Weld Repair of Steam Turbine Rotor with 12 Cr Weld to Mitigate Corrosion Issues

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Abstract. Weld repair of steam turbine rotors has become an acceptable practice to extend the life of rotors. Depending on the type of damage, the extent of weld repair can range from weld build-up of integral discs to stubbing a new forging to replace the damaged portion of an old rotor. Steam turbine rotors made of low alloy steels experience corrosion related damages such as stress corrosion cracking, pitting corrosion, corrosion-erosion etc., Traditional weld repairs have been using low alloy steel welds. While the low alloy welds may have mechanical properties comparable to or even slightly exceeding that of the low alloy steel rotor alloys, the corrosion resistance of the low alloy welds are not great. 12 Chromium weld will provide better resistance to corrosion related damages than typical low alloy welds. However using 12 Chromium weld on low alloy steel rotors provides some additional challenges and limitations. These include selection of optimal combination of weld wire and flux for rotor welding, selection of optimal post weld stress relieve temperature and dealing with abrupt change in chemical composition at the weld interface. This paper discusses development of such a weld procedure and provides some examples where the 12 Chromium weld was successfully applied on steam turbine rotors that experienced corrosion related damages.

1 Introduction

Steam turbine rotors experience different types of damages in service. The damages can be caused by any one or combinations of the following: rubbing, erosion, corrosion, embrittlement, creep and fatigue. Weld repair of damaged rotor is preferred over replacing the damaged one with a new rotor due to reduced lead time and cost. Weld repair has been successfully used to repair damaged rotors for almost three decades [1-3]. Some typical weld repairs are machining away damaged discs and rewelding the discs, dimensional restoration of rotor journal area, and cutting a damaged portion of a rotor and joining (stubbing) a new forging in its place etc. When the amount of weld is significant, submerged arc welding is preferred due to its higher deposition rate. For cases where the amount of weld is small – such as stubbing a new forging to an old rotor- gas tungsten arc welding may be used. Most of the weld is performed while the rotor is slowly rotated in a lathe. This helps to keep the residual stresses due to welding at a manageable level.

Most of the old steam turbine rotors were made of low alloy steel forgings. Typical rotor alloys are NiCrMoV and CrMoV alloys [1]. These alloys are being used as rotor alloys due to their through hardenability and their capability to develop optimal combination of different mechanical properties at relatively lower cost. However their resistance to corrosion is not ideal – particularly when the steam is not pure. Corrosive steam leads to various types of problems in steam turbine rotors. These problems include corrosion fatigue, excessive pitting in rotors and stress corrosion cracking (SSC) at high stress locations. A comprehensive treatment of this subject can be found in reference [4]. Corrosion fatigue is a mechanism where crack propagation occurs due to combination of corrosion and fatigue. This involves corrosive environment and high enough alternative stress. Though pitting and minor amount of corrosion /erosion damage may not be harmful to a certain extent, they pose the risk of acting as crack initiation sites for other types of failures such as fatigue failure. If these types of damages occur at relatively faster rates, some remedial actions need to be taken.

Stress corrosion cracking is a type of cracking that occurs in high stress location over time. Although some modern steam turbines have almost eliminated the stress corrosion cracking by taking several preventive measures [5], older steam turbines and turbines operating with impure steam (such as geothermal steam turbines) do experience stress corrosion cracking. Though cracks develop in rotors due to different causes, metallurgical root cause failure analysis can be used to confirm that the failure mechanism was stress corrosion cracking in the relevant cases.

A recent example of stress corrosion cracking in a steam turbine rotor is discussed briefly below. Magnetic particle inspection of the row 6 integral disc of a steam turbine rotor showed cracks in its ball root blade hook

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area. Figure 1 shows a sample crack as highlighted by magnetic particle inspection [6].

