X-ray investigations of the natural and artificial White Etching Layer

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Keywords: White Etching Layer, WEL, high pressure torsion, HPT, X-Ray diffraction

Abstract. We analyzed X-Ray diffraction data on the White Etching Layer (WEL) excised from the surface of a railway track and WEL-like structures obtained by high pressure torsion of the same steel as the rail was made. Data analysis was performed by the whole-pattern fitting method. The railway WEL shows a clear asymmetry of the diffraction lines, which can be attributed to either tetragonal martensite structure or to the formation of a ferrite nanophase with a lattice parameters larger than that of the raw material. X-Ray patterns of the natural WEL were fitted with the two models. The quality of the fit clearly favors the model with two cubic phases over the model with a single tetragonal phase. Artificial WEL samples could be fitted with a single cubic phase model. Several alternative methods were simultaneously used to extract information on crystallite size and internal stress. The analysis of the natural WEL shows that the secondary cubic nanophase is formed of the crystallites of the average size of 8 nm essentially free of any strain. The lattice parameter 0.2881nm corresponds to the 0.26 wt.% concentration of the dissolved carbon. In the artificial WEL samples the crystallite size decreases down to 9 nm at the maximum shear stress of 430, while the internal strain gradually increases. There is however no change of the lattice parameter. This means that no carbon from cementite dissolves in the lattice of ferrite. It must therefore be located in the grain boundaries and dislocation cores. We conclude that the high pressure torsion produces a WEL with a different distribution of carbon than in the natural process of the WEL formation. It involves an immediate severe deformation the sample while natural process takes numerous subsequent cycles of modest deformation with simultaneous local heating of the deformation area. Such a process may lead to the gradual diffusion of the carbon atoms from the grain boundaries into the crystal lattice of ferrite.

Introduction

The structure of the White Etching Layer (WEL) forming on the surface of railway tracks and the mechanism of its formation still remains a matter of discussion [1-4]. We analyzed X-ray diffraction patterns of *natural* WEL from surface of railroad track, and *artificial* WEL-like structures obtained by high pressure torsion. The analysis was performed by the whole-pattern fitting method.

Natural WEL

The chemical composition of the rail steel sample was as follows: Fe, 0.6-0.8 wt% C, 0.8-1.3 wt% Mn, 0.1-0.5 wt% Si, 0.04wt% P(max), 0.04 wt% S(max). It was cut from a sector far from any stations, after 10 years of heavy exploitation [1,2]

The natural WEL shows clear asymmetry of the diffraction lines. It can be attributed either to tetragonal martensite structure or to the formation of a ferrite nanophase with a lattice parameters larger than that of the raw material. To determine the structure of the sample we fitted diffraction pattern with models corresponding to both possibilities. The whole powder data was fitted simultaneously with peak positions constrained by lattice parameters. In both cases the number of fitted parameters was the same, in particular there were two lattice parameters (in single tetragonal lattice or in two cubic ones).

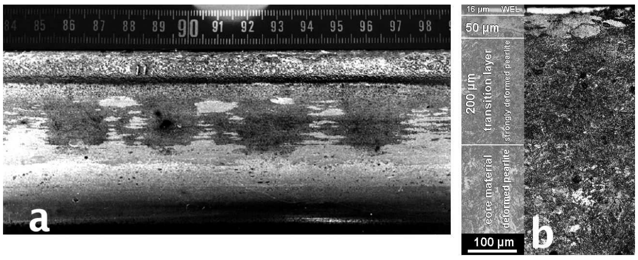

Fig.1. (a) Strongly corrugated surface of a rail with WEL (shiny areas). (b) Optical micrograph of the cross section of the rail sample. The thin white etching layer is seen, followed by a structureless layer and layers representing pearlite at different degrees of deformation.

The quality of the fit clearly favors the model with two cubic phases over the model with a single tetragonal phase (look at the magnified differences between data and models, shown at the bottom of fig. 2). Overlapping of peaks does not allow, with this statistics of data, to determine whether both phases are really cubic, but the presence of the second phase is certain. The lattice parameter of the nanocrystalline phase is 0.5% greater than the original lattice parameter and equals 0.2881(5) nm, what corresponds to a carbon concentration of 0.26 wt.%.

