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Case study

Root cause analysis of bowl-mill pinion shaft failures

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ABSTRACT

Pinion shafts made of 18CrNiMo7-6 material, are used for transmitting torque from motor to gear box used in bowl mills of fossil fuel fired power plants. This work elucidates the metallurgical investigation that was carried out on a failed pinion shaft for analyzing the cause for failure. Fractography revealed the initiation of a crack from the keyway corner. Mechanical testing indicated that the yield strength of the material was lower than the specified value. Observation of the bowl mill at site after failure indicated that hard lumps were present in the bull ring segment, which clearly made it evident that there was sudden jamming of it which in turn led to overloading of the pinion shaft leading to the initiation of crack. A small overload fracture zone was also observed in the interior of the shaft suggesting low stress but high stress concentration torsional failure. Hence, this investigation concluded that this was a consequential failure.

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1. Introduction

Coal in pulverized form is essential for increasing the overall cycle efficiency of fossil fired power plants. The inherent advantage of this form of coal is its ease of transfer to burners of boiler. Bowl mills are very important auxiliaries for boiler units of thermal power plants, as they help to enhance the stability and efficiency of combustion process of coal by pulverization. This inadvertently increases the surface area of the coal, thus enhancing the combustibility in the furnace chamber of the boilers. Bowl mills work predominantly on the principle of crushing. An AC motor coupled to a pinion shaft transfers the torque to worm gear mounted on the vertical shaft. This is mainly responsible for the subsequent movement of the bull ring segments through smaller gears mounted below it. The movement of bull ring segment, therefore, enables the movement of the 3 conical bowl mill rolls oriented at 120° to each other. The coal gets crushed between the rolls and the bull ring segment. Subsequently, a jet of pressurized hot air is used for transporting this fine coal to the burners [1]. Hence, it is essential to ensure the integrity of all the components of the bowl mill for its effective and efficient working.

In general, shafts are used for transmitting torque under a variety of operating conditions and environments in various equipments used in power plants. During their operation or problems arising during their assembly in the components such as misalignments, the shafts are subjected to various kinds of stresses (such as tension, torsion, and bending) due to axial or radial loads which are often supported. These stresses when coupled with either mechanical or metallurgical stress raisers, lead to initiation and propagation of cracks thus, leading to failure of the component [2].

The pinion shafts investigated in this study are made up of 18CrNiMo7-6 grade steel. They rotate at 1000 rpm and transmit power from motor to worm gear kept inside gear box housing. There were 2 shafts which have been received in a

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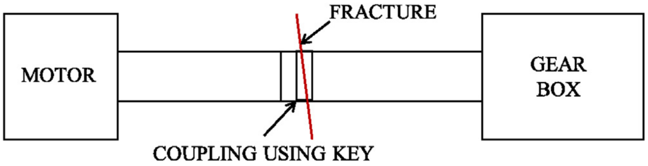

Fig. 1. Schematic of shaft and coupling assembly indicating the location of failure.

period of 6 months for failure investigation. Schematic location of the failure is shown in Fig. 1. This paper analyses in detail the root cause for the failure of shafts which were designed to operate for more than 100,000 h but have failed in just 1200 h.

Procedure adopted for root cause analysis is described below:

1. Visual examination and stereomicroscopy of the failed portions of the shaft.
2. Chemical analysis of the shaft material.
3. Metallography and microstructural examination of the shaft in the transverse direction.
4. Hardness measurements on the transverse section of the shaft from center to the surface.
5. Mechanical testing in transverse direction for assessment of mechanical properties such as yield strength, tensile strength and impact strength.
6. Fractography of the failed surfaces after ultrasonic cleaning.

This paper is organized as follows: Section 2 elucidates the experimentation part of this work. Section 3 is dedicated to results and their critical analysis. We present the discussion part of the work in Section 3.7. The conclusions of this study are given in Section 4.