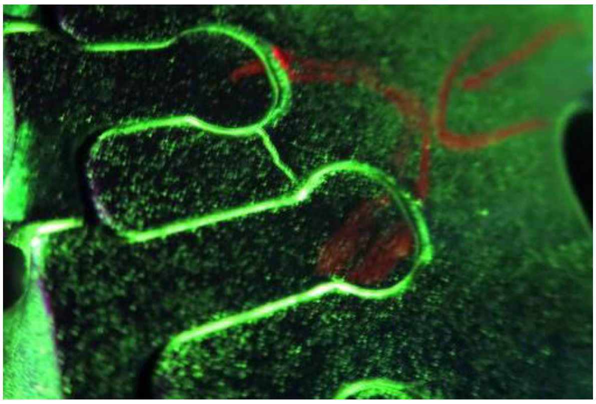

Fig. 1. Magnetic particle inspection highlighting a crack in a blade hook fit of a turbine disc.

The cracks were mechanically opened and the fracture surface showed intergranular fracture as shown by the sample scanning electron microscope (SEM) image in Figure 2.

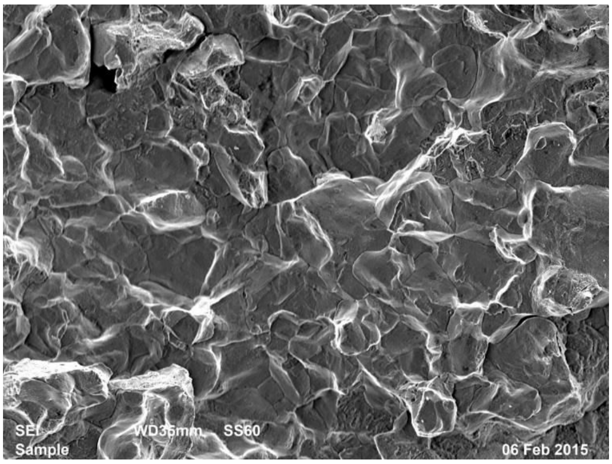

Fig. 2. SEM image of the fracture surface showing intergranular cracking which is a characteristic of stress corrosion cracking.

Additional information on this failure can be found in reference [6]. Complete root cause failure analysis (RCFA) was performed and stress corrosion cracking was determined to be the cause of cracking. The original rotor material was a low alloy steel.

For stress corrosion cracking to occur, the following three factors are mandatory conditions: corrosive environment, high enough stress and a material susceptible for corrosion. Eliminating any one of these three factors will prevent stress corrosion cracking. Using high purity steam to remove the corrosive environment is not always possible. Besides, some steam turbines such as geothermal steam turbines use naturally available steam which is inherently impure. Design modification to decrease the stress level at the crack location would require blade root design modification. However this is not always possible due to space limitations in the disc/blade. Upgrading the rotor to an alloy not susceptible to stress corrosion cracking can help however this option would mean replacement of the entire rotor which is very expensive and the lead time to obtain the new rotor forging is very long.

Typical repair procedure for such cracks in a rotor would be to machine away the disc section with the cracks and to weld build up the machined section with either ER120 or ER 140 filler wire. Though the welds with ER120 and ER140 have strength levels comparable to that of the low alloy steel rotor, their resistance to corrosion or stress corrosion cracking would not be any better than the base metal. This means that the same stress corrosion cracking or corrosion related damages may recur in the repaired rotor.

Increasing the Chromium content in a steel alloy increases the alloy's resistance to corrosion. Chromium content about 12 percent had been determined to be the optimal Chromium content for improved corrosion resistance in steel alloys [7]. Similarly using 12 Chromium weld would improve the corrosion resistance of the weld. Therefore a new welding procedure with 12 Chromium weld had to be developed and qualified for such applications.

