

Method of calculating the cooling rate

This chapter describes method of calculating the cooling rate in HAZ during welding of thick and thin plates besides that of critical cooling rate for steel under welding conditions. Further, significance of peak temperature in heat affected zone and solidification time of weld metal for development of sound weld joint has also been presented.

Keywords: Peak temperature, solidification time, width of HAZ, weld structure

20.1 Calculations of cooling rate

Thickness of the plate to be welded directly affects the cross sectional area available for the heat flow from the weld which in turn governs cooling rate of a specific location. Accordingly, two different empirical equations are used for calculating the cooling rate in HAZ for a) thin plates and b) thick plates, depending upon the thickness of plate and welding conditions. There is no clear demarcating thickness limit to define a plate thick or thin. However, two methods have been proposed to take decision whether to use thick or thin plate equation for calculating the cooling rates and these are based on

- 1) number of passes required for completing the weld
- 2) relative plate thickness

According to first method, if number of passes required for welding of two plates is less than 6 then it is considered as thin plate else thick plate for selection of suitable equation to calculate cooling rate. Since this method is not very clear as number of passes required for completing the weld can vary with diameter of electrode and groove geometry being used for welding, therefore a more logical second method based on relative plate thickness criterion is commonly used. The relative plate thickness criteria is more logical as it considers all the relevant factors which can affect the cooling rate such as thickness of the plate (h), heat input (H_{net}), initial plate temperature (T_o), temperature of interest at which cooling rate is desired (T_i) and physical properties of plate like (specific heat C , density ρ). Relative plate thickness (τ) can be calculated using following equation: $h\{\rho C(T_i - T_o)/H_{net}\}^{1/2}$

Thin plate cooling rate equation is used when relative plate thickness $\tau < 0.6$ and thick plate cooling rate equation is used when $\tau > 0.9$. If value of τ is in range of 0.6 to 0.9 then 0.75 is used as a limit value to decide the cooling rate equation to be used.

Cooling rate (R) equation for thin plates: $\{2\pi k\rho C (h/ H_{net})(T_i - T_o)^3\}^0\text{C/sec} \dots\dots(1)$

Cooling rate (R) equation for thick plates: $\{2\pi k(T_i - T_o)^2\}/H_{net}^0\text{C/sec} \dots\dots\dots(2)$

Where h is the plate thickness (mm), k is thermal conductivity, ρ is the density (g/cm³), C is specific heat (kCal/⁰C.g), T_i is the temperature of interest (⁰C), and T_o is the initial plate temperature (⁰C).

Cooling rate equations can be used to a) calculate the critical cooling rate (CCR) under a given set of welding conditions and b) determine the preheat temperature requirement for the plate in order to avoid the CCR.

20.2 Critical cooling rate (CCR) under welding conditions

To determine the critical cooling rate for a steel plate under welding conditions, bead on plate welds are made with varying heat input. On the basis of thickness of the plate (5 mm) to be welded suitable electrode diameter is chosen first and then accordingly welding current and arc voltage are selected (20V, 200A, T_o=30⁰C) for bead-on-plate (BOP) welding. Number of BOP welds is deposited using increasing welding speed (8, 9, 10, 11, 12.....mm/sec). Once the BOP weld is completed at different welding speed, transverse section of weld is cut to measure the hardness. Thereafter, hardness vs. welding speed plot is made to identify the welding speed above which abrupt increase in hardness of the weld and HAZ takes place. This welding speed is identified as critical welding speed (say 10mm/min in this case) above which cooling rate of the weld & HAZ becomes greater than critical cooling rate. This abrupt increase in hardness of the weld and HAZ is attributed to martensitic transformation during welding as cooling rate becomes greater than critical cooling rate owing to the reduction in heat input (H_{net}) with increase of welding speed. Using welding conditions corresponding to this critical welding speed for a given steel plate, critical cooling rate can be calculate using appropriate cooling rate equation.

Corresponding H_{net} = f X VI/S = 0.9 X 20 X 200 /10 = 360 J/mm or 0.36 kJ/mm.

Calculate relative plate thickness (RPT) parameter for these conditions: $h [(T_i - T_o)C/H_{net}]^{1/2} : 0.31$

RPT suggests use of thin plate equation for calculating the cooling rate: $2\pi k\rho C(h/Q) (t_c - t_o)^3$

Cooling Rate (R): 5.8 ⁰C/s and it will be safer to consider CCR: 6 ⁰C/s

Similarly these equations can also be used for calculating the cooling rate or identifying the preheat temperature to avoid CCR for a particular location under a given set of welding conditions.

