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IN THIS ISSUE

Fabrication of Critical Heat Exchangers involving Ferritic & Martensitic Stainless Steels

With the necessity for usage of corrosion resistant steels across various oil & gas industries, the need for selecting specific corrosion resistant steel plays a vital role in determining the longevity of pressure vessels by mitigating / reducing any failures that can occur during operations. However, selection of superior corrosion resistant steels cannot be a solution for all applications due to monetary reasons. Hence, the need for optimizing both corrosion resistant and cheaper alternatives plays a decisive factor in material selection process. Here, the demand for superior corrosion resistance and high strength over conventional low alloy ferritic steels calls for Ferritic & Martensitic Stainless Steels. On the other hand, Fabrication of these steels are slightly tricky and taking necessary pre-cautions and good manufacturing practices are required to avoid any repercussions that might occur during operation.

This paper deals with various critical aspects which needs to be considered while fabricating these ferritic and martensitic stainless-steel equipment to critical applications like welding consumable selection, selection of suitable welding processes, qualification of welding procedures, applicability of post weld heat treatment, Production test coupons, functional know-how of the involved work force etc

INTRODUCTION

Considering the need for improved operation efficiency and cost competitiveness, usage of various metallurgies for manufacturing of pressure vessels in refineries and petrochemical industries have become very common in present modern era. This also necessitates the fabricators to handle many critical materials and associated welding requirements. In some of the cases, handling these complex materials require ultimate care and attention. Any violation or non-compliance to critical quality requirements during manufacturing may result in catastrophe failure during the operation.

In recent past, Precision Equipments received an order for construction of heat exchanger with following design data and material of construction (MOC). The design and material details of the heat exchanger is as shown in Table 1 and Table 2 respectively. Noticeably the exchanger had ferritic and martensitic steel to be fabricated.

Table.1 Heat Exchanger design Data

Parameters	Shell Side	Tube side
Code of Construction	ASME Sec VIII Div. 1	ASME Sec VIII Div. 1
Design Pressure (kg/Cm2)	33	35.6
Design Temperature (°C)	385 / 175	345 / 175
Min design Metal temperature (°C)	4.4	4.4
Operating pressure (kg/Cm2)	21.2	15.1
Operating Temperature (In/Out) °C	355/293.1	278.4/313.8
Fluid circulated	VR+QUENCH	RCO

Table.2. Material of Construction for Major Components of Heat Exchanger

Component	Material & Thickness
Shell	SA 240 Gr. 410S & 32 mm Thk.
Channel Shell	SA 240 Gr. 410S & 32 mm Thk.
Tube sheet	SA 182 Gr. F6a Cl. 1 & 185 mm Thk.
Tube	SA 268 Gr. TP410 (25 mm OD x 2 mm thk.)
Floating Head Assembly	SA 182 Gr. F6a Cl. 1 & 66 mm Thk. (Nom.)

In order to comply with both design data and construction code, welding procedure for both martensitic and ferritic stainless steel had to be established according to ASME Section IX in addition to compliance with UHA-51 of ASME Section VIII Div.1. This called for impact toughness testing of the weld and heat affected zone (HAZ) at Minimum Design Metal Temperature (MDMT) (which is 4.4°C in this case) for ferritic chromium stainless steels above 3 mm and martensitic chromium stainless steels above 6 mm respectively. Achieving the desired impact toughness values for these grades of stainless steel is always challenging given the nature of these materials. Furthermore, for this heat exchanger, due to larger diameter of the shell cover dish, additional long seam had to be provided on dish head plate prior to forming activities as shown in Figure 1. Since the weldment in the dish end had to undergo the same heat treatment cycles as that followed during the forming activities, selection of a suitable heat treatment cycle meeting the weld mechanical properties including impact toughness was very crucial.

