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Thermal Fatigue and Life Evaluation for the Impeller of Reactor Coolant Pump

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1. Introduction

Fine surface cracks on the impeller hub in the reactor coolant pump of the nuclear reactor were first discovered in December 2015. The impeller is a non-pressure boundary (non-safety related) part that is not related to the leakage of coolant even though the crack in the hub penetrates through the hub thickness (corner 133 mm, inner surface 70 mm). Therefore ASME Section XI does not request inspection requirements and acceptance criteria about this. However, it is the first case where surface cracks are generated in the impeller hub of the reactor coolant pump. And considering this pump is an important facility for transferring the reactor coolant during normal operation. Task team analyzed the cause of the crack, the predicted crack growth rate and residual life of the impeller to assure the reliability of the pump.

2. Review and Evaluation Results

First, task team investigated the possibility of crack generation by the pump operation and analyzed the fracture surface to determine the cause of crack occurrence. Second, to prove the cause of the crack, a scenario of possible cracking was established and analyzed. Finally, the fracture mechanics analysis and residual life of the impeller were evaluated and presented based on the crack and the predicted crack growth rate.

2.1 Apparent Cause Analysis for the Cracks

The seal injection flow (flow rate is approximately 6.6gpm, temperature is around 21~36℃) of the pump is divided into upstream and downstream flow after first mechanical seal stage. The temperature of the fluid flowing into the impeller hub through the downstream channel is usually 25.4~49.3℃, and this flows into the coolant at 293℃ through the impeller hub region. Two different temperatures of fluid are mixed at that region.

According to ASME Section III Appendix W, degradation mechanisms that can cause cracks in operating nuclear power plants are stress corrosion crack (SCC), corrosion fatigue crack, irradiation assisted stress corrosion crack (IASCC), fatigue crack, hydrogen embrittlement and delayed crack. As a result of the pump operating environment review, stress corrosion crack and fatigue crack are highly possible, and the rest seems to be low.

The replica analysis of the cracks shows that crack propagates into the inside of the grains rather than the grain boundaries in a certain direction without twigs (Fig. 1). At the tip of the crack, beach marks and striation appearing in the direction of crack propagation perpendicular to the direction of fatigue fracture surface are shown. And in the direction of crack propagation, the features of the cleavage appear as per fracture analysis of the cracks (Fig. 2).

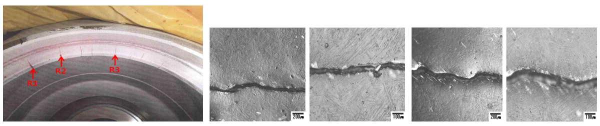

Fig. 1. Replica photos of R1 & R3 location

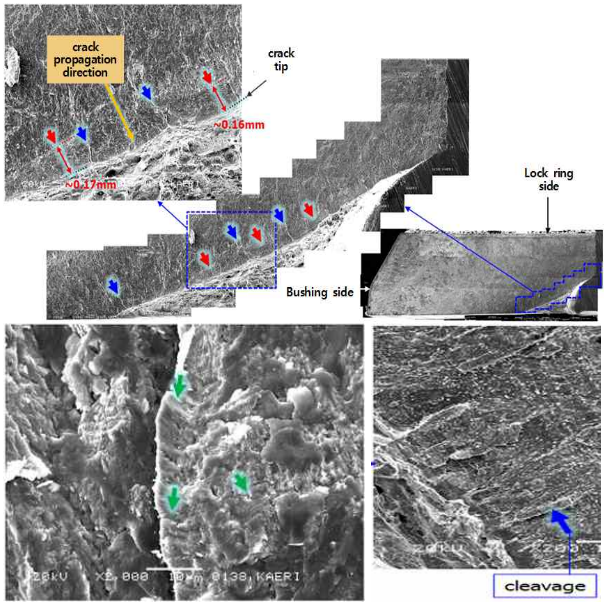

Fig. 2. Electron microscope photos (red arrow : beach mark, blue : ridge, green : striation)

Considering that the surface of the impeller hub is not the part to be subjected to the load, it can be assumed that periodic thermal stress acts and initiates the surface crack due to the fluid fluctuation and the thermal wave of the impeller hub region as per pump operating.

