hydrogen solubility in liquid state and reversal of this situation in solid state [10]. Before and during welding, possible hydrogen sources (moist surfaces, etc.) should be avoided and the hydrogen gas bubbles entering the weld pool must be allowed to escape. The high thermal conductivity of aluminum leads to insufficient melting defect, especially for thick sections [11]. Pre-heat treatment or higher heat input may be required to prevent this problem. In the welding of 6XXX series aluminum alloys, the filler wire chosen has a significant effect on the welding method and parameters used, microstructure and mechanical properties. For this purpose, many studies have been done to minimize the defects of 6XXX series aluminum alloy welding and to increase its quality. Most of these studies are about the recovery of mechanical properties by post-weld heat treatment [12,13]. In addition, studies were carried out to examine the effect of filling materials on welded joints, in these studies ER4043 and ER5356 electrodes were compared [14,15]. The effects of welding method variables such as pulse MIG welding [11] or the application of hybrid welds to improve weld properties are also included in the literature [16]. In addition, the effects of shielding gas compositions on droplet transfer characteristics, penetration depths, porosity and mechanical properties in aluminum welds have been studied. In general, the combination of Ar / He shielding gas mixture has been successful [17–19].

Since the welding of AA6061-T6 alloy is widely used in the industry, every work in which quality and efficiency is increased is valuable. There are limited studies in the literature that examine the microstructures of these sources in detail (with Scanning electron microscopy-SEM, Energy dispersive spectroscopy-EDS, etc.) [20]. In this study, the effects of different shielding gas compositions on the macro and microstructure, possible defects and mechanical properties of the welded joints of AA6061-T6 alloy were investigated. It has been shown how properties are affected only by changing the shielding gas.

2. Experimental

AA6061-T6 aluminum alloy plate with the dimensions of 150x300x5 mm was welded with metal inert gas (MIG) technique in the butt position with KUKA 6-axis welding robot device using ER5356 filler wire. Chemical contents of base material (BM) and filler wire are given in Table 1. The fact that the BM is T6 indicates that solution treatment and aging processes are performed. The filler metal is selected taking into account the heat treatment response, weldability and compatibility of properties. Since 6XXX series aluminum alloys are susceptible to cracking, they should be welded carefully. 4XXX or 5XXX series aluminum filler alloy is widely used to prevent cracking mechanism [13]. Among these, ER5356 and ER4043 electrodes are the most preferred. ER4043 electrode, whose main alloying element is Si, increases the welding fluidity, is sensitive to cracking, facilitates the welding process. Rich in Mg elements, the ER5356 electrode provides high shear strength, corrosion resistance and toughness [10]. In this study, ER5356 filling material was chosen. Keeping the welding parameters constant (Table 2), the shielding gas compositions (Ar / He) were changed. Five different welded joints were produced, with 100% Ar (OHe), 20% He-80 %Ar (20He), 50% He-50% Ar (50He), 75% He-25% Ar (75He) and 100% He (100He) shielding gas compositions. Before welding, the welding grooves were opened at an angle of 60 ° with a milling machine. Then, after cleaning the surfaces, they are centered so that there is a

2 mm gap between the parts to be joined. After the centering process, a copper base was placed under the plates and the plates were made ready for welding. Welding processes are applied in one pass.

Table 1. Chemical composition of base material and filler wire

Material	Cu	Fe	Si	Zn	Mn	Mg	Cr	Al
AA6061-T6	0.15-0.4	0.70	0.4-0.8	0.25	0.15	0.8-1.2	0.04-0.3	Balance
ER5356	0.1	0.40	0.25	0.10	0.05-0.20	4.5-5.5	0.05-0.20	Balance

Table 2. Welding parameters

Base Material (BM)	EN AW 6061 T6
Method	MIG
Plate thickness	5 mm
Filler metal	ER5356 (AlMg5)
Ampere	180A-220 A
Voltage	20-23,8 V
Wire speed	13.800 mm/min
Welding speed	1000 mm/min
Current type/ pole	DC(+)
Gas flow	17 l/min
Filler metal diameter	1,2 mm

Then, 20 mm was cut from the beginning and end parts of the weld and the remaining part was prepared for tensile test, macro examination, microstructure examination and hardness measurements. For macro studies of welded joints, the weld sections were metallographically sanded and polished, then etched with a NaOH solution and the section was examined with an optical microscope (Nicon Eclipse L50). The shape and dimensions of the weld and the pores in the section were examined. For microstructural studies, after metallographic preparation, etching was done using Keller reagent (50 ml H_2O, 1 ml HCl, 1.5 ml HF, 2.5 ml HNO_3). Weld metal (WM), partially melted zones (PMZ), heat affected zones (HAZ) and base metal (BM) of welded joints were investigated. In addition, SEM (Jeol JSM 6060LV) and EDS analyzes were performed to interpret the microstructure in more detail.

