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Trouble Shooting Turbine Blade Damage In 55 Mw Geothermal Power Plant

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***Abstract*—In 2013, there was 55 MW geothermal power plant experienced a damage on 3rd-stage turbine blade due to broken tenon head caused bycorrosion fatigue. Since this was a major disruption affecting business and operational performance of the plant,a quick recovery plan was required to put the plant back online while long term action plan was also prepared to improve the existing design in order to prevent the re-occurrence of the same failure mode that will be executed on the next overhaul schedule.**
This study aims to perform root cause failure analysis (RCFA) and troubleshooting of the failure as a lesson-learned and reference for practitioners and academics of power plant by:

- Implementinga comprehensive reliability management and life cycle management (LCM) to maintain and improve the reliability of the power plant.
- Determining short term and long term action plans

I. Introducing and Background

In 2013, the 55 MW geothermal power plant in Indonesia experienced the following failure:

- Five adjacent segments of rotor shroud of x-stage turbine bladewere broken and apart from their tenons (Figure 1)

- Outer labyrinth that is paired with the 3rd-stage turbine bladesuffered severe damage due to rubbing against the damaged shroud.

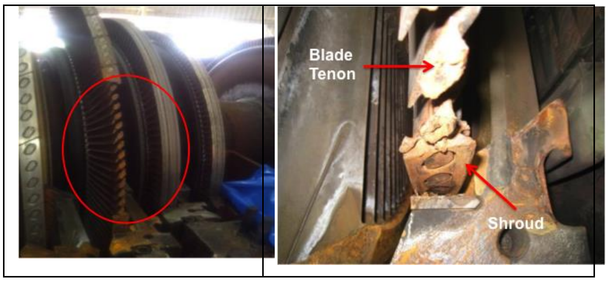


Figure1 Damage of 3rd stage turbine blade and Shroud

II. ROOT CAUSE FAILURE ANALYSIS

There are some factors potentially cause the damage grouped into four categories (method, machine, material and environment) that will undergo five-why analysis to identify potential causes that need to be verified as root causes by performing data analysis, design analysis, metallurgical and material testing.

- **Method**

This failure indicates deficiencies in the implementation of reliability management and life cycle management (LCM) that are expected effectively prevent the failure through the planning and execution of failure defense task (FDT) and defining proper maintenance strategy (MS).

Based on turbine LCM document and the result of remaining life assessment (RLA) in 2007, turbine blade should be replaced in 2015. The feasibility study of rehabilitation of the plant in 2012 confirm the same result and shows the plan of turbine blade replacement in 2014.

Shortfall in the existing implementedreliability management is the failure of turbine Failure Mode and Effect Analysis (FMEA) to identify“blade tenon damage” as one ofthe failure mode. As a result of that, proper control methode and maintenance activities in the maintenance strategy are not set to prevent such failure.

- **Machine**

  Potential causes are:

a. Worn-out and broken blade tenon head detached shroud during operation

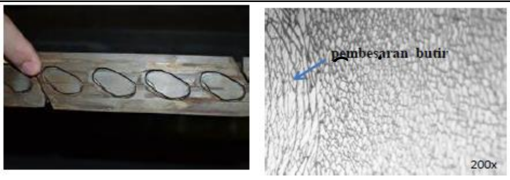
b. Erosion on the blade tenon head and shroud due to steam impurities

c. Fatigue crack on the blade tenon head that subject to cyclic loads

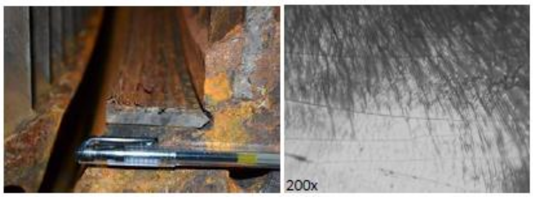
Figure 2 Wornout and broken blade tenon head and shroud

Fractography and in-situ metallography analysis on the shroud fracture surface reveal enlarged grain diameter (Figure 3) adjacent to the shroud that indicates the area has experienced overheating as a result of severe friction between the shroud and the labyrinth. The presence of damage on the labyrinth of stage 3, highly broken-deformed shroud due to high temperature and frictions on the surface of the shroud and blade tenon head that did not fail justify that analysis result.

