공학석사 학위논문

Study on the Suitable Welding Condition for the Horizontal Fillet Welding with FCAW

FCA 용접법을 이용한 수평 필렛 용접시

최적 용접 조건에 관한 연구

지도교수 박 주 용

2013 년 8 월

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조선해양시스템공학과

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Abstract

Welding is the key part of the shipbuilding, and it directly related to the quality and efficiency of the ship building. Nowadays, the analog control DC arc welding machine is widely used in the production of ship and offshore plant. But the requirements of the special ship, offshore plant and high added value ship owners increase gradually. The welding quality, automatic welding, energy conservation are all put forward strict requirements. In this case, the limits of the analog welding machines are apparent. The digital welding machine instead of the analog welding machine is the direction of the development.

The welding expert database, that the digital welding machine takes, is one of

important characteristics. The horizontal fillet welding is prevalently used in ship building industries to fabricate the large scale structures. A deep understanding of the horizontal fillet welding process is restricted, because the phenomena occurring in welding are very complex and highly non-linear characteristics. So in this paper, we have found the optimal relationships between welding parameters for horizontal fillet welding such as current and voltage, current and deposition rate, through literature survey, theoretical study and a lot of welding experiments by a newly developed digital welding machine.

Key Words: fillet welding; optimal welding parameters; expert database; digital welding machine

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CHAPTER 1 INTRODUCTION

1.1 Background and Significance of the Study

The workload of welding counts more than 40% of the construction of the hull. The horizontal fillet welding is prevalently used in ship building industries to fabricate the large scale structures. The shipbuilding industry needs plentiful labor. Some of countries launch into the shipbuilding industry with the strong point of low labor cost, and this make the international competitiveness be more serious. But with the increase of the labor costs, it leads to the profit of the shipyard shrinkage. [1] Welding is the key part of the ship building, and it directly related to the quality and efficiency of the ship building. Welding automation can greatly improve the stability, welding quality, welding efficiency, the working conditions of the workers of welding process, so it makes the ship welding gradually developed in the direction of automatic welding. [2]

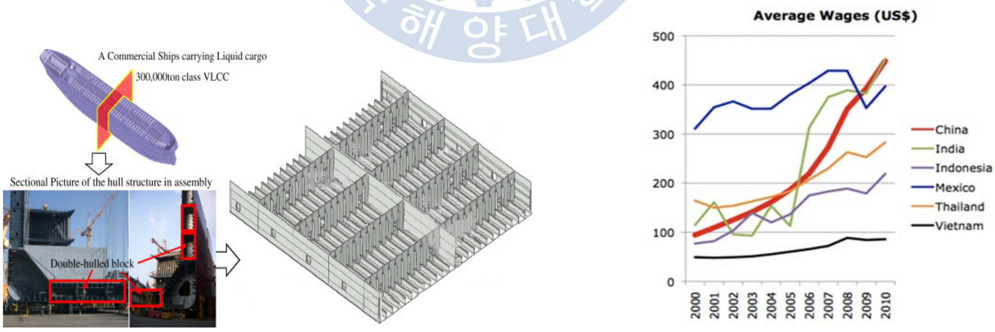


Fig. 1.1 Fillet structure of the hull and variation of labor costs of some countries

Nowadays, the analog control DC arc welding machine is widely used in the production of shipbuilding and offshore plant. But with the requirements of the special ship, offshore plant and high added value ship owners increasing gradually, the welding quality, automatic welding, energy conservation are all put forward strict requirements. In this case, the limits of the analog welding machines revealed. The digital welding machine instead of the analog welding machine is the direction of the development.

Because of this trend, ‘Romex Technology Co., Ltd.’, ‘CELNIS Co., Ltd.’ and ‘SUNGDONG Shipbuilding & Marine Engineering Co., Ltd.’ these three companies have jointly developed a new digital welding machine and automatic systems. The expert system that the digital welding machine takes is one of important characteristics. Expert system [3][4] consists of common database, fuzzy system, neural network system, knowledge base system, calculation programs and graphic user interface, as shown in Fig1.2.

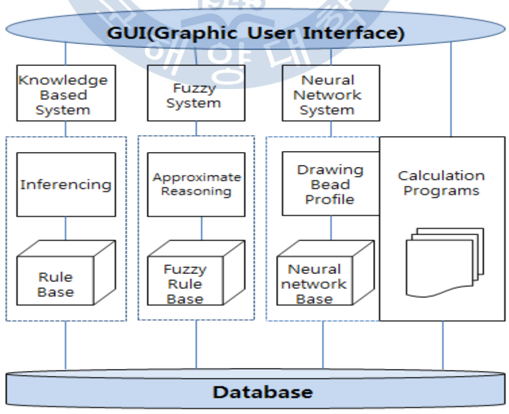


Fig. 1.2 Structure of expert system

Common database contains experimental data and coefficients of empirical functions. Calculation programs perform solving empirical equations and curve fitting to draw the bead profile.

Getting the optimal welding parameters for establishing the common database is an important part for the suitable use of this automatic system. A deep understanding of the horizontal fillet welding process is restricted, because the phenomena occurring in welding are very complex and highly non-linear characteristics. Furthermore, various kinds of weld defects can be induced due to the improper welding conditions. So in this paper, through literature survey, theoretical study and a lot of welding experiments by the digital welding machine, we have found the optimal relationships between welding parameters such as current and voltage, current and deposition rate.

In this study, we have found the optimal welding parameters of a digital machine for horizontal fillet welding and established a common database. It can provide guidance for the welding production and provide the data reference for the development of optimal welding condition expert system.

CHAPTER 2 RELATED KNOWLEDGE OF THE FCAW

FLUX CORED ARC welding (FCAW) [8][9] is an arc welding process that uses an arc between a continuous filler metal electrode and the weld pool. FCAW is similar to GMAW. However the wire electrode is flux cored rather than solid. The electrode is a metal tube with flux wrapped inside. The functions of the flux are similar to those of the electrode covering in SMAW, including protecting the molten metal from air. The use of additional shielding gas is optional.

FCAW was first developed in the early 1950s as an alternative to shielded metal arc welding (SMAW). The advantage of FCAW over SMAW is that the use of the stick electrodes used in SMAW is unnecessary. This helped FCAW to overcome many of the restrictions associated with SMAW.

2.1 Fundamentals and Types of the FCAW

FCAW offers two major process variations that differ in their method of shielding the arc and weld pool from atmospheric contamination. One type, self-shielded FCAW, protects the molten metal through the decomposition and vaporization of the flux core by the heat of the arc. The other type, gas shielded FCAW, makes use of a protective gas flow in addition to the flux core action. With both methods, the electrode core material provides a substantial slag covering to protect the solidifying weld metal.

2.1.1 Gas- Shielded Flux Core Arc Welding

One type of FCAW uses a shielding gas that must be supplied by an external supply. This is known informally as “dual shield” welding. This type of FCAW was developed primarily for welding structural steels. In fact, since it uses both a flux-cored electrode and an external shielding gas, one might say that it is a combination of gas metal (GMAW) and flux-cored arc welding (FCAW). This particular style of FCAW is preferable for welding thicker and out-of-position metals. The slag created by the flux is also easy to remove. The main advantages of this process is that in a closed shop environment, it generally produces welds of better and more consistent mechanical properties, with fewer weld defects than either the SMAW or GMAW processes. In practice it also allows a higher production rate, since the operator does not need to stop periodically to fetch a new electrode, as is the case in SMAW. However, like GMAW, it cannot be used in a windy environment as the loss of the shielding gas from air flow will produce visible porosity on the surface of the weld.

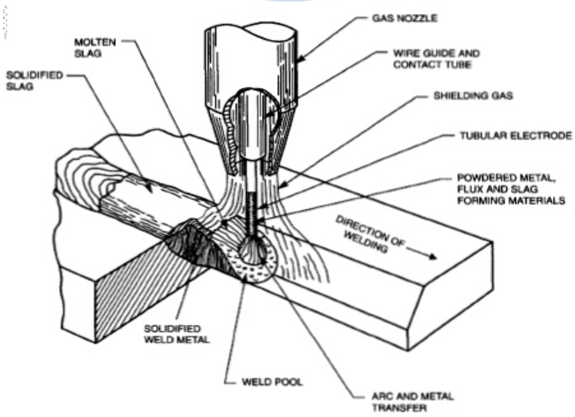


Fig. 2.1 Gas- Shielded Flux Core Arc Welding

2.1.2 Self- Shielded Flux Core Arc Welding

Another type of FCAW requires no shielding gas. This is made possible by the flux core in the tubular consumable electrode. However, this core contains more than just flux, it also contains various ingredients that when exposed to the high temperatures of welding generate a shielding gas for protecting the arc. This type of FCAW is attractive because it is portable and generally has good penetration into the base metal. Also, windy conditions need not be considered. Some disadvantages are that this process can produce excessive, noxious smoke (making it difficult to see the weld pool); under some conditions it can produce welds with inferior mechanical properties; the slag is often difficult and time-consuming to remove; and operator skill can be a major factor.

