Studies on P91 Steel

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Abstract— Chromium – Molybdenum steels are used mainly in power plants, fertiliser plants and oil refineries at service temperatures up to 704°C. They are distinguished from other low- alloy steels by their remarkable oxidation resistance, resistance to sulphide corrosion and high – temperature strength or creep resistance. These properties are derived from Cr and Mo and they improve with the increase of these alloying elements. There are NINE standard types as shown in Table 1 along with their chemical compositions. It is seen that the Mo content is either around 0.50 or 1.0% according to the Cr content of the steel. The 2.25Cr –1Mo steel has the best thigh temperature strength. They are usually supplied in the annealed or normalised and tempered condition.

Keywords: P91 Steel, Chromium- Molybdenum Steels, PWHT

I. Introduction

A. P91 Steel

These Cr-Mo steels are air – hardened steels and undergo microstructural transformations that depend on the rate of cooling from above the upper critical temperatures. The mechanical properties are dependent on these transformations. With faster cooling rate, strength and hardness increase and ductility is reduced. However because of the lower carbon content (0.15% maximum), carbides are present in limited amounts and this results in higher ductility at any given strength level than obtained from high- carbon steels.

II. Chemical composition

A. Nominal Chemical Composition of Chromium-Molybdenum Steels

Type	C	Mn	S	P	Si	Cr	Mo
0.5Cr- 1/2 Mo	0.10- 0.20	0.30-0.60	0.045	0.045	0.10-0.30	0.50-0.80	0.45-0.65
1Cr- 1/2 Mo	0.15	0.30-0.60	0.045	0.045	0.50	0.80-1.25	0.45-0.65
1.25Cr-1/2 Mo	0.15	0.30-0.60	0.030	0.045	0.50-1.00	1.00-1.50	0.45-0.65
2Cr –1/2 Mo	0.15	0.30-0.60	0.030	0.030	0.50	1.65-2.35	0.45-0.65
2.25Cr –1Mo	0.15	0.30-0.60	0.030	0.030	0.50	1.90-2.60	0.87-1.13
3Cr –1Mo	0.15	0.30-0.60	0.030	0.030	0.50	2.65-3.35	0.80-1.06
5Cr –1/2 Mo	0.15	0.30-0.60	0.030	0.030	0.50	4.00-6.00	0.45-0.65
5Cr –1/2 Mo Si	0.15	0.30-0.60	0.030	0.030	1.00-2.00	4.00-6.00	0.45-0.65
5Cr –1/2 Mo Ti	0.15	0.30-0.60	0.030	0.030	0.50	4.00-6.00	0.45-0.65
7Cr –1/2 Mo	0.15	0.30-0.60	0.030	0.030	0.50-1.00	6.00-8.00	0.45-0.65
9Cr – 1Mo	0.15	0.30-0.60	0.030	0.030	0.25-1.00	8.00-10.00	0.90-1.10

When these steels get heated above their transformation temperatures in operations like rolling, forging, hot forming and welding with consequent loss in ductility and toughness due to their air- hardening characteristics, they require further heat treatment to restore these useful mechanical properties. The alternate types of heat treatment applied are:

a) Annealing
b) Normalising and tempering
c) Quenched and tempering
d) Simply tempering.

(a),(b) or (c) restore proper grain size and confer mechanical properties as desired, (a), (b) provide enough strength to meet the design requirements of ASME Boiler and Pressure Vessel Code. (d) is employed to soften the hardened HAZ of a welded joint. The postweld heat treatment of welded joint in Cr-Mo steels consist of heating them to a temperature below the lower critical temperature (approximately 760°C), holding it for a proper length of time and cooling in still air. It not the martensite but also relieves the locked up stresses caused by welding. Air cooling does not result in appreciable hardening, because the cooling takes place from below the critical range. However, rapid cooling caused by cold draughts, if present, can introduce new stresses.

The steels are readily weldable with the conventional arc welding and electrosalg welding processes. The air- hardening property of the base metal and high alloy content of the weld-metal demand that correct welding procedures including preheat, postweld heat treatment, low-hydrogen consumables, and filler metal chemistry are used to prevent HAZ and weld metal cracking.