Friction on the surface of the blade No. 85 and 100



Friction on the blade tenon head and shroud that are not damaged



The friction between the casing and the shroud labyrinth

Figure3 Friction on blade tenon head, shroud and labyrinth

In the existing3rd-stage turbine blade design (Figure 4), there is discontinuity volume between blade tenon head and shroud that is fastened with the process of hot irreversible plastic deformation (rivetting) during the initial blade assembly process.This design create gap between the shroud and tenonhead and become local stress concentrations which prone to corrosion attack that is justify by fractography analysis result that showed the occurrence of crack and corrosion (Figure5).

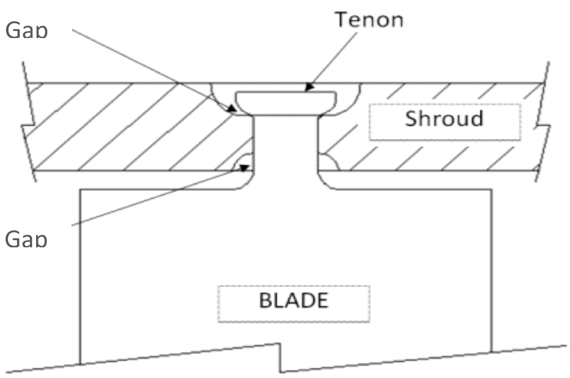


Figure4 Existing 3rd stage turbine bladedesign

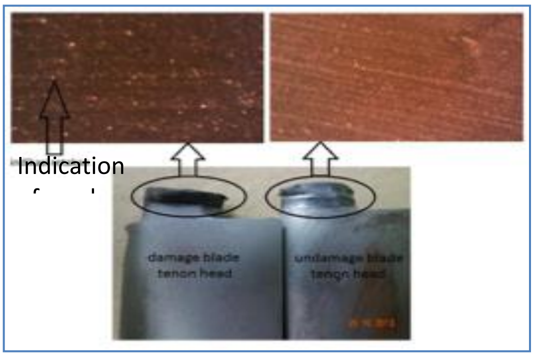


Figure 5 Crack on blade tenon head

There are several designs of the shroud which utilize rivet or integral shroud. Rivet with the square root section of the existing turbine design only suitable for ultra-light service. Punching process during rivetting and some flawson the rivetting resultcreate discontinuityvolume between the blade and the shroud and generate stress concentration on the plate and blade tenon head which initiate the crack. In the design of integral shroud, shroud plate is an integral part of a turbine blade that is used for medium-heavy service (Nauman, 1982).

Erosion on the blade tenon head and shroud may occur due to contamination of steam due to the presence of impurities and particles carried by the vapor (steam carried particles) of pipelines, steam header, separator, demister, and others. There is no evidence of these impurities at the time of dismantling the turbine.

- **Environment**

As in the previous section, the existing turbine design create gap between the shroud and tenonhead and become local stress concentration and withthe presence of water vapor, H2S and other chemicalscause corrosion on the blade tenon head that intiate the crack on the blade tenon head. Fractography analysis
There is no evidence of these impurities at the time of dismantling the turbine.
vapor (steam carried particles) of pipelines, steam header, separator, demister, and others. There is no evidence of these impurities at the time of dismantling the turbine.

- Material

Possible mismatches material specification blade, shroud and tenon head (JIS 10705 BX - stainless steel) material forces that are under design can cause the blade tenon head can not withstand the cyclic loads resulting in fatigue crack on a shorter cycle than the design. Hasiluji chemical composition of materials by using Positive Material Identification (PMI) in some samples showed the chemical composition of the material shroud, blade and blade tenon (Table 1) in accordance with JIS standard BX 10705 - stainless steel.