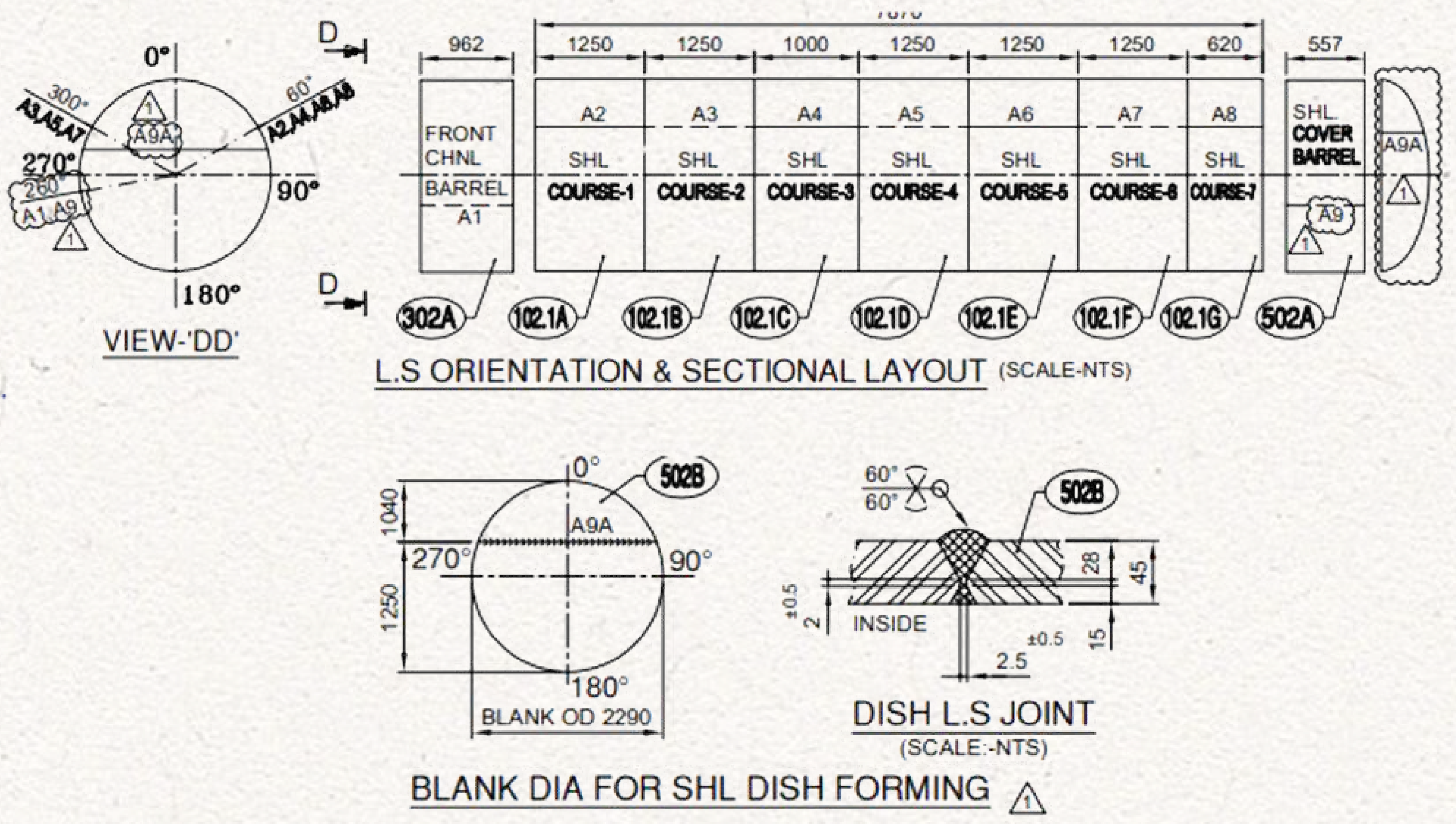

Fig.1 Sectional Layout & weld details of Shell cover dish L.S Joint

As per the code of construction i.e., ASME Section VIII Div. 1, Ed. 2021, UHA-32, post weld heat treatment is required for the welds produced with SA 240 Gr. 410S (P. No. 7) & SA 182 Gr. F6a CL.1 (P. No. 6) materials. Hence all these requirements had to be considered for welding procedure development, which will essentially duplicate the fabrication process. The entire fabrication process had to engineered in such a way that both quality requirements and delivery schedule have been met in order to deliver these equipments on time.

