Stress Corrosion Cracking on Steam Turbine Rotor Grooves: Experiences and Countermeasures from EGAT Power Plants

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Abstract

Although Stress Corrosion Cracking (SCC) can occur in many locations of steam turbine, most of them initiate at LP disc rim, rotor groove or blade attachment area. Usually power plants operating more than 15 years are susceptible to this failure mechanism. If SCC happens, especially in rotor groove, it has a major influence on steam turbine life. Because of the complexity of crack growth behavior, it is difficult to estimate the remaining life of the rotor with cracks found. In some cases short term remedies are urgently needed in order to return the unit back in operation before long term actions can be decided. For our steam turbines in Electricity Generating Authority of Thailand (EGAT) that faced such problem, we had many experiences and countermeasures both from Original Equipment Manufacturers (OEMs) and in-house learning by doing. Several corrective actions, for example blades cutting (partial or entire row) with or without

baffle plate installed, skin machining with retouching included, removal of all blades from row, continuing in operation with periodical inspection, or even retrofitting will yield different results and different costs-benefits. Maximum crack depth, allowed outage duration, spare parts and repair cost are the key factors for deciding on which suitable actions to be taken. Countermeasures from EGAT experiences may be used as a guideline for other units which encounter similar problem.

1. Introduction of Stress Corrosion Cracking Mechanism

In LP turbine section, cracking on rotor due to SCC has been most prevalent in fir-tree or inverted fir-tree groove designs but it also has been noted in other designs such as finger type design.[3] Cracks initiate from surface especially around the notches of the grooves and propagate across the steeples. Failure mechanism is a function of stress intensity, rotor material, and steam environment so that the probability of occurrence is higher in the longer last stage blades when the moisture of condensation begins to form. Figure 1 shows an example of SCC found on LP rotor groove

Figure 1 Example of Stress Corrosion Cracking on LP rotor groove

(left) crack and pitting corrosion at LP rotor groove

(right) microstructure of crack examined by replication

Corrosion induced cracks are brittle, usually branching, and may be either trans-granular or inter-granular depending upon the material composition, stress levels, and corrosive environment.[3] However for EGAT steam turbine rotors that are subject to some heat treatment processes, it can be seen from figure 1 that SCC exhibits multi-branched inter-granular crack pattern in martensitic steel.

Crack propagation rate from SCC can be divided into 3 regions as a function of applied stress intensity factor (K_I) which are dependent, constant, and approaching final failure.[3] In the first phase, SCC can only propagate when stress intensity at rotor groove exceeds the threshold of the crack growth (K_{ISCC}). When $K_I<K_{ISCC}$, indication may be in the form of localized corrosion and its magnitude or degree of severity becomes less significant. The time for cracking is influenced by many parameters especially from applied stress, yield strength of material, service temperature, and steam conditions. For the second phase, crack growth rate is assumed to be constant and independent from applied load or K_I. We call this region "plateau" region. After stable growth phase, SCC may change its mode to Low Cycle Fatigue (LCF) or High Cycle Fatigue (HCF). The crack is accelerated into unstable regime hence fast fracture will soon come.

SCC can cause a catastrophic failure on steam turbine and related equipments. Following consequences of SCC may result in extensive outage shutdowns, expensive countermeasures, or even plant derates.

2. Life Assessment Program and Methods of Evaluation

Despite difficulty of predicting the time of early developing crack, SCC may have been detected after 15 years of operation or more. It is our typical standard to perform life assessment for most EGAT steam turbines between 15 to 20 years after commercial operation. Period of inspection will be considered by optimizing plant life cycle cost, resource available, and demand for electricity. LP rotor groove inspection program consists of blade removal, groove cleaning and magnetic particle examination with replication test to verify indication dimensions. Normally in EGAT power plants, shutdown interval of steam turbine life assessment ranges approximately from 45 to 60 days depending on scope of work.

Figure 2 Replication test after several indications on rotor grooves were found

Once SCC was found, actual crack dimensions had been recorded for reference. In addition, the most two crucial things to be determined are critical crack depth and crack growth rate. The critical crack depth (a_{cr}) can be calculated by Finite Element Analysis (FEA) software where a_{cr} is the minimum crack depth that the applied stress intensity factor (K_I) exceeds the material toughness (K_{IC}).[1] Note that K_I is the function of assumed crack geometry or flaw shape and K_{IC} depends on material properties.

