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White Layer in M76 High Carbon Rail Steel: Formation Mechanism and Properties

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ABSTRACT

High-frequency vibrations resulting from many factors under loads existing in the wheel-rail system have a huge impact on the structure and properties of rail steel: there are significant contact stresses in the surface layer that affect strength characteristics and overall fatigue of the railway track structure. Such an impact results, in particular, in the formation of the so-called White Layer (WL): a hardened layer on the surface of the base material, resistant to chemical etching, and having high hardness (above 1000 HV) and brittleness.

The objective of the research was to study the features of the formation mechanism, as well as the properties of the white layer formed on the metal surface using an integrated approach, namely, of destructive testing methods, electron microscopy, XRD, metallography, and microhardness measurements.

The reliability of experimental studies is due to the use of standardised test methods, developed methods of destructive and non-destructive testing in the main areas, the involvement of an accredited and certified laboratory, which makes it possible to fulfill in full the tasks set with appropriate quality.

The results of the research allowed to present an analysis of the white layer, the formation of which took place in high-carbon M76 rail steel after cyclic tests with a 20 kHz frequency. The morphology, phase composition, and microhardness of these inclusions have been studied in detail in comparison with the base metal. It is shown that the white layer is highly dispersed, pearlite-like, featureless inclusions of a ferrite-cementite structure, while their microhardness is 3–4 times higher than the original steel and is of 1000–1200 HV. A possible explication of a mechanism of the formation of a white layer is suggested: crushing of ferrite and cementite, which are part of pearlite, without intermediate phase transformations.

Keywords: *railways, high carbon steel, high frequency vibrations, cyclic tests, white layer, microstructure, microhardness, diffractogram, diffraction pattern, pearlite structure, rails.*

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INTRODUCTION

Nowadays, railways are one of the most dynamically developing transport industries worldwide due to relatively low air pollution per passenger as compared to cars and high velocities attainable by modern trains. Movement speed of railway transport is continuously increasing. If velocity of 300–350 km/h has been considered as high speed recently, now high-speed trains in some countries can move at 600 km/h, while on Russian railways the highest speed is 400 km/h. Unfortunately, the higher is train speed, the higher are the vibrations and noise associated with it that are considerable even at ordinary railways[1–6] and may reach the ultrasonic level [7]. Main source of the high-frequency vibrations is the wheel impact at junctions and irregularities of rails (such as roughness, waving, etc.) that respectively may have different origins. The impact and frequency spectrum may correspond to the ultrasound range 10–50 kHz.

The nature of the influence of the ultrasonic vibrations on the structure and properties of rail steel is a topical issue studied by many researchers worldwide [8–12]. It was revealed that the process of demolition as well as mechanical characteristics of the object exposed to ultrasonic vibrations are distinct from standard conditions.

According to[13], emergency derailment of high-speed trains in Germany and England were caused by 10^9 cycles of stress accumulated in a wheel due to irregular surface of the rails (roughness). Preliminary tests showed that high frequency vibrations occurring under such loads in a «wheel–rail» system impact heavily on structure and properties of the rail steel. There appear considerable contact stresses in the surface layer affedting mechanical characteristics and total fatigue of the framework. Particularly, such an exposure leads to formation of the so-called white layer (WL), which is a strengthened layer on the surface of the main material characterised by higher resistance to chemical etching, increased hardness (above 1000 HV) and brittleness [14–19].

White layer is considered as a nanocrystalline martensite [14]. It is still arguable, whether largely distorted but still crystalline austenite yields martensite or it is the result of crystallisation of absolutely structurally degenerate (amorphous) material. Authors in [15–17] claim that WL formation is preceded by mechanical and thermal treatment as well as by other operations of tool manufacturing from carbon alloyed hardened steel, high-strength cast iron, and from other alloys. WL structure consists of fine martensite needles, residual austenite, and sometimes contain low-sized carbides with the wear-resistance of WL increasing with carbon content in it.

