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Reverse Bending Fatigue Failure of an Emergency Power Turbine Shaft

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ABSTRACT

A premature failed turbine shaft in an emergency power unit was investigated. Damage and fracture features of the shaft and relative self-lock screw cap and turbine disk were observed with low-powered microscope and Scanning Electronic Microscope. The shaft, including two symmetric fatigue areas and a central instantaneous fracture area, showed typical features of reverse bending fatigue failure. In correspond positions fretting wears were found on both the shaft and the screw cap. This suggests that fretting wear occur before the fracturing of the shaft. Operation principle of the emergency power unit was studied and metallurgical qualities of the shaft and the screw cap were inspected. Grain growth and drop, which implies overlarge electric current in spark-erosion machining, were found near the thread surface in the screw cap. It is reasonable that the grain growth and drop led to crack initiation in screw thread and then fretting in the shaft. Material change and cool forming instead of hot-forming and other preventative measures were provided.

KEYWORD

Turbine shaft, fatigue fracture, failure analysis, reverse bending

INTRODUTION

Turbine shafts are the key components in power units. Their fracture failures often imply disastrous accidents. According to their attributes and stress conditions, shafts fails mainly in (bending, tensile-tensile or torsion) fatigue fracturing, tough fracturing, and brittle fracturing [1]. Therefore, based on the analysis of failure modes of the shafts, we can judge the service conditions whether are normal or abnormal, find further failure causes, and propose effective preventive measures.

An emergency power unit was discovered flamed on the exhaust pipe in operation testing. After the emergency stop and disintegration, it was found that the turbine shaft was fractured, the turbine disk thrown [2].

The damage features of the turbine shaft and the shelf-lock screw cap were observed and analyzed, then the failure modes were determined. For finding the failure causes, metallurgical qualities of the shaft and the screw cap were inspected and the mechanical and technological factors resulted in this failure mode were investigated. At last, the preventive measures were provided.

DAMAGE CHARACTERISTICS OF TURBINE SHAFT AND SHELF-LOCK SCREW CAP

Turbine Shaft

The shaft fractured in the transitional corner of the screw thread near the behind end of the turbine disc, as shown in Figure 1. The are two symmetric fatigue regions and one central tough fracture region on the fracture surfaces, as can be seen from Figure 2. From the roughness, sizes and colors of the two fatigue regions, it can be referred that A region is the main fatigue region and B region is the second fatigue region. The two fatigue regions were originated from the screw thread and appeared multi-origins, where no metallurgical defects were found. The instantaneous fractured region, which has a large area (approximately 50% of the fractured area), shows typical equi-axial dimples. The above fracture features indicate that the shaft was failed by reversal bending fatigue load.

Different damages of the screw thread in the disc hole were found: A side has the most serious damage, showing even wearing plane and high temperature oxidized blue-yellow color (Figure 3). On the surface of the shaft and near the fracture surface 26mm (point C in Figure 1), a wear pit with diameter of approximately 3.0mm was discovered. The bottom of the pit shows typical fretting wear features, which were resulted from the point contact between the disc hole and the shaft. This pit slightly opposites to the main fatigue region. The above features demonstrate that the contact points (A and C) between the disk hole and the shaft surface had a little range of relative movement.

Figure 1: Outward and fracture site of the turbine shaft. C is a fretting wear pit.

Figure 2: Fracture surface of the turbine shaft. A and B are the chief and secondary fatigue regions.

Shelf-lock Screw Cap

The wear marks on the side surface of the shelf-lock screw cap which contact with the disk appeared uneven distribution. More serious wear marks can be seen on the site corresponding to fatigue regions (A and B); very slight wear on the site corresponding to the instantaneous fractured region, where silver-plating layer was loomed as shown in Figure 4. This indicates that there were fretting on the contact surfaces of the disk and the screw cap with a boundary of D-D line.

Figure 3: Serious wears of the thread near A side.

Figure 4: Wear of the screw cap side. A and B sides heavy.

The first thread in the screw cap near the disk side fractured a half at the B side. The origin, propagation and instantaneous areas are obvious. The propagation region has small size whereas the tough region has large size about 70% of the fractured area. Figure 5 gives a zoomed appearance of the origin and the growth region, where arrow shows the crack propagation direction (i.e. axial direction). Fracturing initiated at the transitional corner of the thread bottom. Although the fracture surface underwent axial secondary damage, local fatigue features can be seen in the growth region and shear dimples in the tough region. Therefore, the thread failure is low-cycle shear fatigue fracture.

METALLRUGICAL ANALYSIS

Turbine Shaft

The turbine shaft is made from GH4169 superalloy, its heat treatment is 960°C×10h solution (air cooling), 720°C×8h aging, 50°C/h furnace cooling to 620°C×8h, and then air cooling to room temperature. Microstructure shows fine grains and hardness check indicates HV401~446 (equivalent to HRC42~45). The two test results agree with technical standard requirements.

Self-lock Screw Cap

Made from GH2132 superalloy, the cap underwent 990°C solution, latheing thread, spark-erosion machining for the shape, 710°C×12h aging and then air cooling. The hardness is HV311~349 (equivalent to HRC31~34.5) and agrees with the standard requirement.

