DEVELOPMENT OF ADVANCED 3-ELECTRODE MAG HIGH-SPEED HORIZONTAL FILLET WELDING PROCESS




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ABSTRACT

In the shipbuilding industry, the improvement of welding efficiency and weld quality are desirable in order to cope with the recent growth in shipbuilding orders and the size of ship hulls. Innovation in welding efficiency and weld quality in horizontal fillet welding is an important issue since the amount of horizontal fillet welding work generally accounts for 70 percent or higher of the total welding work for ship hulls. As one of the available high-speed horizontal fillet welding processes, the Twin Tandem One Pool process (hereinafter referred to as the TOP process) has been used in actual fabrication. In the TOP process, a set of two wire electrodes is positioned in tandem on both sides of the web plate of a fillet joint and the wire-to-wire distance is kept short, so as to create one weld pool. However, the maximum welding speed of the TOP process is approximately 1.5 m/min. In order to improve the welding speed of the TOP process, the authors have employed an additional filler wire positioned between the two wires of the TOP process. The additional filler wire carries DC-EN currents, as opposed to DC-EP currents for the main welding wires, thereby reducing the arc interference and arc blow at high currents. With this new technique, the authors have improved the stability of the weld pool formation at high currents. Consequently, horizontal fillet welding at a speed of 2.0 m/min on primer-coated steel plates has been achieved with excellent bead appearance, shape and porosity resistance.

IIW-Thesaurus keywords: *Arc blow; Arc welding; Cavities; Defects; Electric arcs; Filler materials; Fillet welds; Gas shielded arc welding; GMA welding; MAG welding; Porosity; Tandem welding.*

1 INTRODUCTION

Horizontal fillet welding plays an important role in shipbuilding and bridge construction. In shipbuilding, for instance, the ratio of horizontal fillet weld length to the total weld length accounts for approximately 70 %. In particular, CO_2-shielded horizontal fillet welding with flux-cored wires is the main welding procedure in Asian shipyards. Hence, it is vital to improve the welding speed and weld quality of CO_2-shielded horizontal fillet welding with flux-cored wires.

At present, the Twin Tandem One Pool process (hereinafter referred to as the TOP process) is widely used as a horizontal fillet welding process to achieve high welding speeds. A schematic diagram of the TOP process is shown in Figure 1. In the TOP process, a set of two wire electrodes is positioned in tandem on both sides of the web plate of a fillet joint and the two wire electrodes deposit into one weld pool. Compared with the twin-single-electrode process (with a maximum welding speed of 0.8 m/min), the TOP process provides higher welding speeds and excellent porosity resistance. In shipbuilding

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and bridge construction, it is now satisfactorily used to produce horizontal fillet welds with leg lengths of 5 to 6 mm at welding speeds of 1.2 to 1.3 m/min.

With the TOP process, in order to improve the present maximum welding speed (approximately 1.5 m/min.), it is necessary to use higher welding currents than those (290 to 470 A with a 1.6 mm φ wire) used at the present. However, when the welding current of the leading wire surpasses 500 A, serious arc interference occurs because both the leading and trailing wires use DC-EP polarity. The arc interference prevents stable formation of the weld pool which results in poor bead appearance and shape, lower porosity resistance and increased amounts of spatter.

Furthermore, as the welding current increases, the TOP process becomes more susceptible to arc blow depending on the positions of the welding torches and current return (grounding) connections. In the TOP process, it is known that porosity resistance is best when there is no positional shift in the welding direction between the two leading wires and between the two trailing wires respectively on both sides of the web plate [1]. However, at actual shipbuilding and bridge construction sites, the position of welding torches often shifts somewhat. When the welding current is excessively high, the positional shift of the welding torches causes serious arc blow, which in turn renders the weld pool unstable. As a result, poor bead appearance and shape, inferior porosity resistance and increased amounts of spatter occur. In addition, when the welding current is excessively high, the TOP process is easily affected by the magnetic field depending on the location of the grounding connection, with the weld pool in turn becoming unstable. Consequently, the problems of inferior porosity resistance, poor bead appearance and shape and increased amounts of spatter occur.

2 DEVELOPMENT OF ADVANCED 3-ELECTRODE WELDING PROCESS

2.1 Outline of advanced 3-electrode welding process

In order to decrease welding defects caused by arc interference and arc blow induced by an increase in the welding speed – thus an increase of welding current, the authors have developed an advanced high-speed 3-electrode MAG horizontal fillet welding process (hereinafter referred to as the advanced 3-electrode welding process). Figure 2 shows a schematic diagram of the advanced 3-electrode welding process and

