Modeling of the structural evolution of carbon steel hypereutectoid structure subjected to reforging under pulsating contact stress loading

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Abstract: *The paper presents the results of microstructural studies of 16MnCrS5 steel hypereutectoid structure subjected to reforging under pulsating contact stress loading. It is revealed that the local evolution of the structure in the focus of contact loading has signs of self-improvement with the transformation of the isotropic morphology of the carbide phase into an anisotropic one with signs of textural riveting. Instead of the initial structure with a uniform carbide phase distribution, signs of textural anisotropy with reinforcement elements of the modified layer high-carbon hypereutectoid zone with carbide inclusions are formed.*
Keywords: *MICROSTRUCTURE, WEAR, PULSATING CONTACT STRESS, MODELLING.*

1. Introduction

The structure of high-carbon steel grades, which contain 0.8% or more carbon, differs from low- and medium-carbon steels by the presence of a structurally free carbide phase. Carbides have an ambiguous effect on the performance properties of high-carbon steel grades. High hardness of carbide inclusions increases wear resistance, but with an increase in their size over 5 μm, the carbide phase becomes brittle and leads to the metal viscosity decrease. This decrease occurs both due to the higher elastic characteristics of the particle and due to its shape influence [1-2]. At the same time, an assessment of the structural and textural features of the rolled workpiece structure deserves special attention.

After thermomechanical treatment, some particles acquire elliptical outlines elongated along the rolling direction, in many cases acting as initial cracks. In order to eliminate the anisotropy, blanks from high-carbon steel are very often subjected to subsequent reforging, which allows to obtain globular carbide phases with sufficiently small particle sizes. After such processing almost all mechanical and operational characteristics of steel improve, including its contact endurance increases.

Structural analysis of carbonized layers of low-carbon steel shows that the outer hypereutectoid layer of such steel is characterized by a sufficiently ordered composition of a metal matrix and a carbide phase, the morphology of which is largely similar to the optimal structure of high-carbon steel subjected to reforging. Based on this, it can be concluded that full-scale modeling of the contact wear mechanism of forged high-carbon steel can be carried out using low-carbon steels subjected to carburization with subsequent heat treatment. This approach makes it possible to obtain an identical reforged structure of the tested outer layer of the material without performing a costly reforging operation in all respects.

2. Objects and research methods

For experimental evaluation of contact wear of high-carbon steel, a stand for testing materials for contact fatigue and wear was used [3]. 16MnCrS5 low-carbon alloy steel for surface hardening was chosen as a model material for the structure modeling of the hypereutectoid layer of high-carbon alloy steel subjected to reforging. Special samples were prepared from this steel to test on an experimental stand. Surface layer modification of the prepared samples was carried out by carbonization according to two different technological modes, characterized in that in the first case the saturation duration at a temperature of 920 °C was 8 hours, and in the second case saturation duration was 12 hours. Two batches of samples were obtained with 8 samples in each. After that, these samples were quenched at a temperature of 860 °C and tempered at a temperature of 200 °C.

After the surface layer modification, both batches of samples were subjected to a contact wear test according to the method discussed in detail in [4]. The wear assessment was carried out by directly measuring the depth of the wear hole using an hour-type indicator, which has a measurement accuracy of 0.01 mm. Further, the data obtained were compared with the wear measurement results obtained by examining them with an instrumental microscope. The obtained data were subjected to statistical processing by interval estimation of the mathematical expectation of the wear value using the Student's criterion with a confidence probability of 0.9.

The structural changes occurring in the metal surface layer after contact wear tests were studied using optical microscopy. Side surfaces of the samples directly subjected to wear were polished and etched.

The study of the stress-strain state in the area of pulsating stress was carried out using computer simulation by the finite element method in the university version of the ANSYS ED software package.

