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Cracking of AISI 321stainless steel welds in solar thermal power plant: Root cause analysis

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ABSTRACT

AISI 321 stainless steel (SS) tubes are commonly used in solar thermal power plant to transport the chloride ion containing thermic fluid at a temperature of ~ 400^{o}C. It was noted that several of these SS tubes have failed in a short time after being exposed to the thermic fluid under service condition, which led to the leakage of the thermic fluid. The present study aims to understand the root cause of failure of these tubes, as these tubes were seam welded and also had spot welds on the surface. The seam welding had been done either by laser beam welding or by metal inert gas welding (MIG). Dye penetrant tests were performed to the tubes followed by microstructural analysis using optical microscopy, and field emission scanning electron microscopy (FESEM). Subsequently, X-ray diffraction studies were carried out to determine the phase of the tubes at the weld region. Microscopic analysis showed that the leakage of the thermic fluid occurred at different weld joints and adjoining area in each tube. In the case of laser welds, failure occurred due to knife line attack at the interface of weld and base material. In case of in MIG welded tubes failure occurred due to end grain corrosion caused due to high volume fraction of σ phase precipitation and attack at the interface of the σ phase and base material. Further, failure near spot welds occurred due to chloride-induced stress corrosion cracking (SCC) of 321 SS. Improper post weld heat treatment (for laser beam weld and spot weld) and high ferrite content in the filler wire (for MIG welds) was identified to be the root cause of failure of the tubes.

Keywords: austenitic stainless steel 321, welding, stress corrosion cracking.

INTRODUCTION

Austenitic stainless steel (SS) surface welds are have enormous application in different industrial sectors due to its high strength, good weldability, and good corrosion resistance [1-2]. However, these steels are susceptible to localized corrosion, like pitting, crevice corrosion and stress corrosion cracking (SCC) in aggressive environments like chloride ions which can lead to catastrophic failure events in chemical and petrochemical industries, power plants, civil structures etc [3]. SCC is a phenomenon wherein cracking takes place under the synergistic action of tensile stresses and aggressive environment and a susceptible material. Stresses may either be in-service stresses or residual stresses. Tensile residual stresses arise in the material due to different steps involved in component fabrication like bulk deformation, surface finishing [4] etc. Welding in general results in the development of high magnitude of tensile residual stresses due to the constrained weld geometry. The thermal expansion and contraction of the alloy during welding gets restricted due to the constraint geometry resulting in the development of high magnitude of tensile residual stresses [5]. Welding of austenitic stainless steel also leads to sensitization which makes it susceptible to intergranular corrosion. To reducing the sensitization of Welding by using stabilized grades of stainless steel that is SS 321 and SS347 are contains Ti and Nb respectively they have grater affinity to form carbide then Cr [6]. Stabilized grades of stainless steel should be followed by proper post weld heat treatment if it failing which leads corrosion issues like 'knife-line attack' [7]. Moreover, the choice of the filler material plays a major role as it determines the ageing behavior of the austenitic stainless steels [8]. The present study gives a practical illustration of the various corrosion issues that can possibly emerge in welded austenitic stainless steel grade AISI 321 when in service in presence of chloride environment and explains the root cause behind each of the failures and the precautionary measures required.

EXPERIMENTAL PROCEDURE

Material

AISI 321 SS tubes having a length of 3.9 m, the diameter of 7.2 cm and a thickness of 3.0 mm, were used in a solar thermal power plant for the transfer of thermic fluid from the parabolic heat concentrators to the heat exchangers. The pipes were seam welded by either laser beam welding (LBW) or metal inert gas welding (MIG). Spot welds were also present on the surface of the pipes at a particular location as shown in Figure 1. Many of such pipes had undergone failure leading to leakage of hot thermic fluid. Table 1 gives the chemical composition of the AISI 321 SS pipes.