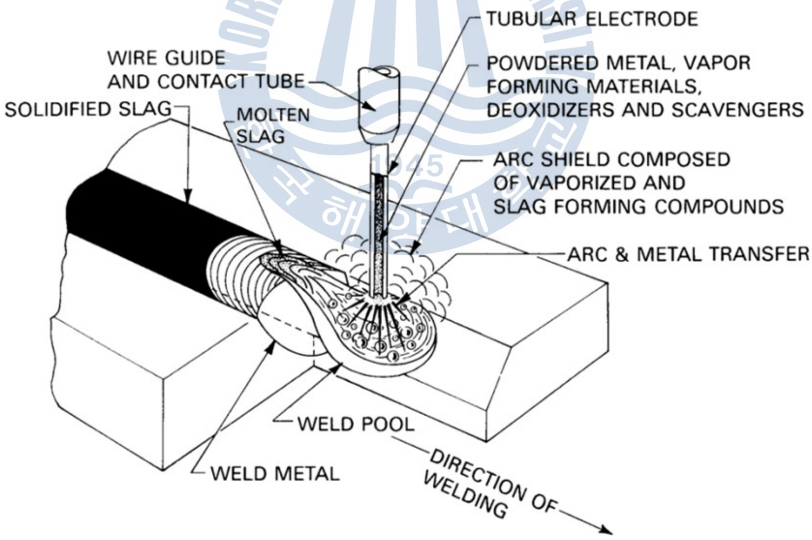


Fig. 2.2 Self- Shielded Flux Core Arc Welding

2.1.3 Advantages and Limitations of FCAW

Advantages of FCAW

FCAW has many advantages over the manual SMAW process. It also provides certain advantages over the SAW and GMAW processes. In many applications, the FCAW process provides high-quality weld metal at lower cost with less effort on the part of the welder than SMAW. It is more forgiving than GMAW, and is more flexible and adaptable than SAW. These advantages can be listed as follows:

- High-quality weld metal deposit
- FCAW may be an "all-position" process with the right filler metals
- Excellent weld appearance — smooth, uniform welds
- Many steels weldable over a wide thickness range
- No shielding gas needed with some wires making it suitable for outdoor welding and/or windy conditions

Limitations of FCAW

The following are some of the limitations of this process:

- FCAW is presently limited to welding ferrous metals and nickel base alloys.

- The process produces a slag covering which must be removed.
- The equipment is less mobile and more costly as compared to SMAW
- The amount of smoke generated can far exceed that of SMAW, GMAW

2.2 Metal Transfer

In FCAW, the same as in GMAW, an electric arc is established between the workpiece and a consumable bare wire electrode. The arc continuously melts the wire as it is fed to the weld puddle.

In FCAW, metal transfer [10][11] with flux cored wire is a combination of the basic gas metal arc welding transfer types and the shielded metal arc transfer. Metal can be transferred in the short-circuiting, globular, spray, and pulse modes. The type of transfer depends on the formulation of the flux as well as the arc voltage and current.

① Short-Circuiting Transfer

Short circuiting welding is an all positional process, using low heat input. The use of relatively low current and arc voltage settings cause the electrode to intermittently short-circuit with the weld pool at a controlled frequency. Metal is transferred from the wire to the weld pool only when contact between the two is made, or at each short circuit. The short-circuit current is sufficient to allow the arc to be re-established. As the wire touches the weld pool, current begins to rise to a short circuit current. When this high current is reached, the metal is transferred. The arc is then reignited. Because the wire is being fed faster than the arc can melt it, the arc will eventually be extinguished by another short.

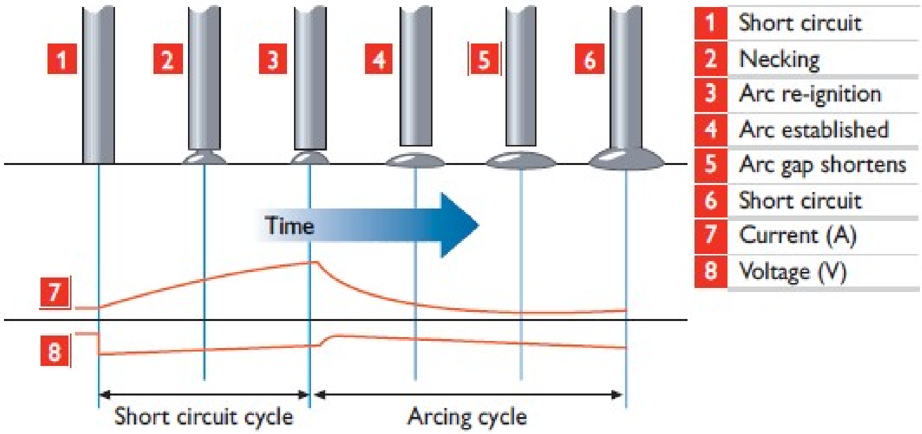


Fig. 2.3 Schematic of Short-Circuiting Transfer

The cycle begins again. The wire short circuits to the workpiece 20 to 200 times per second. It is achieved using shielding gases based on carbon dioxide and argon.

② Globular Transfer

As the welding current and voltage are increased above the maximum recommended for short arc welding, metal transfer will begin to take on a different appearance. This welding technique is commonly known as globular transfer, with metal transferring through the arc. Metal transfer is controlled by slow ejection, resulting in large, irregularly-shaped 'globs' falling into the weld pool under the action of gravity. Carbon dioxide gas drops are dispersed haphazardly. With argon-based gases, the drops are not as large and are transferred in a more axial direction. There is a lot of spatter, especially in carbon dioxide, resulting in greater wire consumption, poor penetration and poor appearance. Globular transfer can take place with any electrode diameter.

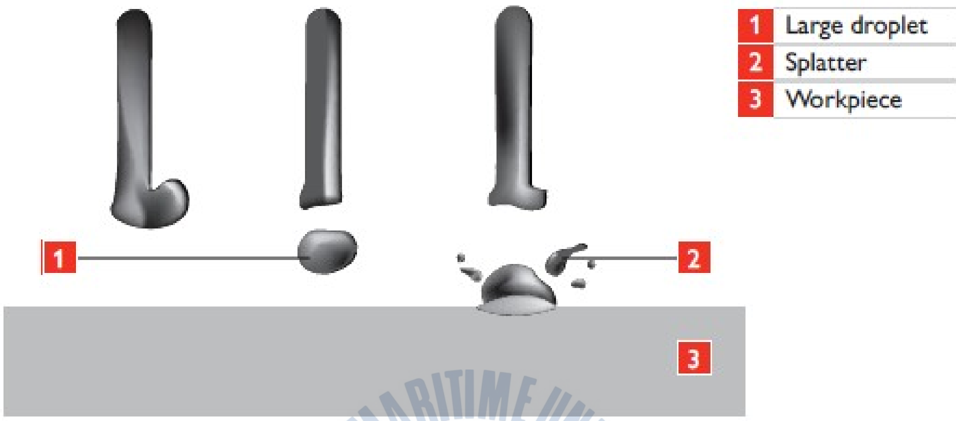


Fig. 2.4 Schematic of Globular Transfer

Basic flux cored wires tend to operate in a globular mode or in a globular-spray transfer mode, where larger than normal spray droplets are propelled across the arc, but they never achieve a true spray transfer mode. This transfer mode is sometimes referred to as non-axial globular transfer.

③ Spray Transfer

By raising the welding current and voltage still further, the metal transfer will become a true spray arc. The minimum welding current at which this occurs is called the transition current. In spray transfer, metal is projected by an electromagnetic force from the wire tip in the form of a continuous stream of discrete droplets approximately the same size as the wire diameter. High deposition rates are possible and weld appearance and reliability are good. The current flows continuously because the high voltage maintains a long arc and short-circuiting cannot take place. It occurs best with argon-based gases.

