Transactions of the Japan Welding Society, Vol. 11, No. 1, April 1980

On Cooling of Underwater Welds*

By Atsushi HASUI and Yasuo SUGA****

Abstract

Thermal cycles of weld in underwater gravity arc welding were studied. The effects of welding factors on cooling process and cooling rate at the bond line were analysed. Moreover, experimental formulas and nomographs were proposed to estimate cooling rate of the underwater weld.

Main results are summarized as follows:

(1) *Underwater weld is cooled rapidly owing mainly to the heat transfer from surface of weld to the surrounding water. Therefore, the cooling rate of underwater weld is much higher than that of open air weld.*

(2) *Welding parameters which have a remarkable effect on cooling rate of underwater weld are heat input, water temperature, water pressure, thickness of base metal, welding position (slope of base metal) and location along weld bead.*

(3) *Cooling rate (R) and cooling times (S_{500}, S_{300}) of underwater weld may be estimated by means of the following experimental formulas.*

$$R = 6.25 \times 10^5 K (0.56 \sin^{2/3}\theta + 1) Q^{-0.95} t^{1/6}$$

$$S_{500} = 455 R^{-1.09}$$

$$S_{300} = 780 R^{-1.09}$$

where θ : *slope angle of base metal,* $0 \leqq \theta \leqq 90°$

Q : *weld heat input,* $8 \leqq Q \leqq 35$ *KJ/cm*

t : *thickness of base metal,* $6 \leqq t \leqq 19$ mm

$K=1$ *at middle part (in a quasi-stationary state)*

$K=1.2$ *at starting point*

$K=2$ *at crater.*

And nomographs based on the formulas for cooling rate and cooling times of underwater welds are made.

1. Introduction

One of the most important problems in "wet" underwater welding is the quenching effect of the surrounding water[1,2]. Especially, the hardened weld caused by rapid cooling has a susceptibility to hydrogen embrittlement[3,4], and its tensile strength and ductility are considerably reduced compared with similar joints welded in air. Accordingly, the wet underwater welding processes are not often put to practical use. Therefore, it is important to make clear the cooling phenomena in underwater welding and effect of welding conditions on the cooling rate and then to develop the processes preventing the weld from quenching. Nevertheless, very few systematic studies on the cooling of underwater welds have been reported[5-7]. So, in this study, the thermal cycle of underwater weld by gravity arc welding process is measured and the effect of welding parameters on cooling rate of underwater welds is studied. Moreover, using the data obtained, an experimental formula and nomographs to estimate the cooling rate of underwater weld are proposed.

2. Experimental method

2.1 *Experimental equipment and materials*

Gravity arc welding equipment for all welding positions was designed and made so that the electrode angle, diameter of electrode and ratio of bead length to electrode length might be changed. In this experiment city water was used. The surface of base metal was situated at water depth of 200 mm usually. But when the effect of water depth on cooling was studied, welding was done in a pressure tank which was able to stand a guage pressure of up to 9 kgf/cm^2. Ilmenite type, cellulose type, lime-titania type, high titanium oxide type and iron-iron oxide type electrodes were used. Base metals were SM41 steel plates of 6,9,12,16 and 19 mm in thickness.

2.2 *Measurement of thermal cycles*

Thermal cycle at bond line in underwater welding was measured by electromotive force of thermocouple. Fixing of thermo-couples to base metal and measurement of thermal cycles were done as follows:

(1) On the back side of base metal three holes of 1.5 mm in diameter are drilled as shown in Fig. 1.
(2) Waterproofed C.A. thermo-couples (diameter of wire: 0.3 mm) are inserted into the hole (Fig. 1).
(3) Tip of thermo-couple is percussion welded to the bottom of the hole.
(4) The hole is sealed with asbestos and waterproofed by vaseline.
(5) Bead welding is done on the base metal.
(6) The thermoelectromotive force is recorded by the photocoder.

Thermal cycles were mainly measured at central part of weld line which is in a thermally quasi-stationary state. As the index of cooling rate of under-

* Received 12 December 1979
** Member, Faculty of Engineering, Keio University

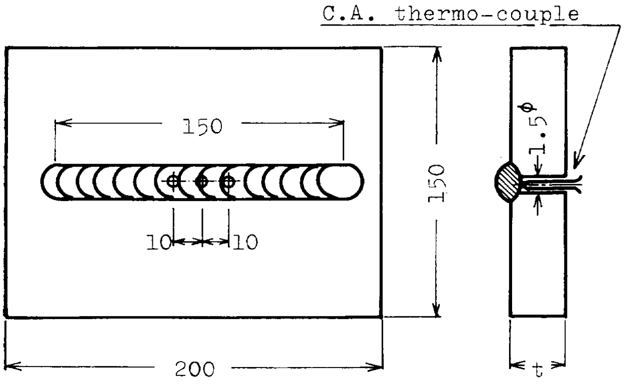

Fig. 1 Dimensions of base metal

water weld, cooling rate at 500°C (R), cooling times from 800°C to 500°C (S_{500}) and to 300°C (S_{300}) at bond line are used so that the results obtained may be convenient for practical use.