According to the authors of [18–19] the most frequent cause of WL formation is mechanical treatment. When temperature near the treated surface exceeds the temperature of α–γ transition, martensite formed via friction can give rise to WL observed in the microstructure. Paper [18] reports on WL hardness ranging at 12,85 ± 0,80 GPa that is considerably higher than in untempered martensite obtained under various thermal treatment conditions. WL grain size was shown to lie within submicron scale spanning from 30 to 500 nm. These two WL characteristics make it distinguishable from a plethora of structures formed in steels by thermal treatment.

WL was found on the surface of railway rails as reported in [20]. Two samples of rails of high-speed railway were object of research. They were produced by the means of hot rolling followed by cooling in air from respectively S54 (0,6–0,8 wt.% C, 0,8–1,3 wt.% Mn) and UIC60 (0,55–0,75 wt.% C, 1,3–1,7 wt.% Mn) steels. Total load on the first and second rails was $3.8 \bullet 10^6$ and $360 \bullet 10^6$ tons, respectively. Hardness of the surface layer was revealed to increase to 10–12 GPa due to ultrafine structure along with solid-solution and disperse strengthening mechanisms. Both cases yielded layered structure, namely, WL consisting of ultrafine ferrite (mean grain size ~200 nm) structure and cementite with low- and high-angle grain boundary misorientation; deformed perlite was also present. There are morphological changes of cementite in WL: fragmentation of carbide's platelets down to fine particles and partial dissolution of Fe_3C.

Industrial high carbon (1,0 wt.% C) steel was chosen as an object for study in the paper [21]. WL was formed after shock tests with falling steel balls due to large heat dissipated on contact and severe plastic deformation, which yielded temperature high enough for austenite-martensite phase transition on one hand, and formation of new austenite grains at heating of martensite phase in the field of austenite phase on the other. Finely dispersed martensite featuring intensive deformation was clearly observed on a microscale. Nanosized equiaxial grains were found inside WL. Distorted regions exhibit a transition from plastically deformed grains to recrystallised structure with round-shape finely dispersed grains.

The *objective* of this research is to study formation mechanism and properties of white layer occurring on rail steel as a result of high frequency vibrations

METHODS

The research was conducted through an integrated approach, using, namely, destructive testing methods, electron microscopy, XRD, metallography, and microhardness measurements.

To achieve the objective of the research, the following methods were, particularly used:

• A method of accelerated high-frequency tests, which, on the one hand, simulates real operating conditions: simulation of high-frequency vibrations that occur in the wheel-rail system during train movement; and makes it possible to obtain the durability characteristics of the materials under study ten times faster than standard method. The originality of the proposed method lies in the fact that there is no generally accepted method of high-frequency testing, which makes it unique.

• A method of comprehensive structural analysis is based on electron microscopy, phase analysis, metallographic and mechanical studies, which allow to fully assess the structural state of the material, identify the places of possible destruction, the centres of destruction and its causes. The originality of the proposed method lies in comprehensive assessment of the structure and identification of factors that precede destruction, which makes it possible to conduct research at various stages of operation of the elements of the track superstructure.

These studies are conducted at the facilities of a testing laboratory accredited and certified in the systems of the Federal Service for Environmental, Technological, and Nuclear Supervision, Federal Service for Accreditation (National accrediation system), Russian Maritime Register of Shipping, which ensures the quality of the work performed.

EXPERIMENTS

Samples made of M76 rail steel were selected as objects of study. The first object: «Rail No. 1», type R65, heat strengthened of T1 category. It was relaid from the straight track of the main line of Bakovka–Odintsovka section (Moscow region) to the receiving and departure track. Accumulated tonnage passed by it is of 600 million gross tons. Second object: «Rail No. 2», type R65, heat strengthened by DT350 process, accumulated tonnage passed by it is of 400 million gross tons. It was removed from the second main track of Dolgoprudny–Lobnya section (Moscow region). The chemical composition of M76 rail steel samples is shown in Table 1.

Fatigue tests were carried out using Shimadzu USF-2000 ultrasonic device at 20 kHz frequency. Sandglass-shaped samples were prepared for fatigue tests with the help of a metal turning lathe as shown in Pic. 1a.

High-frequency load experiments revealed white layer on the samples. Samples (microsections) were prepared for metallography by etching via dipping them for 4–5 min into the mixture of 2 vol.% salicylic acid and 70 vol.% ethanol.

