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Welding Challenges in Reactor/ Pressure Vessel Construction for Oil and Gas Refining Applications

Abby Joseph
voestalpine Böhler Welding India Pvt. Ltd., Mumbai, India
Email: Abby.Joseph@voestalpine.com
ORCID: Abby Joseph: https://orcid.org/0000-0003-0450-2940

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Abstract

In this article, different challenges faced by a welding personnel during reactor/ pressure vessel construction for oil and gas refining applications are discussed in detail. Advancements in the design and materials of the reactor / pressure vessel are outlined and correspondingly the need of selecting appropriate strategy for welding and fabrication of these equipment is highlighted in this paper.

Keywords: Welding; reactor; pressure vessel; oil and gas refinery; challenges.

1.0 Introduction

Petroleum refining today is unusually sophisticated in comparison to the past, and the industry shows every indication of becoming even more complex. Chemical and mechanical engineering advances are being sought to increase product yields and improve plant-operating reliability. Methods are being developed to remove potential pollutants from processes as well as products. Changing national interests among oil-producing countries are affecting sources of raw crude supplies. One result of these changes is a growing emphasis on materials engineering, and greater interest is being shown in the high-alloy, corrosion resistant steels, especially stainless steels, to cope with a wide variety of raw crudes as well as processed outputs.

Oil and gas play an important role in the future global energy supply model. However, the emergence of new and unconventional sources of oil and gas will change the landscape with regard to extraction and processing in many significant ways. Upstream Oil & Gas refers to the search for crude oil and natural gas, followed by their recovery and production. This segment is also referred to as the Exploration and Production (E&P) sector; it includes the search for potential underground or sub-sea oil and gas fields, the drilling of exploratory wells, and the subsequent drilling and operation of the wells that recover and bring the crude oil and/or raw natural gas to the surface. Downstream Oil & Gas refers to the refining and processing of the extracted oil and gas from both conventional and unconventional resources. This segment is also referred to as hydrocarbon processing and includes refineries, natural gas processing plants, Olefins and Aromatics as well as Methanol plants.

Global demand for fuel products is increasing. The quality of petroleum compounds, such as crude oil or natural gas that is extracted in different geographical locations varies, and extra-heavy oil is playing a more significant role than in the past. More sources of unconventional oil and gas from oil sands and shale have been recently explored, and they have been receiving a great deal of attention. Today, environmental regulations with regard to fuels and petrochemical products have become more stringent.

A good example is development of vanadium-enhanced Cr-Mo steels, which require special weld fabrication expertise. Welding consumables may seem to be a very small part of this industry, but almost all oil and gas downstream experts confirm that welding and welding technologies are the main drivers in the development of optimized process reactors and furnaces. The requirements for welding consumables in the downstream segment are generally considered more stringent than the conventional standard requirements for the same grades in other fields.

1.1. Reactor or Pressure Vessel Construction

Mainly there are two different types of reactors –

Clad type –

- Base material: 1.25Cr-0.5Mo / 2.25Cr-1Mo / Enhanced / 2.25Cr-1Mo-0.25V steel plates / forging in Normalized and Tempered or Quenched & Tempered condition with impact requirement down to (-)29°C and in some cases even lower.
- Clad material: 3mm thk. SA240 Type 347/ Type 304L.

Weld overlay type –

- Base material: 1.25Cr-0.5Mo / 2.25Cr-1Mo / 2.25Cr-1Mo-0.25V steel plates / forging in Normalized and Tempered or Quenched & tempered condition with impact requirement at (-) 29°C;
- Weld overlay: Double layer (SS 309L + SS347/308L) or single layer SS347/308L meeting 3mm clean SS347 / 308L chemistry at the top.

To illustrate the criticality in welding of Reactor / pressure vessel, this paper will focus on the following three examples:

1. Fabrication of Hydroprocessing reactors
2. Stainless Steel Bismuth Free Flux-cored Wires for High Temperature Applications
3. Fabrication of Coke Drum within confined Yield Strength criteria.

2.0 Fabrication of Hydroprocessing Reactors

In oil refineries, Hydrocracking / Hydro-treating reactors are vessels meant for hydrogen service and are the most important part of gas oil cracking / treating plant. Process flow schemes for hydro-treating and hydrocracking are similar. Both use high-pressure hydrogen to catalytically remove contaminants from petroleum fractions. In hydro-treating units, reactions that convert organic sulfur and nitrogen into H2S and NH3 also produce light hydrocarbons, hence these are high pressure, high temperature reactors. The reaction occurs in the presence of catalysts and at a pressure of more than $100 kg/cm^2$ (g) and temperature between 425°C and 482°C. Hydrogen is added in the process intentionally and the same hydrogen under very high pressure and temperature creates very high risk of hydrogen dis-bonding and cracking. The situation further gets worsen with the presence of highly corrosive hydrogen sulphide atmosphere. The combined effects of these factors make these reactors among the most critical equipment in refineries.

The common element among hydro processing reactors of this type is the use of advanced 2.25Cr-1Mo-0.25V material, which has numerous merits over conventional grade material, including greater tensile strength at elevated temperatures, enabling the industry to use reactors with lower wall thickness and weight (about 25% less weight). Additionally, it makes reactors less susceptible to damage mechanisms, such as temper embrittlement and high temperature hydrogen attack (HTHA) and last but not least, it provides stronger resistance to weld overlay dis-bonding induced by hot hydrogen.

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 consumables manufacturers 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.

2.1. 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 Normalizing, 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 weld metal; with increasing alloy content, the Post Weld Heat Treatment (PWHT) for welded joints gets more complicated. 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 maximum temperature of 760°C for P91 shall not be exceeded. For T/P23, an Intermediate Stress Relieving is indicated for constructions with different material thicknesses. For each application the optimum PWHT shall be determined. Further elaboration is given in **Table 1** and discussed later.

2.2. 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 weld metal.

Watanabe: J = (Mn + Si) x (P + Sn) x 104 elements in wt%

Bruscato: X = (10 P + 5 Sb + 4 Sn + As) / 100 element in wt% and result in ppm

To which extent this phenomenon will occur depends merely on temperature and time. 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 weld metal. 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/. 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 weld metal 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.

2.3. 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. 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 H_2S, sufficient sulphidation corrosion resistance is required for petrochemical installations. Another important phenomenon is High Temperature Hydrogen Attack (HTHA), a formation of Methane from Cementite (Fe3C + 2H2 $\rightarrow$ CH4 + 3Fe) in the base material under high Hydrogen pressures at high temperatures, This results in decarburization of the base material and loss of mechanical properties. These methane bubbles also initiate cavity formation. The 2.25%Cr1Mo and 3%Cr1Mo steels are typical base materials with good resistance to HTHA in this application, however 2.25%Cr-1.0%Mo-0.25%V, the material results in to stable carbide formation and finally resulting in to restriction of decarburization and increase in methane partial pressure. Hence 2.25Cr-1Mo-0.25V material has got much better resistance to hot hydrogen attack as compared to conventional 2.25Cr-1Mo material. In addition to the above due to the presence of "V" in the form of fine Vanadium carbides in 2.25Cr-1Mo-0.25V steel eventually traps hydrogen, thereby reducing hydrogen diffusivity and that is the reason, such steel shows much improved hydrogen dis-bonding resistance than conventional Cr-Mo steels due to this reason.

2.4. Welding and Welding Consumables for CrMo Steels

As a general practice, 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. On the similar lines, the heat affected zone (HAZ) is a susceptible area, which is always a matter of concern. In principle, all arc-welding processes can be applied as SMAW, GTAW, GMAW, SAW and FCAW. With any welding process with gas- shielding, it is important to ensure to have adequate shielding. Since the preheating requirement is higher in such cases, the gas-shield may get distorted and provide lesser protection as against the requirements. Special nozzles and gas cups are developed to reduce the problem. Over the last decades, voestalpine Bohler Welding 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 1**.

Depending on the alloy level, from only 0.5% to 2.25%Cr-1.0%Mo-0.25%V 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 2**. The consumables should meet the hot tensile at operating temperature after longer max. PWHT (32 Hrs or sometimes 34 Hrs). Generally, for Hydro-Processing unit the operating temperature is 454°C.

