Rolling bearing applications: some trends in materials and heat treatments

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Rolling contact fatigue resistance and dimensional stability are the two important requirements for rolling bearing materials. Rolling contact fatigue can be initiated under the surface due to the presence of elastic inhomogeneities (inclusions) in the material, and, on the surface due to starved or contamination lubrication conditions. Two classical solutions in terms of material or heat treatment are presented and criticised. First, it is shown that ceramic balls, classically used to reduce contact stress, may induce deeper dents under contaminated environment. Second, an integrated approach based on thermoelectric power measurement is used to predict and understand the dimensional stability of bainitic 100Cr6 steel that exhibits dimension change proportional to its retained austenite content.

Keywords: Rolling bearings, Bainite, Ceramic balls, Rolling contact fatigue, Dimensional stability

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Introduction

Rolling bearings are widely used in mechanical equipments to enable rotation and to support significant load, and, as a basic component, in most of rotational mechanisms have contributed significantly to industrial development over the last 100 years.

They require a balance between a wide range of technical factors (e.g. weight, stiffness, friction, reliability, etc.) and service life consistent with the expected use. These requirements can be very different from one application to another. For example, typical automobile applications should last 8–10 years (200 000 km) and have a reliability of 500 ppm during the warranty period, whereas helicopter turbines should last >30 years with a reliability of 100%.

The major cause of failure in rolling bearings is contact fatigue. Rolling contact fatigue (RCF) can be defined as the mechanism of crack initiation and propagation caused by the near surface alternating stress field within the rolling contact bodies, which eventually leads to material removal.[1]

Dimensional stability is another important property that rolling bearings have to fulfil in order to preserve optimal clearance. Dimensional evolutions are due to microstructural transformations that take place in the material during its life cycle, e.g. carbides precipitation, retained austenite decomposition, etc.

In this paper, we will briefly recall the origins of RCF and present two classical materials and/or heat treatments solutions: the use of ceramic balls to reduce RCF and the use of bainitic 100Cr6 steel to achieve good toughness and stability.

Rolling contact fatigue

The two main damage mechanisms observed in RCF are subsurface initiated failure and surface initiated failure. These mechanisms are often competing and depend on loading, speed, friction, surface roughness of contact elements, lubricant contamination and material quality.

Subsurface initiated RCF

When a rolling bearing is properly designed, mounted, loaded, lubricated and kept free of contaminants (fully flooded elastohydrodynamic lubrication conditions), the main mode of damage is material fatigue. Under these conditions, the stresses in bearing contact are governed by Hertzian theory, so that a subsurface crack can be initiated, and depending on operating conditions,[2] propagate towards the surface causing a spalling of the raceway.

Microcracks are initiated at weak points in regions where the microyield limit is locally exceeded and microelastic deformation accumulates. The weak points might be non-metallic inclusions, carbide clusters and networks or short range variations in the microstructure that remains heterogeneous (banding) on the final product despite successive rolling, forging and heat treatment.

During RCF, as a result of cyclic stressing, when load exceeds a certain threshold,[3] microstuctural modifications may develop in the subsurface corresponding to the high stressed region of the Hertzian field, before the initiation of cracks. Depending on contact stress level, temperature and number of cycles, several chronological stages of microstructural modifications (butterflies, dark etching areas and white etching areas) have been identified and are well described in the literature (see the fairly complete review of Sadeghi[1]).

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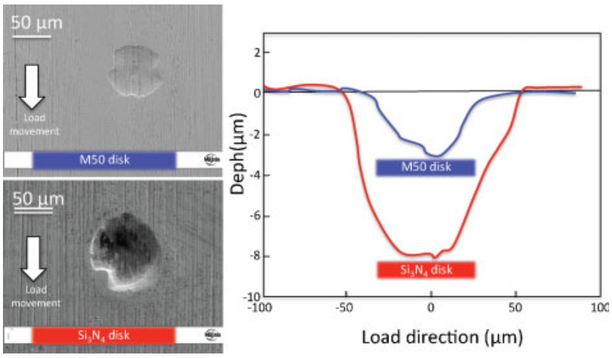


1 Dent profiles made on steel disc by M50 particle with ceramic or steel disc (counterface): ceramic balls lead to deeper dents

Surface initiated RCF

Surface initiated spalling occurs when surface material is subjected to asperity scale cyclic stress field.[4] In this case, surface irregularities such as dents, nicks, scratches, furrows or corrosion pits act as stress raisers able to initiate cracks. Grinding damage (tempered or rehardened material and grinding cracks) as well as surface decarburisation decrease locally the fatigue resistance. Depending on the size of the defect, the damage may be surface distress, micropitting or microspalling.