Recommended preheating temperatures are indicated in Table 2. It is obvious that the preheat temperature must be increased as the thickness and carbon and alloy contents increase to ensure crack- free joints. The welding process can also determine the preheat condition. With a low-hydrogen process such as TIG, or a hifh heat input process such as electroslag, much lower preheat would be justified or even none at all. The chemical composition of the filler metal must be same as of the base metal, except for carbon content which lower for the weld metal.

When different Cr- Mo steels are to be welded at the same time, filler metal selection can be restricted by using the same filler metal for a variety of steels. For example, 1.25 Cr-0.5% Mo filler metal can be used for three base metals: 0.5%Cr-0.5%Mo, 1%Cr-0.5%Mo and 1.25%Cr-0.5%Mo. Similarly 2.25%Cr-1%Mo filler metal can be used for 2%Cr-0.5%Mo and 3%Cr-1%Mo steels.

Minor repairs on Cr- Mo Steels can be carried out with 25Cr- 20 Ni or 25Cr-12 Ni type austenitic stainless steelfiller metals, when postweld heat treatment is not possible. The weld metal has lower yield strength compared to the matching Cr- Mo composition, but is extremely ductile and can resist cracking due to shrinkage stresses. Through hardness in the HAZ cannot be avoided, the austenitic weld metal prevents occurrence of cold cracking in this region. The limitations of the austenitic weld - metal are: a) It may cause failure at the fusion line when subjected to cyclic temperatures in service b) Carbon can migrate from the lower Cr base metal to higher Cr weld-metal at high service temperatures, higher Cr weld-metal at high service temperatures, resulting in the weakening of the weldment.c) Brittle sigma- phase may develop at high service temperature. d)Difference in coefficient of thermal expansion between the weld- metal and base metal may give rise to stresses at high or under cyclic temperatures. Welding with austenitic weld-metal is more prevalent in the petroleum industry, where more-or-less steady temperatures exist than in thermal power stations, where demand fluctuation causes cycling of temperature and pressure.

III. Preheat Temperature

A. Recommended Preheat Temperatures for Cr- Mo Steels

Cr-Mo steel	Preheat temp (°C) for different thicknesses		
	12.7 mm	12.7 to 57mm Preheat temp °C	Above 57 mm
0.5Cr- 1/2 Mo	20	95	150
1Cr- 1/2 Mo	120	150	150
1.25Cr- 1/2 Mo	120	150	150
2Cr –1/2 Mo	150	150	150
2.25Cr –1Mo	150	150	150
3Cr –1Mo	150	150	150
5Cr –1/2 Mo	150	150	150
5Cr –1/2 MoSi	150	150	150
5Cr –1/2 MoTi	150	150	150
7Cr –1/2 Mo	200	200	200
9Cr – 1Mo	200	200	200

Cr-Mo weldments, especially in pressure pipings, have to be stress – relieved as required by relevant codes. Welded joints in pipings are given local stress- relief while vessels and similar fabricationsare wholly stress- relieved. Table 3 gives the stress- relief temperatures which are below the critical range and result in reduced hardness and residual stress level and increased ductility ofweld-metal and the HAZ

IV. Stress Relief Temperatures

A. Stress – Relief Temperatures for Cr-Mo Steels

Alloy type	Temperature range °C
0.5Cr- 1/2 Mo	590-700
1Cr- 1/2 Mo	590-730
1.25Cr- 1/2 Mo	590-745
2Cr –1/2 Mo	680-760
2.25Cr –1Mo	680-760
3Cr –1Mo	680-760
5Cr –1/2 Mo	680-760
5Cr –1/2 MoSi	680-760
5Cr –1/2 MoTi	680-760
7Cr –1/2 Mo	680-760
9Cr – 1Mo	680-760

Cr-Mo steels in lower thicknesses can be put into service without postweld heat treatment, provided proper preheating procedure has been applied during welding. For example, 2.25%Cr-1% Mo steel welded with extra-low carbon filler metal (C-0.03%) has enough as-welded ductility to meet code requirements. Postheating May therefore be avoidable in some cases.