Table 1 : Selection table for the respective welding consumables and welding processes for creep resistant CrMo steels

CrMo type	BASE MATERIAL		WELDING CONSUMABLES FOR CrMo STEEL					
						SAW		FCAW
	ASTM & ASME	EN	SMAW	GTAW	GMAW	WIRE	WIRE	
0.5 Mo	T/P 1	8MoB 5-4	Phoenix SH Schwaz 3K	Union I Mo	Union I Mo	Union S2 Mo	UV 420 TT	Union TG MoR
1.25Cr- -0.5Mo	T/P11	13 CoMo 5.5	Phoenix Chromo 1	Union I CrMo	Union I CrMo	Union S2 CrMo	UV 420 TT	Union TG CrMoR
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 CrMoR
1.25Cr- -1MoV	--	15 CrMoV 5-10	Phoenix SH Kupfer 3K	--	--	--	--	--
--	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 MnMo-Ni 5-5	Phoenix SH Schwarz 3 K Ni	Union I Mo	Union I Mo	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 CrMo2	UV 420 TTR	Union TGr Mo 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	7CrMo-WV MoNb 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	7CrMo- VTiB 10-10	Thermanit P24	Union I P24	Union I P24	Union S P24	UV 430 TTR-IW	-UV P24

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

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	PWHY/STC h°C
0.5 Mo	T/P 1	8MoB 5-4	RT	RT	204h@ 580-630°C		
1.25Cr- -0.5Mo	T/P 11	10CrMo 5-5	200-250°C	>200°C	2-4h @ 660-700°C		STC depending on application
1.00Cr- -0.6Mo	T/P 12	13CrMo 4-5	200-250°C	>200°C	2-4h @ 660-700°C		
1.25Cr- 1MoV		15 CrMo 4-5	200-250°C	> 200°C	2-4h @ 580-620°C		60h @ 550°C + 40h @ 620°C
	T/P 36	15 NiCuNb 5 (WB 36)	200-250°C	> 200°C	2.4h @ 580-620°C		
		21 MnMoNi 5-5	200-250°C	> 200°C	2-4h @ 580-620°C		
2.25Cr - 1 Mo	T/P 22	10 CrMo 9-10	200-300°C	200-300°C	2-4h @ 670-720°C		
2.25 Cr- 1MoV	T/P 22V		200-300°C	200-250°C		1h @ 680°C	8h @ 705°C + STC +32h @ 705°C
+ with great differences in wall thickness ++ no PWHT required for GTAW upto wall thickness of 10 mm							x depends on thickness

The requirement of heat treatment is also based on the thickness of the construction and needs 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 heavier sections, heating up from as many sides as possible to get the required heat distribution in the material and ensuring the mass achieves the equilibrium requires a lot of experience. Such precautions help in safeguarding the base material, the weld metal and the heat affected zone (HAZ).

Depending on the application, there can be requirements for Step Cooling Test and Bruscato's X- factor. Generally, it would be preferred to have X- factor ≤ 12 ppm. 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 voestalpine Böhler Welding has built up over the last decades, the support that can be provided to the customers has become an important link in the supply chain in today's business.

As already mentioned, the thicknesses for a welded part in the 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. However, the usage of usage of 2.25%Cr-1.0% Mo Enhanced is limited due to the complications involved, mainly after welding.

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 preheat and inter-pass temperatures given in **Table 2** are to be followed strictly throughout completion of the joint. For such applications, SMAW is very suitable considering its flexibility and low investments in the infrastructure. In order to increase efficiency, higher weld metal deposition per unit of time, development is ongoing for FCAW consumables for CrMo steels. As listed in **Table 2**, a number is already available but the range will be extended upon the demand of the industry. The SAW process is widely used process for welding of Hydro Processing Equipment. GTAW is mainly used for root welding or automated welding in demanding industries. The GMAW range is available but not so popular; however, some fabricators have already established the procedure as well as using the same in certain areas.

Another practical example is that of a Reactor build in 2.25%Cr-1%Mo steel. **Fig. 1** 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.

Technical Details of the Reactor :

Base Metal	:	2,25%Cr-1% Mo
Thickness	:	124, 132 & 153 mm about 500
Total Weight	:	120 bar pressure and 437°C
Service conditions	:	SAW : Union S1CrMo2/UV 420TTR SMAW : Phoenix SH Chromo 2 KS

Fig.1 : Heavy wall reactor in 2.25% Cr- 1% Mo by Godrej, India

2.5. Parameter control and suggestions for "Best Practice"

CrMo(V) weld metal typically shows a bainitic/martensitic micro structure, which is very sensitive and responds quickly to any kind of heat put, either by means of welding and heat treatments. Furthermore, since the strength achieved in as welded conditions, which is very high, it requires accurate handling in terms of Hydrogen and ISR. This is in order to avoid cracking due to Hydrogen and/or the restrained condition of welds in heavy wall nozzles. To elaborate on some of the influences, typical observations in welds made in CrMo(V) creep resistant steels are illustrated in the next paragraph.

Just to highlight the effect of excessive PWHT in such CrMo steels, refer the **Fig. 2**, which shows ferrite precipitations in P11 due to excessive PWHT temperature and such ferrite precipitation leads to loss of strength mainly impact. The micrograph in **Fig. 3** shows hydrogen damage due to an improperly applied soaking treatment, leaving too much residual Hydrogen in the weld metal. **Fig. 4** 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

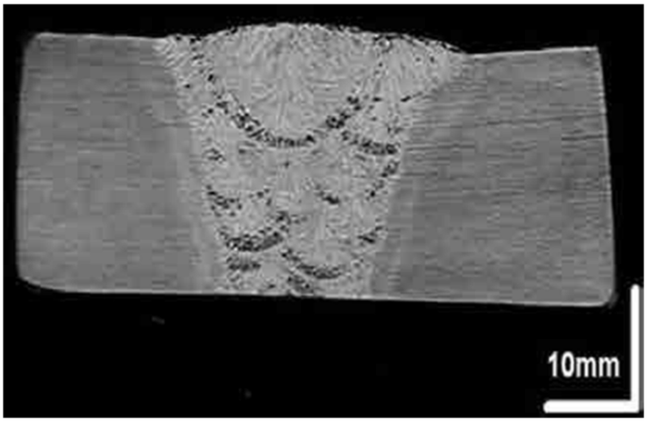


Fig. 2 : Ferrite precipitations in P11 SA welds

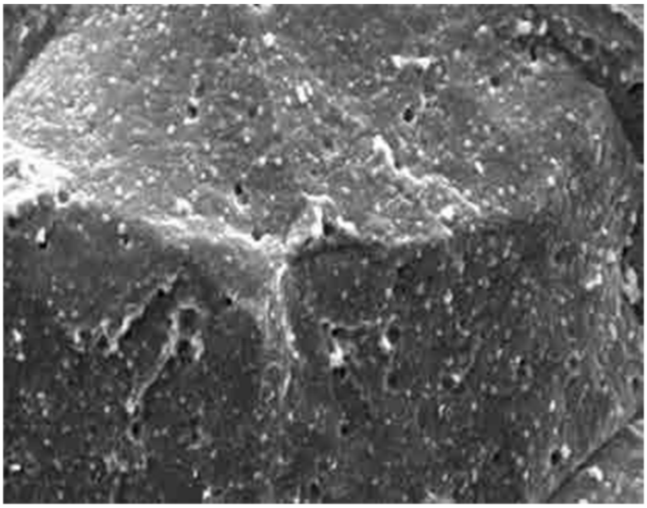


Fig. 3 : Crack surface due to Hydrogen in P22V SA welds

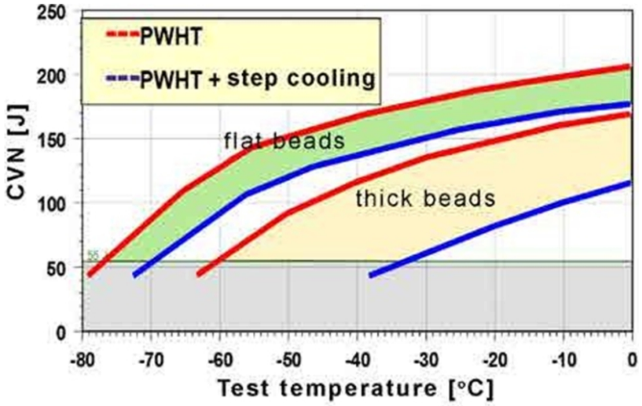


Fig. 4 : Influence of weld build-up on impact toughness

Applicable manufacturing parameters, which comprises of welding parameters employed during the welding and also quality of the welding equipment as well as the skill level of the welders, become more important with an increasing initial strength. The "operating window" will become smaller.

