Structure and properties of differentially hardened 100-m rails after long-term operation

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Abstract. Using methods of modern materials science the analysis of structural phase states of defect substructure and mechanical properties of tread surface at different distance (from 0 to 22 mm) along central axis and fillet of differentially hardened 100 meter rails of DT 350 category manufactured at JSC “Evraz-Integrated West-Siberian” metallurgical combine after long term operation (passed tonnage 1411 mln. t. brutto) at experimental test ring has been performed. Microstructure of rails’ metal is presented by fine-dispersed lamellar pearlite (grain confidence index 2) with inclusions of excess ferrite along grain boundaries estimated by 2 numbers of scale No. 7 of State Standard 8233. The value of interplate distance in rail head varies within 0.10 - 0.15 μm. Long term operation of rails is accompanied by the formation of gradient structure being expressed in regular change in hardness, microhardness, impact strength, destruction degree of cementite plates, scalar dislocation density throughout cross-section of rails head. The failure mechanisms of lamellar pearlite structure have been discussed. It has been shown that microhardness at 2 mm depth from tread surface amounts to 1481-1486 MPa. At depth up to 10 mm the microhardness values decrease up to 1210-1385 MPa that is caused by increase in interplate distance and decrease in level of cold strain hardening of metal in long-term operation of rails.

1. Introduction
In modern conditions of high axial loads and rates of motion the surface layers of rails undergo the intense plastic deformation leading to failures in long-term operation [1, 2]. Analysis of recent papers [3-8] shows that already at a comparative small operating life – 100-500 mln. t. brutto the structural phase states with irregular high microhardness, small size of grain in the interval from 20 to 500 nm are formed. Cementite plates are either bent or fractured with extremely high density of dislocations noted at interphase boundaries. It is clear that different processes (recrystallization, relaxation, phase transitions, formation and decay of phases, amorphisation etc.) may take place in long term operation that result in evolution of structural phase states being accompanied by change in mechanical properties [3-12].

The purpose of the research is to analyze the structure and properties of differentially hardened 100-meter rails being formed in long-term operation.
2. Material and methods of research

The samples of 100-meter differentially hardened rails of DT 350 category made of E76XF vacuum steel removed from the railway at experimental practice ground of Shcherbinka town after passed tonnage of 1411 mln. t. brutto were used as test material. Chemical composition of rail’s fragment under study is given in table 1.

Microstructure of metal was revealed by deep etching in 50% hot water solution of hydrochloric acid on incomplete template (head, neck). Estimation of microstructure was done according to RD-14-2R-2001 Classificator of microstructure defects of rails [13]. Metal microstructure was studied on metallographic sections cut from the upper part of head (fillet and treat surface) before and after etching in 4% alcoholic solution of nitric acid. Studies of steel structure, fine and defect substructure were carried out by using the methods of optical microscopy.

| Chemical composition | C | Mn | Si | P | S | Cr | Ni | Cu | V | Al | Ti |
|----------------------|---|----|----|---|---|---|----|----|---|----|----|
| Tests                | 0.72 | 0.77 | 0.61 | 0.010 | 0.009 | 0.42 | 0.07 | 0.14 | 0.038 | 0.003 | 0.003 |
| Specifications       |         |     |     |   |   |     |     |     |   |     |     |
| TU 0921-276-0124323-2012 for steel E76XF |         |     |     |   |   |     |     |     |   |     |     |
| Impact strength of steel was determined at test temperature +20°C using two samples of 1 type according to State Standard 9454 cut from rails. Head hardness was measured using Brinell and Rockwell method on tread surface and along cross-section of head. Microhardness was determined at distance of 2 mm and 10 mm from surface at place location of both fillets and central zone of tread surface of sample head.

3. Results and discussion

Visually, treat surface of head rail sample has a smoothed and glitter appearance with some wear shift to one of fillets. In zone of working fillet the cracks of contact fatigue located almost at right angle to rolling axis and slight spalling are observed.

Metal microstructure of fragment being tested along axial segregation, point inhomogeneity, segregation strips and cracks is estimated as satisfactory. No internal defect, as well as continuity violations, was detected. From tread surface a darker etching region whose formation is connected with metal deformation processes, having place in long-term operation, is observed.

When scanning the non-etched metallographic sections through optical microscope, the branched continuity violations passing at acute angle to surface to depth up to 1.09 mm are revealed from surface of working fillet to the place of surface cracks of contact fatigue. Etching of rail metal in zone of non-continuities enabled one to reveal the structure with high level of deformation cold hardening.

On metallographic sections cut from tread surface of head the single fine continuity violations to depth up to 0.03 mm are met. Deformation depth from tread surface is insignificant and amounts to 0.035 mm.

Microstructure is sample’s head is represented by fine-dispersed lamellar pearlite with small inclusions of excess ferrite being estimated by grain confidence index 1.5 of scale No. 7 of Standard 8233 (figure 1, a, b). Metal microstructure is presented by fine-grained pearlite with small areas of structurally free ferrite (figure 1, c) being met. In pearlite structure there are rather many colonies with failed cementite plates (figure 1 d) besides regular colonies (colonies with regular located cementite plates). Areas of degenerated pearlite are present as well.
Figure 1. Structure of rail head metal revealed by methods of optical microscopy (a, b) and scanning electron microscopy (c, d) of etched metallographic section at depth of 0.5-1.0 mm.