Cr-Mo steel vessels are sometimes wholly annealed to obtain a softer ferritic structure in the entire base metal., HAZ and weld- netal. Annealing procedure is as follows: the weldments is heated in the critical temperature range of 843-913°C, held at that temperature for one hour per 25mm thickness, cooled to 538°C at a minimum rate of 28°C per hour, then furnace or air cooled to room temperature.

As far as possible, Cr-Mo steels must be preheated, welded and postweld heated in one continuous operation. Experience, however as shown that steels with 2.25 Cr and less can be safely cooled to room temperature before being postweld heat treated.

For steels having higher Cr contents, an interruption between preheat and postheat is likely to produce cracking in the weldment. If interruption is irreversible for some reasons, a practical step to prevent cracking consists of raising the weldment temperature from the preheat temperature to above 427°C and maintaining there for three minutes per 25mm thickness before cooling to room temperature. This results in removal of most of the hydrogen from the weld and the HAZ. The postweld heat treatment is finally carried out at any convenient time.

V. Costs and Benefits of P91

The benefits of using P91 steel over standard alloys such as P11 or P22 can be put into three categories, though we added in the case study this caution:

Caution: The cross-weld rupture strength of P91 steel appears lower than the parent metal due to creep/fatigue interactions. This impact seems greater for P91 than for P22. Type 4 cracking is the issue here and more testing will be needed to fully evaluate this. The benefits listed above are based on parent metal strength.

A. Benefits of P91:

- Greater strength, that permits increased safety margins in existing units.
- Significantly longer component life under given creep and fatigue duty.
- Reduced wall thickness for tubing and piping for the same design conditions, leading to lower thermal storage and less thermal stress.

B. Preheat

The literature suggests that 200°C (~400°F) is adequate for preheating P91 and P92 weldments. Fabricators typically aim for 200°–250°C (~400°–500°F), but will go as low as 121°C (250°F) for root and hot pass layers, thin-walled components, or where GTAW is utilized. Experience indicates that no elevated preheat is required for T23 or T24 weldments; however, some code bodies including ASME require preheat or postweld heat treatment (PWHT) for these alloys

C. Postweld Heat Treatment

Application of PWHT is absolutely necessary with Grade 91, 911, 92, and 122 weldments, regardless of diameter or thickness. • PWHT is one of the most important factors in producing satisfactory weldments. The PWHT methodology and implementation must be verified to ensure that the weldments are actually receiving PWHT at the proper temperature. Additional thermocouples or qualification testing may be required. Proper tempering of the martensitic microstructure is essential for obtaining reasonable levels of toughness. In practice, this involves selecting both an appropriate temperature and time in accordance with governing code requirements.

VI. Expert Conclusions on P91

P91 has been considered to be advantageous steel as thinner wall and smaller component size reduce thermal gradients and hence the adverse effect of fatigue cracking - which in the past has been experienced in thick section components made from the traditional low alloy ferritic steels. Dr. Shibli comments however that preliminary R & D studies have shown that P91 welded components may be equally, or even more, prone to Type IV cracking compared with the conventional low alloy ferritic steels, possibly due to the weakness of weld and low cross-weld creep ductility of the welded material.

Kent Coleman recognized in the original case study that a concern with use of Grade 91 is creep rupture failures of weldments in the Type IV location (failures in the heat affected zone (HAZ) and that these failures occur before damage develops in the base metal. This is generally not a concern for circumferential welds because stress on piping systems is about twice as much in the hoop direction than in the longitudinal direction.

When the system is designed to contain the pressure stress, Coleman says, the Type IV location on circumferential welds are operating at sufficiently low stress to provide desired life. So the concern arises when components are manufactured with longitudinal seams. Components with long seams should take into consideration this damage mechanism and have sufficient thickness to operate at lower stress. If at all possible, longitudinal seams should be normalized and tempered to eliminate the HAZ.

Kent added that EPRI has projects ongoing on heat treatment, normalization, cold forming, temperbead welding, improved welding consumables, and oxidation/ scale exfoliation of Grade 91.

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