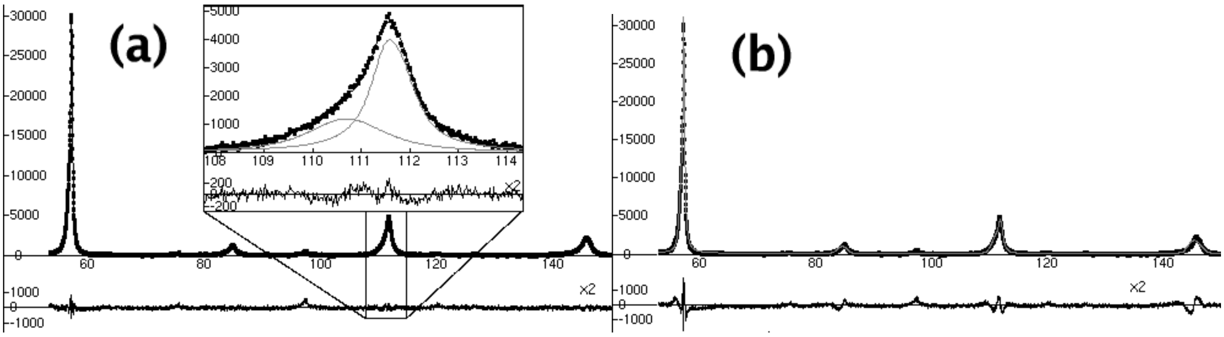

Fig. 2.The same diffraction pattern fitted with two models: (a) two cubic phases – asymmetric peaks are composed from two reflections, the left one (wider) represents nanophase; (b) one tetragonal phase – it is impossible to find a good fit.

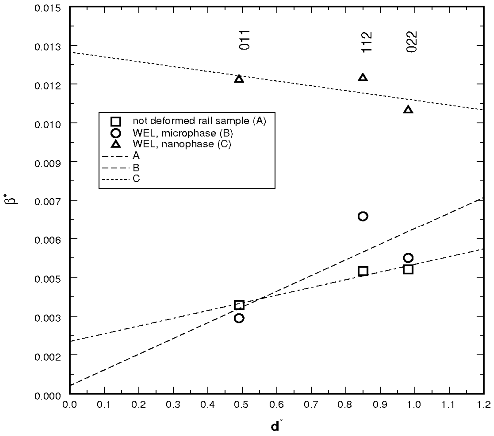

Fig. 3. Williamson-Hall plot.

Widths and shapes of reflections contain an information on lattice defects, such as finite crystallite size and internal stress. However, the influence of these defects on diffraction pattern is very subtle, and estimation of crystallite size and stress is usually very rough. We used a few different methods: *Williamson-Hall* method [5] and its derivative, called sometimes *Halder-Wagner* method [6], *double-Voigt* method – equivalent to *Warren-Averbach* [7], and less known $FW^{1}/_{5}{}^{4}/_{5}M$ method [8]. All of them show that the average size of crystallites in the nanophase is about 10 nm and the strain is negligible.

Artificial WEL

Samples from UIC 860V steel deformed in laboratory were investigated and compared with the natural WEL. Steel with the same chemical composition as the rail steel was treated by one of severe plastic deformation methods – high pressure torsion (HPT).

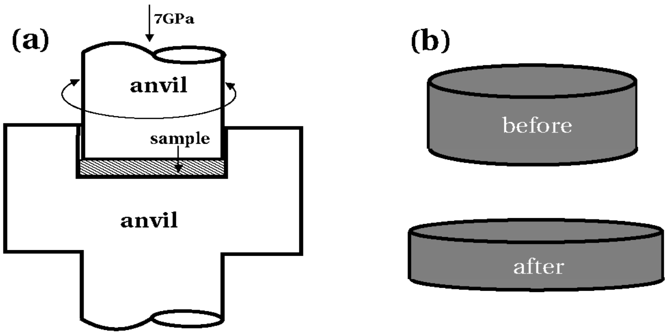

Fig. 4. (a) High pressure torsion was applied by turning one anvil at a speed of ω = 1rpm. There is no slip between the anvils and the surface of the samples. The shear can be estimated as $\gamma=2\pi RN/d\approx60N$. (b) Pancake deformation of the specimen caused by applied pressure. After 5 rotations of anvil and 5 min of pressure the width of washer decreased by 40%.

Washers of 0.3 mm thickness were cut out from a rod and were subjected to HPT strain under a quasi-hydrostatic pressure of 7 GPa by the method illustrated in fig. 4. Six samples with various degree of deformation, with shear strain γ from 0 (not deformed) to 300 (5 rotations), where analyzed. All the samples where cut from the deformed washers at a distance of 3mm from the center [2].

Properties of heavily deformed washer are similar to that of railway WEL – it is much harder then pearlitic steal and resistant to etching.

