Some Metallurgical Aspects of Welding of Chromium-Molybdenum Creep-Resistant Steels

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ABSTRACT

Cr-Mo creep resistant steels are used specially for power tubines and pipings due to their long term creep resistant properties at elevated temperatures and pressures. Welding is commonly required to join the different structural components made of this steel. Therefore weld joints should also possess required properties at elevated temperatures, which depend on correct choice of filler material, preheat treatment, post heat treatment and welding technique used. Possible failures of weld joints and their remedies have been discussed. Various welding processes for these steels are also reviewed.

1. INTRODUCTION

Cr-Mo steels are widely used in power piping where they operate at high pressure (35 to 70 MN/m^2) and temperatures[1] (between 250-600°C). These steels are used because they maintain their high strength at elevated temperatures. Further, they do not deform or creep under prolonged periods of use at high temperatures. Besides this, they also do not become brittle after long period of high temperature service. Carbon steels on the other hand, do tend to stretch at high temperature service and become brittle after certain time of use. So, creep resistant steels are preferred[2]. Welding of these steels requires great care as welded parts are also subjected to adverse conditions of high pressure and temperature. Therefore a detailed study of microstructures, possible failure during welding, and heat treatments that are to accompany the welding processes is essential for satisfactory application of the Cr-Mo creep resistant steels.

2. Cr-Mo STEELS AND THEIR JOINING

These steels are ferritic in nature and are of air hardening type. The ultimate strength of Cr-Mo creep resistant steels varies from 590 MN/m^2 to 940 MN/m^2 at ambient temperature. In Table-I. the compositions of some standard Cr-Mo steels are summarised. Joining of these steels involves high temperature fusion of weld metal. The pool of molten metal formed at high temperature cools rapidly. It is comparable to a small casting wherein molten metal solidifies in a very short time, as a result of which the chemical reactions are suppressed. Due to rapid cooling of metal through transformation temperatures, an increase in hardness occurs together with loss in ductility. This is due to the formation of matensitic structure[3] in heat-affected zone (HAZ). Therefore, in joining of these steels, great care is required to avoid the chances of formation of this hard microstructure in base material and HAZ.

3. FAILURES IN WELDED JOINTS

In fact, problem of welding in these steels arises due to the high temperature of welding, which in turn alters the mechanical properties around the welded area unfavourably and may cause premature failures. The possible types of failures in welded joints of Cr-Mo steels are (a) Hot cracking, (b) Brittle failure and (c) cold cracking.

3.1 Hot Cracking

It consists of microcracks very near the fusion line. When the molten pool solidifies, the low melting non-metallic inclusions segregate in the immediate vicinity of the fusion line and may result in microcracks. Narrow beads with deep penetration are particularly susceptible to hot cracking.

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Table I : Compositions of some of Cr—Mo Steels.[8]

Sl. No.	Type	C	Mn	Si	Cr	Mo (in weight percent)
1.	½ Cr—½ Mo	0.1—0.2	0.3—0.6	0.1—0.3	0.5—0.81	0.44—0.65
2.	1 Cr—½ Mo	0.15 max.	0.3—0.6	0.5 max.	0.8 —1.25	0.44—0.65
3.	1.25 Cr—½ Mo	0.15 max.	0.3—0.6	0.5—1.0	1.0 — 1.5	0.44—0.65
4.	2 Cr—½ Mo	0.15 max.	0.3—0.6	0.5 max.	1.65—2.35	0.44—0.65
5.	2.25 Cr—1 Mo	0.15 max.	0.3—0.6	0.5 max.	1.90—2.60	0.87—1.13
6.	3 Cr—1 Mo	0.15 max.	0.3—0.6	0.5 max.	2.80—3.20	0.87—1.13
7.	5 Cr—½ Mo	0.15 max.	0.3—0.6	0.5 max.	4.80—5.30	0.44—0.65

3.2 Brittle Failure

This type of failure occurs in large welded structures. It is sudden and catastrophic in nature. It usually starts from a small pre-existing defect or notch and propagates quickly, without indication of any ductility in the component.

