Cooling Time and Features of Submerged Arc Weld Beads

Cooling time from 800 to 500°C (1472 to 932°F) can be expressed in terms of fusion area, HAZ area and HAZ boundary length

BY R. S. CHANDEL AND S. R. BALA

ABSTRACT. Submerged arc welds using various combinations of process operating conditions, electrode diameters, and two polarities were deposited on plates and in grooves of various angles. Cooling times between 800-500°C (1472-932°F) were measured for the weld metal and correlated with the weld features.

Preliminary analyses showed that there is a poor linear or curvilinear (log-log) relationship between cooling time and fusion area; however, when bead-on-plate and V-groove welds were compared, it was found that, for the same fusion area, welds deposited in V-grooves required shorter times to cool. Further analysis of the data showed that the cooling times for all welds can be expressed in terms of fusion area, HAZ area and length of the HAZ boundary through a multilinear regression analysis.

Introduction

Since the invention of welding as a fabrication process, numerous attempts have been made to predict and control the cooling rates in the weld metal and the heat-affected zone (HAZ). The most common cooling rate equation based on the classical theory of heat transfer can be written in the following simple form:

$$R_T = \frac{K}{H}$$

where R_T = cooling rate at temperature T, (°C/s); H = heat input, (kJ/mm); K = Proportionality constant.

The constant K varies with preheat, process, joint configuration, and the temperature at which the cooling rate is determined. The values of K are determined empirically, and these values of K are either tabulated or shown graphically.

Such a method was well accepted in the beginning. However, in recent times it has been subjected to some criticism due to sources of error when it is used to evaluate the effect of welding techniques (process variables) on the cooling rates. The main source of this error has been the fact that the arc efficiency for a given process had been assumed to be constant. This was found to be untrue by many investigators (Refs. 1–3), who showed that the arc efficiency was also a function of the welding techniques.

An improved method for determining arc efficiencies was proposed by Jackson (Ref. 4). The method is based on the measurement of the calorific heat content of the weld metal; it requires the measurement of the weld metal cross section area. This area termed as "nugget area" has been shown to have a good relationship with the cooling rates in the weld. Since the development of the nugget area concept, considerable success has been achieved in predicting the cooling rates and the mechanical properties (Refs. 5–8) of welds.

The "nugget area" concept is well established and widely accepted. However, its validity has so far been confined to the "bead on plate" (BOP) deposits. Very little attempt has been made to test this concept for groove welds. Therefore, the aim of this work is to check the validity of nugget area concept on both the BOP and the groove welds.

The cooling time is obviously a complex function of nature of heat flow. This, in turn, is dependent on the heat flow boundary characteristics. Thus, nugget area concept is an oversimplification of the cooling of a weld bead. The heat flow characteristics of a weld bead is dependent on heat content, the heat transfer characteristics of the nugget, the HAZ, and the boundaries through which the heat is being transferred. Hence, cooling characteristics will be correlated with the weldment characteristics such as the fusion area, the HAZ area, the fusion boundary length and the HAZ boundary length. In this analysis, no distinction is made between BOP welds and the V-groove welds.

Various methods of characterizing a weld thermal cycle are in use, *e.g.*, cooling rates at 704, 540, and 300°C or 1299, 1004, or 572°F (Ref. 9). However, in recent years, the time to cool between 800 and 500°C (1472 and 932°F) has become most popular because it is easily and accurately measured; thus, in this

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Table 1—Welding Conditions, the Cooling Time for 800-500°C (1472-932°F) and the Characteristics of Bead-on-Plate Welds Deposited Using Single Wire Submerged Arc Welding With 4 mm (0.16 in.) Diameter Welding Wire and DC(+) Electrode Polarity[a]

Heat input, kJ/mm	Current, A	Voltage, V	Fusion area, mm^2	HAZ area, mm^2	Fusion boundary, length, mm	HAZ boundary length, mm	Cooling time for 800–500°C,s
32 mm (AA) electrode extension:							
3.15	600	28	124.8	57.6	25.2	29.2	17.4
3.15	600	32	118.4	66.6	27.1	32.1	16.5
3.15	600	36	114.0	54.6	25.7	30.3	15.0
3.93	600	28	162.0	91.8	30.5	36.0	24.0
3.93	600	32	140.0	89.6	31.1	35.5	18.0
3.93	600	36	132.8	67.0	28.9	33.0	21.0
4.72	600	28	175.6	99.0	35.0	39.5	27.0
4.72	600	32	174.8	121.2	34.6	41.1	30.0
4.72	600	36	151.4	100.0	33.4	38.2	27.7
3.15	800	28	163.8	65.2	31.4	36.1	16.0
3.15	800	32	176.8	65.0	34.8	37.0	16.5
3.15	800	36	159.8	66.6	31.1	34.9	23.0
3.93	800	28	225.8	86.0	36.8	40.5	24.6
3.93	800	32	207.2	76.0	35.6	38.8	21.0
3.93	800	36	209.8	89.4	37.4	41.1	24.0
4.72	800	28	258.2	90.4	34.2	42.5	27.0
4.72	800	32	239.2	82.0	36.3	41.6	26.0
4.72	800	36	214.4	87.4	34.6	39.4	30.0
76 mm (AI) electrode extension:							
3.93	500	28	139.4	68.6	25.5	31.7	20.8
3.93	500	32	164.0	82.6	29.3	34.0	21.8
3.93	500	36	115.6	73.8	25.7	31.1	20.0
3.93	600	28	172.0	88.0	29.8	35.6	22.8
3.93	600	32	150.0	68.2	28.8	32.7	20.5
3.93	600	36	121.6	75.5	27.6	33.8	19.0
3.93	700	28	193.0	85.6	31.4	37.5	25.5
3.93	700	36	177.8	71.8	29.8	33.5	21.8
3.15	800	36	163.8	52.0	29.3	32.8	20.5
3.93	800	28	204.6	86.0	32.7	38.3	23.0
3.93	800	32	201.6	79.2	33.1	37.6	21.0
3.93	800	36	206.4	69.2	31.8	36.8	21.5