2 Development of 12 Cr Welding Procedure

Different grades of 12 Chromium weld wires are readily available. Plain 12 Chromium weld (ER410) without significant amounts of other alloying elements, is one of the easiest to obtain and to weld. However, ER410 weld is not as strong as most of the low alloy rotor steels. ER410NiMo has nominal 12 percent Chromium with Nickel and Molybdenum additions. Addition of Molybdenum increases the strength while addition of Nickel improves the ductility and toughness in the weld. Strength level of ER410NiMo weld is comparable to the strength level of typical low alloy steel rotor steels while its resistance to corrosion is superior. Hence ER410NiMo was selected as the weld wire to be used.

As mentioned earlier, submerged arc welding is preferred for weld repair of rotor due to its high weld deposition rate. The molten weld would be deposited on the partially machined (weld prepped) disc while the rotor is rotated slowly in a lathe. The deposited amount of weld would have to be small enough so that the weld would solidify quickly without dripping from the curved disc surface when it rotates. On the other hand, there has to be enough time for the slag and any trapped air to escape from the molten weld. Though there may be several different types of fluxes that could be used with ER410NiMo weld wire, the ideal flux-weld wire combination should produce a weld with acceptable weld properties while meeting the limitations mentioned above. For example, a particular flux-weld wire combination may produce excellent combination of mechanical properties. However, the welding parameters that would produce weld with excellent properties cannot be used for rotor welding due to the limitation mentioned above. After reviewing different fluxes meant for stainless steel welds, two fluxes were shortlisted for the weld trials.

The base metal (rotor) would have a Chromium content lesser than 2 percent since most of the common steam turbine rotors have Chromium content lesser than 2 percent. The intention was to weld with ER410NiMo weld with a nominal Chromium content of 12 percent. This would mean a very sharp change in the Chromium percentage at the weld interface. This is not desirable due to the associated abrupt change in the properties at the weld interface. Therefore it was decided to use butter pass layer of different weld at the interface to smooth out the abrupt change. This means that the butter pass will have a lower strength. In the actual rotor weld repair, the location of weld interface needs to be strategically selected to coincide with low stress location due to the lower strength of the butter pass weld at the weld interface.

The Nickel content in the ER410NiMo weld reduces the austenite start temperature to about 621 °C (1150 °F). This means if the weld is heated above 621 °C and held at that temperature during post weld heat treatment (PWHT/stress relieve), the phase of the weld might transform into austenite. Once cooled down, it might transform into martensite. However this will be untempered martensite – which does not have the required mechanical properties. Therefore a PWHT temperature below 621 °C was selected.

The SAW welding was performed on two cylindrical pieces of AISI 4340 that had been quenched and tempered at a temperature to a hardness level between 28-32 HRC. AISI 4340 was selected since it is also a NiCrMo alloy steel comparable to similar rotor steel. The hardness level of 28-32 HRC was selected since this hardness level is comparable to the typical hardness level of low alloy steel rotors. However it should be noted that this particular application is not applicable machines confirming NACE requirements. A separate procedure qualification with different post weld heat treatment is needed for machines confirming to NACE requirements.

After welding and stress relieving, mechanical test samples were extracted for room temperature mechanical property testing to qualify the welding procedure per ASME Boiler and Pressure Vessel Code Section IX. Table 1 compares the measured mechanical properties corresponding to the weld trials with the two fluxes.

Table 1. Measured room temperature mechanical properties from the weld trials with two different fluxes. All composite tensile tests failed at the base metal.

	Trial with Flux A	Trial with Flux B
Tensile Strength - Sample 1 (ksi)	109.6 (Composite)	130.9 (Weld)
Tensile Strength - Sample 2 (ksi)	108.4 (Composite)	131 (Composite)
Bend Tests (4)	Passed	Passed
Weld hardness (HRC)	31 -33	28-30
Weld Impact Toughness (ft-lbs)	19	39

The comparison shows that the weld with flux B has better strength and better toughness. Therefore, it was decided to select the welding procedure with flux B for actual rotor weld repairs.

