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Mechanical Properties of Metal Inert Gas Welding Conditions of Railway-Vehicle Aluminum Under Frame

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철도차량 Al 하부구조의 MIG 용접 조건에 따른 기계적 특성에 관한 연구

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ABSTRACT

In this study, the mechanical properties of railway-vehicle aluminum under frame was investigated based on the metal inert gas (MIG) welding conditions. An aluminum-alloy (6005A-T6) extruded material used in the lower panel of a railway vehicle was connected through MIG welding to determine the mechanical properties of MIG welds. Argon shielding gas and filler materials, such as ER5356 and ER4043, were used as consumable welding materials. For the welding conditions of the test specimen, welding frequencies of 2.5 and 4.5 Hz were applied using the SynchroPuls function, and the root faces were 1.0 and 1.5 mm. The mechanical properties of the MIG welds were determined through tensile, bending, and fatigue tests.

Key Words : Railway Vehicle(철도차량), Aluminium Welding(알루미늄 용접), Welding Condition(용접 조건), Mechanical Properties(기계적 특성), MIG Welding(MIG 용접)

1. Introduction

Worldwide, most railway vehicles, such as high-speed trains, electric trains, and light-rail trains used for passenger transportation, are mainly operated using electric energy, except for diesel multiple units and locomotives that use fossil fuel.

In the case of high-speed trains, in particular, efforts have been made to increase the maximum operating speed to minimize the travel time of the passengers. Furthermore, reducing the weight of the trains is essential to save the electric energy required for their operation. Stainless steel, which is mainly used in the body of electric vehicles, has a specific gravity of approximately 7.9. Comparatively, aluminum alloys have approximately 66% lower specific gravity (approximately 2.7), and thus, they are more favorable for reducing the weight of high-speed trains. Compared to the steel body of the

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high-speed trains initially introduced in South Korea, the high-speed trains that applied aluminum alloys effectively reduced the weight by approximately 13% (1,200 kg).

Fig. 1 demonstrates a cross-sectional view in the width direction of a railway vehicle made of aluminum alloys. The railway vehicle comprises an under frame, a side frame, a roof frame, a cab frame, and an end frame. Each structure is fabricated as a sub-assembly, and then, a large assembly, that is, a finished vehicle, is produced.

A railway vehicle is a large structure with a length of approximately 20 m. When the base panel sub-assembly of its aluminum under frame is assembled through welding, MIG welding, which is approximately three to four times faster than TIG welding[1], is mainly applied to approximately eight weld joints in the upper and lower parts of the entire vehicle considering welding productivity. Of course, the applicability of friction stir welding (FSW), which causes relatively small welding deformation and improves the defects of MIG welding, as a welding method that can partially replace the MIG welding method has been examined, but it has not been applied to domestic railway vehicle production owing to excessive initial investment cost and a need to apply the new design to the welded joint structure and to develop tools.[2–4] In addition, automated welding systems have been applied for mass welding production with consistent quality, but welded products may not be used if welding defects occur owing to the improper setting of essential variables for welding, such as the preset welding method, filler metal[5], welding current/voltage conditions, welding speed, and protective gas[6]. In a related earlier study, Jung et al.[7] derived appropriate welding ranges suitable for production using comparative research and experiments on the welding process essential variables of the 6005A-T6 base panel sub-assembly located in the under frame of a railway vehicle, such as the filler metal, pulse frequency (variation width) input value of the SynchroPuls function of the welding machine, root face of weld joints, welding current, and voltage conditions.

Based on the welding conditions confirmed by the earlier study, in this study, tests on the mechanical properties of welding specimens were conducted under insufficient welding conditions to present optimal welding conditions for product production, and fatigue tests were conducted to verify welding durability.