(a) 1 in. = 25.4 mm.

study, the weld cooling cycle will be characterized by the cooling time for 800-500°C ($t_{800-500}$).

Experimental Work

Materials

The base materials used for the experimental work were CSA G40.21-44W and ASTM A36 steel plates. The G40.21-44W steel was 41.5 mm (1.63 in.) thick and was used to make bead-on-plate (BOP) deposits. This plate was oxygen-cut into 300 × 150 mm (11.8 × 5.9 in.) pieces, and both surfaces were cleaned (sand blasted) to remove dirt and oxides. The A36 steel plate was 38 mm (1.5 in.) thick and was used for making V-groove welds. This plate was cut into 160 × 150 mm (6.3 and 5.9 in.) pieces and grooves of 60, 52½, 45 and 37½ deg were machined in them. In each piece, a root face of 12.5 mm (0.49 in.) was maintained.

AWS EL12 electrode wires with diameters of 4, 2.4 and 2 mm (0.16, 0.09, and 0.078 in.), respectively, along with AWS F64 flux, were used as the welding consumables.

Submerged Arc Welding Procedure

The submerged arc unit used was a constant current type and consisted of a Lincoln Ideal Arc R3R-500 dc transformer/rectifier and ESAB A6 control unit and feeding head. For BOP deposits, 100 mm (3.9 in.) long run-on and run-off tabs were welded on both sides of the 300 × 150 mm (11.8 × 5.9 in.) plates. The run-on tabs allowed enough time to adjust the welding current and voltage, while the run-off tabs absorbed the crater of the bead. Thus, for each deposit, a 150 mm (5.9 in.) long deposit of acceptable quality could be achieved. For V-groove welds, the machined faces were tack welded with a root opening of 1.5 mm (0.06 in.), and run-on and run-off tabs were welded in the same way as for BOP welds. For each deposit, the current and voltage were recorded on a dual pen chart recorder. All welds were made under the same conditions of restraint.

In order to generalize the outcome of the present work, the following variables were used. For BOP welds, single and twin wire processes were used, with electrode wire diameters of 2.4 and 4 mm (0.09 and 0.16 in.) for single wire and 2.4 (0.09 in.) and 2 mm (0.079 in.) for twin wires. For single wire process, both dc(+) and dc(−) electrode polarities for a 32 mm (1.26 in.) electrode extension, and dc(+) electrode polarity for electrode extension of 76 mm (3 in.) were used.

Both dc(+) and dc(−) electrode polarities with electrode extensions of 32 mm (1.26 in.) were used for the twin wire process. Only single wire welding with 4 mm (0.16 in.) diameter wire, 32 mm (1.26 in.) electrode extension and dc(−) electrode polarity was used to deposit root beads in V-grooves. The welding conditions for the BOP and the V-groove welds are given in Tables 1 to 5.

Measurements of Cooling Cycles

The cooling cycles were measured by using Pt-Pt/13% Rh thermocouple. The thermocouple was manually plunged into the weld pool through the slag immediately behind the arc. The output of the thermocouple was recorded on a fast response strip chart recorder. From these curves, the times to cool between 800 and 500°C (1472 and 932°F) were measured.

Table 2—Welding Conditions, Cooling Time for 800–500°C (1472–932°F) and the Characteristics of the Bead-on-Plate Welds Deposited Using Single Wire Submerged Arc Welding Process With 4 mm (0.16 in.) Diameter Welding Wire, 32 mm (1.26 in.) Electrode Extension and DC(−) Electrode Polarity (AC)[(a)]

Heat input, kJ/mm	Current, A	Voltage, V	Fusion area, mm^2	HAZ area, mm^2	Fusion boundary length, mm	HAZ boundary length, mm	Cooling time for 800-500°C,s
3.15	500	28	120.5	49.6	25.3	28.8	17.3
3.15	500	32	102.4	62.4	24.9	29.0	16.5
3.15	500	36	93.8	64.0	24.2	28.9	16.5
3.93	500	28	146.6	77.6	27.2	31.6	24.0
3.93	500	32	131.2	82.4	27.9	33.0	22.5
4.72	500	28	183.0	83.2	29.8	34.9	27.0
4.72	500	32	154.8	104.8	29.0	34.6	28.5
4.72	500	36	140.4	95.0	31.7	36.3	27.0
3.15	800	32	148.0	52.6	26.6	30.7	18.5
3.15	800	36	146.0	57.2	26.1	31.1	18.0
3.93	800	28	224.6	65.6	30.4	36.2	27.5
3.93	800	32	180.8	64.0	27.6	33.6	23.0
3.93	800	36	183.6	60.8	28.8	33.8	21.0
4.72	800	28	184.0	82.0	29.8	36.8	26.0
4.72	800	32	218.0	88.2	31.2	39.5	25.5
4.72	800	36	192.0	80.0	30.8	36.7	27.5

(a) 1 in. = 25.4 mm.

