Jan Hilkes, Volker Gross

Welding CrMo steels for power generation and petrochemical applications - past, present and future

Introduction

Creep and high temperature resistant CrMo steels have been around for a very long time and have found use with great success for applications in the petrochemical, and respectively in the power generation industry. Typical products for these industries are boilers, heaters, heat exchangers, reactors, and hydrocrackers, usually built as heavy wall pressure vessels.

In a continuous strive for optimizing the economics in the various process installations in these industries, the service pressures and/or temperatures have increased. This implied that the respective base materials either had to be made available in heavier thicknesses or they had to be developed to meet higher strength and impact toughness requirements. Increased mechanical properties will reduce or at least restrict the necessary wall thickness which generates an additional economical advantage in production, handling and installation of heavy process equipment. An example of a heavy all pressure vessel is a part of a Hydro Conversion Unit as shown in Figure 1.


Fig. 1: Part of Hydro Conversion Unit by ATB, Italy

The basic and classic CrMo steels are alloyed with 0,5%Mo – 1%Cr/0,5%Mo – 2,25%Cr/1%Mo – 5%Cr/1%Mo – 9%Cr/1%Mo and 12%Cr/1%Mo. From these steels further development has taken place by adding elements such as V, W, Ni, Ti, Nb, B and/or N to arrive at the new grades of today such as the T/P22V, T/P23, T/P24, T/P91, T/P92 and VM 12-SHC. Many of these new grades have been applied successfully in industry but the development continues.

Obviously, development of the welding consumables had to and still must follow the direction of the base materials with the assurance of meeting the same stringent requirements for the process equipment as the base materials, even more so since the HAZ is usually also considered part of the weld. Extensive research and development has taken place at Böhler Schweisstechnik in Germany to arrive at a full consumable range for the new generation of CrMo(V) steels for which also creep data up to 60 000 hours have been collected. With increasing alloy level the specific welding procedures have to be adjusted and will call for more precise and strict control of welding parameters and heat treatment.

Technical Details of a Hydro Conversion Unit

Base material:	2,25%Cr-1%Mo	
Sizes:	thickness:	358 mm
	length:	21 m
	diameter:	5.3 m
	total weight:	706 t
Service conditions:	215.5 bar pressure and max. 454°C	
Welding consumables:	SAW: Union S1CrMo2/UV 420TTR SMAW: Phoenix SH Chromo 2 KS	

Jan Hilkes, Volker Gross - Böhler Schweisstechnik Deutschland GmbH, Hamm, Germany

Creep resistant CrMo steels

Basic metallurgy for base material and weldmetal design

Creep resistant steels are steels that can resist a certain stress at a specific service temperature without exceeding a specified amount of elongation. The maximum stress to rupture at a specific temperature after a specific time, e.g. 600°C and 105 h, is referred to as Creep Rupture Stress. For example, an engineering design criterion for a power plant could require a minimal stress of 100MPa for 105 h at service temperature. The basic idea is that the vessel remains its original sizes and shape while in service for up to 20 to 30 years. Due to the fact that in the processes used within the Power Generation and Petrochemical Industry and the many different service conditions such as pressure, temperature and environment, a wide variety of CrMo creep resistant steels with additions of V, W, Ti, Nb, B and/or N have been developed, while new types are also still under development. Due to increased pressures and temperatures, up to 370 bar and 650°C, as for example in components for Ultra-Super-Critical (USC) steam power generation plants, CrMo creep resistant base materials with increased strength are required to allow wall thicknesses that are within the range of what fabricators can handle in their facilities. Also for petrochemical applications (P22V), sizes now up to 350mm are no longer an exception. An overview of the international standards, chemical compositions and maximum service temperatures of the actual and most popular CrMo creep resistant steels is given in Table 1.

Table 1: Overview of the international standards, chemical composition and maximum service temperature of the actual and most popular CrMo creep resistant steels