The samples for the tensile test were prepared by processing with a milling machine in accordance with the TS 138 EN 10002-1 standard. Five tensile tests for each sample were performed using the Instron 300DX device (1mm / min tensile speed), the results were averaged. Microhardness was measured from the surface of welded sections at a depth of 0.5 mm and at 2 mm intervals (200 g load, 10 sec wait) from WM, HAZ, BM regions with Matsuzawa MHT2 hardness tester.

3. Results and discussion

3.1. Microstrucrutes

One of the biggest problems in aluminum welding is the formation of pores. This is because the dissolved hydrogen cannot escape from the weld bath during solidification. Reasons such as high humidity and poor surface preparation are sources of hydrogen. When solidification occurs (approximately 660˚C), there is a sudden increase in hydrogen solubility, whereas in solid state, hydrogen solubility ratio is low. When cooling is fast, hydrogen in aluminum cannot escape and creates pores [21]. The high thermal conductivity of aluminum and its alloys, high hydrogen solubility in the molten state, low solubility in the solid state, the lack or less solidification range causes pore formation or lack of melting. In order to prevent these problems, preheating or increasing the arc temperature is required.

Before the microstructural examinations of the welded parts, defects such as lack of penetration and porosity of the WM and HAZ regions were examined by macrostructure control. As seen in Figure 1a-e, as the amount of helium gas used in the welding process decreased, the porosity rate increased. For OHe sample (Figure 1a), in macro investigations, intensive pores are observed in the WM and the partially melted zone (PMZ), which is the WM-BM junction. Looking at Figure 1, no penetration deficiency has been observed for all welded samples. It can be seen that as the amount of helium increases, the accumulation in the WM increases (for the cap and root) and the WM expands. The effect of helium on the pore and weld shape observed in Figure 1 is consistent with the literature. [19]. Helium gas has higher thermal conductivity and ionization energy than Argon gas, thus increasing the molten pool temperature during the welding process. Increased heat input allows hydrogen gas bubbles to escape from the molten pool and increases weld penetration depth [19]. Therefore, the use of helium gas also allows higher welding speed. In addition, the addition of helium can be considered to increase the corrosion resistance of the weld zone, since it reduces the porosity ratio. [22]. However, helium is lighter than argon and requires more gas. This increases the cost. In the use of mixed gas, the combined effect of oxide decomposition, arc concentration-condensation characteristics of Argon and arc expansion of Helium occurs. [21]. By adjusting the shielding gas composition, heat distribution, weld metal shape, welding speed can be changed.