Table 3—Welding Conditions, Cooling Time for 800–500°C (1472–932°F) and the Characteristics of the Bead-on-Plate Welds Deposited Using Single Welding Wire Submerged Arc Welding With 2.4 mm (0.09 in.) Diameter Welding Wire and 32 mm (1.26 in.) Electrode Extension[(a)]

Heat input, kJ/mm	Current, A	Voltage, V	Fusion area, mm^2	HAZ area, mm^2	Fusion boundary length, mm	HAZ boundary length, mm	Cooling time for 800-500°C,s
Electrode polarity: dc(−) (CC):							
3.15	400	28	102.6	43.6	18.4	23.0	16.5
3.15	400	32	98.8	58.4	21.6	26.4	15.5
3.15	400	36	90.0	50.0	20.6	24.9	15.7
4.72	400	28	163.8	80.0	24.6	30.9	26.5
4.72	400	32	143.8	81.0	26.0	30.8	25.5
4.72	400	36	117.4	88.2	26.9	31.5	25.0
3.15	300	28	86.4	52.0	18.8	24.4	15.7
4.72	300	36	115.6	69.8	25.3	26.8	28.5
Electrode polarity: dc(+) (CA):							
3.15	400	32	101.2	62.6	24.4	28.4	17.5
3.15	400	36	90.0	64.8	24.6	29.2	15.0
4.72	400	28	147.8	88.2	25.8	31.1	24.5
4.72	400	32	122.8	100.8	28.4	34.9	25.0
4.72	400	36	134.6	91.4	28.8	33.0	23.5

(a) 1 in. = 25.4 mm.

A typical weld cooling curve is shown in Fig. 1.

Measurements of Weldment Characteristics

To measure the bead and the heat-affected zone (HAZ) characteristics, the transverse sections were removed from the mid-length position of the welds, polished, and etched in 2% nital. Using a Reichart microscope, the welds were projected on the screen with a magnification of ×5 and the weldment features were traced on a transparent paper. From these traces, the fusion and the HAZ areas were measured by a planimeter and length of their boundary was measured by a thread.

The features measured are shown in Fig. 2.

Results And Observations

A total number of 119 welds, using various combinations of variables, were deposited. The welding details, the weldment features measured, and the cooling time for 800-500°C (1472-932°F) are given in Tables 1 to 5. Various relationships between welding conditions, weldment features and cooling times were evaluated by graphical and statistical analysis.

Cooling Time vs. Heat Input

The relationships between cooling time and heat input are given in Fig. 3, which shows that cooling time increases, as does heat input. Another important observation is that, for the same heat input, welds made in grooves require less time to cool.

For both BOP and groove welds, there is a wide scatter in cooling times. This indicates that there are other factors besides heat input that have an influence on cooling time.

Cooling Time vs. Fusion Area

Figure 4 shows the relationship between the fusion area (A_f) and cooling time. It can be seen that the cooling time increases linearly with the fusion area. These relationships showed poor correlation coefficients (R) of 0.6 and 0.53 with standard deviations (σ) of 4.2 and 3.2 for BOP and groove welds, respectively.

Even though there is a wide scatter in

Table 4—Welding Conditions, Cooling Time for 800–500°C (1472–932°F) and the Characteristics of the Bead-on-Plate Welds Deposited Using Twin Wire Submerged Arc Welding With 32 mm (1.26 in.) Electrode Extension[a]

Heat input, kJ/mm	Current, A	Voltage, V	Fusion area, mm^2	HAZ area, mm^2	Fusion boundary length, mm	HAZ boundary length, mm	Cooling time for 800–500°C,s
Welding wire diameter – 2.4 mm (0.094 in.); electrode polarity – dc(−); skew – 0 deg (3TC):							
3.15	500	32	96.0	60.8	21.2	26.8	16.5
3.15	600	30	110.4	42.0	19.2	24.4	15.0
3.15	700	30	146.6	61.0	22.8	27.9	22.0
3.15	800	32	142.8	55.0	24.0	28.6	13.5
3.93	500	30	117.8	69.8	20.2	26.9	19.5
3.93	600	30	130.6	57.6	21.5	27.7	19.5
3.93	700	30	157.6	72.6	26.2	30.4	22.0
3.93	800	30	150.0	65.4	25.8	31.5	19.8
4.72	600	30	138.4	69.0	28.1	28.6	26.0
Welding wire diameter – 2 mm (0.09 in.); electrode polarity – dc(−); skew – 0 deg (5TC)							
3.15	500	32	106.0	57.2	21.6	26.4	15.0
3.15	600	30	113.6	51.8	21.2	25.9	15.0
3.93	600	30	144.0	59.8	22.1	27.5	20.4
4.72	500	32	195.4	90.4	29.8	36.2	25.0
4.72	600	30	174.4	66.0	22.5	29.1	24.0
4.72	700	30	189.8	73.4	27.0	33.5	24.3
Welding wire diameter – 2 mm (0.09 in.); electrode polarity – dc(+); skew – 10 deg (5TB):							
3.15	500	32	84.0	66.0	24.3	28.6	16.5
3.15	600	30	101.0	55.2	23.4	26.8	16.5
3.15	700	30	128.0	44.0	24.2	27.8	16.5
3.15	800	30	123.6	51.6	25.8	28.3	23.1
3.93	500	32	112.4	63.6	25.9	29.1	22.5
3.93	600	30	109.2	66.0	26.2	30.1	22.5
3.93	700	30	134.0	68.8	27.4	31.4	21.0
3.93	800	30	160.4	65.8	29.6	33.8	19.5
4.72	500	32	107.6	65.6	22.7	28.5	24.0
4.72	600	30	150.8	80.0	29.8	34.3	27.0
4.72	700	30	160.4	78.2	30.0	34.2	24.0
4.72	800	32	167.4	70.2	29.7	33.7	23.1