3. Experimental results and discussion

3.1 *Cooling process of underwater weld*

Fig. 2 shows thermal cycles at bond line, when bead welding by high titanium oxide type electrode of 4 mm dia. was done on the base metal of 19 mm in thickness under water and in air. It also shows the thermal cycles at starting point and at crater of weld bead in underwater welding. Base metal is 19 mm in thickness.

In the case of underwater welding, the cooling rate at starting point and crater of weld bead is much higher than that at the middle of weld bead which is considered to be in a thermally quasi-stationary state. For example, the cooling rate at 500°C (R) at the middle of weld bead is about 165°C/s, whereas those at starting point and crater are about 190°C/s and 310°C/s, respectively. Therefore, cooling rates at 500°C at starting point and crater are about 1.2 or 2 times higher than that at the middle. Moreover thermal cycles were measured similarly by using the other type of coated electrodes of 4 mm dia.. However, there was little difference in thermal cycle depending on a variety of electrode type. Accordingly, type of coated electrode seems to have no effect on cooling

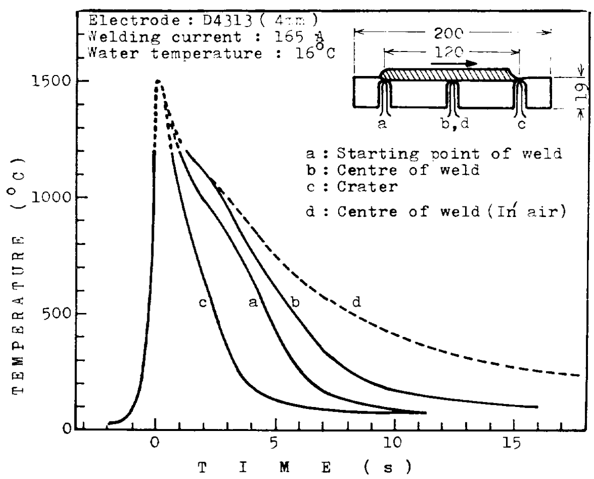

Fig. 2 Weld thermal cycles at bond line

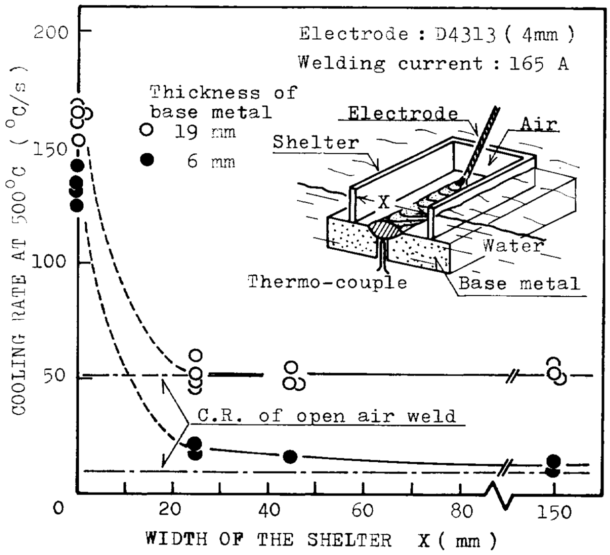

Fig. 3 Effect of width of the shelter on cooling rate at 500°C at bond line

of underwater welds.

Meanwhile, from Fig. 2 it is clear that the cooling rate in underwater welding is much higher than that in open air welding. For example, the cooling rate at 500°C is 165°C/s under water and 54°C/s in air, the former being about 3 times higher than the latter. Although it is evident that rapid cooling of underwater welds is caused by the cooling effect of the surrounding water, it has never been made clear how the surrounding water affects the cooling of underwater welds. So, the following experiments were done. That is, a shelter (L=200 mm, X=25,45,150 mm) was placed along the weld line on the surface of base metal of 6 and 9 mm in thickness to prevent the water from flowing into the weld zone, as seen in Fig. 3. Then bead welding was done, and thermal cycles at weld bond line were measured. The results are summarized in Fig. 3, which shows the effect of width of the shelter on cooling rate at 500°C at weld bond line. Cooling rate of open air weld is represented by a dot-dash-line in Fig. 3 to be compared with that of underwater weld. If only the weld and the vicinity of the weld are not exposed to water, even though the base metal may be placed under water, the cooling rate of the weld is much lower than that of underwater weld (R=165, 135°C/s) and is close to that of open air weld (R=54, 11°C/s). Accordingly, it is clear that the principal cause of rapid cooling of underwater welds is the heat loss from the surface of weld and its vicinity heated to high temperature with progress of welding.

Thereupon, as seen in Fig. 4, oil putty or refractory 20 mm square was put on the base metal along the weld zone to insulate (shield) the weld and its vicinity heated to high temperature from the surrounding water, and then bead welding was done. From Fig. 4 it is apparent that the cooling rate of the shielded weld is much lower than that of the non-shielded weld. For example, in case of refractory shielding the cooling rate at 500°C at bond line is 63°C/s and in case