3.3 Cold Cracking

This defect is also called hydrogen induced cracking (HIC) because it is caused by the presence of hydrogen in electrode. This is also called "under bead cracks", since it appears in the parent plate just below the fusion zone. This is the zone of highest hardenability. Any reaction which produces hydrogen is dangerous to these steels. If any trace of martensite forms during cooling, it results in transient cracks. Actually, the mobile atomic hydrogen goes into the transient cracks at the instant of martensitic formation and stabilizes the cracks even at room temperature. It is well undertsood that conversion of atomic hydrogen to molecular form generates hydrogen pressure in these cracks, which is high enough for expansion of these cracks[4,5,6]. It may be stated that cold cracking occurs due to the formation of martensite plates and hydrogen present at high temperature. If these conditions can be checked, cold cracking can be avoided. HIC depends upon the following factors :

3.3.1 *Carbon equivalent of steel*

Carbon equivalent (C.E.) value is specified (BS 4360) to fix the limit of carbon and alloy content in regard to welding. C.E. is given by the following formula :

$$CE=C+\frac{Mn}{6}+\frac{Cr+Mo+V}{5}+\frac{Ni+Cu}{15}$$

If CE is less than 0.14, no special precautions are necessary with rutile electrodes.

When CE is greater than 0.45, use of low hydrogen electrodes and preheat is required.

When CE lies between 0.14 and 0.45, use of low hydrogen electrodes and/or preheat is required.

Higher the C.E., the harder will be the HAZ with increased risk of cracking.

3.3.2 *Thickness of section*

The thicker the plate, the faster is the rate at which heat is extracted from the weld joint and HAZ. Consesequently, the rate of cooling and the risk of cracking increases with increase in plate thickness. Depending on the configuration of weld joint, the effective thickness of the section responsible for cooling varies.

3.3.3 *Heat input rate*

Higher the heat input rate and/or higher the preheating and interpass temperature, the slower will be the cooling of HAZ. Consequently lesser will be the chances of cracking in welded joints and HAZ.

Heat input rate is given by the formula ;

$$\text{Arc Energy}=\frac{V\times A\times 60}{S}\ \text{Kilojoules per mm.}$$

Where 'V' stands for arc voltage.
'A' stands for welding current.
and 'S' stands for arc travel speed (mm/min).

3.4 Solidification cracking

It is associated with presence of sulphur and phosphorous in parent and weld metal. Hence there is need for close and careful control of phosphorus and sulphur in the parent metal and the weld metal. It occurs in HAZ. Basic coated electrodes are more resistant to sulphur induced weld metal cracking than rutile electrodes.

4. REMEDIAL ACTIONS

The various techniques employed to minimize the cracking of weld joints are :

(i) Use of correct filler material.
(ii) Pre heat-treatment, and
(iii) Post weld heat-treatment.

4.1 Use of Correct Filler Material

Use of correct filler material is very essential in welding of Cr-Mo steels. Otherwise, weld defects may appear in weld joints. Following points are important when choosing filler material for welding :

(i) The coefficient of thermal expansion of weld metal from the electrode should be close to that of the base metal to check differential stresses[7], which may develop during rapid cooling of weld joint from high temperature. So the weld metal selected should have the same nominal composition as the base material. For example, a nominal ½ Cr—½ Mo weld metal can be used for welding of base meterial of ½ Cr—½ Mo.

(ii) Carbon migration is one of the characteristics of Cr—Mo steels. It is observed[8] that carbon migration takes place from lower to higher chromium content material at service temperature above 540°C. To avoid this problem, it is advisable to use filler metal with preferably same chomium content as the base metal.

For shielded metal arc welding, the electrode suffix is the key to match the weld metal with the base metal. the suffixes starting with B are the Cr—Mo steels ranging from B_1 with ½ Cr—½ Mo upthrough the B_4 for the 2.25 Cr—½ Mo. The higher levels of chromium are not specified by means of suffix system. Proprietary electrodes are available for higher Cr—Mo steels. In Table II, recommended electrode suffixes are summarised.