(a) 1 in. = 25.4 mm.

the results, it can be clearly seen that, for the same fusion area, welds deposited in grooves cool faster than those deposited as BOP. As per the nugget area concept, the logarithm of cooling time was correlated with the logarithm of fusion area. This curvilinear relationship also yielded the same poor correlation coefficient as that of linear correlation.

Cooling Time vs. Fusion Area/Length of the Fusion Boundary or HAZ Boundary

The relationship between the ratio of the fusion area A_f and length of the fusion boundary C_f and cooling time is given in Fig. 5. It shows that the ratio increases as does cooling time. Although the coefficient of correlation is only 0.58 and there is a wide scatter ($\sigma = 5$), it can be seen that for the same value of fusion area/length of the fusion boundary ratio ($\frac{A_f}{C_f}$), both BOP and groove welds have the same cooling time. Low correlation coefficients have also been observed for submerged arc welds in a similar work performed by Chakravarti *et al.* (Ref. 10).

The length of the HAZ boundary (C_h) can be measured easily because of its smooth contour (Ref. 11). Its substitution for the fusion boundary length (C_f) did not, however, alter the correlation of the cooling time ($R = 0.57$ and $\sigma = 5.1$).

Cooling Time vs. (Fusion + HAZ) Area/Length of the HAZ Boundary

Figure 6 shows a relationship between (fusion + HAZ) area/length of the fusion boundary ($\frac{A_f + A_h}{C_h}$) and cooling time. It can be seen here that, as the ratio increases, the time to cool a weld between 800–500°C (1472–932°F) also increases. The cooling time now bears a better correlation with the ratio ($R = 0.79$ and $\sigma = 4.9$) than before, and for the same ratio both BOP and groove welds exhibit the same cooling time.

Correlation of Cooling Time with Fusion Area/HAZ Boundary Length and HAZ Area/HAZ Boundary Length

A multilinear regression analysis was attempted to correlate the cooling time $t_{800-500}$ with the fusion area/HAZ boundary length $\left(\frac{A_f}{C_f}\right)$ and HAZ area/HAZ boundary length $\left(\frac{A_h}{C_h}\right)$. The following relationship was observed with a multilinear correlation coefficient of 0.86 (with a standard error of estimate = 2.559), which is reasonably good:

Cooling time $t_{800-500}$, s $= -12.49 + 3.12 \frac{A_f}{C_h} + 9.06 \frac{A_h}{C_h}$ (where A_f and A_h are in mm^2 and C_h is in mm) (Ref. 1).

Discussion

In Fig. 3, as the heat input increases, the time required to cool the weld between 800–500°C (1472–932°) also increases. This is obvious, because higher heat input produces higher heat content of the weld and hence a longer time to cool. These plots show a big scatter in the results, *e.g.*, for welds made with a heat input of 3.15 kJ/mm (80 kJ/in.), the cooling time could vary between 13.5–22.5 seconds(s) for BOP welds and 9.6–16.5 s for groove welds. Such scatters are quite common in welding processes.

Table 5—Welding Conditions, Cooling Time for 800–500°C (1472–932°F) and the Characteristics of the Root Beads Deposited in V-Grooves Using Single Welding Wire Submerged Arc Welding With 4 mm (0.16 in.) Diameter Welding Wire, 32 mm (1.26 in.) Electrode Extension, and dc(−) Electrode Polarity[a]