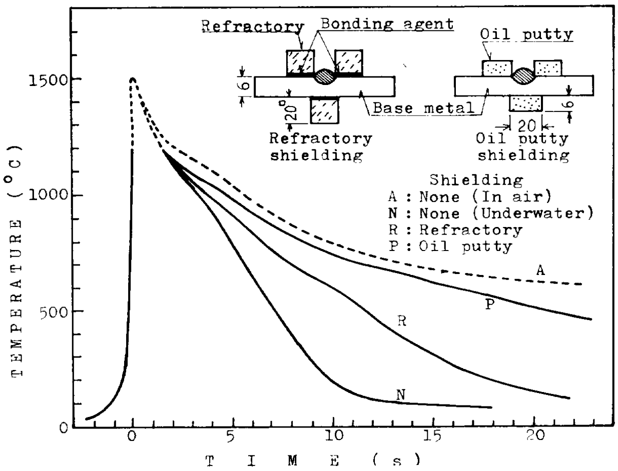

Fig. 4 Effect of shielding on weld thermal cycles at bond line

of oil putty shielding 21°C/s, and these values are much lower than that in case of non-shielding, i.e., 135°C/s. In particular, when oil putty which is thought to be superior in hèat insulation and which is easy to adhere to surface of base metal is used as shielding material, the cooling rate is close to that of air weld, i.e., 11°C/s. This result suggests that oil putty shielding has great effect as a means for prevention of rapid cooling of underwater weld.

From the results of experiments, it is suggested that a cooling of underwater weld is caused by the heat transfer from the surface of the weld and its vicinity to the surrounding water. However, the behaviour of water and gas bubbles near the weld zone can not be observed directly owing to the slag over the weld bead, radiation from arc and disturbance of the surrounding water. Therefore, mean cooling rates at various temperatures were measured from thermal cycle curves shown in Fig. 2 in order to consider the difference between cooling process of underwater welds and that of open air welds. Fig. 5 shows the relation between mean cooling rate and temperature of bond line, where the mean cooling rate at T°C is a value obtained by dividing the temperature difference T=40°C from (T+20)°C to (T−20)°C by the cooling time ΔS s from (T+20)°C to (T−20)°C.

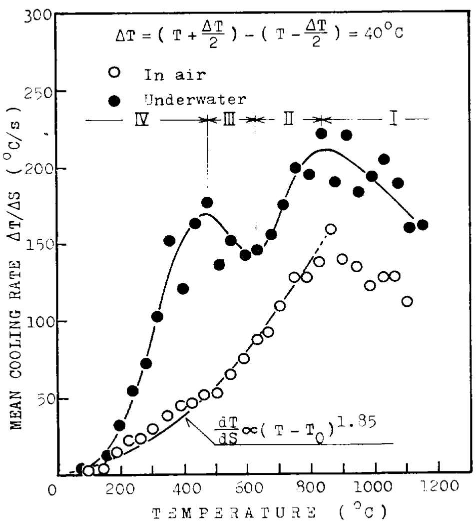

Fig. 5 Relation between temperature and mean cooling curves (b, d) shown in Fig. 2

As for cooling in air welding, some theoretical analysis have been reported. Assuming that the heat source is a point and cooling of the weld occurs only through heat conduction from the weld to base metal, it is said that there is the relation of equation (1) between temperature and cooling rate at the weld[8,9].

$$dT/dS \propto (T-T_0)^n \qquad (1)$$

where T : Temperature of weld
T_0 : Initial temperature of base metal
S : Time

From Rosenthal's analysis[9], we obtain $n=2$ easily. When the exponent n is about 1.85, the experimental results agree with the equation (1). Accordingly it is induced that the cooling of air weld by shield metal arc welding process occurs mainly through heat conduction from the weld to base metal. In case of underwater welding, the mean cooling curve has a much complicated shape, and it is completely different from that in air welding. That is, the curve has a maximum value at about 500°C and minimum value at about 650°C. The result seems to show that cooling of underwater weld is caused by heat transfer, which is subjected to the boiling phenomena, from the weld to surrounding water[7,10]. For example, the fact that the cooling rate of underwater weld sharply increases with a decreasing of temperature from 650°C to 500°C is thought to be caused by a change in type of boiling, that is, from film boiling to nucleate boiling which has an effect on the heat transfer phenomena and the heat transferred from the weld to the surrounding water is increased sharply with the decrease of the weld temperature from 650°C to 500°C.

3.2 *Effect of welding condition on cooling rate of underwater welds*

The relation between cooling rate, cooling time (R, S_{500}, S_{300}) and welding factors, that is, thickness of base metal, water temperature, water pressure and weld heat input, which seemed to have remarkable effect on cooling rate of underwater welds in the preliminary experiment, is investigated.

Figs. 6–9 show the effects of thickness of base metal, water temperature, water pressure and weld heat input on cooling rate at 500°C (R) and cooling time from 800°C to 500°C and to 300°C (S_{500}, S_{300}), respectively. It is obvious that the cooling rate of underwater welds increases with an increase in thickness of base metal and water pressure, and with a decrease in water temperature and weld heat input.

