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Investigation on butterfly white etching area formation mechanism and crack source at different stages in M50 bearing steel

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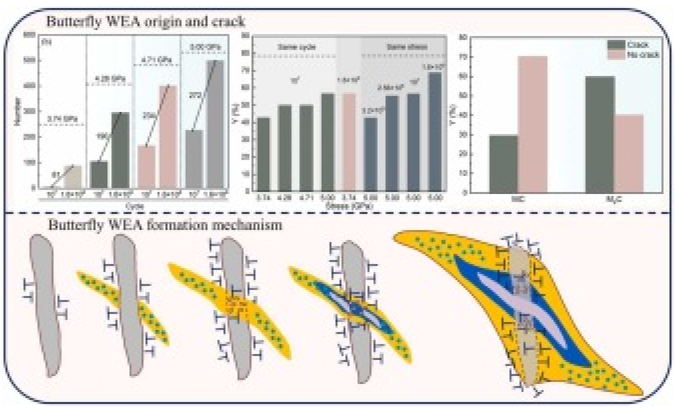
Highlights

- The evolution of butterfly WEA in M50 bearing steel has been studied under different stresses and cycles.
- A new detailed formation mechanism of butterfly WEA is proposed.
- The structural transformation of butterfly WEA is prior to cracks.
- M_2C carbides are more likely to cause butterfly WEA and cracks.

Abstract

Rolling contact fatigue tests with different stresses and cycles have been conducted to study the formation mechanism and crack source of butterfly white etching area (WEA) in different stages of M50 bearing steel. The results suggest that the structural transformation is prior to cracks. The initial microstructure is the nanocrystalline α-Fe formed by dislocation assisted carbon migration. With the extension of cycles, unlike the previous studies, the butterfly-origin carbide is refined into Mo_2C and M_7C_3 nanocrystalline by the accumulated dislocation clusters. Subsequently, the increase of interfacial energy drives the metal elements diffusion and thus the formation of amorphous structures. A new mechanism called diffusion-assisted dislocation has been proposed for butterfly WEA formation.

Graphical Abstract



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Introduction

In aircraft engine, the main shaft bearings are subjected to increasingly severe mechanical wear and rolling contact fatigue (RCF) due to high thrust-weight ratio and high load [1], [2], [3]. Therefore, in order to improve the bearing performance and extend its service life, exploring the potential failure mechanism of the bearing has become the focus of attention. M50 steel is the most popular steel for aero-engine bearing. During the RCF, the microstructure evolution, and crack formation in the subsurface of M50 steel are strongly associated with the final bearing failure[4]. For example, butterfly white etching area (WEA), which usually form in the early stage of RCF, are favorable locations for the cracks. The cracks are linked together to form crack networks, eventually failure, which is extremely disadvantageous to the bearing life [5]. The formation mechanism of butterfly

WEA, including the grain refinement, the complex interaction between stress and microstructure evolution, remain elusive. In recent years, most investigations on the subsurface microstructure alteration have been dominated by AISI52100 steel [6], [7], [8], [9], while the research on M50 steel is still lacking, therefore, it is urgent to understand the subsurface microstructure evolution mechanism of M50 steel during RCF.

The butterfly, which has been studied for several decades [10], begins with an initiating defect in the subsurface layer, surrounded by an altered microstructure known as white etching matter (WEM) or white etching area (WEA) [11]. These initiating defects can be non-metallic inclusions [11], voids [12], large carbides [13] or other factors. The designation is based on the unique butterfly shape and the white appearance resulting from high resistance to etchants under the optical microscope after corrosion [14]. Many studies and have proposed that cracks are a prerequisite for the formation of butterfly WEA, and repeated friction between crack surfaces would induce microstructure changes [15], [16], [17], [18]. However, Li et al. [19] questioned this theory. They believed that the formation of butterfly WEA required sufficient energy for grain refinement. The energy generated by friction between crack surfaces would also be consumed in the form of wear debris. Therefore, the friction between crack surfaces was not enough to provide sufficient energy for the generation of butterfly WEA. Despite extensive research, the sequencing relationship between cracks and butterfly WEA still remains highly controversial. Different with the AISI52100 steel, where butterfly WEA mainly originates from inclusions [20], M50 steel eliminates most inclusions through the double vacuum smelting method of vacuum induction melting and vacuum arc remelting. Therefore, the coarse primary carbides have become the main origin of butterfly WEA [13], [21]. However, due to the high alloying element content, complex carbide types and compositions makes it more challenging to study the origin of butterfly WEA and crack in M50 bearing steel [22]. Currently, there is still a lack of systematic research on the subject.

