Influence of high-frequency cyclic loading on mechanical and structural characteristics of rail steel under extreme conditions

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Abstract. In this paper topical issues of change of a microstructure and microhardness in steel at high-frequency vibration influence which is observed in technological pipelines, connected to the pump and compressor equipment. To study the micro-structures of samples after influence of high-frequency loading, the authors used optical microscopy and microhardness testing. Relevant and timely is the task of modelling and subsequent design and construction of railways, taking into account a wide range of geometric and mechanical characteristics, which is most in demand in the construction of artificial structures in the Arctic, due to the large temperature difference and differences in temperature coefficients of materials. The purpose of this work is to study the mechanical and structural characteristics of 40X steel under high-frequency loading conditions. For mechanical and structural studies the authors prepared the samples from a rod of 40X steel with a diameter of 12 mm. The strength properties of steel was evaluated by tension testing, fatigue testing, then structural analysis (metallographic studies) and microhardness testing.

1. Introduction

Railway transport systems widely used in almost all sectors of the modern economy. They are transporters of explosive and flammable environment at different pressures and temperatures, so ensuring the reliability of these systems is necessary for the effective and safe operation of both: the technological equipment and the enterprise. Relevant and timely is the task of modeling and subsequent design and construction of railways, taking into account a wide range of geometric and mechanical characteristics, which is most in demand in the construction of artificial structures in the Arctic, due to the large temperature difference and differences in temperature coefficients of materials.

The proposed solutions will allow achieving the best transportation parameters, as well as ensuring the necessary compliance of the structure with external dynamic, including seismic effects, allowing not to violate the overall integrity of the structure and operate the railway in seismically active regions and in the Arctic, or artificial structures experiencing dynamic effects transmitted to the ground base, and through it.

An important issue is the compatibility of deformations of the connecting elements of the path under different operating conditions and vehicle speeds. It is important to understand the behavior and condition of the railway track as a multi-element transport system, as well as the condition and...
possible changes in the structure of the materials used in the manufacture of individual parts of the structure.

Due to the fact that the railway track, especially on artificial structures, contains a lot of structural elements made of different materials [1,2], in the places of joining of elements of these systems and in the course of a certain length of the path, vibrations of individual units and structures arise, and under certain conditions (at coincidence of frequencies of forced oscillations, when changing the geometry of the elements, etc.) these values reach the region of ultrasound to frequencies of 20,000 Hz [1,3]. In this regard, for an accurate assessment of the resource of railway transport systems, it is necessary to study the processes of influence of high-frequency vibrations on the structural and mechanical characteristics of the material elements of these systems.

The purpose of this work is to study the mechanical and structural characteristics of 40X steel under high-frequency loading conditions.

2. Research technique
For mechanical and structural studies was prepared the samples from a rod of 40X steel (GOST 4543-2016) with a diameter of 12 mm. The strength properties of steel was evaluated by tension testing, fatigue testing, then structural analysis (metallographic studies) and microhardness testing.

Mechanical tensile testing was carried out in according with GOST 1497-84 to determine the tensile strength $\sigma_b$ and yield strength $\sigma_t$ of experimental samples with working part in the form of a cylinder on AG-X-plus-100kN test machine (Shimadzu, Japan). As a result of tensile tests, the following values were obtained: $\sigma_b = 924$ MPa, $\sigma_t = 604$ MPa.

High-frequency cyclic tests was carried out with a symmetrical cycle loading $R = -1$ by a USF-2000 on an ultrasound unit USF-2000 (Shimadzu, Japan). The experimental samples that had the shape of a body of revolution with cylindrical ends: The generator of the middle part is an arc of a sufficiently large radius. Feature USF-2000 is a method of cyclic loading: enter of the sample into resonant vibrations with a frequency of 20 kHz. The test is completed when the sample is out of resonance due to structural changes.

