J Fail. Anal. and Preven. (2018) 18:727–732
https://doi.org/10.1007/s11668-018-0468-7

CASE HISTORY—PEER-REVIEWED

Root Cause Analysis of Cracking in Shaft End and Coupling of a High-Power Generator

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Submitted: 2 March 2018 / Published online: 30 May 2018

Abstract Failure analyses and root cause determination were carried out on the rotor of a high-power generator of gas–diesel dual fuel which presented cracking due to torsional fatigue in its end (region of section change and coupling), after 30,000 h of service. The generator of 307 MW–3000 rpm has a rotor (shaft of 400 mm Ø) manufactured in a proprietary steel grade equivalent to ASTM A470 type, Class 7 of high hardenability. It was reported that the equipment control system showed, in service, a high level of vibrations, not admissible for continuing the operation. First, and during the equipment shutdown for inspection, the presence of cracks, slant to the rotor shaft, was detected by means of visual inspection and dye penetrant test. The failure region corresponds to the zone of coupling–shaft joint, linked by means of fixation by interference, whereas the cracking spread on two fracture planes at 45° with respect to the rotor shaft. On this zone, where cracking started, a severe fretting corrosion damage was evidenced. The characterization and identification of present damage mechanisms were conducted through macrographic, fractographic, SEM, EDS, chemical analyses, and mechanical tests. It was recognized that from the damage by fretting corrosion, fatigue micro-cracks were produced that spread due to service tensions by a mechanism of fretting fatigue. The fatigue fracture propagation was developed into two orthogonal planes at 45° from the longitudinal shaft, which reveals an inversion in the loading condition, only justifiable by torsional vibrations that were assigned to a torsional resonance typical of the system dynamics. It was considered that the torsional vibrations cause micro-movements between components, promoting fretting corrosion and the subsequent fretting fatigue that finally induced the failure by high-cycle torsional fatigue with low-stress amplitude.

Keywords Failure analysis · *Fretting corrosion* · *Fretting fatigue* · Torsional fatigue · Generator rotor

Introduction

In terms of electric power generation, and specifically, in high-power generators, intensive work has been carried out on the production of systems with higher output power in the last years. Equipment of high-power generation, however, has a main restraint due to the high inertia of movement transmission elements which must be increasingly larger. The shafts of these generators operate under a wide range of service conditions, among which there are atmospheres and extreme temperatures. On the other hand this component will undergo a variety of loads that are generally tension, torsion, compression, bending or a combination of these, often in presence of vibrations [1, 2].

The presence of torsional vibrations related to fluctuations in the network, or lack of controls as well as damping systems with sensitive sites in the group axis coupling, in

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the presence of a joint by interference, are a studied cause of failures by fracture of generator shafts; they result in the creation of superficial damage by *fretting*. Failure by fatigue begins in the most vulnerable regions of the component where there are dynamic acting strains, tension concentrators (which can be of mechanic or metallurgic nature), or a combination of both. High stresses due to these concentrators involve elements such as filets, insufficient fillet radius, spines or keyways, flawed fittings by interference, improper finishing, or machinery roughness. From the metallurgic point of view, stress concentrators could appear as quenching cracks, localized corrosion, large nonmetallic inclusions, second-phase fragile particles, and welding flaws [3].

Since 1970, several shaft failures have been detected and frequently placed in the coupling region associated with a fatigue fracture started with a surface *fretting* damage that, in turn, in most cases showed the presence of torsional vibrations (Fig. 1).

The literature shows a vast review of failure cases for both generator shafts of high and low power; the common point in most cases is the existence of a fracture by fatigue started by *fretting* (in some cases assisted by corrosion) where weakness is shown in shaft regions where there are section changes and joints of stationary type with interference fit. Figure 2 shows the visual inspection of a failure case of a diesel generator shaft. The fatigue fracture, developed over 70% of the shaft section, terminates with the final failure of the resisting ligament. It can also be observed the beginning of fracture on the left image (black arrow). The plane of fracture propagation, at 45° with respect to the element shaft, is related to the presence of torsional stress [4]. A least frequent fracture, but however studied, is fatigue fracture in the presence of torsional loads with inversion in the rotating direction or load application. When the load changes its direction, two fractures are formed at 45° with respect to the shaft longitudinal direction [5]. Figure 3 shows a shaft with fracture by torsional fatigue with inversion in the rotating direction started in circumferential marks (damage by *fretting*). In the presence of that kind of pattern, and as long as the element does not have a load inversion assigned in service, there will be torsional vibrations [3, 5].

