Analysis by Modeling of Horizontal Coaxial Arc Welding Phenomena*

—Automatic Welding Process for Ship’s Bottom Shell Plates—

by NISHI Yasuhiro** and SANO Takanobu**

Abstract

New automatic arc welding process has been developed for welding ship’s shell plates upwards from the ground. In this process, the axis of the leading welding gun corresponds to that of a weld bead, therefore it is called ‘Horizontal Coaxial Arc Welding’ (HCAW). In order to keep the welding process under control, the simplified numerical model expressing the static balance of forces on the leading molten pool has been designed. The model enables to estimate the weld bead height and the bead formation rate. As a result of analysis by the model, the wire extension length will reach its equilibrium state spontaneously in the case of using a constant voltage characteristic power source, and controlling of the wire feeding speed is effective to reduce the change of the wire extension length during welding in various root opening.

Key Words: Horizontal Coaxial Arc Welding, Modeling, Welding process, Process control, Automation, Ship’s bottom shell plates, Simulation, Modeling

1. Introduction

Quite new automatic arc welding equipment has been developed for welding ship’s shell plates upwards from the ground by adjusting the changes of both groove conditions and slope of plates1). The equipment uses a special welding process in which two curved welding guns inserted into a root opening welds shell plates horizontally with one running. In this process, the axis of the leading welding gun corresponds to that of a weld bead, therefore it is called ‘Horizontal Coaxial Arc Welding’ (HCAW)2). Since it is very unique and peculiar process, modeling of the process and analysis of the welding phenomena by using the model have been done.

2. Outline of the Welding Process

The automatic welding equipment for the ship's shell plates is shown in Fig. 1. The equipment consists of an automatic traveling carriage, a welding machine, and a telescopic boom. The welding machine is fixed to the end of the telescopic boom, which is raised to bring the machine against the shell plate. By holding two guide rollers between the groove faces of the plates to be welded, the welding machine traces a weld line and inclines corresponding to the slope of the plate. The telescopic boom moves freely at its root following the movement of the welding machine, and a steering of the automatic traveling carriage is controlled with detecting the direction of the boom’s lean. When the welding machine is pushed up by the telescopic boom, it is possible to weld an inclined part up to 45 degrees in inclination angle. The automatic traveling carriage is equipped with all the devices including a controller, welding power sources, wire feeders, cooling apparatus, and an air compressor.

The outline of the developed welding process is shown in Fig. 2. Two welding guns are inserted horizontally, one above the other, into the root opening between the two plates to be welded. The tip of the leading gun is installed in parallel with a direction of welding. To prevent weld metal from dripping, a water-cooled...
copper shoe is used under the weld pool. Back bead is formed on the glass fiber backing tape supported by the water-cooled copper shoe. A trailing gun is passed through the root opening and overhangs the leading bead to form a final bead. Welded joint shape is a square-groove with the root opening from 11 mm to 18 mm.

3. Static Model of the process

Horizontal Coaxial Arc Welding (HCAW) is similar to the electrogas welding, but the HCAW progresses horizontally, while the electrogas welding does almost vertically. In the HCAW, the formation rate of the weld bead depends on its welding phenomena, because there is no mechanical device to prevent molten metal from flowing into the front. Then, the simplified numerical model expressing the static balance of forces on the leading molten pool has been designed in order to appreciate the phenomena of the weld bead formation quantitatively. Main assumptions used in the modeling are as follows.

1) Forces acting upon the molten pool are only gravity, surface tension, and arc force.
2) Front surface of the molten pool is parallel to a direction of groove width, and penetration is negligible.
3) Arc force is equally distributed in a circle with radius $r_a$.

Based on the assumptions, the horizontal static balance of the forces at the front surface of the molten pool can be expressed as the following equation (see Fig. 3),

$$F_b = F_s + F_a \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdOTS
arc pressure, \( p \), and welding current, \( I \), has been given as
\[
p = 3.62e^{-4} \times I^{2.45}
\]
\((6)\)
in the case of \( r_{0} = 5 \) mm.

Fig. 5 shows the comparison of the measured weld bead height, \( h' \), with the estimated value of the molten pool’s height, \( h \), by eq. \((5')\) and \((6)\), in various root opening conditions. Since close agreement between measured and estimated values was obtained, it is considered that the actual welding bead height can be estimated sufficiently and accurately with the model.

4. Analysis of the Welding Phenomena by the Model

In the Horizontal Coaxial Arc Welding (HCAW) process, the bead formation rate does not depend on horizontal movement of the welding machine. In order to keep the process under control, therefore, it is important to estimate the bead formation rate as a function of the width of groove and welding current, and to know dynamic changes of the wire extension length during welding.