Metallurgical inspection reveals that in the female thread of the screw cap the surface grains grew obviously, some grains fallen and grain boundary became wide, as shown in Figure 6. These suggest there was overlarge electric current in spark-erosion machining, then high temperature in the surface layer and finally surface coarse grain and wide grain boundary.

Figure 5: Origin and propagation of the screw thread fracture surface

Figure 6: Grain growth and drop of the self-lock screw cap

FAILURE CAUSES AND PREVENTIVE MEASURES

Operation Principle Of The Emergency Power Unit

Figure 7 shows the diagram of the emergency power unit. High-pressure admission flows to the blades on the disk, chiefly generates torsional and axial load, which transfer to turbine shaft. The shaft then drives the gears. From Figure 7 we can see that, in normal condition, the turbine shaft mainly undergoes torsional and axial load, and the bending load due to the air flow turbulent and dynamic unbalance of turbine disk are negligible. In another word, if there were no changes of work conditions, the fracture failure of the shaft due to metallurgical or machining quality was only the tensile-tensile or torsion fatigue fracture; if there were other types of fatigue fracture failure, then work conditions of the shaft changed.

Figure 7: Dramatic diagram of the emergency power unit (AB is the fracture site)
1 Turbine shaft; 2 Drive gear shaft; 3 Bearing (2); 4 Turbine disk; 5 Self-lock screw cap.

Failure Causes

According to the macro and micro features of the failed turbine shaft, it is determinable that the shaft failure was a reverse bending fatigue-fracturing [3]. This indicates the shaft underwent cyclic bending stresses at the fracture site. Moreover, because the fracture site is just situated at the transitional corner of the thread bottom, in which high stress concentration existed, the fracture surface embodied the features of reverse bending low-cycle fatigue fracturing.

From the fracture features of the turbine shaft and damage marks of the relative components, it can be referred that the reverse cyclic bending stresses at the fracture site were generated neither from the shaft deformation nor from the peg-top eddy motion. An agreeable situation is that, owing to the axis deviation of the turbine disk, under the impact effects of the high rotation and air flow changes, the disk swung in the axial direction whereas rested to the shaft in rotational direction, then the shaft bore reverse cyclic bending stresses. Because the bending load was supported by A and C points, fretting began at A and C points first. Furthermore, A point is at the thread bottom and had smaller section area than C point, so crack initiated at A point. With the crack propagation, the disk swung more and more violently, then another fatigue crack initiated at B point first, finally the shaft failed in reverse bending fatigue fracturing.

The disk and the shaft assembled in transitional match and fixed by the screw cap. A torsion moment of 35N•m (equivalent to 24kN of axial prestressed force) was applied to the screw cap for preventing relative rotation between the shaft and disk and for ensuring coincidence of the disk axis and the shaft axis. Therefore, the prestressed force is a key factor for normal rotation of the turbine.

The above analysis shows there was low-cycle fatigue fracturing in the first thread of the screw cap. Because the first thread undertook the maximum load (about 30% of the sum load), its fracturing would lead lease of the prestressed force at B side and deviation of the disk axis. Thus the fatigue fracturing of the screw cap is the direct cause of the shaft.

Besides the axial prestressed force, the screw cap carried cyclic axial load coming from the disk. These axial loads act as shear load on the thread, which is the mechanical factor for low-cycle fatigue fracturing of the thread. Made from GH2132 superalloy, the screw cap has lower mechanical properties than GH4169 [4]. In the test to the failed components, the HRC of the screw cap is 10 lower than that of the turbine shaft. More important is that, in the spark-erosion machining, overlarge electric current lead to surface grain growth and drop in the screw cap, which greatly reduced the resistant of the thread. So that the spark-erosion machining is the direct cause of cracking of the first thread in the screw cap, and is also the further cause of the reverse bending fatigue fracturing of the shaft.

Preventive Measures

In order to ensure the operation reliability of the power unit and in accordance with this failure causes, preventive measures should be concentrated on improvement of the self-lock screw cap.

(i) Manufacturing the screw cap with GH4169 alloy instead of GH2132 alloy. This will not only promote the strength and fatigue properties but also eliminate the clearance between the cap and the shaft resulted from the difference of the thermal expansion coefficient, which will augment the clearance and release the prestressed force.

(ii) Using cool forming to machine the shape of the screw cap. This will avoid the surface grain growth and drop in the thread, increase the fatigue resistance, and be beneficial to ensuring the 45° prick plane and rigidity.

(iii) Substituting the slight convexity in the center with slight concave for increasing the contact area and rigidity.

At the same time, other preventive measures will be also effective such as: surveying the side pulsation of the disk, eliminating the combined error in assemble, monitoring the vibration of the power unit, cold extruding the shaft thread for enhance the fatigue strength.

CONCLUSIONS

(i) The failure of the turbine shaft was a reverse bending fatigue fracturing, and its failure cause is resulted from the deviation of the turbine shaft axis.

(ii) The low-cycle fatigue fracturing of the first thread in the self-lock screw cap, which leads to the releasing of the prestressed force, is responsible for the deviation of the disk axis. The surface grain growth and drop in self-lock screw cap is the direct cause of the low-cycle fatigue fracturing of the thread and the further cause of the reverse bending fatigue fracturing of the shaft.

(iii) Substituting the material of the screw cap with same material of the turbine shaft, using cool forming to manufacture the screw cap, and changing the convex plane in the center into concave, will avoid similar failures.

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