Developing WPS for Repairs of Grade P91 Steel Castings with ENiCrFe-3 Electrode

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ABSTRACT

Modified 9Cr1Mo (P91) steel is widely used in manufacturing of power plant components because of its excellent high temperature properties. HP/IP inner and outer casing of steam turbine exposed to extreme high temperature and pressure during its working period. For this purpose, P91 was developed which have high fatigue strength, oxidation resistance and creep strength. In the present paper, repair welding of HP/IP inner casings of steam turbine manufactured by Modified 9Cr1Mo (P91) using ENiCrFe-3 electrode by qualification of welding procedure specification (WPS) is presented. Shielded metal arc welding process (SMAW) was used for welding purpose and then desired properties were evaluated. The use of ENiCrFe-3 electrode eliminated the post weld heat treatment (PWHT) process and improves the strength of welded joint. Castings of casings were machined after solidification and then non-destructive tests were performed in order to visualize surface and sub-surface defects and after identification of defects, grinding was done to eliminate these defects and thus the cavities formed were filled by welding and after that again machining process is done. The qualified Welding Procedure Specification (WPS) can be used in welding for eliminating defects in the machined components in future.

Keywords: Modified 9Cr1Mo steel; Creep strength; Fatigue; Welding Procedure Specification (WPS).

1. INTRODUCTION

Efforts to raise the thermal efficiency of power plants by increasing the operating temperature and pressures have resulted in the development of new families of creep resistant steels. The family of 9Cr1Mo steels is one of the most suitable candidate materials for these applications due to its resistance to stress corrosion cracking, good ductility and toughness, excellent high temperature creep strength, low coefficient of thermal expansion, low oxidation rate and good weldability [1]. The mechanical properties and microstructure of these steels is significantly improved by addition of small amount of vanadium and niobium. Modified 9Cr1Mo steels (often designated as T91 for tubing and P91 for piping) offers creep properties superior to those of other ferritic steels. The P91 steels have excellent mechanical properties due to optimized Nb/V ratio and distribution of fine-sized incoherent niobium and vanadium carbonitride precipitate particles [2]. Welding is an important fabrication process for most of high temperature components. Although P91 is weldable without cracking of any kind but welding of this steel by high productivity processes such as flux cored arc welding (FCAW), gas metal arc welding (GMAW), shielded metal arc welding (SMAW) is a challenge now a days.

Proper care must be taken in the welding parameters of this material like preheat temperature, inter-pass temperature, post weld heat treatment processes otherwise inadequate welding procedures leads to catastrophic failure of the component during its working conditions[3]. The soundness of weld is mainly decided by the proper selection of filler material. The advantage of P91 can fully be utilized provided these steels are welded by the appropriate welding consumable to ensure that the weldment possess intended properties. Post-weld heat treatment (PWHT) is required for tempering the martensitic formed during welding.

The main objectives of this research are as follows:

• Castings are machined after solidification and then non-destructive tests are performed in order to visualize surface and sub-surface defects.
After identification of defects, grinding is done to eliminate these defects.

Thus the cavities formed are filled by welding and after that again machining process is done.

1.1 Literature Review

Kloc et al. started Short-term creep tests on a 9% Cr (P-91 type) steel at temperature from 873 to 923 K and at stress below 100 MPa by means of the helicoids spring specimen technique. They studied preliminary annealing at 873 K for 1.8 x 10^7 s which reduced the primary strain, but it had no effect on the steady state creep [4]. After that Polcik et al. further analyzed microstructural data for creep of the tempered martensitic 9Cr1MoV steel (P 91) at 873 K. They found that the variation of the sub-grain size with strain conforms to an exponential change from the initial to the stress dependent steady-state value. Analysis of the size distributions of precipitated particles confirmed the previous result that in P 91 there is a superposition of growth of particles with the dynamic precipitation of new particles [5]. Spigarelli et al. further analyzed the creep response at 600°C of a P91 (9Cr–1Mo–NbV) steel welded joint by testing small samples from different weld locations. They analyzed the microstructure of the weld by light and transmission electron microscopy and also observed that the heat affected zone material exhibiting a fine-grained structure showed the highest minimum creep-rate values, i.e. the lowest creep strength [6].