CrMo type	INTERNATIONAL STANDARDS		
	ASTM & ASME	DIN/VdTÜV	EN
0.5Mo	T/P 1	16 Mo 3	8MoB 5-4
1.25Cr-0.5Mo	T/P 11	10 CoMo 5-5	10 CrMo 5-5
1,00Cr-0.5Mo	T/P 12	13 CrMo 4-5	13 CoMo 4-5
1.25Cr-1MoV	-	15 CrMoV 5-10	-
	T/P 36	15 NiCuMoNb 5 (WB 36)	15 NiCuNb 5
2.25Cr-1Mo	T/P 22	10 CrMo 9-10	10 CrMo 9-10
2.25Cr-1MoV	T/P 22V	-	-
2.25Cr-MoVW	T/P 23	HCM 2S	7CrWVMoNb 9-6
2.25Cr-1MoVTiB	T/P 24	7CrMoVTiB 10-10	7CrMoVTiB 10-10
5Cr-0.5Mo	T/P 502	12 CrMo 19-5	-
9Cr-1Mo	T/P 9	X12 CrMo 9-1	X12 CrMo 9-1
9Cr-1Mo mod.	T/P 91	X10 CrMoVNb 9-1	X10 CrMoVNb 9-1
9Cr-0.5MoWV	T/P 911	X11 CrMoWVNb 9-1-1	X11 CrMoWVNb 9-1-1
9Cr-0.5MoWV	T/P 92	X10 CrWMoNb 9-2	-
12Cr-0.25Mo +1.4W1.3Co0.2V	-	X12 CrCoWVNb 11-2-2 (VM 12-SHC) t<10mm	-
12Cr-1MoNiV	-	X20 CrMoV 12-1	X20 CrMoV 11-1

The creep resistance of a CrMo steel is based on the formation of stable precipitations such as alloy carbides in a ferritic, bainitic and/or martensitic microstructure in the normalised condition. Due to a subsequent tempering treatment, a stable microstructure with precipitations is generated that remains stable at the service temperature for which the steel has been developed. The precipitations formed will block the grain-boundaries and prevent sliding of the slip-planes to give the desired creep resistance properties. They should therefore have the correct shape, be present in the right amount and be evenly distributed to obtain a homogeneous structure with homogeneous properties. Depending on the alloy level and the heat treatment(s), specific types of precipitations will be formed in a specific amount. The governing parameters for the heat-treatment are temperature and time. The variety of precipitations that can be expected and that are mainly used in the design of classic and modern creep resistant CrMo steels are listed in Table 2.

Table 2: Precipitations that can be found in creep resistant CrMo steels /1, 2/

Precipitations and possible phases in CrMo steels		
Graphite		
Epsilon	= $Fe_{2.4}C$	
Cementite	= Fe_3C	
Chi	= Fe_2C	
M_2X	M_6C	$M_{23}C_6$
M_7C_3	Laves	
M_5C_2	Z-phase	
Mo_2C	Cr_3C	
NbC	NbN	VN

Table 1: Overview of the international standards, chemical composition and maximum service temperature of the actual and most popular CrMo creep resistant steels (continued)

TYPICAL CHEMICAL COMPOSITION (wt%)										SERVICE
C %	Si %	Mn %	Cr %	Mo %	Ni %	V %	W %	Nb %	other %	Temp. °C
0,16	0,30	0,82	< 0,30	0,32	< 0,30	-	-	-	-	< 460
0,10	0,32	0,68	1,25	0,50	-	-	-	-	-	< 545
0,13	0,70	0,60	1,00	0,50	-	-	-	-	-	< 545
0,15	0,30	0,75	1,25	1,05	-	0,26	-	-	-	< 545
0,15	0,35	0,95	-	0,45	1,12	-	-	0,22	Cu: 0,62	< 545
0,10	0,36	0,69	2,20	1,02	-	-	-	-	-	< 545
0,12	0,08	0,50	2,25	1,00	-	0,30	-	-	-	< 545
0,08	0,34	0,42	2,32	< 0,30	-	0,02	1,55	0,06	N < 0,010	< 550
0,07	0,28	0,60	2,25	1,04	-	0,24	-	-	N < 0,010 B: 15-70 ppm Ti: 0,05-0,10	< 550
0,12	0,35	0,65	5,10	0,54	-	-	-	-	-	< 550
0,12	0,60	0,40	9,00	1,00	-	-	-	-	-	< 585
0,10	0,36	0,52	8,82	1,02	< 0,40	0,22	-	0,08	N: 30-70 ppm	< 585
0,11	0,28	0,54	8,80	1,02	0,25	0,22	1,05	0,08	N: 0,05-0,09	< 625
0,10	< 0,50	0,55	8,80	0,52	< 0,40	0,23	1,55	0,08	N: 0,03-0,07 B: 0,001-0,006	< 625
0,11	0,45	0,20	11,50	0,23	0,28	0,24	1,40	0,07	Co: 1,30 N: 0,055 B: 0,003	< 650
0,20	<0,50	<1,00	12,10	1,05	0,65	0,28	-	-	-	<585

Heat treatments for CrMo steels and welded joints

The heat treatments for the base materials are reasonably complex but are required to obtain the optimal mechanical properties. Depending on the alloy content a Normalising, Tempering and Annealing treatment at various temperatures for several hours with a controlled cooling rate have to be executed according strict procedures. The same is valid for the weldmetal, with increasing alloy content the Post Weld Heat Treatment (PWHT) for welded joints gets more complicated as illustrated in Figure 2.

