Cause Analysis of Booster Pump Shaft Cracking in Nuclear Power Plant

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Abstract. The cracking Booster pump shaft is carried out macroscopic examination, crack analysis, metallographic examination, chemical composition analysis, mechanical properties (tensile, impact) analysis, and combined with the pump shaft installation and operation, determine the direct cause of shaft cracking is crevice corrosion, the root cause include O ring in booster pump machine seal sleeve does not meet the requirement, O ring installation damage, and the clearance between pump shaft and machine seal sleeve is too small. According to the root cause of the pump shaft cracking, relevant corrective actions have been formulated, such as changing model of O ring in booster pump machine seal sleeve, change the clearance between pump shaft and machine seal sleeve, increase anti-corrosion coating or protective sleeve on pump shaft etc.

1. Introduction
Motor-driven Feed water Pump (APA) [1] in nuclear power plant is used to extract the deoxygenated water from desecrator, and then send water to high pressure heater after water pressure rises, and then water is delivered to the steam generator. The APA system consists of 3 sets of electric feed water pumps, 2 sets under normal operating conditions, and 1 set in standby state. Each electric feed water pump unit is composed of booster pump, motor, hydraulic coupling and pressure stage pump.

In 2016, a booster pump during normal operation in a nuclear power plant appears high vibration alarm on non-drive end of shaft, and vibration values exceeds the stop value, shutdown the booster pump and strip inspection, confirm non drive end of the pump shaft had cracked. After the incident, the same model booster pump in the other power plants are also found similar problem after investigation.

The fracture of booster pump shaft will lead to the unavailability of APA pump set, and reduces the redundancy of equipment. If pump shaft breaks suddenly, will cause fluctuation in the water supply to the steam generator and the unit will rapidly reduce the load. Replacement cost of booster pump axle is higher, so it is necessary to study the cause of the pump shaft cracking.

2. Experimental methods and results
The cracking booster pump shaft is made of stainless steel forgings, which is processed by rough processing, heat treatment, grinding and fine grinding. The pump shaft length is 2014mm, weight is 75.8Kg, material is 1.4313 martensitic stainless steel (equivalent to china X3CrNiMo13-4), manufactured in accordance with the standard of BS EN 1025-4-2000[2].

The cracking position of the pump shaft is located in the mechanical seal sleeve of non-drive end, as shown in figure 1. The mechanical seal sleeve is used for installing and fixing the mechanical seal
moving ring of pump, the machine seal sleeve and the pump shaft are fixed, and the inner of machine seal sleeve is provided with an O ring, which used to prevent the leakage of medium in the pump.

In this paper, the sample is intercepted near the crack of pump shaft, the cracking behavior of the pump shaft is studied by means of macroscopic examination, crack analysis, metallographic examination, chemical composition analysis, mechanical properties (impact and tensile) analysis and so on. The sealing condition of the machine seal sleeve is analyzed. The reasons for the cracking of the pump shaft are found out, and the corrective measures are made.

3. Experimental methods and results
Macroscopically inspect the surface of the pump shaft, the location of the crack, the distribution of cracks and the inside of the sealing sleeve. Microscopic observation and analysis of cracks are performed by using TESCAN VEGA TS5136XM scanning electron microscopy. ZEISS EVO 18 is used for energy spectrum analysis. Metallographic structure and non-metallic inclusion are checked using Zeiss MEF-4 desktop metallographic microscope, Analysis of chemical composition of pump shaft using inductively coupled plasma atomic emission spectrometry. Use Japanese SHIMADZU AG-IC 100kN universal material testing machine to test pump shaft tensile property. Using German Zwick RKP 450 Charpy impact testing machine to test the impact performance of pump shaft.

3.1. Macroscopic Examination
The cracking of the pump shaft is shown in figure 2. The crack of the pump shaft extends along the circumference of the pump shaft, cleaning the cracking position of pump shaft , it is found that there is a heavy corrosion mark near the crack of pump shaft, and the distribution of corrosion is banded.

Figure 1. Cracking position of pump shaft.