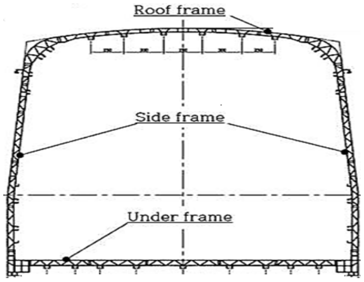


Fig. 1 Cross-section view of aluminium railway vehicles

Table 1 Welding variable for welding coupons

Section		Fixed variable	Testing variable
Welding method	Process	MIG(Pulse)	-
	Type	Auto welding	-
	CTWD	16 mm	-
Welding machine	Synchro -Puls	-	2.5Hz&4.5Hz
Welding joint	V-Groove angle	70˚(35˚×2)	-
	Thickness	4.5 mm	-
	Root gap	0~0.2 mm	-
	Root face	-	1.5mm&1.0mm
Parent material spec.		6005A-T6	-
Polarity		DCEP	-
Welding position		PA	-
Filler metal	Spec.	-	ER5356& ER4043
	Diameter	∅1.2 mm	-
Shielding gas	Type	Ar 99.99%	-
	Flow late	25 ℓ/min	-
Welding speed		62 ㎝/min	-
Welding coupon type		-	Upper&Lower

2. Experiment Contents and Method

Based on the results of earlier studies, in this study, inappropriate welding conditions (×) were excluded, and welding specimens were prepared for 23 excellent welding conditions suitable for production (○) and 22 welding conditions that satisfy quality criteria but are difficult to apply to production (△) to evaluate mechanical properties according to MIG welding conditions.[7] The mechanical properties of the prepared welding specimens were evaluated using tensile and bending tests. Under the finally selected optimal welding conditions for production, specimens were prepared and fatigue tests were conducted to verify their durability.

Fig. 2 depicts the positions of mechanical property specimens. For tensile specimens, three specimens were prepared for each variable condition in accordance with the plate specimen standard of KS B ISO 4136. The bottom weld bead was removed, but the top bead was not removed. For bending specimens, two face bend specimens and two root bend specimens were prepared for each variable condition in accordance with the bending test standard of KS B ISO 5173.

Fig. 3 illustrates the geometry of a weld joint. The upper and lower parts are identical, and single-pass welding was applied. Fig. 4 depicts the external geometry of a specimen that completed welding to prepare a mechanical property specimen.

Fig. 5 shows the upper and lower parts of a welding specimen.

Table 2 presents the welding conditions classified into three items in terms of production applicability based on the quality of earlier research results. Table 3 presents the acceptance criteria for the mechanical properties of the 6005A-T6 alloy and the test results of the actual raw material.

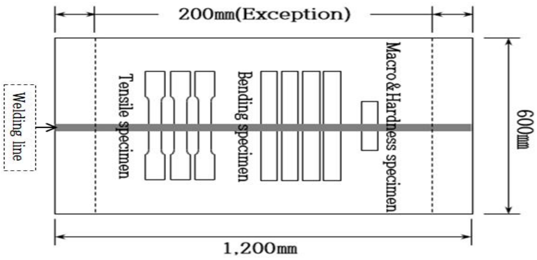


Fig. 2 Location of test specimens for mechanical properties testing on welded aluminium profile