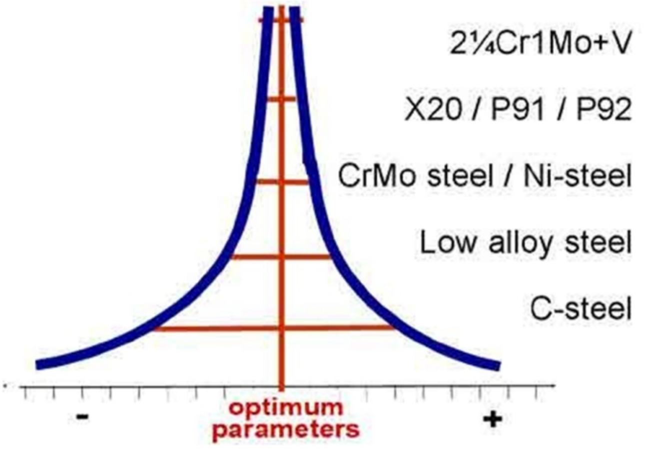


Fig. 5 : A typical Quality Assurance (QA) system

Therefore, suitable control mechanisms and procedures have to be set up to ensure the proper application of the required parameters. To be specific, the control of the following items shall not be neglected for achieving successful welds:

- Selection of the suitable SAW wire & flux combination
- Proper re-drying of fluxes and electrodes
- Verification of preheating & interpass temperatures and following the strict window
- Setting of the electrical welding parameters
- Weld build-up and bead sequence
- Verification of the heat treatment temperature.

Almost all issues encountered in CrMo welds could be related to the non-observance 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 in **Fig. 5.**

To conclude, we can say that CrMo creep resistant steels are widely and successfully applied on Hydro-processing equipment with many precautions, including selecting the right consumables to welding with utmost care.

This means as the as welded strength of the welded joints goes up, the consumables selected needs to have specific properties like very low level of impurities (X factor ≤ 12ppm) with very high resistance to temper embrittlement (consumables meeting step cooling requirements), relatively good level of impact in as welded condition, very high level of consistent impacts after min PWHT, requisite hot tensile properties, stress rupture properties for SAW consumables, compliance to "K" factor for SAW consumables for CrMo(V) and meeting test requirements like to ensure the products meeting resistance to re-heat cracking.

3.0 Stainless Steel Bismuth Free Flux-cored Wires For High Temperature Applications

Flux-cored arc welding (FCAW) is used to achieve good surface finishes, which makes post fabrication cleaning easier when welding stainless steel. Due to wider parameter box, the method is welder friendly. The productivity is higher than in gas metal arc welding (GMAW) with higher deposition rates, which can reduce the total welding costs considerably. Furthermore, pulsing is not necessary. As compared to GMAW, the wide arc in FCAW provides uniform, deep penetration, and improved side-wall fusion. This reduces the risk of weld defects (lack of fusion). There is also less risk of spatter and porosity. In addition, the shielding gas costs are lower than in GMAW. Optimal weldability and mechanical properties are achieved using Ar + 18-25% CO_2, but some fabricators prefer 100% CO_2 to reduce gas costs. FCAW is frequently used for general fabrication and on-site welding of stainless steel.

By optimization of the flux in cored wire, it is possible to deoxidize the weld metal, to form slag, to stabilize the arc, and to add metal powder. This in turn influences the welding characteristics, deposition rates, and mechanical properties. The slag concept also determines in which position the material can be used for welding. AWS T0 types are suitable for welding in flat/horizontal position and overlay welding (cladding). AWS T1 types feature a fast-freezing slag system supporting the weld pool when welding in all positions. These wires are, for instance, used for welding pipes in fixed position.

Modern austenitic stainless steel FCAW wires contain a small amount of bismuth oxide (Bi_2O_3) for improved slag detachability and for the production of a clean toe line, especially in fillet welds [1]. The weld deposit typically contains 0.02 wt% bismuth (200 ppm), and there have been reports of inter-granular cracking and premature creep failure in such weldments after a period of service at 650-750°C. Different fractographic studies have shown presence of bismuth or bismuth oxide on the surface of fractured creep specimens. The vast majority of stain- less steel weld deposits are put into service below about 250°C (480°F), but within power generation and process industries, extended service can exceed temperatures of 480°C (900°F). It is in these latter weldments that bismuth creates problems. Cracking may also occur when carrying out a post weld heat treatment (PWHT), when weld overlaying carbon steel, or after repair of castings. Critical process equipment in refineries such as heavy-wall reactors or pressure vessels for hydro-treating and hydro-cracking is normally made in low-alloyed creep resistant steels, i.e. 1¼Cr-0.5Mo, 2¼Cr-1Mo, 2¼Cr-1MoV and clad internally with alloy 347. Some areas such as the inside of nozzles and fittings cannot be covered by clad plates and/ or strip cladding and need separate overlay welding. This is efficiently done using the FCAW process with a 309 L buffer layer between the creep-resistant steel and the 347 layer. This type of equipment is typically operated at temperatures below 500°C, but, depending on the alloy grade and requirements on mechanical properties, a final PWHT is performed at 660-710°C, in addition to other intermediate PWHT. Thus the weld overlay deposit is exposed to temperatures where bismuth-alloying may cause cracking. FCAW overlay welding is also performed using 308 H. One application is restoration of fluid catalytic cracking (FCC) regenerators that operate at temperatures above 700°C. At these temperatures, bismuth segregates in the grain boundaries and failure cases reported in the literature often refer to FCC regenerator equipment [3].

Once the detrimental effect of bismuth on high temperature properties was recognized, some end user plant operators placed a complete ban on the use of FCAW for certain critical applications [1]. Today there are stainless steel FCAW wires without bismuth (less than 20 ppm) whose deposits do not exhibit heat cracking or premature creep failure. Weld metals deposited from bismuth-free FCAW wires have been shown to have high-temperature creep properties on par with those made with other welding processes and consumables [8]. Konosu et al. [6] carried out creep tests at 650°C on Type 308 FCAW weld metal with 230 ppm bismuth and compared these with bismuth-free FCAW and SMAW deposits. It was concluded that FCAW wire alloyed with bismuth caused segregation of bismuth in the grain boundaries and that this was harmful with respect to creep ductility and creep crack growth properties. There was no large difference in creep fracture elongation between the SMAW and FCAW weld metals both of which contained no bismuth. The American Petroleum Institute (API) has incorporated a limit of 20 ppm bismuth in austenitic stainless steel FCAW deposits in API RP 582 "Welding Guidelines for the Chemical, Oil, and Gas Industries" [9] when these weld metals are exposed to temperatures above 1000°F (538°C) during fabrication and/or during service. AWS A5.22:2012 [10] states that stainless steel electrodes containing bismuth additions should not be used for such high temperature services or PWHT above about 900°F (500°C). Instead stainless steel flux-cored electrodes providing no more than 20 ppm (0.002 wt%) bismuth in the weld metal should be specified. These wires are promoted by manufacturers as bismuth-free.

Farrar et al. [1] performed a round robin within IIW Commission IX-H where nine laboratories from six countries analyzed the bismuth content of weld deposits from two stainless steel flux-cored wires-one with deliber- ate additions of bismuth oxide and one without. The bismuth content in the bismuth-free sample was reported to be 0.6-20 ppm, which reflects the detection limit. On the basis of these results, a practical threshold limit of less than 20 ppm seems acceptable for the specification of "bismuth-free" weld metal. There is, however, no reason to impose this requirement on stainless steel FCAW wires that are not to be used for high temperature service or PWHT. Details are given in **Table 3**.

The increased need of high quality bismuth-free products for high-temperature applications here motivated evaluation and optimization of existing products for joining and cladding. Besides maintaining the mechanical properties, the aim was to ensure welding characteristics and slag detachability to be as good as for the standard FCAW wires containing bismuth. As the alloys 347, 347 H, and 308 H are frequently used in high-temperature applications, matching all-position T1 FCAW wires were developed for welding. For cladding, the largest demand was for flat/horizontal T0 FCAW wires of 309 L and 347 types.