20.3 Peak temperature and Heat Affected Zone

The weld thermal cycle of a particular location exhibits peak temperature and cooling rate as function of time apart from other factors.

Peak temperature distribution around the weld-centre line determines a) shape of the weld pool, b) size of heat affected zone and c) type of metallurgical transformation and so mechanical properties of weld and HAZ.

Variation in heat input and initial plate temperature affects the peak temperature distribution on the plates along the weld line during welding. An increase in heat input by increasing the welding current (for a given welding speed) in general increases the peak temperature of a particular location and makes the temperature distribution equal around the welding arc (almost circular or oval shape weld pool). Increase in welding speed however makes the weld pool (peak temperature distribution) of tear drop shape (Fig. 20.1).

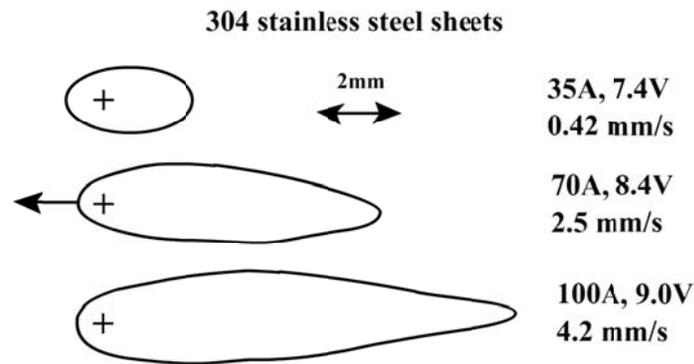


Fig. 20.1 Effect of welding parameters on weld pool profile as dictated by peak temperature

Cooling from the peak temperature determines final microstructure of the weld and heat affected zone. Therefore, peak temperature in the region close to the fusion boundary becomes of great engineering importance as metallurgical transformations (hence mechanical properties) at a point near fusion boundary are influenced by peak temperature (Fig. 20.2). Peak temperature at any point near the fusion boundary for single pass full penetration weld can be calculated using following equation.

$$1/(t_p - t_o) = (4.13 \rho c h Y / H_{net}) + (1/(t_m - t_o)) \dots \dots \dots (3)$$

Where t_p is peak temperature in $^{\circ}\text{C}$, t_0 is initial temperature in $^{\circ}\text{C}$, t_m is melting temperature in $^{\circ}\text{C}$, H_{net} is net heat input, J/mm , h is plate thickness in mm , Y is width of HAZ in mm and ρc is volumetric specific heat ($\text{J}/\text{mm}^3\text{ }^{\circ}\text{C}$).

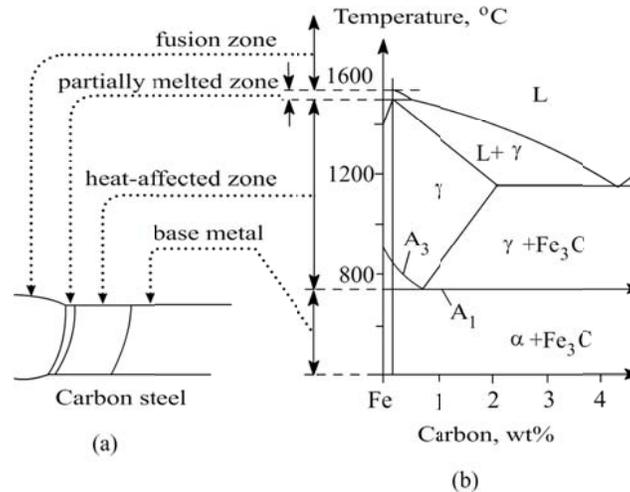


Fig. 20.2 Schematic showing relationship between Fe-C diagram and different zones of weld joints (S Kou, Welding metallurgy, 2003)

This equation can be used for a) calculating peak temperature at a point away from the fusion boundary, b) estimating width of heat-affected zone and c) studying the effect on initial plate temperature/preheating and heat input on width of HAZ. Careful observation of equation reveals that an increase in initial plate temperature and net heat input will increase the peak temperature at y distance from the fusion boundary and so width of heat affected zone.

To calculate the width of HAZ, it is necessary to mention the temperature of interest/critical temperature above which microstructure and mechanical properties of a metal will be affected by application of welding heat. For example, the plain carbon steels are subjected to metallurgical transformation above 727°C i.e. lower critical temperature, hence temperature of interest/critical temperature for calculating of HAZ width becomes 727°C . Similarly, a steel tempered at 300°C after quenching treatment whenever heated to a temperature above 300°C , it is over-tempered so the structure and properties are affected hence for quenched and tempered steel, tempering temperature (300°C) becomes the critical temperature.