3. Results and discussion

3.1. Optical metallography
Sample 1 was loaded with amplitude of stress of $\sigma_a = 800$ MPa, the number of cycles N was $\sim 10^4$ (the exact number could not be fixed). Visual analysis of the sample after the test showed the presence of a distortion neck. On the surface and adjacent areas with a width of 1-2 mm (equal to about 5 mm), was observe heat colors up to blue (which corresponds to a temperature of $\sim 300 ^\circ C$).

Metallographic studies of sample 1 showed that neck had different structure from neighboring (less loading) areas. Structure is:

- homogeneous, it is impossible to divide into ferrite and perlite;
- dispersed: elements are practically indistinguishable with magnification 500×.

The neck corresponds to the structure "white layer", which appears on the surface of details undergo high contact loads [4].This layer is characterized by a high density of structure defects, so the maximum solubility of carbon is much higher than in the original ferrite [5]. Due to this, the "white layer" also differs strongly from the ferrite in terms of mechanical and physicochemical properties. In particular, they have a different nature of etching: the neck is etched much more slowly than the neighboring area [6].

Thus, only samples 3 and 6 have not noticeable structural changes. Sample 6 (the only one of all) was tested at a stress amplitude below the static yield strength of 40X steel. As for sample 3, absence of visible changes in structure can be associated with a small number of cycles - $1.0813 \times 10^4$ (0.54 s
in time) [7]. Perhaps the output from the resonance was due to some internal defect that could not be detected, and the sample just did not have time to heat above 210 °C (the appearance of heat colors).

It is interesting that sample 1 worked a close number of cycles to sample 3 (~ 10^4) with an insignificantly higher amplitude of stresses (800 MPa instead of 780 MPa). But sample 1 differs most from sample 3 after loading (heat color, neck). Samples 2, 4 and 5 occupy an intermediate position and are close in structure to sample 1 outside the deformation neck.

Such a strong difference between samples 1 and 3 can be explained in the following way:
1. the obtaining of a particular structure is determined by the amount of energy not input to the sample, but the energy scattered in it, that is, the dissipation of energy. The dissipation of energy depends on random factors, including the singularities of the structure of the sample. If the sample has several volume defects (for example, nonmetallic inclusions or microcracks) interference of ultrasonic waves scattered on them can occur [8]. Because of this, local maximum (leading to the formation of a deformation neck or a crack) or minimum (in this case, the structure can locally remain practically unchanged) can arise in the amplitude of stresses in the sample;
2. as a consequence of section 1, the change in amplitude of the stresses in used range of values only changes the probability of achieving a result, rather than making it the only possible or impossible.

3.2. Microhardness

After metallographic research of the samples, was measured their micro-hardness. Center ("0 μm" mark) was the middle of the sample’s neck (for sample 1) or the section with the smallest diameter where to be formed the neck (for the remaining samples). The measurement was carried out with a step of 200 μm separately for perlite and ferrite (or "white layer" in the case of sample 1).

The results of measuring the microhardness of samples 1-4 illustrated in Tables 1-4.

| Structural component | Distance from center of the neck | 0um | 200um | 400um | 600um | 800um | 1000um |
|----------------------|---------------------------------|-----|-------|-------|-------|-------|--------|
| **Ferrite**          |                                 |     |       |       |       |       |        |
| 845                  | 480                             | 376 | 284   | 293   | 335   |       |        |
| 833                  | 583                             | 347 | 354   | 318   | 297   |       |        |
| 924                  | 705                             | 354 | 324   | 292   | 293   |       |        |
| 616                  | 734                             | 318 | 333   | 275   | 288   |       |        |
| 833                  | 786                             | 355 | 303   | 336   | 293   |       |        |
| **Average value**    |                                 | 810 | 656   | 350   | 319   | 303   | 301    |
| **Perlite**          |                                 |     |       |       |       |       |        |
| –                    | 504                             | 331 | 332   | 307   | 349   |       |        |
| –                    | 467                             | 393 | 336   | 302   | 347   |       |        |
| –                    | 620                             | 341 | 336   | 339   | 318   |       |        |
| –                    | 354                             | 378 | 389   | 359   | 331   |       |        |
| –                    | 412                             | 355 | 313   | 350   | 305   |       |        |
| **Average value**    |                                 | 471 | 360   | 341   | 331   | 330   |        |

Note: In the neck zone of this sample (from 0 μm to 200 μm from the center of the neck), a "white layer" was detected which is characterized by a high defect density. As a result, the limiting content of carbon in it and its properties are very different from the original ferrite [9].