3.1 Experimental work

The composition of the filler metals used in this work and the measured ferrite number are shown in **Table 3**. The T1 type E 347 H PW-FD has intentionally higher carbon content as the main application for this wire would be joining and there is a typical industry requirement for the carbon content to exceed 0.04 wt%. For cladding applications, the T0 type E 347 L H-FD has lower carbon content as typical industrial solutions result in about 0.03 wt% in the final layer. All weld metal samples were prepared in accordance with EN 15792-1 using Ar + 18% CO_2 as shielding gas. The samples were either left in as-welded condition or underwent PWHT following the Godrej specifi-

Table 3 : Composition of all-weld metal (wt%). All wires had a diameter of 1.2 mm.
All wires with an 'H' in the product name and AWS designation are bismuth free (max. 0.001 wt%)

Filler	AWS	C	Si	Mn	Cr	Ni	Mo	Nb	FN[a]
SAS 2-FD	E347T0	0.040	0.53	1.67	19.58	10.60	0.040	0.370	7.2
E 347 L H-FD	E347T0	0.033	0.59	0.43	18.78	10.24	0.04	0.439	6.7
SAS 2 PW-FD	E347T1	0.024	0.69	1.43	19.35	10.28	0.05	0.340	8.0
SAS 2 PW-FD (LF)[b]	E348T1	0.022	0.73	1.42	19.22	10.60	0.08	0.440	6.1
E347 H PW-FD	E347T1	0.044	0.71	1.46	18.52	10.55	0.08	0.424	6.1
CN 23/12-FD	E309LT0	0.024	0.67	1.43	22.65	12.35	0.07	0.004	17.6
E 309 L H-FD	E309LT0	0.034	0.58	1.36	23.13	12.62	0.07	0.012	14.8
CN 23/12 PW-FD	E309LT1	0.027	0.72	1.53	22.91	12.41	0.05	0.006	20.4
E309 LH PW-FD	E309LT1	0.032	0.65	1.31	23.30	12.29	0.02	0.006	18.2
E 308 H PW-FD	E308HT1	0.053	0.7	1.43	19.69	10.56	0.05	0.003	6.7

a Ferrite measured with Fischer FerritScope MP30
b Low Ferrite version for improved impact toughness at cryoderic temperatures

Table 4 : Welding parameters for V joint

Filler	Base metal	1 [A]	U[V]	Wire feed speed (m/mm)
SAS 2 PW-FD	1.4550	245	30.7	11.0
E 347 H PW-FD	1.4550	250	28.0	11.0
CN 23/12 PW-FD	1.4541/S355N	250	30.5	11.0
E309 L H PW-FD	1.4541/S355N	241	27.9	11.1

cation WCPS/130615–130641 [11]. The heating rate was 85°C/h from 300°C, the test temperature 600–800°C, and holding time 8–48 h. The welded samples were subject to tensile and Charpy V impact toughness testing (DIN EN 1591-1/Form 3). The tensile tests were carried out on single specimens and impact testing on three samples for improved statistics. The mechanical properties of actual joints were also determined using 20 mm thick base material prepared as V joints with 60° opening angle, 1.5 mm unbeveled edge and 4 mm gap. It was filled with 6 layers and in total 10–11 weld beads. The shielding gas was Ar + 18% CO_2 and interpass temperature 150°C. The welding parameters are given in **Table 4**.

Hot tensile testing was performed at 500°C and 700°C in accordance with EN ISO 6892-2. The samples were welded with 100°C preheating and 150°C interpass temperature. The shielding gas was Ar + 18 % CO_2 and the gas flow 17 l/min. The base material was 20 mm thick Grade S 235 JR. The sides were buffered with two layers. The opening angle was 20° and the root opening 16 mm. It was filled with 7 layers and in total 15–16 weld beads. The welding parameters are given in **Table 5**.

Table 5 : Welding parameters for samples used for hot tensile testing

Filler	I [A]	U [V]	Welding Speed (mm/min)	Heat Input (J/mm)	Wire Feed Speed (m/min)
CN 23/12-FD	225	28.8	296	1.30	11.0
E398 K G-FD	225	28.9	300	1.29	11.0
SAS 2-FD	220	28.4	285	1.31	10.4
E 347 L H-FD	215	28.3	295	1.21	11.0

Table 6 : Mechanical properties of 309 type all-weld metal in as-welded condition

Filler	Tensile Test				Impact toughness (J)	
	$R_{P0.2}$ (MPa)	R_m (MPa)	[A_5(%)]	Z (%)	20°C	-60°C
CN23/12-FD	400	529	37.3	48.4	48	43
E 309L H-FD	402	542	40.4	58.0	69 ± 4	51 ± 4
CN 23/12 PW-FD	399	532	37.1	50.3	80 ± 8	45 ± 2
309 L H PW-FD	398	535	40.3	48.0	82 ± 4	64 ± 2

Table 7 : Mechanical properties resulting from the hot tensile test

Filler	Temp (°C)	R_p0.2 (MPa)	R_m (MPa)	A_5 (%)	Z (%)	Failure location[a]
SAS 2-FD	500	304	415	27.2	52.6	1
SAS 20FD	699	238	307	22.9	29	1
E 347 L H-FD	500	307	419	26.4	56.6	1
E 347 L H-FD	700	246	301	30.1	45	2
CN 23/12-FD	700	174	244	18.4	23.8	2
E309 L H-FD	700	180	249	38.9	48.2	2
E 308 H PW-FD	700	223	186	42.7	51.1	1
E 308 H PW-FD	800	151	133	34.0	41.9	1

[a] Failure location 1 means that the fracture was inside the middle half of the reduced section.
Location 2 means that the fracture occured where the distance between fracture and nearest gauge mark was less than 25%.

Overlay welding was performed on ASTM A387 Grade 22 (10 CrMo9-10) using E 309 L H-FD for the first layer and E 347 H-FD for the second. The shielding gas used was Ar + 18% CO_2 and the welding position was flat 1G/PA. The overlapping was about 50% as shown in **Fig. 6**, and the interpass temperature was held below 150°C. The welding parameters used were 240-245 A, 28.8-29.1 V and 12 m/min wire feeding rate. The test was repeated using E 309 L H PW-FD as buffer layer and E 347 H PW-FD as second layer. The interpass temperature was 150°C and the current 210 A with 10 m/min wire feed speed. The total resulting layer height was 5.0-6.5 mm. The wires for welding out of position were also tested in flat position (PA) and vertical up (PF). Good welding characteristics were obtained in flat position using 12 m/min wire feeding and 240-250 A. In vertical up position 8 m/min wire feeding and 160-170 A were used. Mechanical properties obtained at various conditions are tabulated in **Table 6** through **Table 11**. Compositions of first two layers made using TO and T1 wires are shown in **Table 12** and **Table 13** respectively.

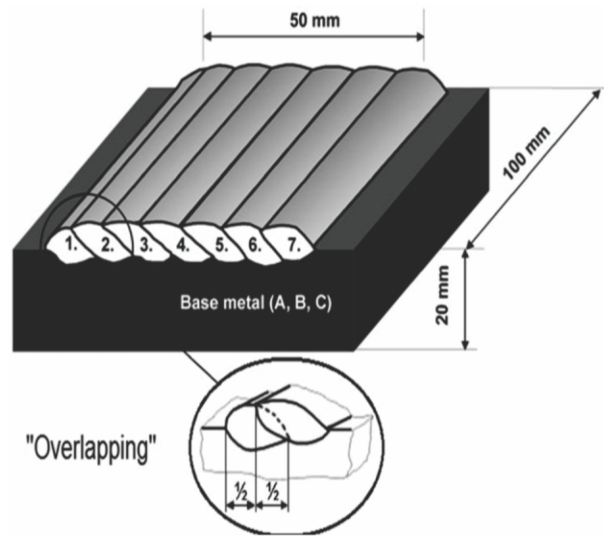


Fig. 6 : Schematic weld overlay with 50 % overlap

Table 8 : Mechanical properties before and after PWHT at 700°C

Filler	PWHT	Tensile test Rp0.2MPA	Rm (MPa)	A5 (%)	Z (%)
SAS 2-FD	None	426	585	40.7	49.3
SAS 2-FD	8 h	412	611	36.8	51.7
SAS 2-FD	36 h	427	646	31.1	41.1
SAS 2-FD	48 h	415	634	35.9	42.2
E 347 H-FD	None	416	582	40.4	54.6
E 347 H-FD	8 h	415	614	38.1	50.6
E 347 H-FD	36 h	425	641	38.7	41.9
E 347 H-FD	48 h	418	644	31.8	42.8

