RESEARCH ARTICLE

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An Experimental Investigation on Welding of 5Cr-0.5Mo Material for Heat Exchanger Application

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Abstract

Chromium-Molybdenum (Cr-Mo) steels are widely used in oil refineries, petrochemical industries and power plants for various applications, including heat exchangers, pressure vessels and piping. The main advantage of these steels are the improved creep strength due to addition of Molybdenum and enhanced corrosion resistance imparted by chromium. 5Cr-0.5Mo steels are extensively used in seamless tubing in petroleum industry because of their corrosion resistance against oils and crude containing hydrogen sulphides and other corrosive agents. The main advantage of 5Cr-0.5Mo steels is the improved oxidation resistance because of increased Chromium content. In modern refineries, a more recent and common application of this steel grade is in the fabrication of desulphurization plants used for the production of clean low Sulphur petrol and diesel fuels.

In recent past, L&T heavy engineering received a challenging project for manufacturing of 2 nos.of high-pressure exchangers involving 5Cr-0.5Mo material having a wall thickness of 85 mm. The severe operating conditions also demanded a stainless steel347 weld overlay on inner surface of the vessel. Producing crack-free weldments in 5Cr-0.5Mo which are adequate for a given service would conventionally entail correct choice of filler metal, stringent welding conditions including preheat, proper welding technique and post-weld heat treatment (PWHT). This paper describes about development of welding procedures for this material and our experience in successful fabrication of high pressure exchangers with 5Cr-0.5Mo as the material of construction.

Keywords: Cr-Mo steels, 5Cr-0.5Mo steels, High pressure exchanger, Weld overlay.

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Introduction

Process plant equipment (PPE) are used in process industries comprising oil and gas, refinery, petrochemical, chemical, fertilizer, cement, thermal and nuclear power.[1-5] The PPE are subjected to varying conditions of pressure, temperature, erosion, corrosion, vibration, fatigue and radiation.[1-5] In addition, each industry has special requirements which need to be factored in while selecting suitable materials.

Sulphur is one of the foremost corrodents which causes problem in refinery.[1-5] It is present in crude petroleum at various concentrations and forms variety of chemical compounds, including hydrogen sulphides, sulphides and elemental sulphur. The crudes that are processed nowadays contain 1–2% of Sulphur.[4] The common materials used in refinery structures are carbon steel, 9Cr-1Mo, 5Cr-0.5Mo, 2.25Cr-1Mo, 1.25Cr-0.5Mo and 18Cr-10Ni steels.[6,7] The main forms of damage caused by sulphur include weight loss by corrosion and sulphide stress corrosion cracking in low temperature aqueous environments.[5-8] Apart from scaling and metal loss, Sulphur action results in internal damage to steel elements. Sulphur causes degradation of steel microstructure and may also form corrosion products beneath the steel surface. Most of these equipment work under severe operating conditions in presence of hydrogen. The presence of hydrogen is a potential source of danger to steels. Under high temperature and pressure conditions, molecular hydrogen is believed to disassociate into atomic hydrogen which then diffuses into the steel. The atomic hydrogen reacts with carbon in the steel under high temperatures to form methane. As methane cannot diffuse out of the steel, it accumulates and builds up pressure thus causing cracks and blisters in the steel.[1-5] The type of steel to be used is selected using Nelson curves of API 941[9] which specifies the temperature versus

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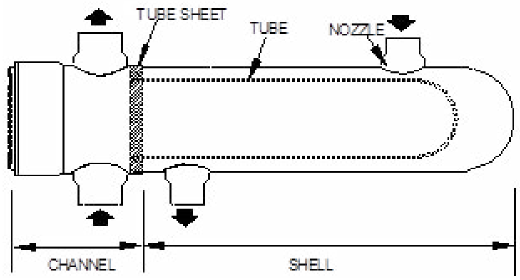

Figure 1: Typical heat exchanger

Table 1: Equipment details

Shell material	*SA 387Gr5 Cl 1 (85 mm thick.)*
Shell side medium	Hydrocarbon Feed
Channel material	SA336 Gr F5 with SS347 overlay.
Tube side medium	Reactor Effluent
Nozzle material	SA 336 Gr F5 (120 mm thick.)
Tube sheet material	SA336 Gr F321
Tube material	SA 213 TP321 (25 OD x 2 mm thick.)
Design temperature (shell/ channel)	391/418°C
Design pressure (shell/ channel)	150/134 Kg/cm^2

hydrogen partial pressure curves for different low alloy steels. As can be seen from the Nelson curve, 5Cr-0.5Mo steels can be used up to temperature of 620°C (1150°F) under hydrogen atmosphere.