The microstructures of the samples were analysed with an Eclipse MA200 (Nikon, Japan) inverted metallurgical microscope, and Ultra Plus (Carl Zeiss, Germany) scanning electron microscope The phase composition was studied by X-ray diffraction (XRD) using an Bruker D8 Advance diffractometer (CuKα, $2° < 2\theta < 90°$), ICDD PDF2–2004 database, and CMPR software [22]. Mechanical characteristics of the samples were studied with an automatic HMV-G-FA-D (Shimadzu, Japan) microhardness tester.

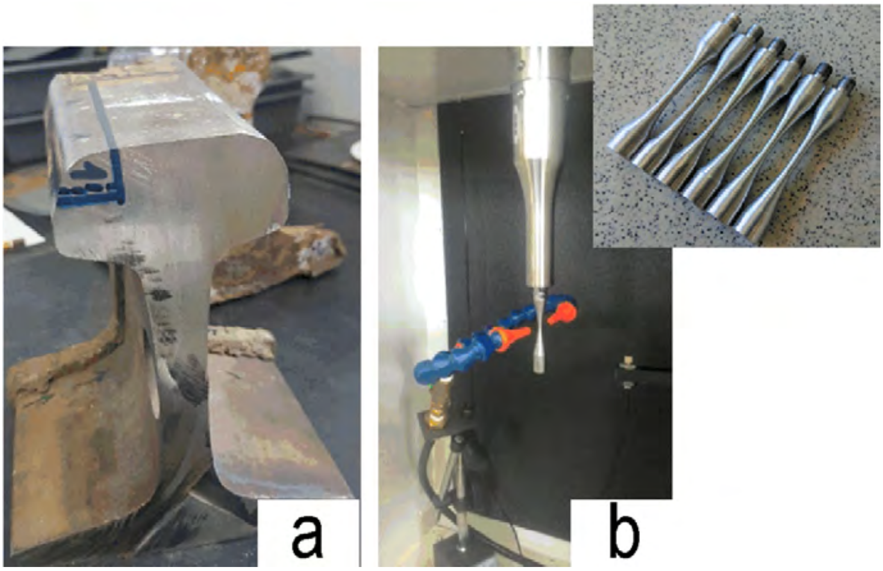
The validity of experimental studies is due to the use of standardised testing methods as well as of specially developed methods of destructive and non-destructive testing for the main testing areas, the use of facilities of an accredited and certified laboratory, which has made it possible to execute the taks set in full and with appropriate quality.

RESULTS AND DISCUSSION

Features of Composition and Microstructure of White Layer in High Carbon Steel

Conducted experiments showed that fatigue endurance tends constantly to reduce at high-frequency load tests. Fatigue characteristics values of the studied M76 steel samples are in the same range and change in the same way. Fatigue endurance was found to be equal (around 700 MPa) for both samples in the VHCF region.

Despite fairly specific impact of high-frequency vibrations, fatigue phenomena occurring during this kind of tests, at rather high values and durations of loads are the same



Pic. 1. The external view of the rail with a working part dedicated for high-frequency testing (a), the process of high-frequency testing (b) (insert – view of the tested sample) [photos made by the authors].

Table 1

Chemical composition of M76 rail steel turnings [data obtained by the authors]

	Element content, wt. %										
	Fe	C	Co	Cr	Cu	Mn	Ni	P	S	Si	V
Rail No. 1	Base	0,745	0,016	0,076	0,125	0,83	0,075	0,013	0,011	0,31	0,04
Rail No. 2	Base	0,77	0,015	0,053	0,10	0,93	0,039	0,015	0,035	0,21	–

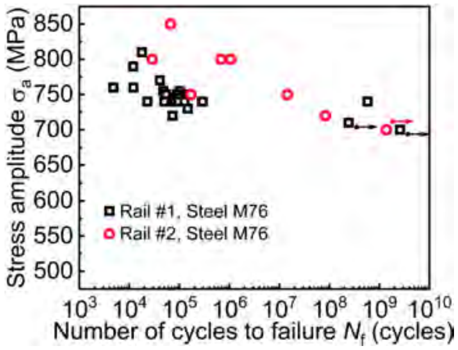
as the ones observed at low-frequency (standard) loads. However, fatigue endurance, collapse process and its rate differ during high-frequency tests.

