An Analytical Approach for Determination of Pre-Heat Temperature

By P. K. GHOSH*

Introduction :

A plethora of base materials with widely diverse chemical and mechanical properties find application in the fabrication of equipment for the chemical and process plant industries. The range is of a variety of ferrous alloys, non-ferrous metals and alloys. Present-day concepts of fabrication of such equipment depend largely on the successful application of metal joining techniques. While non-ferrous metals and alloys are joined both by fusion and non-fusion processes, ferrous alloys are in general preferred to be joined by fusion welding. Some of these ferrous alloys pose considerable difficulties for making a satisfactory joint depending on their chemistry, design and thicknesses. An unsatisfactory joint would mean a disruption in the continuity of metallic structure of the element through the joint in the form of cracks and fissures, an unacceptable deviation of metallurgical and mechanical properties of the joined metals and surroundings or other surface or sub-surface irregularities, which may contribute to fracture or premature failure in service.

This paper will attempt to outline an analytical approach for determination of pre-heat temperatures to avoid cracks and unacceptable brittleness.

Apart from its other beneficial effects, the first and foremost advantage of pre-heat application is that it prevents cracks. Hence, it will be useful to look briefly into the problem of cracks and methods of preventing them.

Cracks :

Cracks associated with welding may be broadly classified into three categories — (1) Hot cracks, (2) Cold cracks and (3) Microfissures.

Hot crack is the incompatibility of the metal to hold at the grain or crystal boundaries mainly on account of low melting impurities while solidifying; this can mainly be ascribed to the metal chemistry. To prevent this sort of cracking, impurity levels should be kept significantly low and Manganese : Sulphur ratio is generally kept high, which also is dictated by the presence of carbon, phosphorus and perhaps nickel.

Cold cracks include under-bead cracks, toe cracks, crater cracks, longitudinal and transverse cracks. These

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cracks occur mainly on account of shrinkage stress and the stress developed by the hydrogen picked up by the heat affected zone. As the metal cools, the stresses develop to such an extent as to separate the metals at high stress region; loss of ductility due to higher cooling rate accentuates the problem.

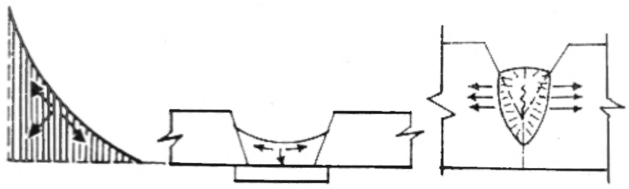


Fig 1

Causes for Weld Cracking : Weld cracks are mainly due to—

(i) Excessive joint restraint leading to high stresses in the weld.

(ii) Concavity of the deposited root bead that may result in high tensile stresses across the weld surface from toe to toe.

(iii) High depth to width ratio under high restraint will develop sufficient shrinkage stresses to generate internal cracks.

(iv) Increase in carbon and alloy content of the base metal will on dilution with weld metal accentuate weld crack due to loss of ductility when cooled faster than the critical cooling rate.

(v) A closed butt joint is also crack prone, as it imposes shrinkage stresses.

(vi) Hydrogen pick up from the electrode coating, moisture in the joint, contaminants on the surface of the base metal will promote weld cracking tendencies.

(vii) Rapid cooling rate increases the effect of (iv) and (vi).

Causes of adjacent base metal (Heat Affect Zone) cracking:

The factors affecting the adjacent base metal cracking may be summarised as :

(i) High carbon and alloy content which increases hardenability and decreases ductility on cooling.

(ii) Hydrogen embrittlement from the migration of liberated hydrogen from the weld metal and

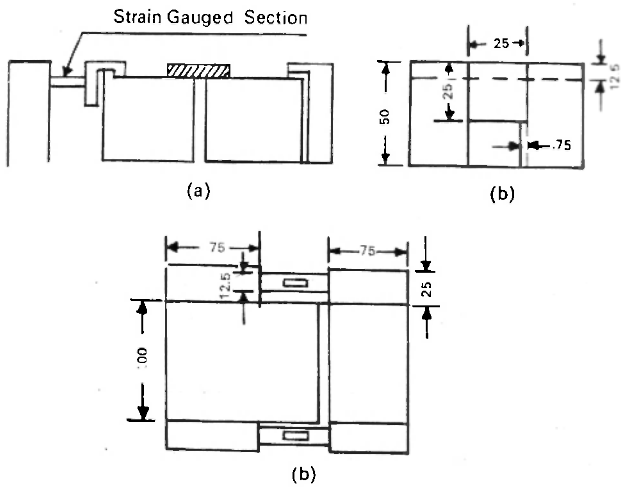
(iii) Rate of cooling which aggravates (i) & (ii).