Schematic sketch of a typical high-pressure exchanger is shown in Figure 1. A typical high pressure exchanger consists of shell, channel, nozzles, tubes and tube sheet. The material of construction varies across the vessel depending on the service it is being exposed to and the application. Refer Table 1 the details of the equipment under consideration.

Shell side of the equipment was under sulphur environment whereas the tube side under hydrogen service. Operating temperature of 391°C and presence of sulphur necessitated the use of 5Cr-0.5Mo steel on shell side. Operating temperature of 418°C and presence of hydrogen demanded 5Cr-0.5Mo steel with SS 347 weld overlay on tube side as prescribed by the process licensor.

EXPERIMENTAL INVESTIGATION

Toughness Requirements for Base Material and Weld

The project technical specification required the toughness values of 48J (min.) and 55J (avg.) for the base metal, weld and heat affected zone (HAZ) at -29°C. Even though enquiries were floated with almost all plate, forging and consumable manufacturers, none of them guaranteed their material to meet the required impact values under the given conditions.

Table 2: Toughness values at different PWHT temperatures

Manufacturer	*PWHT (minimum)*	*Toughness (min)*	
		Temp (°C)	*CVN (J)*
Bohler	740°C x 4 Hrs.	+20	47
Lincoln electric	740°C x 2 Hrs.	+20	55
Kobelco	750°C x 8 Hrs.	0	150
Thyssen	740°C x 4 Hrs.	0	27
Kawasaki	720°C x 12 Hrs.	0	80
Sumitomo	750°C x 2 Hrs.	0	157

The range of PWHT temperatures recommended by various consumable manufacturers for 5Cr-0.5Mo welds are shown in Table 2.

In case of 5Cr-0.5Moweldments, extreme care must be taken while selecting a proper post weld heat treatment (PWHT) temperature in order to ensure good mechanical properties of the weld.[11-17] The use of an excessively high temperature can damage the weld causing inadequate tensile strength. In contrast, the use of an excessively low temperature can cause poor ductility and impact toughness of the weld in addition to inadequate stress relieving.[3]

To meet the impact testing requirements at-29°C, welding consumable suppliers demanded higher PWHT temperature range of 750–760°C. But none of the plate manufacturers were ready to supply the material with simulation heat treatment and tested at this higher PWHT temperature. Moreover, the job specification required tempering of the base material to be done at a temperature more than that of the PWHT temperature i.e., 770°C minimum in this case. However, mill was offering plate at 710°C.

In order to study the effect of PWHT on toughness values and mechanical properties, trials were carried out at different PWHT temperatures. Results are summarized in Table3. It can be observed that, decrease in PWHT temperature results in strong decrease in the achievable toughness level. It can also be noticed that the toughness values scatter with decrease in PWHT temperature. For 5Cr-0.5Mo welds, all major consumable suppliers recommended PWHT at 740 –745°C minimum (Refer Table 2). Also, the impact tests are reported to be carried at + 20°C or 0°C. As per one of the reputed consumable manufacturer, the minimum toughness requirements at 0°C should not exceed 27J in case the PWHT temperature is at the lower side(< 740°C).

In view of above, a proposal was made to the customer/ consultant with strong backup from mill and consumable suppliers. Since the minimum design metal temperature (MDMT) for the equipment was 0°C, the proposal was to increase the toughness test temperature to 0°C. This would help to reduce the PWHT temperature and hence the tempering temperature, there by enabling the mill and consumable suppliers to provide the material meeting the requirements of project specification.