Pics. 3 and 4 show results of microstructural investigations of Rail No. 1 and Rail No. 2 samples with WL found after high-frequency loads: Rail No. 1 sample (amplitude σ_a = 790 MPa, number of cycles N = 1.19●10^4, reason for collapse is crack, colours of tarnishing are present on the surface); Rail No. 2 sample (σ_a = 840 MPa, N = 1,21●10^4, reason for collapse is drop-out from resonance, colours of tarnishing are present on the surface).

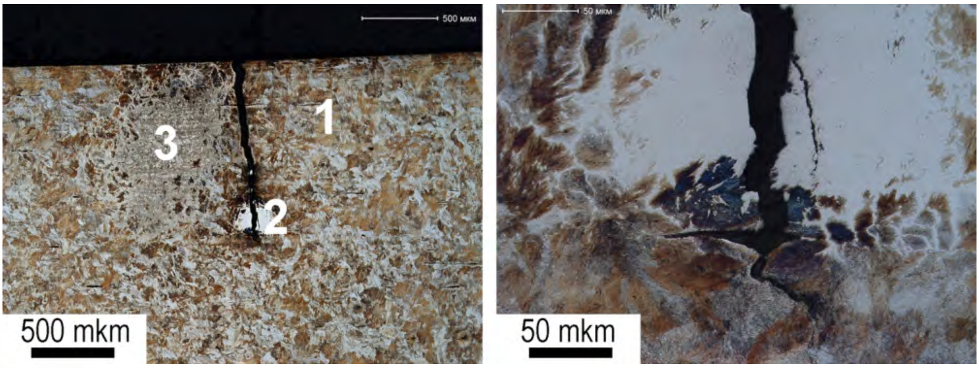
Microhardness (Pic. 5) of the Rail No. 1 sample (Pic. 3) was measured at the centre of WL, from the beginning of the crack (zone 2) at a load of 0,025 kgf (245,2 mN) and step size of 100 μm. Then, measurements were conducted towards zone 1 for 1000 μm with a step size of 100 μm. Metallographic investigations revealed zone 3, which is distinct from WL and main metal. Zone 3 reveals microhardness values being intermediate between zones 2 and 1. Data is given are shown in Pic. 5.

Microhardness of Rail No. 2 (Pic. 5) of the sample (Pic. 4) was measured from the WL (zone 2) edge (because it spans for 2000 μm) with a step size of 100 μm towards zone 1 at HV0.1 (980,7 mN) load for 1000 μm.

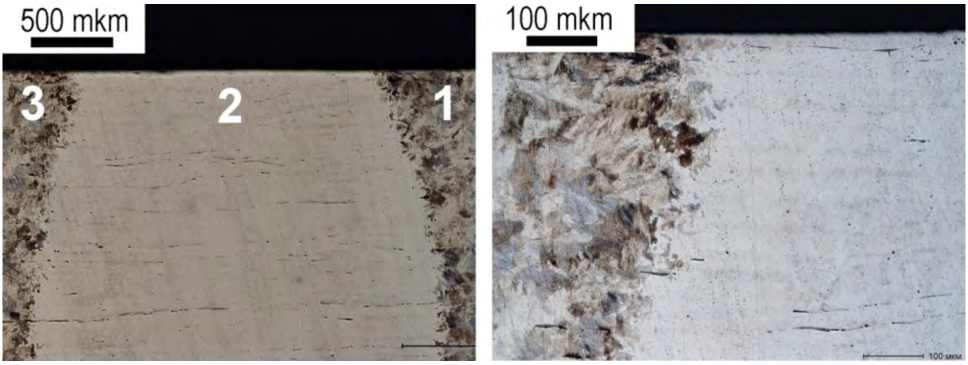
Obtained results clearly show that WL microhardness is extremely high: it reaches 1000–1200 HV, which corresponds to 66 HRC (Pic. 5). Such a high hardness is obviously caused by high density of defects in the white layer. Increase in microhardness is strongly localised, for the Rail No. 2 sample, at 100 μm away from WL microhardness drops by 3–4 times and ranges in 25–400 HV on the rest part of the Rail No. 2 sample. This corresponds to perlite-like structures (perlite-sorbite-troostite) that is quite specific for rail structure. It is noteworthy that zone 3, which is similar to WL (Rail No. 1 sample, Pic. 3), is characterised by microhardness ranging within 484–631 HV. This region had probably undergone partial fragmentation of ferrite and cementite crystals constituting perlite. That is, this structure can be considered as an intermediate element between original structure and WL. Thus, drastic local increase of microhardness indicates a start of collapse processes, but low mean microhardness values do not evidence absence of the initial points of collapse.