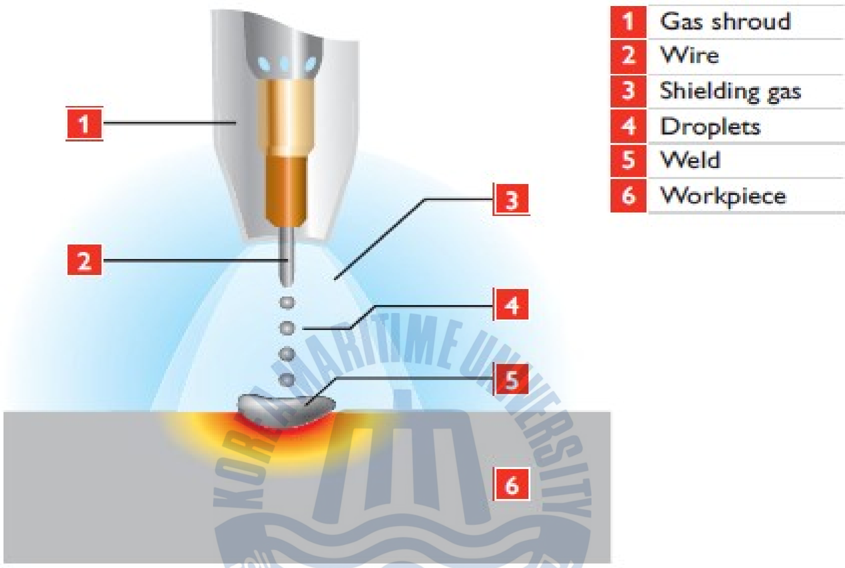


Fig. 2.5 Schematic of Spray Transfer

Flux cored wires do not achieve a completely true spray transfer mode, but a transfer mode that is almost true spray may occur at higher currents and can occur at relatively low currents depending on the composition of the flux.

④ Pulsed Transfer

A variation of the spray transfer mode, pulse-spray is based on the principles of spray transfer but uses a pulsing current to melt the filler wire and allow one small molten droplet to fall with each pulse. The pulses allow the average current to be lower, decreasing the overall heat input and thereby decreasing the size of the weld pool and heat-affected zone while making it possible to weld thin work pieces. The pulse provides a stable arc and no spatter, since no short-circuiting takes place. This also makes the process suitable for nearly all metals, and thicker electrode wire can be used as well. The smaller weld pool gives the variation greater versatility, making it possible to weld in all positions.

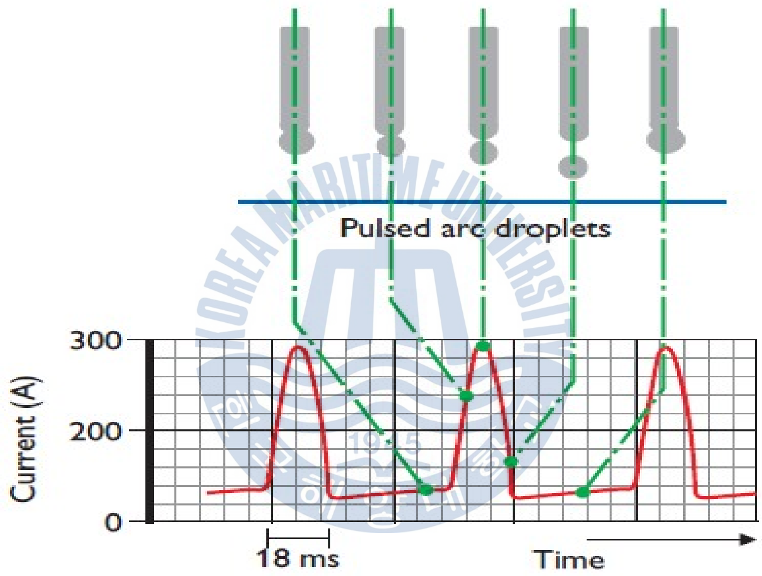


Fig. 2.6 Schematic of pulsed Transfer

Pulsed arc transfer operation has been applied to flux cored wires but, as yet, is not widely used because the other transfer modes are giving users what they require in most cases.

CHAPTER 3 RELATIONSHIP BETWEEN WELDING PARAMETERS AND WELD SHAPE

Making a welding schedule is very important for getting good mechanical properties and a good visual quality of the weld shape. It needs the knowledge about the welding parameters to ensure the welding quality when making the welding schedule. So study the relationship between welding parameters and weld shape [12][13][14][15] is very important. The weld bead shape is heavily influenced by a lot of welding parameters. In the present research, the welding current, voltage, speed, weaving width, and root gap are considered as the main parameters influencing bead shape. In addition to these, the electrode extension, shielding gas composition and electrode position are also influencing the weld bead shape.

1. Welding Current

When all other variables are held constant, the welding amperage varied with the electrode feed speed in a nonlinear relation. This relationship of welding current to wire feed speed for carbon steel electrodes is shown in Figure 3.1. At the low-current levels for each electrode size, the curve is nearly linear. However, at higher welding currents, particularly with small diameter electrode, the curve become nonlinear, progressively increasing at a higher rate as welding amperage increases. This is attributed to resistance heating (I^2R) of the electrode extension beyond the contact tube.

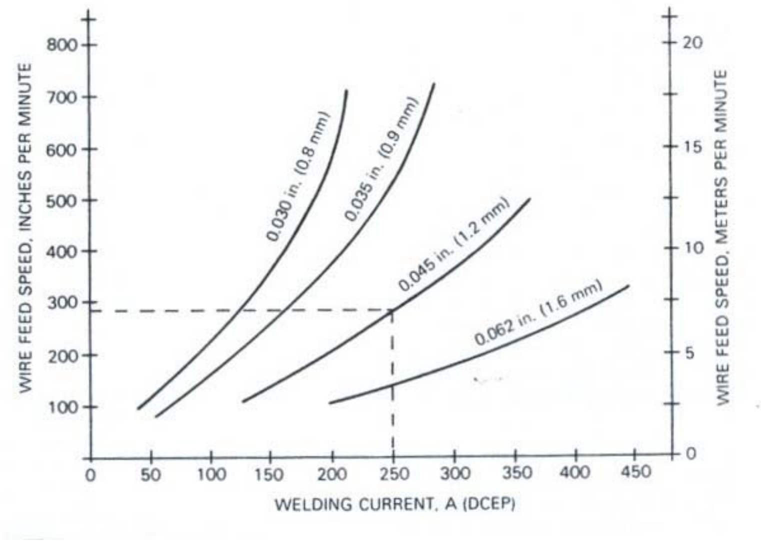
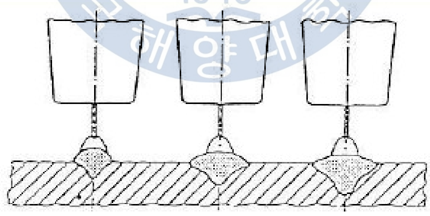


Fig. 3.1 Typical welding currents versus wire feed speeds for carbon steel electrodes

Welding current determines the rate at which the electrode is melted, the depth of penetration of the weld poor into the base metal, and the amount of base metal fused. An increase in current increases penetration and melt-off rate, but an excessive high current produces a high, narrow bead, an erratic arc, and undercut. Excessively low current produces an unstable arc.



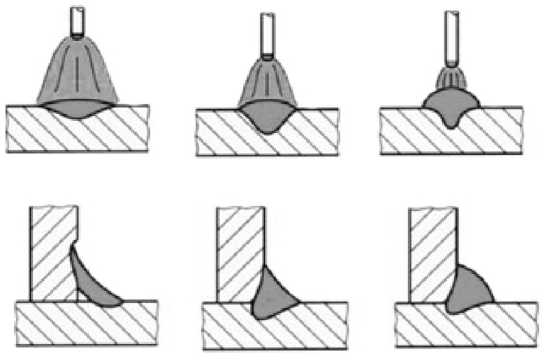
low medium high

Fig. 3.2 Effect of welding current

2. Welding Voltage

Arc voltage and arc length are terms that are often used interchangeably.

Welding voltage influences the shape of the weld cross section and the external appearance of the weld. Figure 3.3 shows the effect of voltage variation when other conditions are maintained constant. By increasing the voltage, it produces a flatter and wider bead and increases resistance to porosity caused by rust or scale.



high medium low

Fig. 3.3 Effect of welding voltage

3. Welding Speed

Welding speed is used primarily to control bead size and penetration. It is interdependent with current. When the speed is decreased, the filler metal deposition per unit length increases. As the speed is increased, the thermal energy per unit length of weld transmitted to the base metal from the arc is at first increased, because the arc acts more directly on the base metal. Therefore, melting of the base metal first increases and then decreases with increasing welding speed. As welding speed is increased further, there is a tendency toward undercutting along the edges of the weld bead because there is insufficient deposition of filler metal to fill the path melted by the arc.