The present work is based on the cause root analysis of cracking in one shaft end of a generator of 307 MW–3000 rpm by a fretting fatigue mechanism with a condition of torsional vibration loads.

Development and Performed Tests

The following actions and tests were carried out:

- Macrographic and fractographic analyses in wear and cracked part and counterpart (shaft–coupling joint).
- Metalographic analysis for revealing steel inclusionary cleaning, shaft and coupling, microstructure, and hardness.
- Chemical analysis of the shaft and coupling steel by means of optical emission spectrometer.
- Mechanical tensile test and Charpy V-notch impact test on shaft material.

Inspection of Cracking Development

Once defined the cracking location by end, the shaft was axially cut for then analyzing the fracture surface. Figure 4 shows, both in the shaft and coupling, the fracture pattern where the arrow points out the main propagation plane in the shaft and coupling. In these zones, a severe damage by *fretting corrosion* is evidenced, which has the same topographic characteristics of damage in part and counterpart of

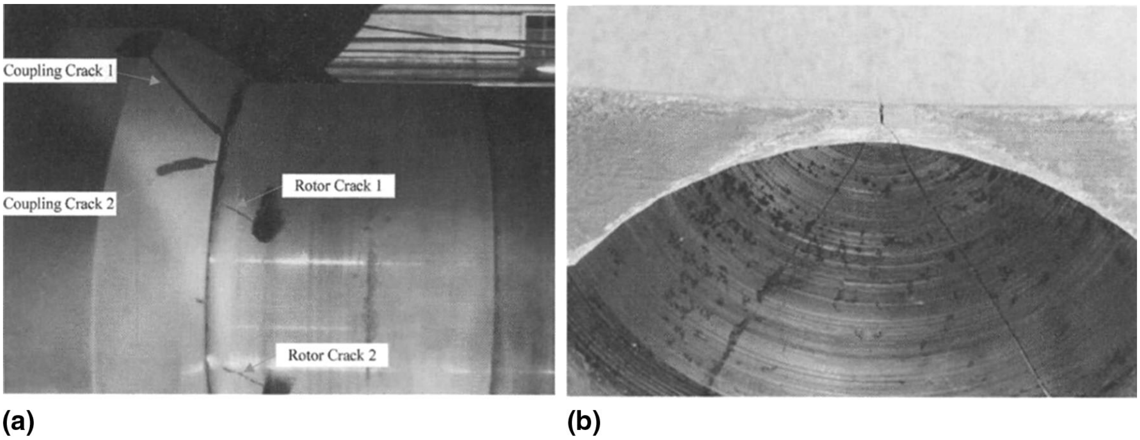

Fig. 1 Fatigue fracture failure in a shaft and coupling of high-power generator. “Coupled torsional vibration and fatigue damage of Turbine Generator Due to Gird Disturbance.” Chao Liu y Col. Beijing, China. 2014

Fig. 2 Generator shaft and coupling with evidence of a torsional fatigue fracture. Craighead and Gray [4] investigation of diesel generator shaft and bearing failures

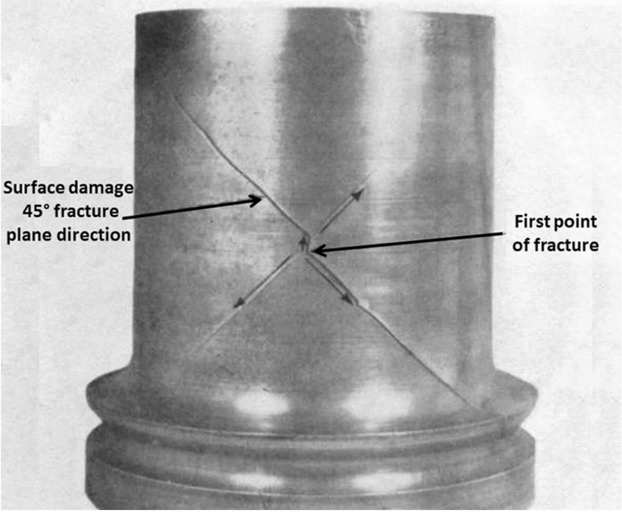

Fig. 3 Fracture in X (starburst pattern) due to the presence of inversion of torsional loads. “Fatigue Failures, With Special Reference to Fracture Characteristics,” G. A. Cottell, M.Sc., A.I.M. 2004 ASM International

what was the stationary interference fitted joint. It is observed in both part and counterpart (shaft and coupling), and the presence of a main plane of fracture propagation at 45° from the longitudinal axis of the element and, in turn, an incipient fracture plane developed orthogonally to the main plane, typical feature of a load state with reversing torsional stresses.