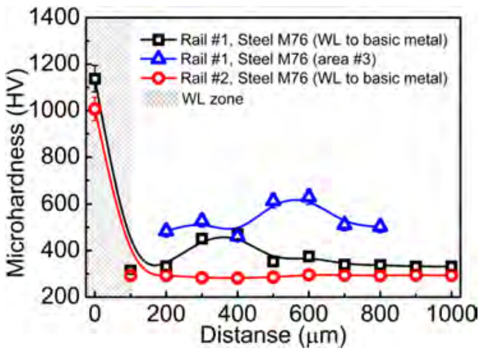
Pic. 2. Experimental data on high-frequency load tests of Rail No. 1 and Rail No. 2 samples. Arrows denote samples that did not collapse at shown amplitude [obtained by the authors].



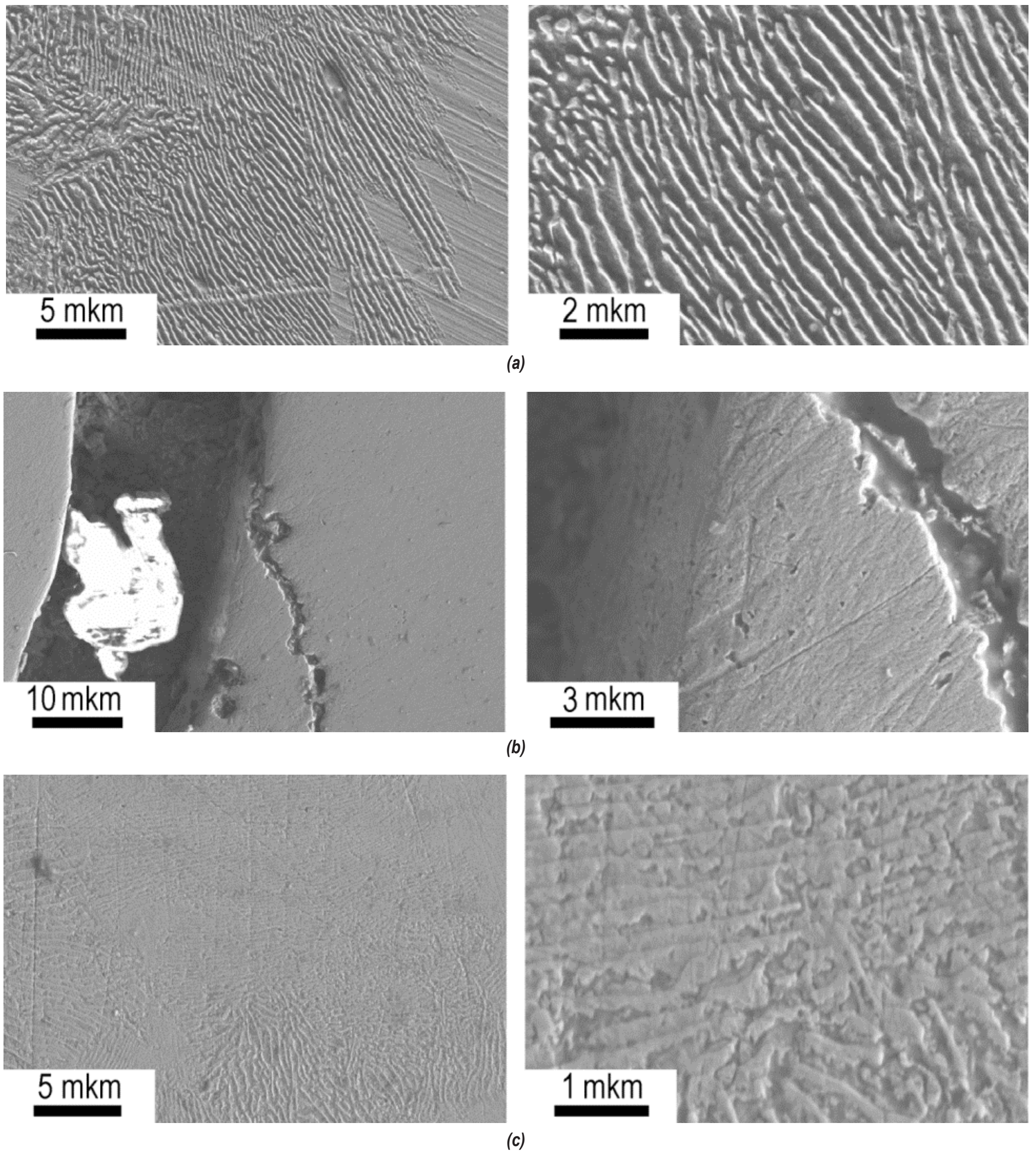
Pic. 3. Metallographic images of characteristic zones 1–3 in the Rail No. 1 sample and layout of the crack with x500 maginification [made by the authors].