When in subsequent PWHT, Intermediate Stress Relieving (ISR) or in service, the ultimate heat treatment temperature of the base material is exceeded too much and too long, the precipitations can dissolve again which causes reduction of the mechanical properties of the base material. This implies that, for example, for this reason the maximum temperature of 760°C for P91 in Figure 2 shall not be exceeded. For T/P23 in Figure 2, an Intermediate Stress Relieving is indicated for constructions with different material thicknesses. For each application the optimum PWHT shall be determined. Further elaboration will follow in the welding chapter of this paper (Table 4).

Temper Embrittlement

When CrMo base material and the weld metal is exposed to a temperature range of 400-500°C for a very long time there is a risk of Temper Embrittlement. This type of embrittlement is caused by trace elements as P, Sb, Sn and As that migrate to the grain boundaries and can reduce the ductility in both base material and weldmetal. To which extent this phenomena will occur depends merely on temperature and time.

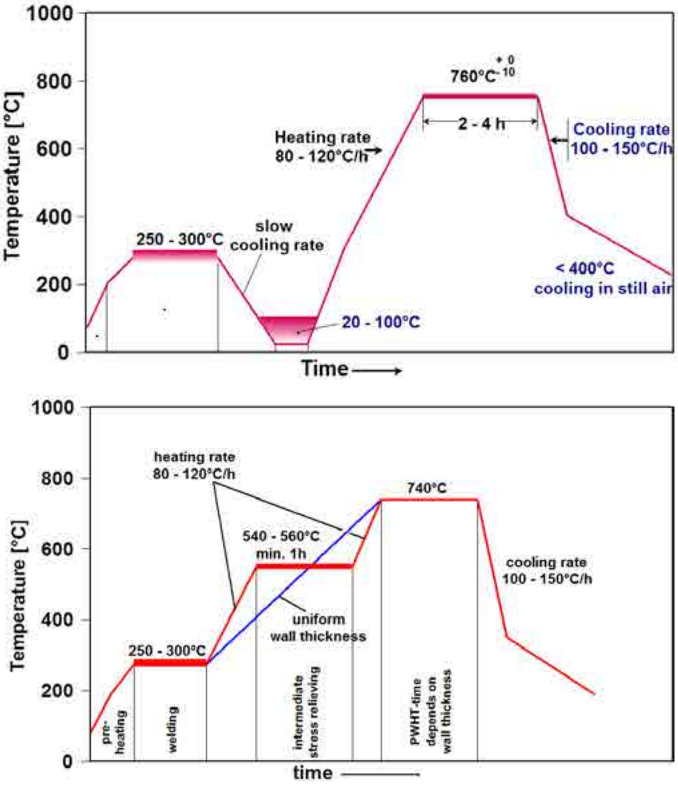

Fig. 2: Temperature cycle and heat control during welding and PWHT of martensitic steel P91, E911 and P92 (above) and ferritic/bainitic steel T/P23 (below). For GTAW joints in <10mm wall thickness T/P 23, no PWHT is required

To establish the sensitivity of a material to temper embrittlement, a Step Cooling (STC) heat treatment is carried out in the range of 593-316°C for a duration of 240 hours. The difference in transition temperature (impact properties) from before and after the heat treatment is a measure for the sensitiveness to temper embrittlement. A maximum allowable shift in transition temperature after step cooling can be specified as a requirement for base material and weldmetal. In order to reduce the risk of temper embrittlement, the responsible trace elements need to be restricted. Bruscato and Watanabe have developed formulas to express the tendency of temper embrittlement /3, 4/.

Watanabe:	$J = (Mn + Si) \times (P + Sn) \times 10^4$	elements in wt%
Bruscato:	$X = (10\,P + 5\,Sb + 4\,Sn + As) / 100$	element in wt% and result in ppm

The formula of Watanabe is only valid for the base material and is usually restricted to a value of J < 160 but also requirements for J < 120 or 80 are being specified by the industry today.

The Bruscato formula, also referred to as the X-factor, is valid for both weld metal and base material. For weldmetal the specifications are becoming more and more stringent with increasing wall thickness and desire for additional assurance of the mechanical properties. Initially, the required value of the X-factor was $X < 15$, but present specifications already ask for $X < 10$. An additional requirement for the Mn and Si content can be set accordingly: $Mn + Si < 1.1\%$.