Heat input, kJ/mm	Current, A	Voltage, V	Fusion area, mm^2	HAZ area, mm^2	Fusion boundary length, mm	HAZ boundary length, mm	Cooling time for 800–500°C,s
Groove angle – 60 deg (5AC):							
3.15	600	28	130	59.8	30.6	37.7	12.0
3.93	600	28	162	70.6	32.6	42.7	15.0
4.72	600	28	192	94.0	35.1	45.0	18.0
3.15	700	36	139	64.6	33.9	41.7	16.5
3.93	700	36	138	74.0	33.8	40.6	15.5
4.72	700	28	161	88.6	33.3	44.5	21.0
Groove angle – 52.5 deg (4AC):							
3.15	600	32	122	55.2	29.8	36.9	13.5
3.15	700	32	127	59.8	29.3	36.2	10.0
3.15	800	32	162	67.0	35.5	41.3	16.5
3.93	600	32	150	73.2	34.0	41.8	16.5
3.93	700	32	163	97.2	36.5	46.9	22.5
3.93	800	32	180	88.2	38.9	48.0	17.0
4.72	600	36	176	93.8	42.0	49.6	16.5
4.72	700	36	175	81.8	38.5	46.5	18.5
Groove angle – 45 deg (3AC):							
3.15	500	30	103	68.0	29.2	37.3	9.5
3.93	500	30	128	76.4	32.7	41.0	12.0
4.72	500	30	138	66.6	34.3	40.2	15.0
3.15	800	30	161	73.6	33.8	44.0	10.5
3.93	800	30	177	91.4	37.9	47.7	16.3
4.72	800	30	209	102.4	39.6	51.0	20.0
3.15	700	30	145	64.2	35.4	39.9	11.5
3.93	700	30	167	89.6	37.0	48.8	15.5
4.72	700	30	198	87.4	40.0	48.1	18.5
3.93	600	30	143	71.8	36.3	42.0	13.0
4.72	600	30	165	98.6	33.9	46.8	19.8
3.15	600	30	119	66.4	33.7	40.1	13.0
Groove angle – 37.5 deg (2AC):							
3.15	500	36	141	57.8	36.4	36.5	11.5
3.93	500	36	163	82.4	44.4	44.4	16.0
4.72	500	36	132	93.2	44.9	45.5	17.0
3.93	600	30	123	79.4	41.5	41.5	13.0
3.15	800	30	168	66.4	41.5	41.5	12.5
3.93	800	30	168	79.0	45.7	45.7	15.0
4.72	800	30	190	94.8	50.1	50.2	17.5

(a) 1 in. = 25.4 mm.

Some of the scatters were probably due to the welding techniques (current, voltage, polarity, travel speed, electrode extension, electrode diameter and V-groove angle) which influence the cooling time. The nugget size or the fusion area has been correlated with the cooling time in Fig. 4, indicating a linear relationship. This was expected, because the fusion area represents the heat content of the weld. A larger fusion area means higher heat content; therefore, longer cooling times would be required. The poor correlation observed (R = 0.6 and 0.53 for BOP and V-groove welds, respectively) reflects the effects of several variables used which gave a wide scatter in the results. The curvilinear (log-log) relationship between the cooling time and the fusion area used in the nugget area concept also yielded poor correlation.

Up to this point, the results are only in qualitative agreement to those of Jackson (Ref. 4). The poor correlation coefficients

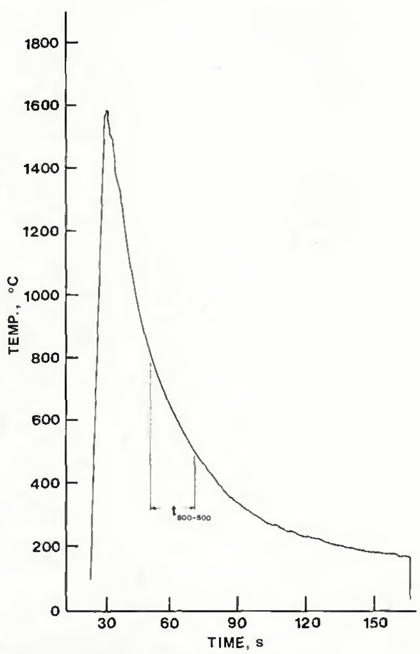

Fig. 1 — Cooling cycle of a weld

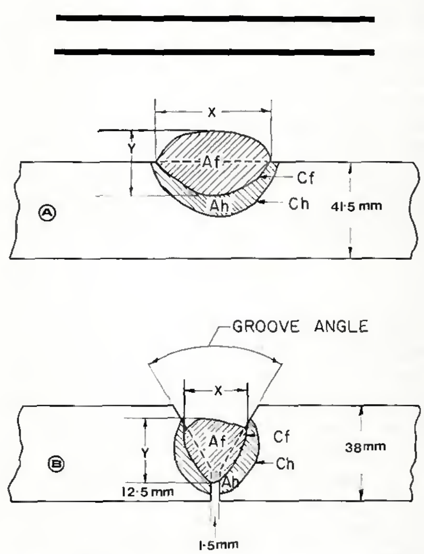

Fig. 2 — Weld features that were measured: A — bead-on-plate welds; B — V-groove welds (Legend: A_f — fusion area, A_h — HAZ area, C_f — length of the fusion boundary, C_h — length of HAZ boundary, x — width, y — depth)