Pic 4. Metallographic images of characteristic zones 1–3 in the Rail No. 2 sample and layout of the crack with x200 maginfication [made by the authors].



Pic. 5. Microhardness profile of M76 Rail No. 1 and Rail No. 2 samples, measured from WL towards main metal (Pics. 3, 4) [developed by the authors].



Pic. 6. SEM images of the zones 1 (a), 2 (b), and 3 (c) in the Rail No. 1 sample [made by the authors].

WL Formation Mechanism in High Carbon Steel during High Frequency Vibrations

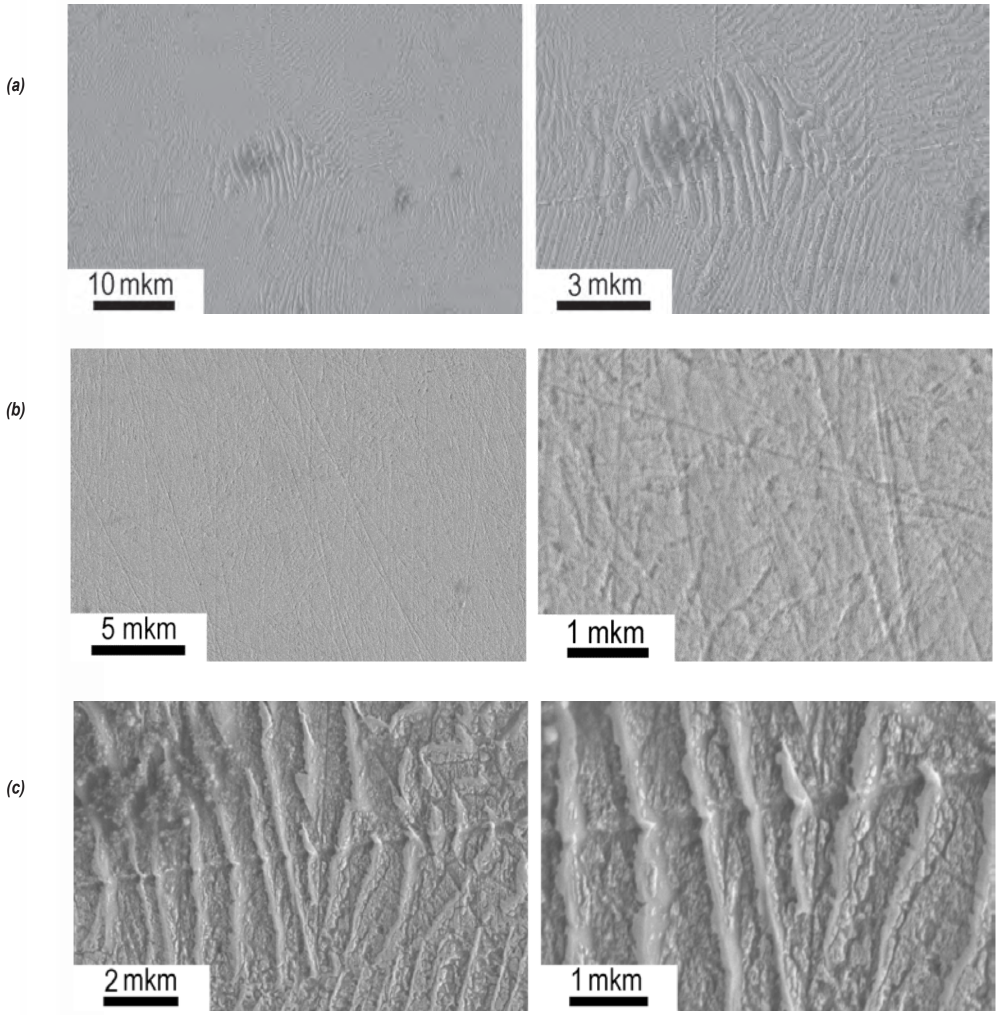
To define more exactly the mechanism of structural changes in the samples and WL formation, zones 1, 2, and 3 in the Rails No. 1 and No. 2 samples were studied with the means of scanning electron microscopy (Pics. 6, 7) with 5000× to 50000× magnification.