It is widely known that the liquid temperature and slope angle of heat-transfer surface have significant effect on boiling phenomena. For example, in the range of temperatures in which nucleate boiling or transition boiling takes place, a decrease of sub-cool temperature difference (difference between saturated temperature and water temperature), ac-

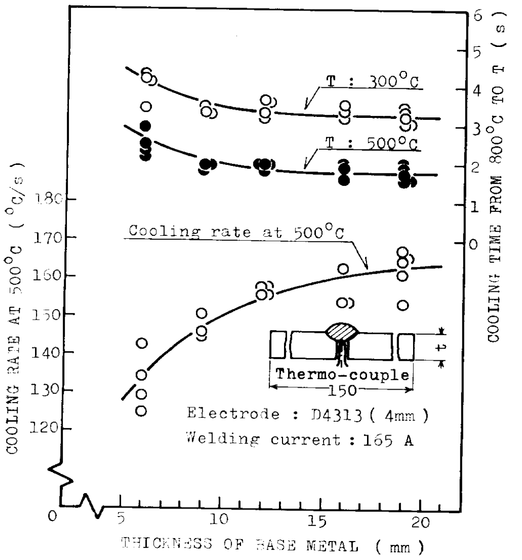

Fig. 6 Effect of thickness of base metal on cooling rate and cooling time at bond line

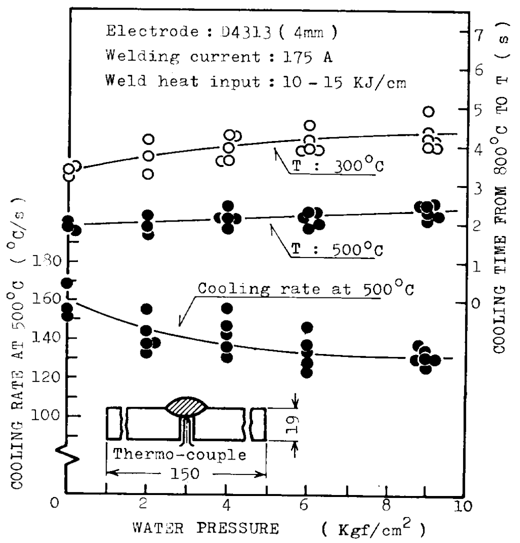

Fig. 8 Effect of water pressures on cooling rate and cooling time at bond line

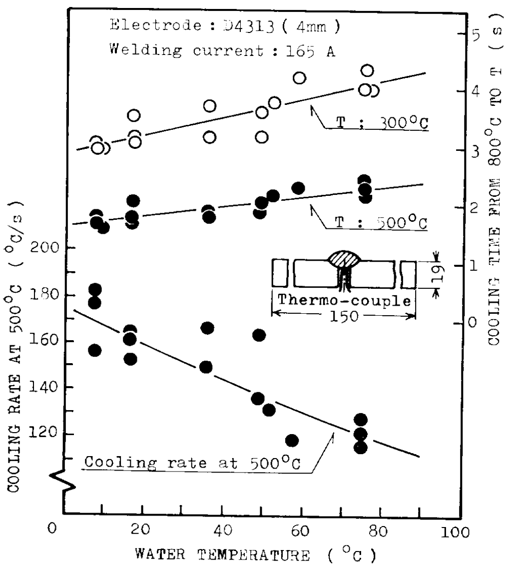

Fig. 7 Effect of water temperature on cooling rate and cooling time at bond line

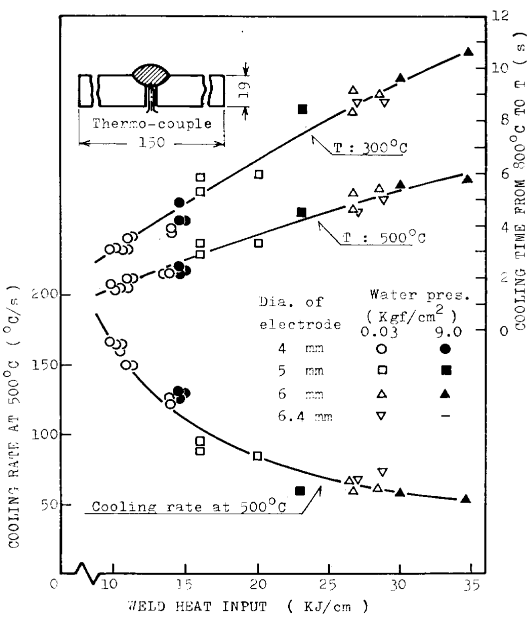

Fig. 9 Effect of weld heat input on cooling rate and cooling time at bond line

companied with a rise of water temperature, lowers the heat load[11]. Thereupon, the cooling rate of weld should decrease with a rise of water temperature as shown in Fig. 7. Meanwhile, an increase in slope angle of heating surface enhances the heat transfer coefficient, because it makes disengagement of gas bubbles from surface easy. This seems to be the principal reason for the experimental result in previous report[12], that the cooling rate considerably increased with an increase in slope angle of base metal. Furthermore, it is said that an increase of water pressure raises the saturated temperature of water and increases the heat flow in the range of nucleate boiling temperatures. Accordingly, the cooling rate of weld should increase with an increase of water pressure. However, the experimental results shown in Fig. 8 do not agree with this theory. This discrepancy can be explained as follows. Fig. 10 shows the effect of water pressure on welding speed and weld heat input in bead welding. It is clear from the figure that the melting rate of electrode by same welding current (175 A) decreases with an increase of water pressure, and consequently the weld heat input increases with an increase of water pressure. Moreover, it is clear from Fig. 9 that an increase of weld heat input makes the cooling rate of weld considerably higher. Consequently, the cooling rate decreases with an increase of water pressure. Furthermore, when the values of cooling rate in water pressure of 9 kgf/cm^2 are plotted in Fig. 9, they situate on or closely to the curve of cooling rate in water pressure of 0.03 kgf/cm^2. The above-mentioned experiments and consideration reveal that an increase of cooling rate with a rise of water pressure is mainly caused by an increase of weld heat input accompanied with a decrease of welding speed. Accordingly, a change of boiling phenomena of water effected by water pressure does not have an effect