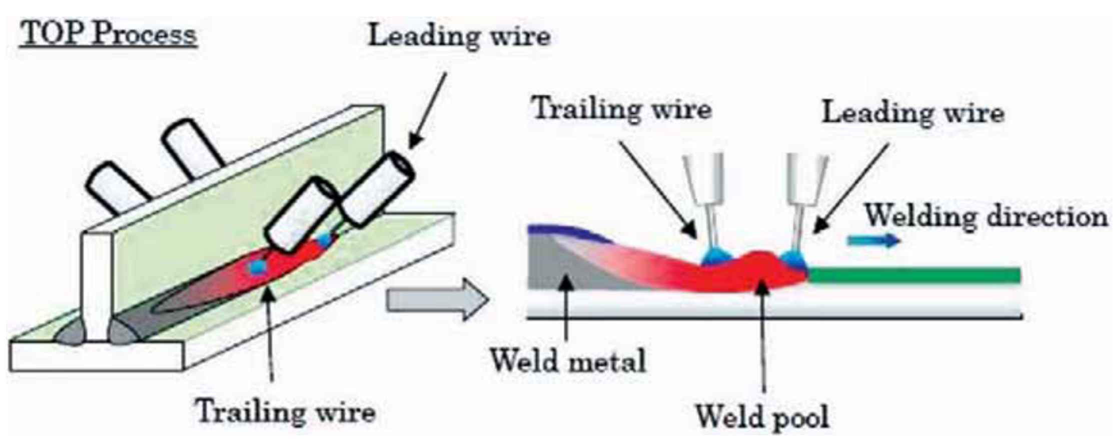


Figure 1 – Schematic diagram of Twin Tandem One Pool (TOP) process

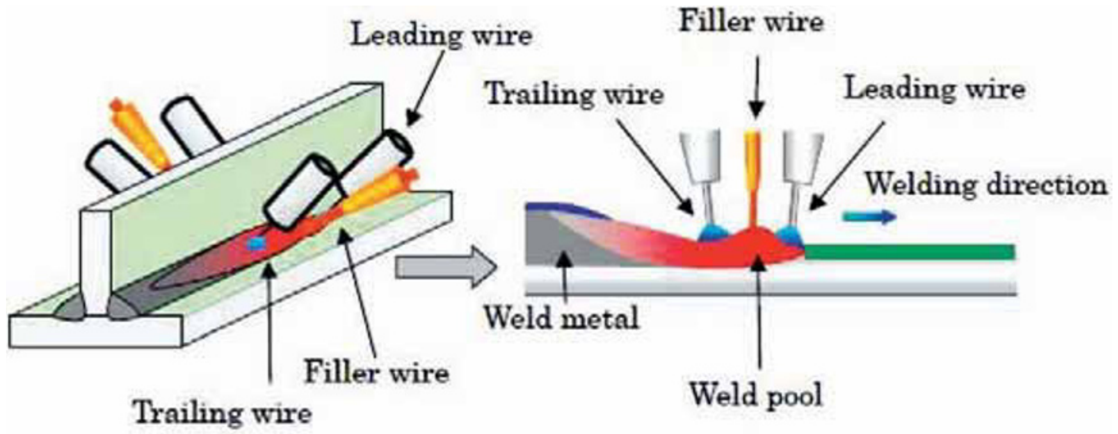


Figure 2 – Schematic diagram of advanced 3-electrode welding process

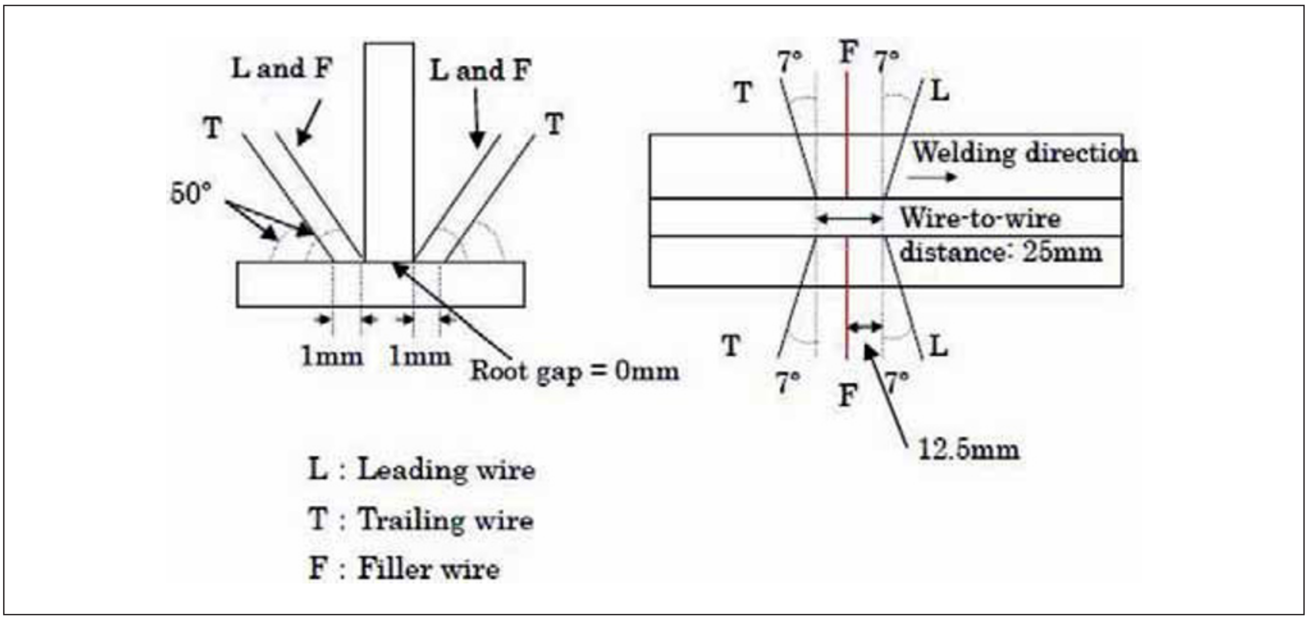


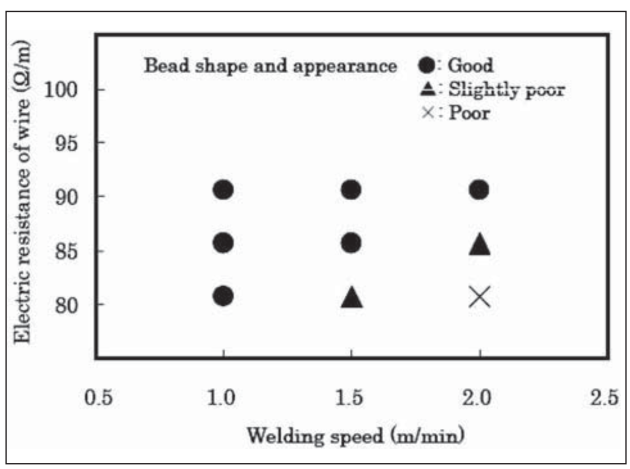
Figure 3 – Location of welding torches of advanced 3-electrode welding

Figure 3 shows the basic location of the welding torches. In the advanced 3-electrode welding process, a filler wire is added as the third electrode between the leading and trailing wire electrodes in the TOP process. The filler wire is heated by applying a DC-EN current. The magnetic field generated by the current applied to the filler wire reduces the arc interference which occurs between the leading and the trailing wires (both wires use DC-EP polarity). Furthermore, the addition of the filler wire produces cooling of the weld pool, thereby increasing the viscosity of the weld pool and in turn facilitating the stabilization of the weld pool. In the advanced 3-electrode welding process, the weld pool is more stable compared with the TOP process, even in high-speed welding at 2.0 m/min. Consequently, good porosity resistance and good bead appearance and shape can be obtained. In this case, the wire extension is set at 25 mm for both the leading and trailing wires and the extension of the filler wire is set at 20 mm. The shielding gas is 100 % CO_2 which is supplied at a rate of 25 l/min. In this research, welding by the TOP process was also conducted for comparison, in which the locations of the welding torches were the same as in Figure 3, but without the filler wires.