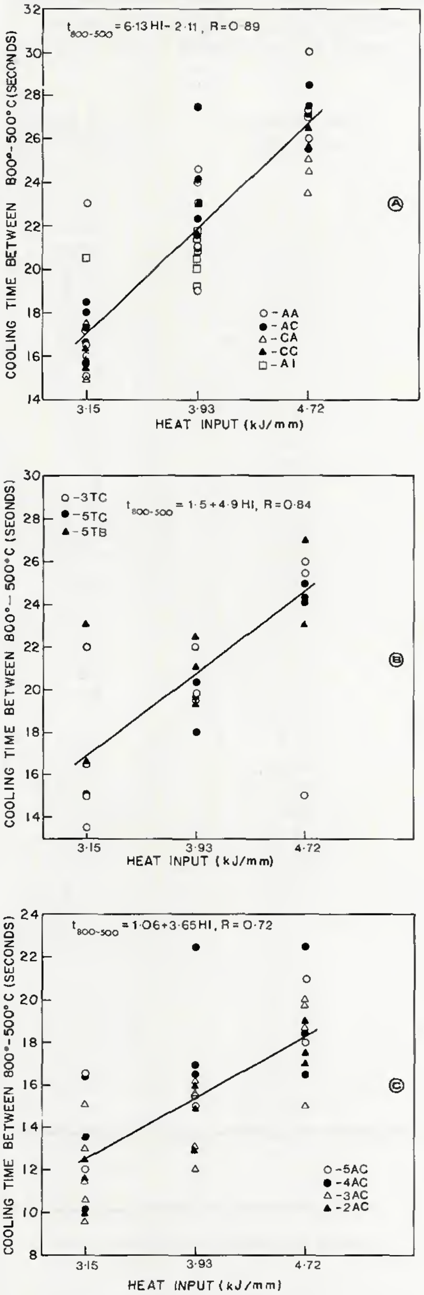

Fig. 3 — Relationships between cooling time for 800-500°C (1472-932°F) and heat input: A — for single wire electrode submerged arc BOP welds; B — for twin wire electrode submerged arc BOP welds; C — for submerged arc groove welds

obtained suggest that the nugget area concept is invalid for both the BOP and V-groove welds in the present study. However, there are two points to be noted here:

1. Scatter is high.
2. There is clear evidence that for the same fusion area, groove welds require less time to cool as compared to BOP welds.

The difference between cooling times of BOP and groove welds can also be explained to a certain extent by theoretical considerations (Ref. 12).

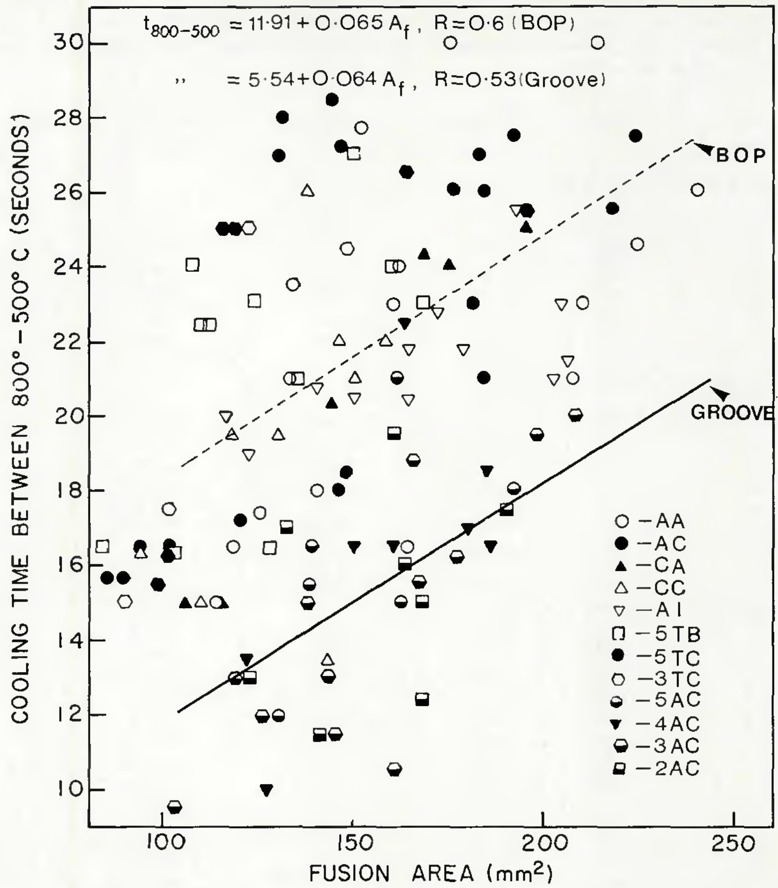

Fig. 4 — Relationship between cooling time for 800-500°C (1472-932°F) and fusion area for the submerged arc welds