Does ceramic balls enhance fatigue life in contaminated lubrication?

Starved or contaminated lubrication

With starved or contaminated lubrication, the service life of bearings is determined by the stress concentration generated at the interaction between surface asperities or at the edges of dents printed when particles cross the contact.[4] The overrolling of the indent shoulder will generate local overpressures and may lead to spalls ahead of the dent along the direction of the load movement.[5]

This is the case of gearbox bearings that may be required to operate with a lubricant carrying particles and other debris (machining burrs and wear particles from gears). The damage mode is then a surface origin spalling (surface distress), either by micropitting or by peeling (abrasive wear) of the surface, leading to a significant reduction in service life. This behaviour can however be improved by adjusting the couple material/heat treatment or by using seals.

The material solution is often found in achieving surface treatments such as carburising or carbonitriding of steels with suitable composition.[6–9] These treatments aim at both increasing the surface hardness, and optimising the amount of retained austenite and residual stress in the case layer to limit the size of the shoulder of indents due to contaminants and the initiation and propagation of cracks from the indent edges. A hardness of about 880–900 HV and a retained austenite content of 15–20% can be obtained on the surface of bearing rings after carbonitriding of 100Cr6 steel, thus improving consistently the fatigue life under contaminated lubrication in comparison with conventionally treated 100Cr6 steel.[9]

Another example is the deep nitriding of 32CrMoV13 steel (enclosing the whole Hertzian area) used to strengthen the surface in case of starved or contaminated lubrication for aerospace applications.[10] Its toughness, >100 MPa m$^{1/2}$, also makes this steel an excellent candidate for the manufacturing of integrated rings submitted to structural fatigue. Finally, coating[11] or graded coatings[12] could also provide promising solutions.

Ceramic balls

Under difficult operating conditions, the use of ceramic balls can provide real improvements compared with steel solutions. First, ceramics present good features at high temperatures: their mechanical properties, hardness for example, remain high, and they offer high corrosion resistance.

Other interesting points can appear in high speed applications: the centrifugal contact stresses are reduced by the lower density of Si_3N_4 balls and light ceramic balls can be accelerated faster than steel balls. The lower density of Si_3N_4 also enables to decrease fuel consumption in aerospace applications because of lighter bearings. Moreover, under starved lubrication conditions or transient operating conditions (stop and go for example), direct contact between the interacting surfaces may occur. In such an event, the advantage of having a ceramic surface rubbing against a steel one is the low friction coefficient compared with the contact between two metallic surfaces.

In case of contaminated lubrication, to prevent the bearings from surface spalling near the dents, some studies have been done to integrate ceramic balls among steel balls.[13,14] They present a smoothing effect caused by the repeated crossing of the Si_3N_4 balls on the shoulder of the dent. This smoothing effect is characterised by very high plastic deformations of the shoulder reducing its height and quickly reducing the local overpressure.

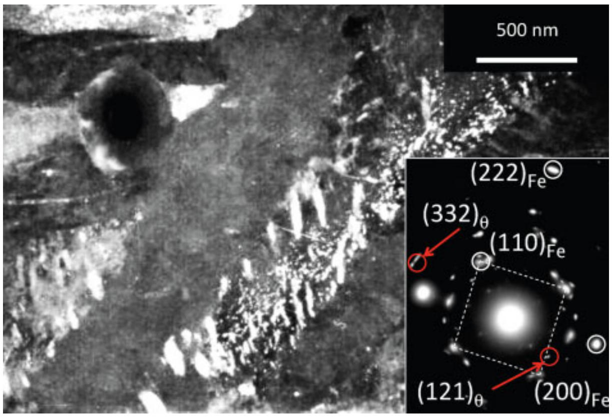
These points are in favour of replacing one of the steel rolling elements by a ceramic rolling element. In order to test these ideas, some experiments have been performed on a high speed twin disc machine. The indentations of nitrided 32CrMoV13 steel specimen discs were tested with either M50 steel or Si_3N_4 as counterface disc. The contact was lubricated with contaminated turbine engine oil. This pollution contained some M50 steel particles or some tungsten carbide particles with a diameter between 30 and 50 μm. Those particles were entrapped in the contact and generated dents. The topography of the dents was analysed and the result exhibited a significant difference between the steel to steel contact and the steel to ceramic contact (Fig. 1). In the latter configuration, the dent was found three times deeper than in the former one.

Indeed, both the high yield stress and high Young's modulus of the ceramic material, can explain the deeper dent created on the steel bearing race, when the particle is entrapped.