Table 9 : Mechanical properties with or without PWHT at different temperature

Filler	PWHT	Impact toughness (J)			Lateral Expansion (mm)		
		20°C	-120°C	-196°C	20°C	-120°C	-107°C
SAS 2-FD	None	80 ±5	41 ± 3	32 ± 2	1.49 ± 0.03	0.70 ± 0.03	0.60 ± 0.03
SAS 2-FD	8 h	64 ± 3	19 ±2	14 ± 2	1.25 ± 0.04	0.42 ± 0.03	0.34 ± 0.02
SAS 2-FD	36 h	36 ± 3	12 ± 1	13 ± 1	0.78 ± 0.11	0.24 ± 0.03	0.29 ± 0.05
SAS 2-FD	48 h	34 ± 1	12 ± 2	12 ± 2	0.78 ± 0.04	0.20 ± 0.03	0.26 ± 0.03
E 347 H-FD	None	86 ± 1	48 ± 2	41 ± 2	1.44 ± 0.17	0.79 ± 0.01	0.68 ± 0.02
E 347 H-FD	8 h	66 ± 3	22 ± 5	18 ± 1	1.20 ± 0.07	0.47 ± 0.07	0.42 ± 0.02
E 347 H-FD	36 h	37 ± 3	14 ± 2	14 ± 3	0.83 ± 0.09	0.26 ± 0.01	0.31 ± 0.04
E 347 H-FD	48 h	37 ± 2	13 ± 2	13 ± 1	0.89 ± 0.04	0.21 ± 0.01	0.29 ± 0.04

Table 10 : Mechanical properties of 347 type all-weld metal in as-welded condition (Z is the reduction of area)

Filler	Tensile Test			
	$R_p0.2$ (MPa)	Rm (MPa)	A_5 (%)	Z (%)
SAS 2-FD	426	585	40.7	49.3
E 347 LH-FD	423	591	40.8	53.9
SAS 2PW-FD	424	592	35	62
E 347 H PW-FD	423	592	39.3	57.8

	Impact Toughness (J)			Lateral expansion (mm)		
	20°C	-120°C	-196°C	20°C	-120°C	-198°C
SAS 2-FD	80± 3	41 ± 3	32 ± 2	1.49 ± 0.03	0.70 ± 0.04	0.60 ± 0.03
W 347 L H-FD	95 ± 1	55 ± 2	40 ± 2	1.64 ± 0.07	0.77 ± 0.02	0.57 ± 0.04
SAS 2 PW-FD	73 ± 2	40 ± 4	32 ± 2	1.53 ± 0.05	0.71 ± 0.04	0.48 ± 0.05
E 347 H PW-FD	100 ± 5	56 ± 4	38 ± 2	1.89 ± 0.01	0.95 ± 0.04	0.54 ± 0.04

Table 11 : Mechanical properties before and after PWHT at 700°C

Filler	PWHT	Tensile Test				Ferrite
		Rp0.2	Rm (MPa)	A_5 (%)	Z (%)	
SAS 2 PW-FD	None	408	577	39.8	61.5	8.0 - 9.5
SAS 2 PW-FD	8 h	415	602	34.0	54.2	4.0 - 5.1
SAS 2 PW-FD	48 h	428	642	33.7	46.5	2.9 - 5.5
SAS 2 PW-FD (LF)	None	443	609	39.5	47.4	5.1 - 6.7
SAS 2 PW-FD (LF)	8 h	466	647	29.8	44.2	2.4 - 3.7
SAS 2 PW-FD (LF)	48 h	444	657	31.4	51.2	1.9 - 2.3
347 H PW-FD	None	410	575	41.7	63.7	4.3 - 5.8
347 H PW-FD	8 h	415	608	36.7	49.6	2.2 - 3.3
347 H PW-FD	48 h	433	644	31.5	42.8	1.8 - 2.2

Table 12 : Measured composition of the first and second layer performed with T0 wires, wt%

Filler	Layer	C	Si	Mn	Cr	Ni	Mo	Nb	Ferrite
E 309 LH-FD	1	0.048	0.529	1.3	19.8	10.33	0.148	<0.004	8.9 FN
E 347 LH-FD	2	0.034	0.593	1.49	19.28	10.21	0.083	0.39	6.5-7.5 FN

Table 13 : Measured composition of the first and second layer performed with T1 wires, wt%

Filler	Layer	C	Si	Mn	Cr	Ni	Mo	Nb	Ferrite
E309 LH PW-FD	1	0.042	0.743	1.21	23.56	12.48	0.034	<0.004	9.3 FN
E347 H PW-FD	2	0.044	0.712	1.46	18.52	10.55	0.082	0.424	6.1 FN

4.0 CONCLUSIONS

New bismuth-free austenitic stainless steel flux-cored wires have been compared here to conventional wires for welding and overlay welding. The bismuth content is below 10 ppm and fulfills the requirement of max. 20 ppm in the weld deposit as stated by AWS A5.22:2012 and API RP 582. The bismuth-free wires showed improved resistance to embrittlement after post-weld heat treatment at 700°C, and the impact toughness and lateral expansion values were higher than for flux-cored wires alloyed with bismuth (**Fig. 7**). Hot tensile tests performed at temperatures typical for service or post-weld heat treatment confirmed significantly better elongation values for the bismuth-free wires as compared to the conventional wires.

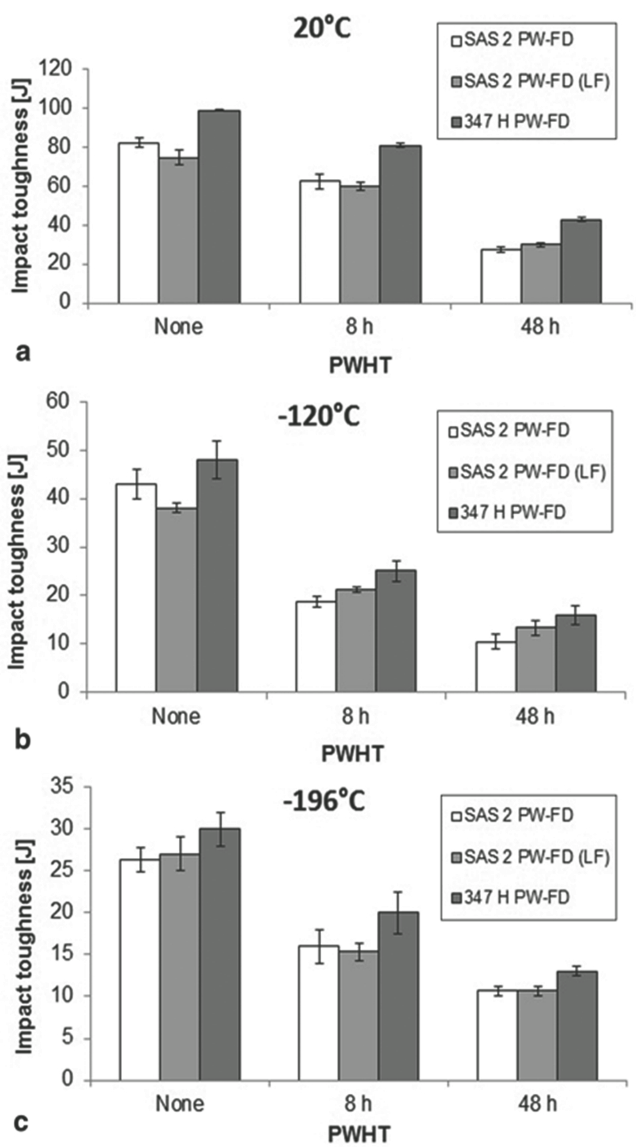


Fig. 7 : Variation of mechanical properties with varying PWHT

Despite the low bismuth content, the slag removal is very good. These wires were optimized for welding with mixed gas shield ing (Ar + 18% CO_2), but the weldability and slag removal were also acceptable with pure CO_2 (**Fig. 8-9**). Impact toughness of as-welded material and after PWHT at 700°C for 8 h and 48 h (a) tested at room temperature, (b) −120°C, and (c) −196°C. First layer cladding with E 309 L H-FD is showing good slag detachability (**Fig. 9**). The clad specimen is shown in **Fig. 10**.