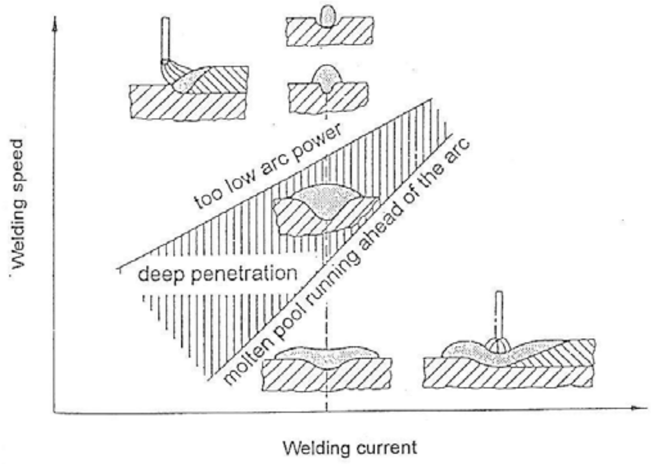


Fig. 3.4 Effect of welding speed

4. Electrode Position

As with all welding processes, the orientation of the welding electrode with respect to the weld joint affects the weld bead shape and penetration. Electrode orientation affects bead shape and penetration to a greater extent than arc voltage or welding speed.

When the electrode is changed from the perpendicular to a lead angle technique with all other conditions unchanged, the penetration decreases and the weld bead becomes wider and flatter. The drag technique also produces a more convex, narrower bead, a more stable arc, and less spatters on the workpiece.

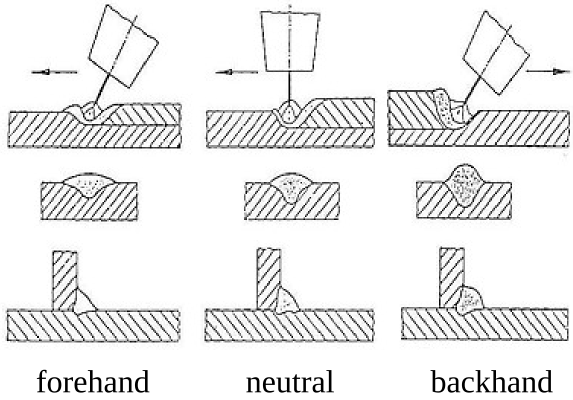


Fig. 3.5 Effect of electrode position and welding technique

5. Shielding Gases

The shielding gas and flow rate have a pronounced effect on the penetration and weld bead profile.

Helium has a higher thermal conductivity than argon and produces an arc plasma in which the arc energy is more uniformly distributed. The argon arc plasma, on the other hand, is characterized by a high-energy inner core and an outer zone of less energy. This difference strongly affects the weld bead profile. A welding arc shielded by helium produces a deep, broad, parabolic weld bead. An arc shielded by argon produces a bead profile characterized by a “finger” type penetration.

Carbon dioxide (CO_2) is a reactive gas widely used in its pure form for gas metal arc welding of carbon and low alloy steels. It is the only reactive gas suitable for use alone as a shield in the GMAW process. In overall comparison to the argon-rich shielded arc, the CO_2 shielded arc produces a weld bead of excellent penetration with a rougher surface profile and much less “washing” action at the sides of the weld bead, due to the buried arc. Very sound weld deposits are achieved, but mechanical properties may be adversely affected due to the oxidizing nature of the arc. Typical bead profiles for argon, helium, argon-helium mixtures and carbon dioxide are illustrated in Figure 3.6

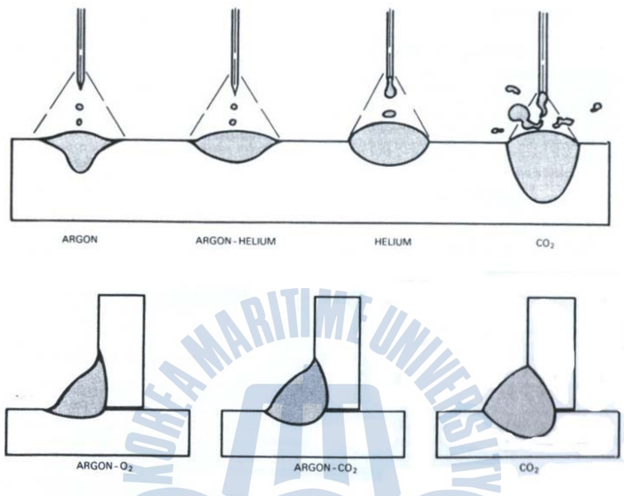


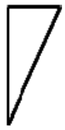
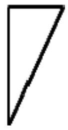
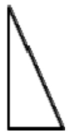
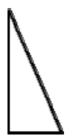
Fig. 3.6 Bead contour and penetration patterns for various shielding gases

From the above, the changing tendencies of the weld bead shape elements following the changing of welding parameters are summed up in the Table 3.1.

Table 3.1 Influences of welding parameters on the weld shape

 high, large, backhand

low, small, forehand

Welding Parameters		Penetration	Bead Width	reinforcement
Welding Current				
Welding Voltage				
Welding Speed				
Torch Angle				
Gap				

CHAPTER 4 EXPERIMENT AND ANALYSIS

4.1 General Requirements to the Weld Shape in Rules

The standards and rules made by the societies and organizations ensure that products and services are safe, reliable and of good quality. For business, they are strategic tools that reduce costs by minimizing waste and errors and increasing productivity. They help companies to access new markets, level the playing field for developing countries and facilitate free and fair global trade.

In this experiment, the quality of the weld bead and the experiment results are all following the ISO and KR technical rules.

4.1.1 ISO (International Organization for Standardization)

The International Organization for Standardization, widely known as ISO, is an international standard-setting body composed of representatives from various national standards organizations. Founded on February 23, 1947, the organization promotes worldwide proprietary, industrial, and commercial standards.

ISO 5817:2007[19] provides quality levels of imperfections in fusion-welded joints (except for beam welding) in all types of steel, nickel, titanium and their alloys. It applies to material thickness above 0.5 mm. It covers fully penetrated butt welds and all fillet welds. The principles of ISO 5817:2007 may also be applied to partial-penetration butt welds. The quality levels of imperfections in fillets provided in ISO 5817:2007 are summed up in Table 4.1.

Table 4.1 Limits for imperfections in ISO 5817:2007

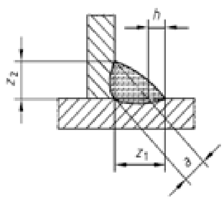
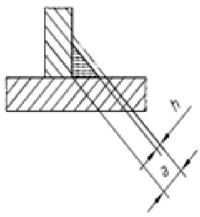
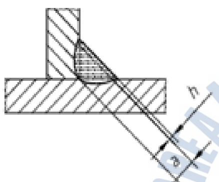
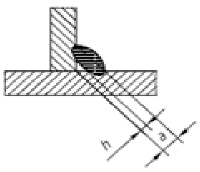
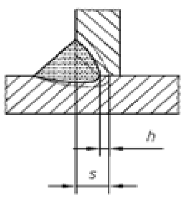
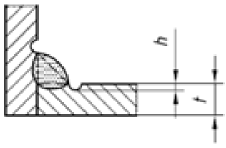
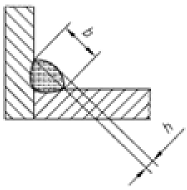
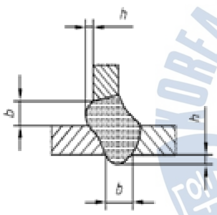
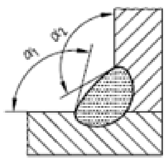
Excessive asymmetry of fillet weld (excessive unequal leg length)		≥0.5	h ≤ 2mm+0.2a	h ≤ 2mm+0.15a	h ≤ 1.5mm+0.15a
Insufficient throat thickness		0.5 to 3	Short imperfections: h ≤ 0.2mm+0.1a	Short imperfections: h ≤ 0.2 mm	Not permitted
		> 3	Short imperfections: h ≤ 0.3mm+0.1a, but max. 2mm	Short imperfections: h ≤ 0.3mm+0.1a, but max. 1mm	Not permitted
Excessive throat thickness		≥0.5	Unlimited.	h ≤ 1mm+0.2a, but max. 4mm	h ≤ 1mm+0.15a, but max. 3mm
Spatter	—	≥0.5	Acceptance depends on application, e.g. material, corrosion protection		
Cracks	—	≥0.5	Not permitted	Not permitted	Not permitted
Lack of penetration		>0.5	Short imperfections: h ≤ 0.2 a, but max. 2mm	Not permitted	Not permitted
	 T-joint (partial penetration)	≥0.5	Short imperfections: h ≤ 0.2 a, but max. 2mm	Short imperfections: h ≤ 0.1 a, but max. 1.5mm	Not permitted