3. Results and discussion

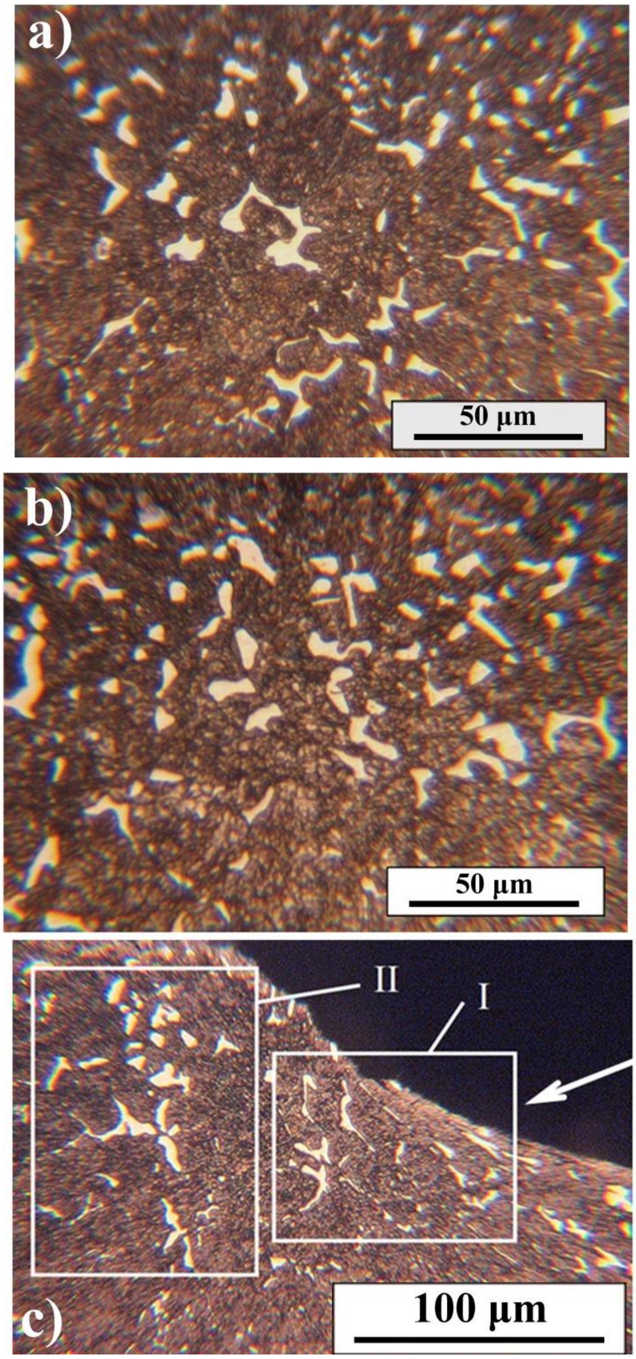
The peculiarity of the structure formation of carbonized layers of low-carbon alloy steels containing chromium is the formation of isolated carbide inclusions that do not form a solid cementite mesh. This morphological feature allows considering the carbonized layer structure of 16MnCrS5 steel as a model of a reforged layer of high-carbon alloy steel with a carbon content of more than 0.8%. As can be seen from Figure 1a-b, the structure of the carbide phase in the samples subjected to chemical-thermal treatment for different times is almost identical. The maximum depth of the hypereutectoid layer is 120 and 170 μm after saturation duration of 8 and 12 hours, respectively.

The effectiveness of quenching and low tempering is demonstrated by the graph in Figure 2a. The graph shows that the total depth of the hardened layer is about 1.5...1.7 mm, while the microhardness zone with a value of more than 6000 MPa (57 HRC) exceeds 1 mm in both cases. The same zone does not contain structurally free sorbitol crystals, which indicates the formation of the outer metal layer by the hypereutectoid and eutectoid sections of the hardened layer.

