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Relationship between the Structural-Phase Composition and the Fracture Mechanism of High-Strength Contruction Steel

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In this work, the fracture surface of a 1.0481 steel sample having a layered ferrite-martensitic structure after special heat treatment was studied by optical and scanning electron microscopy. The samples were subjected to a shock-bending test at negative temperature. A sample made of the same steel with a homogeneous martensitic structure was used for comparative analysis. The features of the destruction mechanisms of the studied samples are described.

Keywords: construction steel, layered structure, fracture surface, visco-brittle mechanism, impact strength.

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The key requirement to selection of material for engineering structures is high structural strength, which is understood as material resistance to loads acting during operation of the facilities (static, impact, cyclic), including those in conditions of negative temperatures and corrosive environment. Impact strength evaluates quality of metal (cold brittleness) and reflects processes causing its behavior in different loading conditions, while standard static mechanical properties of metal in the state of cold brittleness remain unchanged [1–5]. To obtain required set of physical and mechanical properties of engineering structures, a composite material based on a high-strength steel can be used with a structure formed as alternating layers of ferrite and perlite. In this case, the structural-phase composition of the material, along with the strength of interlayer boundaries, has a definitive effect on mechanical properties of these composite materials.

The purpose of this work is to determine the interrelation between the structural-phase composition and the mechanism of destruction of a composite material based on high-strength structural steel. The subject of study is a hypoeutectoid structural steel with sulfur and manganese content at the top level allowed for the given grade composition.

Rolling of this steel with a reduction ratio of $\delta \geq 70\%$ followed by cooling to the intercritical interval of temperatures (ICI) yields a layered structure with maximum length of reinforcement fiber [6].

In this work we studied the structure of fracture after impact-bending test of high-strength structural steel 1.0481 having a structure of natural ferrite-martensite composite material after special treatment. Chemical composition of the obtained material was refined by the method of optical emission spectrometry (Q8 MAGELLAN). Metallographic examination was carried out using a Zeiss Axio Vert. A1 optical microscope. The volume fraction of phases obtained after heat treatment was determined with the use of digital image processing software. The impact-bending tests were performed in accordance with standard procedures with the use of a MK-30 pendulum with maximum pendulum lifting height and U-notch of the specimen. Microhardness of martensite was measured by PMT-3 instrument, indentation load was 50 g. Statistical processing was performed by the Student's method. Fractures were investigated using a MBS-9 binocular microscope, and their fine structure was studied by a Zeiss CrossBeam 340 double-beam scanning electronion microscope (the method of scanning electron microscopy).

In layered composite materials the main parameters of mechanical, physical and operating properties are affected by chemical composition and quantitative ratio of phases. The ratio of ferrite and martensite volume fractions, integral (Rockwell) hardness and microhardness of the reinforcing phase are dependent on the quench temperature from ICI: with increase in this temperature thickness of the martensite layer and integral hardness increase, while microhardness of the reinforcing phase decreases. Refined chemical composition of 1.0481 steel specimens is in conformity with GOST 19281–2014 [7].

Fig. 1, *a, b* shows microstructure of 1.0481 steel before and after quenching from ICI. After quenching at a temperature of 760°C with cooling in water followed by low tempering at 200°C a ferritemartensite structure was obtained with a volume fraction of reinforcing phase (martensite) of $\sim 60\%$ (Fig. 1, *b*). Microhardness of

