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Weld Characteristic Analysis for Weld Process Variables of Tip-Rotating Arc Welding in Butt Joint of Shipbuilding Steels

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조선용 강재의 맞대기 이음에서 팁회전 아크 용접의 공정 변수에 따른 용접 특성 분석

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ABSTRACT

Reduction of weld distortions and increase in productivity are some of the major goals of the shipbuilding industry. To address these issues, many researchers have attempted to apply new welding processes. In the shipbuilding industry, steel is the candidate material of choice owing to its good weldability. However, conventional welding techniques are not feasible for avoiding welding problems. Tip-rotating arc welding is one of the high-efficiency welding process that has several advantages, such as high welding speed, high melting rate, low heat input, and less distortion. The present study investigates the influence of the welding variables on the weld characteristics of tip-rotating arc welding. Welding was performed using EH36 as the base metal and SM-70s as the filler metal, which are widely used in shipbuilding. Basic experiments were conducted to understand the effects of the major welding variables, such as welding and tip-rotating speeds. The distortion and mechanical properties of the optimal welding conditions were used to evaluate the tip-rotating arc welding performance. Consequently, the feasibility of the tip-rotating arc welding process for joining steel components was investigated, so that the optimized welding conditions could be applied directly to ship body welding to enhance the quality of the welded joints.

Key Words : Tip-Rotating Arc Welding(팁회전아크용접), Welding Variable(용접 공정변수), Welding Distortion(용접변형), Welding Optimization(용접최적화)

1. Introduction

Welding is a very important process in the manufacturing of ships, beacuse numerous steel plates need to be joined.

However, several problems, such as productivity losses and welding deformation, may arise during welding. As welding takes a long time, productivity can be improved by increasing the welding speed as much as possible. Furthermore, correcting deformed plates by welding requires a significant amount of

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time, which also leads to increases in process time and labor cost. Consequently, several studies have been conducted to improve the efficiency of the welding process using various methods [1].

In the tip-rotating arc welding method, a hollow motor is installed inside the welding torch to rotate the tip end quickly and generate arcs to weld. In addition to providing the effect of weaving, the rotating tip increases the welding speed and reduces welding deformation by minimizing the heat input and maximizing the deposition rate[1-3].

Yang[4] et al. applied tip-rotating arc welding to narrow-gap welding and analyzed the correlation between tip rotation speed and weld profile in multilayer welding. Li[5] et al. performed a simulation of tip-rotating arc welding and analyzed the welding current and welding speed to estimate the temperature distribution and deformation rate of a weld. Many efforts have been tried to apply tip-rotating arc welding to production, and research[6] has also been conducted to monitor the arc phenomenon that occurs during welding. In order for this tip rotating arc welding process to be applied to an actual production line, the welding process parameters must be optimized[7].

In this study, the properties of tip-rotating arc welding were analyzed to achieve high efficiency in the welding process. The bead profile and mechanical properties depending on the process parameters of tip-rotating arc welding were analyzed. The shape of the weld were analyzed using bead-on-plate (BOP) welding, and the welding conditions were optimized with respects to penetration depth, bead width, and undercut through cross-sectional analysis. Butt welding was performed to determine the field applicability of tip-rotating arc welding. The mechanical properties of the weld after butt welding were evaluated through tensile tests, and the amount of welding deformation was measured. Accordingly, the field applicability of tip-rotating arc welding was determined.

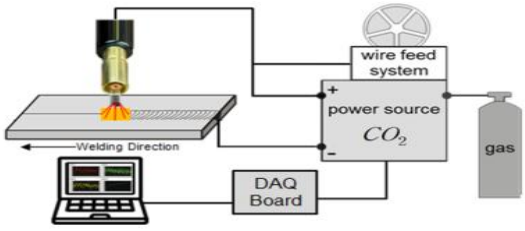
2. Tip-rotating Arc Welding Experiment

2.1 Tip-rotating Arc Welding Method

In tip-rotating arc welding, a welding torch designed to allow the tip of the torch to rotate quickly with a hollow motor is used, as shown in Fig. 1[2]. With this torch, it is possible to achieve fast rotation of the arc and form a wide range of welding beads via rotational weaving. In the straight weaving method with a side-to-side motion, the speed is reduced at the end of the weave, resulting in irregular depositions. However, rotational weaving can create a consistent flux and form a large amount of deposition stably.