Specifically for SAW where the trace elements can be picked up from both wire and flux, the combination should be tested to comply with the requirements. This means one source for both wire and flux would be recommended /5/.

Corrosion: Resistance to Oxidation, Sulphidation and Hydrogen attack

In addition to the creep resistance and resistance to embrittlement, CrMo steels also show increased high temperature oxidation resistance with increasing alloy content. Comparing the scaling loss for plain carbon steel and 1%Cr0.5%Mo with that of 5%Cr0.5%Mo steel at 675°C, the scaling loss is reduced from >2.5 mm/y for the first two to about 0.1 mm/y for the latter. This makes these steels also very suitable for gas-fired furnaces in the petrochemical industry /6/.

Also sulphidation corrosion resistance increases with increasing alloy content. Comparing the corrosion rate of carbon steel with that of 9%Cr1%Mo steel at 700°C, the corrosion rate is reduced from 1.0 to 0.2 mm/y. Sulphur combines with Chromium to form Chromium-Sulphides, and hence reduces the amount of Cr-carbides required for creep resistance. Since most crude oils and other gaseous fuels contain either certain amounts of Sulphur or H2S, sufficient sulphidation corrosion resistance is required for petrochemical installations.

Another important phenomena is High Temperature Hydrogen Attack (HTHA), a formation of Methane from Cementite ($Fe_3C + 2H_2 \rightarrow CH_4 + 3Fe$) in the base material under high Hydrogen pressures at high temperatures, as for example in heavy wall pressure vessels for high-temperature, high hydrogen services in oil refineries. The 2.25%Cr1Mo and 3%Cr1Mo steels are typical base materials with good resistance to HTHA in this application.

Welding and welding consumables for CrMo steels

In general, creep resistant CrMo-steels are welded with matching consumables in order to have a homogeneous welded joint with about equal mechanical properties. Matching compositions also have the same coefficient of thermal expansion, which prevents or at least reduces the risk of thermal fatigue in service. In this respect, the heat affected zone (HAZ) is a vulnerable area.

In principle, all arc welding processes can be applied as SMAW. GTAW, GMAW, SAW and FCAW. For manual processes it is important to take sufficient measures to protect the welders from heat, and then it is of utmost importance that the preheat as well as the interpass temperatures are respected and not reduced to accommodate the welders, as well as while tacking. With the gas-shielded processes it is vital to assure proper shielding of the weld. Due to the high preheat, the gas-shield can be distorted and provide less protection as required. Special nozzles and gas cups are available to reduce the problem.

Over the last decades, Böhler Schweisstechnik Germany has developed a wide range of welding consumables for welding CrMo steels for the processes: SMAW, GTAW, SAW, GMAW and FCAW. A selection table for the respective welding consumables and welding processes for creep resistant CrMo steels can be found in listed in Table 3.

Table 3: Selection table for the respective welding consumables and welding processes for creep resistant CrMo steels