Since "plateau" crack growth rate during stable or constant growth period was purposed in generic form as

$$\ln\left(\frac{da}{dt}\right) = C_1 - \frac{C_2}{T} + C_3\sigma_y \text{ [1]}$$

where

$\frac{da}{dt}$ = the crack growth rate

C_1, C_2, C_3 = material constants

T = the operating temperature of the disc

σ_y = the room temperature yield strength of the disc

Hence, the remaining life of turbine rotor from static stress during operation can be computed from

$$t_r = \frac{a_{cr} - a_i}{\left(\frac{da}{dt}\right)} \text{ [1]}$$

where

$\frac{da}{dt}$ = the crack growth rate

t_r = the remaining life

a_{cr} = the critical crack depth

a_i = the detected crack depth

In general, there is not only static stress during normal operating conditions but also dynamic stress which eventually be generated from cyclic operation. Frequent numbers of unit start/stop can stimulate dynamic loads when temperature gradients in steam turbine rotor increase. This behavior acts as a driving force to build up the defects. If the cyclic stress intensity (ΔK) is greater than the threshold value (ΔK_{th}), fatigue cracking will combine with SCC. Suitable model for crack growth prediction should be able to cope with HCF or LCF in the latter case. Dynamic crack growth can be expressed as

$$\frac{da}{dN} = C\left(\Delta K\right)^n \text{ [2]}$$

where

$\frac{da}{dN}$ = the crack growth rate

C , n = empirical constants

ΔK = the cyclic stress intensity factor

However the method of remaining life evaluation for SCC damage mechanism is quite like a step by step procedure. Practically, there are many uncertainties or errors occur, for example flaw sizing, Non-Destructive Test (NDT) methods, scatter data on K_{IC} from laboratory, or error from calculation. Deterministic approach may result in pessimistic or optimistic outcomes. Therefore probabilistic analysis that considers input probability functions by using Monte Carlo Simulation may present a more realistic outcome. For this reason, determination of remaining life is not a simple task so EGAT occasionally consults OEMs or specialists in order to confirm the evaluation results for making further corrective actions.

3. EGAT's Experiences and Countermeasures

From our EGAT's steam turbine fleet maintenance historical records, rotor groove inspection program has been first carried out since November 1997 for detecting SCC. There are 12 out of 46 units which indications were found including LP steam turbine rotors from EGAT subsidiary companies such as Electricity Generating Company (EGCO) and Ratchaburi Electricity Generating Company (RGCO). However, we have not counted for South Bangkok Combined Cycle Block 3 (SB-C30), Bankpakong Combined Cycle Block 5 (BPK-C50), and Chana Combined Cycle Block 1 (CNP-C10) from this statistical point of view since these power plants are in commissioning or in warranty periods. According to our SCC rotor groove damage records, all of them were axial-entry fir tree grooves and cracks mostly occurred in the last three stages of LP turbines which hereinafter called L-0, L-1, and L-2 respectively. The size and shape of cracking varied unit by unit. The maximum crack depth and length depend on aging of steam turbine, operating conditions, and different in design. Although the location of crack could be initiated from any steeple as shown in figure 3, the crack was most frequently found at steeple 1 and it was usually the critical location because the critical crack depths (a_{cr}) is less than any other steeples in nature.

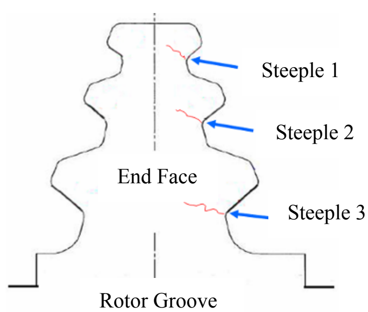

Figure 3 Schematic of axial-entry fir tree groove design in LP rotor with typical cracking locations shown

Table 1 shows the summary of SCC damages found on 11 of 17 units that had performed life assessments. All of them have been operated for more than 15 years. Indications were found at the stage of L-0, L-1, and L-2 in total amount of 8, 6, and 2 rotors respectively. In addition, we observed that crack could propagate both from convex or concave side and may originate from the end face or in the middle of the groove.