2. Experimentation

The failed pinion shaft portions were carefully cut at the site. Both the portions of the shaft were packed without damaging the fractured surfaces and were sent for failure investigation. The nomenclature used for the fractured portions of the shaft is "specimen/shaft towards coupling side" and "specimen/shaft towards the gear box side" as shown in Fig. 2. After visual examination, the shaft specimens were carefully cut to obtain moderately thin slice of fractured surface such that it could be observed in the stereomicroscope. Stereomicroscopy studies were conducted using Leica Z6 APO stereomicroscope. The remaining shaft portion was utilized for preparation of specimens for tensile testing in the transverse direction as described in ASTM E8 standard [3] with a gauge diameter of 7 mm and M10 threads on the head. Chemical composition was

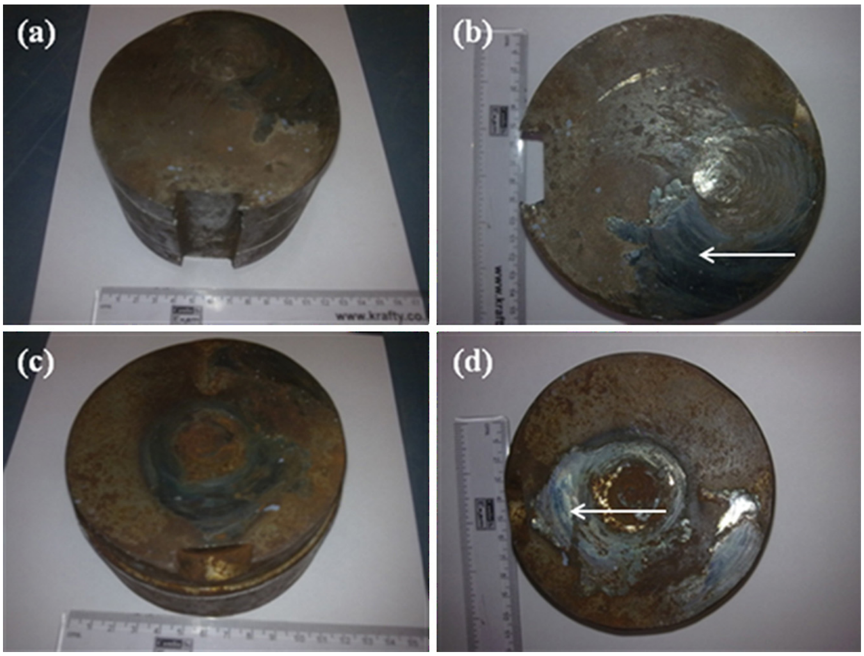

Fig. 2. As-received samples. (a and b) Fractured portion towards coupling side. (c and d) Fractured portion towards gear box side.

obtained using Spectromax X Optical Emission Spectrometer (OES) after grinding the sample as per the sample preparation specifications. For microstructural examination, the samples were ground with a series of emery papers and were polished with suspended particulate solutions subsequently from 9 μm to 0.25 μm and later with 0.05 μm alumina suspension. Etching was carried out on these specimens using 2% nital solution. Microstructural examination and fractography studies were carried out using Zeiss Supra 55 VP Field Emission Scanning Electron Microscope (FESEM) and compatible Energy Dispersive X-ray Spectroscopy (EDS) equipment from Oxford Instruments. Tensile testing of the specimens was carried out on Instron 500 kN Universal Testing Machine. Impact testing was carried out on TINIUS OLSEN, USA make using V-notch Charpy impact specimens prepared as per specifications in ASTM E23 standard [4]. Hardness testing was carried out on Shimadzu-HSV-30 hardness tester with 1 kg load for test duration of 15 s.

3. Results and discussion

3.1. Visual examination

The samples were observed carefully for any failure features using an illuminated low power magnifying glass. It was observed that fractured surfaces of the as-received samples were rusted. They also had rubbing marks over them (Fig. 2). Blue color marks on the sheared surfaces might have occurred due to excessive heating as a result of rubbing of the specimen surfaces after failure. Rubbing of the fractured surfaces led to the destruction of finer and elite evidence required for failure analysis.

3.2. Chemical analysis

Chemical analysis of the specimen at three different locations was carried out and obtained chemical composition results are indicated in Table 1. The nominal composition details for 18CrNiMo7-6 were taken and compared with the average of the results obtained from chemical analysis. It was observed that there is no deviation of the composition from the nominal value.

3.3. Stereomicroscopy

The results for the fractured surface of the gear box side specimen indicate the molten and re-solidified metal regions (as shown in Fig. 3). A small region resembling the final fractured region (overload fracture) was found inside the shaft towards gear box side as shown in Fig. 4. This suggested that this failure could possibly be due to low stress but high stress concentration torsional failure [5].

Table 1
Chemical analysis results of 18CrNiMo7-6 steel.