Fig. 1 Tip-Rotating arc welding torch

(a) Welding Fixture photo



(b) Welding experimental system

Fig. 2 Welding experiment setup

Therefore, tip-rotating arc welding can yield a higher amount of deposition than straight welding with no weaving if the welding speed is constant. Moreover, given the same deposition rate, the welding speed is faster than it is in straight welding [8]. Because of this advantage, tip-rotating arc welding can be obtain high productivity and low distortion.

2.2 Experiment device and conditions

The tip-rotating arc welding experiment was conducted as shown in Fig. 2. The welding specimen was fixed on both sides as shown in the figure, and the experiment was conducted using a carriage to move the welding torch. A CO_2 welding machine was used, with a maximum current of 600 A, a maximum voltage of 50 V, and CO_2 was used as the shielding gas. A solid wire, 1.2 mm in diameter, was used as the welding wire. The torch angle (TA) was fixed at 0° to be set perpendicular to the specimen. The contact tip to workpiece distance (CTWD) was fixed at 20 mm, the rotating diameter (RD) at 3 mm, and the protective gas flow rate (FR) at 25 L/min.

Through a basic experiment, the welding current and voltage were set, and changes according to the welding speed and the tip rotation speed were observed.

2.3 Material for Experiment

The material used in the tip-rotating arc welding experiment was EH36 carbon steel (thickness of 10 mm), which is widely used for building ships. The wire used for welding was SM-70s wire, and the chemical composition of each material is in Table 1 and 2. In the experiment to verify the welding characteristics, a specimen size was 300 × 300 mm and BOP welding was conducted. For the experiment to determine the mechanical properties of the weld, butt welding was conducted on a 300 × 300 mm specimen. Moreover, for the experiment to measure deformation, butt welding was conducted on a 500 × 1,000 mm specimen.

Table 1 Chemical composition of EH36 steel(wt%)

	C	Si	Mn	P	S
EH36	0.18	0.01-0.05	0.9-1.6	0.035	0.035
	Cr	Cu	Ni	Nb	Fe
	0.2	0.35	0.4	0.05	bal.

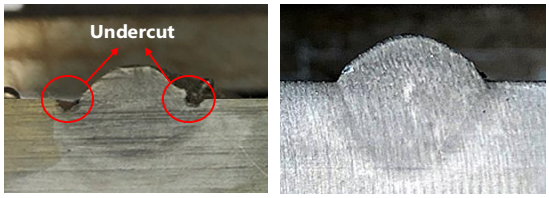
Table 2 Chemical composition of SM-70s wire(wt%)

	C	Si	Mn	P	S
SM-70s	0.07	0.65	1.14	0.015	0.01

3. Experiment Results and Findings

3.1 Welding characteristics analysis based on welding speed

Fig. 3 shows the cross-sectional changes according to the tip-rotating arc welding speed. In both subfigures, the heat input per unit length was almost the same; however, the welding speed was 140 cm/min in (a) and 100 cm/min in (b). The area indicated in (a) shows where an undercut occurred. Under similar heat input conditions, the undercut occurred at a high welding speed. During the



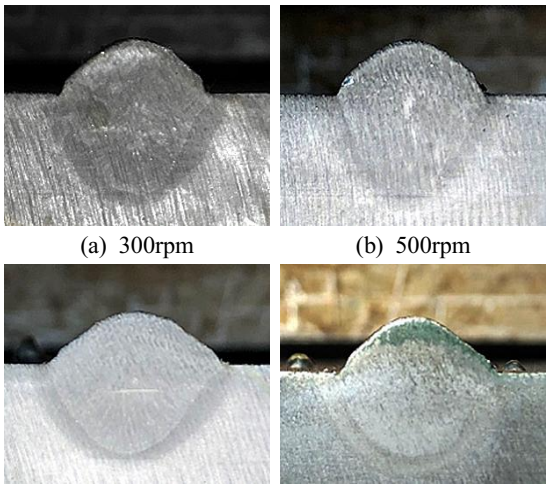
(a) (b)

Fig. 3 Weld bead shape with different heat input condition and welding speed - (a) Welding conditions - WC : 480A, WV : 45V, WS : 140cm/min, RPM : 500rpm, Heat Input : 9257J/cm (b) Welding conditions - WC : 400A, WV : 40V, WS : 100cm/min, RPM : 500rpm, Heat Input : 9600J/cm

process of melting and solidifying under insufficient heat input, the quick solidification and strong surface tension of the molten metal are considered to be the cause of the undercut at the end part of the welding bead. Therefore, to form a stable arc and welding bead, a welding speed of 100 cm/min or less is required.