The chemical composition of the weld with Flux B was analyzed. It was found to contain 12.4 percent Chromium and 4.2 percent Nickel. This level of higher Chromium content would definitely improve the corrosion resistance of the weld.

The following section discusses two geothermal steam turbine rotors on which the developed weld procedure was used successfully for the repair of the turbines.

3 Case Study # 1: 55 MW Double Flow Steam Turbine

This is a geothermal steam turbine rated at 55 MW. It is a double flow type turbine with the steam inlet temperature of 450 ºC. The rated speed of the turbine was 3600 rpm. The rotor material was CrMoV alloy. According to the user, the steeples on six of the discs had cracks. The user had already machined the portions with the cracks when the rotor was sent to Sulzer for repair. According to the user, stress corrosion cracking was the mode of cracking. Incoming inspection of the rotor showed pitting corrosion in several locations including both journal areas and seal areas. Finite element analysis was performed to identify the highly stressed location. Figure 3 shows estimated von Mises equivalent stress distribution in the disc root section of one of the discs.

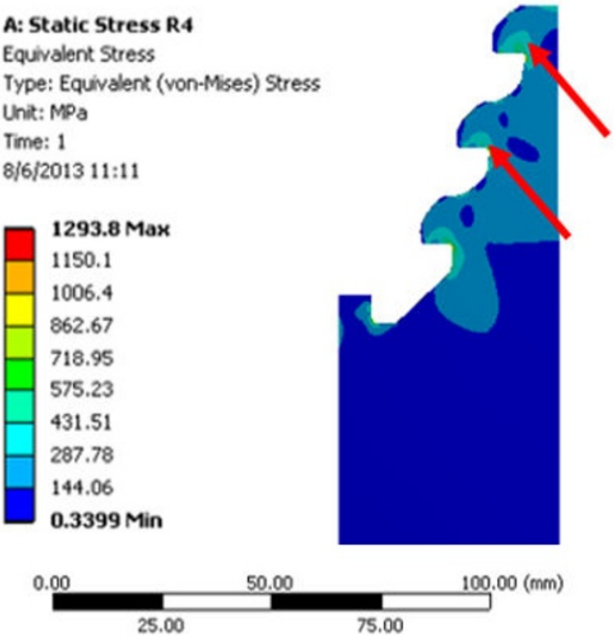

Fig. 3. Equivalent (Von Mises) stresses in the disc (half section). The two red arrows point to crack locations. These locations coincide with high stress locations as well.

High stress locations coincided with the crack locations – supporting customer's conclusion that it was stress corrosion cracking. Therefore it was decided to use the 12 Cr weld (ER410NiMo) for the repair. The six discs were further machined away to strategically locate the weld interface and rewelded with ER 410NiMo as shown in the Figure 4.

Fig. 4. Weld build-up of the discs with submerged arc welding.

After the completion of the welding, the rotor was rough machined, nondestructively tested and then stress relieved. The welded discs passed Sulzer's NDT criteria for welds on rotors. After final machining, the rotor was rechecked non-destructively. After making sure that the rotor passed the NDT criteria, the weld built discs were rebladed with new blades. The rotor was returned to service after the completion of all repairs and no issues had been reported since then.

4 Case Study # 2: 20 MW Steam Turbine

This is also a geothermal steam turbine with a rated output of 20 MW. The rotor alloy was CrMoV. Steam inlet temperature was 165.7 ºC and steam inlet pressure was 7.13 Bar. The rated speed was 3,000 rev/min. It has 8 blading stages. By design, all the rows of blades were loaded in the loading slots of the rotor. The loading slots for the first three stages of the blades were heavily corroded as shown in Figure 5.

Fig. 5. Heavy corrosion damage in the loading slots of the rotor.

In addition, the seal area sustained heavy corrosion damage as shown in Figure 6.

Fig. 6. Corrosion damage in the seal area of the rotor.