Fig. 8 : Dye-penetrant test after first layer of E 309 L H-FD. No indication of cracks or porosity

Fig. 9 : Good slag removal for E 347 H PW-FD

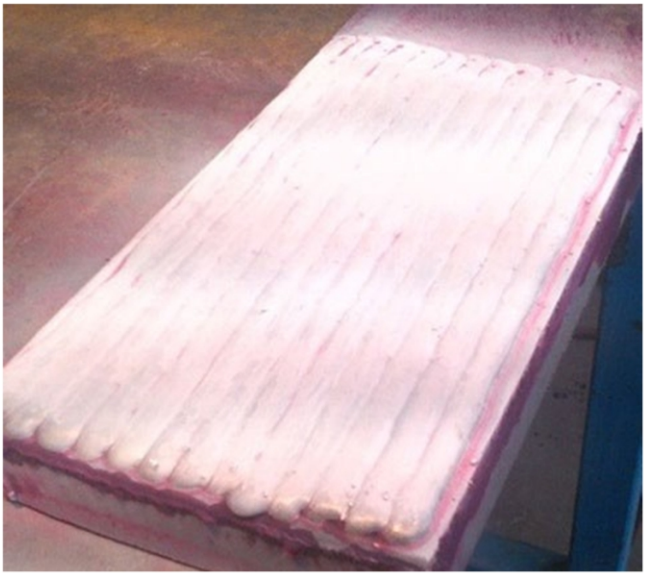


Fig. 10 : The cladded specimen

4.1. Challenges Involved in Fabrication of Coke Drum to Minimize Degradation Mechanism

Delayed coking is a form of thermal cracking used for processing "bottom of barrel" residuum, also called "resid." Products of the coking process include sour fuel gas, sour liquefied petroleum gas (LPG), naphtha, light coker gas oil (LKGO), heavy coker gas oil (HKGO) and coke. The coking process in the coke drums (**Fig. 11**) can be divided into a number of parts including steam out, heat up, feed introduction, warming with vapors from the adjacent drum, coking, steam stripping, quenching, un-heading and drilling. The unit normally takes the same amount of time for coking and decoking with the total cycle varying between 18 and 36 hours. Drums in delayed coking units' experience severe thermal cycling in normal operation, and as a result, incur various forms of damage. The idea of the discussion is to know the types of damages on the drum due to operational aspect of Delayed coking process and remedial action taken for minimizing such possible damages from point of welding.

4.2. Degradation Mechanism(s)

Commonly Observed Damage

Traditionally, drums in delayed coking units' experience severe thermal cycling in normal operation, and as a result, incur various forms of damage. **Fig. 11** illustrates various forms of damage due to thermally cycling encountered on drums. This "damage map" for coke drums provides general information on the nature of the damage and location on the drum where damage can be expected. The damage observed in coke drums occurs because of thermo-mechanical loads experienced during each operating cycle. A coke drum experiences a thermal load during the heating part of the cycle when hot resid is introduced into a relatively cool drum. Additionally, an even more severe thermal load can be experienced during the cooling part of the cycle when cool quench water is introduced into a relatively hot drum.

Drum distortion from thermal cycle is a result of cyclic thermo-mechanical loads that result in through-wall bending stresses in conjunction with membrane stresses. These thermal cycles cause cyclic straining of the material, which can result in failure by fatigue cracking and at the same time produce cyclic incremental growth of a drum, which frequently leads to the formation of permanent bulges or other forms of deformation on a drum. When load control mechanisms dominate, coke drums constructed from lower strength materials are more likely to experience thermal cycles and subsequent bulging than those constructed from higher strength materials.

Out of various form of observed damage mechanism, here we are going to discuss about Bulges in coke drum and the design approach employed mainly through selection of base metal and matching welding consumables (**Fig. 12**) (including the matching mechanical properties of weld metal)

Many drums (**Fig. 13**), especially ones fabricated from carbon and C-½Mo steels display bulges after years in service. **Fig. 14** shows bulging that has been experienced in drums. Experience indicates the most pronounced bulging occurs in the middle shell courses of a drum. This observed bulging has been attributed to large differences in the shell metal temperature from one area in the drum to another.

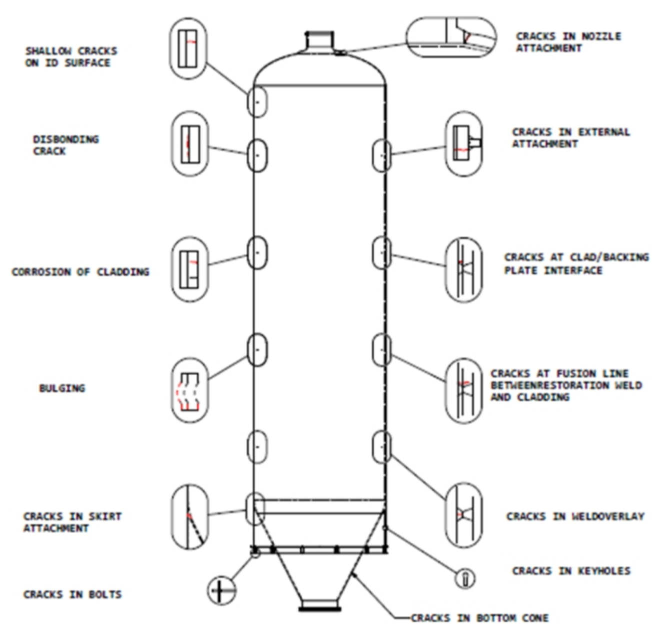
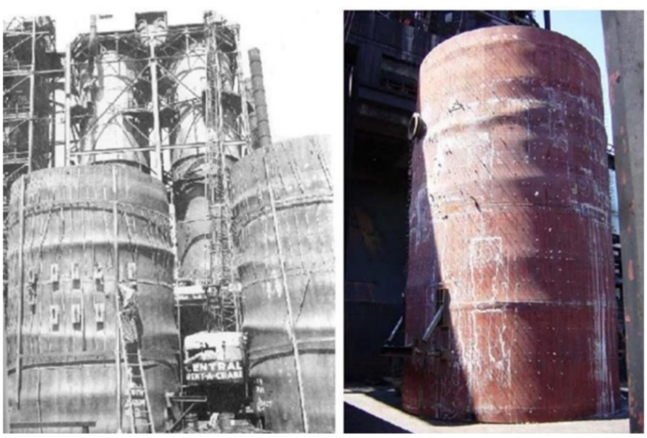


Fig. 11 : Scheme of the Coke Drum

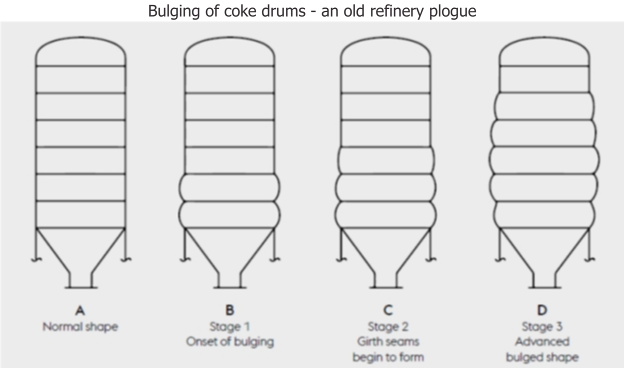
Fig. 12 : The welded portion of the component



Source: API Technical Report 934-G

Fig. 13 : View of the drum

Bulging of coke drums - an old refinery plogue



Bulging of coke drums. Source Coke drum design by Coby W. Stewart, Acron M. Stryk and Lee Presley Chicago Bridge and Iron 2006

Fig. 14 : Different bulging shapes of Coke drum

4.3. Design Approach

Broadly, there are two fundamentally different design approaches taken in the selection of materials for coke drums (**Fig. 13**). The most common approach employed today involves the use of 1¼Cr-½Mo, 1Cr-½Mo or 2¼Cr-1Mo steel, typically supplied as the higher strength Class 2 material with a minimum specified yield strength of 45 ksi. Depending upon the licensors and their philosophy in general, some of them select 1¼Cr-½Mo steel plate meetings the requirements for ASTM A-387 Grade 11, Class 2 and on the other hand some select, 1Cr-½Mo steel plate meetings the requirements for ASTM A-387 Grade 12, Class 2, and some select 2¼Cr-1Mo steel plate meetings the requirements for ASTM A-387 Grade 22, Class 2. Additionally, selected requirements included in either API Recommended Practice 934C or 934E also are included imposed. There are even a few plate suppliers that provide 1¼Cr-½Mo or 2¼Cr-1Mo heat treated to a higher minimum room temperature yield strength of 60 ksi. The reason for specifying the higher yield strength is to improve the resistance of the drum to bulging during cooling in the operating cycle of the drum. A higher strength material is more resistant to deformation and bulging as a result of contraction of the steel against solid coke when the drum cools during each cycle. Based on the stresses resulting from the combination of pressure and weight loads, and the loads associated with the contraction of the drum shell against solid coke during each cycle, it was determined that a higher yield strength material provided the best overall life and resistance to bulging. Drums employing higher strength plate steels tend to display less bulging which is supported by past survey data. However, the past survey data also indicates the drums fabricated from higher strength steels may be more susceptible to cracking earlier in the drum life.