Table 1: Chemical compositions of base metal AISI 321 stainless steel (Wt. %)

Material	C	Si	Mn	Cr	Ni	Ti	Mo	S	P
SS 321	0.024	0.60	1.64	17.41	9.14	0.23	0.37	0.005	0.024

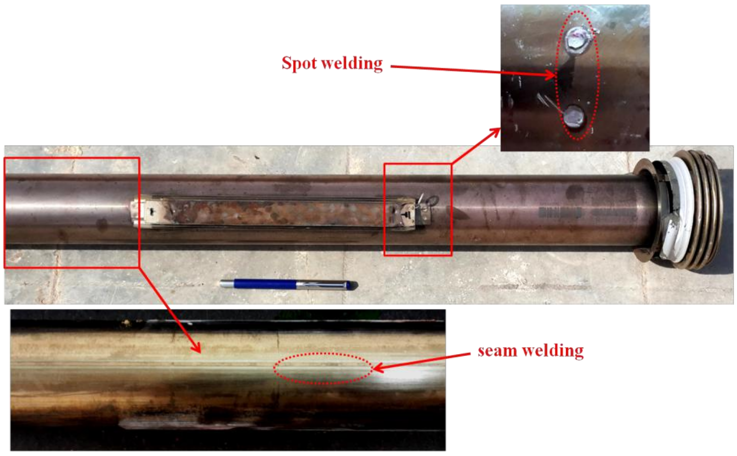

Figure 1: AISI 321 SS heat exchanger pipe indicating the location of seam weld and spot weld

Visual examination and Dye penetrant testing

The entire surfaces of the pipes were carefully cleaned and examined at first by naked eyes and then by dye penetrant test in order to locate cracks on the 321 SS pipes. After dye penetrant test the pipes were cut at several locations to examine the surface and cross-sectional microstructures.

Microstructural characterization

The microstructural characterization of the cross section of the pipes was performed at different magnifications using optical microscopy and field emission scanning electron microscopy (FESEM). EDX was used to analyze the elemental composition of the precipitates. Secondary electron mode of imaging at a voltage of 15 kV was used in FESEM. Energy dispersive X-ray spectroscopy (EDS) analysis was performed at a voltage of 20 kV. Samples were cut from several locations of the pipes both near the region of the welds and away from the welds samples were mechanically polished using various grades of emery paper followed by diamond polishing to obtain mirror-like surface finish. Subsequently, the samples were electrolytically etched using 10% oxalic acid solution. To identify the σ phase, the specimens were etched using 10% KOH solution. After etching the samples were cleaned using water and ethanol. The precipitates present in AISI 321 SS were identified with the help of EDS.

X-ray diffraction

X-ray diffraction was used to confirm the phases present on the surface of welded AISI 321 SS. The Cu Kα radiation source was used having a wavelength of 1.54 Å. The experimental parameters for measurement were as follows: a) accelerating voltage of 40 V, b) diffraction angle ranging from 20°-100° and c) step size of 0.01°. The XRD spectra obtained was matched with the Joint Committee on Powder Diffraction Standards (JCPDS) data to identify the respective peaks.

RESULTS

Visual examination and Dye penetrant testing

No macro cracks were detected on the surface of the pipes by visual examination. However, stains of thermic fluid were found near the seam weld and the spot welded regions. Dye penetration test was adopted to check for micro cracks on the surface of the pipes especially the welded regions. Hairline cracks near the weld zone were detected by this method as shown in Figure 2.

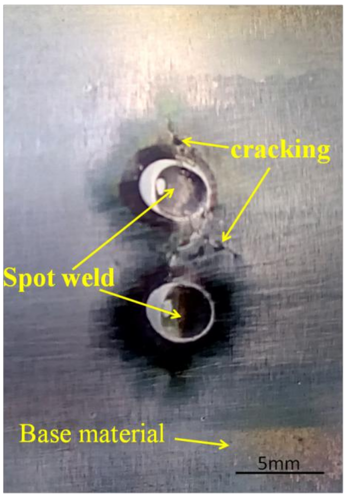

Figure 2: Hairline cracks detected near the spot welded region of the pipe by dye penetration test.

Microstructural characterization of the welded region

Laser beam welded pipes

The cross section of the laser beam welded region of the pipe of AISI 321 SS is shown in Figure 3. The weld fusion zone contained the ferritic structure and the base material had equiaxed polygonal grains with intermetallics. Detailed investigation of the cross-section of the pipe at various locations of the interface revealed that very fine cracks do exist just at the interface of the fusion zone and the base material.