Recently, Kimura et al. investigated Long-term creep strength of ASTM/ASME Grade 91 steels. They observed that the two heats of Grade 91 steels indicated lower creep rupture strength than the other four heats from short-term to long-term due to presence of delta ferrite phase. In the short-term, no difference in creep rupture strength was observed among four heats of Grade 91 steels, however, the large heat-to-heat variation of creep rupture strength was observed in the long-term at 600°C. The higher nickel containing heat indicates lower creep rupture strength in the long-term at 600°C. They observed homogeneously recovered sub-grain structure on the specimens creep ruptured after about 80,000h at 600°C for both high nickel low strength and low nickel high strength [7]. Skorobogatytykh et al. compiled and compared tensile, impact and long-term strength tests of P91 and grade 10Kh9MFb steels. They established the property identity of metals. Design characteristics of long-term strength on the basis of tests with more than one million of hour-samples were determined [8].

Divya et al. has been investigated influence of laser welding (LW) and shielded metal arc welding (SMAW) processes on cracking behavior of modified 9Cr-1Mo (P91) steel. They did comparison of stress rupture lives of modified 9Cr-1Mo steel weldments prepared by SMAW and continuous wave CO2 laser welding processes and found that rupture lives of laser weldment were higher than SMAW weldment at higher stress level and comparable at lower stress level [11].

2. MATERIALS AND METHODS

Two plates of Grade P91 were butt welded by shielded metal arc welding (SMAW) using suitable electrode and then different tests were performed to measure the intended properties of weldment.

2.1. Material

The base material used in the present investigations was modified 9Cr1Mo steel which was supplied in hardened (1050°C) and tempered (730°C) conditions. Stress relieving (720°C) action is also performed prior to welding. The base material used in the present study is 400 × 90 × 25 and 400 × 88 × 25 plates of modified 9Cr1Mo steel. The chemical composition was determined by the optical emission spectroscopy and mechanical properties at room temperature, which are summarized in Table 1 and Table 2.

### Table 1: Chemical composition of P91 base metal, wt%

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>S</th>
<th>P</th>
<th>Si</th>
<th>Ni</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Al</th>
<th>Nb</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specified</td>
<td>110</td>
<td>-</td>
<td>200</td>
<td>-</td>
<td>400</td>
<td>8000</td>
<td>900</td>
<td>180</td>
<td>-</td>
<td>50</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Actual</td>
<td>140</td>
<td>10</td>
<td>20</td>
<td>500</td>
<td>400</td>
<td>800</td>
<td>9500</td>
<td>1050</td>
<td>250</td>
<td>20</td>
<td>80</td>
<td>60</td>
</tr>
</tbody>
</table>

### Table 2: Mechanical properties at room temperature

<table>
<thead>
<tr>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation (%)</th>
<th>Reduction in area (%)</th>
<th>Impact energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>535</td>
<td>697</td>
<td>18</td>
<td>57.1</td>
<td>92</td>
</tr>
</tbody>
</table>

2.2. Welding Electrode

The welding of alloy steel grade 91 can be done by using different methods such as SMAW, GMAW, SAW and FCAW. The most important consideration is choosing right electrode for welding of grade 91 [12]. Recent studies have shown that when welding is done by using matching electrodes than the toughness of weld metal proved to be rather low after tempering. It is therefore necessary to change the weld metal composition from that of base metal [13]. Dittrich et al. investigated that reduction in niobium, nitrogen and silicon contents in weld improves toughness whereas increase in nickel content improves the toughness of weld deposit. Hence ENiCrFe-3 electrode is preferred as it has more nickel content in comparison to other alloys [14]. The chemical composition evaluated by optical emission spectroscopy is given below in Table 3.
Table 3: Chemical composition of filler material

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>S</th>
<th>P</th>
<th>Si</th>
<th>Ni</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>0.005</td>
<td>0.003</td>
<td>0.005</td>
<td>0.150</td>
<td>26.50</td>
<td>2.30</td>
<td>9.10</td>
<td>0.420</td>
<td>-</td>
</tr>
</tbody>
</table>