DESIGN REVIEW AND MATERIAL PROCUREMENT

The ferritic stainless steels contain up to some 27% chromium and are used in applications where good corrosion/oxidation resistance is required but in service loads are not excessive, e.g. flue gas ducting, vehicle exhausts, road, and rail vehicles [1-6]. The martensitic grades contain up to 18% chromium and have better weldability and higher strengths than the ferritic grades. They are often found in creep service and in the oil and gas industries where they have good erosion and corrosion resistance [7-14]. Since martensitic stainless steels is prone to air-hardening, because they can rapidly transform into martensite when cooled in still air after being heated to a certain temperature, necessary technical entities must be addressed at material procurement stage itself [8,12]. Comprehensive design review was carried out to analyse the design parameters, material combinations and sequence of fabrication to determine the material technical delivery condition for both base material and welding consumable. Various other aspects like combination of welding processes planned for fabrication, production test coupon requirements and post weld heat treatment applicability etc. were to be evaluated critically in finalizing the overall requirements. Accordingly, technical delivery condition for both raw material and welding consumables were specifically tailored to ensure project specification compliance.

BASE MATERIAL PROCUREMENT

Both Grades of SA 240 Gr. 410S and SA 182 Gr. F6a CL.1 were procured with mandatory requirements stipulates and per ASME Section II Part A as a minimum with further restrictions as specified below

- Carbon content lesser than 0.08%
- Annealed as part of manufacturing heat treatment condition
- Impact toughness testing carried out at MDMT (4.4°C)
- Mechanical testing at simulated heat treatment condition at both Minimum and Maximum cycles as per the fabrication sequence

WELDING CONSUMABLE PROCUREMENT

Most arc welding processes are suitable to weld ferritic stainless steel; however, it is advisable to lower the heat input and keep the thickness to a minimum—preferably less than 6mm.Heat control reduces the chance of grain growth, and thin sections minimize the overall impact of a loss of toughness in the material. Additionally, low-carbon austenitic steel can be used as a filler material to minimize the loss of ductility. Overall, the weldability of ferritic stainless steel is poorer than that of austenitic stainless steel. Although not hardenable by heat treatment, ferritic stainless steel can be prone to hot cracking or embrittlement if exposed to high temperatures.

In order to fulfil the toughness requirements and take advantage of heat treatment exemption as per UHA-32-1 & UHA-32-2 of ASME Section VIII Division 1, austenitic-chromium-nickel consumable i.e ER/E 309L was selected and for joints where governing thickness was found less than 38mm and non-air hardenable nickel chromium iron consumable i.e. ER NiCr-3 / E NiCrFe-3 were selected for joint thickness above 38 mm. These welding consumables were procured conforming to ASME Section II Part C as a minimum in case of ER/E 309L and whereas for ER NiCr-3 / E NiCrFe-3, mechanical testing was performed at simulated heat treatment condition both at Minimum and Maximum PWHT cycles to verify mechanical integrity.

WELDING PROCESS SELECTION AND PROCEDURE DEVELOPMENT

According to the suitability of welding processes to be utilized during fabrication, list of welding procedures to be established were detailed out considering the base material thickness involved and qualifying variables stipulated as per ASME Section IX. Suitable welding process namely GTAW (Gas Tungsten Arc Welding), SMAW (Shielded Metal Arc Welding) & SAW (Submerged Arc Welding) were employed. GTAW & SMAW welding processes were chosen for smaller thickness combination whereas SAW was selected for relatively higher thickness sections. Additionally for qualification with both ER/E 309L without PWHT and ER NiCr-3 / E NiCrFe-3 with minimum & Maximum PWHT Cycles were planned.