A single pass full penetration weld pass is made on steel plates having $\rho c = 0.0044 \text{ J}/\text{mm}^3\text{ }^{\circ}\text{C}$, $t = 5 \text{ mm}$, $t_p = 25^{\circ}\text{C}$, $t_m = 1510^{\circ}\text{C}$, $Q = 720 \text{ J}/\text{mm}$. Calculate the peak temperatures at 3.0 mm and 1.5 mm and 0 mm distance from the fusion boundary.

On replacing of values of different factors, in $1/(t_p-t_o) = (4.13\rho chY / H_{net}) + (1/(t_m-t_o))$ the peak temperature at distance 3 mm, 1.5 mm and 0 mm is obtained as 1184 °C, 976°C and 1510 °C respectively.

20.4 Solidification Rate

The solidification of weld metal takes place in three stages a) reduction in temperature of liquid metal, b) liquid to solid state transformation and c) finally reduction in temperature of solid metal up to room temperature. The time required for solidification of weld metal depends up on the cooling rate. Solidification time is the time interval between start to end of solidification. Solidification time is also of great importance as it affects the structure, properties and response to the heat treatment of weld metal. It can be calculated using following equation:

$$\text{Solidification time of weld } (S_t) = LQ/2\pi k\rho c(t_m-t_o)^2 \text{ in sec.....(5)}$$

Where L is heat of fusion (for steel 2 J/mm³)

Above equation indicates that solidification time is the function of net heat input, initial plate temperature and material properties such as latent heat of fusion (L), thermal conductivity (k), volumetric specific heat (ρC) and melting point (t_m). Long solidification time allows each phase to grow to a large extent which in turn results in coarse-grained structure of weld metal. An increase in net heat input (with increase in welding current / arc voltage or reduction in welding speed) increases the solidification time. An increase in solidification time coarsens the grain structure which in turn adversely affects the mechanical properties. Non-uniformity in solidification rates in different regions of molten weld pool also brings variation in grain structure and so mechanical properties. Generally, centerline of the weld joint shows finer grain structure (Fig. 20.3) and better mechanical properties than those at fusion boundary primarily because of difference in solidification times. Micrographs indicate the coarser structure near the fusion boundary than the weld center.

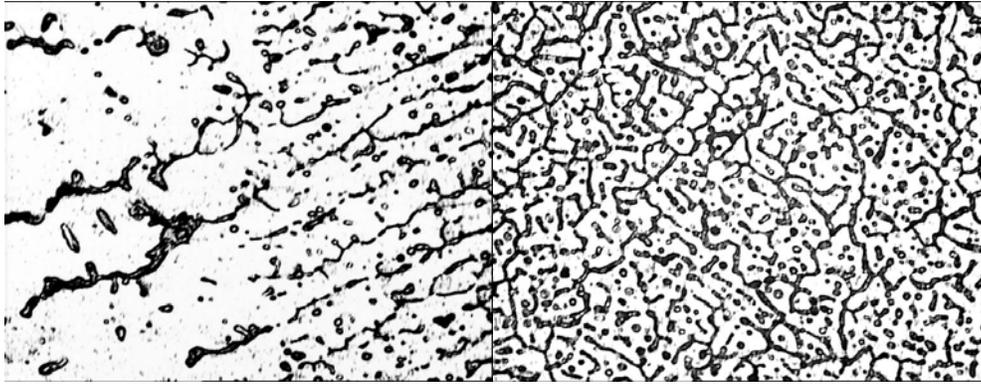


Fig. 20.3 Variation in microstructure of weld of Al-Si alloys of a) fusion boundary and b) weld centre owing to difference in cooling rate (200X)

Example

A single pass full penetration weld pass is made using net heat input at the rate of 500 J /mm on steel having $\rho c = 0.0044 \text{ J/mm}^3 \text{ }^\circ\text{C}$, $t = 5\text{mm}$, $t_o = 25^\circ\text{C}$, $t_m = 1540^\circ\text{C}$, and thermal conductivity $k = 0.025 \text{ J/mm.s. }^\circ\text{C}$ and latent heat of fusion 2.4 J/mm^3 .

Determine the solidification time.

Solution

Solidification time: $LQ/2\pi k\rho c(t_m - t_o)^2$ in sec

Solidification time: $2.4 \times 500 / (2\pi \times 0.025 \times 0.0044 (1540 - 25)^2)$ in sec

Solidification time : 1200/1585.54

Solidification time : 0.75 sec

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