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"Brown etching layer": A possible new insight into the crack initiation of rolling contact fatigue in rail steels?

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A field sample of rail steel was metallurgically examined to characterize its rolling contact fatigue (RCF) damage. In addition to the well-known white etching layer (WEL), a possible different type of surface modification layer was identified in parallel. The layer has some similar features as the WEL but exhibits a significantly different etching response to 3 vol% Nital etchant. After etching, the new layer exhibits a brown color under the same light reflection. This layer was named as "brown etching layer" (BEL) to distinguish it from the WEL. Similar to the WEL, cracks are observed to be closely related to the BEL. The cracks are found to penetrate deeper than those initiated by the WEL reported in existing publications. Further, they are found to propagate downwards without branching, which may eventually cause rail fracture. Although its formation mechanism is not yet clear, WEL has been considered by some authors in the literature as a possible RCF initiation source. It is therefore of critical importance to understand the characteristics of the BEL and its formation mechanism. This may also lead to better understanding of the formation mechanism of the WEL. To this end, microstructural features of the BEL were studied using micro-hardness tests, optical microscopy and scanning electron microscopy. The BEL was found to be distinctly softer than the WEL and lamella-type features are found within the BEL. The microstructural features of the BEL were compared with the WEL reported in the literature. Finally, the formation mechanism of the fatigue damage was discussed based on the comparison, observations and material characterization.
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1. Introduction

After multiple wheel-rail interaction cycles, a type of microstructural alteration called the white etching layer (WEL) usually forms at the surface of the rail, accompanied by severe plastic deformation and an increase in hardness and wear resistance [1–5]. The WEL is so named due to the higher etching resistance to Nital etchant (2–10 vol% HNO_3 in ethanol), therein producing a white color under unpolarized optical light reflection. The hardness of the WEL is significantly higher than that of the matrix pearlite microstructure and can be up to 1200 HV [1]. This hard and brittle surface layer has received substantial attention as it is considered by some authors as a possible cause of crack initiation of rolling contact fatigue (RCF) [1,6,7] and thus its influence on the service life of rail steels. Therefore, it is necessary to understand the formation mechanism of the WEL and develop corresponding methods for avoiding or mitigating WEL-based damage.

The WEL has been extensively studied by many researchers. Generally, two formation mechanisms are assumed possible for the WEL: 1) high temperature causing a martensitic phase transformation and 2) severe plastic deformation leading to strain-induced

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cementite dissolution and grain refinement, e.g., nanocrystalline ferrite with carbon supersaturation [8]. The first formation mechanism is generally attributed to the frictional heat generated by wheel/rail contact. When the temperature is sufficiently high to reach the austenitization temperature, followed by rapid cooling, a martensitic structure is formed together with possible retained austenite or undissolved cementite. This assumption was supported by Clayton and Allery [1], who noted that the WEL was produced by a short thermal process. By using the techniques of cross-sectional transmission electron microscopy (XTEM) and synchrotron X-ray diffraction, Österle et al. [2] characterized the WEL in rail steels under a specific loading condition, compared the microstructure and hardness with the WEL produced by laser treatment, and concluded that the WEL consisted of martensite with high dislocation density. Wild et al. [3] analysed corrugated rail materials with multiple experimental facilities, and the WEL at the corrugation crest was identified as martensite of nano-scale grain size containing cementite particles. Research by Wang et al. [4] detected retained austenite via X-ray diffraction (XRD) and further confirmed the martensitic nature of the WEL. Takahashi et al. [5] analysed the WEL with atom probe tomography and found that lamella thinning had not occurred in the WEL near the surface; in addition, they concluded that the WEL region did not undergo severe plastic deformation. Together with the prediction of the increased temperature via frictional heat, possibly to temperatures above the austenitization temperature and the shape analysis of manganese-enriched zones, they concluded that the WEL was formed by martensitic transformation.