2.2 Development of suitable wire for advanced 3-electrode welding process

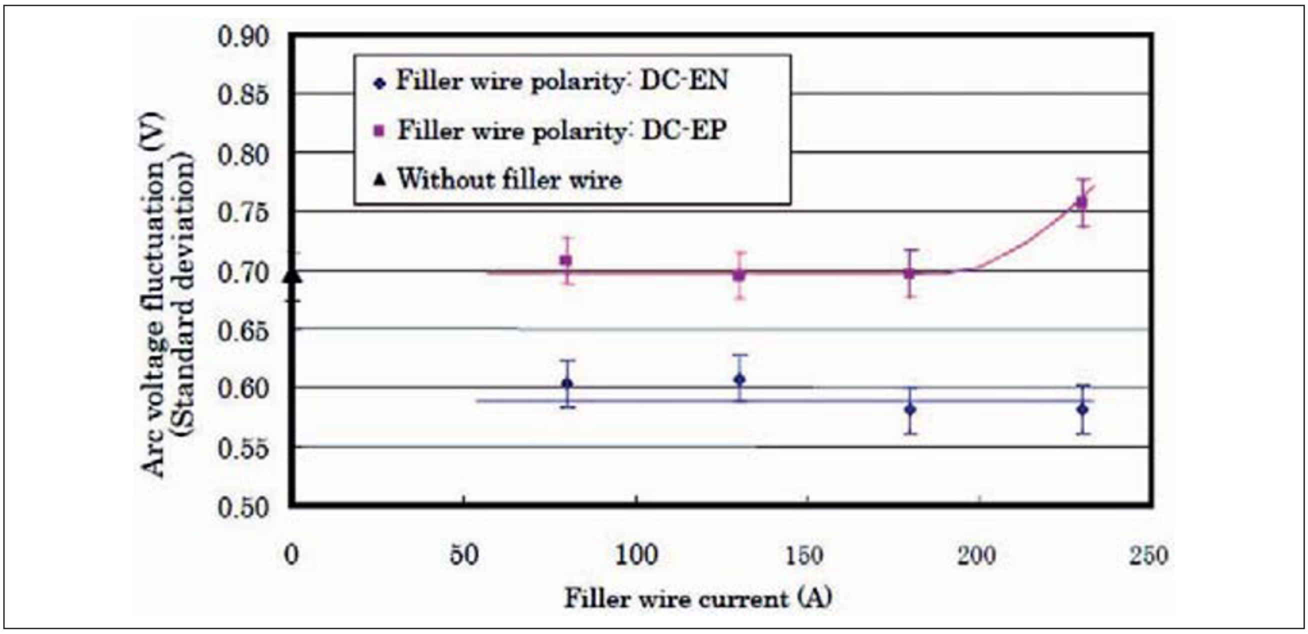
Generally, the welding current is increased to obtain the same amount of deposited metal when welding at a higher speed. The higher welding current causes greater arc interference between the leading and trailing wires. Thus, the reduction of the welding current to obtain the same amount of deposited metal is effective in minimizing arc interference during high-speed welding. The authors investigated the reduction of the welding current by means of increasing the electric resistance of wires. Figure 4 shows the influence of electric resistance of experimental wires to bead shape and appearance. Three experimental wires were designed to have different electric resistance by changing the wall thickness of the sheath metal to the flux core. As a result, the experimental wire designed to have the highest electric resistance produced the best bead shape and appearance at a welding speed of 2.0 m/min, because of its more stable arc performance. Following this observation, the authors developed a special flux-cored wire for the advanced 3-electrode welding process by means of its more suitable electric resistance.

