An Investigation of Shaft Failure on Induced Draft Fan in A Steam Power Plant

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Abstract. A failure phenomenon on induced draft fan (IDF) shaft became a crucial attention in Power Plant with capacity 350 MW because the failure is catastrophic without early warning information. Also, the failures on the IDF shaft occurred in a short period within two months. This paper reported an investigation and evaluation of the root cause of the failure by vibration data monitoring and material analysis. The objective of the investigation and evaluation is to identify the main root cause and specific symptoms of IDF shaft failure. According to the data collection and analysis result, each phenomenon indicated an identical vibration pattern, however, the duration of each step is different. A series of tests of shaft samples was carried out to get comprehensive information, such as chemical composition test, tensile test, hardness test, microstructural examination (SEM), and fractography examination. The shaft repair procedure was also evaluated. The results were showed that multi initial of micro-scratch and martensitic embrittlement played an important role in the shaft failure. Micro-scratch triggered high-stress concentration on shaft surface. Martensitic embrittlement was found on weld metal and heat-affected zone.

1. Introduction

In a balanced draft boiler system, an Induced Draft Fan is one of the important equipment for maintaining the boiler pressure furnace. For many years, the most common problem of axial ID fans is blade, shaft bearing, and blade thrust bearing, over 50% [1].

From statistical data in Table 1, the failure mode of shaft bearing damage is around 19% of the total [1]. In general, the failure that occurs in the shaft is crack, fatigue, corrosion, torsional-bending, improper repair procedure, design errors, or handling error [1][1][2][3]. Crack on the shaft has become one of the factors limiting the reliability and safe operation of rotating part equipment [4]. Often, the crack in the shaft causes catastrophic failure of the equipment, leading to long downtime, production loss, and high-cost repair process. Several studies have been carried out to detect cracks on the shaft, so that the early warning system can run properly [4][5][6][7][8].

| Problem Area          | ID Fan % |
|-----------------------|----------|
| Blades                | 19       |
| Shaft bearings        | 19       |
| Hydraulic supply unit | 9.5      |
| Shaft                 | 7.1      |
In some types of materials, especially ductile materials, used for turbomachinery shafts, cracks are initiated from tiny discontinuity which can grow to some depths when the shaft is subjected to cyclic stress [4]. Crack can develop in a rotating shaft and propagate to some depths without producing any disturbance on vibration value and operating conditions of the shaft [9]. The tiny discontinuity may be initiated by mechanical stress-raiser, such as keyways, cross-sectional change, heavy shrink fits, dents, and groove, of metallurgical factor, such as welding flaws, inclusion, porosity, and void [4].

During disassembly of the impeller, flame heating was introduced to the impeller to expand the inner diameter of the hub. Impeller and shaft are installed with shrink-fit methods with P5/m5 fit tolerance (based on ISO 286-1). Scratch was found on the surface of the shaft. Welding or metal build-up was done on a scratched shaft surface that had contact with the inner diameter of the hub. Then, the impeller and shaft are re-assembled and IDF put back into operation. Not long after being operated, IDF failed with shaft cracked on metal build-up area.

2. Problem Statement

From October to November 2019, 3 sets of shafts IDF suddenly failed, after underwent a series of repairs. The vibration value on the bearing fan side increased for a moment then returned to normal, but after that, the vibration value increased rapidly. These three events have an identical vibration pattern, catastrophic. In each case, a transverse crack was found in the shaft’s bearing (Error! Reference source not found. & Fig. 2). One of the unique phenomena from all the shaft failure is crack located not in common stress concentration areas such as shaft-step, groove, or chamfer.

![Fig. 1. Schematic illustration of IDF](image)

![Fig. 2. Crack location on (a) IDF shaft 1B, (b) IDF shaft 2A, and (c) IDF shaft 2B](image)
3. Experimental Setup and Data Acquisition
The required data is taken from field inspections and material examinations in the laboratory. Vibration monitoring data was collected according to a certain time span. The data vibration analysis is also taken to see the vibration spectrum that occurred.

![Flow chart of failure analysis methodology](image)

**Fig. 3.** Flow chart of failure analysis methodology

Step by step of data acquisition was carried out to identify failure cause, included site inspection, material examination by test at laboratory, and vibration data check (**Fig. 3**).

3.1. Vibration analysis
All IDF vibration data was collected from the Distribution Control System (DCS) depend on the specific failure time. The vibration sensor installed on each fan bearing is a velocity type. Vibration measurement also carried out using Vibration Analyzer tools VibXpert II to figure out the spectrum and time waveform.

3.2. Material examination
The sample was divided into several segments to represent each area of the shaft (**Fig. 4**). Segment A, C, and D were examined to verify the material of the shaft itself. Segment B was examined to analyze the fractured surface. All sample was observed and tested in the laboratory. A series of test procedures have been carried out, such as chemical composition test, tensile test, hardness test, microstructural examination using optical and SEM, and fractography.

![Shaft's sample segmentation](image)

**Fig. 4.** Shaft's sample segmentation
4. Results and Discussion

4.1. Vibration analysis

All vibration trend from DCS is shown in Fig. 5, Fig. 6, and Fig. 7 for Induced Draft Fan 1B, 2A, and 2B respectively.

These three vibration trends show similar vibrational patterns. At first, the vibrations were normal, but suddenly the vibration value increased for a moment then returned to normal. After that incidental increase, the vibration suddenly increased drastically and the IDF trip protection due to high vibration became active. Vibration on IDF 1B was measured using a vibration analyzer a month before failure. The time waveform and spectrum of vibration are shown on Fig. 8 & Fig. 9.
Fig. 8. Time waveform & spectrum of IDF vibration on bearing no.1 each direction: (a) vertical, (b) horizontal, and (c) axial.
Fig. 9. Time waveform & spectrum of IDF vibration on bearing no.2 each direction: (a) vertical, (b) horizontal, and (c) axial

The time waveform & spectrum graphic above (Fig. 8 & Fig. 9) shows that the vibration value is still in acceptable range and no indication of misalignment or unbalance has occurred. Measurement was carried out using a vibration analyzer one month before failure, which means incidental increase also not yet occurred.

Initial symptoms occurred an incidental increase in vibration then returned to normal. This incidental increase in vibration indicates that the beginning of the crack had been started. Or possibly, the crack had already existed far before the incidental increase of vibration occurred. Theoretically, the existence of crack will affect the dynamic condition of the rotor, such as an indication of unbalance or misalignment will appear as a result of crack existence. But actually, crack existence is still undetectable by the tools or installed sensor. The research of cracked rotor detection has been done and still in progress in the past 30 years [8]. The initial crack then continued to propagate to the center of the shaft to a certain depth, which can be readily detected by a vibration sensor. At this step, crack propagate in catastrophic behavior and is detected by a vibration sensor. As a protection of the equipment, IDF trip with the shaft was still 10-15% of the cross-section uncracked condition.

4.2. Chemical Examination and Other Mechanical Testing
a) Chemical Composition Test
The sample of the cracked shaft (segment D) was analyzed by Optical Emission Spectrometer (OES) ARL 3460 equipment and the result is given below (Table 2):

| C     | Si     | S      | P      | Mn    | Ni     | Cr     | Mo    | V     | Cu    | W      | Ti     | Sn     | Al     |
|-------|--------|--------|--------|-------|--------|--------|-------|-------|-------|--------|--------|--------|--------|
| Sample| 0.443  | 0.268  | 0.01   | 0.013 | 0.604  | 0.08   | 0.91  | 0.197 | 0.004 | 0.142  | 0.004  | 0.004  | 0.016  | 0.050  |

From Table 2, chemical composition is confirmed that the shaft’s material is steel AISI 4140.
b) Tensile Test
The samples from segments A, C, and D were tested by tensile tester Zwick Roel Z250 with a maximum load of 250 kN.

| Sample        | Ultimate Tensile Strength (MPa) | Yield Strength (MPa) | Elongation (%) |
|---------------|----------------------------------|----------------------|----------------|
| Reference (AISI 4140) | 655                              | 415                  | 25.7           |
| Segment A     | 805                              | 425                  | 22.6           |
| Segment C     | 798                              | 453                  | 22.8           |
| Segment D     | 794                              | 454                  | 20.0           |

Table 3 shows the mechanical properties of the sample and reference AISI 4140. Generally, The Ultimate Tensile Strength (UTS) and Yield Strength of the sample higher than the reference.

c) Hardness Test
The samples from segments A, C, and D were tested by hardness tester with Rockwell B scale referred to ASTM E18 standard [10]. Each sample indented in 5 different testing points to get more reliable data.

| Sample        | Hardness Number (HRB) | Average (HRB) | Reference          |
|---------------|-----------------------|---------------|--------------------|
| Segment A     | 99.1 99.0 98.6 98.8 98.5 | 98.80         | AISI 4140: 92 HRB  |
| Segment C     | 98.8 99.3 99.5 99.5 99.8 | 99.38         |                    |
| Segment D     | 100.5 99.6 99.5 100.4 99.1 | 99.82         |                    |

In line with tensile strength, the hardness number of the sample higher than the reference (Table 4). For comparison, the sample of segment B (fracture area) was also tested by hardness tester micro-Vickers in the transversal and longitudinal direction of the fractured shaft. Hardness number was measured in the range of thickness 7 mm from shaft surface to center, with an interval of 1 mm each hardness sampling point.