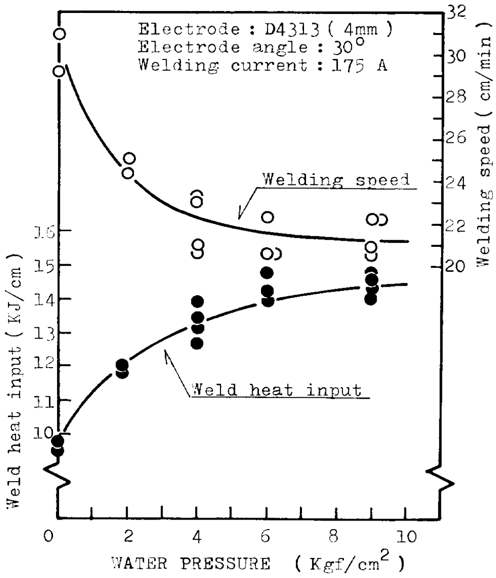

Fig. 10 Effect of water pressures on welding speed and weld heat input in underwater welding

on cooling rate of underwater weld.

3.3 *Estimation of cooling rate and cooling times*

It becomes clear from results of the above-mentioned experiments that the main factors which affect the cooling rate of weld made at water temperature of about 20°C are thickness of base metal (t), weld heat input (Q), welding position[12] (slope angle of base metal : θ) and location along weld line (for example; starting point, middle part, crater). The relations between these factors and cooling rate at bond line were investigated.

3.3.1 Estimation of cooling rate at 500°C

Fig. 11 shows the relation between cooling rate at 500°C at bond line of underwater welds (R) and thickness of base metal (t) on the log-log graph paper. From the figure it is clear that the log$R$ is in proportion to log$t$, when thickness of base metal is in the range from 6 to 19 mm. Measuring the

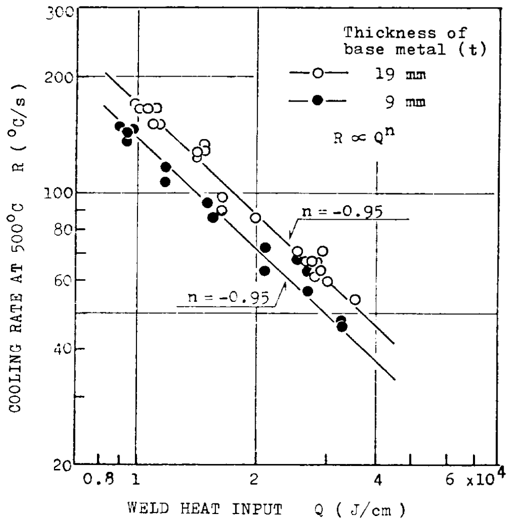

Fig. 12 Relation between weld heat input and cooling rate at 500°C at bond line

slope m of the line, m=0.17 was obtained. Accordingly, cooling rate R is expressed as follows;

$$R \propto t^m,\ m=0.17\ (\simeq 1/6) \qquad (2)$$

where $6 \leqq t \leqq 19$ mm.

Fig. 12 shows the relation between cooling rate (R) and weld heat input (Q) on the log-log graph paper. The figure shows that the log$R$ is in proportion to log$Q$, when weld heat input is in the range from 8 to 35 KJ/cm. Measuring the slope n of the graph, n=−0.95 was obtained for both base metals of 9 and 19 mm in thickness. Accordingly, cooling rate R is given as follows;

$$R \propto (60EI/v)^n \quad n=-0.95 \qquad (3)$$

where E : Arc voltage (V)
I : Welding current (A)
v : Welding speed (cm/min).

Fig. 13 shows the relation between cooling rate (R) and slope angle of base metal (θ), in bead welding which was done in the range of slope angles from 0° to 90°.

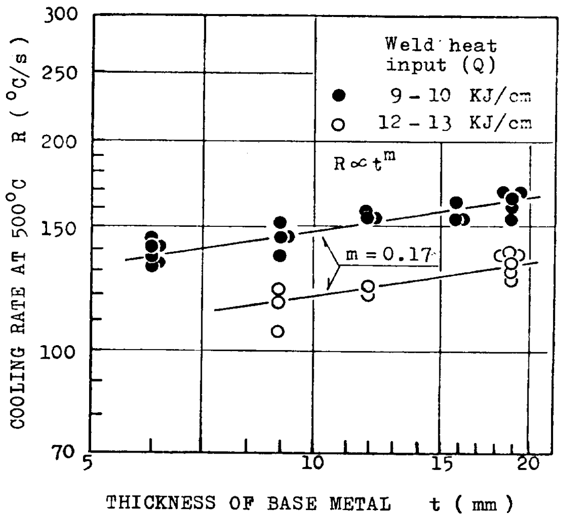

Fig. 11 Relation between thickness of base metal and cooling rate at 500°C at bond line