In addition to this observation, the special flux-cored wire was also designed to secure good porosity resistance during high-speed welding, by optimizing the amounts of slag formers and deoxidizing agents in the wire conforming to JIS Z 3313YFW-C50DM with a diameter of 1.6 mm. As for the filler wire, an ordinary solid wire conforming to JIS Z 3312 YGW17 was used.



Wire feed speed: 17.6 m/min for the leading wire; 13.2 m/min for the trailing wire; Arc voltage: 36-38 V for the leading wire; 34-36 V for the trailing wire.

Figure 4 – Effects of electric resistance of wire on bead shape and appearance



Leading wire: 560 A-38 V; Trailing wire: 440 A-34 V; Welding speed: 2.0 m/min.

Figure 5 – Effects of filler wire polarity and current on arc voltage fluctuation

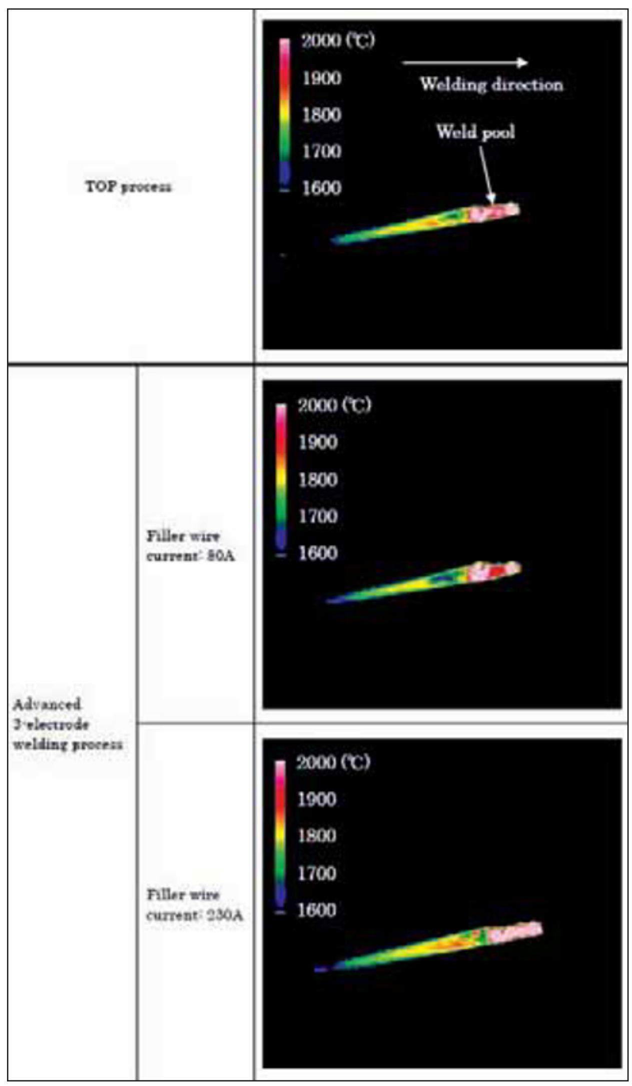
2.3 Investigation of electric parameters suitable for inserted filler wire

In order to determine the best electric polarity and current for the filler wire and to check the stability of the weld pool, welding tests were conducted with polarities of DC-EN and DC-EP at 80 A, 130 A, 180 A and 230 A. For the purpose of comparison, the TOP process was also included in the welding tests.

In this investigation, the fluctuation of the arc voltage of the trailing wire was measured to evaluate the stability of the weld pool. The results are shown in Figure 5. When the weld pool was disturbed, the arc length fluctuated considerably, causing a violent fluctuation in the arc voltage.

When the filler wire had DC-EN polarity, there was less arc voltage fluctuation in the current range of 80 A to 230 A than with DC-EP polarity and the TOP process. In this case, the weld pool was confirmed to be more stable. Furthermore, with DC-EN polarity, the degree of arc voltage fluctuation was more or less the same at all the currents tested.

Figure 6 shows variations of weld pool temperature observed by an infrared thermography camera. In this investigation, the polarity of the filler wire was DC-EN and the currents were 80 A and 230 A. The same observation was made for the TOP process for comparison. At the current of 80 A, the addition of the filler wire had a cooling effect on the weld pool. In Figure 5, it is obvious that there is less arc voltage fluctuation with the filler wire of DC-EN polarity at 80 A when compared with the TOP process. This is presumably because of the effect of reducing the arc interference due to the DC-EN filler wire and the effect of increasing the viscosity of the weld pool, due to the lower temperature of the weld pool, provided by an addition of the filler wire.



Leading wire: 560 A-38 V; Trailing wire: 440 A-36 V; Filler wire polarity: DC-EN; Welding speed: 2.0 m/min.

Figure 6 – Comparison of weld pool temperatures by infrared thermography

By contrast, when the current applied to the filler wire was 230 A, the cooling effect of the filler wire could not be observed as in Figure 6. Therefore, the viscosity of the weld pool can be considered to be the same as in the case of the TOP process. Nevertheless, as shown in Figure 5, there was less arc voltage fluctuation compared with the TOP process, even when the current applied to the filler wire was 230 A with the polarity of DC-EN. Therefore, the governing factor for less arc voltage fluctuation can be considered to be the reduction of the arc interference, by setting the polarity of the filler wire to DC-EN, when a high current is applied to the filler wire.