4.1 Bead Formation Rate

The bead formation rate, \( W \), in a square-groove is expressed as eq. \((7)\), if electrode metal transfer efficiency was 100 percent.
\[
W = \frac{V_f \cdot S}{d \cdot h}
\]
\((7)\)
Here, \( V_f \) is wire feeding rate and \( S \) is sectional area of wire. Fig. 6 shows the comparison of the estimated bead formation rate, \( W \), with proper values of welding speed obtained by experiments in various root opening conditions. Both estimated results and measured values show a similar tendency.

4.2 Wire Extension Length

When horizontal traveling speed of the welding machine, \( V' \), is different from the bead formation rate, \( W \), expressed by eq. \((7)\), the wire extension length should be changed during welding. Relationship between the difference of \( V' \) from \( W \) and the wire extension length, \( L \), is given as eq. \((8)\) (see Fig. 7).
\[
\frac{dL}{dt} = V' - W
\]
\((8)\)
Substitution of eq. \((7)\) into eq. \((8)\) gives
\[
\frac{dL}{dt} = \frac{V_f \cdot S}{d \cdot h}
\]
\((9)\)
As the molten pool’s height, \( h \), is a function of welding current, \( I \), eq. \((9)\) can be transformed as a function of the wire extension length, \( L \), by using Lesnewich’s empirical equation\(^3\), where \( a \) and \( b \) are constants.
\[
V_f = aI + bI^2
\]
\((10)\)

With eq. \((7)\), \((6)\), \((9)\), and \((10)\), the change of the wire extension length with time can be calculated numerically. The calculated result is shown in Fig. 8, in the case of assuming that the width of root opening, \( d \), changes from 13 mm to 13 ± 2 mm suddenly at time = 0. The wire extension length changes considerably slowly, and converges to a certain value as shown in Fig. 8. The result indicates that the traveling speed of the welding machine, \( V' \), and the bead formation rate, \( W \), will reach their equilibrium state spontaneously, owing to the change of welding current corresponding to that of the wire extension length.
Controlling Method

The extreme change of the wire extension length damages stability of the process, although it will converge to a certain value. The typical method to make the wire extension length constant is to control the traveling speed of the welding machine, $V$, in order to keep a constant welding current, which is conventional method used in electrogas arc welding. In the developed welding equipment for ship’s shell, however, rapid change of the traveling speed is undesirable for ensuring quality welds, because its process is tandem welding with two different weld pools, furthermore, it is difficult to control the traveling speed of the welding machine accurately in movement on the uneven ground. Then, other controlling method of the wire extension length has been investigated by using the model.

Fig. 9(a) shows calculated wire extension lengths in various root opening when $V$ and $W$ are in equilibrium with a certain welding condition. Meanwhile, Fig. 9(b) shows those when the wire feeding speed is controlled in order to make welding current constant. The results in Fig. 9 indicate that controlling of the wire feeding speed is effective to reduce the change of the wire extension length to a narrow range. When the wire feeding speed is controlled automatically in order to obtain constant welding current, the traveling speed of the welding machine is not required for rapid and accurate control.

Application of the process

Using the wire feeding control along with the traveling speed control, a smooth and stable running process has been achieved in the welding of ship’s shell plates. The application of the welding process of a ship hull is shown in Fig. 10. This welding equipment uses two 1.6 mm diameter solid wires with CO₂ shielding gas. Welding currents are 500 A in the leading welding gun and 420 A in the trailing welding gun. 22 mm thickness hull plate has been completely welded with 16 cm/min (2.67 mm/sec) average welding speed.
6. Conclusion

In the developed welding process, the axis of the leading welding electrode corresponds to that of a weld bead, therefore it is called ‘Horizontal Coaxial Arc Welding’ (HCAW). Since the bead formation rate in HCAW depends on its welding phenomena, not on traveling speed of machine, the simplified numerical model expressing the HCAW phenomena has been developed. The model enables to estimate the weld bead height and the bead formation rate. As a result of analysis by the model, the wire extension length will reach its equilibrium state spontaneously in the case of using a constant voltage characteristic power source. And controlling the wire feeding speed is effective to reduce the change of the wire extension length to a narrow range. Furthermore, the combination of the wire feeding control and the traveling speed control enables to stabilize the running process in welding of ship’s shell plates.

7. Nomenclature

- $F_b$ : total hydrostatic pressure of molten pool in horizontal direction
- $F_s$ : total surface tension in horizontal direction
- $F_a$ : total arc force
- $y$ : coordinate
- $\rho$ : density of molten metal
- $g$ : acceleration of gravity
- $h$ : molten pool’s height
  ($h'$ : actual weld bead height)
- $d$ : width of root opening
- $T$ : surface tension
- $\alpha$ : contact angle of molten pool’s upper surface on groove side walls
- $\theta$ : contact angle of molten pool’s front surface
- $p$ : arc pressure
- $r_o$ : radius of arc
- $L$ : wire extension length,
- $V$ : traveling speed of welding machine
- $W$ : bead formation rate
- $V_f$ : wire feeding speed
- $S$ : sectional area of wire
- $I$ : welding current
- $a, b$ : constants.

References