Causes of In-service cracks: In-service cracks may occur due to

(i) Insufficient weld size,

(ii) Improper notch toughness at low temperature due to incompatible material or poor workmanship and

(iii) Fatigue cracking under unusually severe stress reversals due to notch effect of poor joint geometry.



G—BOP test to measure stress & restraint

Fig 2

Hydrogen cracking in weld metal studies by McFarlane and Graville[1] revealed that the longitudinal stress in G-BOP (Gapped Bead-on-Plate) test increases with joint restraint and weld metal transformation temperature. Except in high restraint cases, a reduction in transformation temperature due to increased alloying decreased longitudinal stresses. The final stress in G-BOP test is not likely to be influenced by the transformation characteristics for carbon equivalent less than 0.60.

Pre-heating :

Pre-heating may be necessary for one or more of the following reasons :

a To reduce shrinkage stresses in the weld and adjacent base metal particularly in highly restrained joints.

b To prevent excess hardening and loss of ductility of both the weld and HAZ through slower cooling rate in the region of critical temperature (980° — 720°C).

c To allow absorbed hydrogen to diffuse away from the weld and HAZ by providing a slower cooling rate through 210°C range to prevent under-bead cracking.

d To increase the allowable cooling rate below which no under-bead cracking will occur. Therefore, with the same welding procedure a higher initial plate temperature increases the maximum safe rate of cooling whereas the cooling rate is actually slowed down. This obviously tends to make the welding heat input less critical and consequently the range increases. Cottrell and Bradstreet[2] have shown the following critical welding rates (Rcr) for a given steel at 390°C using low hydrogen electrodes in order to prevent under-bead cracking :

Initial Plate Temperature (°C)	Critical Cooling Rate (°C/sec)
– 50	3.8 — 5.5
20	4.8 — 6.5
100	12 — 21

e To increase the notch toughness in the welding zone, and

f To lower the transition temperature of the weld metal and HAZ.

Even a couple of decades ago, pre-heat temperatures were normally decided on empirical formulae and thumb rules. One of the frequently used formula for plain carbon steel is given as
pre-heat in °F = 100 (%C — 0.10) + 18 × thickness of plate in inch. Present-day understanding of physics of welding has shifted the attention to heat input, critical cooling rate, carbon equivalent and joint restraint.

Heat Input :

The weld heat input has a predominant influence on the selection of pre-heat temperature. The heat input in a specific welding procedure is given by

$$H = 60 \times \frac{E \times I}{V}, \text{ where}$$

E — Arc Voltage in Volts,
I = Welding Current in Amps, and
V = Travel Speed of the Arc.

The unit of heat input works out to Joules/mm and Watt-sec/mm in metric and Joules/inch and Watt-sec/inch in BTU. The heat generated by the arc is not transferred to the plate in its entirety. For manual arc welding, some heat is lost by convection through the arc atmosphere and radiation. The heat transfer efficiency for MMAW is usually in the region of 75 to 80% and for submerged arc welding between 85 and 97%. Expressed mathematically, net heat input in the plate —

$$H_{net} = (0.75 \text{ to } 0.80) \times H \text{ for MMAW}$$
$$H_{net} = (0.85 \text{ to } 0.97) \times H \text{ for SAW.}$$

The pre-heat considerations for MMAW are generally based on welding procedures having a H_{net} = 0.3 kJ/mm to 3 kJ/mm, which mainly depends on the arc length (arc voltage), impurity, type of electrode used (all types of electrodes do not develop the same arc voltage for a particular length) and travel speed, whereas with SAW procedures, the H_{net} varies between 0.8 kJ/mm to 10 kJ/mm.

