Weld Thermal Cycle

This chapter describes the need of studying the heat flow in welding and concept of weld thermal cycle. Different factors related with welding affecting the weld thermal cycle have been elaborated. Further, the need of evaluating the cooling rate during welding of hardenable steels has also been presented.

Keywords: Weld thermal cycle, cooling rate, continuous cooling transformation, critical cooling rate

19.1 Importance

Arc welding processes involve the melting of the faying surfaces and the filler metal, if any, followed by solidification of the molten weld metal. Melting and solidification steps of welding are associated with the flow of heat and are affected by rate of heat transfer in and around the weld metal. Metallurgical structure of metal in weld and region close to the weld metal is mainly determined by the extent of rise in temperature and then cooling rate experienced by the metal at particular location of HAZ and weld. Further, differential heating and cooling experienced of different zones of weld joint cause not only metallurgical heterogeneity but also non-uniform volumetric change which in turn produces the residual stresses. These residual stresses adversely affect the mechanical performance of the weld joint besides distortion in the welded components if proper care is not taken. Since heating, soaking and cooling cycle affect the metallurgical & mechanical properties, development of residual stresses and distortion of the weld joints therefore it is pertinent to study various aspects related with heat flow in welding such as weld thermal cycle, cooling rate and solidification time, peak temperature, width of heat affected zone. Further, mechanisms of development of residual stresses and common methods relieving residual stresses apart from the distortion and their remedy will be discussed in this chapter on heat flow in welding.

19.2 Weld Thermal Cycle

Weld thermal cycle shows variation in temperature of a particular location (in and around the weld) during the welding as a function of welding time. As the heat source (welding arc or flame) approaches close to the location of interest first temperature increases heating regime followed by gradual decrease in temperature cooling regime. A typical weld thermal cycle shows (Fig. 19.1) the rate of heating (slope of a b), peak temperature, and time required for attaining the peak temperature, cooling rate (slope of b c). Since distance of the point of interest away from the weld centerline directly affects all the above parameters heating and cooling rate, peak temperature of weld thermal cycle therefore each location/point offers different and unique weld thermal cycle (Fig. 19.2). In general, an increase in distance of point of interest away from the weld centre-line:

- decreases the peak temperature
- decreases the rate of heating and cooling
- increases time to attain peak temperature
- decreases rate of cooling with increase in time

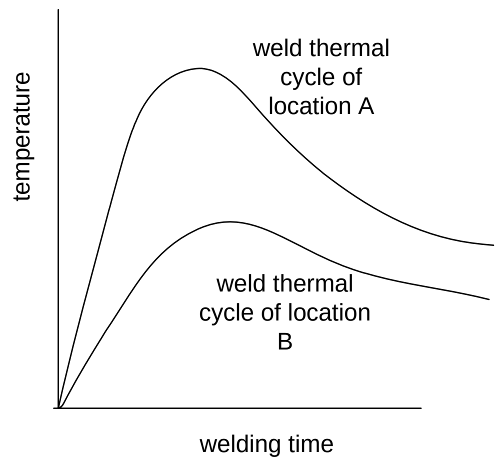

Fig. 19.1 Schematic of weld thermal cycle of two different locations away from the weld centerline

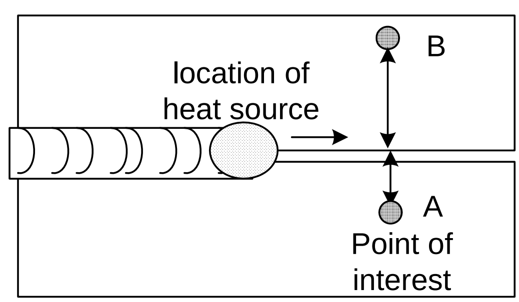

Fig. 19.2 Schematic of welding showing location of two points A & B

19.2.1 Factors affecting welding thermal cycle

However, weld thermal cycle varies with distance form the weld centre line but it is also influenced by heat input rate, amount of heat supplied for welding, weldment geometry, thermal properties of base metal and initial plate temperature. Rate of heat input is primarily governed by the energy density of heat input source which to a great extent depends upon the welding process being used for development of weld joints besides the welding parameters. High energy density processes like plasma arc welding and laser beam welding offer higher rate of heating, peak temperature and cooling rates than low energy density processes such as gas welding, shielded metal arc welding as shown in Fig. 19.3. Higher is the energy density of welding process, lower will be the heat input. Weld geometry parameters such as thickness of plates being welded also affect the heating rate, soaking time and cooling rate for a given rate of heat input (welding parameters) owing to changes in heat transfer conditions. In general, an increase in thickness of plate increases the rate of heat transfer from the weld pool/heat affected zone to the base metal which in turn a) decreases the high temperature retention time of HAZ, b) decreases the solidification time and c) increases the cooling rate experienced by the HAZ and weld metal.