Fractograph

Figure 5 shows how the crack opening exposed the fracture with the characteristic pattern of a propagation by fatigue, where *ratchet marks* are pointed out together with *beach marks* in black arrows and the fracture origin is circled. On the right, the region of fracture (enlarged by SEM) is seen where a severe damage by *fretting* (shaft surface) can be observed and, on the other hand, the concentric advance marks of the fracture plane at the beginning of the failure are observed.

Fretting Damage

Figure 6 shows a shaft section with fretting damage; on the right image it the machining marks and deformation resulting from the micro-movements present in the stationary joint can be observed via SEM, and also a crack (indicated in black) crosses the image from the region with *fretting* to the zone where the machining roughness still persists.

Besides, Fig. 6 shows the section A-A that will be presented as a micrograph transversal to the fretting damage, showing severe alterations (Fig. 7), where deformations, with a depth in the order of 200 µm, and intrusions of wear particles (debris) corresponding to the shaft and coupling steel, together with oxides and possibly lubricant remains, are observed.

Chemical Analysis

Table 1 presents the chemical composition of the shaft and coupling steel. The shaft material is a propietary steel grade equivalent to ASTM A470, *Class* 7 equivalent to EN SEW 555 26NiCrMoV14-5/SEW 555 26NiCrMoV11-5, 1.6957/1.6948.

The coupling steel is according to the AISI grade 4340 and equivalent to the DIN grade 1.6562, 40NiCrMo7-3.

Microstructure and Mechanical Properties

The rotor steel presents a fine microstructure of tempered martensite with an average hardness of 320 HV_{10}. Its inclusionary cleaning is quite good, whereas the coupling steel presents a fine microstructure of tempered martensite with an average hardness of 279 HV_{10}. These material features are the most suitable for this kind of application and service (see Table 2).

Discussion of Results and Damage Model

In general, the phenomenon of fretting wear appears as damage mechanism on two surfaces in contact under pressure and stationary fitting (with or without interference) with the presence of cyclic loads or relative movements of extremely low amplitude with high local deformation by shearing (micro-weldings are produced between two surfaces that do not displace in relation to

Fig. 4 Cracking of shaft (left) and coupling (right) before opening fracture surfaces. Cracking is pointed out in arrows (with the main fracture plane indicated in black) and fretting damage circled

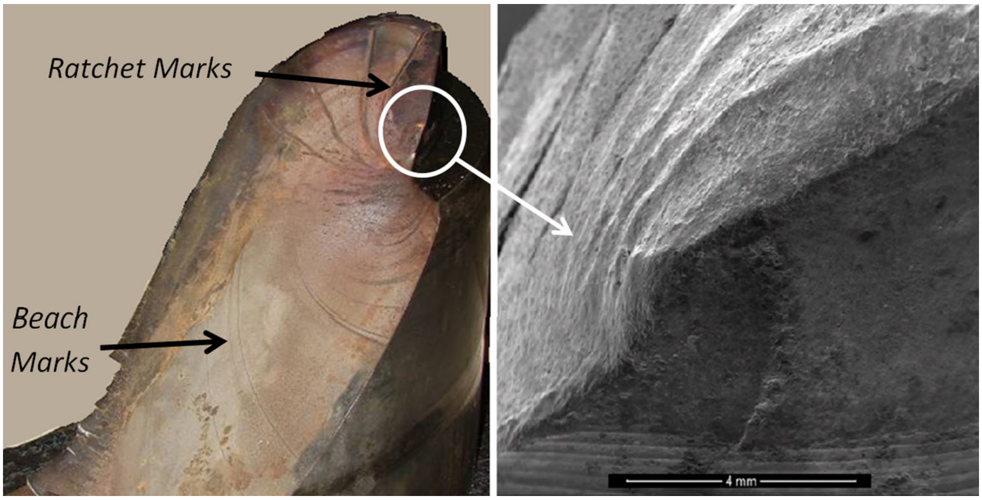

Fig. 5 Left: shaft fracture surface where it is observed the pattern of fracture by fatigue. The beginning of fracture is indicated with a circle. Right: SEM image where the region of fracture origin is seen

