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How To Minimize Axial Cracking Failures

Although the root cause of axial cracking failures in gearboxes is not well understood, there are several possible prevention methods.

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The failure of bearings due to the development of cracks on the inner ring of the bearing has become a major source of wind turbine gearbox unreliability. Gearboxes at some sites have experienced failure rates as high as 70% within the first two years of operation. While failure rates this high are not typical, axial cracking is the leading cause of gearbox failure for many wind turbine gearbox original equipment manufacturers. The failures are not confined to any single gearbox or bearing manufacturer; they are systemic throughout the industry. The root cause of the failures is not known, although many theories have been proposed and are currently under investigation.

Even though the cause of failures is not well understood, risk factors that make a bearing more prone to experience axial cracking failures are known, as are factors that make a bearing less prone to such failures. By following some simple best practice guidelines when selecting bearings, owners and operators can minimize axial cracking failures.

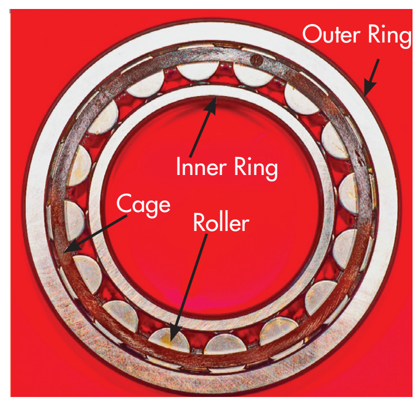
Wind turbine bearings are selected and analyzed to meet their intended 20-year design lives, with a low likelihood of failure. Most manufacturers follow Germanischer Lloyd (GL) guidelines for gearbox bearings. GL requires that gearbox bearings be analyzed for rolling contact fatigue (RCF) using several industry-standard methodologies, the resulting calculated life be quite high (from 130,000 to 175,000 hours depending on the methodologies used) and the likelihood of failure be fairly low, at 10% or less.

Although most wind turbine gearboxes meet or exceed these design criteria, axial cracking failure rates are very high and typically occur within the first or second year of operation. How can it be that a bearing that has been analyzed using well-understood and validated methodologies fails much sooner than predicted? The answer lies in the fact that the axial cracking failure mode differs from the classic RCF failure mode.

RCF failures are caused by damage to the bearing material that accumulates over time – at well-understood rates – and differ according to the bearing steel alloy type, heat treatment, cleanliness, surface finish and other factors. The axial cracking failures are relatively recent phenomena and occur at stress levels much lower than those required to cause RCF.

Axial cracking failures were first observed in the automotive industry in the 1990s. The failures occurred in alternator bearings, and the failure rates and consequences of failure were both much lower than those seen in modern wind turbine gearboxes. The components of a cylindrical roller bearing are shown and labeled in Figure 1.

Figure 1: Cylindrical Roller Bearing Components



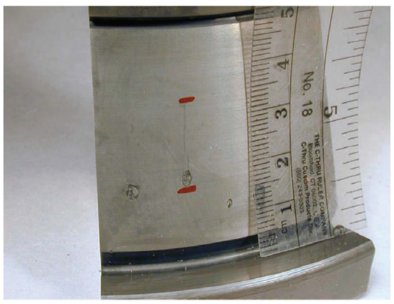
Source: RBB Engineering

The axial cracking failure mode occurs most often in the inner ring of a bearing. The reasons for this are twofold. First, the inner ring is smaller in diameter than the outer ring, and this implies that for a given load, the contact stress is higher.

Second, the inner ring is typically mounted to a shaft by heating the ring during assembly and slipping the expanded ring onto the shaft. When the ring cools, it shrinks – holding the ring in place, but also creating tensile stress in the ring. These two factors combine to make the inner ring more susceptible to cracking than the outer ring.

Figure 2 shows an inner ring with an axial crack. The crack shown is in the early stage of growth. With continued operation, the crack would lengthen and lead to spallation of the roller path, making the bearing non-functional. Metallurgical analyses show the axial crack is associated with microstructural alterations manifested by white etching areas and white etching cracks.

Figure 2: Early Stage Inner Ring Axial Crack



Source: RBB Engineering

Figure 3 shows a micrograph of a portion of an inner ring in the area beneath the roller path. The specimen has been treated by a chemical etching process used to bring out the details of the damage. The white structure seen in the figure is a white etching area, so named because it is turned white by the etching process. The branches radiating from the white etching area are white etching cracks. The image shows the crack has reached the roller path of the inner ring section. While it is not universally agreed upon by researchers, most believe that the damage originates in the subsurface of the bearing and propagates to the surface. The method of heat treatment applied to the bearing steel has a significant effect on the likelihood of axial cracking.