Table II : Recommended Electrode Suffix of some Cr—Mo Steels[8]

Sl. No.	Type	Recommended electrode suffix
1.	½ Cr—½ Mo	B_1
2.	1 Cr—½ Mo	B_{2L}
3.	1.25 Cr—½ Mo	B_{2L}
4.	2 Cr—½ Mo	B_{4L}
5.	2.25 Cr—1 Mo	B_3

4.2 Pre-Heat Treatment

This is an important aspect of welding of Cr-Mo steels, when cracking of the weld metal or HAZ is a problem. It is essentially raising of the temperature of the entire part or area of the weld, to a temperature above that of the surroundings. Its purpose is to produce a slower and therefore more even cooling. The preheat must be sufficiently high to prevent the formation of the hard, brittle martensitic structure in the weld metal and HAZ. The desired structure is a low temperature intermediate transformation product. Pre-heat temperature should be close to the martensitic transformation temperature to minimise the effect of martensite on ductility. Section thickness also affects the pre heat temperature. As the section thickness increases, the minimum pre-heat temperature must be increased to eliminate the greater quenching effect of thicker cross-section.

Pre-heating temperatures range from a minimum of 38°C to as high as 370°C. Pre-heat temperature depends upon the carbon content and thickness of the material being welded. If carbon content is around 0.05%, section thickness is 9.5 mm, the minimum 38°C pre-heat can be used. If carbon is above this figure and wall thickness is greater, then the temperature should be increased correspondingly. For higher Cr-Mo steels and thicker sections, the preheat will be upto 370°C. Preheat temperature can be considerably lowered by using consumables of 'extra low' hydrogen rating and higher heat input rate. Preheat temperatures may be reduced by 40°C when low carbon Cr-Mo filler metals are used. When electrodes with low carbon content are used, the as-welded ductility increases as shown in Fig. 1. Table III shows the recommended pre-heat temperatures for various Cr-Mo steels.

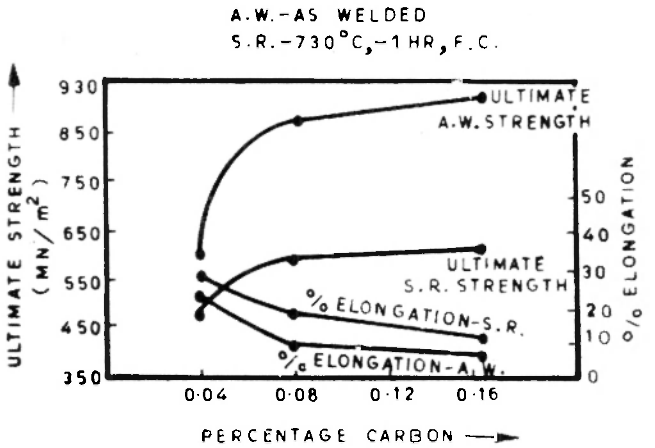

Fig. 1. Effect of Carbon Content on the room temperature mechanical properties of 2.25 Cr—1.00Mo weldmetal.

Chemical analysis of the weld metal and the base material are further factors to be considered in determining the minimum pre heat temperature. In calculating the preheat temperature, the following steps are involved[9] :

Step-1. Determination of the chemical carbon equivalent "$(C)_c$" of the Cr-Mo steel.

Step-2. Determination of the carbon equivalent for plate thickness, which is given by ;

$$(C)_t=(1+0.005\ t)$$

Where 't' is thickness of the plate in mm.

Step-3. Determination of the total carbon equivalent by the formula

$$(C)_T=(C)_c+(C)_t$$

Step-4. Calculation of pre heat temperature from the relation ; $T_{(oC)}=350\,(\sqrt{(C)_T}-0.25)^{1/2}$

Table III : Recommended minimum pre heat temperature (°C) for welding Cr-Mo steel[8]

Sl. No.	Type	Thickness upto 12.7 mm.	 12.7 to 57 mm.	 Over 57 mm.
1.	½ Cr—½ Mo	20	94	150
2.	1 Cr—½ Mo	120	150	150
3.	1.25 Cr—½ Mo	120	150	150
4.	2 Cr—½ Mo	150	150	150
5.	2.25 Cr—1 Mo	150	150	150
6.	3 Cr—1 Mo	150	150	150
7.	5 Cr—½ Mo	150	150	150

4.3 Post Weld Heat Treatment

The post weld heat treatment of a welded joint or part may consist of stress relieving heat treatment, annealing, normalizing, hardening, hardening and tempering, and/or martempering.