Table 2 shows that in the neck zone on sample 1 the average microhardness is HV 810, which corresponds to HRC 61 (hardness of hardened high-carbon steel) [10]. In fact, at a distance of 200 μm from the center of the neck, when the structure can be divided into ferrite and perlite, the microhardness of ferrite (average HV 656, or approximately HRC 55) exceeds the microhardness of perlite (average HV 471, or approximately HRC 46). At a distance of 400 μm or more from the center of the neck, the microhardness values of ferrite and perlite are close [11].
Table 2. The results of measurements microhardness of sample 2.

| Structural component | Distance from center of the neck |
|----------------------|---------------------------------|
|                     | 0um    | 200um | 400um | 600um | 800um | 1000um |
| Ferrite              |        |       |       |       |       |       |
|                      | 338    | 264   | 292   | 301   | 308   | 299    |
|                      | 312    | 315   | 285   | 333   | 316   | 312    |
|                      | 302    | 309   | 294   | 320   | 318   | 318    |
|                      | 347    | 313   | 298   | 302   | 308   | 324    |
|                      | 338    | 323   | 309   | 309   | 299   | 324    |
| Average value        | 328    | 309   | 296   | 313   | 310   | 315    |
| Perlite              |        |       |       |       |       |       |
|                      | 295    | 299   | 330   | 285   | 322   | 322    |
|                      | 322    | 332   | 329   | 301   | 299   | 335    |
|                      | 327    | 322   | 329   | 301   | 310   | 308    |
|                      | 308    | 317   | 331   | 285   | 316   | 278    |
|                      | 331    | 320   | 322   | 307   | 302   | 301    |
| Average value        | 317    | 318   | 328   | 295   | 310   | 309    |

The microhardness of sample 2 (Table 3) is approximately the same at all points (for ferrite and for perlite it is at the level of 300-320HV). Thus, microhardness this sample corresponds to sample 1 at a distance of 600-1000 μm from the center of the neck.

Table 3. The results of measurements microhardness of sample 3.

| Structural component | Distance from center of the neck |
|----------------------|---------------------------------|
|                     | 0um    | 200um | 400um | 600um | 800um | 1000um |
| Ferrite              |        |       |       |       |       |       |
|                      | 154    | 174   | 211   | 175   | 150   | 178    |
|                      | 163    | 176   | 186   | 209   | 188   | 188    |
|                      | 181    | 178   | 181   | 199   | 153   | 160    |
|                      | 143    | 180   | 184   | 171   | 155   | 179    |
|                      | 150    | 175   | 200   | 188   | 163   | 180    |
| Average value        | 158    | 176   | 192   | 188   | 162   | 177    |
| Perlite              |        |       |       |       |       |       |
|                      | 226    | 261   | 225   | 316   | 301   | 312    |
|                      | 319    | 259   | 269   | 240   | 277   | 235    |
|                      | 267    | 212   | 253   | 265   | 213   | 259    |
|                      | 262    | 270   | 301   | 211   | 222   | 210    |
|                      | 254    | 258   | 238   | 224   | 201   | 214    |
| Average value        | 266    | 252   | 257   | 251   | 243   | 246    |

The microhardness values of sample 3 (Table 4) generally correspond to the level characteristic for perlite-class steel: the microhardness of ferrite does not exceed 200HV, and perlite is at the level of ~ 250HV. The only thing that goes beyond the standard picture is that the microhardness of ferrite is maximum not in the thinnest part of the sample, but at a distance of 400-600 microns from it. One of the reasons for this phenomenon could be certain features of the microstructure (for example, volume defects - microcracks, nonmetallic inclusions), which positively influenced accumulation of defects in this area.