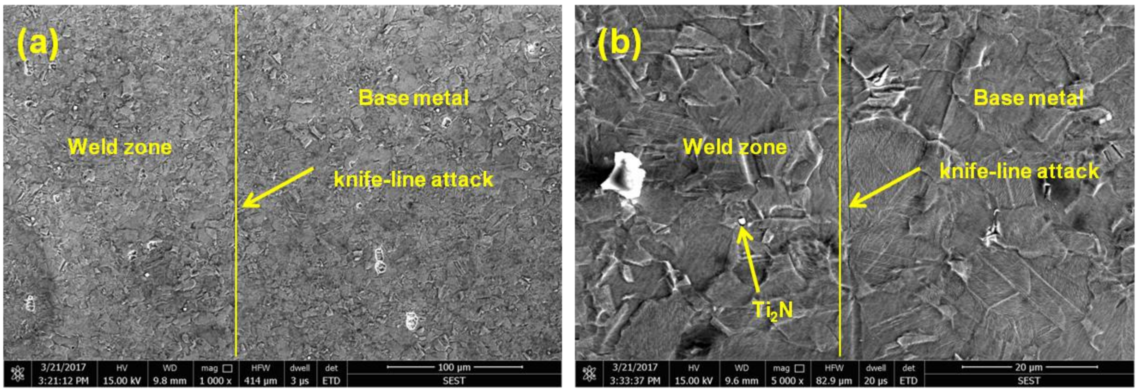

Figure 3: Optical Micrograph of cross section of LBW 321 SS pipe (a) showing cracks at the interface of the fusion zone and base material (b) image of the interface at a high magnification

Figure 3 (a) shows the weld zone with the attack at the interface of the fusion zone and base material. Figure 3 (b) gives a magnified view of the cracked region. The attack in the case of laser beam welded samples were very sharp in nature just at the interface of fusion zone and a base material exhibiting the typical characteristics of 'knife-line attack' in stabilized grades of stainless steel like AISI 321 and AISI 347. The TiC/ NbC dissolve at temperatures above 1150°C. The region just adjacent to the fusion zone is exposed to very high temperatures. Thus the carbon in this region remains in solid solution and no carbides (TiC/ NbC/$Cr_{23}C_6$) were precipitated due to rapid cooling. However, at a later stage if this alloy gets exposed to the sensitization temperature range of 400-750°C $Cr_{23}C_6$ precipitates form in this region making the alloy susceptible to intergranular corrosion. Hence proper post weld heat treatments of these alloys are compulsory before these can be put to service [7]. In the present case study, the service temperature to which the pipes had been exposed in the solar thermal power plant was 400°C and the service environment i.e. the thermic fluid flowing through it contained Cl^- ions. Hence the AISI 321 SS welds exhibited intergranular corrosion along a very narrow region just adjacent to the weld fusion zone which is a characteristic of a knife- line attack. Hence the leakage of the thermic fluid from the pipe in case of laser beam welded pipes were due to the occurrence of knife-line attack due to improper post weld heat treatment applied to the AISI 321 SS.

Metal inert gas welded pipes

Figure 4 (a) shows the FESEM micrograph of the pipe in the MIG welded region showing the interface of the fusion zone and the base material (in this case the specimen was etched in 10% oxalic acid solution). The average grain size of the base metal is ~ 30 ± 10 µm. FESEM images of the weld region revealed a high density of σ phase formed near the weld region and extended throughout the austenitic base material. Figure 4 (b) shows the FESEM micrograph of the pipe in the MIG welded region showing the interface of the fusion zone and the base material (the specimen is etched in 10% KOH solution, in order to reveal the σ phase. The micrograph clearly shows the σ phase formation near the interface of the weld region. The morphology of σ phase is stringer like and it is oriented in the hot working direction of the plate from which the pipe is fabricated. The needle-like morphology of the σ phase results in high-stress concentration at the tips resulting in stress assisted dissolution. Hence the formation of σ phase is detrimental for the corrosion behavior and cracking resistance of the austenitic stainless steel AISI 321 SS. It is difficult to prevent the precipitation of σ phase when Cr content is above 20 wt% in SS. In addition to this, the presence of strong ferrite stabilizers (like Cr, Si, Mo) in SS rapidly leads to the formation of σ phase. When the Cr content is below 20 wt. %, the precipitation of the σ phase is not readily observable in austenitic stainless steels [9].

