Structure of carbon steel under plastic deformation

G V Shlyakhova 1,2, L B Zuev 1,3, A V Bochkareva 1

1 Institute of Strength Physics and Materials Science, Siberian Branch, Russian Academy of Sciences, 3/4 Akademichesky ave., Tomsk 634055, Russia
2 Seversk Technological Institute, MEPhI National Research Nuclear University, 65 Kommunistichesky ave., Seversk 636036, Russia
3 Tomsk State University, 36 Lenin ave., Tomsk 634050, Russia

E-mail: avb@ispms.tsc.ru

Abstract. Results of studies on the structure of carbon steel 1045 under severe plastic deformation are presented. The atomic force microscopy method was used to estimate the metallographic structure of steel damage after cyclic impact. It was found that the plastic flow localization process occurs in narrow micro-volumes. During the process of cyclic loading, fatigue strength increases, while plastic deformation decreases, and vice versa.

1. Introduction
During the operating of equipment and engineering production, in a large number of structures the fracture occurs at loads below the yield point. As a result of repeated effects of cyclic loads on the material, there is a change in its structure, due to which different microscopic discontinuities form. These discontinuities can subsequently grow in size and eventually result in the development of a main crack. This process is particularly facilitated by a multiple alternation of stresses in local areas of the materials. The majority of products and structures, such as bridge structures, road and railway transport, metalworking machines and tools, presses, aircrafts, lifting mechanisms, pipelines and others, operate under the conditions of cyclic loads [1].

The complexity of studying and predicting the fatigue failure of materials is caused by the fact that the formation and propagation of a crack occur in small local regions of a material. Such regions are determined by the structural components of the material and their orientation relative to operating loads. This significantly increases the probabilistic nature of the occurrence of a micro-crack and its ability for further development [2].

With increasing the frequency of cyclic loading, the deformation rate increases. As the time period for softening of materials decreases and the distortion of crystal lattice increases, the intensity of grain fragmentation into blocks and their mutual disorientation increases [3].

It is well known that the resistance to fractures in metals and alloys under cyclic loading depends on many factors, such as the chemical composition of the metal, operating temperature, stress concentration, cyclic loading asymmetry, cyclic loading frequency, etc. [4]. To carry out such investigations, atomic-force microscopy and optical microscopy are widely used. These methods of comprehensive analysis of metal surfaces allow obtaining the metallographic images with high spatial resolution [5-9].

The aim of the work is to study the degree of damage of surface and structural changes in carbon steel 1045, which is widely used in engineering and metallurgy under different cyclic loads.
2. Materials and methods
The studies were carried out with flat samples of hot-rolled carbon steel 1045. The chemical composition of steel 1045 is presented in table 1.

The specimens for the experimental studies having a dog-bone shape were cut from a hot-rolled 4-mm steel sheet. The obtained metallographic test samples were etched with 4% alcohol solution of nitric acid, after that they were subjected to fatigue fracture tests using a Biss UTM 150 fatigue testing machine with the number of cycles \(N\) \(1 \times 10^3, 5 \times 10^3, 20 \times 10^3\) and \(90 \times 10^3\). The maximum load reached 150 kN and the peak displacement was 150 mm. Microstructure studies of the surface of the deformed and unloaded samples were carried out using an Neophot-21 (OHM) optical microscope and an atomic force microscope (AFM) (Solver PH47-PRO, manufactured by JSC "Nanotechnology-MDT", Zelenograd, Russia). The Solver PH 47-PRO device software, as well as a set of cantilevers, allows us to use different modes of atomic force analysis. Therefore, all sorts of structural features of a solid surface can be observed. The mechanical properties of carbon steel were determined using a portable hardness tester TPP-10.

| C    | Si   | Mn  | Ni  | S    | P    | Cr  | Cu  | As  |
|------|------|-----|-----|------|------|-----|-----|-----|
| 0.42±0.5 | 0.17±0.37 | 0.5±0.8 | < 0.3 | < 0.04 | < 0.035 | < 0.25 | < 0.3 | < 0.08 |

3. Experimental results
Metallographic investigations of the surface of carbon steel samples in the initial state are shown in figure 1. As it is seen, a significant part of the image of the sample presents a Widmanstatten structure, consisting of large grains without a regular geometric shape, whereas the other part show a normal structure. The ferrite and pearlite ratios are 45% and 55%, correspondingly, as can be seen in figure 1. The average grain size, measured by interception method, is about 21.9±1.2 µm. For ferrite and pearlite, this is 18.6±1.1 µm and 25.1±1.3 µm, respectively. The results obtained are comparable with the AFM data.

![Figure 1](image1.png)

**Figure 1.** Microstructure of low-carbon steel 1045 according to optical microscopy (a) and atomic-force microscopy (b) of a 50×50 µm area

One can see in figure 1 b that the cementite lamina has almost the same direction within a certain pearlite grain and this direction is markedly different from this orientation within consecutive grains. Several nodular pearlites are segregated at the boundaries of pearlite grains.

The results of metallographic studies of low-carbon steel 1045 under cyclic loading are presented here. The changes in the microstructure of pearlite and the extent of the surface damage were obtained...
for a certain number of cycles (N), such as $1 \times 10^3$, $5 \times 10^3$, $20 \times 10^3$, $90 \times 10^3$, see figure 2. Analysis of surface scan images of steel 1045 at $N=1 \times 10^3$ did not reveal any structural changes in pearlite grains, see figure 2 a. However, at $N=5 \times 10^3$, it can be seen that some cementite plates are bent or even partially crushed without formation of micro-cracks, see figure 2 b. Like cementite, a brittle carbide, is prone to micro-cracks formation, especially if it has an elongated shape when $N=20 \times 10^3$. The cracks are located mainly across the plates and less along them, see figure 2 c. Within a number of cycles $N=95 \times 10^3$, the crushed cement plates are separated, the distance between them becomes greater, and the cavity can be filled with a softer phase – ferrite. In some cases, the destruction of cementite plates is carried out on a number of closely spaced planes, which leads to the formation of defective zones. In such zones there are numerous fragments of cement plates that are displaced relative to each other, see figure 2 d.

**Figure 2.** Scanning-probe images of the lamellar pearlite structure at the interface under different cyclic loading: (a) $N=1 \times 10^3$, (b) $N=5 \times 10^3$, (c) $N=20 \times 10^3$, (d) $N=95 \times 10^3$.

Experimental results obtained for low carbon steel under cyclic loading showed that for the number of cycles ($N$) in the interval from $5 \times 10^3$ to $20 \times 10^3$ the hardness of steel increases. But the future increment of $N$ leads to a reverse decrease to the initial values (see table 2).
Table 2. The dependence of hardness (HV) low-carbon steel 1045 on the number of cycles (N)

| Number of cycles (N) | Hardness, HV (MPa) |
|----------------------|---------------------|
| Initial state        | 1735                |
| 1×10^5              | 1735                |
| 5×10^5              | 2178                |
| 20×10^5             | 2178                |
| 95×10^5             | 1735                |

4. Summary
The experimental study of carbon steel 1045 revealed special features of lamellar pearlite appeared during plastic deformation. Localization of the plastic flow occurs in narrow microvolumes. The lamellar perlite decay starts from the impaired subcolonies and the critical concentration of damage gives rise to the destruction of cementite laminae.

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