The American Welding Society defines stress-relief heat treatment as "the uniform heating of a structure to a suitable temperature below the critical range of the base metal, followed by uniform cooling".

The temperature at which the stress relief is performed for welded power boilers and unfired pressure vessels is prescribed by the boiler constuction code of the American Society of Mechanical Engineers.

The post weld heat treatment depends upon application size, shape and chemical analysis of the weldment and requirements of governing codes[10]. Depending on the conditions in which these welds are placed in service, the prescribed heat treatments are :

(i) no special heat treatment, the preheat temperature having been employed to obtain weldment ductility.

(ii) a subcritical stress relieving treatment in the temperature of 590 to 740°C, and

(iii) an annealing heat treatment of the complete weldment.

The subcritical postweld stress-relieving heat treatment is employed to increase the ductility of the weldmetal and HAZ of the base metal.

The primary aim of the post weld heat treatment is to check the formation of undesirable martensitic structure in weldment and HAZ, which would otherwise cause fracture failure. Martensite formation can also be avoided by sufficiently high preheat temperature (about 250°C) and limiting the maximum hardness of the weld and HAZ to a value of about 250 VPN. Thus, if sufficient ductility is ensured by preheat treatment, the postweld heat treatment can be avoided. The ASA code for pressure piping, does not specify postweld treatment of Cr—Mo steels as essential. The requirement of heat treatment depends upon the maximum hardness of weld and HAZ for different material groups.

In some cases, such as the welding of large fabrications on site, it is difficult to apply postweld heat treatment due to the risk of damage of parts. For example, in case of fixed tube sheet exchangers, stress relieving of complete exchanger with tubes welded at both sides involves the risk of damaging tube joints due to uneven thermal expansion. Other methods involve stress relieving after the tubes are welded to one tube sheet only followed by welding of tubes on the other side and again stress relieving by introducing the exchanger partially into the furnace. But it involves extra time, expense and the risk of scaling of the tube holes and tube surfaces at the free end which might impair expansion and/or welding. Use of sufficiently high preheat treatment temperature gives the satisfactory ductility in the weld joint and HAZ. For example, tests have been carried out without problem on plain buttwelds in 8 mm. thick 1 Cr—$\frac{1}{2}$ Mo steel using preheat of 250°C without any postweld treatment. It has been possible to get hardness in the weld and HAZ less than acceptable value[11] of 250 VPN.

Therefore, if desired properties can be achieved by pre heat treatment, post weld heat treatment can be avoided. Recommended post weld heat-treatment temperature ranges for Cr—Mo steels are given in Table IV.

Table IV : Recommended postweld heat-treatment temperature (°C) ranges for Cr-Mo steels[8]

Sl.No.	Type	Temperature range (°C)
1.	$\frac{1}{2}$ Cr—$\frac{1}{2}$ Mo	590—700
2.	1 Cr—$\frac{1}{2}$ Mo	650—730
3.	1.25 Cr—$\frac{1}{2}$ Mo	675—745
4.	2 Cr—$\frac{1}{2}$ Mo	—
5.	2.25 Cr—1 Mo	675—760
6.	3 Cr—1 Mo	675—760
7.	5 Cr—$\frac{1}{2}$ Mo	700—760

5. WELDING PROCESSES

The major welding processes used for welding of Cr-Mo steels are : shielded metal arc welding, gas metal arc welding, submerged arc welding and electroslag welding[12,13]. Comparative details of these processes are given in table V. Besides this, atomic hydrogen welding, induction and electron beam welding processes are also employed. Electron beam welding has been successfully employed for welding of pressure vessels.