To define more exactly the mechanism of destruction and WL formation, XRD analysis of the zones 1, 2, and 3 (Pic. 8) was done of Rail No. 1 (Pic. 8a) and Rail No. 2 (Pic. 8b) samples.

Rail No. 1 sample possesses perlite structure (structurally free ferrite is not observed; Pic. 8a). Microstructure of the sample is characterised by the following features:

1. There exist non-metallic inclusions in the sample. Probably, these impurities are glass-like slags. One of such inclusions are on the lower edge of WL (a tip of the crack passes through it). WL formation at this place can be caused by this inclusion, there are areas featuring signs of perlite fragmentation and of start of its homogenisation. If these processes evolve, such areas may become WL and give a rise to collapse. There is a reflex at $2\theta \sim 38{,}5°$ (interplanar distance d ~ 0,234 nm), which is the most pronounced (Pic. 8a) and presumably corresponds to nonmetallic inclusion in the Rail No. 1 sample.

2. With longer distance from crack in the Rail No. 1 sample, WL becomes discontinuous and alternates with unchanged perlite colonies (then



Pic. 7. SEM images of the zones 1 (a), 2 (b), and 3 (c) in the Rail No. 2 sample [made by the authors].

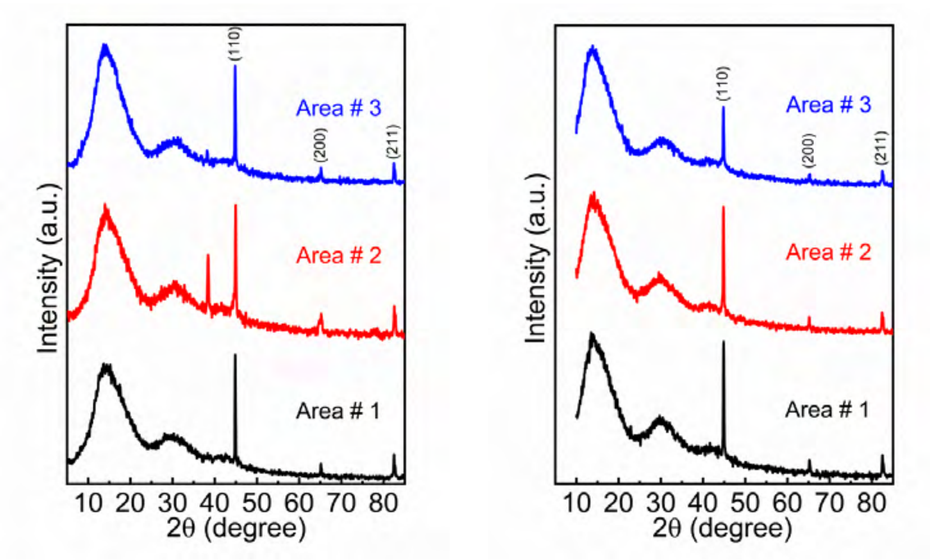
the structure completely turns into unchanged ferrite).