3.2 Welding characteristics analysis based on rotation speed

An experiment was conducted to analyze the effect of rotation speed during tip-rotating arc welding. Following were the conditions for welding: welding current (WC) of 400 A, welding voltage (WV) of 40 V, and welding speed (WS) of 100 cm/min. At this welding current and voltage, undercuts were not occurred. To observe the influence of the tip rotation speed, the experiment was conducted starting from a rotation speed of 300 rpm, increasing to 1,400 rpm in increments of 100 rpm. Furthermore, the experiment was additionally conducted at a maximum rotation speed of 2,500 rpm. Fig. 4 and 5 show the experiment results.

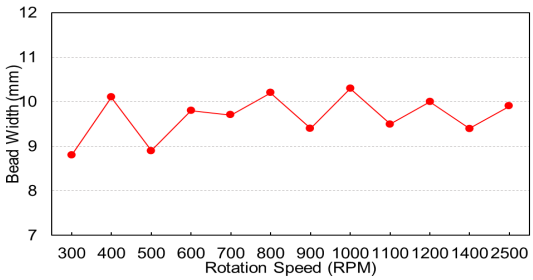


(a) 300rpm (b) 500rpm

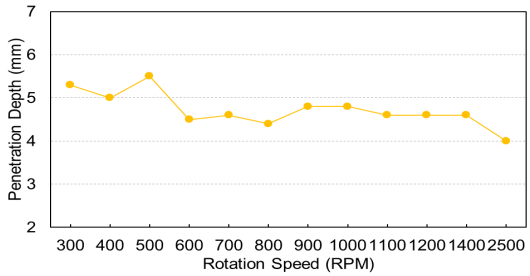
(c) 1000rpm (d) 2500rpm

Fig. 4 Weld bead shape with different rotating speed(rpm)

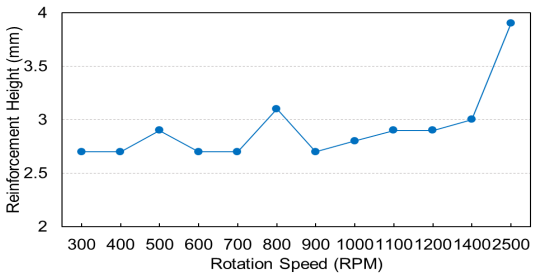
As shown in Fig. 4, defects such as undercuts were not formed on the cross-section of the weld. Fig. 5 shows the profile of the welding bead depending on the rotational speed. As shown in Fig. 5(a), the bead width of the weld at 9–10 mm changes with no particular tendency as the number of rotations per minute increases. This indicates that the bead width is almost proportional to the rotational radius of the tip during rotational weaving, and similar values are exhibited by fixing the rotational diameter at 3 mm.



(a) Weld bead width



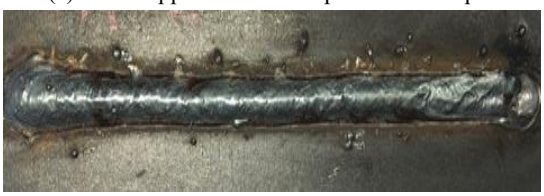
(b) Penetration depth



(c) Reinforcement height

Fig. 5 Welding bead features according to rotating speed (rpm)

(a) Bead appearance and spatter at 300rpm



(b) Bead appearance and spatter at 2500rpm

Fig. 6 Weld bead appearance

The penetration depth in Fig. 5(b) decreases with increasing rotational speed, whereas the reinforcement height increases with increasing number of rotations per minute, as shown in Fig. 5(c). This is attributed to the dispersion of the input heat of the arc around the weld by the fast rotational speed, preventing the concentration of heat. The wire deposition does not penetrate but rather builds up as a reinforcement, increasing the height.