2.2 Thermal Stress Analysis

As a result of the analysis of the operating environment of the pump and the fracture analysis of the defective specimen, the crack in the impeller hub region was confirmed as fatigue crack due to thermal stress. In order to analyze and confirm this phenomenon analytically, task team performed fluid flow analysis and heat transfer analysis on 7 kinds of sealing water flow rate and temperature conditions. Thermal stress analysis was performed by applying impeller temperature distribution and constraint obtained from heat transfer analysis.

As a result of the thermal stress analysis, it was analyzed that the maximum tensile stress was formed on the inner surface and the corner surface of the impeller hub in which the sealing water flowed through the bushing outer surface in case 6 in case of circumferential direction. The stress distribution on the impeller hub surface due to the fluid fluctuation and the pump operation was in the range of about 44~359 MPa (315MPa) (Fig. 3). Comparing this value with the S-N curve of the impeller material (ASME SA487, CA6NM), it can be seen that cracks can occur after about 3×10^{5} cycles [3].

This means that surface cracks may occur in the early stage of operation when this pump is operated at 1,800 rpm. It is not clear how often the fluid and thermal fluctuation appears, but it is expected that the fluctuation frequency will be considerably fast. Actually, the surface crack was generated in the impeller hub after one cycle operation (18 months) with the new impeller installed.

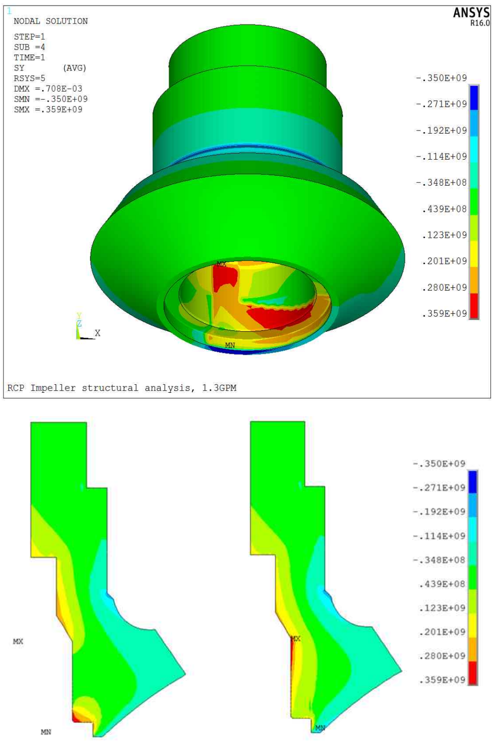

Fig. 3. Circumferential Stress Distribution of Impeller hub

However, the thermal stress distribution in the thickness direction is maximized at the surface of the impeller hub, and decreases toward the inside and changes from tensile stress to compressive stress. This means that cracks on the surface of the impeller hub can occur relatively early in the operation, but the crack growth rate slows down toward the inner surface, which means that the crack no longer grows at any depth. In fact, the depth of cracks in the impeller of pumps operated for more than 20 years was similar to the impeller of pumps operated one cycle, because the crack growth rate dropped significantly toward the inside.

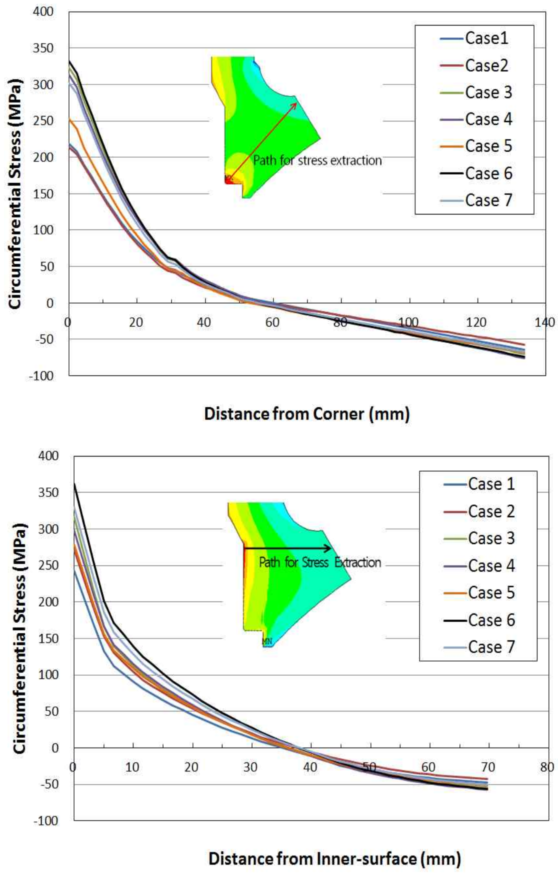

Fig. 4. Circumferential Stress Distribution
(from corner/Inner-surface to crack propagation dir.)