In the next stage of the investigation, weld bead shape was examined with the TOP process and the advanced 3-electrode welding process to determine the optimum current (wire-feed speed) required by the filler wire.

Changes in the shape of the weld bead, in relation to an increase of the filler wire current, were evaluated by the index H/L shown in Figure 7. L is the length of the hypotenuse of the right triangle defined by the upper and lower legs of the fillet weld, with H being the shortest distance between L and the farthest point from L on the section of the weld bead. H/L becomes bigger when the weld bead becomes more convex.

Figure 8 shows the measurements of H/L at various currents applied to the filler wire. On the whole, the H/L value tends to be bigger as the current increases. In the current range of 0 to 90 A (equivalent to 2.2 m/min of wire-feeding speed), the H/L value does not greatly increase.

From the above-mentioned arc voltage fluctuations that represent the stability of the weld pool and the shape of the weld bead, the optimum current applied to the filler wire was determined to be 80 A (equivalent to 2.0 m/min of wire-feeding speed) for the advanced 3-electrode welding process.

2.4 Welding conditions of advanced 3-electrode welding process

Figure 9 shows a comparison of the arc voltage fluctuation of the trailing wire between the advanced 3-electrode welding process and the TOP process at welding

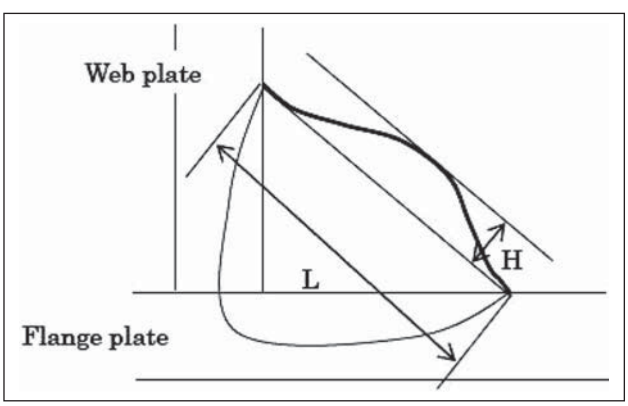
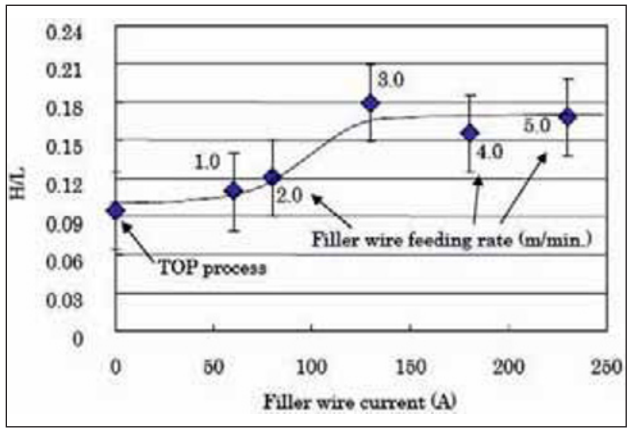
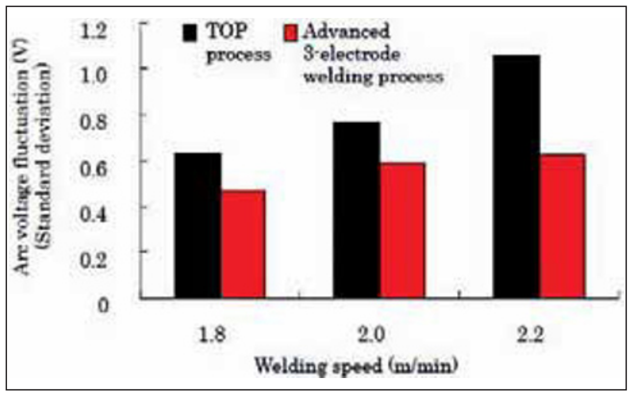


Figure 7 – Definitions of H and L for evaluation of the bead shape



Leading wire: 560 A-38 V; Trailing wire: 440 A-34 V; Filler wire polarity: DC-EN; Welding speed: 2.0 m/min.

Figure 8 – Effect of filler wire current (wire-feeding rate) on H/L

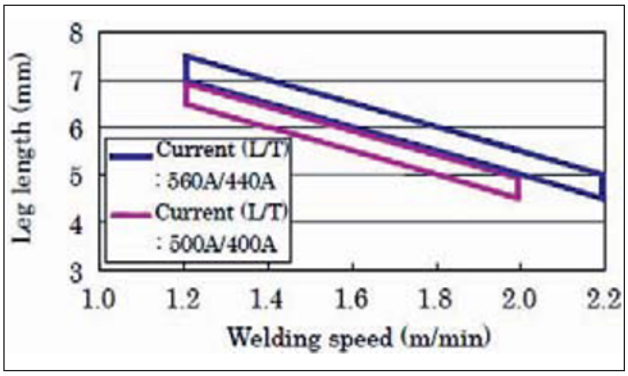


Leading wire: 560 A-38 V; Trailing wire: 440 A-36 V; Filler wire current: 80 A; Filler wire polarity: DC-EN.