The second explanation for the WEL concerns severe plastic deformation. Plastic deformation can cause cementite lamella alignment to the shear plane, fragmentation, and reduction in interlamellar spacing [9]. Under severe deformation conditions, this process facilitates the dissolution of cementite and promotes grain refinement [10,11]. The formation of the WEL is thus explained as a nanocrystalline microstructure mainly consisting of ferrite, together with not fully dissolved cementite in the form of fragmented lamellae or particles. Feller and Walf's research [12] revealed that the WEL formed in the rail is not martensite; rather, it is produced through the breaking of cementite into fine dispersed particles. The results obtained by Newcomb and Stobbs [13] using transmission electron microscopy (TEM) and transient temperature estimation indicated that the WEL is a severely deformed ferrite in which cementite is dissolved, in analogy to mechanical alloying that is well known as a low temperature process [14]. Based on investigations of the microstructure of the WEL using TEM and X-ray diffraction and on discussions of the nanostructure formation mechanism, Lojkowski et al. [10] concluded that the WEL is a nanocrystalline ferrite produced by cyclic heavy plastic deformation far below the austenitization temperature. Baumann et al. [11] investigated the WEL in corrugated rails and observed the WEL at corrugation crests, with a hardness of 1000 HV to 1200 HV. TEM analysis revealed a nanocrystalline structure with a grain size of less than 50 nm. Based on these observations, they claimed that WEL formation due to a temperature increase alone does not seem possible and indicated the possibility of the dissolution of cementite due to severe plastic deformation [11].

A recent work by Zhang et al. [15] indicated that the WEL is composed of deformed cementite lamellae as well as nanocrystalline martensite, austenite and cementite. Thus, the formation mechanisms of the WEL are complex. There is no single mechanism that can explain all WEL phenomena, i.e., under certain conditions, one mechanism might be dominant, whereas under other conditions, both mechanisms may be responsible [2]. As an alternative, a complete explanation of the WEL under a specific condition seems more feasible and realistic.

Our original intention was to investigate the damage of rail materials in the presence of corrugation. Similar to previous research [4,12], the WEL, as a type of rail surface damage, was observed using optical microscopy (OM). In addition to the WEL, a possible new type of microstructurally altered layer was recognized in the current investigation. The new layer appears as brown (rather than white, as is the case for the WEL) or as mixed white/brown colors after exposure to the same Nital etchant (see Fig. 3). Because it exhibits similar features as the WEL, such as distinct interfaces with the bulk material and the isolated or continuous distribution of "islands", this new type of layer was denoted as the brown etching layer (BEL) in analogue with the WEL. To the authors' knowledge, the BEL has yet to receive substantial attention despite having been reported in [10,16,17]. Note that on the one hand the observation of BELs in the aforementioned publications and in the present paper, with differences in traffic conditions, e.g. train speed and annual axle load, indicates that the occurrence of the BEL is not related to a specific traffic condition. On the other hand, there is insufficient evidence in the existing publications to correlate the BEL to a specific rail material. Compared to the previous reported BEL, the observed BEL in the present paper has shown different features that will be elaborated in subsequent sections. In addition to the microstructural morphology, the mechanical characteristics of the BEL, measured by a micro-hardness test, is also shown to be different from that of the well-known WEL. Considering that the mechanism for WEL formation is as of yet unknown, the discovery of the BEL arouses the authors' interest in determining the following: could an investigation of the BEL provide a possible better insight into the formation of the WEL? Moreover, cracks caused by the WEL usually grow with shallow angles with respect to the rail surface and eventually cause surface spalling [1,18]. However, a crack formed in front of the BEL and near the BEL and Int-1 has been found to grow considerably deeper into the less deformed or undeformed material, and the orientation of the crack tip is downwards without branching, which may produce rail fracturing at a certain stage. Therefore, the study of the formation mechanism of the BEL is of practical concern and importance. In this research, the microstructural features of the BEL are characterized using optical microscopy, micro-hardness tests, and scanning electron microscopy. This study is expected to provide an understanding of 1) the microstructural features and mechanical properties of the BEL, 2) correlations between the WEL and the BEL, and 3) the possible formation mechanism of the BEL.

2. Sample description and experimental details

2.1. Sample

The rail in this investigation was removed from a straight track in the Dutch railway network between Meppel and Leeuwarden. The track is a mainly passenger line, with a highest operating speed of 140 km/h. The line on average carried approximately

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