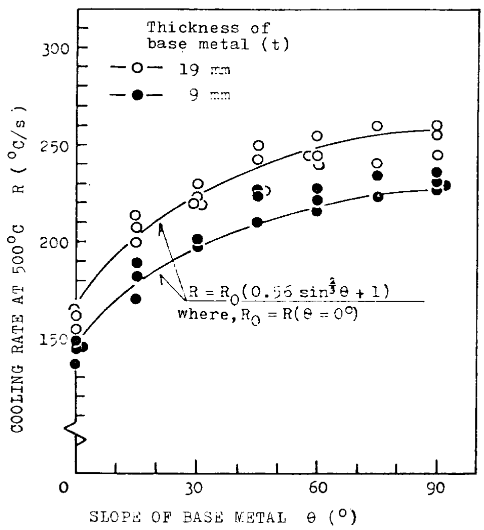

Fig. 13 Relation between slope of base metal and cooling rate at 500°C at bond line

Now, we assume that the relation between R and θ may be expressed by the equation

$$R/R_0 = a \sin^k\theta + b \qquad (4)$$

where R_0: cooling rate of weld in flat position welding ($\theta = 0°$)
a, b and k: constants

Upon substituting 0° for θ in equation (4), we obtain $b=1$. Consequently, equation (5) is given as follows:

$$(R-R_0)/R_0 = a \sin^k\theta \qquad (5)$$

Let us examine whether equation (5) just indicates the relation between R and θ or not. When $\sin\theta$ is plotted on the abscissa and $(R-R_0)/R_0$ on the ordinate of the log-log graph paper, the equation (5) should give a straight line. Plotting the experimental values in Fig. 14, a straight line with a slope of about 0.65 ($\simeq 2/3$) was obtained as shown in Fig. 14. Accordingly it is clear that the equation (5) rightly indicates the relation between R and θ, when the welding was done in the range of experimental conditions used here. Finding the coefficient a from Fig. 14, we obtain $a=0.56$. Thus the experimental formula which shows the relation between R and θ is expressed approximately as follows;

$$R = R_0(0.56 \sin^{2/3}\theta + 1) \qquad (6)$$

In the paragraph 3.1, it was shown that cooling rate measured at middle part of weld, which is in a thermally quasi-stationary state, is considerably lower than those measured at starting point and at crater. Now, expressing the ratios of cooling rates at starting point and at crater Rs, Rc to that at middle part R as Ks and Kc respectively, from the results in paragraph 3.1, they are given as follows;

$$\left.\begin{array}{l} Ks = Rs/R \simeq 1.2 \\ Kc = Rc/R \simeq 2 \end{array}\right\} \qquad (7)$$

Synthesizing the formulas which show relations

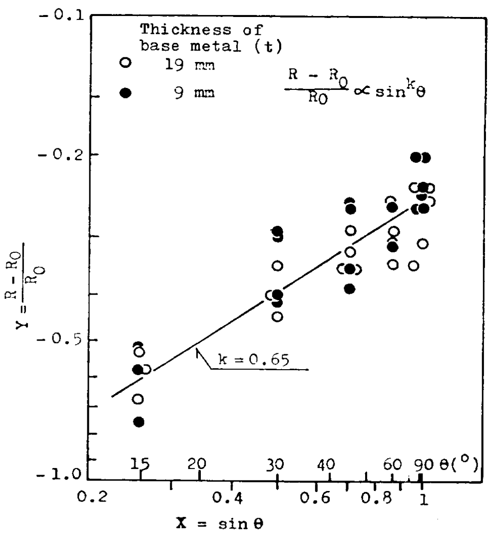

Fig. 14 Relation between $X = \sin\theta$ and $Y = \frac{R-R_0}{R_0}$

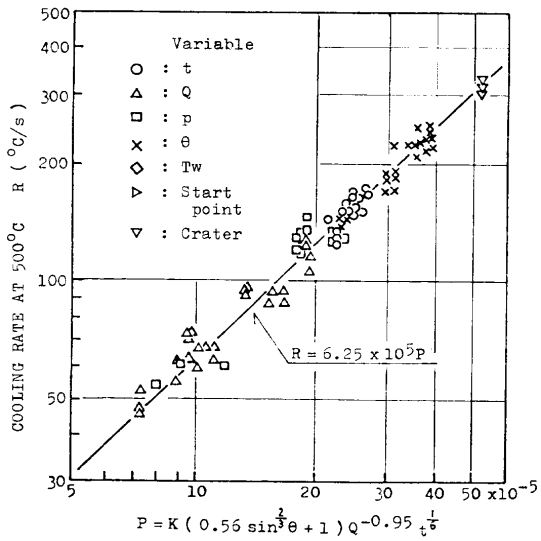

Fig. 15 Relation between parameter (P) and cooling rate at 500°C (R)

between cooling rate at 500°C at bond line and main factors, parameter P, which includes all the main factors, is obtained as follows;

$$P \equiv K(0.56 \sin^{2/3}\theta + 1)Q^{-0.95} t^{1/6} \qquad (8)$$

where $K=1$: at middle part (in a quasi-stationary state)
$K=1.2$: at starting point
$K=2$: at crater

Plotting values of R and P on the log-log graph paper, a straight line with a slope of about 1 is obtained as shown in Fig. 15. Accordingly, assuming that R is expressed as $R=CP^n$, R is expressed as $R=CP$, for the value of n is 1. Moreover, the coefficient C is obtained from the relation between R and P as $C=6.25\times10^5$. Consequently, an experimental formula which shows the relation between cooling rate and welding factors is given as follows;

$$R = 6.25\times10^5 K(0.56 \sin^{2/3}\theta + 1)Q^{-0.95} t^{1/6} \qquad (9)$$

where $0 \leqq \theta \leqq 90°$, $8 \leqq Q \leqq 35$ kJ/cm, $6 \leqq t \leqq 19$ mm.