Figure 9 – Effect of welding speed on arc voltage fluctuation

speeds of 1.8, 2.0, and 2.2 m/min. Generally, the weld pool tends to be more unstable as the welding speed increases. The instability of the weld pool causes the fluctuation of the distance between the tip of the trailing wire and the surface of the weld pool, which leads to the fluctuation of the arc length accordingly. So the arc voltage fluctuation of the trailing wire tends to be larger as the welding speed increases. However, the arc voltage fluctuation with the advanced 3-electrode welding process was small even at a welding speed of 2.2 m/min, and the welds were acceptable.

Figure 10 shows the applicable ranges of welding speeds and leg lengths obtained by using this advanced welding process. The optimum welding speed range is 1.2 to 2.2 m/min. The optimum leg length range is 4.5 to 7.5 mm. When a leg length of 7.5 mm or larger is required, the heat input inevitably becomes excessively large because it is necessary to obtain a large volume of deposited metal. In turn, the cooling rate of the weld pool is lowered. As a result, the weld bead tends to contain an overlap defect. By contrast, when a leg length of 4.5 mm or smaller is required, the cooling rate of the weld pool increases because it is necessary to raise the welding speed. As a result, the



Filler wire current: 80 A; Filler wire feeding rate: 2 m/min.

Figure 10 – Leg length as a function of welding speed

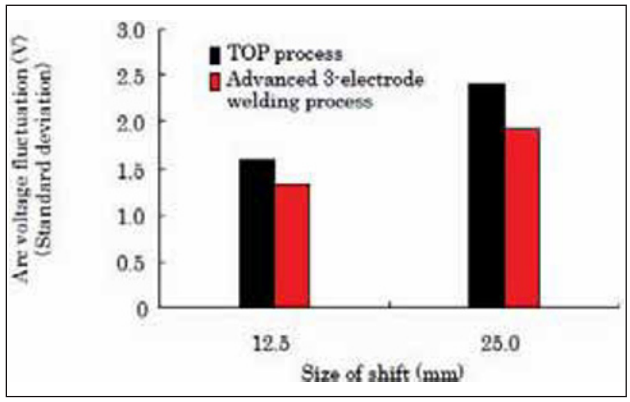
desired shape of the weld bead cannot be obtained due to too much convexity. Figure 11 shows examples of weld bead appearance and shape when the welding speed is 2.0 m/min.

3 RESISTANCE OF ADVANCED 3-ELECTRODE WELDING PROCESS AGAINST ARC BLOW AND POROSITY

3.1 Comparison of arc blow resistance between TOP process and advanced 3-electrode welding process

Figure 12 shows arc voltage fluctuations when the sizes of shift between the two leading wires and between the two trailing wires (the shift between the wires on the right and left sides of the web plate, as defined in Figure 13) are respectively 12.5 mm and 25.0 mm. In both cases, the arc voltage fluctuation of the advanced 3-electrode welding process is lower, which reveals that the weld pool is more stable compared with the TOP process. Figure 14 shows the bead appearance when the size of shift is 12.5 mm. With the TOP process, the weld pool is unstable and the weld bead extremely flawed, while with the advanced 3-electrode welding process, the appearance of the weld bead is considerably improved.

Furthermore, the stability of the advanced 3-electrode welding process against arc blow in relation to the location of grounding connection was investigated. In actual welding fabrication sites, the stability of the weld



Size of shift: 12.5 mm and 25.0 mm; Leading wire: 560 A-38 V; Trailing wire: 440 A-36 V; Filler wire polarity: DC-EN; Filler wire current: 80 A; Welding speed: 2.0 m/min.

Figure 12 – Arc voltage fluctuations when wires are shifted

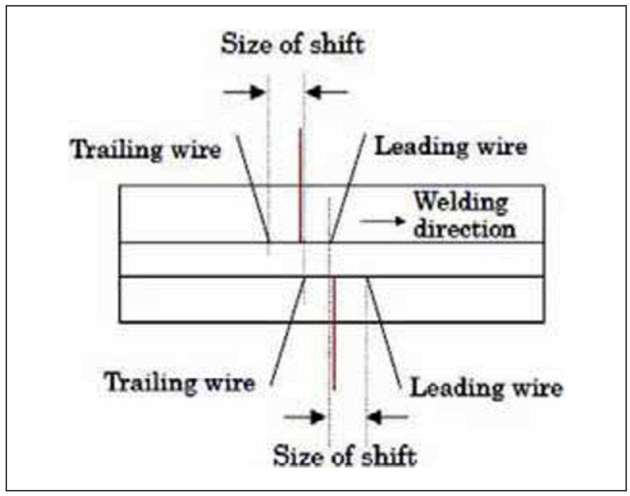
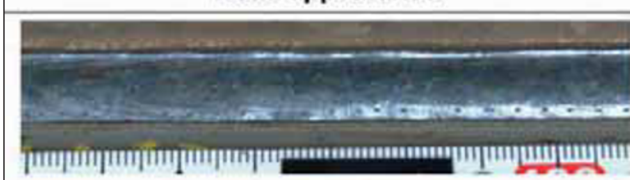
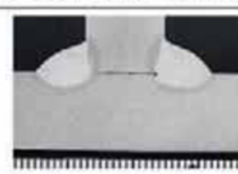


Figure 13 – Definition of shift of wires

pool is markedly affected by the location of grounding connection, as the welding speed increases. By using an apparatus as shown in Figure 15, welding tests were conducted with three variations of the location of the grounding connection: at the start of the web plate, the end of the web plate and at the centre of the flange plate, as shown in Table 1. Figure 16 shows a comparison of arc voltage fluctuations in relation to the three locations of grounding connection for both processes. Inspection of the location of the grounding connections indicates that the advanced 3-electrode welding process exhibits less arc voltage fluctuations; that is, the weld pool is more stable. Figure 17 shows

Bead appearance	Cross-sectional bead shape
	

Leading wire: 560 A-38 V; Trailing wire: 440 A-36 V; Filler wire polarity: DC-EN; Filler wire current: 80 A; Welding speed: 2.0 m/min; Targeted leg length: 5.0-5.5 mm; Base metal surface: with inorganic zinc primer coating.