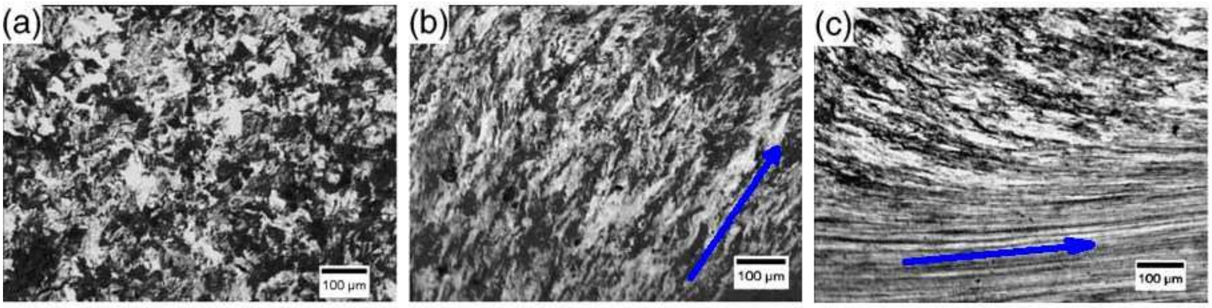

Fig. 5. Optical micrographs of the surface of the samples of the UIC 860 steel in the initial state and after the HPT deformation: (a) $\gamma=0$, $N=0$; (b) $\gamma=200$, $N=3$; (c) $\gamma=300$, $N=5$. The arrows show the shear direction.

It was possible to fit diffraction patterns of artificial WEL samples with a single cubic phase model. The crystallite size decreases down to about 10nm at the maximum shear stress of 300, while the internal strain gradually increases (fig. 6).

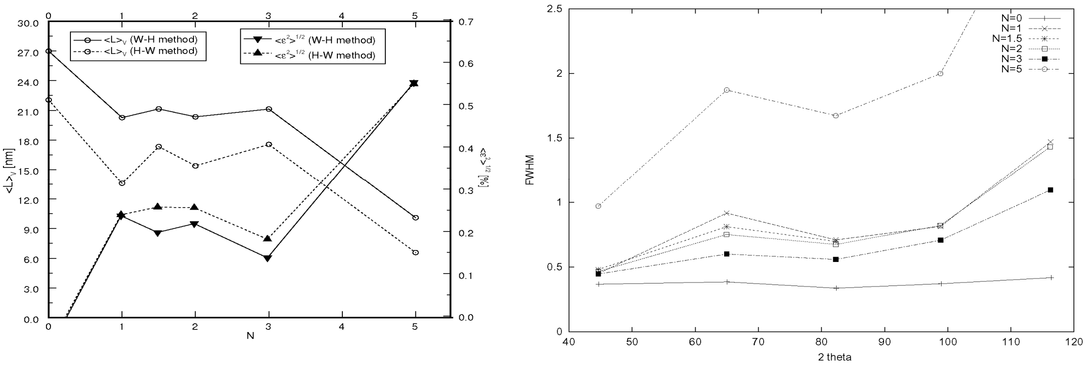

Fig. 6. (a) Coherent domain size and internal lattice strain as a function of number of anvil rotations, determined by two methods: Williamson-Hall and its modification (sometimes called Halder-Wagner). (b) FWHM (Full Width at Half Maximum) of peaks as a function of diffraction angle.

The change of the lattice parameter is less than 0.0003 nm. This means that less than 0.06 wt.% of carbon from cementite can be uniformly dissolves in the lattice of ferrite. On the other hand the cementite, as measured using thermomagnetic method, completely disappears after $\gamma = 300$. Therefore the carbon from cementite must be located in the grain boundaries and dislocation cores.

Conclusions

The high pressure torsion is able to produce a material with properties similar to the WEL formed on the surface of railway tracks. A nonstructure with dissolved carbides is formed. However, the distribution of carbon in the matrix is different in each case. In the case of WEL excised from railway tracks, carbon is dissolved in the lattice causing its distortion, leading to formation of a ferrite nanophase with lattice parameters larger than that of the raw material. On the other hand, during high pressure torsion the carbon dissolves most likely at grain boundaries and dislocation cores. The difference in structure can be attributed to the differences in the deformation mode. HPT involves an immediate severe deformation of the sample while natural process takes numerous subsequent cycles of modest deformation with simultaneous local heating of the deformation area. Such a process may lead to the gradual diffusion of the carbon atoms from the grain boundaries into the crystal lattice of ferrite.

Acknowledgments

European Commission grant No. ICA1-CT-2000-70005), the Polish State Committee for Scientific Research under contract PBZ:KBN-013:T08:30 and the Polish–German cooperation project POL 01/051.

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