Peak Temperature :

The heat input concept also leads to an interesting deduction which will indicate peak temperature attained at different distances of the plate from weld fusion boundary. Depending on the metallurgy of the base metal, we may prescribe a peak temperature value below which structural transformations are not likely to occur — in short, the width of the HAZ. The peak temperature equation is given by Adams Jr[3] as

$$\frac{1}{T_p - T_o} = \frac{4.13\, PC\, tY}{H_{net}} + \frac{1}{T_m - T_c}, \text{ where}$$

T_p = Peak temperature in °C at a distance Y from weld fusion boundary.
T_o = Initial temperature of sheet or plate.
T_m = Liquidus temperature of metal to be welded.
H_{net} = Net heat input.
PC = Volumetric specific heat of the metal in J/mm³. °C.
t = Thickness of sheet or plate.

Example : Suppose E = 24V, T_p = 730°C
I = 180 amps, T_o = 30°C
V = .3 mm/sec, T_m = 1510°C

Heat transfer efficiency = 0.8 PC = 0.0044 J/mm.
i.e., H_{net} = 1152 J/mm.

The peak temperature in this instance has been chosen as 730°C since in most of the plain carbon and low alloy steels, there is a distinct etching boundary revealed on polished and etched weld cross-section, corresponding to a peak temperature of 730°C. The distance of this etching boundary from the line of fusion has been assumed as the width of HAZ.

Applying the peak temperature equation,

$$\frac{1}{730-30} = \frac{4.13 \times .0044 \times 10 \times Y_{HAZ}}{1152} + \frac{1}{1510-30}$$

$$\text{Or, } Y_{HAZ} = 4.8 \text{ mm}$$

Hence, HAZ etching boundary will be located at a distance of 4.8 mm from the fusion boundary.

Now let us look at another example of quenched and tempered steel, tempered at 450°C. Here, the metal within the distance from the fusion boundary that has reached a peak temperature of 450°C will be over-tempered. Hence, width of the base metal adjacent to the fusion boundary that has undergone structural change will be

$$\frac{1}{450-30} = \frac{4.13 \times .0044 \times Y_{HAZ}}{1152} + \frac{1}{1510-30}$$

$$\text{Or. } Y_{HAZ} = 10.8 \text{ mm.}$$

These steels are normally welded under pre-heat. Let us examine how a pre-heat of say 200°C (T_o) will affect the width of HAZ

$$\frac{1}{450-200} = \frac{4.13 \times .0044 \times Y_{HAZ}}{1152} + \frac{1}{1150-200}$$

$$\text{Or, } Y_{HAZ} = 20.5 \text{ mm.}$$

The pre-heat has almost doubled the HAZ width.

Cooling Rate :

During and after welding, the weld metal and the adjacent base metal cool very rapidly. The cooling rate depends on a combination of factors such as :

(i) Initial plate temperature (T_o) which includes cumulative effect of pre-heat and interpass temperatures,
(ii) Weld heat input (H_{net})
(iii) Plate thickness and
(iv) Joint geometry.

As the welding arc passes by, under a given set of conditions, the change in the temperature of HAZ is shown in FIG. 3. It will be observed that pre-heat significantly decreases the cooling rate at a given temperature.

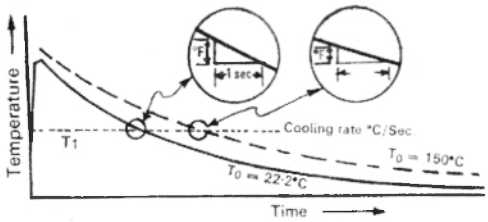


Fig 3

For a particular chemistry of the metal, there is a critical cooling rate (R_{cr}) at a given temperature level (T_1) below which under-bead cracking is generally avoided. The given temperature level is accepted as 300°C for safe practice, since it is generally believed that rate of cooling below that temperature does not affect the metal significantly.

The cooling rate investigations have been based, by and large, on two mathematically developed equations by Rosenthal on two extreme conditions :

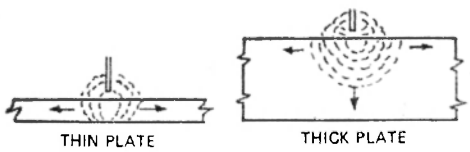


Fig 4

Thin plate equation — The applied heat is assumed to flow in two axes transversely.

$$R = 2\pi \text{ K.P.C.} \left(\frac{t}{H_{net}}\right)^2 (T_1 - T_o)^3$$

Thick plate equation — The applied heat is assumed to flow in three axes, i.v. transversely and through the thickness

$$R = 2\pi \text{ K.} \left(\frac{T_1 - T_o}{H_{net}}\right)^2$$

Here: R = Cooling rate, T_1 = Temp. level at with R is considered.