CrMo type	BASE MATERIAL		WELDING CONSUMABLES FOR CrMo STEELS					
	ASTM & ASME	EN	SMAW	GTAW	GMAW	SAW wire	SAW flux	FCAW
0.5Mo	T/P 1	8MoB 5-4	Phoenix SH Schwarz 3 K	Union I Mo	Union I Mo	Union S 2 Mo	UV 420 TT	Union TG Mo R
1.25Cr-0.5Mo	T/P 11	10 CrMo 5-5	Phoenix Chromo 1	Union I CrMo	Union I CrMo	Union S 2 CrMo	UV 420 TT	Union TG CrMo R
1.00Cr-0.5Mo	T/P 12	13 CoMo 4-5	Phoenix Chromo 1	Union I CrMo	Union I CrMo	Union S 2 CrMo	UV 420 TT	Union TG CrMo R
1.25Cr-1MoV	-	15 CrMoV 5-10	Phoenix SH Kupfer 3 K	-	-	-	-	-
-	T/P 36	15 NiCuNb 5 (WB 36)	Phoenix SH Schwarz 3 K Ni	Union I Mo	Union I Mo	Union S 3 NiMo 1	UV 420 TT(R)	-
-	-	20 MnMoNi 5-5	Phoenix SH Schwarz 3 K Ni	Union I MoMn	Union I MoMn	Union S 3 NiMo 1	UV 420 TT(R)	Union TG Mo R
2.25Cr-1Mo	T/P 22	10 CrMo 9-10	Phoenix SH Chromo 2 KS	Union I CrMo 910	Union I CrMo 910	Union S 1 CrMo 2	UV 420 TTR	Union TG CrMo 9 10 R
2.25Cr-1MoV	T/P 22V	-	Phoenix SH Chromo 2 V	-	-	Union S 1 CrMo 2V	UV 430 TTR-W	-
2.25Cr-MoVW	T/P 23	7CrMoWVMoNb 9-6	Thermanit P23	Union I P23	Union I P23	Union S P23	UV 430 TTR-W	→UV P23
2.25Cr-1MoV	T/P 24	7CrMoVTiB 10-10	Thermanit P24	Union I P24	Union I P24	Union S P24	UV 430 TTR-W	→UV P24
5Cr-0.5Mo	T/P 502	12CrMo 19-5	Phoenix Chromo 5	Union I CrMo 5	Union I CrMo 5	Union S1 CrMo 5	Marathon 543	-
9Cr-1Mo	T/P 9	X12 CrMo 9-1	Thermanit Chromo 9 V	Thermanit MTS 3	Thermanit MTS 3	Thermanit MTS 3	Marathon 543	Thermanit MTS 3 PW
9Cr-1Mo mod.	T/P 91	X10 CrMoVNb 9-1	Thermanit Chromo 9 V; Thermanit Chromo T91	Thermanit MTS 3	Thermanit MTS 3	Thermanit MTS 3	Marathon 543	Thermanit MTS 3 PW
9Cr-0.5Mo-WV	T/P 911	X11 CrMoWVNb 9-1-1	Thermanit MTS 911	Thermanit MTS 911	Thermanit MTS 911	Thermanit MTS 911	Marathon 543	-
9Cr-0.5Mo-WV	T/P 92	X10 CrWMoNb 9-2	Thermanit MTS 616	Thermanit MTS 616	Thermanit MTS 616	Thermanit MTS 616	Marathon 543	-
12Cr-0.25Mo +1.4W1.3Co0.2V	-	X12 CrCoWVNb 11-2-2 (VM12-SHC) t<10mm	Thermanit MTS 5 CoT	Thermanit MTS 5 CoT	-	-	-	-
12Cr-1Mo-NiV	-	X20 CrMoV 11-1	Thermanit MTS 4	Thermanit MTS 4 Si	Thermanit MTS 4 Si	Thermanit MTS 4	Marathon 543	-

Depending on the alloy level, from only 0.5%Cr to 12%Cr-1%Mo the welding condition regarding preheat (Tp) and interpass (Ti) temperature as well as the subsequent temperature cycles during SR, ISR, STC and PWHT´s change drastically. An overview with typical guidelines in this regard for is provided in Table 4. Also see Figure 2 above for examples of complicated heat treatments. The required heat treatment

Table 4: Overview of typical guidelines for Preheat & Interpass temperatures and PWHT as SR, ISR and STC for CrMo steels. Also see Figure 2.

CrMo type	STANDARDS		PREHEAT & INTERPASS TEMPERATURE, PWHT as SR, ISR and STC GUIDELINES for CrMo STEELS				
	ASTM & ASME	EN	Tp °C	Ti °C	SR h, °C	ISR h, °C	PWHT/STC h, °C
0.5Mo	T/P 1	8MoB 5-4	RT	RT	2-4h @ 580-630°C		
1.25Cr--0.5Mo	T/P 11	10 CrMo 5-5	200-250°C	> 200°C	2-4h @ 660-700°C		STC depending on application
1,00Cr--0.5Mo	T/P 12	13 CrMo 4-5	200-250°C	> 200°C	2-4h @ 660-700°C		
1.25Cr--1MoV		15 CrMoV 5-10	200-250°C	> 200°C	2-4h @ 660-700°C		
	T/P 36	15 NiCuNb 5 (WB 36)	200-250°C	> 200°C	2-4h @ 580-620°C		60h @ 550°C + 40h @ 620°C
		21 MnMoNi 5-5	200-250°C	> 200°C	2-4h @ 580-620°C		
2.25Cr-1Mo	T/P 22	10 CrMo 9-10	200-300°C	200-300°C	2-4h @ 670-720°C		
2.25Cr--1MoV	T/P 22V		200-300°C	200-250°C		1h @ 680°C	8h @ 705°C + STC +32h @ 705°C
2.25Cr-Mo-VW	T/P 23	7CrWVMoNb 9-6	200-300°C	200-300°C		1h @ 540-560°C*	0.5-4h @ 740°C**
2.25Cr--1MoV	T/P 24	7CrMoVTiB 10-10	200-280°C	200-280°C			0.5-4h @ 740°C**
5Cr-0.5Mo	T/P 502	12 CrMo 19-5	225-300°C	> 225°C	2-4h @ 730-760°C		
9Cr-1Mo	T/P 9	X12 CrMo 9-1	200-300°C	200-300°C	slow cool after welding		xh@ 750°C
9Cr-1Mo mod.	T/P 91	X10 CrMoVNb 9-1	200-300°C	200-300°C	slow cool after welding		
9Cr-0.5Mo-WV	T/P 911	X11 CrMoWVNb 9-1-1	200-300°C	200-300°C	slow cool after welding		xh @ 730-780°C
9Cr-0.5Mo-WV	T/P 92	X10 CrWMoNb 9-2	200-300°C	200-300°C	slow cool after welding		xh @ 730-780°C
12Cr-0.25Mo		X12 CrCoWVNb 11-2-2	200-280°C	200-280°C	slow cool after welding		xh @ 770°C
+1.4W1. 3Co0.2V		(VM 12-SHC) t<10mm					
12Cr-1Mo-NiV		X20 CrMoV 12-1	200-280°C	200-280°C	slow cool after welding		xh @ 760°C
							x depends on thickness

