Cooling Rate in Welding—A Aid to Weldability Evaluation

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Introduction :

Weldability evaluation always involves the consideration of microstructural changes and in most of the alloy steels these are greatly dependent on the cooling rates to which the steel is subjected. The determination of cooling rates in weld-metal and HAZ has attracted the attention of many investigators. Rosenthal[1 4] and, Adams[2 3] have done pioneering work in this direction. However, their findings are limited to a few simple weld configurations and the data presented are not in the form suitable for direct use. An attempt has been made in this paper to explain how certain conclusions of great practical utility can be derived from this.

Weld centre line cooling rate :

There exists great variation of heating and cooling rates at various points over the plate subjected to welding. The peak temperatures also vary considerably. The degree of austenitization, which depends on the peak temperature and the duration of heating above the recrystallisation temperature, also varies as a consequence of the variation in peak temperature and cooling rate. It is needless to say that the microstructural changes depend on these factors. To determine the cooling rates and peak temperatures, the complete transient temperature field is to be considered. However, the hypothesis of quasi-stationary state, first proposed by Rosenthal[1], implies that the peak temperature and cooling rate at all the points along the weld centre line will be the same. Also both the peak temperature and cooling rate are maximum at the weld centre line. This combination results in the most severe microstructural change. Adams states that the cooling rates at points in the heat affected zone are only slightly different from that along weld centre line. Thus, weld centre line cooling rate can be taken as the most appropriate criterion of evaluating the material and welding conditions in so far as the growth of crack sensitive microstructure is concerned. The welding conditions (electrode size, arc voltage and

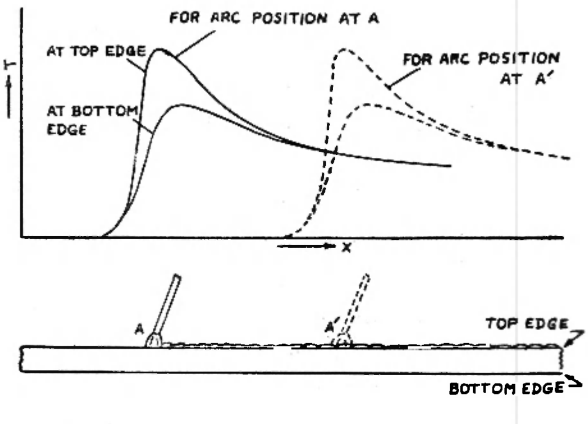

FIG. 1 TEMPERATURE DISTRIBUTION ALONG WELD-CENTRE-LINE

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current, plate thickness, preheat temperature etc.) can be deemed appropriate if these do not lead to a weld centre line cooling rate faster than that which is just sufficient for the development of an appreciable amount of crack sensitive microstructure. The cooling rate required for such comparison can easily be deduced from continuous cooling diagram for the material.

The temperature distribution along the centre line of the weld is shown in Fig. 1. The implication of quasi-stationary state is clearly seen there. When the arc is at position A, the temperature distribution at various points is shown by the solid lines. The temperature distribution for arc position at A' is shown by dashed line. It is apparent that the two distributions are exactly similar and differ only in their positions. This means that all the points along weld centre line experience similar variation of temperature and the time-temperature plot for any such point will also be an identical curve shown in Fig. 2.

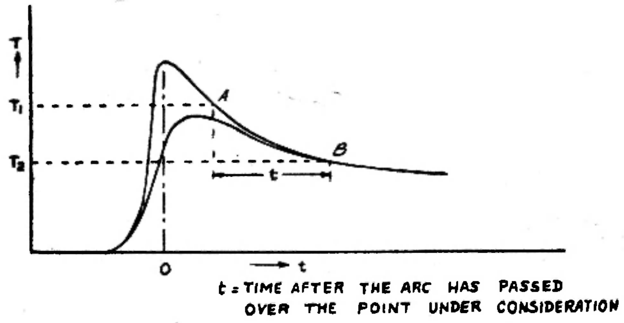

FIG. 2

Metallurgical transformations and cooling rate :

The microstructure developed by rapid cooling can be predicted with the help of continuous cooling transformation diagrams. One such diagram for the eutectoid plain-C-steel has been plotted in Fig. 3. A cooling rate faster than curve 1 results in the formation of complete martensite and a cooling rate in between curves 1 and 2 results in the fomation of partly martensite and partly pearlite while a still slower rate results in the formation of pearlite alone. Alternatively, if the temperature falls from T_1 to T_2 in a time less than t', the microstructure will be full martensite and if this drop in temperature occurs in more than t'' sec., the micro-structure will be pearlite only. Hence if an estimate is made regarding the time for the weld to cool from the temperature T_1 to T_2 and if it is more than t'', conditions could be assumed to yield no martensite and be safe for the material under consideration. The estimate of such time value is easy once the time-temperature plot for the weld centre line is known. It is shown in Fig. 2.

