Influence of an EM field on Changes in Microstructure of Bearing Steel

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Abstract

An electromagnetic (EM) impact to changes in microstructures of bearing steel, which occur during their exploitation, is investigated with a stress on white etching areas (WEA) formation. The early WEA is an urgent problem in bearing industry as far as this phenomenon leads to unpredictable decay of bearings. In this work a new hypothesis of impact of EM effects on the WEA formation is proposed and analyzed by means of numerical simulation of the processes that occur in the microstructure of the martensitic steel.

Introduction

The most wide-spread bearing material is steel in a martensite form. Martensite is formed from carbon steel by the rapid cooling (quenching) of austenite at such a high rate that carbon atoms do not have time to diffuse out of a crystal structure in large enough quantities to form cementite (Fe₃C). As a result, the face centred cubic austenite transforms to the highly strained body centred cubic form of martensite that is supersaturated with carbon. Shear deformations lead to a large number of dislocations, which is a primary strengthening mechanism of steel. The necessary cooling rate to achieve such structure is at least 120 °C/s in the temperature interval between 700 °C and 230 °C. Martensite has significant residual stresses due to this reason, and it is metastable, and can decay back to austenite [1]. The transition can be triggered by temperature (starting from 300 °C) [2], but also other factors, mainly mechanical stresses in the material starting from approximately 100-200 MPa [3].

In addition to well-known dark etching areas and cracks, which appear due to classical fatigue decay of the steel microstructure to amorphous matter, the white etching area (WEA) appears in the bearings. A course of WEA is localized deformations, which initiate dynamic recrystallization and leaves a fine equiaxed structure of grains and which have a size of the order of 20 nm [4,5]. Such nanostructured material after an acid etching is observed as a white area. An interface of this recrystallized region is not strong and it has been shown that cracks are forming in these regions.

Generally, a majority of bearing steels like SAE 52100 contain few percentages of a retained austenite and a significant number of cementite particles that concentrate mostly at boundaries of the grains of the martensitic structure (see the microscope photo on Figure 1 a). Martensite is in a form of thin needles with anisotropic properties as it is shown on Figure 1 (b). The needles preferentially conduct current in a longitudinal direction and contact resistance appears on their boundary. Opposite to good conductive martensitic matrix, conductivity of the cementite grains is relatively low.
According to prevalent opinion, the WEA phenomenon is connected to excessive impulse fatigue during the exploitation of the bearing [6]. Nevertheless, as it is mentioned in ref. [7], recent experiments and industrial tests show that it is possible to observe the WEA even within an idealized test without any impulse fatigue but with current discharge in the bearing. Based on such tests we are investigating EM effects that may induce significant localized stresses between the elements of bearing steel microstructure.

1. Electromagnetic effects

All effects, which can lead to mechanical stresses in microscale or macroscale are summarized in Figure 2. Excluding a strong impulse fatigue, which can appear during industrial usage of the bearing but is definitely excluded in rolling tests, several types of stresses exist outside of an EM model.

Residual stresses are observed in all materials. During a hardening process the austenite-martensite transformation results in numerous differently oriented mono crystals of martensite, which lead to localized stresses between them. Despite a significant reduction of these stresses during an annealing process, a noticeable level of the residual stresses is typical for the martensitic structure and should be added to the stresses caused by mechanical and electromagnetic impacts.

Hertzian stress is a well-known effect. The value of this stress is significant, however, rapidly decreases as moving away from the surface. Therefore, due to the localization of this effect in a thin layer near the surface, it can be not associated with WEA.

Thermal stresses as a result of overall heating of bearing as well as the residual stresses are very important for definition of a reference level of the stresses in the microstructure of steel.

Finally, the most part of our attention was spent to the study of EM influence on the microstructure level. We believe that these effects can explain the unexpected WEA formation rapidity in bearings. The interconnections of the EM effects are shown in the red box on the Figure 2.
However, it is found that the mechanical stress caused by the most of these effects is small. Only resistivity heating and induced current can reach necessary value of few hundred MPa, which is sufficient to initiate WEA formation.

2. Modelling of current discharge

A spark discharge through a lubricant layer may be observed during tests. A non-stationary numerical model is developed to calculate current and a magnetic field distribution in the material. It is found that the spark discharges can create a significant magnetic field and high local current density, but a subsequent heating is small because of a short time of the discharge. A current density is defined as Gaussian function from a coordinate and time:

$$j = j_0 \cdot \exp(-r^2 / R^2) \cdot \exp(-t^2 / \Delta t^2),$$

where the channel radius is $R=10 \, \mu m$ and the discharge time is $\Delta t=10 \, ns$, the peak current density is $j_0=10^{10} \, A/m^2$, which are realistic values in case of the small scale electric discharges in insulators. Current density decreases proportionally to $1/r^2$ inside the material. Figure 3 (a) shows magnetic field at a moment when current is maximal. As we see for a short time very high magnetic field above 10 T may exist. However, all phenomena related to the spark discharge take place on the surface or in a thin layer close to it. This effect is difficult to model quantitatively because parameters of the spark discharge may vary at a wide range.