Table 1 Material composition testingresultof shroud, tenon blade and blade (wt.%)

10705BX	Cr	Mn	Fe	Ni	Cu
Max	15.50	0.50		3.00	3
Min	16.50			4.50	3.70

No.	Description	File #	DateTime	Application	Method	Cr	Mn	Fe	Ni	Cu	Mo	Acuan Standard		Comment
												Material	Standard	
1	SHROUD ROTOR C3	296	9/27/2013 9:05	Alloys	St. Steel	15.48	0.49	74.79	4.43	2.77	0.26	10705BX/ St. Steel	MS/AISI630	accepted
2	SHROUD ROTOR C3	297	9/27/2013 9:06	Alloys	St. Steel	15.24	0.39	76.03	4.84	2.93	0.20	10705BX/ St. Steel	MS/AISI630	accepted
3	BLADE ROTOR C3	298	9/27/2013 9:08	Alloys	St. Steel	15.11	0.62	75.02	4.31	3.08	0.10	10705BX/ St. Steel	MS/AISI630	accepted
4	TENON ROTOR C3	300	9/27/2013 9:10	Alloys	St. Steel	15.80	0.44	75.37	4.52	3.07	0.06	10705BX/ St. Steel	MS/AISI630	accepted
5	TENON ROTOR C3	302	9/27/2013 9:21	Alloys	St. Steel	16.02	0.41	75.62	4.17	3.14	0.05	10705BX/ St. Steel	MS/AISI630	accepted
6	ROOT	303	9/27/2013 9:25	Alloys	St. Steel	16.21	0.35	75.66	4.75	2.46	0.05	10705BX/ St. Steel	MS/AISI630	accepted
7	ROOT	304	9/27/2013 9:27	Alloys	St. Steel	16.49	0.32	75.56	4.62	2.51	0.06	10705BX/ St. Steel	MS/AISI630	accepted
8	LABYRINTH CASING C3	305	9/27/2013 9:34	Alloys	St. Steel	18.02	1.53	70.07	9.70	0.13	0.07			St. Steel (SS 304)
9	LABYRINTH CASING C3	307	9/27/2013 9:36	Alloys	St. Steel	18.16	1.37	69.49	9.49	0.20	0.07			St. Steel (SS 304)

and metallographic results showed corrosion on the surface of the shroud and blade tenon head. In addition to that, pitting corrosion and corrosion deposits is found on the bottom surface of the shroud and the joint area (figure 5 and 6) that have contactwith blade tenon headis an evidence of corrosion attack that area. This corrosion attack and cyclicload lead to dimensional changes in the blade tenon that enlarge the gap and the relative movement that cause abnormal vibration. The combination of corrosion, worn-out blade tenon head, the influence of the bending load (unsteady steam forces, rotor torsion, radial vibration, axial vibration),the plant start-up and shut down process and steam conditions (pressure and temperature) cause the blade tenon head failure due to corrosion fatigue (Mc.Closkey, 1999). The presence of impurity in the vapor can accelerate corrosion rate and fatigue of blade tenon. The worn-out blade tenon head and the shroud is then broken that cause the shroud to detach from the turbine

The results of the analysis support this findings. Failure on the blade tenon head – the blade tenon head found on the shroud broken part so that the upper surface of the shroud rubbing against the labyrinth experiencing great friction with labyrinth, blade which is justified by the indication of worn-out on overheating and subsequently ripped. shroud due to pitting corrosion and corrosion fatigue are typical of damage on steam turbine blade (Roberge, 2000), and has been widely reported in the literature / engineeringpaper (Mc.Closkey, 1999). Damage usually starts from localized corrosion caused by fretting, manufacturing defect, inclusion and pitting due to environmental factors such as the level of impurity steam, fault shutdown procedures, and the level of steam cation conductivity. A dewpoint lead the condensation process of the steam during shutdown process so that moist, liquid and oxygenated films formed on the surface of the blade and disc. A level of steam cation conductivity could acceleratesthat.Based on mechanistic models of corrosion fatigue, corrosive environments caused the vacancies as a result of dissolution phenomena on a metal surface (Mc.Closkey, 1999).