To assess the adequacy of the applied approach, a numerical model of the loaded part being tested for contact loading with a pulsating stress of 1300 MPa was constructed (Figure 3). It can be seen that the neighborhood of the face formed by the intersection of the sample end surface with its lateral planes is in the zone of the maximum equivalent stresses and strains calculated according to the Mises theory.

The value of equivalent stress (Figure 3a) at the edges of the sample reaches 1270 MPa, and in the center of the site decreases to 1000 MPa. The detected distribution gradient is identical for equivalent strain (Figure 3b). Maximum value of 0.006 occurs in the vicinity of the sharp edge of the sample. In the center of the contact area the amount of strain is reduced to 0.0046. The zone covered by the maximum equivalent stress and strain is located not only on the end surface of the sample, but also on the lateral plane to which the contact load is not applied. The dimensions and configuration of this zone have semicircular outlines and reflect the area of pitting development characteristic of contact wear.

The study of the distribution of normal stress shows that at the boundary between the zone of application of contact stress and the surface free from contact load, the magnitude of stress reaches 1500 MPa. At the same time, on most of the contact area the value of normal stress is 1300 MPa (Figure 3c). An increase in stresses is also observed in the area of crack propagation on the lateral plane of the sample. The magnitude of strain in this area reaches 0.0056 (Figure 3d).



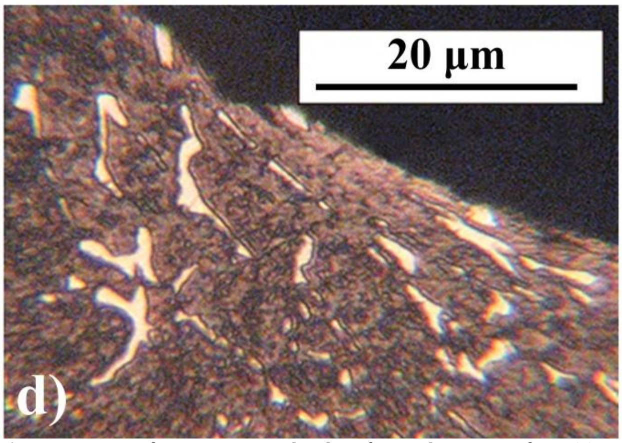


Fig. 1 *Structure of 16CrMnS5 steel: a,b - after carbonization for 8 (a) and 12 (b) hours; c,d - after 8-hour carbonization, quenching, low tempering and 1000 loading cycles with a contact stress of 950 MPa*