T_o = Initial plate temperature.

K = Thermal conductivity at T_o

P = Density.

C = Specific heat of the metal.

H_{net} = Heat Input.

There is no clear indication as to where the thin plate or thick plate equation is to be used. One approach is to find out an empirical constant given by

$$\tau = t\sqrt{\frac{\rho C(T_1 - T_o)}{H_{net}}},$$

where if τ is 0.9 or more, the use of thick plate equation and when τ is 0.6 or less, thin plate equation will be justified. But this leaves us a gap between 0.6 and 0.9. Hence, instead, if we accept the average value of 0.75 above which to use thick plate equation and below which the thin plate equation, we might be approaching a practical solution. By applying this rule it may be observed that the cooling rate for quite thick plates welded by submerged arc process using high H_{net} has to be calculated by using thin plate equation. This tallies fairly with our experience.

So far we had been considering bi-thermal heatflow as in the case of butt joints. In the case of tri-thermal heatflow when the heat has three avenues for escape as in the case of a tee joint, some modifications are needed. The modifications to be incorporated in the foregoing equations are — (a) using 2/3rd of H_{net} and (b) adjusting plate thickness to half the sum of three thicknesses along the avenue of heatflow. These considerations will afford enough safety for practical applications.

Carbon Equivalent

Carbon and other alloying elements contribute to the hardenability of the metals. ASME has grouped the various plain carbon and alloy steels in "P" groups based mainly on the hardenability. The hardening of HAZ due to cooling impairs its ductility making it crack-prone.

The carbon equivalent is determined by adding proportionate percentage of various alloying elements with the percentage of carbon present. There are at least 14 different CE formulae and one currently recommended formula is

$$CE = C\% + \frac{Mn\%}{4} + \frac{Ni\%}{20} + \frac{Cr\%}{10} + \frac{Cu\%}{40} - \frac{Mo\%}{50} - \frac{V\%}{10}$$

In some recent investigations by Cottrell and Bradstreet, carbon equivalent has been tied to the critical cooling rate by the equation

$R_{cr} = \frac{6.598}{CE - .3074} - 16.26$, where R_{cr} is the critical cooling rate at 300°C. Hence, R_{cr} can also be determined from the results of CE.

CE	Rcr in °F/sec.
0.40	57.6
0.45	36.0
0.50	19.8
0.55	10.8
0.60	7.7
0.65	3.6

There also exists some relations between the actual plate thickness, effective plate thickness, heat input and cooling rate. They are given as

$$\frac{t}{t_{me}} = \sqrt{\tfrac{1}{2}\left(\frac{T_1 - T_o/me}{T_1 - T_o}\right)^3} \quad \text{for thick plate, and}$$

$$\frac{t}{t_{me}} = \sqrt{\frac{T_1 - T_o/me}{T_1 - T_o}}\left[1 - \frac{1}{\sqrt{2}}\sqrt{1 - \left(\frac{T_1 - T_o/me}{T_1 - T_o}\right)^2}\right]$$

and $T_1 - T_o/me = \sqrt{\frac{R_{cr} H_{net}}{5.961}}$, where

t = actual plate thickness in inches

t_{me} = maximum effective plate thickness in inches of given values of H_{net}, and

R_{cr} and this is obtained from

t_{me} = $.42457\sqrt[4]{\frac{H_{net}}{R_{cr}}}$

T_1 = 572°F, i.e., the temperature at which the cooling rate is considered.

T_o = pre-heat temperature dependant on R_{cr} H_{net} and t,

T_o/me = maximum effective pre-heat temperature dependant on H_{net} and R_{cr}.

Calculation of Pre-heat and Interpass Temperature

A. Find out Ceq. from Ceq. formula.

B. Determine R_{cr} from $R_{cr} = \frac{6.598}{Ceq - 3076} - 16.26$

C. Work out $T_1 - T_o/me$ from

$$T_1 - T_o/me = \sqrt{\frac{R_{cr}(H_{net})}{5.961}}$$

D. Determine t_{me} from $t_{me} = .42457\sqrt[4]{\frac{H_{net}}{R_{cr}}}$ and then $\frac{t}{t_{me}}$.

E. Graph, Fig. 5, to be used for finding the value of $\frac{T_1 - T_0/me}{T_1 - T_0}$

F. From the value obtained from graph find out required pre-heat temperature.

Example ; Say :

H_{net} = 20000 J/inch.