Per the customer, the rotor only ran for 3-4 years. The amount of corrosion seen was too much for a rotor that ran for 3-4 years. To mitigate the corrosion issue, it was decided to machine away existing loading slots that experienced severe corrosion and to use 12 Cr weld (ER 410 NiMo) to build up them. In addition, it was decided to undercut the corroded seal and journal areas and to reweld them with 12 Cr filler wire. Figure 7 shows the rotor being welded after machining away the damaged portions.

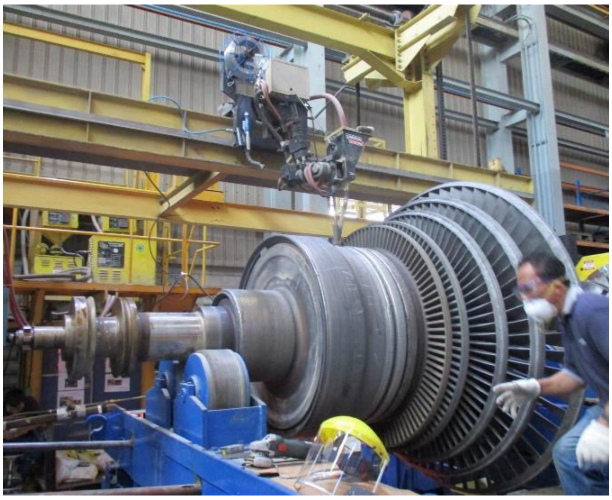

Fig. 7. Weld repair of the seal area and blade slots on the rotor.

As the amount of weld to be deposited was high, submerged arc welding process was used. After welding, the welded portions of the rotor were rough machined and inspected non-destructively confirm that it passes Sulzer's internal criteria. Then it was stress relived per the qualified welding procedure. This was followed by machining the required features such as loading slots etc. Figure 8 shows the weld repaired rotor being rebladed. The weld repaired and machined seal area can also be seen in the figure.

Fig. 8. Reblading of welded slots. The weld repaired and machined seal area can also be seen in the photo on the right.

As in the case 1 mentioned earlier, the weld repaired rotor was evaluated non-destructively to make sure that it passed the criteria for rotor repair. After reblading and balancing, the rotor was put back in service.

5 Conclusion

Turbine rotors experience damages due to different issues. One of the main factors that leads to types of various damages in rotors is corrosion. Corrosion may directly manifest as a crack due to stress corrosion cracking or localized corrosion sites may act as crack initiation sites for other failure mechanisms. Weld repair is an acceptable method of repairing damaged turbine. Typical weld repair with low alloy steel filler wire generally produces weld that is comparable to low alloy steel rotor alloys in terms of its mechanical properties. However, low alloy steel weld would not address the corrosion related issues. Using a high Chromium weld such as a weld with 12 percent Chromium will provide improved resistance to corrosion related issues in the rotor.

Using a weld wire with high Chromium for rotor weld repair posed some unique challenges. Mock weld build-up trials were performed to resolve these issues and to makes sure that weld would meet or exceed the mechanical properties of the rotor alloys. The main challenge was getting the right 12 percent Chromium weld wire and flux combination that would provide optimal mechanical properties when welded using the welding parameters as allowed by the limitations corresponding to rotor weld repair. Welding trials were conducted to find the optimal combination. The post weld heat treatment temperature was carefully selected to make sure that weld microstructure would be primarily tempered martensite. A butter layer of 5 percent Chromium weld was introduced at the weld-base metal interface to smoothen the gradient in the chemical composition. A successful weld procedure was developed using a filler wire with 12 percent Chromium (ER 410NiMo).

Two case studies where the developed welding procedure with high Chromium weld was used for the weld repair of the rotors are discussed. The damages on the rotors were primarily due to corrosion. The rotors were successfully weld repaired using the newly developed weld procedure with ER 410NiMo weld wire and the rotors have been in operation without any issues since then.

The authors would like to take this opportunity to thank the Sulzer family and their customers.

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