Figure 11 – Examples of bead appearance and shape by advanced 3-electrode welding process

Welding process	Bead appearance
TOP process	
Advanced 3-electrode welding process	
Size of shift: 12.5 mm; Leading wire: 560 A-38 V; Trailing wire: 440 A-36 V; Filler wire polarity: DC-EN; Filler wire current: 80 A: Welding speed: 2.0 m/min; Base metal surface: with inorganic zinc primer coating.	

Figure 14 – Comparison of bead appearance when wires are shifted

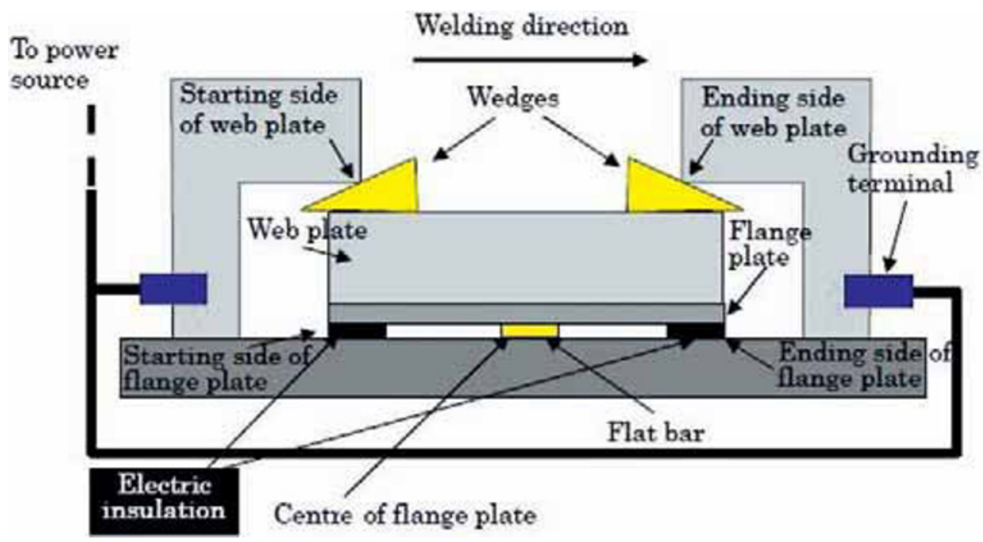
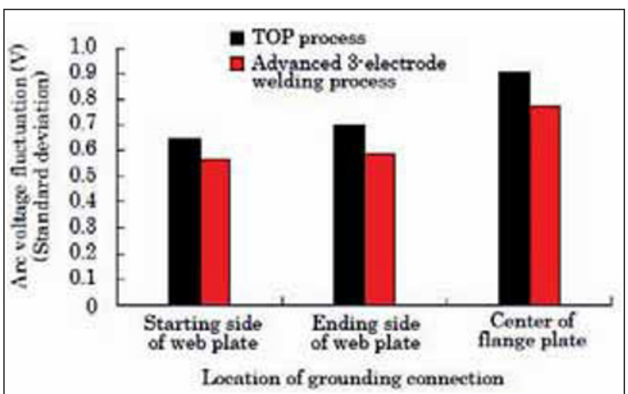


Figure 15 – Locations of grounding connection

Table 1 – Locations of grounding connection

Grounding location	①	②	③
Starting side of web	Currents carried	Insulated	Insulated
Ending side of web	Insulated	Currents carried	Insulated
Centre of flange	Insulated	Insulated	Currents carried



Leading wire: 560 A-38 V; Trailing wire: 440 A-36 V; Filler wire current: 80 A; Filler wire polarity: DC-EN; Welding speed: 2.0 m/min.

Figure 16 – Effect of grounding location on arc voltage fluctuation

a comparison of weld bead appearances when the grounding connection was located only at the starting side of the web plate. Apparently, the appearance of the weld bead made with the advanced 3-electrode welding process is better than that made with the TOP process.

3.2 Porosity resistance of advanced 3-electrode welding process

Tables 2, 3 and 4 show the results of testing the porosity resistance at the welding speeds of 1.6, 1.8, and 2.0 m/min. To evaluate porosity resistance, the number of pits generated, the ratio of worm-tracking porosity on the surface of the weld bead and the ratio of blowholes were investigated. On the whole, the test results indicate good porosity resistance, though it tends to

Welding process	Bead appearance
TOP process	
Advanced 3-electrode welding process	

Grounding location: Starting side of web; Leading wire: 560 A-38 V; Trailing wire: 440A-36V; Filler wire current: 80 A; Filler wire polarity: DC-EN; Welding speed: 2.0 m/min; Base metal surface: with inorganic zinc primer coating.