In case of Shell cover dish end longitudinal weld seam which will undergo both forming heat treatment and stress relieving were subjected as part of PWHT cycle for that procedure qualification. The mechanical test results of the welding procedures are compiled in Table 3, Table 4, Table 5, Table 6, and Table 7 respectively. The results were found meeting the requirements of the code of construction and project technical specification.

Table.3 Martensitic SS Butt Joint [Thickness (t): 38 mm, PWHT: Nil]

Welding Process	Filler Metal / Electrode	Welding Process	Transverse Tensile Strength of Weld (Mpa)	Impact Sample location	Lateral Expansion at 4°C (mm)
GTAW	ER 309L	4 mm	T1-564 T2-562	Weld	0.77~1.28
				HAZ	0.74~1.03
SMAW	E 309L	19 mm		Weld	0.95~1.10
				HAZ	1.41~2.32
SAW	ER 309L	15 mm		Weld	1.18~1.61
				HAZ	1.13~1.24

Table.4 Martensitic SS Butt Joint [Thickness (t): 40 mm, PWHT: 760°C @ 420 Minutes]

Welding Process	Filler Metal / Electrode	Welding Process	Transverse Tensile Strength of Weld (Mpa)	Impact Sample location	Lateral Expansion at 4°C (mm)
GTAW	ER NiCr-3	10 mm	T1-639 T2-649	Weld	2.00 ~2.05
				HAZ	1.34~1.50
SMAW	E NiCrFe-3	20 mm		Weld	2.22~2.42
				HAZ	1.56~1.90
SAW	ER NiCr-3	20 mm		Weld	2.48~2.58
				HAZ	1.33~1.96

Table.5 Ferritic SS Butt Joint [Thickness (t): 32 mm, PWHT: Nil]

Welding Process	Filler Metal / Electrode	Welding Process	Transverse Tensile Strength of Weld (Mpa)	Impact Sample location	Lateral Expansion at 4°C (mm)
SMAW	E 309L	12 mm	T1-507 T2-506	Weld	0.74~0.84
				HAZ	1.61~1.82
SAW	ER 309L	20 mm		Weld	1.67~2.36
				HAZ	0.46~0.49

Table.6 Ferritic SS Butt Joint [Thickness (t): 45 mm, PWHT: 745°C @ 360 Minutes]

Welding Process	Filler Metal / Electrode	Welding Process	Transverse Tensile Strength of Weld (Mpa)	Impact Sample location	Lateral Expansion at 4°C (mm)
GTAW	ER NiCr-3	4 mm	T1-494 T2-496	Weld	1.14 ~1.60
				HAZ	1.31~1.60
SMAW	E NiCrFe-3	20 mm		Weld	2.34~2.64
				HAZ	0.41~0.52
SAW	ER NiCr-3	20 mm		Weld	1.98~2.28
				HAZ	0.41~0.61

Table.7 Ferritic SS Butt Joint for Dish end seam [Thickness (t): 45 mm]

Ferritic to Ferritic SS Butt Joint, Thickness (t): 45 mm, PWHT: Hot Forming Cycle (1080°C @ 50 Mins) & Max. PWHT (750°±10°C @ 360 Minutes)					
Welding Process	Filler Metal / Electrode	Welding Process	Transverse Tensile Strength of Weld (Mpa)	Impact Sample location	Lateral Expansion at 4°C (mm)
GTAW	ER NiCr-3	10 mm	T1-507 T2-506	Weld	1.49 ~1.54
				HAZ	0.50~0.93
SMAW	E NiCrFe-3	20 mm		Weld	1.43~1.80
				HAZ	1.46~1.68
SAW	ER NiCr-3	20 mm		Weld	1.26~2.36
				HAZ	0.42~0.72