As it is complicated to calculate the cooling rate R by means of formula (9), a nomograph to estimate R is proposed for practical use. The nomograph, which is based on formula (9), is shown in Fig. 16. It may be used as follows. At first, the weld heat input Q is calculated from welding current I, arc voltage E and welding speed v. Then plot the weld heat input on the Q scale line and thickness of base metal on the t scale line. Subsequently, connect the point t and the point Q by a straight line, and the intersection of the straight line and the R_F scale line gives a cooling rate at 500°C at bond line of underwater weld made under this welding condition in the flat position. Both cooling rates at starting point and at crater of weld bead are obtained by multiplying the R_F value by 1.2 and 2 respectively. In the case of welding in an inclined position and a vertical position, the cooling rate is obtained by plotting the slope angle of base metal on the θ scale line and connecting the point θ and

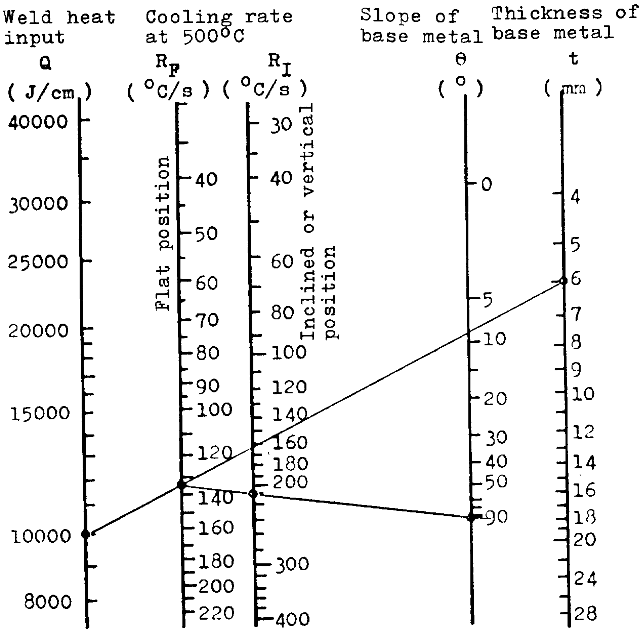

Fig. 16 Nomograph to estimate the cooling rate at 500°C (R)

the point R_F by a straight line, that is, intersecting of the straight line and the R_I scale line gives the cooling rate.

3.3.2 Estimation of the cooling time

As the index indicating the cooling rate of weld, the cooling times from 800°C to 500°C (S_{500}) and from 800°C to 300°C (S_{300}) are frequently used. Provided that the relations between cooling rate R and cooling time S, which have been measured from thermal cycles of underwater welds made under various conditions, are given, these cooling times may be evaluated easily. Plotting all the experimental results of cooling rate at 500°C R vs. S_{500} and R vs. S_{300} on the log-log graph paper, two straight lines with a slope m of -1.09 are obtained as shown

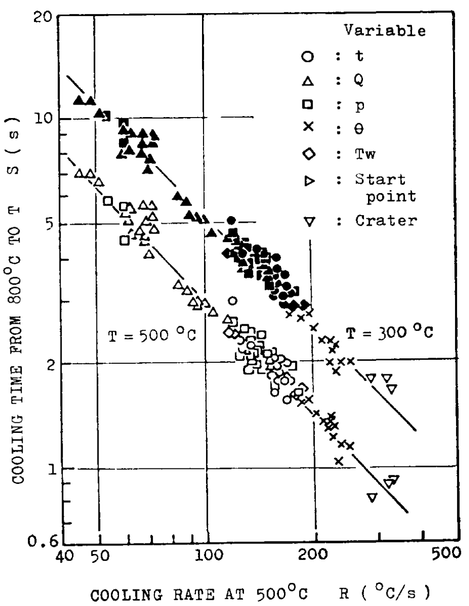

Fig. 17 Relation between cooling times from 800°C to 500°C and to 300°C (S_{500}, S_{300}) and cooling rate at 500°C (R)