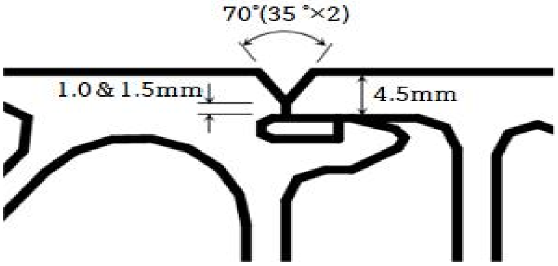


Fig. 3 Detail of welding joint

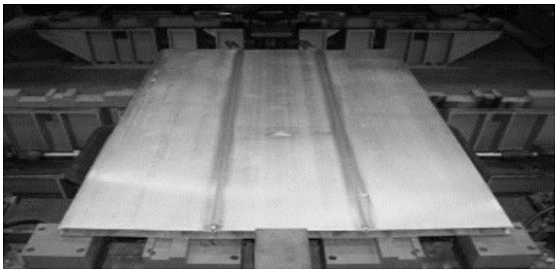


Fig. 4 Welded coupon for mechanical property testing

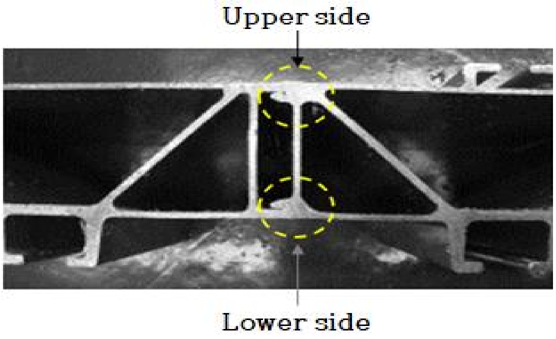


Fig. 5 Upper and lower of welded coupon section

Table 2 Classification of three different welding quality

Section		ER5356				ER4043			
	Sync. Hz	2.5Hz		4.5Hz		4.5Hz		2.5Hz	
	R/F(mm)	1.5	1.0	1.5	1.0	1.5	1.0	1.5	1.0
Lower	150A,20V		×		×		×		△
	160A,20.5V		×		○	△	△	×	△
	170A,21V	×	×	△	○	△	×	×	△
	180A,21.5V	×	×	○	×	△	×	△	×
	190A,22V	○	△	○	×	×		△	
	200A,22.5V	○		○		×		△	
	210A,23V	○		○					
Upper	165A,20.5V						×		×
	175A,21V		×		○	△	×	×	×
	185A,21.5V	×	△	○	○	△	×	×	×
	195A,22V	○	○	○	○	△	×	△	×
	205A,22.5V	○	○	○	×	△	△	△	×
	215A,23V	○	○	○	×	×		△	
	225A,24V	○		△					

Table 3 Acceptance criteria of tensile testing and hardness testing for 6005A-T6 base metal

Sec.	T/S (N/mm²)	Y/S (N/mm²)	EL (%)	Hardness (Hv)
Spec.	Min. 255	Min. 215	Min. 6	Min. 98
Act.	272~275	238~242	7.4~9	107~109

3. Experiment Results and Optimal Welding Conditions

3.1 Tensile test

A hydraulic servo type universal testing machine from Kyoungsung Testing Machine Co., Ltd. (Model KSU-50HSO) was used to conduct the tensile test.

The test was conducted in accordance with the KS B 0802 standard, and three specimens were tested for each variable condition. The acceptance criteria for the tensile test of the weld joint of the aluminum extruded material are presented in Table 4. Both 22 conditions with insufficient production applicability (△) and 23 excellent conditions (○) exhibited satisfactory results as they exceeded the acceptance criteria.

Table 4 Acceptance criteria of tensile testing of welded 6005A-T6 alloy

Sec.	T/S(N/mm²)	Y/S(N/mm²)	EL(%)
Spec.	Min. 165	Min. 115	Min. 3

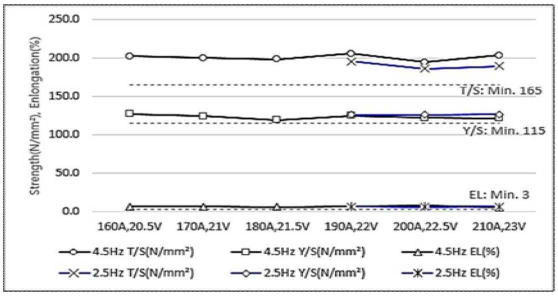


Fig. 6 Each average value of tensile testing result for lower side welding by ER5356

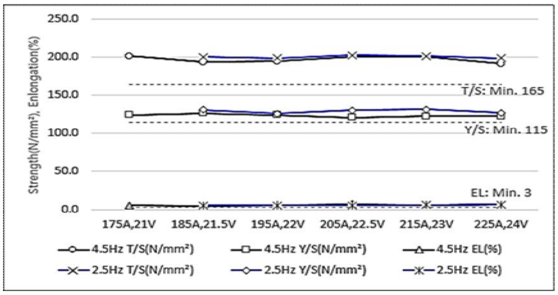


Fig. 7 Each average value of tensile testing result for upper side welding by ER5356