The microstructures of the welded parts were examined. With the change of shielding gas ratio, there was no significant structural change, except for the expansion of WM and HAZ regions. For this reason, for microstructure evaluations, only microstructure images of the WM, HAZ and BM regions of the 50He sample are given in Figure 2. Generally, microstructures are compatible with structures formed in MIG welding. AA6061-T6 (BM) is a heat treated alloy, sensitive to thermal cycling [6]. Aluminum alloys of the 6XXX series are known to have a strong over-aging tendency during welding, especially in the fully aged (T6) state [10]. In the molten weld pool, phases accumulate on the partly molten base metal grains by epitaxial solidification. Welding metal consists of ER 5356 electrode and base metal. Grains are coaxial and thin, with dendritic structure in the center of the WM (Figure 2a). In addition, intermetallic particles dissolve in the weld metal or it is thought that low melting point phases with Si-Mg content segregate to the grain boundaries. The reason for the formation of dendritic microstructure is the solidification and cooling rate. In Figure 2d, it is observed that the dendrite arms are partially melted in the WM region. It is also known that alloying elements such as Mn, Cu, Cr in ER5356 electrode have a grain refining effect. [23]. Pores (black circle) are seen in the fusion region, which is quite common in aluminum alloys. In the PMZ, the grain structure is coarse and columnar, unlike the WM (Figure 2b, Figure 2e). Some grain coarsening can be seen in the HAZ area (Figure 2e). The width of the PMZ and HAZ can be controlled by the heat input generated in the WM. HAZ covers the region between the melting temperature of the alloy and the artificial aging temperature [10]. Depending on the thermal cycle, the HAZ can be divided into two zones, the part close to the weld metal exposed to the solution temperature (530-570 ° C) and the part close to the base metal exposed to extreme aging temperature (100-300 ° C) [13]. PMZ microstructure tends to naturally age. The temperature drops towards the base metal and an excessive aging zone occurs. In the over-aging zone, precipitates containing Mg-Si are expected. The precipitates can dissolve in and near WM by the effect of heat during the welding process. Different shades in the microstructure indicate different concentrations of Aluminum solid solution grains. The BM microstructure has a homogeneous distribution (Figure 2c, Figure 2f). The dark etched regions are thought to represent the low melting point phases, while the lightly etched regions represent the aluminum solid solution. The dissolution of the phases is due to high temperatures. Phase segregation depends on temperature and composition. The EDS results given in Table 3 were taken from the grain inside (GI), grain boundary (GB) and precipitates (P) of WM, HAZ and BM, respectively, in the SEM images (Figure 2d-f). Since the WM region consists mainly of the ER5356 electrode, the Mg content decreases from the WM region to the BM. In addition, the amounts of alloying elements (Mg, Si, Fe, Cr) are slightly higher in the grain boundaries than in the grain for all three regions (WM, HAZ, BM). This shows the segregation of alloying elements at grain boundaries.