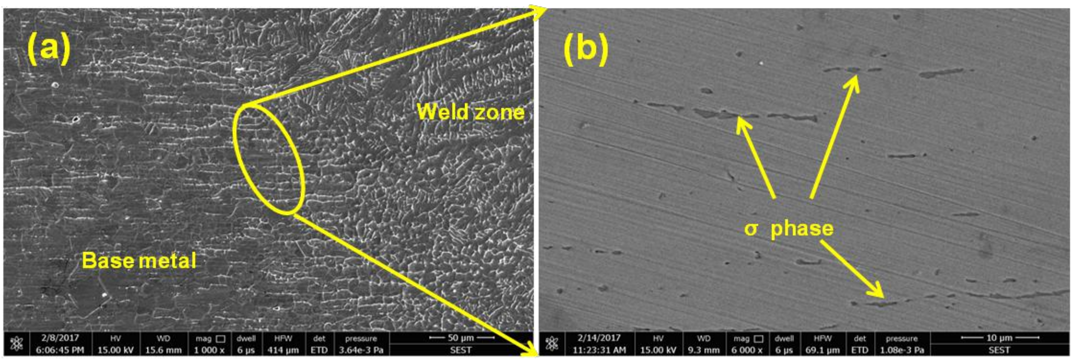

Figure 4: a) FESEM of cross section of metal inert gas welded AISI 321 stainless steel pipe near the weld interface and b) FESEM image of the σ phase at higher magnification (etched using 10% KOH solution)

Cracking in the spot welded region of the pipes

The microstructural characterization of the spot welded region provided clear evidence of the occurrences of stress corrosion cracking in this region of the AISI 321 SS pipes. Figure 5 (a) shows the cross-sectional view of the pipe in the region near the spot weld with a number of cracks. Figure 5 (b) gives the magnified view of cracked region and the spot welded region can be seen as a dark patch near the outer surface of the pipe. The Figure clearly indicates that the cracks initiated from the inner surface of the pipe and extended towards the outer surface. Extensive cracking was observed and the cracks were transgranular in nature. Crack branching and transgranular cracking are a characteristic feature of chloride induced stress corrosion cracking of austenitic stainless steel in chloride environment. SCC is a phenomenon which occurs under the synergistic action of tensile stresses, aggressive environment and susceptible material. Austenitic stainless steel is highly susceptible to chloride induced SCC in presence of tensile residual stresses and Cl^- ions [] Hence, the initiation of SCC from the inner surface of the pipe indicates the presence of tensile residual stresses in the inner surface of the pipe which may result from improper post weld heat treatment.

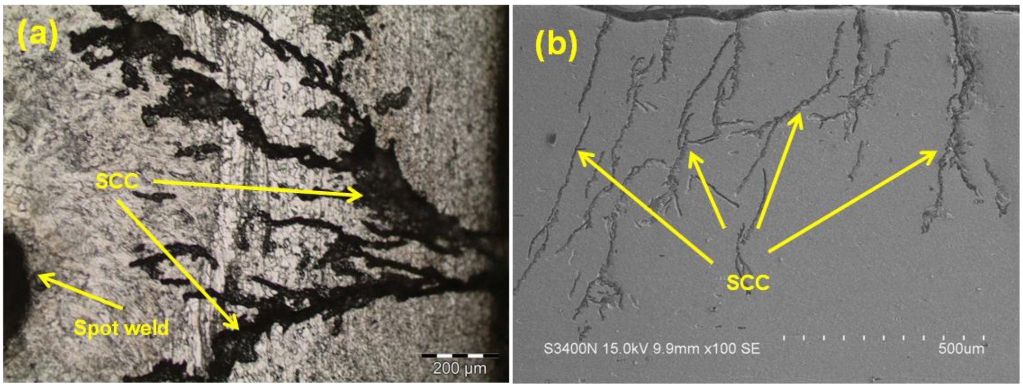

Figure 12: Shows the optical micrograph of stress corrosion cracking in the spot welded region of AISI 321 SS pipe. Transgranular cracks with extensive crack branching seen

X-ray diffraction

The X-ray diffractograms of the weld regions of the LBW, MIG weld and spot welded specimens, along with the base material are shown in Figure 3. The presence of the signature peaks of austenite for the all weld specimens can be clearly seen. Whereas the other peaks also identify those are Ti_2N and martensite.