Thermal properties of metal like thermal conductivity and specific heat also have affect on weld thermal cycle similar to that of thickness of plates as they increase the rate of heat transfer from the weld metal and HAZ. Preheating of the plates reduces the rate of heating and cooling and increases the peak temperature and soaking period above certain temperature because preheating reduces the rate of heat transfer away from the weld zone.

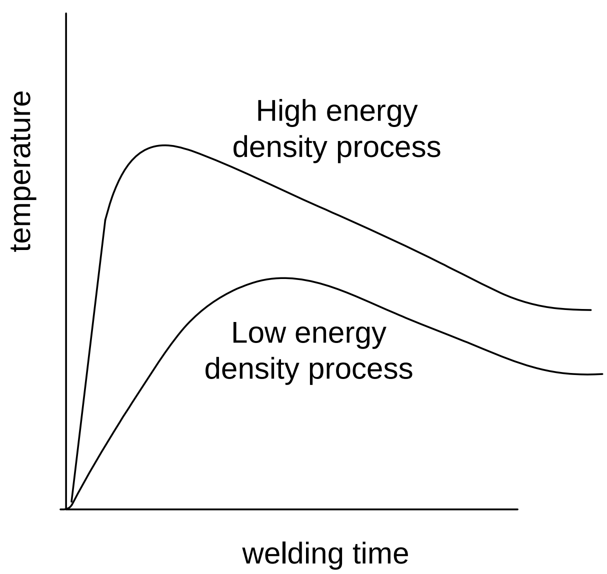

Fig. 19.3 Influence of energy density of heat source related with welding process on weld thermal cycle of HAZ.

Peak temperature near the weld fusion boundary decides the width of heat affected zone (HAZ). Heating and cooling rate affect the microstructure of weld metal and HAZ therefore weld thermal cycle of each point becomes of great interest especially in structure sensitive metals like high carbon steels.

19.3 Cooling Rate

The final microstructure of weld zone and HAZ is primarily determined by the cooling rate (CR) from the peak temperature attained due to weld thermal cycle during welding. Cooling rate above a particular temperature say 550^{o}C for plain carbon eutectoid steel is of great importance in case of hardenable steel where a cooling rate (CR) determines the final microstructure and mechanical properties of weldment and HAZ. Since microstructure of hardenable steel has direct correlation with mechanical properties therefore, structure sensitive mechanical properties are affected by the cooling rate experienced by the weld metal and heat affected zone. This is evident from the continuous cooling diagram of hypo-eutectoid steel as shown in Fig. 19.4. In the diagram, letter A, F, P, B, M indicates regions of austenite, ferrite, pearlite, bainite and martensite respectively.

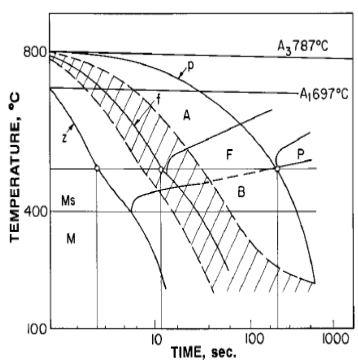

Fig. 19.4 Effect of cooling on structure of weld joints shown in form of CCT diagram (S Kou, 2003)

Weld thermal cycle indicates both heating and cooling rate. Cooling rate varies as a function of time, location of point of interest and temperature (at any moment on commencement of the cooling) during cooling regime of weld thermal cycle. The cooling rate calculation for HAZ of hardenable steel weld joint is mostly made at 550 ^{0}C (corresponding to nose temperature of CCT) as cooling rate at this temperature predominantly decides the end microstructure and mechanical properties of the HAZ and weld joint. During welding, two welding parameters dictate the cooling rate a) net heat input during the welding and b) initial plate temperature besides the thermal and dimensional properties of material being welded. In general, increases in heat input decreases the cooling rate while reverse happens with increase of initial plate temperature during welding of a given metal having specific thickness and thermal properties. An increase in both heat input and initial plate temperature raises temperature of base metal around the weld which in turn decreases the rate of transfer away from the weld zone primarily due to reduction in temperature difference between the weld zone and surrounding base metal. Reduction in heat transfer rate from the weld metal to the base metal with increase in heat input and initial plate temperature means decrease in cooling rate. In view of above, major practical application of cooling rate equation is to determine the preheat requirement for plate to be welded so as to avoid critical cooling rate in weld and HAZ.

Net heat input (H_{net}) during welding is obtained using following relationship:

$$H_{net} = f\,.VI/S$$

where V is arc voltage (V), I welding current (A) and S welding speed mm/sec and f is the fraction of heat generated and transferred to the plate.

Example

Calculate the net heat input used during welding of plates if welding of steel plate is given below:

- Welding current: 150 A
- Arc voltage: 30 V
- Welding speed: 0.5 mm/sec
- 80 % of heat generated by the arc is used for welding.

Solution

Net heat input : Hnet = f .VI/S

= 0.8 X 30 X150/0.5

= 600 J/mm

= 0.6 kJ/mm

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