Table 1 SCC damage records on LP rotor grooves

No.	Plants	COD (year)	Inspection (year)	SCC Indications L-0	L-1	L-2	Sampling (/stage)	Countermeasures
1	NB-T1*	1961	2003	No	No	No	1 groups	No Actions
2	SB-T1**	1970	1998	No	No	No	2 groups	No Actions
3	SB-T2**	1971	1997	Yes	Yes	No	2 groups	Grinding
			2000	Yes	Yes	No	100%	Grinding
4	SB-T3	1974	1997	Yes	N/A	N/A	1 group	Grinding
			2000	Yes	No	No	100%	Grinding
			2001	Yes	N/A	N/A	100%	Re-machining (drop steeple)
			2006	N/A	N/A	Yes	at end face	Blade Cutting
								(with Baffle Plate installed)
5	SB-T4	1975	2001	Yes	No	No	100%	Re-machining (drop steeple)
			2005	N/A	N/A	Yes	at end face	Blade Cutting
								(with Baffle Plate installed)
6	SB-T5	1977	1999	No	No	No	2 groups	No Actions
			2002	Yes	N/A	N/A	100%	Re-machining (drop steeple)
								Welding Repair (partial)
			2007	N/A	N/A	No	at end face	No Actions
7	MM-T1***	1977	1998	N/A	Yes	N/A	5 grooves	Grinding
8	MM-T3***	1978	1999	Yes	N/A	N/A	100%	Grinding
9	MM-T4	1984	2002	No	No	No	2 groups	No Actions
10	MM-T5	1985	2008	No	No	No	2 groups	No Actions
11	MM-T6	1985	2005	No	No	No	2 groups	No Actions
12	MM-T7	1985	2007	No	No	No	2 groups	No Actions
13	MM-T8	1989	2004	Yes	N/A	N/A	100%	Grinding
			2006	Yes	N/A	N/A	12 grooves	Grinding
			2008	No	Yes	N/A	17 grooves	LP Turbine Retrofit
14	MM-T9	1990	2006	Yes	Yes	Yes	100%	Blade Removal
								(without Baffle Plate installed)
			2007	N/A	N/A	N/A	N/A	LP Turbine Retrofit
15	MM-10	1991	2006	Yes	Yes	No	100%	Grinding
			2009	Yes	Yes	N/A	10 grooves	LP Turbine Retrofit
16	BPK-T1	1983	2003	No	Yes	No	1 group	Grinding
							at end face	Remaining Life Evaluation
			2005	N/A	N/A	N/A	N/A	LP Turbine Retrofit
17	BPK-T2	1983	2001	No	Yes	No	1 group	Grinding
							at end face	Remaining Life Evaluation
			2003	N/A	Yes	N/A	at end face	Remaining Life Evaluation
			2005	N/A	Yes	N/A	at end face	Remaining Life Evaluation
			2006	N/A	N/A	N/A	N/A	LP Turbine Retrofit

Remarks:

- Units with mark *, **, and *** have been disconnected from the grid in year 2002, 2008, and 2000 respectively.
- "N/A" means no information or not available during that time.
- NB-T1 to NB-T3, SB-T1 to SB-T2, SB-T3 to SB-T5, MM-T1 to MM-T3, MM-T4 to MM-T7, MM-T8 to MM-T13, and BPK-T1 to BPK-T2 are of the same type group by group.
- The material of all rotors is NiCrMoV steel forging.
- The other 4 power plants, not listed in the table above, had been performed condition assessments which are RY-C10 to RY-C40. No indications were reported at that time but notice that only magnetic particle testing had been done around the finger type grooves on some selected stages.

When SCC is detected, repairs or corrective actions must be considered carefully. For short terms, some remedies should have been done in order to resume the unit back into operation. These actions may help to restore the operator confidence and reduce operating risks. Furthermore, these can give us some extended time before finding the long term corrective actions. From our experiences, if the critical crack depth and crack growth rate can be accurately calculated and objective constraints from power plant are cleared then we may select and implement a suitable long term strategy for unit in both economical and technical aspects. Examples of short term countermeasures are running until next outage with or without load limitation, crack grinding, blade cutting or removal which can be done with or without baffle plate installation. The others are long term actions that can be welding repair, dropped steeple machining, or rotor replacement. These actions may be conducted with an improve design such as material upgrading, re-blading with titanium[3] or modification with large blade root and groove to minimize the centrifugal stress[7]. This section will describe each countermeasure that we had faced in the cost-benefit way. The items that EGAT has encountered are as follow.