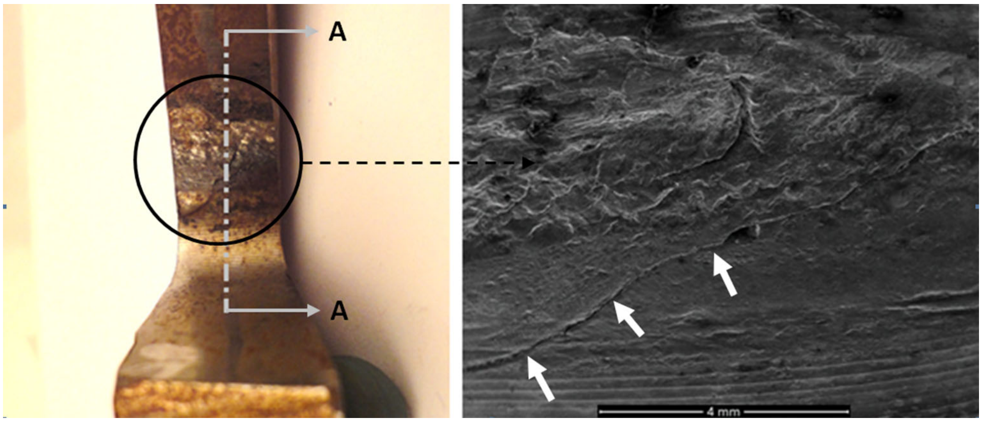

Fig. 6 View of the surface affected by fretting via SEM. On the right image, the machining and deformation marks can be observed. On the left image, the cross section performed for the transversal view of damage by fretting is indicated

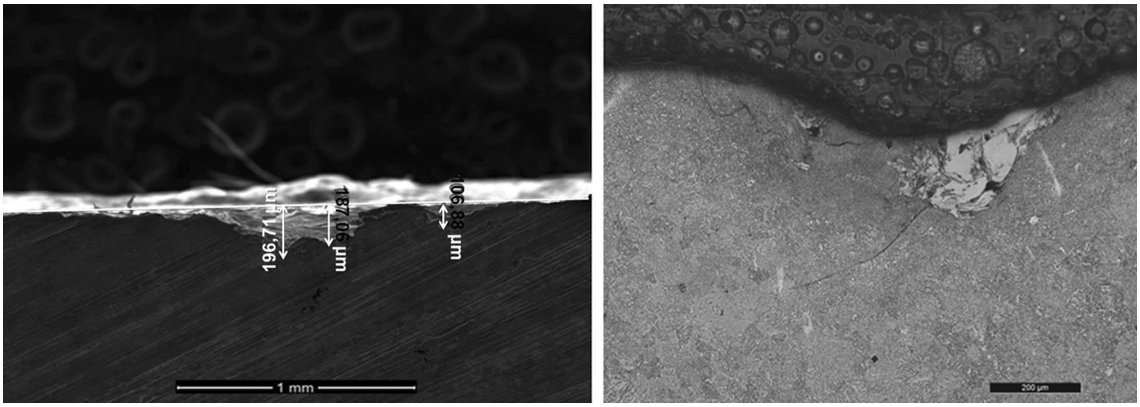

Fig. 7 View of cross-section A-A shown in Fig. 6. Fretting damage is evidenced with a depth in the order of two-tenths of millimeter. The right micrograph shows the presence of the counterpart metal as well as a severe damage by deformation

Table 1 Chemical composition of shaft and coupling steel

	C (%)	Si (%)	Mn (%)	Cr (%)	Ni (%)	Mo (%)	P (%)	S (%)	Cu (%)	Al (%)
Shaft	0.25	0.09	0.20	1.70	3.93	0.34	0.0128	0.0015	0.036	0.044
Coupling	0.42	0.12	0.61	0.80	1.81	0.24	0.0111	0.0058	0.119	0.008

Table 2 Mechanical properties of the shaft steel (ASTM E8)

	Fracture stress (MPa)	Yield stress (MPa)	Elongation (%)	Charpy (J) (ASTM E23)
Average	908	788	19.86	158

each other, though they can vibrate and micro-displace and therefore be welded, be torn, or micro-worn) [8, 9]. These features, typical of damage mechanism, have been a common factor in reviews and emblematic cases dealt by the literature [3, 4, 6, 7]. In addition, the adhesive wear can be identified by changes produced at surface level of the materials in contact (Fig. 7), being able to cause a hardness decrease (by tempering) or material fragility with the appearance of micro-cracks that could grow by fatigue (*fretting* corrosion not only neutralizes the fatigue limit of material but also reduces its performance in this service).