Table 4.1(continued)

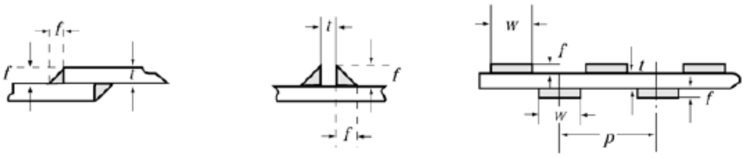
Imperfection designtion	Remarkd	t mm	Limits for imperfections for quality levels		
			D	C	B
Continuous undercut Intermittent undercut		0.5 to 3	Short imperfections: h ≤ 0.2 t	Short imperfections: h ≤ 0.2 t	Not permitted
		> 3	h ≤ 0.2 t, but max. 1mm	h ≤ 0.1 t, but max. 0.5mm	h ≤ 0.05 t, but max. 0.5mm
Excessive convexity (fillet weld)		≥0.5	h ≤ 1mm+0.25b, but max. 5mm	h ≤ 1mm+0.15b, but max. 4mm	h ≤ 1mm+0.1b, but max. 3mm
Excess penetration		0.5 to 3	h ≤ 1mm+0.6b	h ≤ 1mm+0.3b	h ≤ 1mm+0.1b
		> 3	h ≤ 1mm+1.0b, but max. 5mm	h ≤ 1mm+0.6b, but max. 4mm	h ≤ 1mm+0.2b, but max. 3mm
Incorrect weld toe	 α1≥α α2≥α	≥0.5	α≥90°	α≥110°	α≥110°

4.1.2 KR Technical Rules

Classification Technical Rules published by Korean Register of Shipping [20] are grouped into “Rules”, which means all rules for the classification of ships, offshore installations and related equipment, etc.

Special attention is to be paid to the arrangements of hull structural members so that welding may be carried out without much difficulty. The kinds and sizes of fillet welds are to be in accordance with Table 4.2 and their application to the hull construction parts is to be as required by Appendix.

Table 4.2 Kinds and sizes of fillet weld (Unit: mm)

Kind of fillet weld / Thickness of members	Lap joint	Tee joint	Measurement of weld length and pitch			
						
	continuous fillet weld		Intermittent fillet weld			
	size of fillet f		Size of fillet f	Length of fillet w	Pitch p	
	F1	F2			F3	F4
Up to 5	3	3	3	60	150	250
6	4	3	4	75	200	350
7	5	4	5			
8						
9	6		6			
10						
11						
12	7	5	7			
13						
14						
15	8	6	8			
16						
17						
18	9	7	9			
19						
20						
21						
22	10	7	10			
23						
24						
25						
from 26 to 40	11	8	11			

4.2 Previous Researches

It is known that the welding voltage is related to the welding current in a linear or third order polynomial. Through literature survey [3][16] and theoretical study, the research showed that the sigmoid functions had consistency to experimental results as shown in Figure 4.1. These sigmoid functions are written in Equations (4.1) and (4.2).

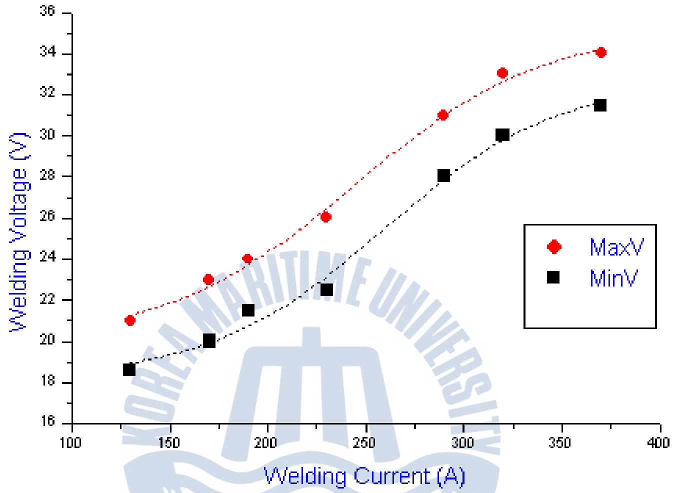


Fig. 4.1 The relationship between the welding voltage and current

$$V_{\min} = \frac{C_{11} - C_{12}}{1 + e^{(I - C_{13})/C_{14}}} + C_{12} \tag{4.1}$$

$$V_{\max} = \frac{C_{21} - C_{22}}{1 + e^{(I - C_{23})/C_{24}}} + C_{22} \tag{4.2}$$

In addition to the energy supplied by the welding arc, electrical resistance heating of the electrode by welding current affects the melting rate of the electrode. This heating is caused by the resistance of the electrode to the flow of the current.

This effect is particularly significant in welding processes that use small-diameter electrodes. Electrical resistance is greater with small-diameter electrodes, long electrode extensions, and low conductivity metals and alloys [17].

According to Lesnewich [18], melting rate is dependent on the welding current and wire extension, as shown Equation (4.3). Since the deposition rate is the product of the melting rate by the ace efficiency it can also be the function of the welding current as well as the wire extension therein. The regression analysis with an experimental data gives the deposition rate [3] by using the Equation (4.3). Dividing Equation (4.3) by the current I yields Equation (4.4). Figure 4.2 shows the relationship between welding current, wire extension and deposition rate.

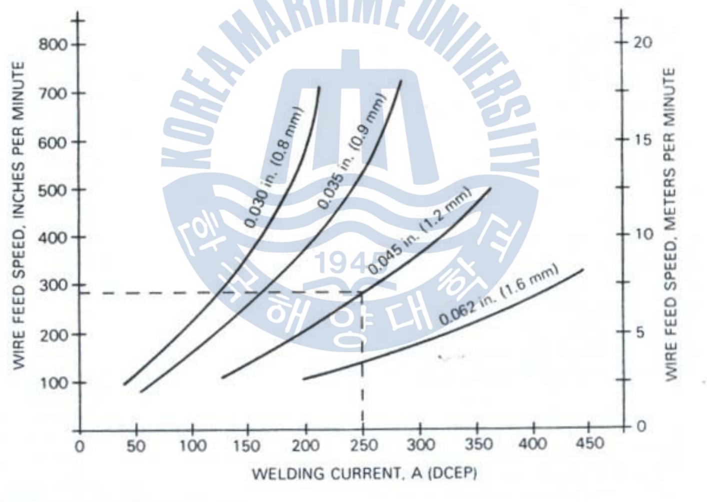


Fig. 4.2 The relationship between welding current, wire extension and deposition rate

$$V_D = a \cdot I + b \cdot I^2 \cdot l_w \tag{4.3}$$

$$\frac{V_D}{I} = a + b \cdot I \cdot l_w \tag{4.4}$$

Where

V_D = Electrode melting rate;

a = Constant of proportionality for anode or cathode heating;

b = Constant of proportionality for electrical resistance heating and includes the electrode resistivity;

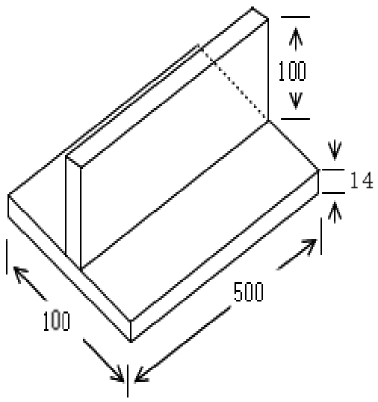
L = Electrode extension;

I = Welding current.

4.3 Experiment

4.3.1 Experimental Conditions and Preparation

In this experiment, the high tensile strength steel—AH32, that widely used for shipbuilding & platform, is used. The dimension and specification of the plate are illustrated in Fig.4.3. The size of the plate is 500mm × 100mm × 14mm.



