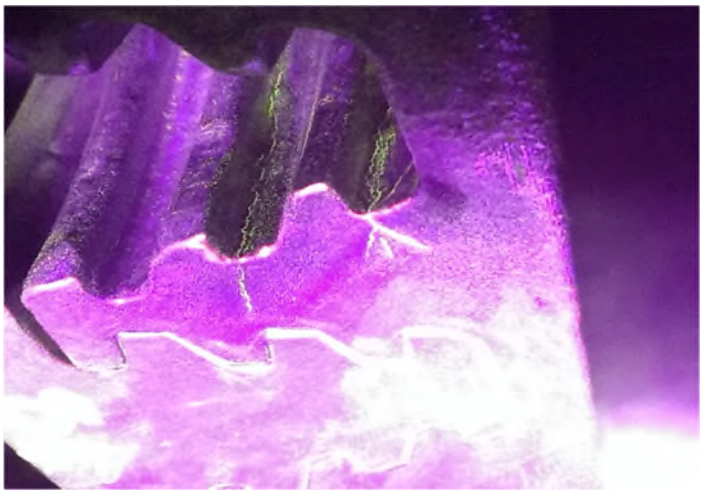
Assessment of Crack Growth in the L-1 Stage Blade Root Slots of the LP-2 Low-Pressure Turbine Rotor of Hsinta Unit 2

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1. Research Background

Units 1 and 2 of the Hsinta Power Plant commenced commercial operation between 1982 and 1983. During the 2013 major overhaul, multiple stress corrosion cracks (SCC) were detected in the dovetail slots of the rotor for the penultimate (L-1) stage moving blades of the LP-2 low-pressure turbine (Figure 1). SCC is a failure phenomenon in metallic materials that occurs under the simultaneous presence of a susceptible material, a specific environment, and tensile stress. Although Hsinta Unit 2 was placed on emergency standby in January 2024, it is still required to complete one startup, grid-connected operation, and shutdown cycle every six months. To maintain equipment and operational safety, the power plant commissioned a fracture mechanics analysis to assess the remaining service life of the cracked blade root slots and determine the allowable number of future operational cycles.



Source: This study

Figure 1. Cracks detected in the L-1 stage blade root slots of Hsinta Unit 2.

2. Research Results and Analysis

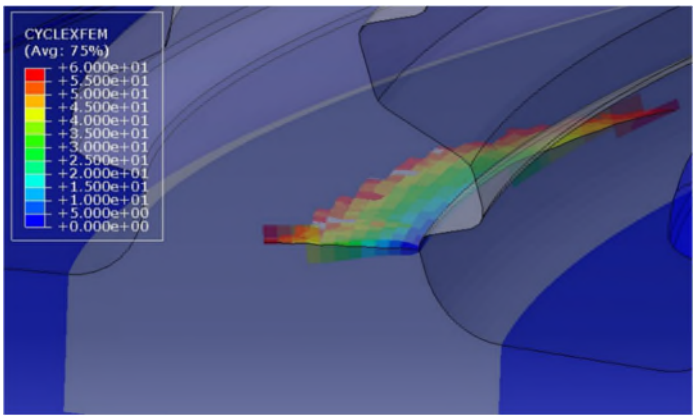
(1) Crack Growth Prediction for Original Stainless Steel Blades

This analysis began with an initial crack corresponding to one mesh element. Figure 2 illustrates the simulated crack distribution after 60 stress cycles. Table 1 presents the growth lengths of the end-face and groove-face cracks.

According to power plant documentation, the cracks were first discovered in 2013, with the largest being an 8x6 mm crack on the end face. This crack size corresponds to approximately 50 cycles in the simulation analysis steps (Table 1). Assuming the unit undergoes 10 startup-shutdown cycles per year, this translates to a timeframe of about five years. The year 2013 was roughly 30 years after commissioning; extrapolating backward suggests the cracks likely initiated around the 25th year of operation. Based on previous research utilizing FE-SAFE software to analyze the time to fatigue crack initiation for this unit, it was estimated that fatigue failure occurs after approximately 211 stress cycles (about 21 years). Consequently, it took about 8-9 years for the crack to propagate from a micro-crack to an 8 mm length on the end face. In comparison, the present crack growth analysis predicts approximately 50 cycles, equivalent to about five years, for the crack to reach this size. Although the timeframes are close, discrepancies remain. Fatigue and crack growth analyses rely heavily on empirical formulas and can only provide approximate estimates rather than exact predictions. Furthermore, over decades

of unit operation, it is difficult to record operational and maintenance states with complete accuracy; thus, the estimation of the crack growth timeline is fundamentally an oversimplified, idealized theoretical model.

If the existing stainless steel blades are retained, the end-face crack is predicted to reach 18 mm, while the crack within the groove is predicted to reach 60.5 mm after 100 startup-shutdown cycles (Figure 3). At this stage, the numerical model begins to encounter convergence difficulties, indicating a practical risk of the crack extending through the end face. Accordingly, the number of additional full-speed startup-shutdown cycles after the year 2022 should be limited to 40, based on the estimated accmulated count of approximately 60 cycles at that time.