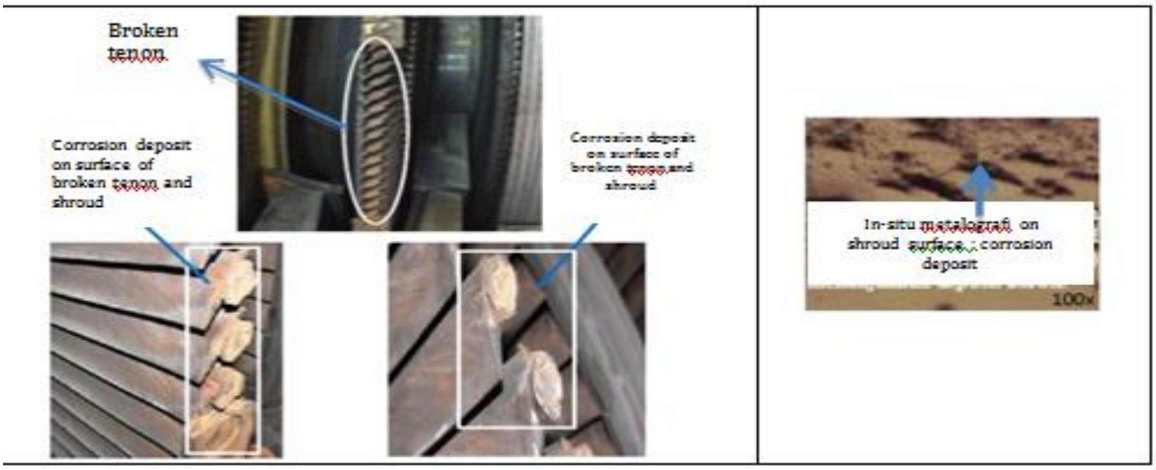


Image 5 Corrosion Tenon Blade Head

Figure 6 corrosion pitting on the surface of the bottom shroud

RCFA process shows some potential cause proved to be the root cause of this failure.

Table 2 Root cause of turbine blades failure and its long term action plan

No	Root Cause			Analysis	Long-Term Action Plan
1	Method	1	Shorfall in the process of identifying failure modes blade tenon damage on Failure Mode and Effect Analysis (FMEA) and Maintenance Strategy.	Failure mode "blade tenon damage" is not identified in the FMEA	1. Review FMEA and analyze"blade tenon damage" and define its proper maintenance strategy 2. Improvement on existing predictive maintenance for advance vibration analysis for similar damage symptom.
2	Machine	1	Wornout of blade tenon head and shroud	Fractography and in-situ metallographyanalysis shows the presence of friction and wornout in the area of blade tenon head and shroud	3. Proactive maintenance by redesign turbine blade into Integral Shroud Blade (ISB)
		2	Fatigue crack on the blade tenon head: inadequate blade design	Existing turbine blade design create a gap between the shroud and blade tenon heads which is prone to corrosion and rivet fastening methods generate stress concentration area that initiate crack	
3	Environment	1	Corrosion and pitting on the tenon and shroud that initiate the crack	Fractography and in-situ metallographyanalysis find corrosion and pitting on the surface of the shroud and blade tenon head	
		2	Trapped water between tenon and shroud on the gap between the shroud and blade tenon heads	The blade design with tenon is prone to corrosion attack due to trapping of water vapor in the gap	

III. PROPOSED ACTION PLAN

The recovery plans of geothermal turbine blades failure consists of immediate and long term action plan (Table 2). Short-term measures are mean to immediately put the plant back online and prevent similar failureoccurred in other plants. Long-term measures are proactive steps to eliminate root causes permanently by doing the engineering design of the existing turbine blade and review and improve existing FMEA.

Repair dan Immediate ActionPlan

RCFA process is part of the immediate action plan to identify the chronology and root causes of the failure as the basis to determine short–term improvement, scope of repair, equipment replacement or refurbishment plan and determine

the long–termaction plan to mitigate the failure permanently.
Immediate action plan (Table 3)basically consist of the following steps :

Tabel 3 Immediate action plan

	Immediate Action Plan
1	Demolition and mobilization turbine rotor to the workshop and turbine rotor cleaning with chemical cleaning
2	Check the condition of the entire turbine: ▪ Visual inspection ▪ Dimensional check ▪ Run out check ▪ NDT inspection (UT, MT, PT)
3	Reverse engineering turbine blade and shroud: Rotating blade 4pcs, 4pcs damper blade, shroud: 21 segment
4	Demolition of turbine blade
5	Integrity inspection rotor turbine
6	Replacement of turbine blades and parts (Image 4.22): ▪ Turbine blade: 84 pieces ▪ Plate intersegment: 13 pieces ▪ Replacement diaphragm level 3, the seal strip 20 Segment and inpengement (4 segments)
7	Mobilization and installation of turbine

