Fracture analysis and improvement of charging pump shaft in nuclear power plant

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Abstract. The charging pump of a nuclear power plant is a multi-stage double shell centrifugal pump. From the installation period, the pump shaft broke after 25 times of start-up and shutdown and 2913 hours of cumulative operation. As the charging pump is one of the core equipment in the normal operation and accident of the nuclear power plant, the root cause of the pump shaft fracture must be found and corrective measures must be taken, otherwise there will be major safety hazards. Through the analysis of the material, design structure and mechanical properties of the pump shaft, it is found that the root cause is that there is a deviation in the processing of the structural dimension of the stress relief groove of the pump shaft, which leads to the insufficient fatigue strength margin and the occurrence of abnormal operation conditions during the superposition commissioning, which leads to the fracture of the pump shaft. By optimizing the structural design of the stress relief groove and controlling the reasonable operation, no fracture occurred again. The causes and treatment of this typical event can provide certain theoretical support for the design, operation and maintenance of similar equipment.

1. Introduction
The main function of charging pump in nuclear power plant is to provide charging flow to primary circuit (charging pump for short) and stabilize the pressure of primary circuit system. Provide cooling water for mechanical seal of three main pumps to ensure normal operation of mechanical seal of main pump [1]. When a loca occurs in the primary loop, the charging pump injects high concentration boric acid water into the primary loop to control the reactivity. The charging pump needs to operate under different flow conditions, including small flow operation (13.6m3/h), rated flow operation under normal conditions (34m3/h), primary circuit automatic replenishment operation (about 75m3/h) and safe injection operation after accident (144m3/h). It is very important for the safe and stable operation of the power plant, and has high requirements for design and manufacture, so the reliability of the equipment must be guaranteed. The fracture position is the necking position of the balance thrust clasp of the pump shaft, which is the maximum tensile stress position of the whole pump shaft. The local structure and fracture appearance of the pump shaft are shown in Figure 1.
2. Root cause analysis

2.1. Pump shaft material and hydraulic analysis

2.1.1. Pump shaft material chemical composition. The pump shaft is made of Z5CND13-04, low carbon and high strength martensitic stainless steel. The corresponding Chinese brand is ZG0Cr13Ni4Mo, and the corresponding American standard is F6NM (S41500) ASTM-A182. It is widely used to manufacture impellers and pump shafts of nuclear grade pumps in nuclear power plants. The chemical composition of the pump shaft material in the factory report is shown in Table 1, and the key elements of the pump shaft analyzed and measured in the laboratory are shown in Table 2. The contents of the main components C, Cr, Mo and Ni are basically consistent with the factory documents.

Table 1. Pump shaft original material composition requirements

| Elements | C     | Mn | P    | S    | Cr   | Mo   | Or   | Co   | N    |
|----------|-------|----|------|------|------|------|------|------|------|
| Components | 0.035 | 0.800 | 0.021 | 12.850 | 0.530 | 4.400 | 0.018 | 0.034 |

Table 2. Laboratory analysis of pump shaft material composition

| Elements | C     | Cr   | Mo   | Or   |
|----------|-------|------|------|------|
| The test results | 0.034 | 13.05 | 0.54 | 4.42 |
| ASTM-A182 requirements | ≤0.05 | 11.5-14 | 0.5-1 | 3.5-5.5 |

2.1.2. Pump shaft material gold phase tissue. Metallographic analysis was carried out on the cross section near the fracture. The results are shown in Fig. 2, which are acicular martensite and feathery widmanstatten structure. The structure characteristics are consistent with the material grade, and no abnormality is found.

The section of the break was scanned by an electric mirror (SEM) and the fault showed a typical ligament-like appearance of a fractured toughness, as shown in Figure 3.
2.1.3. The hydraulic properties of the pump shaft material. View the process records for the entire process of pump shaft smelting, forging and heat treatment, in line with the original design requirements. The proportional tensile specimen with circular cross section is cut from the pump shaft equidistant from the center along the axial direction, and the tensile test is carried out according to the standard GB/t228.1-2010. The results are shown in Table 3. The average maximum load of the sample is 16.55KN, the average tensile strength is 842.96MPa, the average elongation after fracture is 25.68%, and the average reduction of area is 72.74%. Compared with the original design requirements and factory inspection values, the tensile properties of the material meet the requirements.

Table 3. Stretch test results

| The sample number | Sample diameter mm | Minimum diameter mm at neck shrink | Maximum load kN | Pull strength MPa | Provides for plastic extension strength Mpa | The elongated rate % after break | Section shrinkage % |
|-------------------|--------------------|------------------------------------|-----------------|------------------|-------------------------------------------|-------------------------------|-------------------|
| 1                 | 4.894              | 2.544                              | 16.63           | 846.95           | 730.45                                    | 26.00                         | 72.98             |
| 2                 | 4.982              | 2.577                              | 16.53           | 841.86           | 729.78                                    | 26.48                         | 73.24             |
| 3                 | 4.914              | 2.601                              | 16.49           | 840.08           | 725.09                                    | 24.56                         | 71.98             |
| Average           | 4.930              | 2.574                              | 16.55           | 842.96           | 728.44                                    | 25.68                         | 72.74             |
| Factory value     |                    |                                    | 828             | 716              | 24                                         | 73                            |                   |
| Original design requirements | |                                      | 780-980        | 685.0            | 15.0                                      |                               |                   |

For the pump shaft along the radial direction and the center of the center of the equal distance cut 6 sets of impact samples, the sample length and width of 56mm, 10mm, according to the standard GB/T 229-2007 shock test. The results are in Table 4, with a sample impact absorption average of 133.9J and an impact toughness average of 1690.65KJ/m2. Comparing design requirements with factory inspection values, the impact toughness of pump shaft materials meets the requirements, and the difference between test results and factory values is due to the difference in sample sampling position.