2.3. Welding Procedure

Welding process employed is shielded metal arc welding (SMAW) in this investigation. The base plate is butt welded with an included single V groove angle of 80° C and dimension of weld geometry were a root opening of 62 mm and a root face of 25 mm and backing was done. The backing material used was mild steel with buttering of base metal. The filler material ENiCrFe-3 rods of diameters 3.2 mm, 4 mm, 5 mm was preferred for welding. First three passes were welded by electrode of diameter 3.2 mm, next three passes by diameter of 4 mm and further passes with diameter of 5 mm and travel speed. The preheat temperature was in the range of 50-100°C and the interpass temperature employed was 150°C. For welding, stringer bead is considered best suited and DC electrode positive power source was used. Electrical characteristics are given below in Table 4.

Table 4: Welding parameters details

<table>
<thead>
<tr>
<th>Process</th>
<th>Weld Layer</th>
<th>Dia(mm)</th>
<th>Current(A)</th>
<th>Voltage(V)</th>
<th>Travel Speed(mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMAW</td>
<td>Root</td>
<td>3.2</td>
<td>70-95</td>
<td>18-26</td>
<td>100-145</td>
</tr>
<tr>
<td>SMAW</td>
<td>other</td>
<td>4</td>
<td>90-120</td>
<td>22-28</td>
<td>140-190</td>
</tr>
<tr>
<td>SMAW</td>
<td>other</td>
<td>5</td>
<td>120-160</td>
<td>24-32</td>
<td>160-240</td>
</tr>
</tbody>
</table>

The Electrical characteristics such as current, voltage etc., were taken from the specification given on the packet of electrode ENiCrFe-3.

2.4. Post Weld Heat Treatment

After the welding post-weld heat treatment (PWHT) was not required as nickel content in the electrode is such that the lower critical temperature does not fall below the post-weld heat treatment (PWHT) temperature. The need to balance filler material composition to restrict the occurrence of δ-ferrite and also to ensure the fully developed martensitic structure in the fusion zone as investigated by Sireesha et al. in their studies of joining P91 steels [15].

2.5. Measurements

After welding the joints were radiographed in accordance with ASME sec-IX to check for any flaws in welding. Sampling plan as per ASME sec-IX was prepared and the specimens were prepared according to the given specifications. After that metallographic inspection, tensile test, transverse side bend test, impact test and hardness test were performed to compliance with the mechanical properties of welded joint with grade P91 steel.

3. RESULTS AND DISCUSSION

The results based on different analysis are discussed below which are used in the qualification of welding procedure specification (WPS).

3.1. Microstructures

The microstructures of P91 base material and weldment were examined by Transmission electron microscopy (TEM). The microstructure of weldment shows randomly dispersed heavy carbide particles in FCC matrix, Ph 1 at 200x & 2 at 500x. The microstructure of the P91 base material in the as-received normalized and tempered condition consists of partially tempered martensite matrix, Ph 3 at 200x & 4 at 500x are shown in figure 2.

Fig. 1: Typical microstructures of P91 steel in weld metal

Fig. 2: Typical microstructure of P91 steel in base metal after hardening, tempering and stress relieving

Fig. 3: Side bend specimen, free of cracking

3.2. Transverse side bend

The weld was transverse to the longitudinal axis of the specimen. Transverse side bend test specimens were prepared as per given specification in ASME sec-IX Fig.3. The bent specimens were tested in bending machine where they were successfully bent up to 180° without failure or crack. Therefore results were found satisfactory. Mechanical properties are given in Table 5 and Table 6.
4. CONCLUSIONS

Mod 9Cr1Mo steel is one among those complex materials which are difficult to work upon. The most important task is to maintain its unique microstructure during whole process.

1. The properties of the material can be completely ruined permanently if whole parameters do not meet the specified guidelines given in the codes.
2. The use of ENiCrFe-3 electrode eliminates the necessity of post weld heat treatment process due to its high nickel content.
3. The tensile tests performed as part of the weld qualification program tested complete welded joint.
4. The welding procedure specification for P91 steels is qualified for SMAW.

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REFERENCES