The most detrimental effect of damage by *fretting corrosion* is that it can lead to *fretting* fatigue (fractures by fatigue due to fretting). In the case of shafts, fractures can be of bending or torsional type or combined. Torsional fatigue fractures are typically oriented at 45° with respect to the axial direction, whereas bending ones at 90°. If there are two fracture planes at 45° in a shaft whose nominal load does not change direction (the case under study), this is an indicator of torsional vibrations (Figs. 4 and 5).

Torsional vibrations are oscillations in the angular deformation of a shaft along its axis. Generally, the dynamics of a shaft is the superposition of the free response (lack of excitation) to an initial condition and the forced response to an external excitation. In the first case, the oscillation is periodic and decay over time due to dissipation. In the latter, the oscillation is a transformation of the excitation source and the dynamic amplification of deformation (resonance) occurs if the excitation spectrum contains frequencies close to the eigenfrequencies of the system and it performs work on the corresponding deformation modes.

In damped linear systems, if the excitation source is periodical, then the response will also be periodical. The causes of periodical torque reported in the literature [10, 11] are as follows:

- Periodic phenomena in fluid flow.
- Misalignment causes a synchronous excitation (1X) and harmonics (mainly 2X).
- Bending–torsion coupling.

A possible mechanism of bending–torsion coupling is due to the conservation of angular momentum; thus, the lateral–angular interaction results from the required torque variation if the trajectories of the geometric center of any shaft section (orbits) deviate from circular one. Another form of coupling is present in rotors subjected to radial forces with lower symmetry than axial, due to the necessary torque variation for passing through the symmetry planes of the bent rotor. As the coupling is nonlinear, it causes a synchronous excitation (1X) and higher harmonics (2X, 3X, etc.).

The non-periodical excitation sources can be understood as a distribution of impulsive excitations over time, and the response is the superposition of the corresponding free oscillations. The causes of impulsive torques reported in the literature [10, 11] are as follows:

- Poor synchronization and sudden load changes in the network.
- Start-up, run down, and tests.
- Rotor–stator contact, i.e., rubbing.

An important situation, disregarded in previous cases, is the self-excited response. This occurs when a static excitation causes the oscillatory interaction between machine components, modifying the dynamic characteristics of the system. Especially, the stick–slip phenomenon, resulting from the micro-displacement in couplings or the action of brakes, can cause a spectrum formed by the fundamental frequency of the relative displacement and sub- and higher harmonics.

It is noteworthy that, unlike the bending (or lateral) vibrations, which transfer energy to bearings, torsional vibrations are damped primary by means of the internal dissipation in the material and due to the presence of mechanical couplings. Consequently, the modal damping in torsion is one order of magnitude lower than in bending [11], causing slower decay of the transient response, allowing the superposition of oscillatory bending–torsion modes for a longer period of time, and amplifying the steady-state oscillations.

Conclusions

- Shaft cracking is typical of a fracture by torsional fatigue of high-cycle, low nominal-strain regime (fatigue propagation zone with *beach marks* occupies a surface over 300 mm long), developed from the shaft fillet radius. Cracking spread on two fracture planes at 45° with respect to the shaft axis.
- It is assumed that from damage by *fretting corrosion* and in the shaft fillet radius, the stress concentration produced was enough for promoting fatigue microcracks that spread due to service stresses (by a mechanism of *fretting fatigue* resulting from *fretting corrosion*).
- Preventing or reducing *fretting* is accomplished by eliminating or decreasing vibrations and micro-displacements (increasing pressure of contact or adjustment between parts as long as this achieves immobility), introducing residual compressive stresses on both surfaces in contact, increasing superficial hardness by hardening thermochemical treatments (nitriding), and using *anti-fretting* lubricants.

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