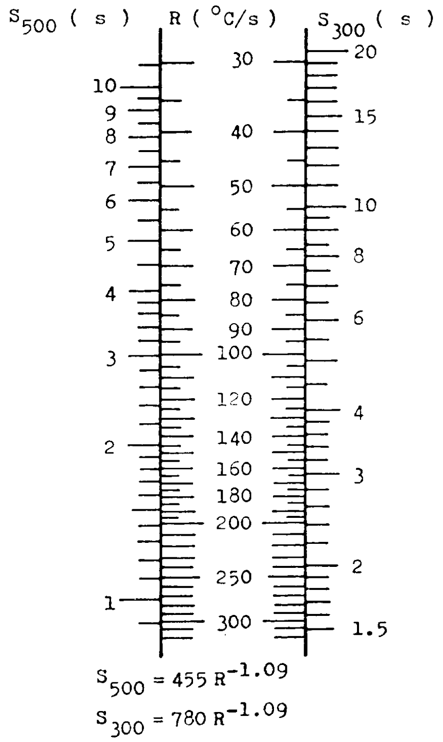

Fig. 18 Relation between cooling times from 800°C to 500°C and to 300°C (S_{500}, S_{300}) and cooling rate at 500°C (R)

in Fig. 17. Expressing the cooling time S by the equation $S=CR^m$, we obtain $S=CR^{-1.09}$, for the slope m is -1.09. And calculating the coefficient C from the relation between R and S, we obtain the following experimental formulas.

$$\left.\begin{aligned} S_{500}&=455R^{-1.09}\\ S_{300}&=780R^{-1.09}\end{aligned}\right\} \qquad (10)$$

Moreover, substituting the relation $R=6.25\times10^5P$ obtained in 3.3.1 into formulas (10), we obtain the following formulas.

$$\left.\begin{aligned} S_{500}&=2.19\times10^{-4}P^{-1.09}\\ S_{300}&=3.75\times10^{-4}P^{-1.09}\end{aligned}\right\} \qquad (11)$$

As it is relatively complicated to calculate S from R by means of formula (10), the nomograph shown in Fig. 18 was prepared for practical use. The figure is based on formula (10). In the figure, S_{500} and S_{300} are graduated on both sides of the R scale. For example, setting the value 150°C/s on the R scale, we obtain $S_{500}=1.95$ s and $S_{300}=3.3$ s.

4. Conclusions

Main results obtained by this experiment are summarized as follows:

(1) Cooling of open air welds is caused mainly by heat conduction from the weld to base metal, whereas that of underwater welds is by heat transfer from the surface of weld to the surrounding water. Therefore, cooling rate of underwater weld is much higher than that of open air weld.

(2) Cooling rate of underwater weld decreases remarkably when the weld and the zone adjacent to it are shielded.
(3) Welding factors which have a remarkable effect on cooling rate of underwater welds are thickness of base metal, water temperature, water pressure, weld heat input, welding position (slope of base metal) and location along weld bead.
(4) Cooling rate (R) and cooling times (S_{500}, S_{300}) of underwater welds may be estimated by means of the following experimental formulas.

$$R=6.25\times10^5K(0.56\sin^{2/3}\theta+1)Q^{-0.95}t^{1/6}$$

$$S_{500}=455R^{-1.09}$$

$$S_{300}=780R^{-1.09}$$

where θ : slope angle of base metal, $0\leqq\theta\leqq90°$
Q : weld heat input, $8\leqq Q\leqq35$ kJ/cm
t : thickness of base metal, $6\leqq t\leqq19$ mm
$K=1$ at middle part (in a quasi-stationary state)
$K=1.2$ at starting point
$K=2$ at crater.

And nomographs based on the formulas for cooling rate and cooling times of underwater welds are made.

The authors wish to express their thanks to Mr. T. Mizuno (Keio University, now at Shimano Industries, Ltd.) and S. Kishi (Keio University, now at Sumitomo Metal Industries, Ltd.) for their assistance in experimental work.

References

1) C.L. Tsai, K. Masubuchi; Interpretive Report on Underwater Welding, WRC Bulletin, 224, (1977) P. 1-37
2) A. Hasui, Y. Suga; On Underwater Gravity Arc Welding (The 1st Report), Journal of JWS, 43-8 (1974) P. 767-775 (in Japanese)
3) H. Ozaki, J. Naiman, K. Masubuchi; A Study of Hydrogen Cracking in Underwater Steel Welds, Weld. J., 56-8 (1977) P. 231s-237s
4) V. Nagarajan, C.R. Loper; Underwater Welding of Mild Steel a Metallurgical Investigation of Critical Factors, OFF-SHORE TECHNOLOGY CONFERENCE (OTC), Paper No. OTC 2668, (1976)
5) A.J. Brown, J.A. Staub, K. Masubuchi; Fundamental Study of Underwater Welding, OTC, Paper No. OTC 1621, (1972)
6) K. Masubuchi, A.H. Anderssen; Underwater Application of Exothermic Welding, OTC, Paper No. OTC 1910, (1973)
7) J. Kinugawa, T. Fukushima, S. Fukushima; Cooling of Underwater Plasma Welds, Journal of JWS, 44-10 (1975) P. 834-839 (in Japanese)
8) Adams C.M.; Cooling Rates and Peak Temperatures in Fusion Welding, Weld. J., 37-5 (1958) P. 210s-215s
9) D. Rosenthal; Mathematical Theory of Heat Distribution during Welding and Cutting, Weld. J., 20-5 (1941) P. 220s-234s
10) Japan Soc. Mech. Engrs.; Futtoh Netsu Dentatsu, P. 3-6 (1965) (in Japanese)
11) W.H. McAdams; Heat Transmission, 3rd. Ed., (1954), McGraw Hill
12) A. Hasui, Y. Suga, H. Toma; On Underwater Gravity Arc Welding (The 2nd Report), Journal of JWS, 44-4 (1975) P. 337-344 (in Japanese)