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Failure analysis on abnormal wear of roller bearings in gearbox for wind turbine

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ABSTRACT

The booming wind power industry as one of the predominant approaches of renewable energy resources is not independent of components reliability within the wind turbines, especially the rotating ones including blades, motors, gearboxes etc. Hence, case studies on failed parts of such components play an important role for failure prevention and deserves to be publicly reported for experience sharing. In this paper, a failure case concerning severe abnormal wear of the roller bearing's inner ring in the gearbox of one 1.5 MW wind turbine in China was reported. Since such roller bearings were imported from a foreign company and operated by a Chinese company, not only economic losses but also international commercial dispute would be induced if this case would not be immediately and properly solved. To this end, by means of comprehensive and systematic investigation into the base materials, process media, surface morphologies, micro-area compositions and even service environments, root causes of this failure were determined, detailed mechanisms were discussed, and pertinent countermeasures were proposed. Achievement of this paper would provide the solid evidence to distinguish the responsibilities for the failure, and would also help to prevent such failures of roller bearings with similar design in wind turbines.

1. Introduction

The installed wind power capacity of China has reached nearly 170 GW till the end of 2016 [1], which still remains the top position in the world since 2010 [2] and accounts for more than 10% of the total installed capacity in the country. In China, the Inner Mongolia Autonomous Region holds the largest quantity of wind power generators (commonly known as wind turbines) thanks to its superior climate and geographical conditions, and over half of them are in the scale of 1.5 MW. That is to say, safe and economic operation of these 1.5 MW wind turbines ensured by effective reliability assessment and failure analysis of their components, particularly the rotating ones including blades, motors, gearboxes etc., would play a crucial role in continuous development of this renewable energy resource domestically, nationally and even globally under the increasing pressure from environmental protection [3–5].

As for the average failure rates of all the components within a wind turbine, gearbox ranks in the top ones [6–9], only always falls behind the blades whose failure incidents could be easily found in the literature [10–18]. However, study of the gearboxes primarily focused on fault diagnosis through vibration monitoring [19–24], while similar failure cases of them have been rarely reported. In detail, a gearbox is used to increase the rotational speed from the low-speed rotor through the shafts to the high-speed electrical

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generator for electricity generation, and its bearings are regarded as one of the most vulnerable subcomponents to failure according to the statistics [25,26]. Although plentiful investigation has been conducted into the failure mechanisms of the roller bearings within wind turbine gearboxes, such as the peculiar morphology of the butterfly cracks and the accompanied white etching areas that are induced by rolling contact fatigue [27–31], they were mostly from the laboratories rather than the engineering practices. Also, the existing handful of failure analysis incidents on gearboxes mainly dealt with broken of the gear teeth in the shafts [32,33], and fatigue fracture of the rotor shafts [34–36] and the shear pins that connect the gearbox and the generator [37], while only a little emphasis was laid on the bearings, e.g. Gould et al. recently elucidated the causes of premature cracking on a failed bearing by utilizing X-ray tomography [38]. Thus, it can be now recognized that failure analysis on the bearings of wind turbine gearboxes deserves special attention, and should be immediately reported in public for experience sharing.

In this paper, failure analysis was addressed on abnormal wear of the roller bearings within the gearbox of one 1.5 MW three-stage wind turbine installed in the Baotou city in the Inner Mongolia Autonomous Region in China. Since this batch of roller bearings was manufactured by and imported from a foreign company (the supplier), while installed and operated by a Chinese company (the owner), which one should be blamed for the economic losses due to outage for this failure was urgently required to be identified. To this end, systematic failure analysis was carried out by means of various characterization instruments and methods based on our previous experiences on industrial equipment in the past several consecutive years [39–49], including photoelectric direct reading spectrometer, metallographic microscope (MM) and Vickers micro hardness tester for inspection of the roller bearing base materials; optical microscope (OM), three-dimensional stereomicroscope (3D SM), scanning electron microscope (SEM) and energy disperse spectroscope (EDS) for observation of the wear-out surfaces morphologies; and gas chromatography-mass spectrometer (GC–MS), Fourier transform infrared spectroscopy (FT-IR), and thermogravimetric analysis (TGA) for detection of the environmental medium lubricant. Then, relevant mechanisms were discussed and pertinent countermeasures were proposed. Considering the fact that under-performance is a common problem [50] and potential risk is high [51] for most Chinese wind turbines, achievement of this paper would not simply settle the international economic dispute between these two companies, but help to improve the reliability of wind turbine gearboxes that are domestically designed, manufactured, tested, operated and maintained in China.

2. Experimental and results

2.1. Visual observation

Fig. 1(a) and (b) respectively displayed the external appearances of the gearbox and the layout of its three planetary gears around the main shaft, and the roller bearings of concern were located inside these gears, seen in Fig. 1(c). In more detail, it was acquired from the owner that this cylindrical type of roller bearings consisted of one inner ring with inside diameter of 220 mm, one outer ring with outside diameter of 340 mm, and two parallel raceways with total width of 160 mm, each containing 24 cylindrical rollers in the grooves, seen in Fig. 2(a) and (b). After disassembly of some failed bearings, it was found that the inner rings had suffered severe localized wear on their raceways (Fig. 3(a)), and even had fractured to several parts (Fig. 3(b)).

In order to identify the root causes of such failure, one of the severely worn roller bearing's inner rings and eight of its cylindrical rollers was provided from the site. As displayed in Fig. 4(a), there were totally three wear-out areas in sizes ranging from several to a dozen centimeters existing on the raceways of this inner ring. For the purpose of further investigation, five samples were then wire-cut from the inner ring, and their locations were marked in Fig. 4(b) and (c). As for the rollers, since they were nearly the same and free of distinct wear traces, only one of them was taken as sample, seen in Fig. 4(d).

2.2. Material examination

Firstly, chemical compositions of the base materials of the roller bearing's inner ring and cylindrical rollers were detected by photoelectric direct reading spectrometer. Based on the results listed in Table 1, it could be determined that they conformed to the requirements of 100Cr6 and 100CrMnSi6-4 bearing steels specifications in the ISO 683-17:2014 standard [53] as designed, which are respectively equivalent to GCr15 and GCr15SiMn in the GB/T 18254-2016 standard [54] of China.

Metallographic structures including both polished states and etched states of the roller bearing's inner ring and cylindrical roller were then inspected under the metallographic microscope. As presented in Fig. 5(a) and (c) respectively, no inclusions existed in the inner ring, while Group D (globular oxide type) inclusions with a rating index number between 0.5–1.0 according to the ISO 4967:2013 standard [55] could be obviously observed in the cylindrical roller. After being etched, the inner ring and the cylindrical roller both exhibited a mixture microstructure of fine martensite, carbides, and retained austenite, seen in Fig. 5(b) and (d).

After that, Vickers hardness (HV) of the surfaces of the inner ring raceway and the cylindrical roller was measured by micro hardness tester with load of 9.8 N and holding time of 20 s. As listed in Table 2, the average hardness from four sites of the inner ring raceway was nearly 25% lower than that of the cylindrical roller, which might be responsible for the fact that the former was severely worn while the latter was almost intact, as displayed in Fig. 4 above.

2.3. 3D stereomicroscopy

Because of similarity of the five samples and limitation of the paper length, only the sample from area 3 (Fig. 4(c) and Fig. 6(a)) was taken as the representative for subsequent investigation. As shown in Fig. 6(b) and (c), indentations in sizes of several millimeters and in shapes of dots, eggs and rabbit ears etc., and cracks in lengths of several centimeters were found existing on the original