* with great differences in wall thickness

** no PWHT required for GTAW up to wall thickness of 10mm

depends also on the thickness of the construction and has to be determined by the fabricator as part of the welding procedure development. The main factor is to have a controlled, slow and even heating up and cooling down to prevent additional stresses in the welded joint. For heavy thicknesses this means heating up from as many sides as possible to get the required heat distribution in the material. These precautions have to be taken to safeguard the base material, the weldmetal and the heat affected zone (HAZ).Recent developments in P22V, P23, P24, P92 and VM 12-SHC have governed more detailed and precise welding and production procedures to retain control over the outcome of the final product. Although these materials are not as forgiving as the basic CrMo steel, the weldability is excellent when the correct procedures are followed. Depending on the application, there can be requirements for STC and Bruscato´s X- factor. For very heavy wall-thickness in P22V it could be necessary to apply intermediate stress relieving treatments as to reduce the overall stress level before the final heat treatments applied. With the experience that Böhler Schweisstechnik Germany has built up over the last decades, the support that can be provided to the customers has become a vital link in the supply chain in today's business.

As already mentioned, the thicknesses for a welded part in the power generation and petrochemical industry keeps increasing and higher tensile strength materials, with more stringent mechanical properties and chemical composition, are used to keep fabrication feasible. This means that the welding consumables have to be adapted to follow this trend.

Figure 3 shows a very heavy wall example of a pipe connection of a live-steam pipe of P91 base material in a Power Station.

Fig. 3: Weld preparation and final weld in a pipe connection of a live-steam pipe of P91, welded with SMAW using Thermanit Chromo 9 V

As indicated the heat treatments including preheat and interpass temperature have to be under strict control to successfully complete these types of welded joints. The temperature ranges for the preheat and interpass temperatures given in Table 4 are to be respected throughout completion of the joint. For this application, SMAW is very suitable due to its flexibility and low investments regarding equipment. In order to increase efficiency, higher weldmetal deposition per unit of time, development is ongoing for FCAW consumables for CrMo steels. As listed in Table 3, a number is already available but the range will be extended upon the demand of the industry.

Fig. 4: Heavy wall Reactor in 2.25%Cr-1%Mo by GODREJ, INDIA

Technical Details of the Reactor:

Base material:	2,25%Cr-1%Mo
thickness:	124, 132 and 153 mm
total weight:	about 500 t
Service conditions:	120 bar pressure and 437°C
Welding consumables:	SAW: Union S1CrMo2/UV 420TTR SMAW: Phoenix SH Chromo 2 KS

The SAW consumables range covers all the CrMo steels available today. GTAW is mainly used for root welding or automated welding in demanding industries. The GMAW range is available but not popular in the Power Generation industry.

Another practical example is that of a Reactor build in 2.25%Cr-1%Mo steel. Figure 4 shows one of a number of these types of heavy wall pressure vessels produced by Godrej in India. They have built up excellent and practical experience to be able to build such units. When dealing with heavy wall thicknesses, modern CrMo creep resistant steels and very stringent specifications, it is absolutely necessary to build up sufficient experience to be able to satisfy the demanding engineering companies as well as the Oil and Power companies, who are the ultimate client.