As described above, the cause of the surface cracks of the impeller hub is confirmed by the high cycle thermal fatigue, which is consistent with the fracture surface analysis results of the defective specimen.

2.3 Fracture Mechanics Analysis

In order to perform FMA, the maximum value of the thermal stress obtained in Section 2.2 and the total stress due to the mechanical load depending on the rotation, flow rate, and pressure loading conditions were used as the working stress. Calculation of fracture toughness (K_I) by operating stress is performed by ASME Section XI A-3320, the K_I equation for surface cracks of was applied.

$$K_I = [(A_0 + A_p)G_0 + A_1 G_1 + A_2 G_2 + A_3 G_3]\sqrt{\pi a / Q} \quad (1)$$

Where

$A_0 \sim A_3$: Coefficient of crack depth direction

A_p : Internal pressure

$G_0 \sim G_3$: Surface correction factor

Q : Cracking shape parameter

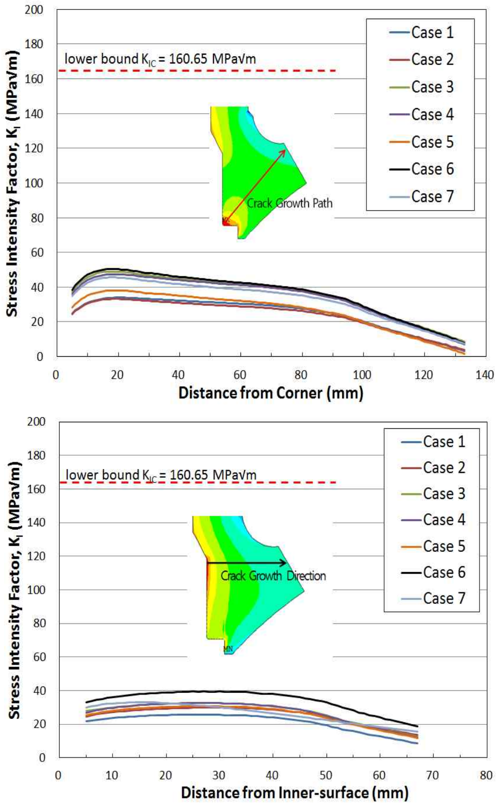

Fig. 5. K_I and K_{IC} Distribution (from corner/Inner-surface to crack propagation direction)

The calculated K_I value and the lowest fracture toughness value (K_{IC} : 160.65 MPa√m) measured on the actual impeller material were used to evaluate the crack instability according to the requirements of ASME Section XI IWB-3612. As a result, the impeller was evaluated that sudden brittle fracture would not occur due to satisfying the following formula (2)[5].

$$K_I < K_{IC} / \sqrt{10} \quad (2)$$

According to the results of the thermal stress evaluation, the residual life evaluation was unnecessary but was evaluated by applying 2mm/cycle, which was obtained by multiplying the last 1 cycle crack growth (approx. 0.15~0.2mm) at the crack tip confirmed by the fracture analysis of the specimen with the maximum crack depth by 10 times safety factor. This is a very conservative residual life assessment and it has been confirmed that penetration crack does not occur during the lifetime of the pump. This means that the pumps will remain sound throughout lifetime of the plant.

3. Conclusions

In this study, the reliability of the long-term operation of the pump was verified by evaluating the cause of surface cracks and residual life of the impeller hub part which was unprecedented in this type of pump. For this purpose, the possibility of thermal fatigue fracture was confirmed through the analysis of cracks, and the results of the fracture analysis were verified through thermal stress analysis. FMA showed no rapid breakdown, and the residual life was conservatively evaluated and confirmed the soundness of the pump during the lifetime and over.

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