	Standard condition
Plate Specification	ASTM A131
Class Grade of Plate	AH32
Mechanical Properties	315MPa
Chemical Composition (wt%)	C<0.18, Mn:0.7-1.6, Si:0.1-0.5, S<0.04
Thickness	14mm

Fig. 4.3 Dimension of fillet joint for experiment and specification of the plate

The 1.4mm diameter flux core wire, widely used in the shipyard now, is used. And the D plus Sixaxis Control robot made by Kawasaki is used. The welding machine is a new developed digital welding machine named as SUNGDONG DS-600A. The robot and welding machine are illustrated in Fig.4.4.

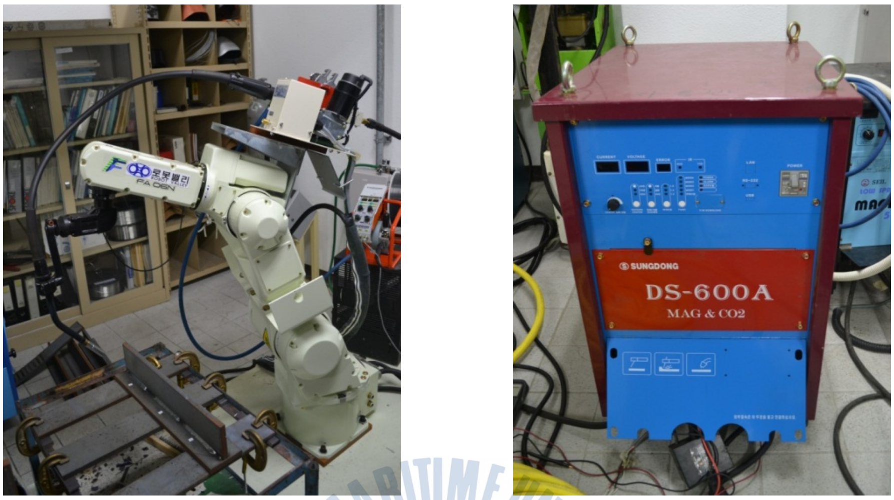


Fig. 4.4 Kawasaki D plus robot and SUNGDONG DS-600A

The experiment conditions are summed up in table 4.3.

Table 4.3 Experiment condition

Welding machine	SUNGDONG DS-600A
Robot	Kawasaki D plus
Base metal	high tensile strength steel—AH32
Welding wire	1.4mm flux core wire
Shielded gas	100% CO_2 (20-25L/min)
Temperature and humidity	20℃，60%

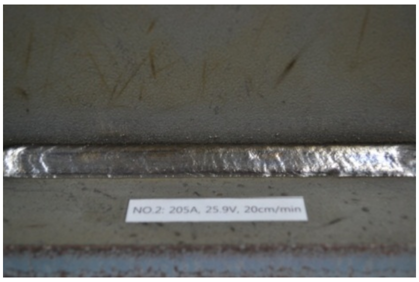
4.3.2 Experimental Results and Analysis

1. relationships of Current—Voltage and Deposition Rate—Current—Wire Extension

Table 4.4(a) Representative experimental data

NO.	Fillet Angle	Current (A)	Voltage (V)	Speed (cm/min)	Wire Extension (mm)	Size of Fillet (mm)	Throat (mm)	Comment
1	90°	199	24.6	20	13	6.4/7.8	5.2	
2	90°	205	25.9	20	13	7.2/7.2	5.2	
3	90°	215	26.5	20	13	7.7/7.0	5.4	
4	90°	218	27.8	20	13	7.2/7.6	5.4	
5	90°	212	28.8	20	13	7.3/7.5	5.4	
6	90°	210	30	20	13	7.4/7.3	5.5	

NO.1 199A, 24.6V, 20cm/min Leg length: 6.4/7.8 Throat: 5.2



NO.2 205A, 25.9V, 20cm/min Leg length: 7.2/7.2 Throat: 5.2

NO.3 215A, 26.5V, 20cm/min Leg length: 7.7/7.0 Throat: 5.4

NO.4 218A, 27.8V, 20cm/min Leg length: 7.2/7.6 Throat: 5.4

NO.5 211A, 28.8V, 20cm/min Leg length: 7.3/7.5 Throat: 5.4

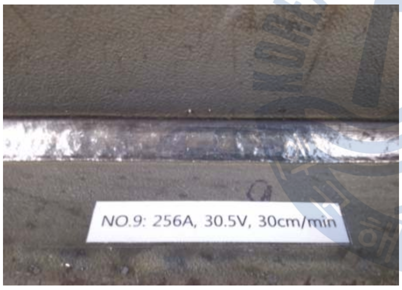
NO.6 210A, 30V, 20cm/min Leg length: 7.4/7.3 Throat: 5.5

Fig. 4.5(a) Representative weld bead

Table 4.4(b) Representative experimental data

NO.	Fillet Angle	Current (A)	Voltage (V)	Speed (cm/min)	Wire Extension (mm)	Size of Fillet (mm)	Throat (mm)	Comment
7	90°	250	28.1	30	13	6.4/6.8	4.6	
8	90°	250	28.2	30	13	6.6/6.8	4.9	
9	90°	256	30.5	30	13	7.0/7.7	4.7	
10	90°	263	30.4	30	13	7.0/7.9	4.9	
11	90°	255	32.5	30	13	6.7/6.9	4.9	
12	90°	253	32.5	30	13	6.9/7.0	4.9	

NO.8 250A, 28.2V, 30cm/min   Leg length: 6.6/6.8   Throat: 4.9



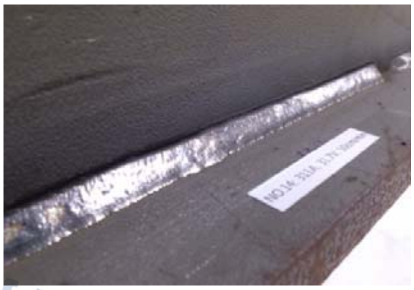
NO.9 256A, 30.5V, 30cm/min   Leg length: 7.0/7.7   Throat: 4.7

NO.11 255A, 32.5V, 30cm/min   Leg length: 6.7/6.9   Throat: 4.9

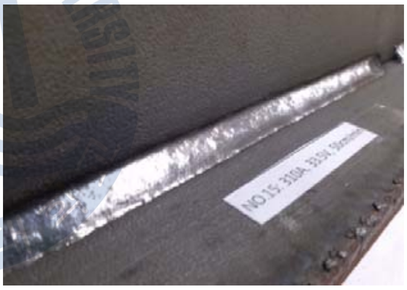
Fig. 4.5(b) Representative weld bead

Table 4.4(c) Representative experimental data

NO.	Fillet Angle	Current (A)	Voltage (V)	Speed (cm/min)	Wire Extension (mm)	Size of Fillet (mm)	Throat (mm)	Comment
13	90°	302	31.4	50	20	6.2/5.8	4.7	
14	90°	311	31.7	50	20	6.6/5.7	4.6	
15	90°	310	33.5	50	20	5.9/5.6	4.3	
16	90°	311	33.4	50	20	5.6/6.1	4.3	
17	90°	311	35.8	50	20	5.7/6.9	4.7	
18	90°	319	35.2	50	20	5.7/7.1	4.7	



NO.14 311A, 31.7V, 50cm/min   Leg length: 6.6/5.7   Throat: 4.6



NO.15 310A, 33.5V, 50cm/min   Leg length: 5.9/5.6   Throat: 4.3

NO.17 311A, 35.8V, 50cm/min   Leg length: 5.7/6.9   Throat: 4.7

Fig. 4.5(c) Representative weld bead

Deposited area consists of three parts as shown in Fig.4.8. After we got the leg length and the throat, we can calculate its deposited metal area by Equation (4.6) through (4.11)

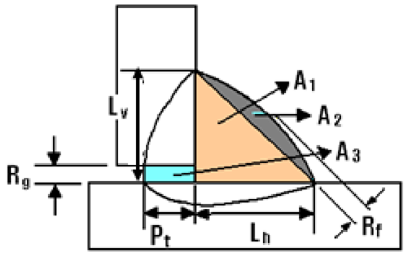


Fig. 4.6 Deposition area

$$A_1 = L_h \cdot L_v/2 \tag{4.5}$$

$$A_2 = \sqrt{L_h^2 + L_v^2} \cdot R_f \cdot 2/3 \tag{4.6}$$

$$A_3 = P_t \cdot R_g \tag{4.7}$$

$$A_{dep} = A_1 + A_2 + A_3 \tag{4.8}$$

After we calculated the deposited metal area by Equation (4.5) through (4.8), we have summarized it in the Table 4.5.