Table 3: Weld properties at different PWHT temperatures

Property	*PWHT (730-760°C x 4 Hrs.)*	*PWHT (700-730°C x 4 Hrs.)*
Rp 0.2 (Mpa)	400	437
Rm (Mpa)	559	589
A (%)	26	24
CVN at 0°C (J)	180,188,190	90,50,72
CVN at -20°C (J)	87,94,96	12,25,23

Based on the technical inputs provided, customer/ consultant agreed to increase the impact testing temperature to 0°C, however the impact values of 48J (min.) and 55J (avg.) had to be met. The biggest challenge lying ahead was to develop the welding technology to meet this stringent toughness requirement in welding procedure qualifications and production test coupons. The maximum hardness level specified for the base metal, weld metal and HAZ for 5Cr-0.5Mo steels was 235 BHN, which was required to be met after a single PWHT cycle.

Welding Procedure Development

Butt joint qualifications

Selection of filler metal and PWHT

Initial experiments were carried out on a 38mm thick plate. Inspite of utmost care taken while producing these welds; the toughness values were not even meeting the minimum requirement. Trials were continued with different brands and size of electrodes. Summary of the trials are captured through Figure 2.a-2.e. Brand, optimum size of electrode and wire flux combination was chosen based on the toughness and mechanical testing results. Welding procedures were qualified meeting all the stringent requirements of code and customer specification. Based on these qualification results, PWHT temperature was finalized as 720–740°C x4 hours (min.).

Following were the key observations:

- 4 mm dia. SMAW electrode, when used in vertical up position, failed to meet the toughness requirement. Same shall be used only in flat position.
- 3.2 mm dia. SMAW electrode was giving satisfactory toughness values in vertical up position.
- Locally available brands of electrodes could not meet the toughness requirement. Moreover, the toughness values were highly scattering.
- Welding parameters need to be followed very strictly to control the heat input.
- Flat stringent beads are recommended. Maximum bead height shall be restricted to 3mm.
- Follow temper bead technique for the top layer. This will help in achieving good impact values near the surface.

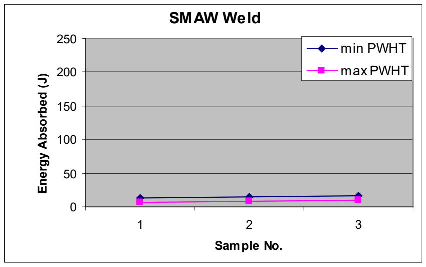

Figure 2: (a) Toughness values, SMAW weld (Local brand- 4 mm dia.)

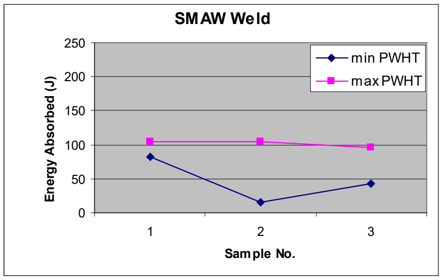

Figure 2: (b) Toughness values, SMAW weld (Thyssen- 4 mm dia.)

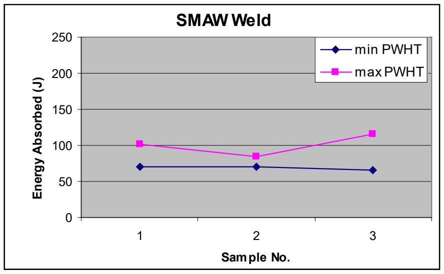

Figure 2: (c) Toughness values, SMAW weld (Thyssen- 3.2 mm dia.)

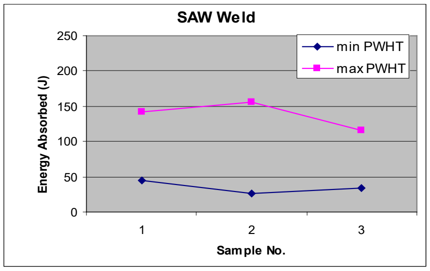

Figure 2: (d) Toughness values, SAW weld (EB6+UV 420 TTR flux (Thyssen))

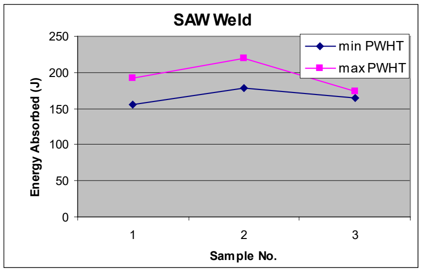

Figure 2: (e) Toughness values, SAW weld (EB 6 + Marathon-543 flux (Thyssen))