Figure 3: White Etching Area

Source: RBB Engineering

There are two types of bearing heat treatment processes: through-hardening and case carburization. Through-hardened bearings use a steel with high carbon content that is heated, quenched and tempered – a hardening process that results in the same high hardness throughout the depth of the bearing. Meanwhile, case-carburized bearings are heated in a carbon-atmosphere furnace, then quenched and tempered. This produces a high carbon hard outer "case" and a low carbon tougher core. Through-hardened bearings are much more prone to axial cracking than are case-carburized bearings.

Axial cracking failures most often occur in bearings in the high-speed and intermediate-speed stages of the gearbox, for reasons that are not well understood. Not all bearing types are equally prone to failure either. Cylindrical roller bearings appear to be more prone to axial cracking failures than are other bearing types, while tapered roller bearings appear to be less susceptible.

Potential root causes

There are several theories regarding the root cause of axial cracking failures currently under investigation by bearing manufacturers, including the following:

Sliding. In addition to a maximum allowable load, bearings require a minimum allowable load. This minimum load is required to ensure that the rolling elements in the bearing actually roll and do not slide. If the rollers slide, damage to the bearing surfaces can occur, and some researchers suspect that this damage can lead to axial cracking failures.

Hydrogen embrittlement. Hydrogen reduces steel's ductility, which is a measure of how much the steel can permanently deform without failing. Potential sources of the hydrogen required for embrittlement are moisture in the oil, as well as the oil itself. Some oil additives are also suspected of playing a role in hydrogen embrittlement.

Electrostatic discharge. This theory is related to hydrogen embrittlement. It holds that electrostatic energy from the lubrication filtration system, turbine electrical system or some other source provides the energy required to disassociate the hydrogen in compounds such as water or oil into the elemental form of hydrogen required to cause embrittlement.

Corrosion fatigue. As discussed earlier in this article, axial cracking failures occur at stresses well below those required to result in RCF. It is well known, however, that some environments result in corrosion of steel and that, in these environments, the allowable levels of stress are significantly reduced.

Adiabatic shear. When steel is subjected to impact loads, the steel microstructure can be transformed by rapid plastic deformation. Fatigue cracks can initiate in the deformed areas under subsequent cyclic loading.

There is some evidence to support each of these theories, and it could be the case that axial cracking failures have more than one root cause or interacting root causes.

Means of prevention

Although the root cause of axial cracking failures is not known, experience and experimentation have shown that there are steps that can be taken to significantly reduce the likelihood of bearing failure due to axial cracking. These steps include the following:

Use of case-carburized bearings. Case carburization can be an expensive process due to the large amounts of time and energy expenditure required to implement the process, but case-carburized bearings have been shown to be much less susceptible to axial cracks than through-hardened bearings in many applications. Potential reasons for this are the higher levels of compressive residual stress obtained in the case-carburization process and the higher toughness of carburizing steels. The higher levels of residual compressive stress act to keep small cracks closed, which limits their growth, as does the higher level of ductility of the steel.

Proper heat treatment practices. This is related to the case-carburization process. Heat-treated steel exists in many crystal structures, the most important of which are martensite and austenite. Martensite is the most abundant structure in case-carburized steel and is important because of its high level of hardness. Austenite is not as hard as martensite, but it does add toughness, which is known to increase fatigue resistance.

The appropriate blend of martensite and austenite can result in a bearing of optimal fatigue resistance. It is noted that through-hardened bearings have extremely low levels of austenite, and some researchers believe that this is at least partially responsible for the bearings' increased susceptibility to axial cracks.

Black oxide coatings. Some researchers and end users believe that black-oxide-coated bearings are resistant to axial cracking failures. Black oxide coatings have been used in bearings for many years. They have historically been used to improve bearing surface break-in and provide a measure of corrosion protection.

Bainitic heat treatment of through-hardened bearings. The vast majority of through-hardened bearings are heat treated such that the steel crystalline structure is almost entirely martensite. An alternative method results in steel with a bainite structure. The resulting bearing has a small amount of compressive residual stress at the surface and a higher level of toughness than a martensitic heat-treated through-hardened bearing. However, it does not match the superior case-carburization process.

Appropriate inner ring fitting practice. Bearing inner rings are typically made smaller than the shafts on which they are mounted in order to properly secure them in service. The rings are heated at assembly, which causes them to expand, and slipped into place on their shafts. The resulting interference fit causes tensile stress in the inner ring, as the shaft is exerting a large force on the ring. This stress in the inner ring is additive to the stress that results due to radial loads seen in service, and excessive levels of tensile stress due to interference can increase susceptibility to axial cracking failures. NWP

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