A total energy released by the discharge is proportional to the discharge time and the peak current squared. Usually the time is short, thus this mechanism cannot cause significant temperature increase. The Lorentz force can reach a high peak value as shown in Figure 3, but it exists in very small area and for very short time. If the discharge parameters are chosen appropriately, this force can easily cause the stress level higher than necessary for WEA initialization.
2. Modelling of microstructure

To estimate the thermal stresses in the microstructure, a microscale numerical model is developed. A cubic geometry is created as shown in Figure 4 (a). The thermal stresses at the initial temperature are zero and then the material is heated by 100 K. Calculated thermal stresses are shown in Figure 4 (b). As we can see, the maximal stress value is at the grain boundaries. As expected the maximal stress value is above 700 MPa. This order of magnitude also is in good agreement with an analytical estimation,

\[
\sigma = E \cdot \Delta T (\alpha_1 - \alpha_2) \approx 300 \text{MPa},
\]

where \( \Delta T = 100 \text{ K} \) is the temperature difference, \( E = 300 \text{ GPa} \) is the Young's modulus and \( \alpha_1 = 6 \cdot 10^{-6} \text{K}^{-1} \) and \( \alpha_2 = 1.5 \cdot 10^{-5} \text{K}^{-1} \) are the thermal expansion coefficients of the cementite and the austenite grains. This result indicates an elevated temperature may ease lead to formation of WEA and that WEA most likely starts at a contact point between two grains.

We have observed the cementite particles at the boundaries of the martensitic grains as a promising point in context of the WEA (Figure 1 a). Different electrical, thermal and mechanical properties of the martensitic lattice and the cementite may lead to significant stresses and deformations when impulse current conducts through the system. It should be mentioned that other inhomogeneities of the microstructure (nanocracks, voids, non-metallic inclusions) may also play the role like the cementite grains.

Taking into account the analysis of the microstructure of the bearing steel, an axially symmetric model is created around the spherical cementite particle that is situated at the boundary of the martensitic grains (see Figure 5). The conductivity of different elements is ranged as follows: \( \sigma_1 << \sigma_2 << \sigma_4 = \sigma_5 \) (the indexes denotes the areas numbered on Figure 5).
Thermal conductivity follows the same range due to a coupled physical mechanism in metals. Additional contact resistivity is applied between the needles (2) and on the interface (2-4).

![Diagram of current density distribution](image)

Fig. 5. Distribution of current density in the axially symmetric model of the microstructure around the cementite grain (1) at the boundary of the martensite grains (3); 2 – the monocrystals of martensite, 4 – the area of the differently oriented monocrystals, 5 – the interior zone of the martensitic grain.

Mechanical boundary conditions are physically indefinite due to a lack of the proper data. However, two extreme cases are considered: free boundary conditions and fixed constraint. In fact, the real conditions are somewhere between the already mentioned conditions. Figure 6 demonstrates the significant strain in the both cases. As far as the cementite particles are poor conductive, dense distribution of them at the boundary between the grains force the current to flow around the cementite and, consequently, the current concentrates there. The oriented martensite needles even enforce the effect.

![Diagram of principal strain distribution](image)

Fig. 6. Distribution of the 1st principal strain in the axially symmetric model after 100 μs long current impulse for two different boundary conditions: free boundary (the upper image) and fixed constraint (the lower image).

Due to thermal expansion the crystals of martensite around the cementite “open” like wings and uncover the cementite particle in the case of free boundary and, alternatively, deform the cementite particle in the case of fixed constraint condition. As it is shown on Figure 5 the both cases result in the localized strain between these “wings” and lead even to formation of a very tiny void. Apparently, the void and magnitude of the strain depend on the parameters of the model, such as the ratio of conductivity of the area, the incoming current density, etc.

**Conclusions**

Several EM effects are described and analyzed in our work in order to evaluate the level of mechanical stress produced by these EM effects. However, it is found that mechanical
stress caused by the most of these effects is small. Only resistivity heating and spark discharge can reach necessary value of few hundred MPa, which is sufficient to initiate WEA formation.

The created model of electro-thermal expansion of elements of steel microstructure demonstrated that different properties of cementite grains can provoke the significant deformations in microstructure of bearing steel up to appearance of nano-voids that can lead finally to white etching cracks under the rolling pressure.

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