FABRICATION ASPECTS FOR FERRITIC AND MARTENSITIC STAINLESS STEELS

SELECTION OF SUITABLE WELDING CONSUMABLE

There are various factors to be considered and kept in mind while carrying out fabrication activities. Metallurgically, weldments of similar of grades of ferritic / martensitic will be air-hardenable, thus more brittle in structure leading to lesser toughness. Higher hardness can prove fatal in high cyclic environments which will eventually lead to failure. Hence, selection of welding consumables preferably of weldments of austenitic chromium-nickel or non-air-hardenable chromium-nickel-iron plays a vital role in meeting these requirements. This also enables us to avoid post weld heat treatment up to certain thickness by employing pre-heating while welding. Maintenance of pre-heating during fabrication is very critical and same shall be carried out in a controlled manner preferably by resistance coil method to prevent rapid cooling of weld and HAZ thus preventing hardenability of heat affected zones corresponding to the base materials. Carrying this out irrespective of base material thickness might prove beneficial in controlling the hardness.

DISH HEAD FORMING AND HEAT TREATMENT

For dish ends having larger diameter might require welding of additional longitudinal seams and the same dish ends will undergo cold forming to obtain hemispherical form. Cold forming is generally not recommended as it can lead to brittle failures when load is applied while forming. Irrespective of the fibre elongation of the dish end configuration, the hot forming is recommended along with welded joint to avoid any brittle / cracking failures when loading is subjected during forming process. Hot forming is typically performed in the 1100°C - 700°C (2012°F - 1292°F) temperature range followed by air cooling. Limit the holding time at high temperature and finish between 800°C (1472°F) and 700°C (1292°F) in order to refine grains. Further stress reliving can be carried out to relieve all the stress that would have developed during the process.

TUBE TO TUBE SHEET WELDING

Tube to Tube sheet welding is one of the most critical activities in manufacturing of any heat exchanger. Due to dissimilar metallurgy, the joint is highly prone for solidification cracking and thus proper care should be taken while designing the joint configuration. Suitable joint configuration was selected based on mock-up welding and examination. During mock-up evaluation some of the joint configuration was resulting in solidification cracking. Typical joint configuration followed during production is as shown in Figure 2