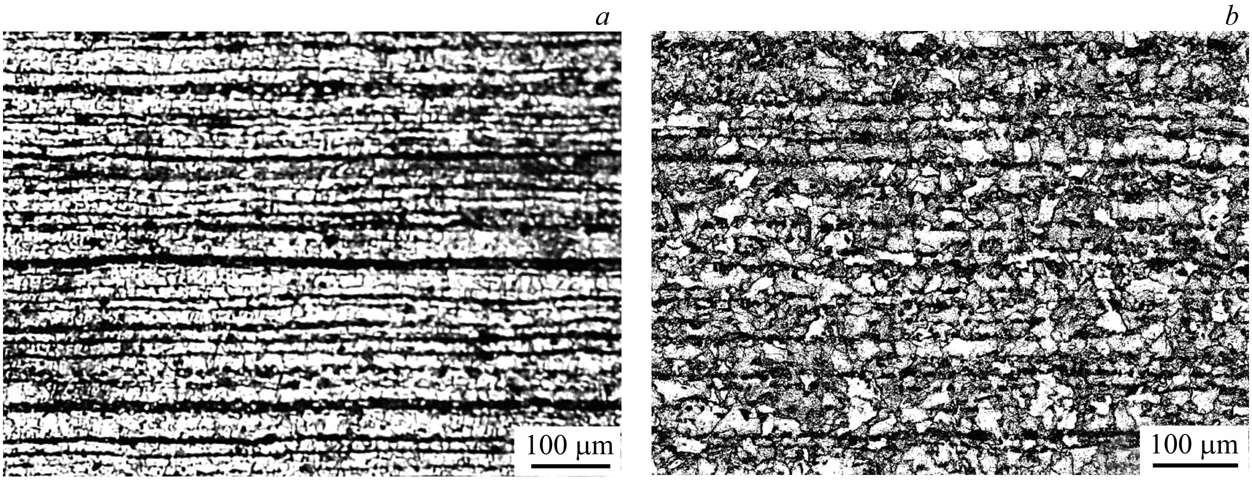

Figure 1. Microstructure of steel grade 1.0481. *a* — in hot-rolled state, *b* — after quenching from the ICI.

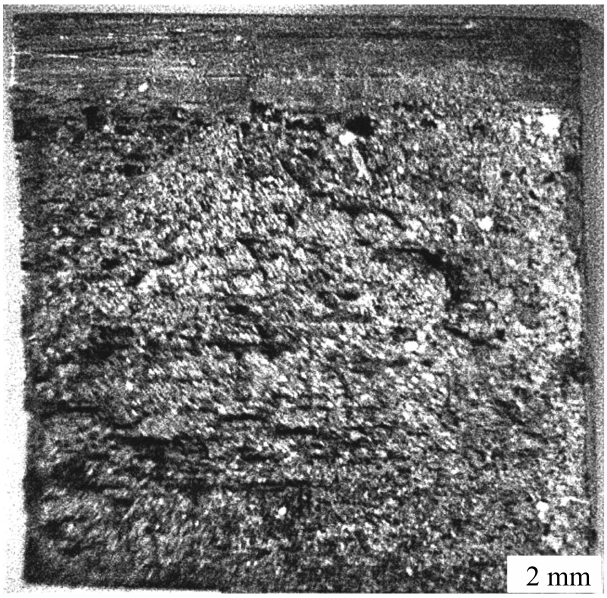

Figure 2. Fracture of 1.0481 steel with a layered ferrite-martensitic structure after an impact-bending test at -70°C.

martensite was 652 HV 0.05, microhardness of ferrite was 103.2 HV 0.05.

Bending tests were performed at a temperature of -70°C, which stability with an accuracy of 1°C was ensured by a mixture of carbon dioxide ice with ethyl alcohol. The composite material took up the load normally to the layers orientation (Fig. 2). For comparison, a specimen of the same steel quenched to martensitic structure was tested.

The performed impact-bending tests have shown that the specimen with a layered structure has an impact strength several times higher than that of the specimen with a homogeneous structure (40 and 25 J/cm^2 respectively). This is explained by the presence of 40% of ferrite in the composite material. Hence, the suggested composite material has an advantage in terms of mechanical properties [8,9].

The analysis of macrorelief of the composite material fracture (Fig. 2) has shown the presence of open flakiness areas on the fracture surface having a layer-stepped structure and oriented parallel to the surface of deformation, which is not typical for fractures with a homogeneous structure. The flakiness arises due to sulfide inclusions that take on the form of lines after hot plastic deformation.

In the analysis of specimen fracture by the method of electron microscopy we have been based on the idea of the fracture of perlitic structure steel, because perlite grain is a natural layered composite material. Three areas of the fracture surface were analyzed (Fig. 3): notch mouth area, central part, peripheral area.

In general, the specimen fracture is ductile-brittle, as evidenced by the presence of ductile dimple fracture areas on the fracture (Fig. 3, *a*) that are formed by the mechanism of micropores fusion, as well as the presence of individual facets of brittle fracture by shear that are formed as a result of martensitic plates cracking under the action of high local stresses. At the martensite–ferrite interface there are ductile fracture ties between the facets of intragranular shear (Fig. 3, *b*). The dimensions of shear facets match the dimensions of martensitic layers, which is correlated with the data reported in [10–12]. Also, individual secondary open cracks can be seen on the fracture that indicate cracking in the direction perpendicular to the main plane of the fracture (Fig. 3, *c*). The revealed specifics of the fracture are explained by the ratio between dimensions of martensite and ferrite layers, as well as high strength of the martensitic component.

