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Modelling and characterisation of stress-induced carbide precipitation in bearing steels under rolling contact fatigue

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ABSTRACT

The nucleation and growth of lenticular carbides (LCs) in bearing steels occur near to deformed ferrite bands after exposure to prolonged rolling contact fatigue (RCF). Since the first observations in 1947, a large number of attempts have been made to explain the formation mechanisms of such stress-induced microstructural alterations, but a reliable model was still not available. In this research, a novel theory is proposed to describe the carbon redistribution process during LC formation. The theory suggests a dislocation assisted LC growth mechanism on the basis of the classic Cottrell atmosphere formation theory. The mechanism considers (1) $J_{LC} = J_d$, the carbon flux equilibrium between LC thickening (J_{LC}) and dislocation-assisted carbon migration (J_d), and (2) $M_0 = M_{LC} + M_b$, the carbon mass conservation of the system, where M_0 denotes the total amount of carbon within the system, M_{LC} denotes the amount of carbon within a LC, and M_b denotes the amount of carbon left within the ferrite band, respectively. The solution to these two equations, which addresses the problem that has been puzzling researchers for several decades, makes good predictions on LC thickening rate under various testing conditions. The stress-induced carbide precipitation was examined using high resolution characterisation techniques such as scanning and transmission electron microscopy, obtaining significant evidence to support the postulated theory. The successful description of LC growth implies a potential extension of the theory to other types of stress induced microstructural changes in bearing steels where carbon redistribution occurs. The model presented here provides a more comprehensive understanding of RCF from a microstructural point of view, and thus can enhance the accuracy of traditional bearing life prediction approaches.

1. Introduction

Material instability of bearing steels under rolling contact fatigue (RCF) is manifested by the appearance of microstructural alterations, which alter the mechanical properties of the steel, diminish the capability of the material to sustain load, create favourable conditions for crack nucleation and propagation and lead to the final failure of the component [1,2]. One of the most striking alterations is the formation of plate-like lenticular carbides (LCs), adjacent to which are ferrite bands (Fig. 1 (b) and (c)). These microstructural features can be revealed by nital etchant, exhibiting white contrast to the surrounding matrix under visible light and usually being referred to as white etching bands (WEBs) [3–7]. Under normal RCF testing conditions, WEBs starts to appear at very late stages of a bearing life, i.e., > 10^8 cycles, but it has been experimentally proved [8] that increasing either contact pressure or operational temperature can significantly accelerate the development of WEBs. Some authors [3,5,6] argued that prior to the nucleation of WEBs, the formation of a dark etching region (DER), another type of microstructural alteration resulting in martensite decay, is necessary, although experimental evidence shows that WEBs can occur in the absence of a DER when the parent martensite is softened by tempering to 670 HV [9]. The region where WEBs form, the subsurface of a bearing inner ring, has a strong correlation with the region of maximum shear stress as predicted by Hertzian theory [10], suggesting that the formation of WEBs is stress-induced, despite the fact that temperature also plays an important role [11]. Additionally, the special directionality of WEBs (shown in Fig. 1 (b)) is believed to be related to the local stress state [12,13].

A fully developed WEB can be 50–60 μm in length and ~ 10 μm in width, while the thickness of a LC can reach 1 μm [7]. The

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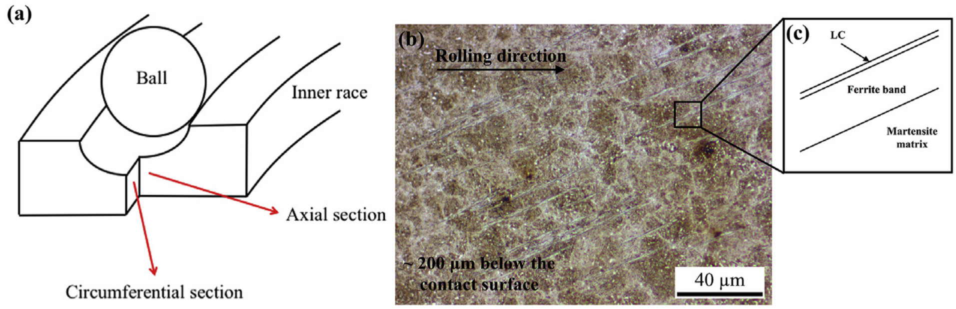

Fig. 1. (a) Circumferential and Axial sections of a bearing inner ring. (b) Optical microscopic image of the circumferential section of a bearing inner ring, where WEBs are formed at the subsurface with an inclination angle of $\sim 30^\circ$ to the rolling direction. (c) Schematic showing the structure of a WEB consisting of a ferrite band and a LC adjacent to it.