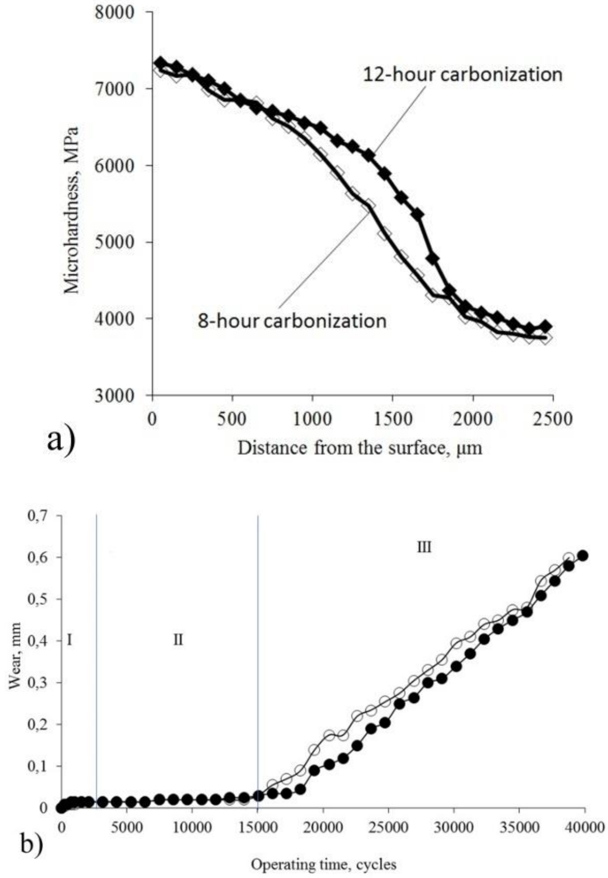
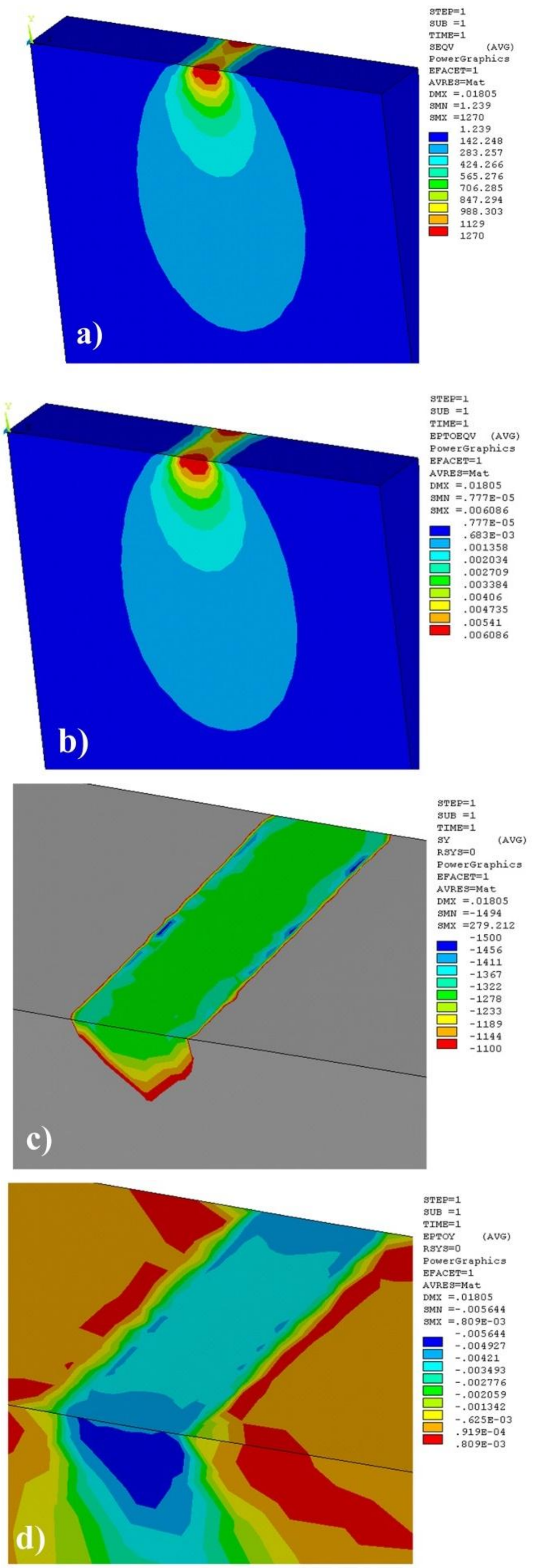


Fig. 2 *Experimantal curves: a - Microhardness distribution of 16CrMnS5 steel carbonized layers; b - Wear of 16CrMnS5 steel after carbonization, quenching, low tempering and loading with contact stresses of 950 MPa*