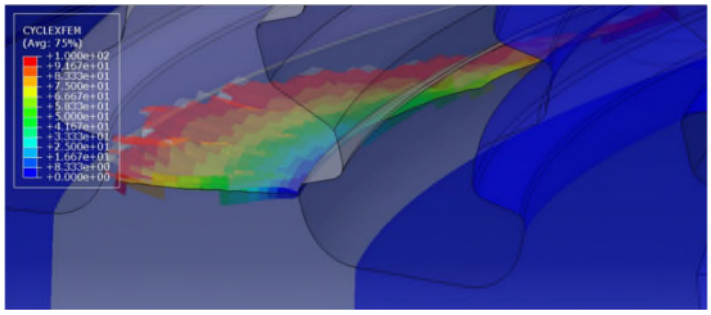
Source: This study

Figure 2. Crack distribution after 60 stress cycles

Table 1. Crack growth lengths of end-face cracks and groove cracks in stainless steel blades

Cycle	End-face(mm)	Groove(mm)
10	2.8	7.5
20	3.7	15.3
30	4.6	21.5
40	6.4	25
50	8.2	33.2
60	10	40
70	11.2	45.3
80	14.6	48.8
90	16.9	58.1
100	18	60.5

Source: This study



Source: This study

Figure 3 Crack distribution after 100 stress cycles

(2) Life Extension Benefits of Replacing with Titanium Alloy Blades

The Taiwan Power Research Institute (TPRI) previously conducted emergency replacements of blades with titanium alloy blades at locations where cracks had been clearly identified in the blade root slots. To assess the mitigation of crack growth, this study simulated the effectiveness of retrofitting with titanium alloy blades. Because the titanium alloy blades weigh only about 56% as much as the stainless steel blades, the centrifugal force exerted on the blade root slot can be substantially reduced. Table 2 illustrates the crack growth cycles following the replacement with titanium alloy blades. The numerical analysis similarly applies stress cycles starting from an initial crack length assumed to be near-zero. The results indicate that the crack growth is remarkably slow; after 100 cycles, the end-face crack propagates marginally by only 2.04 mm, reaching a state of near-arrest. Therefore, replacing the blades above the severely damaged root slots with titanium alloy blades is expected to effectively restrict crack propagation.

Table 2. Crack growth lengths of end-face cracks and groove cracks in titanium alloy blades

Cycle	End-face(mm)	Groove(mm)
10	1.19	1.86
54	1.98	3.86
100	2.04	5.27

Source: This study

(3) Discussion on Crack Tip J-Integral and Elastic-Plastic Fracture Parameters

The study analyzed the most severe crack observed, which is a 10x40 mm crack with an end-face crack length of 10 mm and an internal groove crack length of 40 mm within the blade root slot. Further analysis of the crack's stress intensity revealed that although the maximum stress intensity factor (K_I) reaches as high as 1226 MPa$\sqrt{\text{mm}}$, the critical stress intensity factor of the steel used for the dovetail slot is conservatively estimated to be around 6300 MPa$\sqrt{\text{mm}}$, Therefore, the crack in the dovetail slot is not expected to rapidly propagate to failure and cause a system collapse. However, because this value is close to the material's threshold for environmentally assisted cracking (K_{ISCC}), the crack may still grow due to stress corrosion under static full-load conditions. This would accelerate the crack propagation rate and increase the uncertainty of the prediction. After replacement with titanium alloy blades, the crack-tip stress intensity factor, K_I, decreased to approximately 60% of its original value, with values of about 500-700 MPa$\sqrt{\text{mm}}$, substantially reducing the crack growth rate and the associated risk.

3. Conclusions and Recommendations

Based on XFEM predictions, crack growth generally exhibits a linear trend following initiation. If the existing stainless steel blades are maintained, the end-face crack poses a practical risk of penetrating through after 100 startup-shutdown cycles. Therefore, to establish a safe operational limit, operations must be restricted to a maximum of 40 additional full-speed startup and shutdown cycles following the 2022 major overhaul.

Titanium alloy blades can significantly reduce the centrifugal stress exerted on the blade root slot, remarkably reducing the crack-tip stress intensity factor to approximately 60% of its original value, thereby mitigating crack propagation. This aligns with prior engineering experience. It is recommended to replace the entire stage of blades with titanium alloy blades. Although the material cost is higher, the subsequent crack growth rate would be exceptionally slow. Furthermore, the maximum K_I remains below the environmentally assisted cracking threshold (K_{ISCC}), making it less susceptible to stress corrosion cracking. When combined with meticulous overhaul inspections of the blade root slots and targeted Phased Array Ultrasonic Testing (PAUT) for critical cracks, this constitutes a highly viable life-extension operational strategy.

While titanium alloy blades offer excellent life-extension benefits, considering that the unit has been transitioned to emergency standby, blade replacement is less economical and more time-consuming than blade removal because of its high cost and long lead time. Ultimately, the power plant adopted a blade removal and load reduction strategy. During the March 2026 major overhaul, the entire stage of L-1 blades was directly removed, and baffle plates were installed. Although this approach requires the unit to operate at a reduced load, decreasing power generation by 75 MW, it permanently eliminates the risk of continued crack propagation and structural rupture.