When the rotational speed increases in welding experiment the centrifugal force caused by the fast rotation affects the metal transfer. Even though welding status is not short circuit transfer mode, many spatters are made by high rotating speed. As shown in Fig. 6, very little spatters occurred when welding at 300 rpm, whereas many spatters occurred at 2500 rpm. This indicates that too many spatters make the deposition rate reduced and the additional work would be required to remove the spatter after welding in the field.

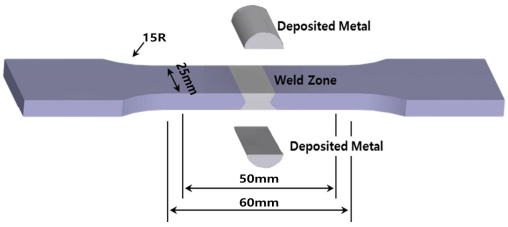
Therefore, considering the bead profile, penetration depth, and the spatter amount, the most appropriate rotational speed was determined to be 500 rpm. Using this rotationg speed, the butt welding experiment for evaluating the mechanical properties was conducted.

4. Analysis of Mechanical Properties using Butt Welding

4.1 Evaluation of Weld Strength in Butt Welding

In order for tip-rotating arc welding to be applied at an actual site, a weldability assessment must be conducted in butt welding. In this study, double-sided butt welding was performed, as the steel plate with 10 mm thickness could not be welded only on one side. In terms of the experimental conditions, the welding current (WC) was set at 360 A, 440 A, and 520 A, and the welding voltage (WV) was set at 34 V, 41 V, and 48 V. The welding speed was fixed at 100 cm/min and the rotational speed at 500 rpm. After welding, the strength evaluation was conducted according to the KS standard, and the size of test speciment follows the KS B0801 No. 5 and weld reinforcement was eliminated by KS B0802. Three tensile test samples were collected from each welding specimen, and the strength was assessed based on the average values. Fig. 7 shows the tensile test specimen and size. Fig. 7 (b) and (c) shows the test piece without and with undercuts.

Table 3 provides the tensile strength and fracture location of the weld after the tensile test. The tensile test of the base material was performed to compare the strength of the weld to that of the base metal. The tensile strength of the base metal was 490±2 N/mm^2. Fractures occurred in the base metal when the tensile strength of the weld was higher than that of the base metal, whereas fractures occurred in the weld when the tensile strength of the weld was lower. The reason for the fractures occurring in the weld in most cases is incomplete welding in the weld due to partial penetration or the presence of defects such as undercuts. Fig. 8 and Fig. 9 show the fracture profile on the cross-section after welding, confirming the main cause of the weld fractures in Table 3.



(a) Size of tensile test specimen (KS B0801)

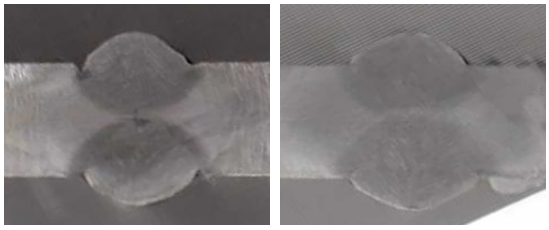
(b) Tensile test specimen without undercut

(c) Tensile test specimen with undercut

Fig. 7 Tensile test specimen

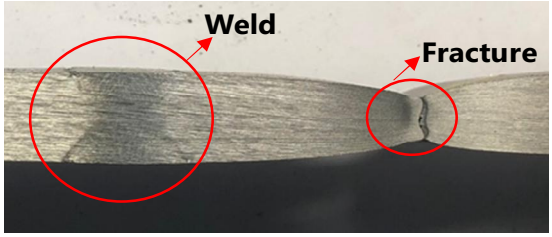
Table 3 Tensile test results and fracture type

	WC (A)	WV (V)	Tensile Strength (N/mm^2)	Fracture Location
1	360	34	203	Weld Metal
2	440	34	476	Weld Metal
3	520	34	503	Base Metal
4	360	41	499	Base Metal
5	440	41	499	Base Metal
6	520	41	391	Weld Metal
7	360	48	464	Weld Metal
8	440	48	500	Base Metal
9	520	48	501	Base Metal