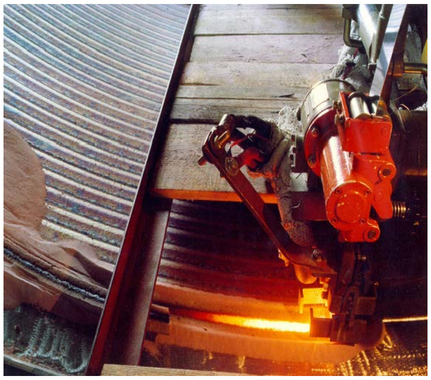

Figure 3: ESSC weld overlay in progress

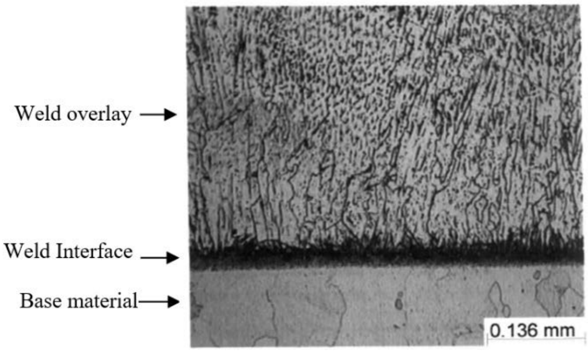

Figure 4: Micro photograph of ESSC weld overlaid sample

ii) Weld Overlay Procedures

To resist corrosion due to the process environment, exchangers require protection of the wall. This protection which resists the high temperature corrosion in the process stream is generally provided by stainless steel.[2] The weld overlay, that is normally employed has a nominal composition of 18Cr-8Ni and is usually deposited in two individual deposition passes. The electrode combination generally used, has 309L chemistry for the first layer and type 347 chemistry for the second or final layer. This electrode essentially deposits a stabilized 18Cr-9Ni weld metal composition at the process surface of the overlay. The low carbon type 309L deposit tends to balance the overlay composition chemistry when dilution occurs with low chrome base metal. This overlay provides an excellent protection against corrosion and protection against sensitization during the final PWHT of the equipment. Figure 3 shows the ESSC weld overlay in progress on the channel side of the equipment

The project specification had the requirement of 3mm undiluted SS 347 chemistry on the channel side of the equipment. Three weld overlay procedures were to be qualified using ESSC, FCAW and SMAW process on 5Cr-½Mo base material to meet the project requirements. The specification demanded much stringent testing, including susceptibility for intergranular corrosion as per ASTMA 262 (Practice-E) and hydrogen disbonding test to be carried out at equipment design conditions.[18]

The ferrite content in the weld overlay plays an important part in the integrity of the weld overlay. The specification restricted the ferrite to a range between 3% minimum (to guard against hot cracking) and 8% maximum (to minimize delta ferrite transformation into brittle sigma phase during the final PWHT). Moreover, the project had the requirement of ferrite to be checked after PWHT as well, with an acceptance of 2.5% minimum. Proper welding methodology was developed and welding parameters were chosen accordingly to meet these ferrite requirements.

Hydrogen disbonding Test

The most critical part of the weld overlay qualification was autoclave hydrogen disbonding test to be performed on overlaid sample. 5Cr-½Mo steels provide superior high-temperature mechanical properties and resists high-temperature hydrogen attack. The stainless steel cladding present on channel side provides corrosion resistance. However, the interface between the cladding and base metal may be susceptible to disbonding under certain high-temperature hydrogen conditions[4]. Under severe operating conditions, crack propagation occurs along the carbide precipitation zone and along the grain boundaries developed in stainless steel overlay near the interface with the base material.

When enquired with different laboratories ,those who generally perform autoclave tests, there was no previous history of hydrogen disbonding test carried out on 5Cr-0.5Mo steel. Disbonding samples were prepared as per ASTM G146 and were subjected to design pressure and temperature.[4] Tests were conducted for all three processes ESSC,FCAW and SMAW. The results were satisfactory with zero disbonding reported. Figure 4 depicts a Micro photograph of SS 347 weld overlay on 5Cr-0.5Mo steel using ESSC.