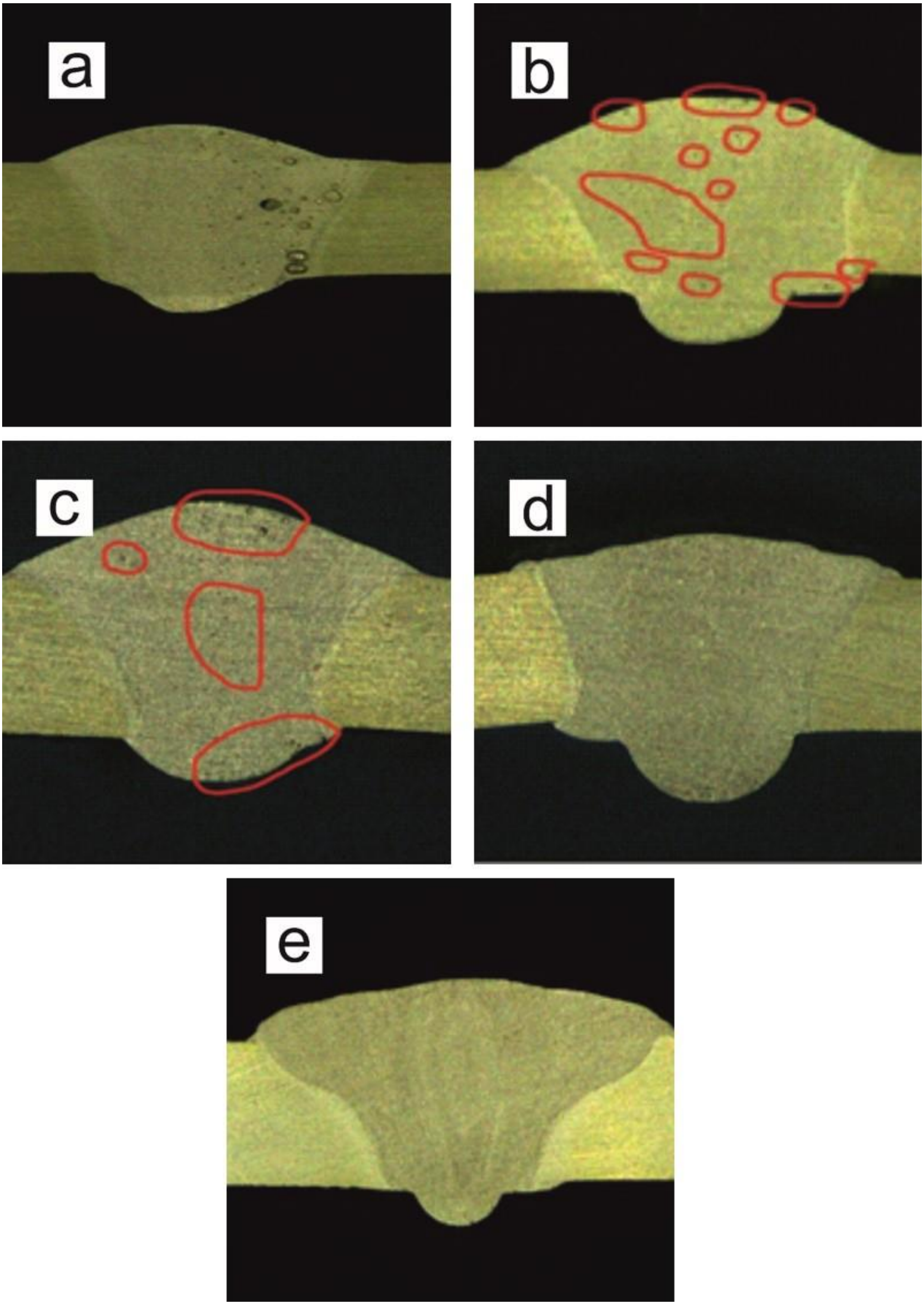

Figure 1. Macro images of a) OHe, b) 25He, c) 50He, d) 75He and e) 100He welded parts