Figure 2. macro inspection of pump shaft.
Measure the corrosion position and combine the mechanical seal mounting drawings, confirm the corrosion is at the gap position behind the sealing ring of sleeve. Further check the corrosion of shaft and machine seal sleeve, see figure 3. There is a large amount of corrosion products at the back of the sleeve seal ring, which are corrosion products of the pump shaft. Pump shaft corrosion pattern is broad and shallow, according to corrosion location and corrosion pattern, the corrosion type of pump shaft is crevice corrosion.

![Corrosion position](image1)

**Figure 3.** Corrosion of pump shaft and corrosion of machine seal sleeve.

Open the crack of pump shaft and observe the macroscopic fracture features, as shown in figure 4. The fracture surface is grey brown, bright colored area is free of cracking; the region of crack not penetrated is smaller. The fracture has no obvious plastic deformation, obvious fatigue curve exist in the fracture surface, so the crack of pump shaft is fatigue crack. The crack begins at one side of the fracture and extends to the center, the surface of the pump shaft near the crack source is further observed, it is confirmed that the crack formation is related to the corrosion of 3 positions (A, B, C) on the pump shaft surface.

![Fatigue characteristic](image2)

**Figure 4.** Macro characteristics of pump shaft cracks.

3.2. **Microscopic morphology and energy spectrum analysis of crack source**

The characteristic areas of fracture are observed by scanning electron microscope (SEM). There are obvious step features in the crack source region, as shown in figure 5a, the step features are caused by surface corrosion, and there is no obvious material defect in the crack source area. Obvious fatigue bands can be observed in the fatigue crack growth zone, as shown in Figure 5b. The artificial fracture zone is a typical ductile fracture, as shown in figure 5c; it shows that the material has better toughness.
The energy spectrum of the pump shaft crack source is analyzed, and the result is shown in figure 6, the main chemical components of crack source include Fe, O, Cr and so on, no halogen corrosion products, further proof, corrosion type is crevice corrosion.

3.3. Metallographic analysis

Metallographic analysis shows that there is no decarburization layer on the surface of pump shaft. There are many corrosion pits and micro cracks on the surface of the pump shaft crack source; there is a micro crack at the bottom of corrosion pit. See figure 7a, the crack extends to the interior of the pump shaft in a transgranular manner, which further indicates that the crack in the surface of the pump shaft lead to cracking of the pump shaft. The central part of the pump shaft is lath martensite, the austenite grain boundary is clear, the grain size is 4-6, and no abnormal microstructure is found, as shown in Figure 7b. The non-metallic inclusion level of pump shaft is D1.5, The size of non-metallic inclusion is smaller, see figure 7C.
The pump shaft is processed by forging, roughing, heat treatment, grinding and fine grinding. The heat treatment specification is quenching + tempering + stabilizing treatment, the analysis result shows that the material of pump shaft conforms to the characteristics of martensitic stainless steel, the manufacturing process of pump shaft is normal.

3.4. Chemical composition analysis

Samples are obtained near the crack of the pump shaft, and the chemical composition of the pump shaft is analyzed, the results is shown in table 1, the chemical composition of the pump shaft meets the requirements for 1.4313+QT780 in the standard of BS EN 10250-4.

Table.1. analysis results of chemical composition wt%.

|   | C    | Si   | Mn   | P    | S    | Cr   | Mo   | Ni   |
|---|------|------|------|------|------|------|------|------|
| sample | 0.016 | 0.30 | 0.74 | 0.015 | <0.010 | 13.26 | 0.62 | 3.86 |
| Standard requirement | ≤0.05 | ≤0.70 | ≤1.50 | ≤0.040 | ≤0.030 | 12.00~12.50 | 4.00 | 0.30~0.70 | 3.50~4.50 |

3.5. Mechanical Properties Analysis

According to GB/T 228.1-2010 tensile test of metallic materials, part first: room temperature test method[3], GB/T 229 -2007 metallic materials Charpy pendulum impact test method[4], The analysis sample is drawn along the axial direction of the pump shaft, and the tensile properties, impact properties and hardness of the pump shaft are tested. The results of mechanical performance analysis are shown in Table.2.