Table 4. Impact Test Results

| The sample number | Shock absorption work J | Impact toughness KJ/m2 |
|-------------------|--------------------------|------------------------|
| 1                 | 124.23                   | 1568.56                |
| 2                 | 134.88                   | 1706.48                |
| 3                 | 135.44                   | 1710.10                |
| 4                 | 136.28                   | 1724.19                |
| 5                 | 135.16                   | 1699.70                |
| 6                 | 137.40                   | 1734.85                |
| Average           | 133.90                   | 1690.65                |
| Factory value     | 177                      |                        |
| Original design requirements | 56                      |                        |
The hardness of the pump shaft material is checked from the surface to the center at the pump shaft section close to the section, and the near surface hardness is measured from the uncoated part of the necked section. The measurement shows that the hardness of the coating on the surface of the pump shaft is close to 500Hv, and it has good wear resistance. The hardness distribution of pump shaft matrix is normal. The surface hardness of necking section is normal, and there is no obvious work hardening. The hardness required in the design is 217-302HB, and the factory measured value is 270-280HB. The hardness of the sample is 238-303HB, which meets the design requirements.

2.2. Pump shaft machining and surface process analysis

2.2.1. Pump shaft surface coating. The surface coating gold phase check shows that the coating is basically uniform, and the binding and transition of the substate is generally normal, as shown in Figure 4.

![Figure 4. Pump shaft coating tissue](image)

2.2.2. Neck shrink processing size. The shrink neck out dimensions were measured and compared with the original design drawings, and several processing dimensions were found to be skewed, as shown in Figure 5.

- Stress-reducing groove fillet radius Processing is ultra-poor, with a design value of 2mm (R2) and measured at 1.2mm (R1.2).
- The groove bottom diameter is designed to be Φ 53.6 mm and measured to be Φ 53.3 mm.
- The slope angle of the groove is too large, the design requirement is 27 ° and the measured value is 30 °.
- The total width of necking is too large, the design requirement is 16mm, and the measured value is 18.5mm.

![Figure 5. Original dimension of necking section](image)

2.3. Pump shaft structure Strength proof

2.3.1. Pump shaft force analysis. 1) Mechanical strength analysis of the pump shaft

The forces on the pump bearings include torsional stress, axial force, and bending stress. The cross-sectional dimensions of the pump shaft are calculated according to the parameters of the pump, and it can be seen from the calculation that the minimum size of the pump shaft is 53.6mm to meet the strength requirements.
2) Stress concentration coefficient analysis

The design requirement of the stress relief groove radius is 2mm, and the actual measurement result is 1.2mm. According to the relationship between the stress concentration factor and the groove size [2], the stress concentration factor corresponding to the 2mm radius is about 2.33, the stress concentration factor corresponding to 1.3mm is about 2.88. When the radius becomes smaller, the stress concentration factor increases by 1.236 times, and the stress concentration factor increases by 23.6%, as shown in Figure 6.

![Figure 6. The stress concentration coefficient varies with the size of the groove](image)

2.3.2. Anti-fatigue capability analysis. In this study, small flow condition is used for analysis. When the flow rate \( Q = 13.6 \text{m}^3/\text{h} \), the axial force \( F = 168600 \text{N} \), and the bending moment \( M = 103.6 \text{N.m} \). The tensile strength, yield strength and fatigue strength of pump shaft material are 754MPa, 659MPa and 169MPa respectively.

Considering the safety factor [3-4] under the action of bending moment, the judgment basis of section fatigue strength is \( S_{\sigma} \geq S_{p} \).

Where \( S_{\sigma} \) is the calculated fatigue safety factor and \( S_{p} \) is the allowable safety factor. When the load determination is not accurate [3], and the stress calculation is approximate, \( S_{p} \) is taken as 2.5.

1) When the radius of the original design stress relief groove \( R = 2 \text{mm} \) and the section diameter \( D = 53.6 \text{mm} \), the fatigue safety factor \( S_{\sigma} \) can be calculated as 3.17

2) When the radius of stress relief groove \( R = 1.2 \text{mm} \) and section diameter \( D = 53.3 \text{mm} \), the fatigue safety factor \( S_{\sigma} \) is 2.98

It can be seen from the above calculation that when the radius of the stress relief groove is reduced from R2 to R1.2, the fatigue safety factor decreases from 3.17 to 2.98, which is close to the allowable safety factor of 2.5, and the safety margin decreases significantly.

3. treatment measures

Optimize the structural design. From a more safe and conservative point of view, The original design stress relief groove 2mm (R2) is modified to 6mm (R6). After modification, although the minimum diameter of pump shaft is reduced from \( \Phi 56 \text{mm} \) to \( \Phi 45 \text{mm} \), the calculated strength meets the requirements, the stress concentration is reduced, and the fatigue safety factor is increased to 4.63, which effectively improves the fatigue life.

After replacing with R6 pump shaft, all parameters were stable from 2014 to 2020, and no defects were found after two times of non-destructive inspection.

4. Conclusion

If the core equipment of the power plant is damaged in use, it will bring serious losses to the enterprise. What is worth thinking about is that the quality control of major equipment in the power plant should not only focus on installation and maintenance, but also extend forward, strengthen the review of the rationality of the original design, and ask a third party to check independently when necessary. In the process of equipment manufacturing and acceptance, the conformity of all parts and their key dimensions with the original design should be tested, not just the performance acceptance after the final
overall assembly. The equipment has been running continuously from 2014 to 2020, during which the pump parameters are stable.

References
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