In general, sample 4 (Table 5) for microhardness is similar to sample 1 in the 400 μm from the center of the neck (slightly harder than sample 2). However, it has feature: in the center of the neck some grains of ferrite have microhardness below 200 HV [12,13]. This indicates that the accumulation of defects even in the most stressed zone happen unevenly: some grains harden faster, others can
remain in the initial state for a long time (sample 4 passed 3,4889·108 loading cycles). This can be due to both the factors already mentioned (the presence of volume defects) and the different orientation of atomic planes in grains, including slip planes [14,15].

### Table 4. The results of measurements microhardness of sample 4.

| Structural component | Distance from center of the neck |
|----------------------|----------------------------------|
|                      | 0um  | 200um | 400um | 600um | 800um | 1000um |
| Ferrite              |      |       |       |       |       |        |
| 295                  | 339  | 316   | 314   | 337   | 341   |
| 273                  | 316  | 330   | 328   | 343   | 348   |
| 332                  | 326  | 316   | 340   | 367   | 339   |
| 293                  | 288  | 332   | 328   | 377   | 399   |
| 306                  | 310  | 343   | 346   | 341   | 312   |
| 195                  | 128   |       |       |       |       |
| Average value        | 300/260* | 316   | 327   | 331   | 353   | 347   |
| Perlite              |      |       |       |       |       |        |
| 341                  | 322  | 357   | 393   | 393   | 350   |
| 343                  | 326  | 339   | 339   | 388   | 370   |
| 365                  | 332  | 346   | 365   | 324   | 365   |
| 399                  | 372  | 388   | 330   | 365   | 343   |
| 324                  | 295  | 357   | 357   | 357   | 370   |
| Average value        | 354  | 329   | 357   | 357   | 365   | 359   |

Note: in the thinnest part of this sample, the ferrite grains have different micro-hardness: either about 300HV or less than 200HV. Accordingly, 300HV is the aver-age microhardness of ferrite at the first five points (without taking into account soft grains), 260HV is the average value for all grains of ferrite in this zone.

### 4. Conclusions

Based on the results obtained, the following conclusions can be drawn:

3. The influence on the steel 40X high-frequency cyclic loading with a stress amplitude above the static yield strength can’t cause visible plastic deformation, but leads to the accumulation of defects in the structure. This is reflected in the change in the microhardness of the structural components and in the change nature of the influence etchant on steel;

4. The influence of high-frequency cyclic loads with a high amplitude of stresses on 40X steel leads to homogenization and an increase in the dispersion of its structure. Presumably, the result is a ferrite-based phase having a high defect density and a high microhardness. This phase is analogous to the so-called "white layer" formed on the surface of parts experiencing high contact loadings;

5. Short-term influence high-frequency cyclic loadings with stress amplitude exceeding the static yield strength can't cause noticeable changes in the structure and properties of 40X steel [16-18]. Nevertheless, the accumulation of structure defects at high-frequency cyclic loading is a self-accelerating process, and therefore the effect of high-frequency loads on structural materials needs further study;

6. The accumulation of defects occurs unevenly in grains even in one section of the sample. This can be due to factors such as the presence of volume defects in the initial sample (microcracks, nonmetallic inclusions) and different orientation of the slip planes in the grains;

7. In general, the studies have allowed a better understanding of the nature of changes in the internal state of steel under dynamic load, which will more accurately calculate the residual life of the entire railway track, its separate elements and structures, taking into account the extreme conditions of the Arctic;

8. The results of studies may affect the extension of the service life of individual elements and structures of the transport system, as well as to identify the most dangerous places, in terms of violations of the integrity of the upper structure of the track, welded joints and fastening units.
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