- Crack grinding

One common countermeasure to cracks found on EGAT's LP rotor grooves is grinding technique. After NDT confirmed cracks discovered, grinding with small grinding machine (Figure 4) would be performed by skilled technicians. The first grinding will be limited to about 0.1 mm deep before another NDT to check for crack remaining. If cracks still exist, another 0.1 deep grinding and NDT will be repeated until there is no crack remained. The final depth and length of all ground cracks are measured by using silicone replication, and recorded along with cracks' location in the inspection sheet for further consideration. The whole process of crack grinding normally takes about 2 days per turbine stage. However the duration may vary depending on numbers and depth of cracks discovered.

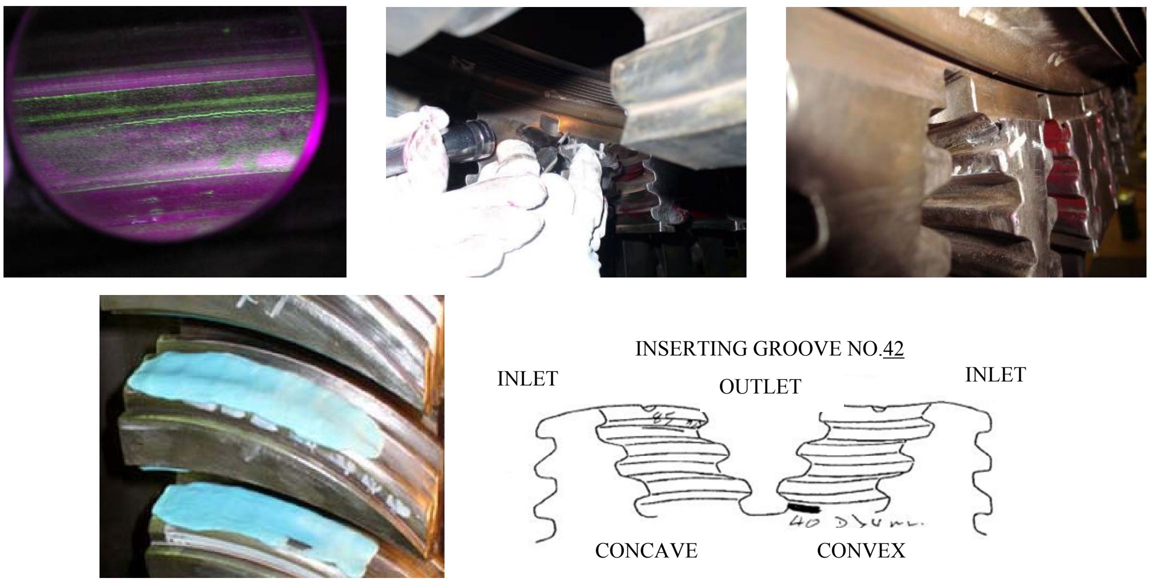

Figure 4 Steps of crack grinding

(Left) Crack found on LP rotor grooves

(Middle) Grinding-off crack found on LP rotor groove with small milling

(Right) 0.5 mm depth of ground-off crack

(Bottom-Left) Silicone replication of ground crack for measuring final depth & length

(Bottom-Right) Inspection sheet recorded all ground cracks found

Crack grinding is common solution to every crack found on LP rotor grooves discovered at EGAT power plant. This countermeasure can be considered as short to medium term corrective actions, depending on the maximum crack depth found. If the deepest ground crack depth found on rotor grooves is not over the critical depth allowed, rotor blades can be reinstalled into grooves and resumed normal operation. However, if final crack depth exceeding critical depth allowed, that particular groove is considered damaged with less load carrying capability. Blade cutting or removals are, therefore, inevitable solutions.