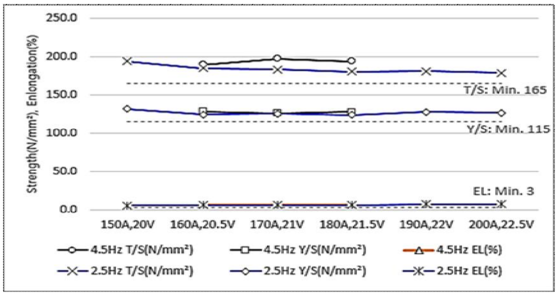


Fig. 8 Each average value of tensile testing result for lower side welding by ER4043

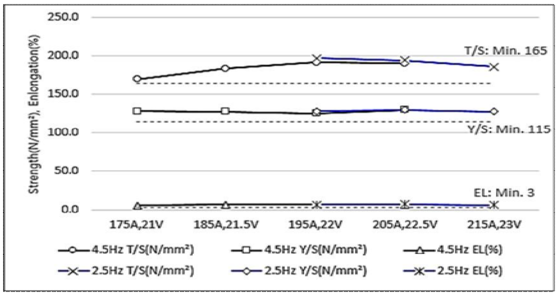


Fig. 9 Each average value of tensile testing result for upper side welding by ER4043

Figs. 6, 7, 8, and 9 depict the results of comparing increments and decrements for the average value under each condition. As the welding voltage and current conditions increased, the tensile or yield strength exhibited insignificant differences with no significant tendency.

On the completion of the tensile test, the 160 A, 20.5 V, R/F 1.5 mm, and 4.5 Hz conditions that used the ER4043 filler metal exhibited a fracture at the weld joint as shown in Fig. 10(a). This was because the molten metal flowed excessively into the joint during welding and flattened the top weld bead, thereby reducing the cross-sectional area. Under all the other conditions, a fracture occurred at a position approximately 6 to 9 mm away from the weld center toward one side, as demonstrated in Fig. 10(b). This range is the softening zone where strength and corrosion resistance rapidly decrease as the artificially aged alloy is heated to a temperature above the aging temperature owing to welding.

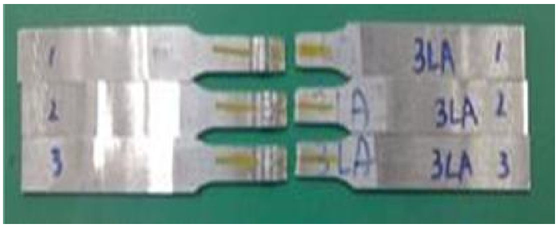
The 6005A-T6 alloy has excellent extrudability, but is known to exhibit approximately 40% lower yield and tensile strengths when welded because it is an age-hardenable alloy.

In this study, the 6005A-T6 alloy also exhibited a reduction in tensile and yield strengths after welding. The results of the tensile test on the raw material of the 6005A-T6 alloy exhibited an average tensile strength of 273.5 N/mm², average yield strength of 240 N/mm², and average elongation of 8.2%.

Tables 5, 6, 7, and 8 present the lowered tensile test values and ratios after welding by dividing the average values of the test results for the main variables into the minimum and maximum ranges and comparing them with the tensile test results of the raw material.

The test results of the specimens that applied the raw material, ER5356, and ER4043, including tensile strength, yield strength, and elongation, were derived as follows.

(a) Fracture of weld zone



(b) Fracture of heat affected zone

Fig. 10 Comparison of fracture location after tensile testing

Table 5 Percentage of decrease in tensile test value compared to raw material of welded coupon by ER5356, 2.5Hz

Sec.	ER5356, 2.5Hz	Compared ratio(Min.~Max.)		
		T/S (N/mm²)	Y/S (N/mm²)	EL (%)
Lower	190A,22V ~210A,23V	68.2%~71.6% (186.5~195.8)	52.5%~52.9% (126.1~126.9)	78%~86.2% (6.4~7.1)
Upper	185A,21.5V ~225A,24V	72.6%~74.1% (198.7~202.7)	52.4%~54.7% (125.7~131.4)	69.9%~85.4% (5.7~7.0)

Table 6 Percentage of decrease in tensile test value compared to raw material of welded coupon by ER5356, 4.5Hz