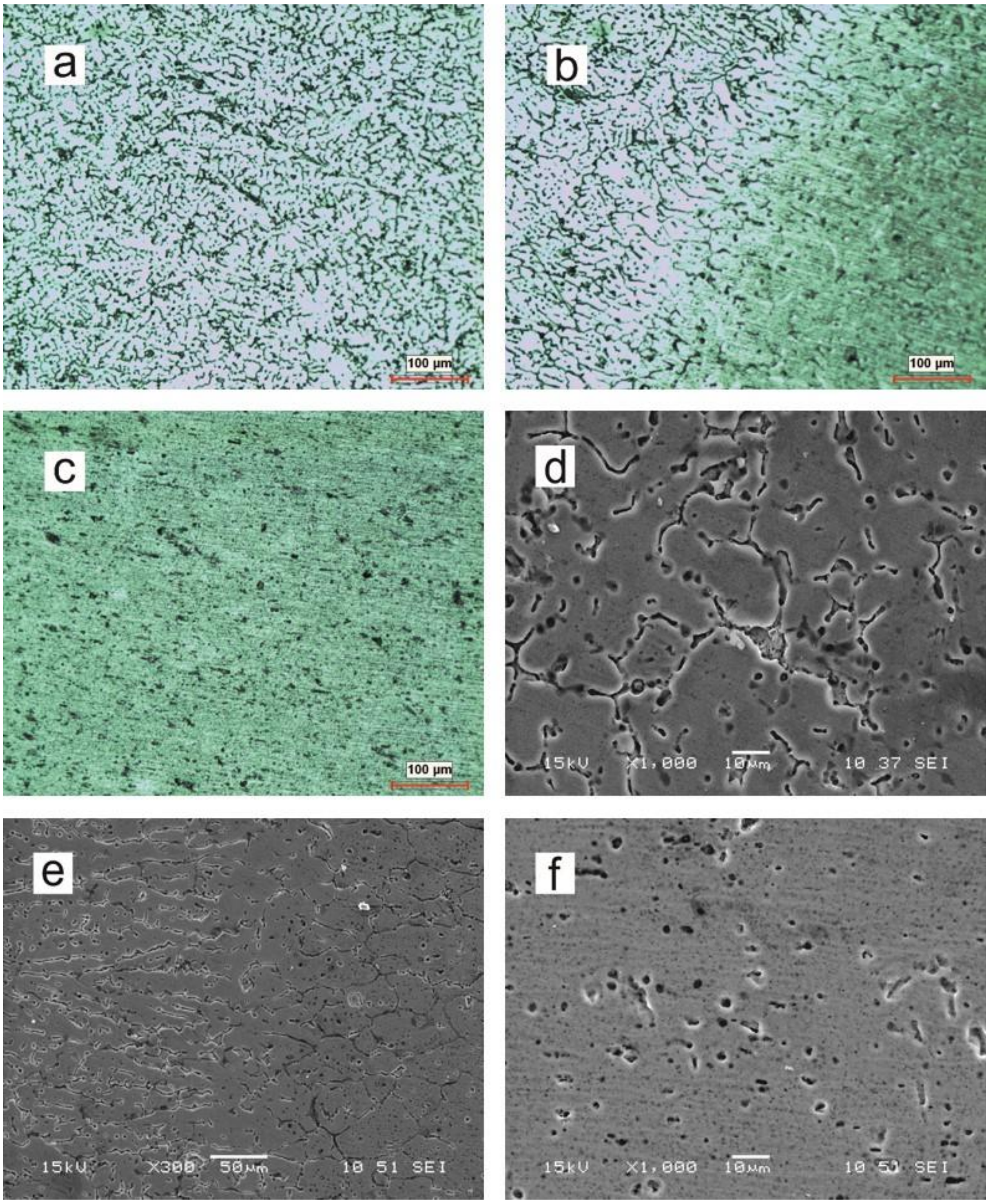

Figure 2. Images of optical (a) WM, b) HAZ, c) BM) and SEM (d) WM, e) HAZ, f) BM) microstructures of the section of 50He welded part

Due to the high temperature in the WM, the precipitates dissolved. However, some deposits were found in the HAZ and BM regions due to the welding process thermal cycle and the characteristics of the AA6061-T6 base material. Looking at the EDS results, while the Al content of these deposits decreased, the alloying element content increased (Table 3).

Table 3. EDS results of the weld cross section of the 50He welded part (wt.%)

Region		Al	Mg	Si	Cr	Mn	Fe	Cu	Zn
WM	GI	97.317	1.496	0.012	0.418	0.050	0.170	0.260	0.278
	GB	95.308	3.062	0.045	0.404	0.444	-	0.295	0.443
HAZ	GI	97.071	2.028	0.116	0.186	0.023	0.063	0.101	0.412
	GB	95.941	2.030	0.014	0.33	0.171	0.119	0.896	0.499
	P	86.277	2.183	9.423	0.3	0.171	0.433	0.006	0.206

Region		Al	Mg	Si	Cr	Mn	Fe	Cu	Zn
BM	GI	97.283	1.011	0.106	0.205	0.218	-	0.088	0.088
	GB	96.956	1.046	-	0.282	0.218	0.312	0.432	0.753
	P	86.854	0.664	0.282	0.719	0.246	8.701	0.870	1.664

3.2. Mechanical properties

Figure 3 shows the microhardness profiles of welded joints containing different shielding gas compositions. It is seen that there is a significant change in hardness from the WM region towards the BM region. Hardnesses of approximately 62-65HV, 65-77HV and 80-90HV were measured for regions WM, HAZ and BM respectively. The WM hardness corresponds to the hardness of the WM in a previous MIG welding study using the ER5356 filler wire [24]. The hardnesses of the AA6061-T6 and HAZ regions are also approximately consistent with the literature. [16]. With the increase of helium gas in the shielding gas composition used in welded connections, the heat input increased and the HAZ expanded, the hardness distributions in Figure 3 proved this. In the WM region, there is a decrease in hardness due to alloy segregation at the grain boundaries, dendritic grains, complete dissolution of hardening phases at temperatures above 500 ° C, loss of alloying elements due to high weld pool temperature [16]. Generally, in 6XXX series aluminum alloys, as a result of heat input during welding, hardness decrease is observed in the HAZ region as a result of excessive aging [20,25]. The softening mechanism in the HAZ zone is an expected result in precipitation hardening alloys when subjected to weld thermal cycling. In the HAZ zone, mechanical properties decrease in temperature ranges where β^{I} precipitate begin to grow (250-300 ° C) and equilibrium β phase is formed (380-480 ° C). The hardness of the HAZ region can be increased to the range of 80-84 HV by forming β^{II} precipitates by post-welding heat treatment (180-200 ° C) [11]. In previous studies, after heat treatment, even the hardness of the ER5356 weld fill area increased from about 60 HV to 80HV [13]. In addition, grain thinning processes such as using pulsed current in welding or multi-pass applications can increase the mechanical properties [3].