RESULTS AND DISCUSSIONS

Preheat and Interpass Temperature

Preheat and interpass temperatures have significant effect on the strength levels attained with 5Cr-0.5Mo welds. These welds are affected by rapid cooling rates which tend to produce more martensitic or bainitic microstructures.[6] These microstructures will often exhibit higher yield and tensile strengths with a decrease in ductility. Hence it is very important to select a suitable preheat andinterpass temperature for these steels for maintaining the ductility. Too low preheat will cause cracking as this is the most common problem encountered during fabrication of 5Cr-0.5Mo steels. It is recommended to prepare a comprehensive plan regarding the method of preheat application and the method for monitoring.

Based on various recommendations and manufacturing considerations it was decided to use a preheat temperature of 200°C and interpass temperature of 300°C irrespective of the joint thickness. Same preheat was followed for any thermal cutting, weld tacking and vwelding temporary attachments. In case of flame or arc cutting, the area to be

Figure 5: Preheating arrangement- Nozzle welds

cut must be properly preheated and the heat affected zone up-to 3 mm must be removed by grinding or machining. Electrical preheating arrangement for nozzle welds during production is shown in Figure 5.

Intermediate Stress Relieving

As cracking rarely occurs at temperatures above ambient, maintaining the temperature of the weldments during fabrication is equally important. For susceptible steels, it is usually appropriate to maintain the preheat temperature for a given period, typically between 2 to 3 hours, to enable the hydrogen to diffuse away from the weld area. Generally followed post heating cycle for Cr-Mo steels is 300-350°C for three to four hours. The conflict of whether to carry out dehydrogenation heat treatment (DHT) or Intermediate Stress relieving (ISR) always arise during fabrication Cr-Mo steels. In majority of the cases, it is left to the fabricator to choose among based on his fabrication experience and recommended industrial practices.

But in case of crack sensitive materials such as 5Cr-0.5Mo materials, it is highly recommended to subject the weld joint to Intermediate stress relieving (ISR) before cooling from preheat temperature. ISR can be carried out either in furnace or by wrapping the weld area with electrical coils. The purpose of carrying out ISR is twofold, to reduce residual weld induced stresses and to improve the weld's toughness properties in addition to driving out hydrogen from the weld. As deposited weld metal can have very low toughness and any flaw in the weld metal(stress raisers) has potential for generating cracks as the welded section cools to ambient conditions[14,15]. Moreover, it is highly possible that the weld may cool down below the preheat temperature before being transported to the ISR furnace. For this reason, it is necessary to carefully plan not only all fabrication steps but also the logistic steps.

All the long seams, circ seams and nozzle welds were subjected to ISR at 600–650°C x 2 hours (min.) before cooling from preheat temperature. Other attachment welds and fillet welds were subjected to DHT at 300-350°C x 3 hours (min.).

Temper Bead Technique

Poor toughness after PWHT is a major concern with 5Cr-0.5Mo steels. More prone area will be that close to the surface. This can be related with refinement of weld during passes. Unrefined area would lead to poor toughness property. Deposited weld bead need to be relatively thin of maximum 3 mm height and flat to promote grain refinement during subsequent passes, especially when welding near surface region. Usage of temper bead passes helps in overcoming this problem. The amount of heat produced by subsequent passes promote grain refinement i.e., to re-crystallize previous passes as the weld metal resists softening to produce the requisite tempering[10]. This technique was effectively applied during procedure qualification, production welding and preparation of product test coupon.

Weld Joint Configuration

The joint configuration plays a vital role in obtaining proper grain refinement of the weld. A narrow gap weld tends to give a uniform bead height and shape, and hence uniform degree of grain refinement and tempering. For joints with a bevel angle, placement of beads and the number of beads per layer can be critical. All long seams and circ seams were welded with narrow grove weld joint preparation. This largely contributed to improved toughness property of the weld.

Welding consumable storage and Issue

5Cr-½Mo welds are highly prone for cold cracking if proper precautions are not taken. Control of Hydrogen (<5 mL per 100 gm) and a very lesser moisture content is essential to avoid cold cracking. Low hydrogen electrodes and flux were procured in hermetically sealed packages to avoid any moisture absorption. Rigid controls over storage, handling, drying and holding of electrodes and flux were emphasized during production. Special procedures were issued for storage and handling of consumables.