Parameter control and suggestions for "Best Practice"

CrMo(V) weld metal typically shows a bainitic/martensitic micro structure that respond very sensitively to any kind of heat put in by means of welding and heat treatment. Furthermore, the high strength in the as welded condition requires accurate handling in terms of Hydrogen and ISR in order to avoid cracking due to Hydrogen and/or the restrained condition of welds in heavy wall nozzles for example.

To elaborate on some of the influences, typical observations in welds made in CrMo(V) creep resistant steels are illustrated in the next paragraph.

Figure 5 shows ferrite precipitations in P11 due to excessive PWHT temperature. The micrograph in figure 6 shows Hydrogen damage due to a improperly applied soaking treatment, leaving too much residual Hydrogen in the weldmetal. Figure 7 shows the effect of bead-thickness in SMA welds, a shift of the impact properties to higher temperatures, due to a much courser grain-structure.

Applicable manufacturing parameters, which include the welding parameters as well as the quality of the welding equipment and the skill-level of the welders, become more important with an increasing initial strength. The "operating window" will become smaller. Therefore suitable control mechanisms and procedures have to be set up to ensure the proper application of the required parameters. In particular the control of the following items shall not be neglected for achieving successful welds:

- Selection of the suitable SAW wire & flux combination
- Proper rebaking of fluxes and electrodes
- Verification of preheating & interpass temperatures
- Setting of the electrical welding parameters
- Weld build-up and beadsequence
- Verification of the heat treatment temperature.

Almost all issues encountered in CrMo welds could be related to the non-observance

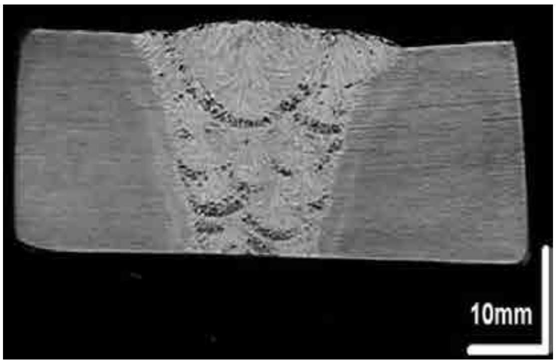

Fig. 5. Ferrite precipitations in P11 SA welds

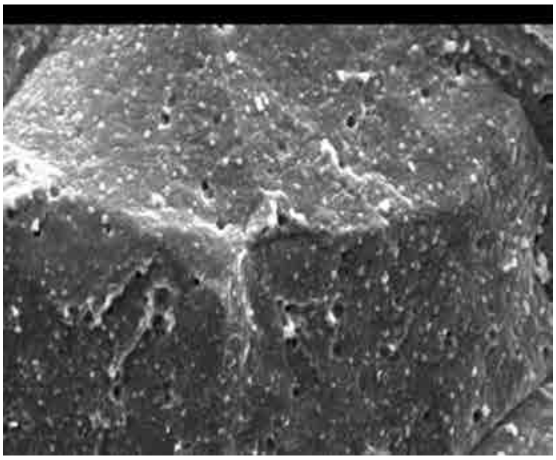

Fig. 6. Crack surface due to Hydrogen in P22V SA welds

Table 5: Overview of typical applications of CrMo steels in the Power Generation & Petrochemical Industry