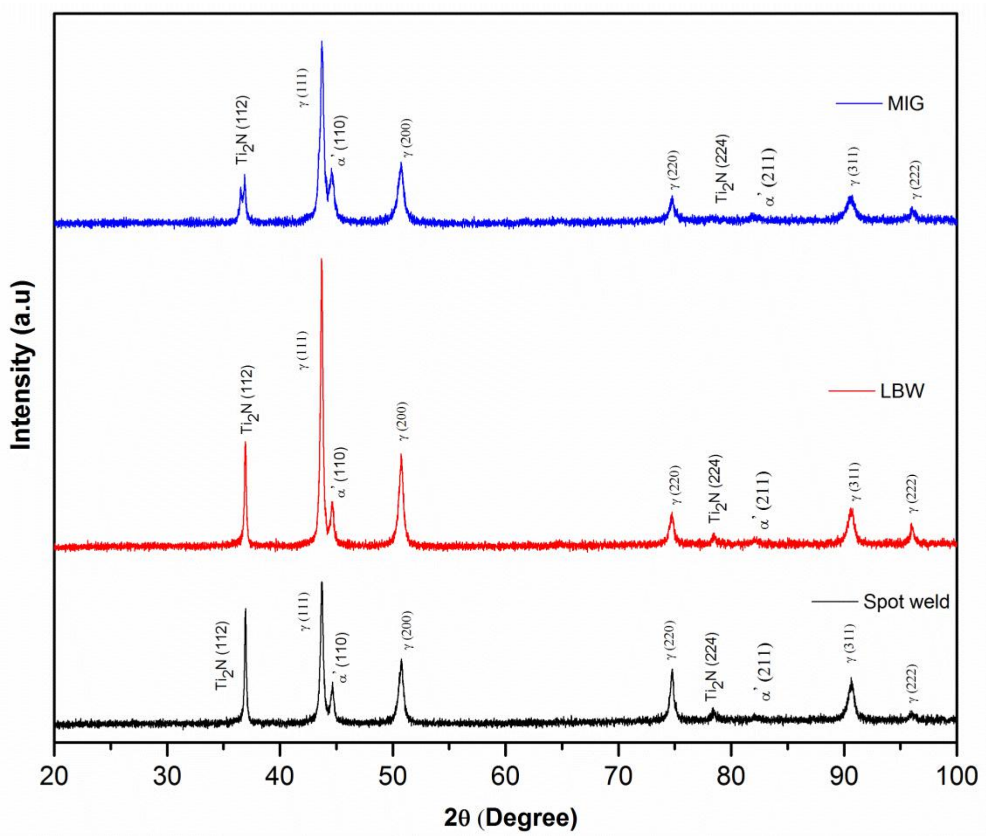

Figure 3: X-ray spectra of 321 SS under different welded conditions

CONCLUSIONS

The present study analyzed three different types of failures which occurred in AISI grade 321 stainless steel welded pipes used in solar thermal power plant. The aggressive environment containing chloride ions flowed through these pipes. The pipes had seam welding done by a) laser beam welding in one case and b) MIG welding in another case together with spot welding on the surface. Failure of the pipes near the welded region led to leakage of thermic fluid at 300 - 400°C. Detailed characterization of the failure was done to understand the root cause of the failure. The study yielded the following conclusions:

a) The laser beam welded pipes underwent knife-line attack due to improper post weld heat treatment of the welds. The attack led to leakage of the thermic fluid through this region.

b) The MIG welded pipes had a high density of detrimental σ phase precipitated near the weld zone which resulted in corrosion at the interface of the σ phase and austenitic matrix resulting in leakage of the thermic fluid. Such a failure can be avoided by keeping careful control over the filler wire composition. Lowering the ferrite content in the filler wire would prevent such an attack.

c) Chloride induced stress corrosion cracking of the spot welded region led to the leakage of the thermic fluid from this region. Proper post weld heat treatment should be given to relieve the tensile residual stresses present in the inner surface of the pipes to prevent such stress corrosion cracking instances in future.

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