The use of ceramic rolling elements to replace steel rolling elements might be interesting in case of higher operating conditions (temperature, speed, transient conditions and starved lubrication), but the drawback is that under contaminated environment deeper dents will be created compared with steel bearing. This fact has to be taken into account, as well as the smoothing effect described in Refs. 13 and 14, to assess the real benefits of ceramic balls to fatigue life in contaminated lubrication.

Bainitic 100Cr6 steel: prediction of dimensional evolution

To withstand contact fatigue, bearing components need to be treated for high hardness (>60 HRC) usually



2 Dark field micrograph of bainitic 100Cr6 steel before isothermal aging: both nodular nanometric carbides and fine elongated carbides can be identified as cementite; inset: diffraction pattern; selected waves are pointed by arrows

by the use of tempered martensites. For some special applications, bainite microstructures (through hardened structures obtained by isothermal holding above the martensite start temperature) can be used when dimensional stability and toughness are required.

Toughness of bainites is expected to be greater than that of martensites, as they are obtained at higher temperatures and longer times, decreasing internal stresses in the structure.

Recently, an approach was developed in order to predict the dimensional evolutions of martensites during tempering.[15] Phase fractions were estimated from thermoelectric power (TEP) measurements[16] performed at different aging temperatures.

From TEP to dimensional evolution

We present here the same approach for a bainitic 100Cr6 steel (same material as in Ref. 15). The alloy has been austenitised 15 min at 870°C and held 20 min at 270°C. The resulting structure is bainitic and countains 4·7% of retained austenite (measured by X-ray diffraction).

Figure 2 shows a dark field micrograph obtained by TEM of such bainite, where both nodular nanometric carbides and fine and elongated carbides can be identified as cementite.

Three isothermal aging treatments were performed at 100, 200 and 240°C. During these treatments, TEP was measured as a function of aging time. In Fig. 3*a*, a sigmoidal evolution of TEP is observed. Using an activation energy of 80 kJ mol^{-1} leads to the TEP master curve shown in inset of Fig. 3.

During isothermal aging treatments, it is assumed that the nanometric carbides transform into larger carbides (No nanometric carbides were observed in the TEM after 10 days at 200°C.) and, simultaneously, the retained austenite transforms into ferrite+cementite, following a JMAK equation

$$Y(t)=1-\exp[-(kt)^{n}] \qquad (1)$$

To interpret the TEP evolutions ΔS, we use the expression derived in Ref. 15

$$\Delta S=\left(f^{0}_{\gamma_R}-f_{\gamma_R}\right)K_{\gamma_R}+\left(1-f^{0}_{\gamma_R}\right)\Delta S_{B} \qquad (2)$$

where $f^{0}_{\gamma_R}$ and f_{γ_R} are the initial and actual volume fractions of retained austenite respectively. $K_{\gamma_R}=75\ \mathrm{nV/K/\%}\gamma_R$ is the retained austenite influence coefficient.[15] The TEP variation in bainite ΔS_B has two contributions: the transformation of nanometric carbides ΔS_P and the recovery ΔS_R: $\Delta S_B=\Delta S_P+\Delta S_R$.

The retained austenite fraction is given by $f_{\gamma_R}=[1-Y(t)]f^{0}_{\gamma_R}$ and TEP evolution due to the nanometric carbides dissolution is proportional to carbide phase fraction: $\Delta S_P=K_P Y(t)$. Finally, the recovery is assumed to follow a JMAK equation such as $\Delta S_R=K_R Y_R(t)$ with

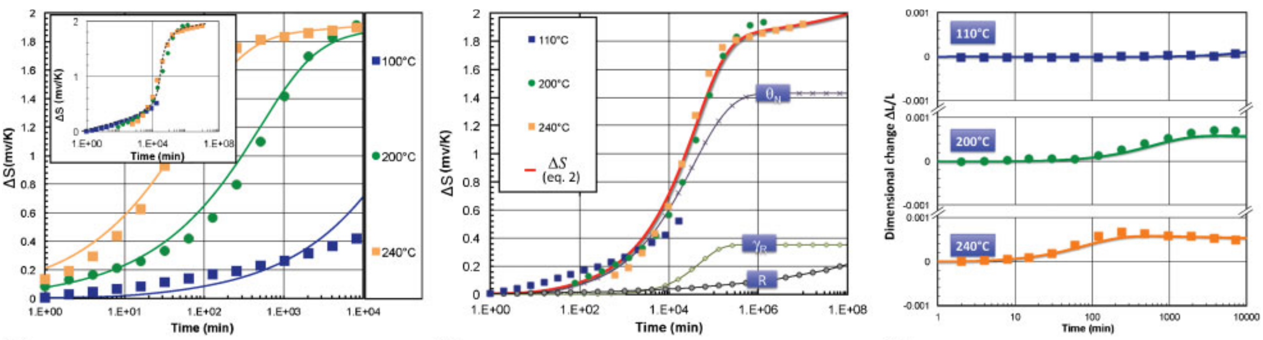
$$Y_R(t)=1-\exp[-(k_R t)^{n_R}] \qquad (3)$$

Equation (2) is used to quantify the TEP master curve at 110°C (*see* Fig. 3*b* where all contribution of TEP evolution are shown), leading to the parameters listed in Table 1.