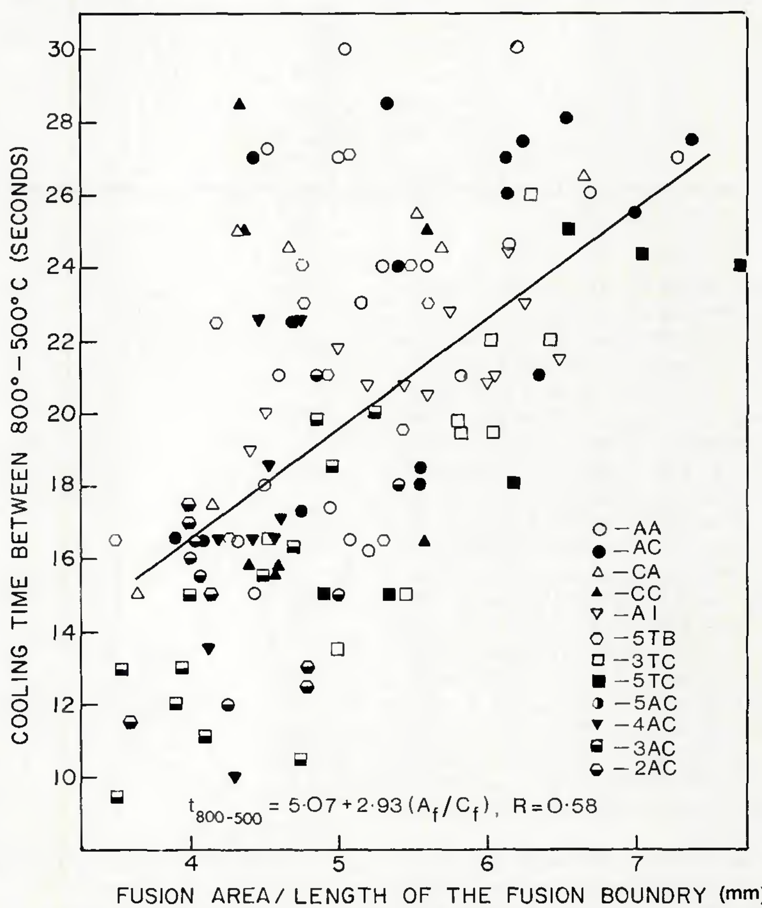

Fig. 5 — Relationship between cooling time for 800-500°C (1472-932°F) and fusion area/length of the fusion boundary for the submerged arc welds

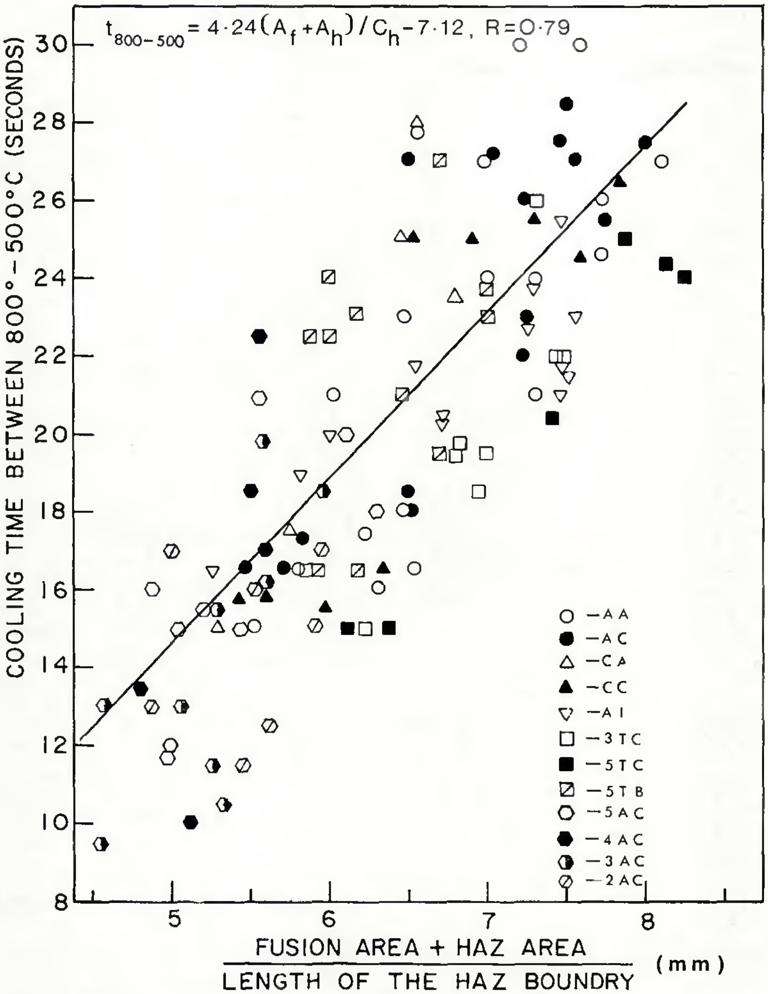

Fig. 6 — Relationship between cooling time for 800-500°C (1472-932°F) and (fusion area + HAZ area)/length of the HAZ boundary for the submerged arc welds

To explain the poor correlation observed, it would be useful to consider the fact that the time required to cool a body depends on more than its volume; it also depends on the surface area through which the heat flows out. The same fact, when applied to a weld, means that the cooling time of a weld would depend upon the ratio of the fusion area and the periphery of the weld bead.

In submerged arc welds, it is considered that heat loss through the slag and the flux is negligible, and most of the heat is conducted through the base metal, *i.e.,* the fusion boundary. To confirm this hypothesis, a relationship between the ratio of the fusion area and length of the fusion boundary and cooling time was plotted as shown in Fig. 5. It can be seen that there is an increase in cooling time with an increase in fusion area/length of the fusion boundary ratio. Figure 5 also suggests that, for the same fusion area/length of the fusion boundary ratio, the cooling times are the same for both BOP and V-groove welds. This is probably due to the fact that, for the same fusion area, a weld (root bead) deposited in a groove has longer fusion boundary; therefore, the ratio is reduced and hence shorter times are needed to cool.

Similarly, a welding technique that influences this ratio (for the same fusion area) will also influence the cooling rate. To illustrate this point, consider two welds: one deposited with dc(+) electrode polarity and one with dc(−) electrode polarity and both have the same fusion area. It is well known that welds deposited with dc(−) electrode polarity are shallower, *i.e.,* have shorter fusion boundaries. Since the fusion area is the same in both cases, the fusion area/length of the fusion boundary ratio is higher in some of the welds made with dc(−) electrode polarity; therefore, they would require longer times to cool. Similarly, the effect of other variables can be evaluated. Although the above hypothesis seems reasonable, the coefficient of correlation was still low (R = 0.58).