presence of LCs is detrimental to the RCF resistance of the material as the interfaces between the LCs and the matrix were proved to be weak planes that may initiate damage when subjected to loading [4]. The ferrite bands, on the other hand, are produced by strain localization where carbide dissolution is found at their interiors [9,14]. Moreover, microindentation tests indicate material softening in the deformed ferrite [6,14], which is generally believed to be a consequence of carbon depletion by precipitating LCs at the boundaries [15]. With increasing number of cycles (N), both LCs and ferrite bands thicken [7]. Therefore, the formation of WEBs can also be regarded as a process of carbon redistribution under RCF. However, it has been debated for decades as to the driving force for such carbon migration. The early theories [4,9,16] suggesting the microstructural changes result from tempering due to local temperature rise at the subsurface have no evidence to support. Moreover, the finding of the threshold stresses under which no microstructural change occurs, no matter how long the bearing operation time is, supports a stress-induced mechanism [5]. Bush et al. [5] referred to the fatigue of aluminium alloys and postulated a material extrusion-intrusion theory, where the importance of spherical carbide shearing is emphasized, to explain the origination of LCs. Besides, Swahn et al. [3] argued the energy increase caused by plastic deformation is the driving force for carbon flowing towards the surrounding matrix. Buchwald and Heckel [7] presumed the outflow of carbon from ferrite bands to LCs results from both carbon concentration and stress gradients, and for the first time put forward a quantitative model to calculate the thickening rate of LCs based on this theory. However, the results demand a temperature rise of at least 200 °C to achieve the observed growth rate, which is unrealistic. After that, Polonsky and Keer [13] argued that carbon injection into the solid solution during dislocation annihilation promotes the carbon leaving ferrite bands and postulated a diffusion-based mechanism, yielding better predictions on Buchwald and Heckel's data [7]. Nonetheless, Polonsky and Keer's model is rather approximated and the effect of applied stress was not taken into consideration despite the experimental evidence that increasing contact pressure accelerates WEB formation [8]. In this context, focus should shift to the rearrangement of dislocations in ferrite bands, although this was previously seldom considered to be related to the redistribution of carbon. This is because: (i) the ferrite bands stem from plastic deformation and may contain a high number density of dislocations; (ii) the strain fields around dislocations can attract carbon atoms as pointed out by Cottrell and Bilby [17], and thus result in a strong interaction between carbon in solid solution and dislocations; (iii) the cyclic loading of bearing operation generates a large amount of dislocation gliding, which can be the source of the driving force for carbon migration. Briefly speaking, the most likely mechanism for LC formation is that the gliding dislocations act as vehicles transporting carbon atoms to the band-matrix boundaries and precipitate LCs. Therefore, in this work, a dislocation-assisted carbon migration process is postulated to predict LC growth. The model is compared with experimental observations under various conditions. In addition, high resolution characterisation was carried out on WEBs to investigate the redistribution of carbon.

2. LC thickening model

2.1. Dislocation assisted carbon migration theory

When subjected to cyclic loading, a bearing inner ring experiences stress pulses with a period of t_c when the balls roll over. Such stress history is schematically illustrated in Fig. 2. Within each stress pulse, if the local stress exceeds the threshold for dislocation movement, the dislocations will be pulled away from their original carbon atmospheres, glide a distance and then come to a stop until the advent of the next stress pulse after t_c. Therefore, dislocation glide in each stress cycle is discontinuous, and t_c is the time interval for carbon in the surrounding matrix to return back to a dislocation that just moved, forming again a Cottrell atmosphere around it. According to Cottrell and Bilby [17], the total number of carbon atoms (n_C) that can be captured by a free dislocation per unit length can be expressed as:

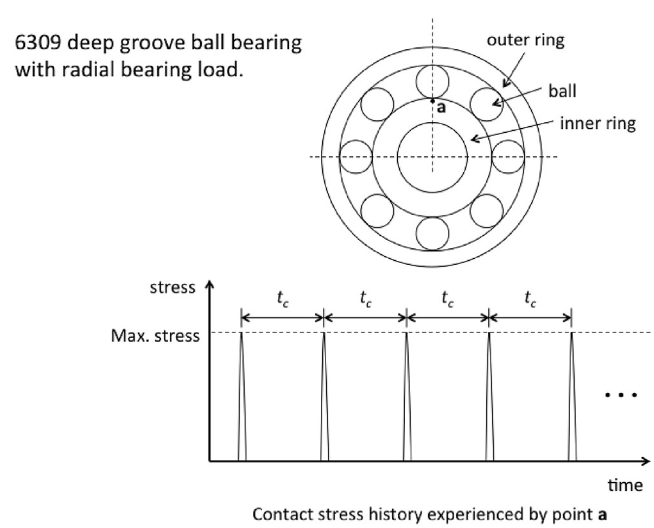

Fig. 2. Schematic of a 6309 type bearing geometry and the loading history experienced by a subsurface point during bearing operation. t_c is the time interval between each stress cycle.