| Distance from surface (mm) | Hardness number (HV) |
|-----------------------------|-----------------------|
| 1                           | 365                   |
| 2                           | 372                   |
| 3                           | 346                   |
| 4                           | 344                   |
| 5                           | 252                   |
| 6                           | 268                   |
| 7                           | 272                   |

| Distance from surface (mm) | Hardness number (HV) |
|-----------------------------|-----------------------|
| 1                           | 411                   |
| 2                           | 663                   |
| 3                           | 632                   |
| 4                           | 310                   |
| 5                           | 312                   |
| 6                           | 258                   |
| 7                           | 249                   |
As shown in Table 5, the highest hardness near the surface and closer to the center the lower the hardness number. The average hardness number of segments A, C, and D is 99.33 HRB, which is equal to 241 HV. Compare to the hardness number of segments A, C, and D, hardness on the surface fracture area is the highest. The hardness profile gives information that microstructure on surface fracture area is different from others segment (bulk material). As mentioned previously that the shaft was repaired by the metal build-up to eliminate surface scratch. This should be confirmed by microstructural examination.

d) Microstructural Examination

The samples from segments A, C, and D were examined by optical microscope Olympus GX71 with 200x magnification. All samples were prepared and etched by 3% nital etch. The microstructure image of each sample is shown in Error! Reference source not found. Bainite and Ferrite-Pearlite phase is identified in every sample. Bainitic steel has a finer structure than pearlite steel, thus are generally give stronger and harder in mechanical properties, yet they produce a good combination of strength and ductility [11][12]. So, a combination of pearlite and bainite structure is preferred than martensite in terms of toughness and ductility for shaft material application.

![Fig. 10. Microstructure of sample segment (a) A, (b) B, and (c) C](image)

The welding on the shaft was done in a longitudinal direction (Fig. 11). AISI 4140 steel with carbon equivalent to approximately 0.77% is susceptible to martensite transformation. Martensite transformation can occur easily with a higher carbon content or a very high cooling rate. Martensite is a non-equilibrium phase that results from diffusionless transformation and this transformation occurs only when rapid cooling is introduced and enough to prevent carbon diffusion [13].

Martensite is very high in tensile strength, yet very brittle, low toughness [14][15]. In the welding process of AISI 4140 steel, as the steel from high temperature exposed to cooling, the AISI 4140 steel experienced martensite transformation [15][16].

![Fig. 11. Illustration of metal build-up and heat transfer](image)
The heat generated during welding, flows more toward the center direction than longitudinal or to the air, as shown in the illustration above. Heat flow on conduction manner much easier than convection. This phenomenon will affect the cooling rate after welding. Combined with improper preheat and post-weld heat treatment process, martensite phase more possible to form on the surface and sub-surface of the shaft.

![Fig. 12. Martensite phase in shaft (a) longitudinal and (b) transversal cross section](image)

Martensite phase was found on the surface fracture of the shaft both in longitudinal and transversal cross-section (Fig. 12a & Fig. 12b).

e) Scanning Electron Microscope (SEM) & Fractography

The samples from segments A, C, and D were examined by SEM Hitachi SU3500 with EDAX Octane Pro.

![Fig. 13. SEM image of surface fracture at (a) initial crack and (b) propagation area](image)

![Fig. 14. Fractography image of the shaft’s surface fracture](image)

Some of the initial cracks were identified on the surface fracture of the shaft and the surface look rougher (Fig. 13 & Fig. 14). These multi-initial cracks were propagated which area is shown by a circular line around the crack and formed beackmark. Surface fracture is very smooth which is indicates that crack propagation needs a long time. Weld metal can be recognized by lighter color than the base metal. Penetration of weld metal approximately 4 – 5 mm. The hardness number on the
transversal direction in Table 5 clearly shows that 4 – 5 mm in the depth of the shaft is martensite phase.

5. Conclusions

In this paper, the investigation of induced draft fan shaft failure in a 350 MW power plant was carried out. The root cause of the failure is related to the formation of the martensite phase on the shaft surface, which leads to martensitic embrittlement. Multi-initial crack and benchmark path also found on surface fracture. Failure starts when stress concentration occurred in a multi-initial crack. As induced draft fan running, crack propagate start from each crack origins.

Improper welding, preheat, and post-weld heat treatment play important role in the formation of martensite. Hardness test result and microstructural examination clearly proved that martensite is almost evenly formed over the entire welded shaft surface. It is very recommended to follow the welding procedure specification and choose a proper welding electrode to achieve a good result and prevent martensite formation.

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