Element	C	Si	Mn	P	S	Cr	Ni	Mo	Cu
Coupling side	0.15–0.20	0.40 max.	0.50–0.90	0.02 max.	0.025 max.	1.50–1.80	1.40–1.70	0.25–0.35	0.25 max.
Spot 1	0.19	0.27	0.55	0.02	<0.01	1.60	1.60	0.28	0.18
Spot 2	0.185	0.26	0.54	0.02	<0.01	1.63	1.60	0.28	0.18
Spot 3	0.19	0.27	0.55	0.02	<0.01	1.60	1.60	0.28	0.18

Fig. 3. Molten and re-solidified regions on the gear box side fractured surface.

Fig. 4. Possible final fracture region on gear box side fractured surface.

3.4. Hardness testing and optical microscopy

Hardness measurements were conducted on the shaft specimen towards coupling side from center to the periphery. The hardness profile obtained from center to periphery is shown in Fig. 5. The average hardness observed was 335 HV_1 while the standard deviation was 21 HV_1. It was observed that the hardness at regions closer to the surface (points 13 and 14 as shown in Fig. 5 inset) was not varying much as compared to the interiors which depicted that there is no case hardening/ softening. The microstructure of the same specimen showed similar microstructure on surface as well as in the interior, i.e., tempered martensite as shown in Fig. 6, complementing the hardness results.

3.5. Mechanical property evaluation

Tensile testing was carried out on 3 transverse section specimens and the obtained results are reported in Table 2. These results were compared with the design specifications for this material. As per the specifications, the average UTS range of transverse section specimens was 1080–1320 MPa and the average 0.2% yield strength of transverse section specimens was 785 MPa minimum. It was observed that the average UTS and 0.2% yield strength of the specimens being 1012 MPa and 698 MPa, respectively, thus, were not meeting the specifications. No specimen was taken from the gear box side as the availability of material was limited.

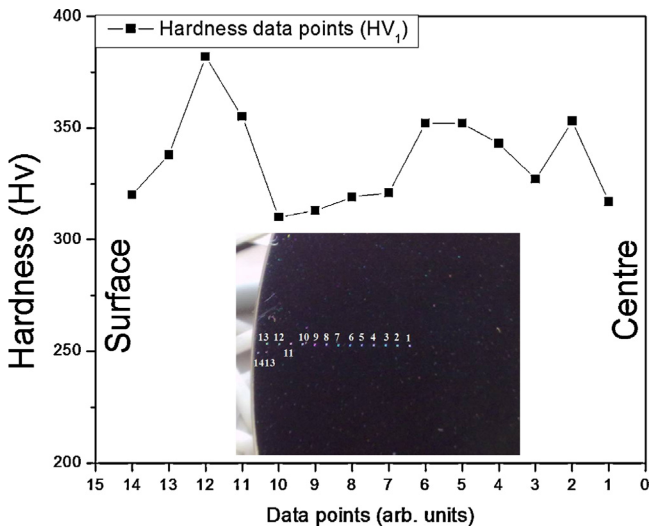

Fig. 5. Hardness profile from center to surface on the transverse section towards coupling side (inset: actual image of the indents).

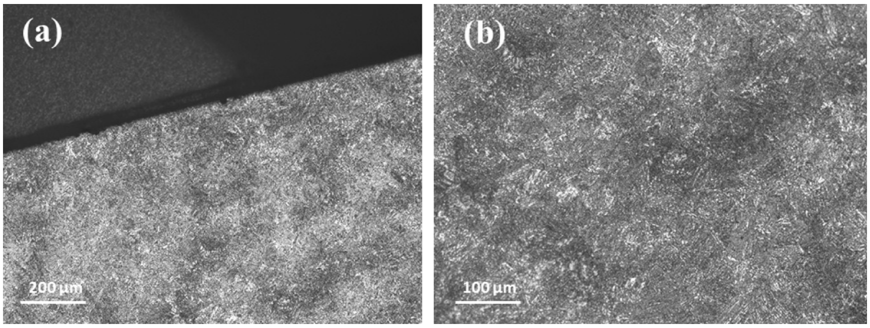

Fig. 6. Optical micrographs of the (a) surface and (b)interior.

Table 2
Tensile testing results.