For every EGAT power plant encounter cracks on LP rotor grooves, crack grinding technique is chosen to be the first countermeasure implemented. These happened to all five units of South Bangkok thermal plants (SB-T1 to 5), five units of Maemoh thermal plants (MM-T1, 2 and MM-T8 to 10) and two units of Bangpakong thermal plants (BPK-T1 and 2) where cracks were discovered during the life assessment of steam turbine which normally applied in their 15-25 years of services. All cracks were discovered when selected LP blade groups were removed for thorough magnetic particle inspection at blade-rotor assertion area. In 2004, during life assessment inspection of MM-T8, we found many cracks on L-0 stages with final ground-off depth range between 0.85 to 1.0 mm. Since the depth did not exceed the critical crack depth allowed for this type of groove design (maximum crack depth is 4.0 mm), all L-0 blades were reinstalled and normal operation was resumed. After one year in service, the unit was down for safety reason, for another L-0 grooves inspection to investigate on the ground-off crack growth. Although several new cracks at L-0 grooves were found, no ground-off cracks propagated. Usually the final ground cracks in LP rotor of EGAT are found to be less than 2 mm deep, grinding technique therefore can extend life of LP rotor. MM-T10 can continue to operate for up to 3 years. This life extension can be used for decision making on long term solution.

- Running until next outage

Running until next outage could be a temporary solution that may have economical advantages if continuous operation is the first necessity. Remaining life assessment is very important thing before choosing this action. Maximum crack depth and crack growth rate with some degree of safety concern are the keys because period of plant operation is limited by these two factors. However such evaluation usually takes time since calculation method consists of several steps as mentioned earlier above in section 2.

In case of EGAT power plants, this short term corrective action was selected for Bangpakong thermal power plant unit 1 and 2 (BPK-T1, 2). Local stress analysis had been done by OEM at the same time SCC was found on L-1 steeples of BPK-T2 rotor in

2001. The result shows that this groove type has relatively high local stress at the inlet and outlet (see figure 5).

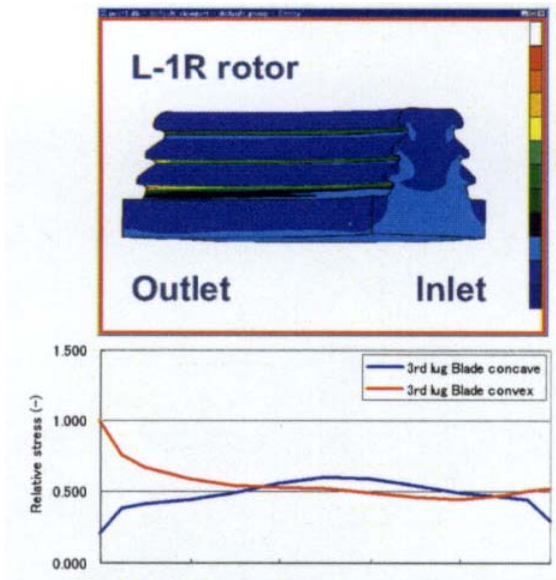

Figure 5 Relative stress distributions on L-1 groove (BPK-T1, 2)

The FEA coincides with actual inspection results both BPK-T1 and 2 performed during 2003 and 2001 respectively. Firstly, remaining life of 2 LP rotors of BPK-T2 were estimated at around 18,500 hours. Because maximum crack depth will occur at the end face of rotor groove so we can reexamine the crack depth and crack growth rate without removing L-1 blades off. The rotor end face inspection (magnetic particle test) can be done every ½ to 2 years by removing cross over pipes and opening upper LP half casings without lifting up the rotors. Outage schedule can be accomplished within 25 days. So running until next Minor Inspection (MI) was preferred to Bangpakong power plant's steam turbines. Finally at the end, these failed rotors were replaced and upgraded by retrofitting LP turbines in year 2005 and 2006 respectively.

- Blade cutting or removal (with or without Baffle Plate installation)

In the case of ground-off crack depth approaching maximum depth allowed and may not last until the next outage, blade cutting or removals become suitable solutions for short term remedies. These techniques were applied to several of EGAT power plants ranging from a small single cylinder of 30 MW Suratthani thermal plant to large LP rotors of multiple cylinder 300 MW thermal plants (Maemoh and South Bangkok). There are varieties of solutions taken by EGAT concerning blade cutting or removal. The decisions were made based on degrees of damage and outage time available at each plant. EGAT has experienced partial blades removal from one stage (South Bangkok), removal of all moving and stationary blades from 2 opposing L-2 stages with baffle plates installed (South Bangkok), and all blades removals from 2 opposing L-1 without baffle plates installed (Maemoh).