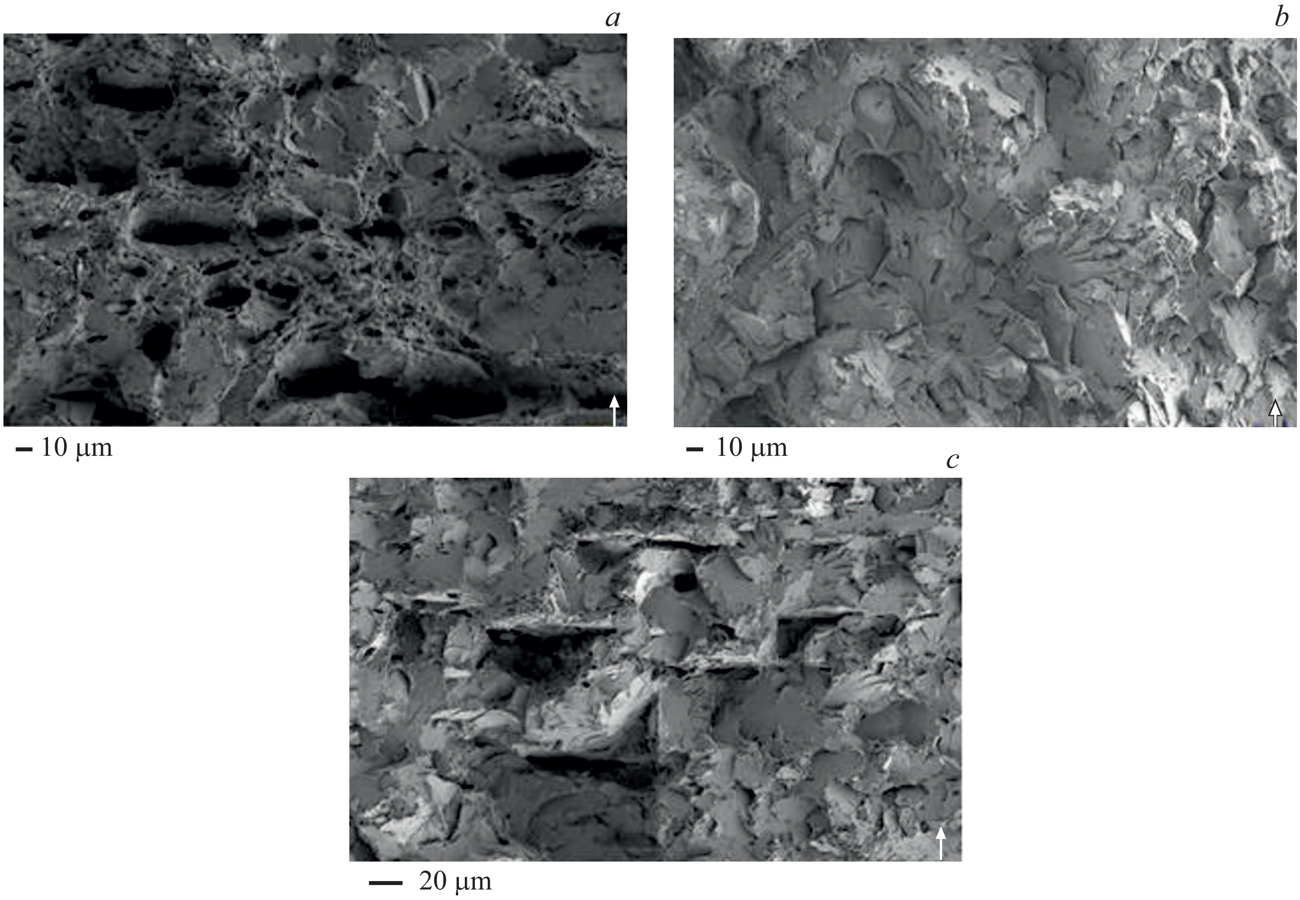

Figure 3. Electron microphotos of the 1.0481 steel fracture surface with a layered structure (arrow shows the direction of load application during the test). *a* — notch mouth area, *b* — central part, *c* — peripheral area.

Conflict of interest

The authors declare that they have no conflict of interest.

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