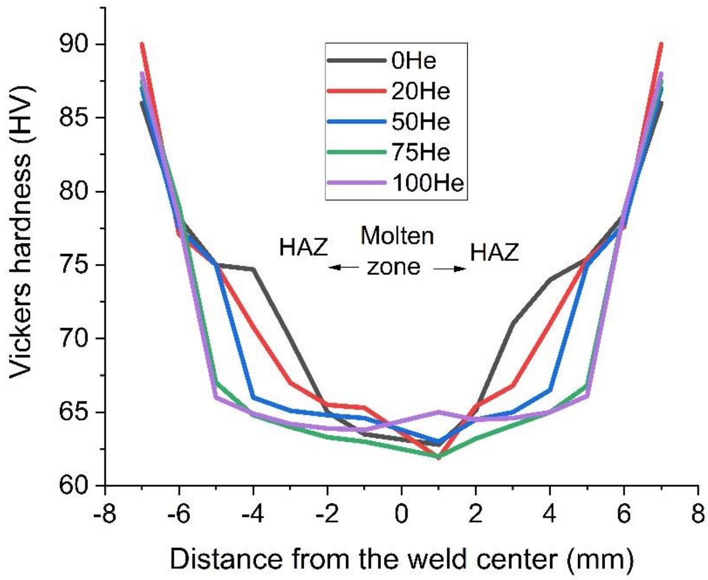

Figure 3. Microhardness distribution of welded joints

Tensile test results of AA6061-T6 alloy and welded joints are given in Table 4. Yield, tensile strength and percent elongation of AA6061-T6 alloy were obtained, respectively, 240 MPa, 290 MPa and 20%. The strength and elongation values of the welded joints have decreased compared to the base material. As a result of the thermal cycle during welding, the decrease in strength due to microstructure change is an expected result. In the weld joint where the helium content is used medium or high (50-100%), the yield strength is increased by about 28% compared to the welded joint containing little (%20) or no Helium in the shielding gas composition. The reason for this difference is that the increased helium content has a porosity-lowering effect. Fracture occurred in the WM region due to the presence of pores when the helium content was low (20%) or absent. In the weld joint with 50-100% helium shielding gas content, fracture occurred in the HAZ region due to grain coarsening and residual stresses. In this way, breaks occurred in the areas most susceptible to damage. In studies related to welding connection in the literature, fractures occurred in WM or HAZ regions where the strength was the lowest [4]. In order to improve the mechanical properties of welded joints, aging heat treatment is recommended, which provides the formation of precipitation and makes the structure homogeneous.

Table 4. Tensile test results of base material and welded joints

	Yield strength (MPa)	Ultimate strength (MPa)	Strain (%)
0He	110,77525	190,65184	7,04641
20He	116,05824	201,15717	6,94708
50He	155,18219	219,06119	7,5888
75He	156,06355	220,19017	5,19600
100He	160,85293	221,18144	5,57784
BM	240	290	20

4. Conclusions

The joining of AA6061-T6 alloy was made by MIG welding method in different shielding gas compositions. Accordingly, macro / microstructure studies and mechanical properties of welded joints were examined.
Due to the high thermal conductivity and ionization energy of the He gas, the porosity ratio in the weld joint decreased with the increase of He content in the shielding gas composition. No pores were found in the macro examinations of welded joints using shielding gas in 75% and 100% content of helium.
Dendritic / fine grained structure, columnar extending grains, coarse grains were observed in all welded joints for the WM, PMZ and HAZ regions, respectively. The increase of helium content in the shielding gas composition caused the HAZ width to increase. The precipitation phases in which alloying elements (Mg, Si, Fe, Cr) are increased in the HAZ and BM regions have been determined. Due to the temperature increase in the WM and PMZ zone, the precipitates dissolved. In welded joints, segregation of alloying elements has been found at the boundaries of the grains.

The hardness distributions in the cross sections of the welded parts differed according to the microstructure change caused by the thermal cycle. The hardness has increased from about 60 HV to 90 HV from the WM region towards the BM region. The tensile strength of the base material (290 MPa) was found higher than the welded joints (190-221 MPa). With the increase of helium content used in welded joints, the strength increased due to the decrease in the porosity ratio. Considering the microstructure, mechanical properties and cost, it can be said that 25% Argon-75% Helium shielding gas content is the most appropriate composition.

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