The second approach that has more recently been proposed is based on specifying a material which has improved fracture ductility. In this case, the primary concern are thermal loads that occur during each operating cycle of the drum. Thermal loads are associated with uneven heating and cooling of the drum. They are displacement controlled loads and are much different than the more commonly encountered applied loads like those due to pressure and weight. In this situation materials are selected to maximize the fracture ductility to best accommodate displacement controlled loads without cracking. In general, this involves selecting steels with a lower strength than commonly specified today and with a fine grain size in order to maximize fracture ductility. This also generally involves the use of steels that are less hardenable (carbon steel and C-½Mo instead of Cr-Mo steels) so that weld deposit, heat affected zone and base metal generally have similar strength levels. Because of the lower yield strength that will be associated with these materials, distortions such as bulging from ratcheting will typically be more prevalent. However, steels in this condition typically will accommodate more deformation and bulging before cracking occurs.

4.4. Materials Selection Including Plate Material, Welding Consumables and Cladding

Five materials typically have been used for plates to fabricate coke drums. These are carbon steel, C-½Mo, 1Cr-½Mo, 1¼ Cr-½Mo and more recently 2¼Cr-1Mo. By far, the most commonly used materials today for coke drums are 1¼Cr-½Mo and 1Cr-½Mo. The use of Cr-Mo steels over carbon steel and C-½Mo has occurred as furnace outlet temperatures have moved above the 900ºF (482°C) to 940ºF (504°C) range favoring the use of steels with improved strength at higher temperatures. However, some refiners still prefer replacing carbon steel and C-½Mo drums in kind because of their past experience and their ease of repair. Other refiners have moved in a different direction using higher alloy steels such as 2¼Cr-1Mo and even 3Cr-1Mo-¼V.

1Cr-½Mo and more predominantly 1¼Cr-½Mo plate have been selected for drums designed using the fatigue curves in Section VIII of the ASME Code as further discussed in paragraph 4.4 below. 1Cr-½Mo steel is favored by some licensors and owners/operators over 1¼Cr-½Mo steel because the properties of repair welds especially those performed without PWHT are expected to be better. More recently 2¼Cr- 1Mo plates have been selected for coke drums in a limited number of cases since this steel has better crack arrest properties, higher toughness and can more readily achieve a higher minimum specified yield strength, when one is specified. Additionally, in some recent drum fabrication, it has been specified that all plates used for a single drum shall not have a variation in yield strength greater than 6 ksi between adjoining plates. This requirement has been used for the lay-out of plates in the shop and not as part of the specification in the purchase order of the plates. This has been specified in order to minimize the strength mismatch between adjoining plates in a single drum. **Fig. 12** may be seen for a typical coke drum plate layout indicating plate yield strengths and thicknesses. In order to comply with a requirement to minimize the variation of the yield strength to less than 6 ksi between adjoining plates, it is necessary to layout individual plates with their respective mill certificates to ensure the strength variation requirement for adjoining plates is met.

In some more recent designs, as discussed in paragraph 4.1, the emphasis has been placed on maximizing fracture ductility and not yield strength. In this case, C-½Mo manufactured to a fine grain practice has been specified. This means the steel is normalized with the possible addition of a tempering step after normalizing. Additionally, the C-½Mo has toughness requirements, typically requiring a minimum average Charpy impact value of 40 ft-lb (55 J) at 0°F (-18°C) and meeting the Charpy impact levels at the minimum design metal temperature (MDMT) as defined in the ASME Code Section VIII Division 1 (paragraph UG-20). The primary reason for specifying C-½Mo versus the more commonly specified 1Cr-½Mo and 1¼Cr-1Mo is that it maintains good high temperature ductility in the weld heat affected zone (HAZ), unlike 1¼Cr-½Mo heat treated to a higher strength level which displays a reduced ductility in the weld HAZ in high temperature service. Additionally, C-½Mo weld repairs pose less difficulties than Cr-Mo weld repairs. This is a major consideration in maintaining drums in coking units. The one concern associated with the use of C-½Mo that can operate at temperatures for long periods of time above 850°F (454°C) is graphitization and/or spheroidization. Graphitization and/or spheroidization can result in a loss of the high temperature strength and does represent a potential concern with the use of C-½Mo for drum construction, especially if the drum operates at temperatures above 850°F (454°C). Additionally, "eye brow" graphitization in the HAZ of welds is likely to create a zone of low ductility that may crack in service.

Most coke drums are clad with a layer of corrosion resistant alloy (CRA) to prevent high temperature sulphidation. The most commonly used cladding material is Type 410S stainless steel. There are, however, a minimal number of drums clad with Type 405 stainless steel. Both steels contain a nominal 12% by weight chromium to resist sulphidation and have a specified low carbon level that allows back cladding restoration without PWHT. Additionally, Type 405 and 410S stainless steels have a thermal coefficient of expansion compatible with the commonly used Ferritic steels for coke drums. In situations where an austenitic stainless steel like Type 304 stainless steel has been used for the cladding, the large thermal coefficient of expansion for this steel has resulted in accelerated cracking of the cladding. Typically, cladding on coke drum plates is applied either by a hot rolling process or explosive bonding during the plate manufacturing process. The 12Cr cladding applied by either of these processes is specified by ASTM Standard A 263, Standard Specification for Stainless Chromium Steel-Clad Plate. Inconel 625 also has been used for cladding in a few coke drums. This alloy has a very high strength compared with Type 410S or Type 405 stainless steel and its thermal coefficient of expansion more closely matches the various backing steels used for coke drums. In several cases, Inconel 625 has been used to clad the bottom cone in a coke drum, because overlay plates in some circumstance can be supplied faster than clad plates. Experience indicates that Inconel 625 appears to provide superior erosion and corrosion resistance that in some cases is needed for the bottom cone. Type 410S and Type 405 stainless steel possess an inferior erosion resistance and have been known to wear away in the bottom cone from coke erosion when the coke is dumped from the drum. Inconel 625 also has been used in cases where a 12Cr cladding has experienced severe corrosion from the quench water introduced during the cooling portion of the operating cycle.

It is necessary to restore the cladding at all seam welds on the coke drum. Most commonly used welding consumables to restore Type 405 or 410S stainless steel cladding at the weld seams are Ni-based welding consumables using either GMAW, GTAW, SMAW, FCAW, SAW and ESW. welding processes. These welding consumables provide the best combination of properties (strength, corrosion resistance and coefficient of thermal expansion) suitable for a restoration weld of Type 410S stainless steel cladding.

4.5 Compositional Controls for 1¼Cr-½Mo Plate and Welding Consumables

1¼Cr-½Mo is the most commonly specified material for coke drums as indicated in the most recent survey of owner/users. Special compositional controls have been specified by some for both the plate and welding consumables in order to minimize embrittlement which can occur during extended service at high temperature. Typical compositional controls imposed on 1¼Cr-½Mo plate, forgings and welding consumables are expressed as the X-bar factor as follows:

$X\text{-bar} = (10P + 5Sb + 4Sn + As)/100 < 15$ ppm

where P, Sb, Sn and As are in ppm.

Additionally, C is 0.15 wt% max; P is 0.01 wt% max; S is 0.007 wt% max; Cu is 0.20 wt% max; Ni is 0.30 wt% max.

The major challenge for the welding consumable supplier is to meet the requirement of Yield Strength (YS) within ±10% of actual YS of the plates received from the supplier of the plates.

EPCs set a very narrow requirement, which was tough to achieve. The critical requirement was, the fabricator shall arrange the plates, forgings and welding consumables for the vessel as such to minimize the difference in actual yield strengths at room temperature between adjacent components (plate vs. plate, plate vs. weld, forging vs. weld, forging vs. plate, etc.). The maximum difference in yield strength between adjacent components shall be within 10%, which means, the YS of the all weld metal after the PWHT cycles shall meet ±10% of the actual YS of every plate supplied by the base metal supplier. The actual yield strength of commercially available weld metal exceeds the base metal YS typically by more than 10%. After analyses of the batch chemical composition and mechanical properties of both steel and filler materials, a mismatch of ±10 % was agreed upon with IHZL, under the condition voestalpine Böhler Welding would render support in establishing WPQR's for the critical sections of the drums and to be confirmed in a so called YS mapping chart. Control of strength mismatch through the welding procedure was difficult, because of the many variables involved. Key factors of influence are heat input, layer thickness, number of beads, preheating, inter-pass temperature and post weld heat treatment. The chosen welding procedure aims at grain refining of the weld beads and the tempering of the heat affected zone (HAZ) in the base material. For PQR qualification, parameters were strictly controlled in order to have proper bead sequencing and controlled heat inputs. Also proper tacking was done in order to control distortion that may affect mechanical properties. Other good welding practices were also followed. Plate mapping was performed based on the yield strength of the base material and the actual yield strength values of the welds. This required a great effort

4.6 Weld Joint Design Details including Finishing

Weld finishing on internal and external weld surfaces on coke drums is considered important by some users in providing optimum coke drum fatigue life. For this reason, close attention has been paid to the quality of the weld finish. Some users specify that all longitudinal and circumferential welds be ground smooth and flush including feed nozzle attachment welds. For nozzles other than feed nozzles usually no specific surface finish is prescribed, however, weld undercutting should never be permitted.