In recent years, many researchers have investigated the important role of carbon in the formation of butterfly WEA. By dissecting the inner ring of AISI52100 deep groove ball bearing, Curd et al. [23] found that there were both carbon-rich and carbon-poor regions in butterfly WEA relative to the matrix, and attributed this difference to the different lattice defects at different locations of butterfly WEA. Curd et al. [24] then further expounded the carbon distribution in the butterfly WEA of 18NiCrMo14–6 and AISI52100 steel, and confirmed that the total carbon content of butterfly WEA was lower than that of the matrix for both materials, but there was no obvious carbon enrichment in the matrix near WEA, then where does the carbon diffuse remains a problem. However, Li et al. [25] previously observed the butterfly WEAs of AISI52100 bearing steel through atom probe tomography

(APT), the results showed that the carbon concentration in WEA was higher than that of the matrix and the phenomenon was considered to the carbide dissolution caused by deformation. In addition to carbon, Kang et al. [26] unexpectedly found that the Cr concentration had a slight change in the butterfly WEA. Similarly, Morsdorf et al. [27] thought that crack surfaces would reweld during contact based on the anisotropic redistribution of Cr elements in butterfly WEA, and then proposed the formation mechanism of WEA. It can be seen that the distribution of elements plays an important role in the microstructure change of bearing steel. However, for M50 steel, the influence of C and other alloying elements in carbides on butterfly WEA has been less studied.

Until now, researchers have generally believed that the butterfly WEA is equiaxed nano-crystalline with ferrite grains ranging in size from 10 to 300 nm [7], [28]. However, Evans et al. [11] found that both nanocrystalline and amorphous structure existed in WEA, but the cause of amorphous structure was not clearly explained. In the latest study, Wang et al. [29] verified that the butterfly WEA was a mixed nanocrystalline structure of body-centered cubic (BCC) and face-centered cubic (FCC). The above studies are all about a certain stage of the butterfly WEA formation. In order to further study the structure and formation mechanism of butterfly WEA, the exploration from the initial formation stage to the development process is still an unresolved problem. Meanwhile, most literatures study the microstructure and element distribution separately, and we believe that it is very necessary to combine the two aspects.

This paper focus on the analysis of microstructures of the butterfly WEA at different formation stages using SEM, EBSD, TEM to elucidate the formation and evolution mechanism after different stresses and cycles RCF experiments. At the same time, EPMA is used to analyze the chemical composition changes of butterfly WEA at different stages, elucidating the relationship between element migration and dislocation movement. Nanoindentation tests are conducted to examine the hardness of butterfly WEA, providing further evidence for their formation mechanism investigation.

Section snippets

Materials

The investigation of “butterfly WEA” in this study had been conducted on M50 bearing steel subjected to RCF testing on an MJP-15 ball-on-rod RCF machine. The M50 bearing steels were prepared via vacuum induction melting and vacuum arc remelting, after forging and annealing process, RCF specimens were extracted along the axis of the steel rod, and these specimens were machined into a small rod shape with a certain amount of finishing allowance. Afterwards, the specimens were austenitized at…

Microstructure

The typical microstructure of M50 bearing steel consists of plate and lath martensite with two types of primary carbides, as shown in Fig. 2. The back scattered-electron (BSE) image and maps of the elemental distribution are shown in Fig. 2(a–c). The two-type carbides show different contrast under BSE due to different elements content. Combined with the element mappings, the white carbide is Mo-rich called M_2C, the gray carbide is V-rich called MC. The morphology of two-type carbides is…

Carbide dissolution and butterfly WEA formation mechanism

Although the mechanism of carbide dissolution in pearlitic steel has been extensively investigated [35], [36], [37], [38], [39], [40]. It only begins to be attracted attention when a certain relationship between carbide dissolution and WEA formation is accidentally found after RCF in bearing steel [6], [11], [25], [26]. According to our study, two phenomena are closely related.

Two prevailing interpretations are available for the decomposition of carbide, namely mechanical deformation induced…

Conclusions

In this paper, the evolution mechanism and crack source of subsurface butterfly WEA in M50 bearing steel has been studied with different stresses and cycles after RCF test. The microstructure characteristics of butterfly WEA at different stages have been analyzed in detail by SEM, TEM, EBSD and nanoindentation technique, and the element diffusion accompanying the butterfly WEA development at different stages has been also analyzed by EPMA. The main conclusions are summarized as follows:
1） The…

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CRediT authorship contribution statement

Yang Liqi: Writing – original draft. **Xue Weihai:** Writing – review & editing. **Cao Yanfei:** Formal analysis. **Liu Hongwei:** Visualization. **Duan Deli:** Conceptualization. **Li Dianzhong:** Resources. **Li Shu:** Methodology.…

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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Statement of Originality

The authors declare that this manuscript "Investigation on butterfly white etching area formation mechanism and crack source at different stages in M50 bearing steel" is original and is not under consideration for publication elsewhere, that its publication is approved by …

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