Sec.	ER5356, 4.5Hz	Compared ratio(Min.~Max.)		
		T/S (N/mm^2)	Y/S (N/mm^2)	EL (%)
Lower	160A,20.5V ~210A,23V	71.2%~75.2% (194.8~205.6)	49.8%~53.1% (119.5~127.4)	78%~97.6% (6.2~8)
Upper	175A,21V ~225A,24V	70%~73.7% (191.6~201.5)	50.4%~52.8% (120.9~126.8)	67.5%~91.9% (5.5~7.5)

Table 7 Percentage of decrease in tensile test value compared to raw material of welded coupon by ER4043, 2.5Hz

Sec.	ER4043, 2.5Hz	Compared ratio.(Min.~Max.)		
		T/S (N/mm^2)	Y/S (N/mm^2)	EL (%)
Lower	150A,20V ~200A,22.5V	65.4%~71% (178.9~194.3)	51.8%~54.9% (124.2~131.8)	67.5%~91.1% (5.5~7.5)
Upper	195A,22V ~215A,23V	68%~72.1% (186~197.1)	53.2%~54.2% (127.8~130.1)	75.6%~90.2% (6.2~7.4)

Table 8 Percentage of decrease in tensile test value compared to raw material of welded coupon by ER4043, 4.5Hz

Sec.	ER4043, 4.5Hz	Compared ratio.(Min.~Max.)		
		T/S (N/mm^2)	Y/S (N/mm^2)	EL (%)
Lower	160A,20.5V ~180A,21.5V	69.4%~72.3% (189.9~197.7)	52.6%~53.5% (126.4~128.4)	75.2%~82.1% (6.2~7.4)
Upper	175A,21V ~205A,22.5V	62.1%~70.1% (169.9~191.7)	52.3%~54.1% (125.5~129.8)	69.1%~85.4% (5.7~7.0)

Compared to the average tensile strength of the raw material, the tensile strength of the specimens that applied ER5356 ranged from 68.2% to 75.2%, showing an average tensile strength reduction of approximately 28% (77.5 N/mm^2). The tensile strength of the specimens that applied ER4043 ranged from 62.1% to 72.3%, indicating an average tensile strength reduction of approximately 33% (89.7 N/mm^2) compared to that of the raw material. In addition, the average tensile strength of the ER5356 filler metal was approximately 4% (7.9 N/mm^2) to 9.8% (16.6 N/mm^2) higher than that of the ER4043 filler metal.

Compared to the average yield strength of the raw material, the yield strength of the specimens that applied ER5356 ranged from 49.8% to 54.7% (131.4 N/mm^2), showing an average yield strength reduction of approximately 48% (114.6 N/mm^2). The yield strength of the specimens that applied ER4043 ranged from 51.8% to 54.9%, indicating an average yield strength reduction of approximately 46% (112 N/mm^2) compared to that of the raw material. In other words, ER5356 and ER4043 exhibited an insignificant difference of approximately 2% in terms of the yield strength reduction.

Compared to the average elongation of the raw material, the elongation of the specimens that applied ER5356 ranged from 67.5% to 97.6%, indicating an average elongation reduction of approximately 18% (EL 1.5%). The elongation of ER4043 ranged from 67.5% to 91.1%, exhibiting an average elongation reduction of 21% (EL 1.7%) compared to that of the raw material.

3.2 Bending test

The bending test was also conducted using the same equipment as the tensile test. The test was conducted in accordance with the KS B ISO 5173 standard, and two face bend specimens and two root bend specimens were used.

Bending specimens were prepared for 22 conditions with insufficient production applicability (△) and 23 excellent conditions (○) to conduct the bending test, similar to that in the tensile test. The acceptance criterion of the bending test required the bent surface to not exhibit any crack after a bending test of at least 90° was conducted for the center of the weld joint.

Fig. 11(a) shows an example of the crack generated during the bending test. During the root bend test under the 160 A, 20.5 V, R/F 1.0 mm, and 4.5 Hz conditions for the lower part that used the ER4043 filler metal, a 1 mm crack was confirmed in the weld joint of the specimen. This appeared to be because the micropores formed inside the weld joint during welding were grown by the bending test.

The other bending test results were excellent with no defect in the welding range. Fig. 11(b) illustrates the geometry of an excellent specimen for which the bending test was completed with no crack.

3.3 Optimal welding conditions

Among a total of 78 welding conditions, 45 welding conditions (22 insufficient conditions and 23 suitable conditions), excluding unsuitable conditions in the weld bead appearance and macro analysis results, exhibited excellent results that satisfied the quality criteria in the analysis of mechanical properties, such as tensile and bending tests.

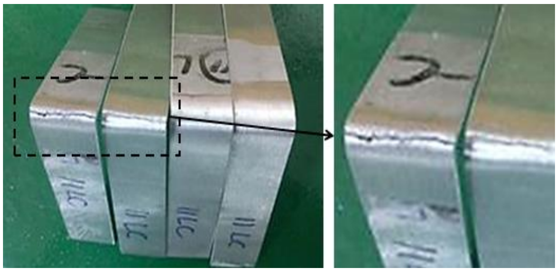
The selection criteria for optimal welding conditions in the earlier welding experiments were as follows.

First, three or more suitable (○) welding current and voltage conditions had to be continuously distributed based on the welding experiment item. Robust and appropriate welding conditions suitable for production had to maintain appropriate quality even though there were sensitive changes in process variables that affected welding current and voltage conditions during welding production. The welding current and voltage conditions expressed in the experiment were the average output values of the welding machine. They were in the range of up to approximately 10% from the average value and in the range of ±5 A when stabilized during the arc generation for welding, excluding the current and voltage changes at the beginning and end of the arc.

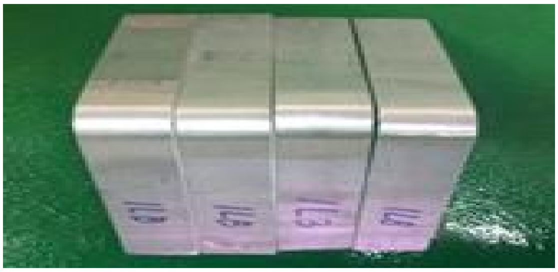
Second, one type had to be applied for the filler metal specification of the upper and lower parts for the base panel aluminum extruded material for consistent quality management for the weld joint of the finished product.

Third, the preferred root face of the weld joint was 1.5 mm. The design specification of the weld joint applied to several railway vehicle projects has a root face of 1.5 mm. The root face of 1.0 mm was considered as a welding experiment variable to improve weldability, but it was observed that the application of 1.0 mm required changes in the design drawings, modification of extrusion molds, and processing and modification of the aluminum extruded material already produced. Considering the required additional cost, it was recommended to maintain the currently used root face of 1.5 mm.

Fourth, the pulse frequency of the SynchroPuls function of the welding machine had to be set with one parameter for continuous automated production considering the function of the welding machine.



(a) Example of crack by bending test



(b) Specimen of passed bending test

Fig. 11 Specimen of finished bending test

Table 9 A and B group of welding conditions

Section		ER5356				ER4043			
	Sync. Hz	2.5Hz		4.5Hz		4.5Hz		2.5Hz	
	R/F(mm)	1.5	1.0	1.5	1.0	1.5	1.0	1.5	1.0
Lower	150A,20V		×		×		×		△
	160A,20.5V		×		○	△	△	×	△
	170A,21V	×	×	△	○	△	×	×	△
	180A,21.5V	×	×	B ○	×	△	×	△	×
	190A,22V	A ○	△	B ○	×	×		△	
	200A,22.5V	A ○		B ○		×		△	
	210A,23V	A ○		B ○					
Upper	165A,20.5V						×		×
	175A,21V		×		○	△	×	×	×
	185A,21.5V	×	△	B ○	○	△	×	×	×
	195A,22V	A ○	○	B ○	○	△	×	△	×
	205A,22.5V	A ○	○	B ○	×	△	△	△	×
	215A,23V	A ○	○	B ○	×	×		△	
	225A,24V	A ○		△					

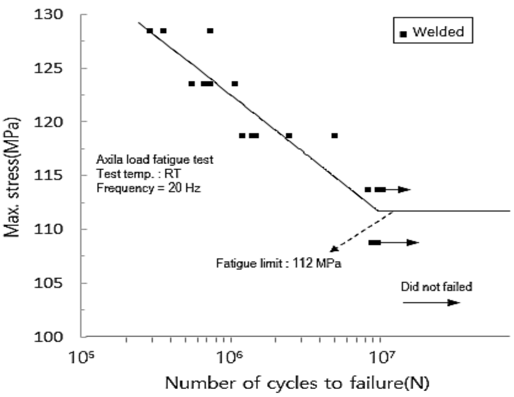


Fig. 12 S-N Curves of welded 6005A-T6 alloys

The common variable for this group is the condition of the 1.5 mm root face that used the ER5356 filler metal. When groups A and B, which were appropriate welding conditions, were examined, group B was determined to be the robust and optimal welding condition that could maintain quality in a stable manner because it had better weldability compared to the 2.5 Hz frequency condition of group A SynchroPuls function, and its excellent current and voltage value ranges were relatively wider. In the experimental range, group B was determined to be the optimal welding condition. Therefore, 4.5 Hz 180 A, 190 A, 200 A, and 210 A (4 types) were selected for the under frame and 4.5 Hz 185 A, 195 A, 205 A, and 215 A (4 types) for the upper structure.

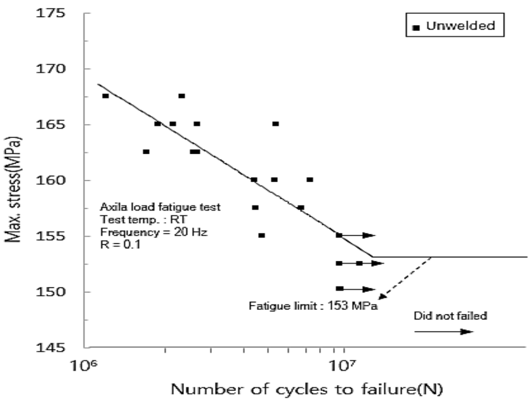


Fig. 13 S-N Curves of 6005A-T6 base metal

3.4 Fatigue test

The railway vehicle is subjected to continuous fatigue loads during its operation. To verify whether the vehicle under frame assembled under the optimal welding conditions selected in this study met the fatigue test criterion, welding specimens were prepared based on the optimal condition group B, and then welding specimens and the fatigue test specimens of the raw material were prepared in accordance with Annex C of the EN 13981-1 standard.

The fatigue test was conducted by an internationally accredited testing agency that was recognized by the Korea Laboratory Accreditation Scheme (KOLAS). In the fatigue test, cyclic loads were applied using the constant load width of a sine wave with a stress ratio of 0.1 and a load frequency of 20 Hz at room temperature. When the number of repetitions exceeded 10 million times, infinite life was considered. For the fatigue test, a total of 44 specimens were prepared, including 22 raw material specimens and 11 weld joint specimens for the upper and lower parts, respectively.

Fig. 12 depicts the fatigue test graphs of the welding specimens. Notably, the fatigue test result (112 MPa) satisfied the acceptance criterion (55 MPa). Fig. 13 shows the S-N curve result of the raw material fatigue test. Notably, the result for the raw material (153 MPa) also satisfied the acceptance criterion (110 MPa).

4. Conclusion

In this study, mechanical property tests were conducted for the welding specimens prepared by the application of 45 welding conditions, which were classified using previous experimental research on the 6005A-T6 base panel sub-assembly of the railway vehicle under frame. The following conclusions could be drawn.

1. The tensile strengths of the specimens that applied ER5356 and ER4043 were approximately 28% and 33%, respectively, lower than the average tensile strength of the raw material. The yield strengths of the specimens that applied ER5356 and ER4043 were approximately 48% and 46%, respectively, lower than the average yield strength of the raw material. The elongations of the specimens that applied ER5356 and ER4043 were approximately 18% and 21%, respectively, lower than the average elongation of the raw material.
2. In the mechanical property test range, 4.5 Hz 180 A, 190 A, 200 A, and 210 A (4 types) were selected for the under frame and 4.5 Hz 185 A, 195 A, 205 A, and 215 A (4 types) for the upper structure as the optimal welding conditions.
3. The fatigue test was conducted using the specimens prepared under the optimal welding conditions. The specimens satisfied the acceptance criterion of 55 MPa, thereby verifying their welding durability.

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