Table 4.5 Data of experiment

NO.	Fillet Angle	Current (A)	Voltage (V)	Speed (cm/min)	Wire Extension (mm)	Deposition area (mm^2)	Size of Fillet (mm)	Comment
1	90°	199	24.6	20	13	27.65	6.4/7.8	
2	90°	205	25.9	20	13	27.96	7.2/7.2	
3	90°	215	26.5	20	13	29.03	7.7/7.0	
4	90°	218	27.8	20	13	29.45	7.2/7.6	
5	90°	212	28.8	20	13	28.77	7.3/7.5	
6	90°	210	30	20	13	28.4	7.4/7.3	
7	90°	250	28.1	30	13	23.63	6.4/6.8	
8	90°	250	28.2	30	13	24.97	6.6/6.8	
9	90°	256	30.5	30	13	27.64	7.0/7.7	
10	90°	263	30.4	30	13	28.35	7.0/7.9	
11	90°	255	32.5	30	13	24.4	6.7/6.9	
12	90°	253	32.5	30	13	25.46	6.9/7.0	
13	90°	302	31.4	50	20	20.81	6.2/5.8	
14	90°	311	31.7	50	20	19.97	6.6/5.7	
15	90°	310	33.5	50	20	18.69	5.9/5.6	
16	90°	311	33.4	50	20	18.74	5.6/6.1	
17	90°	311	35.8	50	20	20.26	5.7/6.9	
18	90°	319	35.2	50	20	21.45	5.7/7.1	
19	90°	350	34.8	50	20	26.68	6.7/7.0	
20	90°	346	35.1	50	20	24.95	6.5/6.9	
21	90°	346	36.5	50	20	24.51	6.3/6.8	
22	90°	356	36.5	50	20	26.76	6.8/7.1	
23	90°	363	38.4	50	20	25.91	6.4/7.1	
24	90°	354	38.8	50	20	25.37	6.6/7.1	
25	90°	274	29.8	40	20	19.98	6.3/5.8	
26	90°	286	29.4	40	20	22.74	6.7/6.6	
27	90°	274	31.9	40	20	24.75	6.6/7.3	
28	90°	283	32	40	20	20.96	5.9/6.9	
29	90°	287	33.8	40	20	20.38	6.3/6.1	
30	90°	277	34.1	40	20	21.35	6.1/6.8	

The regression analysis with the experimental data gives the relationship between current and voltage as shown in Fig 4.7. these sigmoid functions are written in equations (4.9) and (4.10). The deposition rate is given by using the equation (4.11).

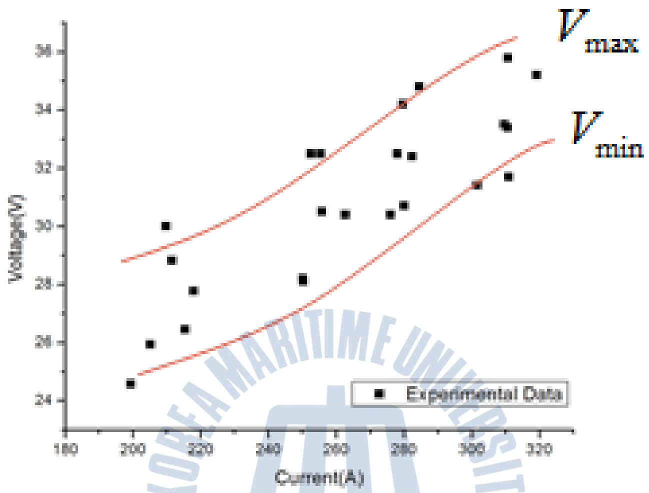


Fig. 4.7 Current-Voltage

$$V_{max} = \frac{22.18 - 37.43}{1 + e^{(I - 244.63)/47.964}} + 37.43 \tag{4.9}$$

$$V_{min} = \frac{20.03 - 35.104}{1 + e^{(I - 259.6)/44.816}} + 35.104 \tag{4.10}$$

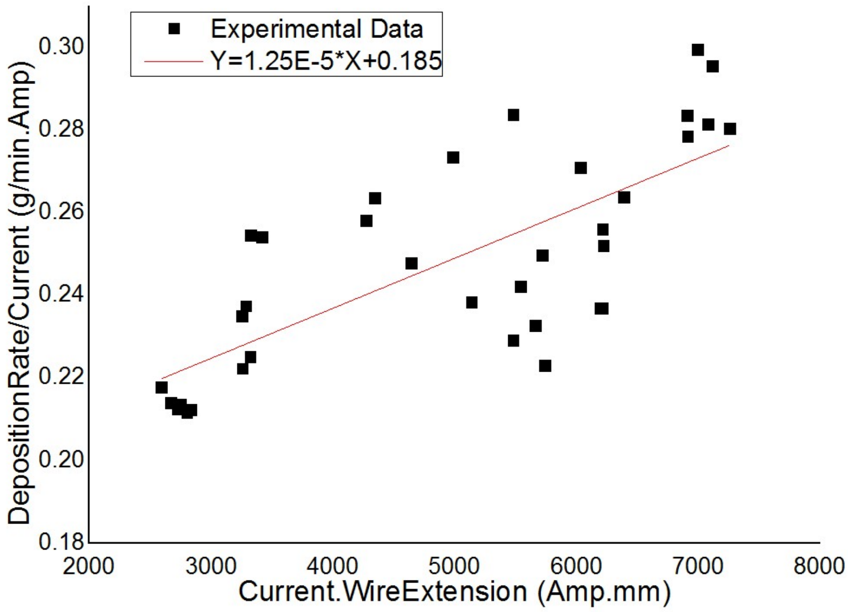


Fig. 4.8 Current-Wire extension-Deposition rate

$$V_D = 0.185I + 1.25\times10^{-5} I^2 \cdot l_w \tag{4.11}$$

The deposited area can also be expressed as in the equation (4.12) with the welding speed V_s and deposition rate V_D. The equation (4.13) and (4.14) are obtained from equation (4.11) and (4.12). Welding speed V_s is determined by equation (4.14).

$$A_{dep} = \frac{V_D \cdot 100}{V_S \cdot \rho} \quad (mm^2) \tag{4.12}$$

$$V_D = \frac{A_{dep} \cdot V_S \cdot \rho}{100} = b_1 \cdot I + b_2 \cdot I^2 \cdot l_w \quad (g/\min) \tag{4.13}$$

$$V_S = \frac{(b_1 \cdot I + b_2 \cdot I^2 \cdot l_w) \cdot 100}{A_{dep} \cdot \rho} \quad (cm/\min) \tag{4.14}$$

2. Suitable deposition rate considering the gap size.

Through the equation (4.11) and (4.14), we can determine and calculate the welding speed for the horizontal fillet weld. We can get a sound bead by this welding speed when doing the welding work.

Table 4.6 Experimental data with gap

NO.	Fillet Angle	Current (A)	Voltage (V)	Speed (cm/min)	Wire Extension (mm)	Size of Fillet (mm)	Throat (mm)	Comment
1	90°	360	36.6	40	20	8.3/6.9	5.4	gap=0mm
2	90°	349	36.6	40	20	7.6/7.1	5.6	gap=1mm
3	90°	319	31.8	36	20	7.1/7.0	4.6	gap=2mm
4	90°	290	31.4	30	20	6.5/6.9	4.4	gap=3mm

NO.1 360A, 36.6V, 40cm/min   Deposition area: 32.23mm^2

NO.2 349A, 36.6V, 40cm/min   Deposition area: 29.75mm^2

NO.3 319A, 31.8V, 36cm/min   Deposition area: 25.51mm^2

NO.4 290A, 31.4V, 30cm/min   Deposition area: 23.06mm^2

Fig. 4.9 Weld bead with gap

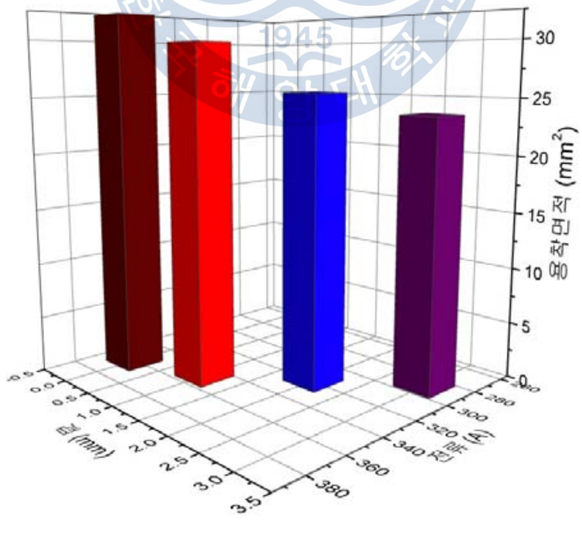


Fig. 4.10 Relationship of deposition area, gap and welding current

CHAPTER 5 CONCLUSION

In manual welding, a skillful worker can weld adjusting the welding parameters to the optimal point during the welding. In the case of robotic arc welding, all of the welding parameters should be set to the definite values such as 280A, 30V, and 40cm/min, before the welding. This research aims to find the optimal welding parameters and build a database for developing an expert system for CO_2 robotic arc welding. During the experiment, edit some variables by prepending the following to the existing value, such as wire extension, welding speed, torch angle and so on. By these conditions, the relationships between the welding parameters were found as described in the following.