Specimen	0.2% yield strength (MPa)	UTS (MPa)	% elongation	% reduction in area
Coupling side	698 ± 37	1012 ± 35	9.81 ± 0.9	54.13 ± 1.2
Specified values	785 min	1080–1320	8 min	35 min

Table 3
Impact testing results of transversely prepared impact specimens.

Specimen	Impact strength (J)
Coupling side	56 ± 4
Gear box side	59 ± 4
Specified value	46 min

Impact testing was carried out on 6 samples taken from the transverse section of the shaft specimen towards coupling side and 3 samples taken from the transverse section of the specimen towards gear box side. The results obtained from impact testing were reported in Table 3. The results were in good agreement with the specified impact strength (46 J min).

3.6. Fractography studies

Fractured surfaces towards the coupling side and gear box side were cut and ultrasonically cleaned twice in ethanol. The regions of interest were keyway corners as they are usual stress raisers in shafts [2,6]. Fractographs of the coupling side fractured surface indicated the presence of a crack at a keyway corner (Fig. 7 inset). After ultrasonicating the sample in 1% HCl, it was evident that this crack originated from the corner of the keyway (Fig. 7) and deposits found earlier were removed

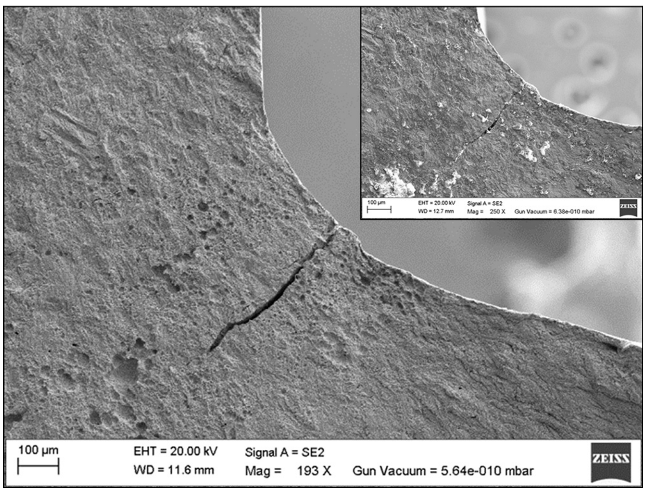

Fig. 7. Fractographs indicating crack origination from keyway corner after ultrasonic cleaning with 1% HCl solution (inset: after ultrasonic cleaning with ethanol).

Fig. 8. Image of the actual damaged bowl-mill rolls after failure.

from the crack. The crack was approximately 430 μm in length. Neither the other corner of the keyway for this surface nor keyway corners of gear box specimen had cracks before and after ultrasonicating in 1% HCl solution.

3.7. Discussion

Keyway corner regions in shafts usually act as stress concentration raisers (sometimes up to 10 times) due to the presence of torsional stress [2]. This leads to initiation of cracks which might further progress under fluctuating (dynamic) loads leading to a fatigue failure. The keyway corners in this case were not sharp. They had a generous radius made as per design to avoid stress concentration. After a detailed examination of the operating history, it was observed that at the time of the failure, hard, rock-like lumps were present in the inlet coal discharge and they were struck in the bull ring segment as they could not be crushed. One of the bowl mill roll also was damaged as a result of this blockage (Fig. 8). This led to locking of the bull ring segment, which led to sudden overloading of the entire mechanism. This overloaded the pinion shaft, thus favoring the initiation of the crack at one of the keyway corners. Moreover, the material having yield strength and UTS lower than specified values, has yielded and favored the crack initiation due to sudden application of load.

4. Conclusions

On the basis of the metallurgical and mechanical investigations carried out as mentioned in previous sections, it can be concluded that the pinion shaft had failed due to overload despite the keyway and its corners manufactured as per the design specifications. This overload consequentially arose from the sudden restriction of motion of the bull ring segment due to the presence of hard lumps in the ingress (coal feed) which could not be crushed. Yielding of the material was also favored as the yield strength of the material is lower than the specified value. This led to the initiation of the crack at keyway corner which progressed over a period of time and caused failure. Also, as observed from the stereo-micrographs, the small region inside the shaft resembling the final fracture region or overload fracture region also corroborates the fact that this could possibly happen due to low stress, high stress concentration torsional fatigue although fatigue marks were not observed as the fractured surfaces rubbed against each other after failure. Hence, this failure was a consequential failure.

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