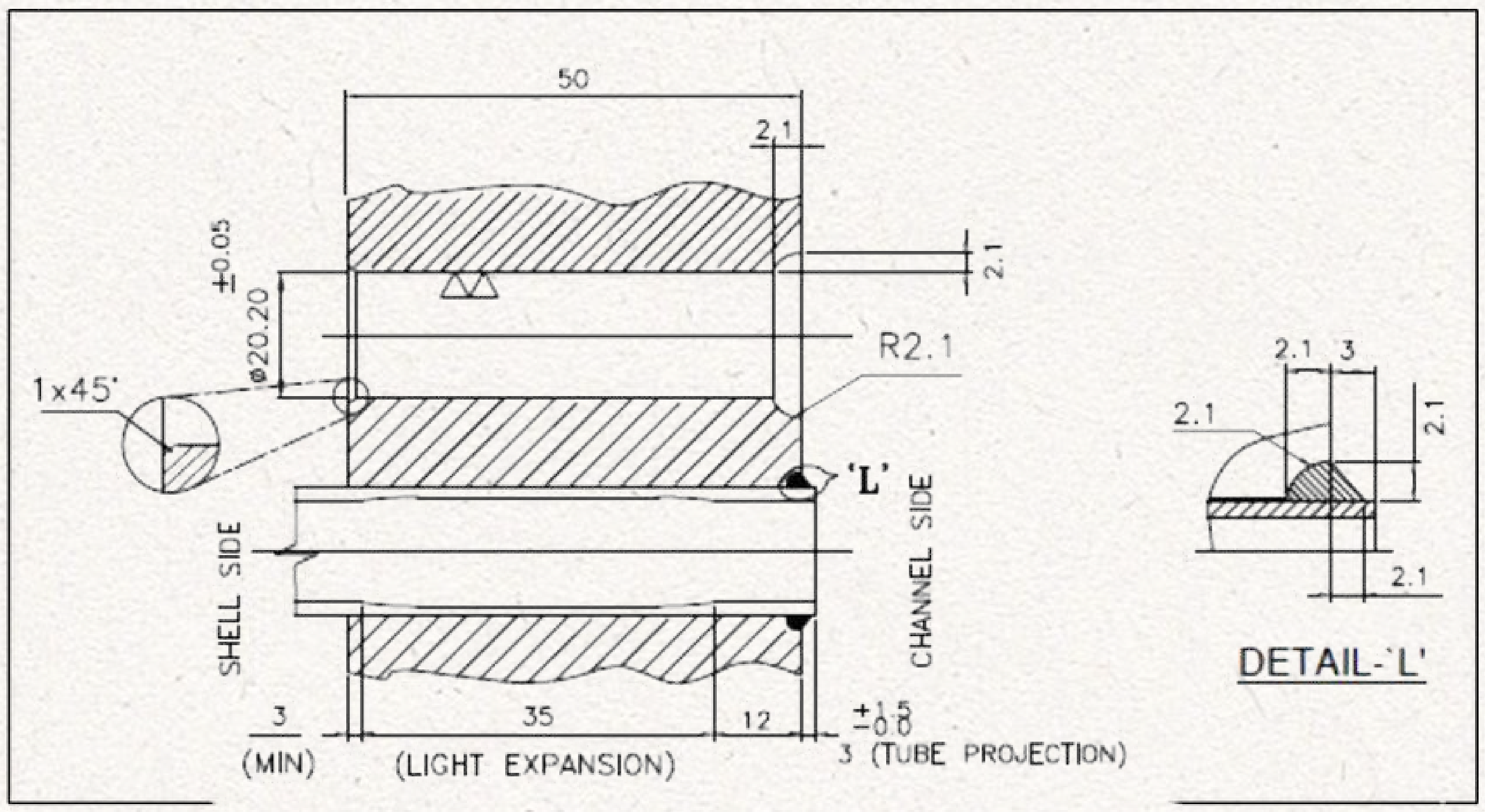

Figure.2 Tube to Tube sheet weld joint configuration

These welds are prone for solidification cracking if proper weld sequence and welding parameters are not followed. Enough filler should be provided in the groove during welding and the resultant fillet should have a slightly convex shape. It is advisable to preheat the entire tube sheet with electrical preheating rather than heating them locally using burners. This ensures slow cooling and prevent the weldment and HAZ from getting hardened due to rapid cooling down. Tube to tube sheet welding was performed using automatic orbital welding technique in order to achieve consistent quality and improved productivity. All the tube to tube sheet welds cleared visual and dye penetrant examination with first time right quality. Refer Fig. 3 for the tube to tube sheet weld finish.

Figure 3 Orbital tube to tube sheet-Root weld

Figure 3 Orbital tube to tube sheet-Completed weld

CONCLUSION

Handling of martensitic and ferritic stainless-steel equipment require a suitable strategic and disciplined approach throughout the fabrication cycle. The process starts with detailing out the material requirements including simulation PWHT requirements, welding consumable technical delivery conditions, and finding out a suitable supplier in getting them manufactured tailored to those requirements. Next stage is finalizing the fabrication sequence and articulating the fabrication with the selection of suitable welding process. This necessitates qualification of necessary welding procedures meeting all the requirements of code of construction and applicable project specifications and successfully deploying them in production with trained and qualified welders. Lastly, ensuring that strict work instructions are being followed to avoid any repair / re-work that might hamper the fabrication schedule as well as the construction material is of paramount importance.

The study also emphasizes the need for selection of a suitable weld joint configuration coupled with a correct welding technique in tube-to-tube welding execution involving these materials.

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