In 2004, South Bangkok thermal plant unit 4 (SB-T4) encountered SCC problem at L-2 stage (gen-side) grooves. After grinding, 6 of 198 grooves had final depth exceeding maximum depth allowed. New rotor replacement was not appropriated due to shutdown time constraint. In order to resume the plant back in service, full-row of moving and stationary blades were removed both side from double flow LP turbine and replaced with baffle plates in order to maintain the same pressure drop inside and minimize effect to nearby stages. After complete installation, operation resumed with limited load of 90%. Estimated time frame for blade removal and baffle plate installation is 2 weeks excluding delivery period of baffle plates.

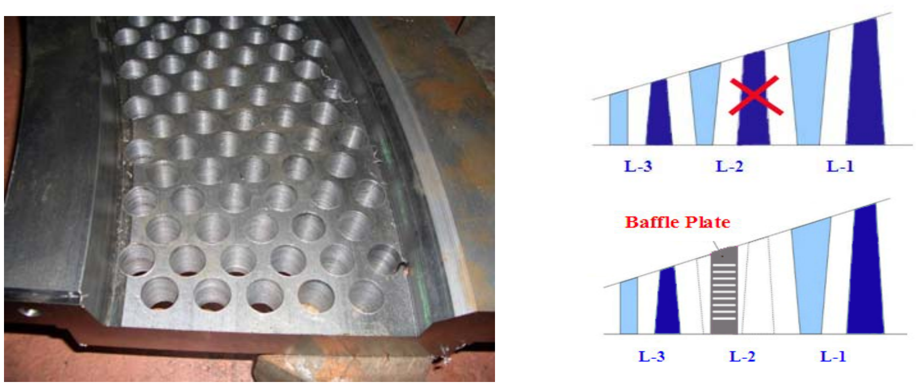

Figure 6 Illustration of baffle plate and installation in place of stationary blade of LP inner casing at SB-T4

In 2006, Maemoh thermal plant unit 9 (MM-T9) encountered SCC on L-1 grooves. After grinding, numbers of grooves had ground crack depth over 10 mm, which exceeded allowable depth. Unfortunately, blade removal and baffle plates installation were not suitable to this case, because of the downtime constraint. To resume the plant in service as soon as possible, EGAT had considered the moving blades removal with stationary blades remained. Although this action could cause changes in pressure drop across LP stages, especially to the adjacent stages of L-0 and L-2, limiting operation to 75% load was chosen to mitigate this effect. The unit was operated for 5 months with normal conditions before the new LP rotor arrived for replacement. Estimated time frame for L-1 blade removal from both sides of LP turbine is 2 days.

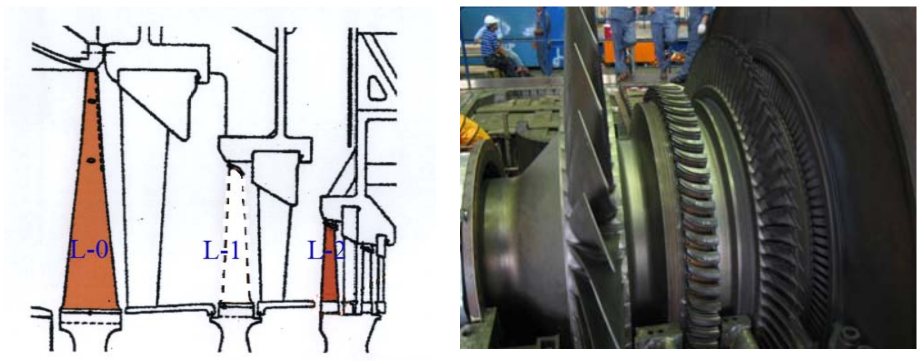

Figure 7 Illustrated the full-row blade removal of L-1 stage without installation of baffle plate

- Dropped steeple machining (with Flow Guide modification plus shot peening)

Re-machining groove by precise lathe machine with special cutting tools is the one of mechanical repairs. It can be classified into 2 subcategories which are skin cutting or dropped steeple machining. Skin cutting will work only for shallow crack. This method is usually followed by surface polishing and shot-peening to generate residual compressive stress.[3] Dropped steeple machining on the other hand is the machining to the new pitch circle downward to the centerline of turbine rotor. Both have the same disadvantages that are moderately high cost and unfavorable extended outage. Figure 8 illustrates the idea of dropped notch steeple or undercutting machining. However, groove machining with enlarge radii or steeple drop machining may be inappropriate in some cases, BPK-T1 and 2 for example, 3rd steeple crack still exists in groove as shown in figure 8 (left). Limitation of re-machining is the geometry of groove itself.