CrMo type	BASE MATERIAL		INDUSTRIAL APPLICATIONS		Service max. T in °C
	ASTM & ASME	EN	POWER GENERATION	PETROCHEMICAL	
0.5Mo	T/P1	8MoB5-4	Pressure vessels; Rp0.2 > 290 MPa, Rm > 500 MPa	Pressure vessels	< 460
1.25Cr--0.5Mo	T/P11	10CrMo5-5	Steam headers	Heavy Wall Pressure Vessels, Coke Drums,	< 535
1.00Cr--0.5Mo	T/P12	13CoMo4-5	Water walls; parts of evaporater	Hydrofiner Reactors, Catalytic Reformer Reactors	< 545
1.25Cr--1MoV	-	15CrMoV5-10	Main steam pipe; reheater steam pipe; Rp0.2 > 440 MPa, Rm 590-780 MPa	Heat exchangers	< 545
-	T/P36	15NiCuNb5 (WB 36)	Feed water pipe	High pressure steam drums	< 545
-	-	20MnMoNi5-5	Reactor vessels (nuclear)	-	
2.25Cr-1Mo	T/P22	10CrMo9-10	Parts of superheaters; Rp0.2 > 310 MPa, Rm 515-690 MPa	Reactors, coke drums, furnaces, piping	< 535
2.25Cr--1MoV	T/P22V	-	Rp0.2 > 415 MPa, Rm 585-760 MPa -->	Hydrocrackers, Heavy Wall Pressure Vessels for Hydrogen Service	< 482
2.25Cr-Mo-VW	T/P23	7CrMo-WVMoNb9-6	Parts of superheater; membrane walls	-	< 550
2.25Cr--1MoV	T/P24	7CrMo-VTiB10-10	Parts of superheater; membrane walls	-	< 550
5Cr-0.5Mo	T/P502	12CrMo19-5	-	Pressure vessels in high temperature sulfur corrosion, resistance reactor furnaces and reactors	< 550
9Cr-1Mo	T/P9	X12CrMo9-1	-	Reactors, High Temperature Sulphur corrosion resistance, furnaces and piping	< 585
9Cr-1Mo mod.	T/P91	X10CrMo-VNb9-1	Steam headers, superheaters for ultra super critical boilers; Rp0.2 > 450 MPa, Rm 630-790 MPa	High pressure steam headers & piping	< 585
9Cr-0.5Mo-WV	T/P911	X11CrMo-WVNb9-1-1	Steam headers, superheaters	-	< 625
9Cr-0.5Mo-WV	T/P92	X10CrWMo Nb9-2	Steam headers, superheaters for Ultra Super Critical boilers	-	< 625
12Cr--0.25Mo +1.4W 1.3Co0.2V	-	X12CrCo-WVNb11-2-2 (VM12-SHC) t<10mm	Superheater tubes with thickness < 10mm	-	< 650
12Cr-1Mo-NiV	-	X20 CrMoV11-1	Steam headers, superheaters; Rp0.2 > 500 MPa, Rm 700-850 MPa	Tubing in H2S environments	< 585
			High Pressure & High Temperature	**High Pressure, High Temperature & Corrosion**	

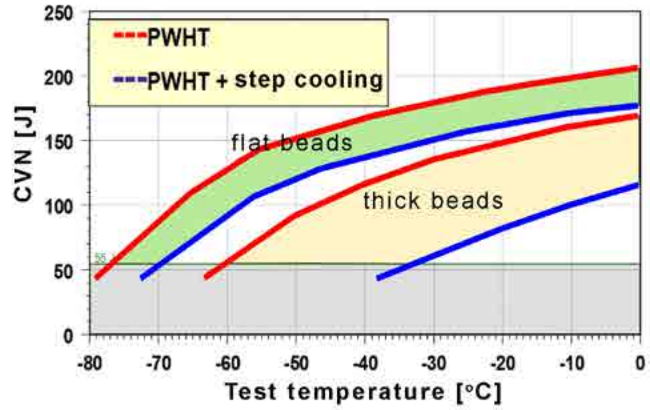

Fig. 7. Influence of weld build-up on impact toughness

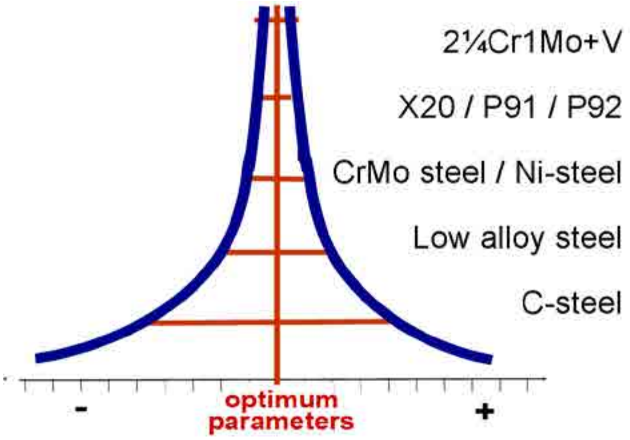

Fig. 8: QA to be included to verify required parameters

of the above mentioned items. Consequently suitable control mechanisms have to be developed to ensure proper welds. Quality assurance becomes a major factor and must be included in the CrMo welding fabrication. QA has to be considered as an essential variable, as illustrated with Figure 8.

In conclusion we can state that CrMo creep resistant steels are widely and successfully applied in the Power Generation and Petrochemical Industries. The development towards higher service temperatures ask for new materials, both for base material as for welding consumables.

To illustrate typical examples of where the various CrMo materials are applied, an overview of typical applications of CrMo steels in the Power Generation and the Petrochemical Industry is given in Table 5.

With this paper we intended to provide an overview of the available materials, the standards, the consequences and the implications with regard to welding, heat treatments and fabrication. When the correct procedures are developed up front and adhered to throughout the production, projects can be and have been successfully completed.

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