Table—V : Major welding processes used for welding of creep resistant steels

Sl. No.	Shielded Metal Arc Welding	Gas Metal Arc Welding	Sub-merged Arc Welding	Electroslag Welding
1.	**Heat for Welding**			
	An arc is produced between the flux-covered consumable electrode and the part to be welded.	An arc is struck between the filler metal and the work piece which, in turn supplies heat.	The heat for welding is supplied by an arc between the consumable electrode and the base metal to be welded.	The heat of welding is supplied by resistance offered to the current during its passage from electrode wire through the slag into the weld pool.
2.	**Protection from Oxidation**			
	The molten pool is protected from atmospheric oxidation by gas shield supplied by the decomposition of the flux coating during combustion. Additional shielding is supplied by the molten slag.	Since the filler metal is bare wire, the work piece must be protected from oxidation by a gas or mixture of gases. The shielding gas usually employed for this process is carbon-dioxide or an argon carbon-dioxide mixture.	Work piece is protected from oxidation or other contamination by a layer of granular flux. The molten weld pool made up of the molten metal and molten flux is highly conductive and conducts the electricity from the arc to the base metal. In addition to acting as protective shield, flux may supply alloying elements, deoxidisers, and scavangers which react with weld metal.	The molten slag pool acts both as heat source and shielding agent. Most fused salts used as basic flux become increasingly electrically conductive as their temperature is raised. The depth of slag is critical and has a bearing on the quality of the weld.

Sl. No.	Shielded Metal Arc Welding	Gas Metal Arc Welding	Sub-merged Arc Welding	Electro-slag Welding
3.	**Filler Metals** The filler metal comes from the center or core of the electrode. Low hydrogen electrodes (ASTM specification 316) (EXX18) are recommended. The high cellulose (EXX10 and EX-11) and high titania (EXX-13) electrodes should be used only with ½ Cr—½ Mo steels.	The most commonly employed filler metals deposit 1.25 Cr—½ Mo or 2.25 Cr-1 Mo analyses. The filler metals are similar to those for submerged arc welding except that the silicon content nominally is 0.50% or greater. The 5 Cr-½ Mo solid wire filler metal is designated as class ER-502 of ASTM specification A371 or AWS specification A5.9.	The most commonly employed fillers are 1.25 Cr—½ Mo and 2.25 Cr-1 Mo weld metals. These metals are not listed in ASTM or AWS specifications. The 5 Cr-½ Mo analysis filler metal is occasionally employed and is designated as class ER-502 of ASTM specification or A371 AWS A 5.9.	The filler metal is of same normal chemical composition as the base meterial used.
4.	**Positioning** It can be used in nearly any position, overhead, vertical or horizontal. It can be used in almost every kind of joint.	It can be used for flat or horizontal positions.	The process can be used on nearly any tnickness of the metal. The process is restricted to horizontal & flat positions to avoid run-off of the flux.	This process is used for welding of 7.6 cm thick sections or greater cross-sections. The plates to be welded are kept in vertical position and the welding process can be compared with continuous casting.
5.	**Design of Weld Groove** The weld groove must be designed to accommodate the comparatively large volume of slag characteristic of low hydrogen electrodes.	The design of weld groove in this process is usually determined by accessibility requirements of welding torch. Because the groove must be wide enough for the torch head and its gas cap, it usually requires a greater width at the base than covered electrode weld grooves.	The groove of Cr-Mo steels is designed to employ a minimum quantity of weld metal following sound welding procedures.	The electroslag weld groove design consists of squared material edges set approximately 3.1 cm apart. Thermally cut surfaces from which oxide has been removed to prevent oxidation and porosity of weld metal may be used.
6.	**Pre or Post Heat Treatment** May require pre heating or post weld heat treatment to prevent cracking.	Thermal post weld heat treatment may be suspended for thin cross-section in alloys upto and including 2.25 Cr-1 Mo steels.	Requirements of pre heat and post weld heat treatments are same. the ½ Cr-½ Mo steel with cross-section ⩽12.5 mm. can have the weldment lowered to room temperature prior to post weld heat treatments.	The large quantities of heat generated during this process pre heats the base material ahead of the actual welding process and in effect forms a stress relief. The weldment can be cooled to room temperature before postweld treatment.

6. CONCLUSION

Cr—Mo steels are used in thermal power plants as pressure vessels and pipe lines due to their inherent properties. Welding is commonly used for fabrication of pressure vessels and pipe lines. Therefore welded joints in these assemblies are also required to have properties comparable with base material so that the assembly can be used without any danger of failure. Choice of filler metal, pre heat and/or post weld treatment and welding process play a crucial role in this context.

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