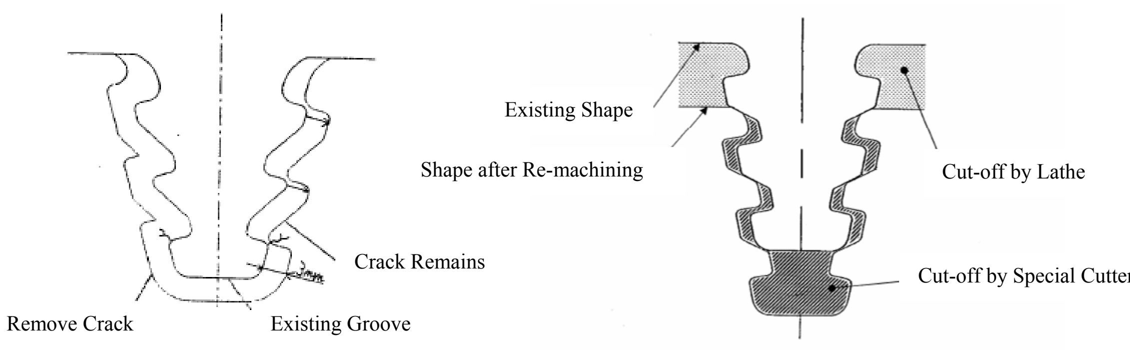

Figure 8 example of LP rotor groove modification

(left) groove machining with enlarge radii

(right) steeple drop machining

South Bangkok thermal power plant unit 3 to 5 had been tired dropped steeple machining in year 2001, 2001, and 2002 respectively. The rotors were shipped to OEM factory for machining. Some modification works on L-0 rotating blades, flow guides, and gland cones were required since the dimension of rotor groove had been changed. For L-0 rotating blades, blades had been removed and the platforms were machined a little bit thinner than original shape as shown in figure 9. Lining plates have been attached into flow guides and gland cones have been grinded as shown in figure 10. Estimated time frame for corrective is around 9 months including transportation.

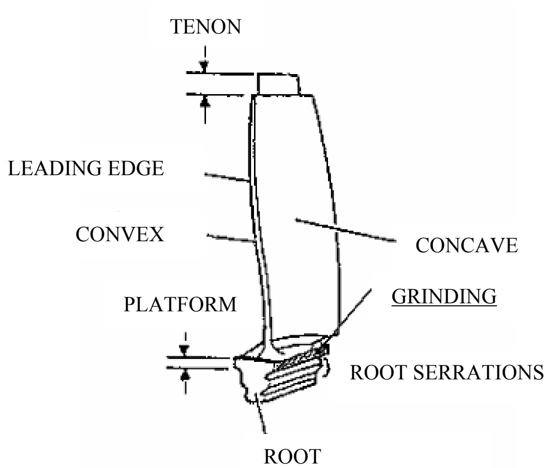

Figure 9 L-0 rotating blade platform grinding

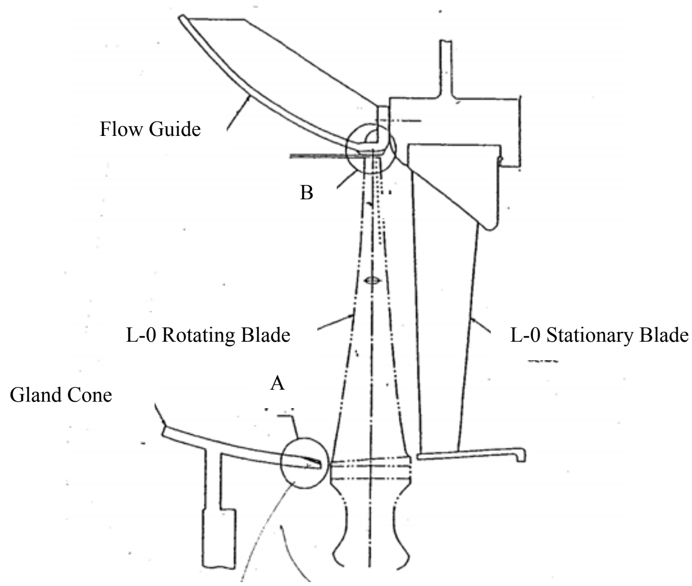

Figure 10 Flow guide and gland cone modification (detail A and B)