Recently, Glickstein and Freidman reported that for GTA welds, the corresponding HAZ always had a smooth contour (Ref. 10). Similar effects were observed in the recent investigation, and in some cases the weld beads were so irregularly shaped that it was very difficult to measure their areas and length of the fusion boundaries accurately. These inherent difficulties might be partly responsible for the experimental scatter and the low coefficient of correlation. To overcome and/or reduce some of these difficulties, the HAZ areas and HAZ boundary lengths were measured. No improvement in correlation was obseved over the fusion area/length of the fusion boundary, when the cooling time was correlated with the fusion area/HAZ boundary length (R = 0.57).

A new ratio for each weld, *viz.,* the sum of the fusion and HAZ area over the HAZ boundary length was then linearly related to the cooling time as shown in Fig. 6. The plot showed a good correlation and much less scatter in the experimental points (R = 0.79 and $\sigma = 4.9$). There is evidence that good relationship between fusion and HAZ area exists. Thus, it seems reasonable to include the HAZ area in the analysis of the cooling behavior of the welds.

Also, one would expect that the cooling characteristics of the fused metal and the HAZ would be different due to different heat contents of the fused metal and the HAZ and the boundary through which the total heat is dissipated. Thus, the weld metal cooling time is a function of the fusion area, the HAZ area and the HAZ boundary length. Several multilinear regression analyses were performed to correlate the cooling time with various combinations of the fusion area, the HAZ area and the HAZ boundary length. These analyses yielded the relationship given in equation (1) with a reasonably good correlation coefficient (R = 0.86).

It is quite evident from the present analysis that the HAZ characteristics, for the range of variables studied, are partly responsible for the cooling characteristics of the weld metal. Also, it can be stated that the concept of correlating the cooling time with the weldment characteristics can also be extended to other systems and welding processes.

Conclusion

1. BOP and groove welds were deposited using submerged arc welding processes with various combinations of welding conditions and techniques, and their cooling characteristics were recorded.

2. The cooling time for 800-500°C (1472-932°F) was linearly related to the heat input and the fusion area. As the fusion area and the heat input of the weld increased, the time required to cool

it was also increased as expected. For the same heat input and fusion area, weld beads deposited in V-grooves cooled faster than those deposited on the plates.

3. There was a poor linear correlation between the cooling time and the fusion area. The log-log relationship between the cooling time and the fusion area, as per nugget area concept, also yielded the poor correlation for both the BOP and the V-groove welds.

4. Relating the cooling time linearly with the fusion area/length of the fusion boundary and the fusion area/HAZ boundary length yielded poor correlation.

5. The HAZ area, which bears a linear relationship with the fusion area, was combined with the fusion area; and the cooling time was related to the sum of the fusion and HAZ area/HAZ boundary length. This improved the correlation quite significantly.

6. One would expect that the cooling characteristics of the fusion and HAZ area are distinctly different because of the thermal gradients. The multilinear regression analysis, thus, attempted to relate the cooling time with the fusion area/HAZ boundary length and the HAZ area/HAZ boundary length yielded the following relationship with reasonably good correlation:

$$t_{800-500} = -12.49 + 3.12 \frac{A_f}{C_h} + 9.06 \frac{A_h}{C_h}$$

(where t is in s, A_f and A_h are in mm^2 and C_h is in mm).

This showed that the HAZ characteristics, for the range of variables studied, were partly responsible in determining the cooling characteristics of the welds.

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Announcement and Call for Papers

The Canadian Society for Nondestructive Testing, the Canadian Council of the American Society for Metals and the Canada Centre for Mineral and Energy Technology have announced the Second International Conference on Pipeline Inspection, to be held in Edmonton, Alberta, Canada on June 23-26, 1986.

Papers are invited on recent developments in applicaton, investigation or research of state-of-the-art technologies for transmission pipeline inspection, including topics related to: standards and regulations; mill inspection of pipe; field inspection with respect to weld and pipe integrity; and in-service inspection.

Authors wishing to submit papers should indicate their intent as soon as possible, providing a title and abstract of at least 300 words, by July 1, 1985. Papers (of 3000 to 5000 words) are required by December 1, 1985.

Submissions and inquiries should be addressed to: Charles A. Kittmer, Chairman, Technical Program, International Conference on Pipeline Inspection, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J 1J0.

Call for Papers— International Welding Research

Papers are solicited for the ASM/AWS/WRC-sponsored conference on "International Trends in Welding Research," to be held in Gatlinburg, Tenn., May 18-22, 1986. This eight-session symposium will cover heat and fluid flow problems in welds, solidification, solid state transformations, mechanical behavior of welds, and welding processes and process control. Conference proceedings will be published. Submit abstracts up to 300 words by November 15, 1985, to S. A. David, Materials Joining Laboratory, Metals and Ceramics Divisions, Oak Ridge National Laboratory, P. O. Box X, Oak Ridge, TN 37831. Inquiries for future information should be addressed to American Society for Metals (ASM) Conference Dept., Metals Park, OH 44073.