R_{cr} = 25°F/Sec. — This value is obtained from Ceq. formula.

t = 1 inch.

Steps: A & B have been included in finding out H_{net} & R_{cr}.

Step C $T_1 - T_0/me = \sqrt{\frac{25 \times 20000}{5.961}}$ =289.6°F

Step D $t_{me} = .42457 \sqrt[4]{\frac{20000}{25}}$ =2.26 inches

i.e $\frac{t}{t_{me}} = \frac{1}{8.26} = .4429$

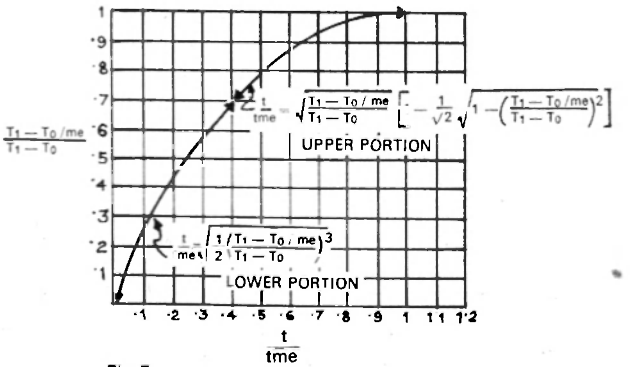


Fig 5

Step E From figure 5

$\frac{T_1 - T_0/me}{T_1 - T_0} = 0.73$

Step F $T_1 - T_0 = \frac{289.6}{0.73} = 396.7°F.$

Therefore, T = 176.3°F (T_1 = 572°F)

In practice, the pre-heating should be well spread around the joint to be welded. A good rule will be to spread the heat approximately to a 3" width along the adjacent base metal of the joint and a slower cooling rate after completion of the weld. This will allow a considerable diffusion of the trapped hydrogen.

Pre-heating renders the other factors less critical, but the involved cost of slower production rate calls for its application only when absolutely necessary. Over and above, higher-pre-heat temperature may even adversely affect the tensile trength of the joint and promote a coarse grain structure at the HAZ.

Methods of Pre-heating

Normally pre-heating is done by the application of oxy-fuel or air-fuel torch before the start of the welding. The temperature is checked by a temperature measuring crayon, some material melting at that specified temperature or any contact thermometer designed for the purpose. Although this method is almost universally applied, for highly hardenable materials, particularly those which may dictate the maintenance of pre-heat temperature till the start of the post-weld heat treatment, the use of more sophisticated methods will be essential. This will include heating by resistance elements or induction heating under insulation wrapping with thermo-couples placed at selected locations for temperature monitoring. In recent years, use of radiant heat produced by oxy-fuel burning through a number of small orifices is also used with some degree of advantage.

Conclusion

Pre-heating should not be applied indiscriminately since it makes the procedure uneconomical. The pre-heating temperature may be determined analytically from the information obtained from a given set of welding procedures. Judicious application of pre-heat will reduce cracking tendencies, allow less shrinkage stresses to be built up and help in the escape of diffusible hydrogen from the weld and HAZ.

References :

1. McFarlane M and Graville, B.A. — Hydrogen Cracking in Weld Metal — Welding Journal, Volume 55(4), 95S — 102S.
2. Cottrell and Bradstreet — Effect of Pre-Heat on Weldability — British Welding Journal, July 1955 — 309.
3. Adams CM JR — Cooling Rate and Peak Temperature in Fusion Welding — Welding Journal 1958 — Volume 37(5) 210S — 215S.
4. Rosenthal D — The Theory of Moving Source of Heat and Its Application to Metal Treatment — Transaction ASME 68 : 819-866.
5. West, Oha — Temperature Distribution in the Work-Piece by Welding — Document 212 — 144-68, 1968 — Institute for Mekanisk Teknologi, Ved Norges Tekniske Hogskole, Trondheim.
6. Welding Handbook Volume 1, 7th Edition AWS.
7. Design of Welded Structure — Omar W Blodgett.