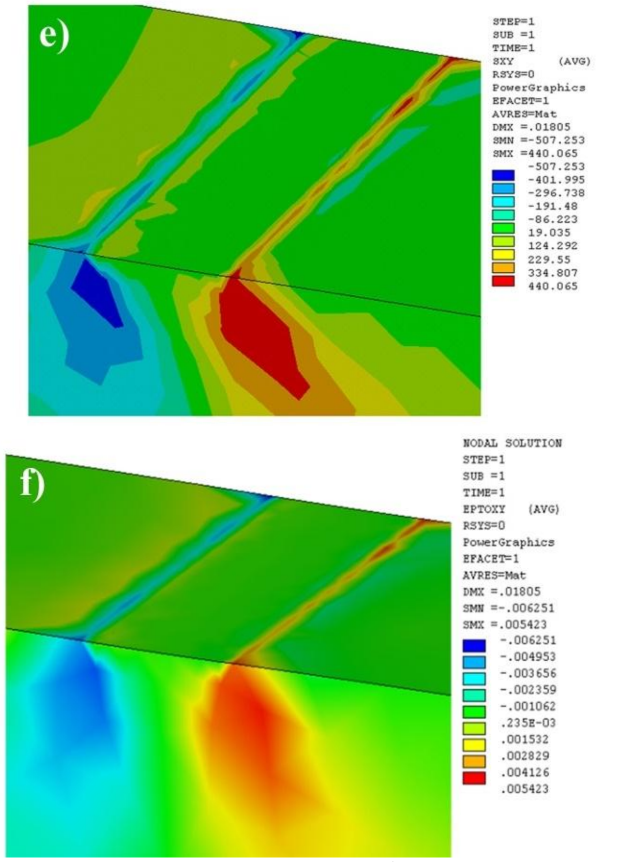


Fig. 3 *Stress-strain state: a,b - distribution of equivalent stress (a) and strain (b); c,d - distribution of normal stress (c) and strain (d); e,f - distribution of tangential stress (e) and shear strain (f)*

The boundary between the area of the working surface with an applied contact load and without it is under the influence of high tangential stresses, their values reach 500 Mpa (Figure 3e). Concentration areas tangential stresses arising on the lateral surface of the working part are located in the depth under the extreme points of load application to the sample surface. In these zones contact fatigue cracks originate and grow. This is confirmed by the shear strain distribution (Figure 3f).

The contact load, realized due to the interaction of the flat surfaces of the sample and the counterbody, causes an uneven distribution of stress and strain in the surface layer, the thickness of which does not exceed the hardening depth. The analysis shows the possibility of productive use of 16MnCrS5 steel carbonized layer as a model of a high-carbon steel reforged layer in the analysis of structural transformations occurring in a composite material with the development of contact fatigue processes in it.

The transformation of the carbonized layer structure revealed at the first stages of contact loading showed that, despite the high integral hardness of the composite material and the influence of high amplitude contact stresses (950 MPa), under comprehensive compression conditions of individual inclusions and their surroundings, the process of plastic deformation develops. The initial morphology of inclusions undergoes significant changes (Figure 1c-d).

The stretching of individual carbides along and the orientation of their longitudinal axis parallel to the contact strip surface indicates the hardening process. Instead of the initial structure with a uniform distribution of the carbide phase, signs of textural anisotropy with reinforcement elements of the high-carbon hypereutectoid zone of the modified layer with carbide inclusions are formed. Such structural evolution can be attributed to the self-improvement process of the material morphology, and its large-scale effect can be attributed to the self-hardening category, transferred to the original forged workpiece.

The fact of the structure further positive transformation of all the studied samples, as well as a quantitative assessment of the contact wear parameters in the form of wear curves shown in Figure 2b, testifies in favor of the formulated thesis. At the same time, both batches of samples are characterized by three pronounced stages of contact wear – run-in (I), precision resistance (II) and catastrophic wear (III).

4. Conclusion

The modeling hypothesis in laboratory conditions of contact wear tests of forged high-carbon steels with the use of carbonized layers of low-alloy low-carbon steels is formulated and tested. It is shown that the initial structure of the carbonized layer is identical to the structure of the forged metal, and the test conditions provide a directed force effect on the hardened layer. It is revealed that the local structure evolution in the contact loading focus has signs of self-improvement with the isotropic morphology transformation of the carbide phase into an anisotropic one with signs of textural riveting. The effectiveness of the structure evolution provides an increase in the resistance characteristics to contact fatigue with a hypereutectoid structure.

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