NDT Requirements

Since these materials are highly susceptible for cold cracking, all the NDT's were carried out only after 48 hours of weld completion. All long seams, circ seams and nozzle welds were subjected to PT, RT and UT. PT and UT were repeated after PWHT and hydro test of the equipment.

Fabrication Techniques

The following techniques were practiced during fabrication:

- Only trained welders were used on production. welders, fabricators and welding supervisors were given awareness sessions, emphasizing the criticality of this steel and precautions to be taken during fabrication. Welders received special training for producing temper beads and for bead placement inside narrow groove.
- Abrupt changes in cross section, sharp corners and partial penetration joints were avoided as these points act as stress raisers and can initiate cracks.

Table 4: Mechanical and toughness values obtained in Production Test Coupon

Property	*UTS (MPa)*	*Sample Location*	*Toughness in Joules (at 0°C)*				*Hardness (BHN)*
	PWHT: 720-740°C x 4 Hrs + 600-640°C x 4 Hrs.						
			1	2	3	Avg	
PTC - 1 (SMAW + SAW) Rep: Circ seams	553	Weld (SAW)	88	121	115	108	184-189
	567	Weld (SMAW)	144	189	163	165	187-193
	-	HAZ	294	292	294	293	156-180
	PWHT: 720-740°C x 7 Hrs + 600-640°C x 6 Hrs.						
PTC - 2 (SMAW + SAW) Rep: Long Seams	564	Weld (SAW)	112	79	91	94	170-174
	555	Weld (SMAW)	88	105	80	91	179-182
	-	HAZ	294	294	292	293	155-185
Required Values	515 MPa (min.)	-	Min: 48J, Avg: 55J				235 BHN (Max)

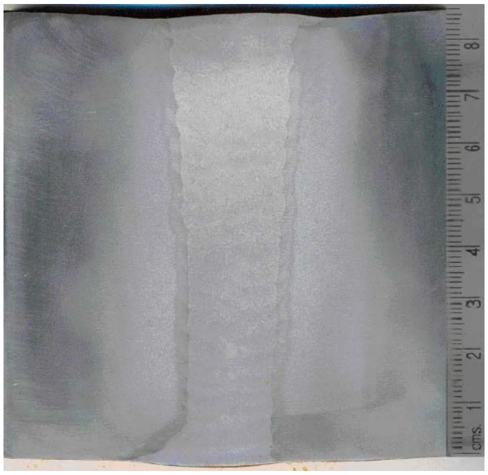

Figure 6: Weld joint cross section

- The toe region, which has high hardness and low toughness, is prone for cracking. Same was controlled by smooth merging, rounding of corners and by producing controlled weld reinforcement.
- The joint faces and adjacent areas were thoroughly cleaned before welding. The same was ensured to be free of contaminants such as paint, cutting oils and grease.
- Electrodes (MMA) and the flux (submerged arc) were dried in accordance with the manufacturer's recommendations.
- Arc length was kept as short as possible. Weaving width was limited to be within 2.5 times the diameter of the electrode.
- The joint was preheated to a distance of at least 100 mm from the joint line ensuring uniform heating through the thickness of the material. Preheat temperature was measured on the face opposite that being heated.
- The heat input requirements were strictly followed, as this decides toughness property of the weld and HAZ.

Production Test Coupon

The specification and code required two test coupons to be welded with same heat as that of job material, one representing long seams and other representing the circ seams. The results were satisfactory (Refer Table 4) meeting all the stringent requirements of code and specification. Cross section of the weld is shown in Figure 6.

Conclusion

In today's challenging market, heavy engineering companies needs to adapt the upper end of the technology spectrum by introducing new processes, products and materials in order to meet the demand of these sectors. Manufacturing of these equipments within the stipulated time frame, meeting all the stringent requirements of the customer, proved a step forward in the ongoing journey.

The salient achievements include:

- Development of weld overlay procedures on 5Cr-0.5Mo steels with hydrogen disbonding test
- Successful development of welding technology meeting the stringent requirements of toughness values in welding procedure qualifications and production test coupons.
- Repair percentage of<0.5 in radiography in case of long seam and circ seam welds
- No reportable defects in ultrasonic testing in case of long seams, circ seams and nozzle welds both before and after PWHT.
- No reportable defects in ultrasonic testing in case of weld overlay in channel and nozzles.

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