Degree of failure of lamellar pearlite structure depends on position of volume being analyzed: on tread surface it is twice as high as surface layer of working fillet.

In scientific literature two mechanisms of cementite plate failure are mainly described [1, 5, 6]. The first one involves the intersection of plates by moving dislocations and carrying out carbon atoms by them into ferrite to stress field of dislocations. The second one consists in pulling of carbon atoms by dislocations from cementite lattice due to marked difference in binding energy of carbon atoms with dislocations (0.6 eV) and atoms in cementite lattice (0.4 eV). Dislocation substructure in the form of chaotically distributed dislocations (figure 2 a) and net-like dislocation substructure (figure 2 b) are detected. Scalar density of dislocations on tread surface amounts to 7.5-8.0·10^10 cm^-2 and it decreases linearly with increase in distance from surface.

When analyzing the results of quantitative microstructure estimate presented in table 2 a more dispersed pearlite structure of tread surface may be noted relative to structure of fillet pearlite of fillet pearlite.

Figure 2. Electron microscopic image of dislocation substructure.
Table 2. Quantitative characteristics of metal structure of rail’s head detected by methods of optical and scanning electron microscopy.

| Rail index | Interplate distance, μm | Value of pearlite colonies, μm | Grain diameter, μm (grain number) |
|------------|-------------------------|-------------------------------|----------------------------------|
|            | min | max | mean | min | max | mean | min | max | mean |
| fillet     | 0.073 | 0.256 | 0.132 | 2.711 | 12.157 | 6.17 | 15.042 | 51.169 | 29.8 |
| tread surface | 0.073 | 0.225 | 0.125 | 2.634 | 10.731 | 5.6 | - | - | - |

Table 3. Impact strength and hardness of steel on tread surface of head, along its section as well as in upper part of neck.

| Specifications | KCU +20°C | Hardness, HB |
|----------------|-----------|--------------|
|                | J/cm² | TSH | 10 mm | fillet | No. 1 | No. 2 | 22 mm | neck |
| TU 0921-276–01124323-2012 for rails of DT 350 category | 30 | 27 | 388 | 399 | 381 | 364 | 362 | 373 | 345 |

From test results shown in Table 3 it follows that the metal of the test sample meets specifications TU 0921-276-01124323-2012 for rails of DT 350 category for impact strength and hardness on tread surface on head and along its cross-section. Hardness, measured in neck has slightly increased values relative to requirements of specifications.

Analysis of results presented in Table 4 shows that hardness values at 2 mm depth in central zone and working fillet are at a higher level (38.5-37.1 HRC) compared with nonworking fillet (35.3 HRC) that is caused by the presence of dup deformation being accompanied by cold hardening of the material in the zone. At 10 mm and 22 mm from tread surface the hardness of metal is characterized lower level (by 2-3 HRC) compared to depth of 2 mm and has correlated values (34.8-35.8 HRC).

Table 4. Metal hardness along cross-section of rail’s head in transverse direction.

| Place of measurement | Hardness HRC, at distance from surface, mm |
|----------------------|------------------------------------------|
|                      | 2 | 10 | 22 |
| Working fillet       | 38.5 | 35.5 | 34.8 |
| Central zone         | 37.1 | 35.8 | 35.6 |
| Nonworking fillet    | 35.3 | 35.5 | 35.2 |

Table 5. Rail’s microhardness at a distance of 2 mm and 10 mm from surface at place of both fillets and central zone of tread zone.

| Zone measurement | Microhardness, MPa, at distance from surface |
|------------------|---------------------------------------------|
|                  | 2 mm | 10 mm |
| Working fillet   | 1475 | 1385 |
| Nonworking fillet| 1486 | 1274 |
| Tread surface    | 1481 | 1210 |

Averaged (by results of four measurements in each zone) values of microhardness determined at distance of 2 mm and 10 mm from surface at place of both fillets and central zone of head tread surface are shown in table 5. It is seen that microhardness at depth of 2 mm has close values -1481-
1475 MPa. At depth of 10 mm from surface the microhardness values decreases to 1210-1385 MPa that is evidently caused by increase in interplate distance (decrease in dispersion) and decrease in level of metal deformation hardening taking place in long-term-operation.

4. Conclusion

It has been stated by methods of physical materials science that:

- Microstructure of rail metal is presented by fine-dispersed lamellar pearlite of grain confidence index 2 with inclusions of excess ferrite along grain boundaries estimated by grain confidence index 2 of scale No. 7 of Standard 8233. Value of interplate distance in rail head varies within the limits 0.10-0.15 μm. Average value of pearlite colonies in fillet zone amounts to 6.2 μm, on tread surface -5.6 μm. The main value array of real grain dimensions estimated only in zone of nonworking fillet is 7-8 number of Standard 5639-82.

- Scalar density of dislocations amounts to 7.5-8.0˟10^{10} cm^{-2} and decreases linearly with increase in distance from tread surface.

- Impact strength and hardness on tread surface of head and along its cross-section meets specifications TU 0921-276-01124 324-2012 for rails of DT 350 category. Hardness measured by Rockwell method at depth of 2 mm from surface amounted to 38.5-37.1 HRC, at depth of 10 and 22 mm – 34.8-35.8 HRC, respectively.

- Microhardness at depth 2 mm from tread surface amounts to 1481-1486 MPa. At depth up to 10 mm microhardness values decrease to 1210-1385 MPa that is caused by increase in interplate distance and decrease in level of metal deformation level in long-term operation of rails.

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