ITEM	PART	INSPECTION METHODE	EVALUATION
Rotor	**Outer surface**	**VI, MT or PT, UT, Replica, HT**	**Crack Indication Erosion**
	1st,2nd & 3nd stage disc corner	**Replica, HT**	**Crack Indication**
	Blade groove (T- root)	**UT**	**Crack Indication**
	Blade groove (Side entry root)	**Replica, HT**	**Crack Indication**
Blade and Shroud	**Outer surface, semua tingkat**	**VI, MT, or PT**	**Crack Indication Erosion**
Stationary Blade and Diapraghm	**Outer surface, semua tingkat**	**VI, MT or PT,**	**Crack Indication Erosion**

VI = Visual Inspection
MT = Magnetic Particle Test
UT = Ultrasonic Test
Replica = Replica Inspection
PT = Pentrant Test
DI = Dimensional Inspection
HT = Hardness Test

Figure 9 Integrity inspection of rotor shaft

1. Replacement of damaged blade turbine by reverse engineering process.
2. Checking the condition of the turbine blade and rotor shaft condition (integrity inspection) (Figure 9) to analyze the impact of the failure to another parts
3. Integrity inspection ofspare rotor shaft

After rotor shaft mobilization to workshop, comprehensive examination of the condition of the turbine is performed to determine the level of damage and determine the scope of improvements in detail as a basis for procurement process. Checking on inventory levels of turbine blade spare parts shows that there is no spare for 3rd-stage turbine blade in the warehouse so it has to buy a new turbine blade and do the reverse engineering process as an input to the engineering database.

Long Term Action Plan

Long term action plan (Table 2) incorporate various methods to address "corrosion fatigue"failure mode permanently by technical method and by improvingexisting FMEA. Improvement in existing FMEA by incorporating "blade tenon damage" to define ropermaintenance strategy. It is done by optimizing proactive measure to prevent and predict failure during operation by equiponline turbine blade vibration monitoring. In case of that measure is not possible, the prediction can be done through monitoring the magnitude and phase angle change of journal bearing vibration.

At the time of overhaul, it is necessary to conduct non-destructive test (NDT) to investigate the corrosion fatigue (Mc.Closkey, 1999).

Another technical method is by decreasing cyclic load or level of mean stress couldsignificantly reduce the corrosion rate by design improvement to reduce mechanical stress on the blade such as freestanding blades design(Atrens et. Al, 1983), continuous banding (Mayerand Besigk, 1983) and damping design with lacing or shrouding.

Turbine blades will be replaced with new design,Integral Shroud Blade (ISB) (Mitsubishi, 2009) (Figure 7). Its segment shroud has integrated profile with the blade so need no rivets or welding fastening process to reduce possibilityof cracking due to residual stress, corrosion and fatigue. When the turbine reaches optimum operational rotational speed, shroud on adjacent blade will be aligned and strengthenthemself thatgive significant damping effect of the blade vibrations that reduce vibrations by 20% than conventional blade and increase blade reliability and corrosion fatigue resistance in corrosive environments of geothermal steam.

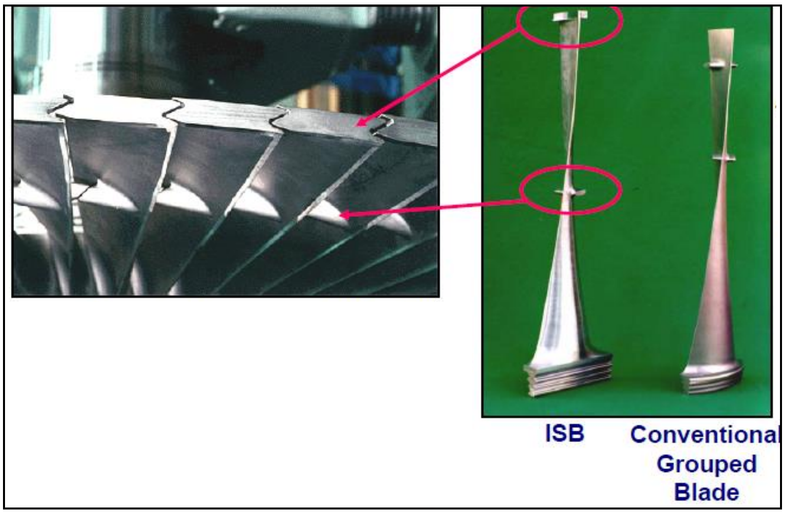


Figure 7Integral Shroud Blade (ISB)

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