Table.2. Mechanical Properties Analysis of pump shaft.

|   | $R_p 0.2$ (Mpa) | $R_m$ (Mpa) | A (%) | $A_k$ (J) |
|---|----------------|-------------|-------|-----------|
| 1# | 770            | 866         | 19.0  | 176.0     |
| 2# | 769            | 865         | 19.5  | 175.5     |
| 3# | 771            | 865         | 19.0  | 166.5     |
| Standard requirement | ≥620 | 780~980 | ≥15 | ≥70 |

The analysis shows that room temperature tensile properties and room temperature impact properties of the pump shaft meet the requirements of 1.4313+QT780 in the standard of BS EN 10250-4:2000.

4. Analysis and Discussion

The above analysis shows that the structure and properties of the pump shaft are normal, and the crack of pump shaft are fatigue cracks. The fatigue crack source is located at the 3 crevice corrosion location on the pump shaft surface. The stress of the fatigue crack source is smaller, which is only 4.1Mpa. Therefore, the cracking of pump shaft is mainly related to the crevice corrosion of the surface.

According to the conditions for crevice corrosion, check the relevant configuration of booster pump. Check O ring of booster pump machine seal sleeve, found that the O ring was damaged during installation, and its design compression rate is low [5], causes the pump medium through the O ring, leaks to the corrosion position.

Once the pump medium leaks, the corrosion position of pump shaft meets the conditions of crevice corrosion [6]. The pump shaft is made of martensitic stainless steel, which is self - passivation metal, the crevice corrosion sensitivity of self – passivation metal is high. The pump medium contains very little dissolved oxygen (3ug/Kg), but the medium is still a sensitive electrolyte. The clearance at the back of O ring is between 0.007mm and 0.0395mm, which satisfies the crevice corrosion condition (0.025-0.15mm).

According to the mechanism of crevice corrosion [7], the occurrence of crevice corrosion in the pump shaft is deduced:
1) The clearance of the pump shaft corrosion position is smaller, and the decompression action of the O ring before the corrosion position, cause leakage medium to remain in the gap. An anode reaction occurs in the pump shaft in the gap: \( M \rightarrow M^+ + e \), and cathodic reactions occurs in the crevice solution: \( O_2 + 2H_2O + 4e \rightarrow 4OH \).

2) Oxygen within the gap is depleted and not supplemented, a macroscopic oxygen concentration cell is formed in the interior of the gap and outside the gap, the interior of the gap is an anode, and the outside of the gap is a cathode, the above reaction continues.

3) The increase of metal cations in the gap attracts anions into the gap, resulting in the concentration of metal salts in the crevice solution; the hydrolysis of metal salts reduces the pH value and accelerates dissolution of the anode. That also attracts external anions into the gap to form metal salts. The metal salt continues to hydrolyze and the metal continues to corrode.

In summary, analysis and illustrate the cracking process of booster pump shaft. The pump shafts no special anti-corrosion design. Selection of machine seal sleeve O ring does not meet the requirement, and the machine seal sleeve O ring installation damage, leading to the media into the gap between the pump shaft and the machine seal sleeve. The clearance of the gap is smaller, leading to leaking medium remains in the gap, and eventually lead to serious crevice corrosion of booster pump shaft. In normal operation, the stress concentration in the corrosion position of the pump shaft leads to fatigue cracking and fatigue expansion. The fatigue crack expands to a certain size; the pump vibration exceeds the alarm value, and eventually leads to the booster pump shutdown.

5. Conclusions and solutions
According to the above analysis, the crevice corrosion is the direct cause of booster pump shaft cracking, the root cause include: selection of booster pump machine seal sleeve O ring does not meet the requirement, the machine seal sleeve O ring installation damage, the clearance between the pump shaft and the machine seal sleeve is too small. Preventive measures are hereby formulated as follows:

(1) Check all pump shafts and determine the corrosion of pump shafts, check the machine seal sleeve O rings and determine the integrity of O rings;
(2) Replace the model of booster pump machine seal sleeve O ring, to ensure the sealing performance of machine seal sleeve, reduce the leakage of pump medium;
(3) Change the clearance between the pump shaft and the machine seal sleeve, an anti-corrosion coating or protective sleeve can be added to the pump shaft, once the machine seal sleeve leaks, it can prevent the pump shaft from crevice corrosion.

6. References
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