To validate our approach, dimensional changes are predicted. It is assumed that only decomposition of retained austenite and recovery lead to volume change.

The eigenstrain associated with recovery is given by

$$\varepsilon^{T}_{\alpha}=\frac{1}{3}\ln\left[\frac{\Omega_{\alpha}(t)}{\Omega_{\alpha}(0)}\right] \qquad (4)$$



3 *a* and *b* comparison between experimental TEP measurements (symbols) and empirical approach based on JMAK formalism (lines: equation (2)). In *a*, calculated TEP has been shifted according to activation energy of 80 kJ mol^{-1}. In *b*, experimental TEP measurements have been shifted according to same activation energy. *c* dimensional change of bainitic 100Cr6 steel during aging: comparison between experiments (points) and overall approach presented in this paper (line)

Table 1 Parameters used to model TEP evolution during aging at 110°C

k	n	k_R	n_R	K_R	K_P
2×10^{-5}	1	10^{-12}	0·2	2 μV K^{-1}	1·5 μV K^{-1}

where $\Omega_\alpha(t)=0{\cdot}287^3+\Omega_R^0[1-Y_R(t)]$. $\Omega_R^0=0{\cdot}0001$ nm^3 has been set to obtain an eigenstrain due to recovery of 0·15%, in agreement with the contraction measured after non-isothermal aging performed in the dilatometer.

The eigenstrain associated with transformation of retained austenite to ferrite+cementite was calculated in Ref. 15 for the same steel: $\varepsilon^T_{\alpha+\theta}=1{\cdot}38\%$. The eigenstrain of retained austenite $\varepsilon^T_{\gamma_R}$ is zero, since it does not evolve during tempering.

Knowing the phase fraction of austenite f_{γ_R}, ferrrite+cementite $f^0_{\gamma_R}-f_{\gamma_R}$ and bainite $1-f^0_{\gamma_R}$ derived from TEP (*see* Fig. 3*b*), it is now possible to predict the dimensional changes of the bainitic steel during isothermal aging. Figure 3*c* compares these predictions (for which Voigt and Reuss limit are shown and superimposed) with experimental dilatation values. The good agreement validates the whole proposed approach.

In conclusion, dimensional evolution of 100Cr6 bainitic steels during isothermal aging is mostly due to the presence of retained austenite. It has been verified with other retained austenite content that the dilatation due to the decomposition of retained austenite is proportional to the volume fraction of retained austenite.

To prevent such evolution, retained austenite free bainite could be an interesting solution. However, it would involve very long transformation times, which may not be compatible with industrial cost requirements.

In martensitic 100Cr6 steel, dimensional changes induced by thermal aging are associated with two antagonist phenomena almost cancelling each other out: precipitation of carbides leading to a macroscopic contraction, and transformation of the retained austenite leading to a macroscopic expansion. Compared with their martensitic counterparts, bainitic 100Cr6 steels may not be such an interesting solution, as far as dimensional stability is concerned.

Finally, bainites could be promoted when the bearing must withstand shocks, or difficult solicitations when enhancement of toughness can lead to better performance. For some applications, bainites may exhibit a better hardness/toughness compromise than martensites.

However, it is to be remembered that if toughness is really needed, bainites will only offer a slight increase in toughness compared with martensites, and that solutions introducing surface compressive residual stresses, such as induction heating or carburising, have to be promoted.

Conclusions

Surface RCF can be limited by enhancing the surface hardness through appropriate heat treatment, or by using ceramic rolling elements in the boundary lubrication regime.

However, it has been shown that such solution may induce deeper dents under contaminated environment.

An integrated approach using TEP measurements to characterise the phase fraction evolutions during aging has been used for 100Cr6 bainitic steels. It leads to very good prediction of dimensional changes under aging treatments at various temperatures.

Baintic 100Cr6 steel exhibits larger dimensional evolution than its martensitic counterpart. This is because no precipitation of carbide counterbalances the dilatation associated with the decomposition of retained austenite.

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