① The relationship between welding current, wire extension and deposition rate was found.

② When the fillet joint has no gap, from the experiment data we found that the enough deposition area can be obtained by the low current, low welding speed (such as 218A, 20cpm) or high current, high welding speed (such as 356A, 50cpm). So when in the actual welding production, the high current with high welding speed is recommended.

③ By using the equation obtained by regression analysis with experimental data, the welding speed for a sound weld bead can be determined.

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I want to thank all the past and present members of the Ship Production Research Lab. There is also my gratitude to all other friends at Korea Maritime University for the friendly environment and emotional supports. I will not forget the time we spent together before and in the future.

Finally, I would like to dedicate this thesis to my family for their continued love and strong supports throughout all these years. You are always the persons who believe in and encourage me in all my endeavors, which is a contributing factor to any success I may achieve. Without these endless and priceless loves, it will never be possible for me to still live happily and accomplish my tasks. I feel great fortune to have you all accompany with me, only in this way, my life is complete and honorable.

Appendix

Line No.	Item			Application		Kind of weld
1	Rudders	Rudder frames		Rudder plates		F3
2				Vertical frames forming main pieces		F1
3				Rudder frames (except above)		F2
4	Single bottoms	Floors plates		Shell plates	In strengthened bottom forward, aft peaks and deep tanks	F2
5					Elsewhere	F4
6				Face plates of floor plates	In strengthened bottom forward and main engine rooms	F2
7					Elsewhere	F4
8				Through plates and rider plates of centre keelsons		F1
9		Centre keelson	Girders	Flat plate keels	In strengthened bottom forward	F2
10					Elsewhere	F3
11				Rider plates		F3
12				Floor plates		F2
13		Side keelson	Girders	Shell plates	In strengthened bottom forward	F2
14					Elsewhere	F4
15				Rider plates	In main engine rooms	F2
16					Elsewhere	F4
17				Floor plates		F3
18	Double bottoms with transverse framing	Solid floors		Shell plates	In strengthened bottom forward	F2
19					Elsewhere	F4
20				Inner bottom plates	Bed plates of main engine and thrust bearings	F2
21					In strengthened bottom forward and engine rooms (except above)	F2
22					Elsewhere	F4
23				Girders under inner bottom below main engine seatings		F1
24				Centre girders	In strengthened bottom forward and main engine rooms (except above)	F2
25					Elsewhere	F3
26				Margin plates		F2
27		Oiltight and watertight floors		Boundaries		F1
28		Stiffeners on floor plates		Oiltight and watertight floors		F3
29				Elsewhere		F4
30		Open floors	Frames	Shell plates		F4
31			Reverse frames	Inner bottom plates		F4
32			Brackets	Centre girders		F3
33				Margin plates		F2
34			Vertical struts	Side girders		F4
35		Centre girders		Flat plate keels	Where oiltight or watertight	F1
36					Elsewhere	F3
37				Inner bottom plates	Where oiltight or watertight	F1
38					Lower portion of girders for main engine seatings or thrust bearings	F2
39					Elsewhere	F3
40		Side girders(intercostal plates)		Shell plates	In strengthened bottom forward	F2
41					Elsewhere	F4
42				Inner bottom plates	In engine rooms	F2
43					Elsewhere	F4
44				Solid floors	In strengthened bottom forward and main engine rooms	F2
45					Elsewhere	F4
46		Main engine girders		Inner bottom plates		F2
47				Shell plates		F2
48		Margin plates		Shell or gusset plates		F1

Line No.	Item		Application		Kind of weld
49		Hold frame brackets	Margin plates		F1
50			Gusset plates		F2
51		Shell stiffeners	Connections to shell plates are as required for longitudinal frames		
52		Half height girders	Connections to shell plates and solid floors are as required for side girders		
53	Double bottoms with longitudinal framing	Longitudinal frames	Shell plates in strengthened bottom forward		F2
54			Shell plates(except above) or inner bottom plates		F4
55		Solid floors	Shell plates and inner bottom plates	For two frame spaces at the end of floors	F2
56				Elsewhere	F3
57			Centre girders		F2
58		Brackets on centre girders	Centre girders, shell plates and inner bottom plates		F3
59		Brackets on margin plates in double bottoms	Margin plates		F2
60			Shell plates and inner bottom plates		F3
61		Stiffeners on side girders	Side girders		F4
62	Frames	Shell plates	In aft peak tanks, for $0.125L$ from fore end, and in deep tanks		F3
63			Elsewhere		F4
64	Built-up frames	Webs	Shell plates or face plates	$0.125L$ from fore end, and in deep tanks	F2
65				Elsewhere	F3
66	Decks	Stringer plates	Shell plates	In strength decks	F1
67				Elsewhere	F2
68		Beams	Decks	In tanks	F3
69				Elsewhere	F4
70	Built-up beams	Webs	Decks or face plates	In tanks	F2
71				Elsewhere	F3
72	Pillars	Pillars	Heels and heads		F1
73			Connections of built-up pillar members		F3
74	Hatchways	Coamings	Decks(except below)		F2
75			Hatchway corners on strength decks		F1
76		Portable beams	Connections of members		F3
77	Bulkheads	Stiffeners	Bulkhead plates	Above the lower ends of brackets connecting stiff-eners to deck girders	F1
78				In deep tank bulkheads	F3
79				Elsewhere	F4
80		Bulkhead plates	Boundaries	In oiltight and watertight bulkheads	F1
81				Elsewhere	F3
82	Seatings	Girders or brackets	Bed plates	In seatings for main engines, thrust bearings, boil-er bearers and main dynamo engines	F1
83			Inner bottom plates or shell	In seatings for main engine or thrust bearings	F2
84			Girder plates	In seatings for main engine or thrust bearings	F1

85	Web beams, web frames, side stringers, deck girders and girders on bulkheads	Web plates or girder plates	Shell, decks or bulkhead	In tanks, web frames for 0.125L from fore end and side stringers		F2
86				Elsewhere		F3
87			End connections of web or girder plates to shell, decks, inner bottom plates or bulkheads			F1
88			Webs or face plates of webs	In tanks, web frames for 0.125L from fore end and side stringers		F2
89				Elsewhere	Where face area exceeds 65 cm^2	F2
90					Where face area does not exceed 65 cm^2	F3
91		Tripping brackets on webs or girder plates	Boundaries			F2
92		Serrations of webs or girder plates	Webs of frames, beams or stiffeners			F2
93	Brackets at ends of members		Connections of members to brackets(except otherwise specified)			F1

NOTES:

1. Where longitudinal strength members are mutually, connected by fillet weld, the fillet sizes are to be in accordance with **Table 3.1.10** and this **Table,** except that the total throat areas of fillet joints are not to be less than the minimum sectional area of the members.
2. Where the ends of frames, beams and stiffeners are directly fillet welded to decks, shell, inner bottom plates or bulkhead plates, the fillet sizes are not to be less than 0.7 times the web thickness of members.
3. Where beams, frames, stiffeners and girders are intermittently welded to decks, shell, inner bottom plates and bulkhead plates, the fillet welds are to be partly continuous as shown in **Fig (a).** Where members are fitted at the opposite side of brackets as shown in **Fig (b)** or **(c),** the fillet welds are to be continuous for proper length at the ends of members or at the toe of brackets of members. The fillet weld may be as shown in **Fig (d),** where the whole lengths of the joints are light continuously welded with the fillet size not less effective than F2
4. Where the rider plates or inner bottom plates consist of bed plates of main engine seating or important seatings, the kind of fillet is to in accordance with the requirements for the seatings.
5. As to the connections not specified in double bottoms with longitudinal framing, the requirements for transverse framing are to be applied.