3. SEM and microhardness tests give ground for statement that zone 3 is similar to WL. Partial fragmentation of ferrite and cementite took place there, and this structure can be considered an intermediate one between initial structure and WL.

4. XRD patterns of Rail No. 1 sample recorded from 3 points contain peaks of (110), (200), (211) of ferrite (the most intensive peaks of cementite (103), (022), (210) merges with peak (110) of ferrite, and cementite's peak (121) merges with peak (111) of austenite). On the positions, where peaks of austenite (111), (200), (220), (311) and martensite should have been located the patterns are at the background level. Martensite XRD pattern is distinct from ferrite one in the way that instead of single lines (110), (200), (211), (220) of ferrite, the martensite lattice gives rise to doubled lines with the line (310) being a tripled one. Higher carbon content is observed in martensite (i.e., the greater is the difference between *c* and *a* periods), the wider is the gap between such paired lines[1]. However, spread and splitting of the peaks referring to ferrite were not observed (Pic. 8a). Thus, main phases in the samples are ferrite and cementite. Austenite and martensite are either absent or their content does not exceed 5 wt.%.

5. Significant halo (higher signal on the XRD pattern without clear resolution) is observed at $2\theta \sim 7\ldots23°$ that can be attributed to partial amorphisation or at least to high defect density in that area (Pic. 8a).

[1] Mirkin, L. I. X-ray structural control of machine-building materials: a Handbook [*Rentgenostrukturniy kontrol' mashinostroitelnykh materialov: Spravochnik*]. Moscow, Publishing House of Moscow State University, 1976, 140 p. Mirkin, L. I. Handbook of X-ray diffraction analysis of polycrystals [*Spravochnik po rentgenostrukturnomy analizu polikristallov*]. Moscow, Fizmatgiz publ., 1961, 863 p.



(a) *(b)*

Pic. 8. Diffraction patterns of the zones 1, 2, and 3 for Rail No. 1 (a) Rail No. 2 (b) samples [developed by the authors].

6. Special attention should be paid to the peak at $2\theta \sim 38{,}5°$ (Pic. 8a). It is known that metal peaks can be shifted by the strains. Since ferrite peaks were not shifted, there is no macrostrains at all. At the same time, peak width at $2\theta \sim 38{,}5°$ referring to unknown phase is the same as for ferrite one that also evidences no microstrains in the unknown phase. It can be explained by the assumption that oriented microstrains can cause peak shifts, but all microstrains lead to peak spreading. On the other hand, according to ICDD PDF2-2004 database, this peak can be attributed to 76 various compounds. That is why identification of the peak at $2\theta \sim 38{,}5°$ is challenging.

Rail No. 2 sample is characterised by the following features:

1. Microcracks were not found in that sample, WL was observed on the rail's web throughout the whole profile with a total width of 2000 µm.

2. Microstructure of the zones 1 and 3 preserves morphology inherent to perlite.

3. Main phases in the Rail No. 2 sample are the same as for M76 sample: ferrite, cementite, and a halo at $2\theta \sim 10…23$ (Pic. 8b).

CONCLUSIONS

Study has refered to microstructure and phase composition of the white layer formed following cyclic tests at the frequency of 20 kHz in the experimental samples of M76 high carbon rail steel. XRD has shown that main phases constituting white layer are ferrite and cementite. Austenite and martensite are either absent or their content does not exceed 5 wt.%. Microhardness of the white layer is considerably (by several times) higher than that of original steel and reaches 1000–1200 HV. Thus, formed white layer is a finely dispersed, perlite-like, featureless structure. In the area similar to WL (Rail No. 1 sample; Pic. 3), microhardness is 484–631 HV. Partial fragmentation of ferrite and cementite crystals constituting perlite took place there with their relief being less pronounced after etching (Pic. 6c) compared to the original perlite (Pic. 6a). That structure can be considered as an intermediate one between the original structure and WL. Conducted comprehensive study yields a possible mechanism for white layer formation: fragmentation of ferrite and cementite constituting perlite without intermediate phase transitions.

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