Coke drum shells experience high bending stresses during the fill cycle as the hot feed fills the drum and the hot liquid level rises in the drum, and conversely, as the quench water level rises in a hot drum cooling the drum. These cyclic and reversing bending stresses have a significant effect on the fatigue life of the drum. The consequence is that the shorter the drum cycle is, the more severe are the temperature gradients in the drum and the shorter is the drum fatigue life. Stress concentrations resulting from weld surface finishes or weld undercutting can have severe effects on fatigue life at the location of the stress concentrations.

Thus, several users consider careful attention be paid to not having stress concentrations by grinding welds smooth with minimal grind marks and no undercutting. In these cases, grind marks should be oriented preferably parallel to but no more than 20 degrees from the longitudinal axis of the coke drum. Shell and cone internal and external weld seam surfaces and inlet nozzle ID and OD weld seams should also have a surface finish no coarser than 125Ra. Of course, any adjacent plate thickness transition caused by individual plate tolerances should be no greater than 1/8-inch (3.2mm) and this transition should be smooth from one plate to another over the width of the weld.

Temporary attachment welds should be made using an approved welding procedure specification. The manufacturer should strictly adhere to any material preheat and slow cooling requirements of the WPS. All temporary attachments should be removed prior to final PWHT by cutting no closer than 1/8-inch (3.2mm) from the vessel wall. The reminder of the attachment should be ground flush with the surface to eliminate defects and surface stress concentration. Weld repairs should be performed as required to ensure no loss of minimum base metal, cladding, or weld overlay thickness. Locations where temporary attachments have been removed should be examined visually and by MT or PT.

Recently some coke drum fabricators have used a “vertical plate” construction in order to minimize circumferential welds on a drum. In this construction detail, shell plates are oriented along the length of the drum resulting in a very long longitudinal weld along the length of the drum. Since most cracking appears to occur along circumferential welds on drums, it is believed this fabrication detail will mitigate cracking by reducing the number of circumferential seams on a coke drum. This is a relatively new practice that has been used in only a few cases, so it has not been determined whether it is effective in reducing cracking in coke drums.

4.7 Clad Restoration Welds

An internally 12Cr clad drum surface requires overlay of the completed weld area on the ID, including where the cladding was cut back to make the weld, in order to obtain complete coverage of the ID surface with corrosion-resistant material. Typically, this is accomplished with a high nickel alloy wire deposited using a GTAW, GMAW, SMAW, FCAW, SAW or ESW welding process. The high nickel alloy provides the best combination of weldability and thermal expansion properties for this restoration weld. However, the deposited high nickel alloy restoration weld is significantly stronger than the 12Cr cladding and steel plate and shell weld. Additionally, the thermal expansion properties are different enough that there is a significant likelihood for dissimilar weld cracking between the cladding and the high nickel alloy restoration weld. For this reason, it is important to make the restoration weld as thin as possible to reduce the effect of a dissimilar weld cracking between the high nickel alloy weld deposit and 12Cr cladding. A thinner restoration weld will minimize the thermal load generated by the dissimilar restoration weld and reduce the possibility of cracking at the fusion line between the nickel based restoration weld and 12Cr cladding. The restoration weld should be limited to 1/8 inch (3.2 mm) thick and the weld finishing should be per Section 5.1.

4.8 Weld Property Requirements

In the past few years, coke drum manufacturers and the filler metal suppliers have worked together to lower the yield strength of the weld metal to levels closer to that of the base metal. This addresses the stiffening effect of the higher strength welds which may have exacerbated bulging and cracking in coke drums. Filler metals are now available whose deposited yield strengths do not exceed the shell plate yield strength value by more than 10%. This has been primarily achieved by targeting yield strengths of the base metal higher than the minimum Code allowed yield strength.

Matching weld properties with the plate is a particular challenge when using 1¼Cr-½Mo or 2¼Cr-1Mo steel for the drum. These steels typically achieve a higher hardness and strength than the base metal on welding even after post weld heat treatment. During initial fabrication under the control conditions that exist in a typical shop, it is possible to routinely match the weld deposit strength within 10% of the plate strength after a final PWHT.

4.9 PWHT Requirements

PWHT is normally performed after all welding is completed to reduce welding residual stresses and temper hard martensitic phases that may form during the welding process. Typically, PWHT is not performed on carbon steel for either initial fabrication or repair welds unless dictated by Code maximum thickness requirements before PWHT becomes mandatory normally at thicknesses of 38 mm (1½ inch) and above. C-½Mo also possesses limited hardenability and does not require PWHT for fabrication or repair welds less than 5/8 inch (16 mm) thick. 1Cr-½Mo, 1¼Cr-½Mo and 2¼Cr-1Mo have progressively increasing hardenability compared to either carbon steel and C-½Mo and will typically require PWHT in order to control hardness in both repair and initial fabrication welds.

PWHT of new coke drums as required by the code of construction can occur in the fabrication shop and in the field or both. The PWHT can take place as:

- A whole assembly all at once in an oven, electric heating elements on the shell, or by internal heating with gas burners,
- A whole assembly with each half done separately in an oven,
- Separate components with closing seams seeing a Local PWHT (LPWHT) for the closing seams.

The preferred method of PWHT of new coke drums at fabrication shops is in one piece in a large PWHT furnace. This method provides a lower overall PWHT exposure time and minimizes the risk associated with sub-assemblies seeing PWHT in smaller furnaces with closure seams experiencing a LPWHT on the shop floor. The entire coke drum also can receive PWHT by wrapping with electric heating elements or by hot gas firing the inside of the coke drum but these options are not so frequently used.

The coke drum can also be PWHT'd by placing a little over one half of a complete coke drum into the furnace and then PWHT the other half of the coke drum while overlapping a portion that has experienced PWHT. Typically, an insulated baffled is place in the coke drum and insulation is placed on the portion of the coke drum nearest the oven to ensure a smooth thermal transition to the cold portion of the drum.

A facility without the ability to PWHT coke drums in one piece will typically PWHT a coke drum in halves. The two halves are then welded together with a circumferential weld which receives a LPWHT. A portion of the longitudinal weld seams that meets the final circumferential seam will see two PWHT's, requiring longer PWHT qualifying times for construction materials such as plate and weld wire.

The PWHT of field fabricated coke drums can consist of PWHT of sub-assemblies at a fabrication facility followed by LPWHT on the closing seams. LPWHT can be performed in a shop or in the field. LPWHT is performed by wrapping the weld area being PWHT'd with electric heating elements or by hot gas firing the inside. LPWHT should be done in accordance with Welding Research Council WRC Bulletin 452 "Recommended Practices for Local Heating of Welds in Pressure Vessels". WRC Bulletin 452 provides guidelines for LPWHT in terms of soak bands, heated band and gradient bands that are necessary to avoid unacceptable thermal gradients that can result in high residual stresses. LPWHT typically takes place in a circumferential band or a spot on the drum.

LPWHT for new coke drums should be performed in a full circumferential (360°) band. All thermocouples shall be placed on the opposite side of the shell from the heating elements. Temperature gradients shall be minimized by employing heated and gradient bands. Heating and insulating requirements are included in WRC Bulletin 452 for PWHT of a drum.

Typically, for Grade 11 and Grade 12, the PWHT temp and time are observed as min. PWHT @ 690±10°C /2 Hrs and Max. 690°±10°C /20 Hrs and meeting the requirement, especially after max. PWHT for plates (base metal) is a difficult task and a very few suppliers are there worldwide meeting the requirements. Similarly, for welding consumables also meeting impact requirements i.e. CVN IMPACT Min/Avg (J) 47/55 @ -18°C is difficult after max. PWHT and on the similar lines there are a few suppliers for such consumables.

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