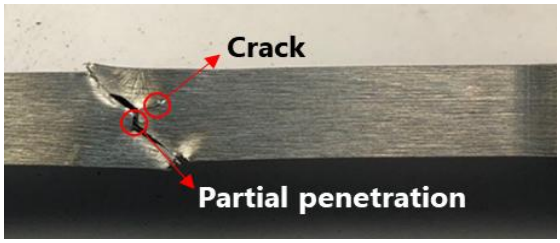


(a) partial penetration with undercut (b) full penetration

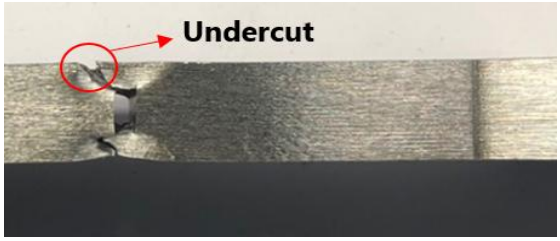
Fig. 8 Weld cross section after both side welding



(a) Base metal fracture



(b) Weld fracture: crack and partial penetration



(c) Weld fracture : undercut

Fig. 9 Fracture type after tensile test

4.2 Welding Deformation under Optimal Welding Conditions

The deformation of weld plates after welding was measured to determine the field applicability of tip-rotating arc welding. Double-sided welding was performed at the welding current of 440 A, the welding voltage of 41 V, the welding speed of 100 cm/min, and the tip rotational speed of 500 rpm, and the deformation of the base metal was measured after welding.

The dimensions of the experimental specimen before welding were 500 mm × 1,000 mm, and the two plates were butt-welded. The dimensions of the plate for measuring the deformation after welding were 1,000 mm × 1,000 mm. Fig. 10 shows the

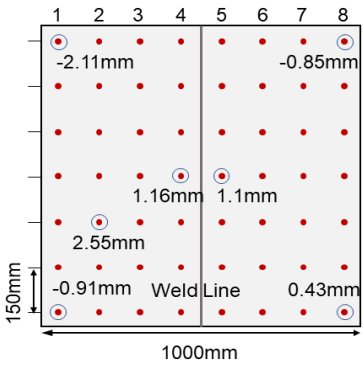


Fig. 10 Distortion measuring points and some distortion values

dimensions of the welded specimen. As the method for measuring deformation, measurement points were set at regular intervals on the surface of the welded plate, and the deviation in height was measured with a laser distance sensor. Fig. 10 shows the welding deformation measurements in points. A total of seven lines were measured at intervals of 150 mm, starting at 50 mm from the end in the direction of welding, and a total of 56 locations were measured at equidistant intervals for each line.

Fig. 10 shows the deformation measured at seven representative locations. A "+" deformation measurement indicates deformation in the upward direction from the surface, and a "-" deformation measurement indicates deformation in the downward direction. The measurement result of 2.55 mm was the maximum in the positive direction, and that of -2.11 mm was the maximum in the negative direction. Becuse maximum deformation value was 2.55 mm, tip-rotating arc welding is deemed to have appropriate field applicability.

5. Conclusion

The properties of tip-rotating arc welding were analyzed for field application to achieve high efficiency in the manufacturing process of ships. Bead-on-plate welding was performed to identify the properties of the weld, and the optimal welding ranges were established by analyzing the changes in penetration depth and bead width through cross-sectional analysis. Butt welding was performed to determine the field applicability of tip-rotating arc welding. After the application in butt welding, the mechanical properties of the weld were analyzed through tensile tests, and the welding deformation was measured. Accordingly, tip-rotating arc welding was confirmed to be applicable for butt welding thick plates in shipbuilding, and the following conclusions were obtained:

1. Undercuts occurred when the welding speed was too high, and the penetration tended to become shallower when the tip rotation speed was too high. Accordingly, the process parameters for tip-rotating welding were optimized with a welding speed of 100 cm/min and a tip rotation speed of 500 rpm.
2. Butt welding was performed to determine the field applicability of tip-rotating arc welding, and tensile tests were conducted on the weld. Under the optimal welding conditions, the tensile strength was observed to be higher than that of the base metal at 490 N/mm^2 with fractures occurring in the base metal, which confirmed the field applicability.
3. To measure the deformation of the material depending on the weld, welding plates were produced using the optimal welding conditions, and the deformation was measured at 56 points in total. The measurement results indicated a maximum of 2.55 mm in the positive direction and a maximum of -2.11 mm in the negative direction.

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