From EGAT's operating experience, this countermeasure can be considered as a medium term corrective action when the objective for power generation ranges from 5 to 10 years. The reason behind is that there is high probability that SCC will developed in other stages years after. If SCC reoccurs again somewhere on LP rotor then it would be troublesome and SB-T3 and 4 have been suffered from this case. It can be seen from Table 1 that SCC was found again but at L-2 stage instead. Plants must be connected to the dispatch system until 2010 so blades cutting with pressure plates installed were taken as short term remedy. Decision making, based on cost minimization, for SB-T3 and 4 in 2006 and 2005 can keep units running until it will be removed from the grid but of course with higher heat rate or lower electricity output.

- Welding repair (partially along with drop steeple machining)

One possible method to eliminate SCC from rotor grooves is welding. Filler metal of same composition as rotor material or highly SCC resistant material can build up the new groove partially or entire row. After machining or cutting damaged grooves, welding is commonly employed layer by layer together with pre-heat control. The direction of finishing layer is different from others to make the shape of welding better. Re-machining of grooves proceeds by side-entry machine. Penetrant test, magnetic particle test, and ultrasonic test shall be executed for checking porosity or crack. Post weld heat treatment must be carefully controlled. Moreover, hardness test and replication test should be confirmed after post weld heat treatment.

Figure 11 Schematic of welding repair steps

(left) Cutting grooves after blade removal

(middle) Hammering should be proceeded to prevent undercut

(right) Repair welding

EGAT has one LP rotor welding repair case which is South Bangkok thermal power plant unit 5. Since only dropped steeple machining could not get rid of some cracks on 3rd steeple of rotor then partial welding repair had been employed in additional. Figure 12 shows photographs of L-0 grooves during building up and machining processes. Note that repair job was done at OEM workshop in 2002.

Figure 12 building up metal and re-machining on L-0 grooves (SB-T5)

(left) Penetrant test on build up metal after finished welding repair

(right) L-0 re-machining

- Rotor replacement

LP turbine replacement can be the final solution for SCC problem but with very high investment cost and long time to implement usually not less than 2 years. Rotor replacement can be with original prototype or upgraded design. The latter could achieve benefits from heat rate improvement or SCC resistance. Retrofit or modernization gains more advantages from upgrading rotor material or applying state of the art technology. Technical and commercial point of view should be taken into account when retrofitting. Economic feasibility should be studied for helping decision making. The acceptance criteria, for example performance guarantee or SCC warranty should be written in the contract for vendor. Furthermore nearby component interface compatibility such as Generator, HP/IP turbine, or extraction piping should be examined during execution phase of LP turbine retrofit. This action is considered as long term countermeasure.

Bangpakong thermal power plant unit 1 and 2 had LP turbine retrofits in year 2005 and 2006 or 2 and 5 years from first SCC find. Maemoh thermal power plant unit 8 to 10 had LP turbine retrofits between 2007 and 2009, approximately 1 to 4 years since SCC had been detected. Pre and post performance tests under international standard test code were performed to calculate the increasing MW output. The results show satisfactory efficiency improvement both Bangpakong and Maemoh. Hence economical value can be met since BPK-T1 and 2 have a plan to extend operating period for another 10 years. MM-T8 to 10 have a plan to extend period for not less than 15 years.

4. Conclusion

No unique countermeasure for solving SCC problem on LP rotor groove is typically applied because of inspection, operation, and economic constraints. There is also significant variation among various manufacturers. The influence of the environment which is generated during operation and startup-shutdown varied from rotor to rotor and from stage to stage on a given LP rotor.[3] Major root causes are the combination of susceptible material, steam environment, and localize stress concentration which may be difficult to determine. However, detection of SCC indications on LP rotor can be done for units around 15 years in operation. Despite the fact that SCC problem is reduced through using upgrade material, applying compressive stresses, or minimizing stress concentration in the blade attachment areas in most of modern LP rotors manufactured today, severe environment composition may influence on SCC initiation with unknown period of times.

The maximum crack depth, allowed outage duration, spare parts and repair cost are the key factors for deciding on which suitable actions to be taken. Appropriate actions shall take cost-benefit into account. Inspection programs and countermeasures from EGAT experiences may be used as a guideline for other units which encounter similar problem.

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