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# Strain-induced martensite decay in bearing steels under rolling contact fatigue: Modelling and atomic-scale characterisation

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ABSTRACT

Martensite decay in bearing steels manifested as dark etching regions (DERs) under rolling contact fatigue (RCF) is modelled. The proposed model is established based on a dislocation-assisted carbon migration mechanism. The proposed model is capable of predicting the progress of DER formation and the corresponding mechanical property evolution with increasing number of cycles, in good agreement with the experimental data reported throughout seventy years. The effects of RCF testing conditions on DER formation are studied and a useful tool, DER% maps, is developed for illustrating the temperature, contact pressure and number of cycles for DER occurrence. Moreover, an atom probe tomography study is carried out, revealing the nature of DER ferrite and obtaining strong evidence supporting the postulated DER formation mechanism. The successful application of the dislocation assisted carbon migration mechanism to DER formation provides a plausible explanation to the phenomenon of martensite decay under rolling contact fatigue.



## 1. Introduction

Bearings are important engineering components to deliver rotational loads. High carbon martensitic steels are most frequently used for bearing applications to meet harsh serving environments, including high contact pressures, high rotational speeds and sometimes elevated temperatures [1]. However, after a high number of stress cycles, microstructural alterations occur in the material, signalling the onset of rolling contact fatigue (RCF) [2,3]. One of the key microstructural alterations is the decay of martensite manifested as dark etching regions (DERs). DERs are formed at the subsurface of bearing inner rings, and the occurrence of DERs is an implication of microstructural instability [4]. As the name indicates, DERs display a dark contrast under optical microscopy (OM) after etching with nital when they are studied in either the axial section or the circumferential section of a fatigued bearing inner ring (Fig. 1(a)). Fig. 1(b) shows a DER observed in the axial section. The formation of DERs is detrimental as the resultant microstructure exhibits lower hardness than the parent martensite [5–11] and consequently becomes less resistant to cyclic loading.

First observed by Jones in 1946 [12], the microstructure of DERs was described as “mechanical troostite”, which was later confirmed to be ferrite by electron diffraction analysis [13–15]. Actually, a DER consists of dark patches distributed in the parent martensite matrix, with the former gradually consuming the latter with increasing the number of stress cycles. Given that the solubility of carbon in ferrite is only 0.02 wt% [16], the question arises as to the whereabouts of the excess carbon when such martensite-ferrite transformation occurs. Therefore, describing the carbon redistribution process during DER formation becomes the key to understanding such martensite decay. Although having been discussed for several decades, a plausible formation mechanism for DERs is still unavailable. Some authors [5,6] argued that DERs formation results from the over-tempering of martensite, and the fact that DERs have never been observed in the fatigued bearing samples initially tempered to a hardness of around 700 HV [13,17] supports this argument. However, the operation temperatures of bearings, which are usually lower than 100 °C, are not sufficiently high to thermally activate the growth of carbides [18], and there is no evidence showing distinct temperature rise in DERs caused by cyclic stressing. Besides, Bush et al. [5] found threshold contact pressures below which DERs were never formed, indicating the essential role

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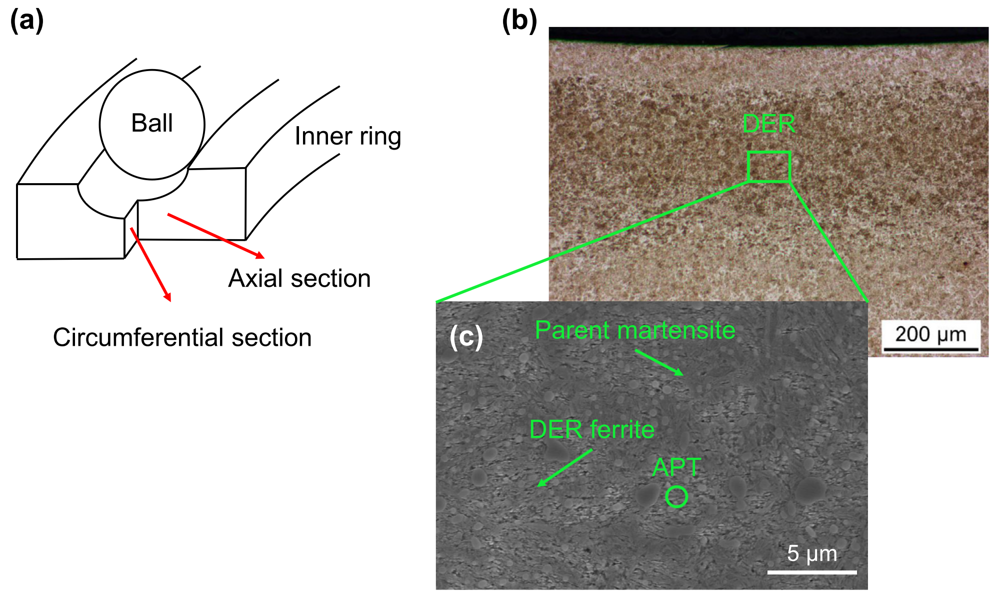