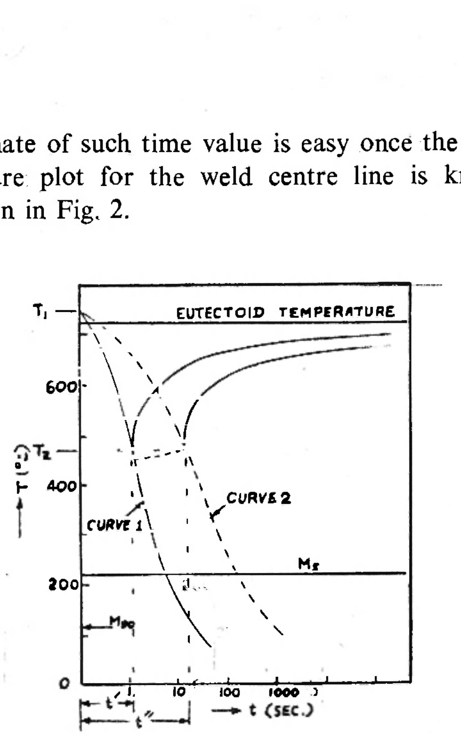

FIG. 3

The temperature distribution in a moving coordinate system with arc centre as the origin was first analysed by Rosenthal[1] and he gave the formulae for the cases of thin and thick plates. Thin plate was the one where there existed little difference between the temperatures of points on the top edge (where the weld-bead is deposited) and the corresponding points on the opposite edge of plate. Thick plate was termed as the one where the opposite edge of the plate did not experience any change in temperature. The more practical case of the plate of moderate thickness (where both edges experience different temperature changes) was also analysed but the formula for temperature distribution was quite complicated involving series summation of the terms containing Bessels functions and plotting the time temperature curve (Fig. 2) itself involves the use of computers.

Adams tackled the problem from a different angle and determined cooling rates at different points along weld-centre line instead of finding the actual temperatures there, as in Fig. 2. It is possible to determine time t if the cooling rates at points A and B in Fig. 2 are known. Adams gave a generalised plot of cooling rate, at the top and bottom sides of the plate. It was valid for all the three cases of thin, thick and moderately thick plates. The cooling rate could be determined easily for any temperature of interest, say T_1 (for point A) or T_2 (for point B). The generalised cooling rate curves are replotted in Fig. 4. In the discussion to follow, it has been explained how these curves can be used to derive results of great practical significance.

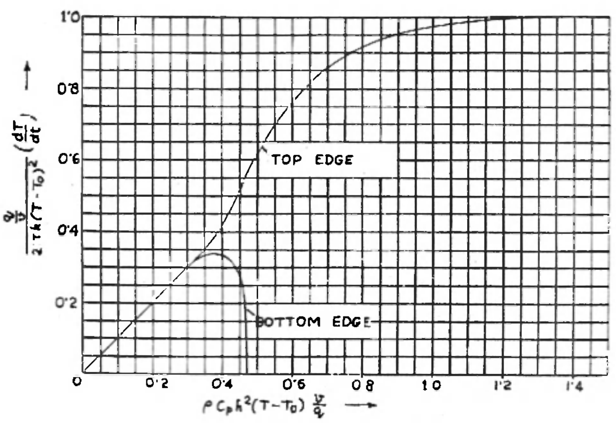

FIG.4 GENERALIZED COOLING RATE CURVE (REF. 3)

Weldability evaluation from cooling rate curves :

The generalised cooling rate curves involve the following terms.

$$Q = \text{arc power (cal./sec.)} = \frac{V.I}{4.18} \times \eta$$

where V = arc voltage (volts)

I = welding current (amps.)

η = efficiency of heat input to the plate (generally 0.65).

v = welding speed (mm/sec.)

K = thermal conductivity (cal/mm. °C sec.)

ρ = density (gm/mm^3)

C_p = specific heat of metal (Cal./mm °C)

h = plate thickness (mm)

T = temperature at which cooling rate is determined (°C)

T_o = Initial temperature (room temperature or preheat temperature) (°C).

$\frac{dT}{dt}$ = Cooling rate at weld centre line (t represents time).

For illustration we may take the physical properties = material as follows :

K = 0.01 Cal/mm °C sec.

ρ = 7.86×10^{-3} gm/mm^3

C_p = 0.166×10^{-1} Cal./mm °C

The use of a generalised cooling rate curve can be illustrated by a numerical example, as follows.

Let us assume T_1 and T_2 to be 750°C and 470°C respectively and time t" is 16 sec. The conditions for manual welding with an electrode having 4 mm wire diameter can be taken as

V = 25 volts

I = 150 amps.

v = 150 mm/min. = 2.5 mm/sec.

On substituting the values of welding conditions and physical properties of the material, the abscissa and ordinate of generalised cooling rate curve (Fig. 4) can be written as :

$$\text{abscissa} = 0.56 \times 10^{-6}\, h^2\, (T - T_0) \quad \ldots (1)$$

$$\text{ordinate} = \frac{3720}{(T - T_0)} \cdot \frac{dT}{dt} \quad \ldots (2)$$

Assuming the room temperature (T_o) of 20°C, the values of $\frac{dt}{dT}$ for various plate thicknesses and at different temperatures can be calculated easily from the above data and Fig. 4. These are tabulated below. The weld centre line cooling time (t in Fig. 2) can be calculated by graphical integration using the following formula.

$$t = \frac{1}{2}\left\{\left(\frac{dt}{dT}\right)_{\text{at } T_1} + \left(\frac{dt}{dT}\right)_{\text{at } T_m}\right\}(T_1 - T_m) + \frac{1}{2}\left\{\left(\frac{dt}{dT}\right)_{\text{at } T_m} + \left(\frac{dt}{dT}\right)_{\text{at } T_o}\right\}(T_m - T_2) \quad \ldots (3)$$

where Tm is some intermediate temperature between T_1 and T_o.

The limited number of calculations shown in the table above clearly demonstrates the utility of this method and brings out the following interesting facts.

(1) For eutectoid plain-c-steel "Steel A" the use of 4 mm dia. electrodes is safe for 20 mm thick plate but not recommended for a plate of thickness 30 mm or more.

(2) Increasing the size of electrode to 5 mm dia. makes it possible to weld even 30 mm thick plate in "Steel A" without any special precaution.

(3) The low alloy steel "Steel B" is difficult to weld even in the plate thickness of 8 mm with a 4 mm dia. electrode and it is not recommended while a preheat of 200°C makes it

Tabular Calculations

Material and plate thickness (mm)	Temperature (T)°C		(T—T₀)	h²(T—T₀)	Abscissa (from eq. 1 or similar eq)	Corresponding ordinate from Fig. 4 (C)	dt/dT (from eq. 2 or similar eq)	Cooling time (t) sec	Permissible cooling time (t'') sec
"Steel A"	750	(T_1)	730	29.2×10^4	0.163	0.163	0.0428		
20 mm	610	(T_m)	590	23.6×10^4	0.132	0.132	0.0810	27†	16
(4 mm electrode)	470	(T_2)	450	18.0×10^4	0.101	0.101	0.1810		
"Steel A"	750	(T_1)	730	65.7×10^4	0.368	0.370	0.0188		
30 mm	610	(T_m)	590	53.1×10^4	0.297	0.297	0.0360	12*	16
(4 mm electrode)	470	(T_2)	450	40.5×10^4	0.227	0.227	0.0808		
"Steel A"	750		730	Same as	0.276	0.276	0.0337		
30 mm	610		590	second	0.223	0.223	0.0640	21†	16
(5 mm electrode)	470		450	set	0.170	0.170	0.1440		
"Steel B"	780		760	4.86×10^4	0.0272	0.0272	0.236		
8 mm	680		660	4.23×10^4	0.0237	0.0237	0.360	77*	180
(4 mm electrode)	580		560	3.59×10^4	0.0201	0.0201	0.590		
"Steel B"	780		580	3.71×10^4	0.0208	0.0208	0.530		
8 mm	680		480	3.07×10^4	0.0172	0.0172	0.945	215†	180
(4 mm electrode)	580		380	2.43×10^4	0.0136	0.0136	1.890		
200°c preheat									

†recommended *not recommended.

safe to weld in this thickness with 4 mm electrode.

Many other similar conclusions for various welding conditions and plate materials can be made if the calculations are carried out on the lines suggested above.

Cooling rates in difficult weld configurations :

The above analysis is applicable to butt welding of plates of some thickness in one or few passes. If the two plates differ in thickness or a fillet weld is to be made or special edge preparations are required for joining thick plates, the cooling rate expressions used above are no more applicable. The suitable theoretical analysis for such cases has not been carried out. However, work is in progress at I.I.T. Kharagpur in this direction.

Conclusions :

A method of evaluating welding conditions for their suitability in given circumstances is suggested. It is simple but gives very useful results like the degree of preheat required, the thickest plate which can be welded without any special precautions or the electrode size suitable for a particular plate thickness in different alloy steels.

References :

1. Rosenthal, D., Mathematical Theory of Heat Distribution During Welding and Cutting, Welding Journal, May '41, p 220-S to 234-S.

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4. Rosenthal, D., The Theory of Moving Source of Heat and its Application to Metal Treatment, Transactions ASME, No. '46, p 849-866.