Figure 17 – Comparison of welding processes in terms of bead appearance

Table 2 – Comparison of welding processes in terms of number of pits (pc/600 mm)

Welding speed (m/min)	1.6	1.8	2.0
TOP process	0.7	2.0	25.0
Advanced 3-electrode welding process	0	0	0.7
Leading wire: 560 A-38 V; Trailing wire: 440 A-36 V; Filler wire polarity: DC-EN; Filler wire current: 80 A; Base metal surface: with inorganic zinc primer coating of (15 ± 5) µm; Mean value of 3-time tests.			

Table 3 – Comparison of welding processes in terms of generation ratio of worm-tracking porosity (%)

Welding speed (m/min)	1.6	1.8	2.0
TOP process	0.9	2.4	12.5
Advanced 3-electrode welding process	0.3	0.6	2.5
Leading wire: 560 A-38 V; Trailing wire: 440 A-36 V; Filler wire polarity: DC-EN; Filler wire current: 80 A; Base metal surface: with inorganic zinc primer coating of (15 ± 5) µm; Mean value of 3-time tests.			

Table 4 – Comparison of welding processes in terms of generation ratio of worm-tracking porosity (%)

Welding speed (m/min)	1.6	1.8	2.0
TOP process	1.9	4.5	15.0
Advanced 3-electrode welding process	0	0.2	0.6
Leading wire: 560 A-38 V; Trailing wire: 440 A-36 V; Filler wire polarity: DC-EN; Filler wire current: 80 A; Base metal surface: with inorganic zinc primer coating of (15 ± 5) µm; Mean value of 3-time tests.			

deteriorate as the welding speed increases. In this investigation, for the test plates, 490 N/mm^2 class high tensile strength steel (JIS G 3106) was adopted, which is often used for shipbuilding and bridge construction. The dimensions of the test plate were 12 mm in thickness, 85 mm in width, and 600 mm in length, both for the web and flange plates. The test plates were coated with inorganic zinc primer. The coating thickness of the primer was controlled to be (15 ± 5) µm. In order to evaluate porosity resistance in the severe condition in which generated gases are difficult to move out of the root of the fillet joint, the edge of the web plate was machined to make close contact with the flange plate surface. As for pits, the mean value of the numbers of pits on the weld beads on both sides of the web plate was regarded as the number of pits for one test. The ratio of worm-tracking porosity and blowholes on one side of the web plate was calculated by the following formula.

Σd (mm)/600 (mm) × 100 (%)

where

d: is the length of individual worm-tracking porosity occurring on the weld bead surface (see Figure 18), or the length of individual blowhole on the fracture surface of the weld bead (see Figure 19).

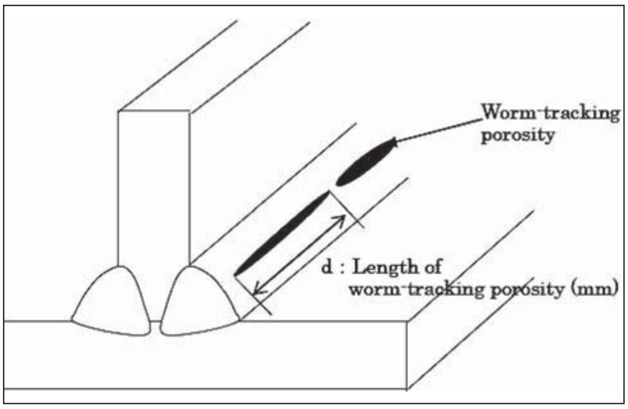


Figure 18 – Length of worm-tracking porosity

The mean value of the figures obtained by the above-mentioned formula on both sides of the web plate was regarded as the generation ratio for one test. For the number of pits, the ratio of worm-tracking porosity on the weld surface, and the ratio of blowholes, the mean values obtained in three tests were used for the evaluation.

4 CONCLUSIONS

It has been confirmed that, in high-speed horizontal fillet welding at a welding speed of approximately 2.0 m/min, the advanced 3-electrode welding process produces a more stable weld pool and generates less arc interference and arc blow, compared with the TOP process. As a result, the advanced 3-electrode welding process can reduce the generation of welding defects and offers good porosity resistance.

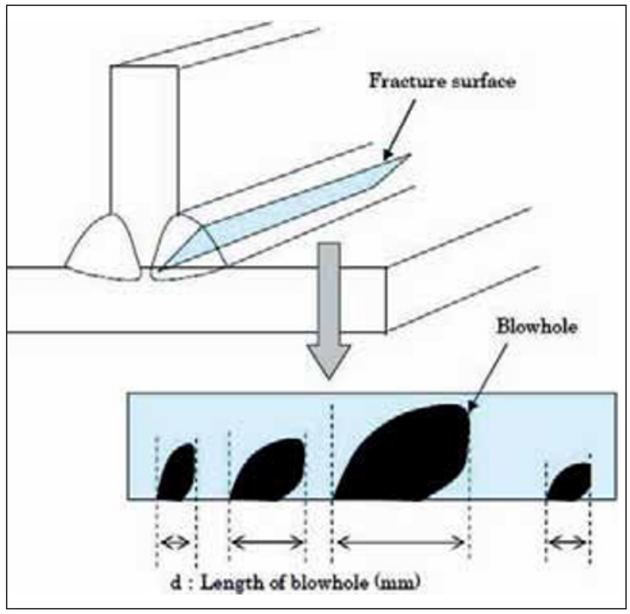


Figure 19 – Length of blowhole

From the above-mentioned research results, the authors are convinced that the advanced 3-electrode welding process will contribute significantly to improving welding speeds and weld quality in horizontal fillet welding in shipbuilding and bridge construction.

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