**Fig. 1.** (a) Schematic showing the circumferential and axial sections of a bearing inner ring. (b) OM image of a DER observed from the axial section. (c) Secondary electron (SE) image of the DER showing the location where the APT specimen was prepared.

played by stress. Moreover, the depth range where a DER is formed is considered to be related to the stress state of Hertzian contact, although there is still in disagreement as to the stress component responsible for such phenomenon with some authors [15,19] arguing it is the maximum shear stress, others [13,20] that it is the 45° shear stress, the orthogonal shear stress [5,6] or the von-Mises stress [9]. Nevertheless, it was experimentally proved [15] that increasing either contact pressure or operation temperature can accelerate DER formation. As for the carbon distribution in DERs, Swahn et al. [8] postulated that the excess carbon resides at dislocations and the cyclic stress somehow promotes the carbon migration, but this requires an unrealistically high dislocation density of $10^{17}$ m$^{-2}$ contradicting the observation of hardness decrease in DERs, which apparently implies a carbon depletion in the matrix. Recently, Kang et al. [19] postulated a more plausible mechanism, stating that during DER formation the excess carbon migrates to pre-existing carbide precipitates with the assistance of gliding dislocations thickening them; the model managed to explain the material softening in DERs but failed to accurately describe the effects of temperature, rotational speed and contact pressure. In this context, a dislocation-assisted carbon migration theory was suggested by a recent study [21] to describe the precipitation of lenticular carbides (LCs) in rolling contact fatigued bearing steels, which can also be applied to describe the thickening of pre-existing carbide precipitates in DERs.

In this work, a novel DER formation model is established based on the dislocation assisted carbon migration theory, and the predicted results are compared with experimental measurements from both this research and the literature. As for the characterisation of DERs, studies [22,23] on white etching areas have shown atom probe tomography (APT) to be a powerful tool to reveal carbon redistribution in rolling contact fatigued bearing steels. Therefore, APT is also performed on DER ferrite specimens.

## 2. DER formation model

Prior to RCF testing, the initial microstructure of bearing steels, as schematically illustrated in Fig. 2 (c), is tempered martensite, containing a large amount of nano-sized precipitates, namely temper carbides, evenly distributed within a martensitic matrix supersaturated with carbon [24]. Hence, from a thermodynamic point of view, carbon in solid solution tends to migrate towards the precipitates for their further growth, but the kinetics are suppressed at usual bearing operation temperatures due to insufficient carbon diffusivity. However, this process can be reactivated if a dislocation-assisted carbon flux is present. It is believed that the microstructural alterations in bearing steels occur at the plastic shakedown stage of RCF where a steady state plastic flow is present [25]. According to the analysis in Ref. [21], gilding dislocations can drag the Cottrell atmospheres formed around them and generate a carbon flux owing to the unique stress history of rolling contact. Such dislocation-assisted carbon flux is schematically shown in Fig. 2 (a) and (b), where the time interval $t_c$ between neighbouring stress pulses allows for carbon to migrate back towards those dislocations that just moved for $\Delta L$ to form Cottrell atmospheres. The magnitude of such carbon flux ($J_d$), referring to [21], is given by:

$$J_{\rm d} = \frac{\Delta\gamma\dot{N}}{b}\left[3\left(\frac{\pi}{2}\right)^{\frac{1}{3}}\left(\frac{AD}{kT\dot{N}}\right)^{\frac{2}{3}}C_{\rm Vm}\right], \quad (1)$$

where $\Delta\gamma$ denotes the plastic shear strain amplitude within each stress cycle, $\dot{N}$ denotes the rotational speed, $b$ denotes the magnitude of Burgers vector, $A$ denotes the interaction energy between a carbon atom and a dislocation strain field, $D$ denotes the diffusion coefficient of carbon atoms in body-centred cubic iron, $k$ denotes the Boltzmann constant, $T$ denotes the temperature and $C_{\rm Vm}$ denotes the carbon concentration in the matrix per unit volume.

The dislocation assisted carbon flux can contribute to the kinetics of precipitate thickening, leaving a carbon depleted matrix which eventually transforms into DER ferrite. Hence a DER formation model can be established. As shown in Fig. 2 (d), a temper carbide is taken as a thin plate with a half width $r_p$. This morphology was detected by transmission electron microscopy [24,26] and was used in previous modelling work on bearing steels [19]. The carbide precipitate can be thickened from its both sides, and thereby at the proceeding interface on each side, a carbon flux equilibrium can be obtained as: