Studying the Impact of Blast Treatment on the Structure and Mechanical Properties of Carbon Steel

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Abstract. The study has covered the effects of blast treatment on the microstructure parameters and mechanical performance of carbon steel. The calculation results of examining the structure and properties of carbon steel in its initial state and after explosive hardening in various sections of cylindrical carbon steel workpieces have been verified with the finite-element analysis using the ANSYS Workbench software environment. Blast treatment has been demonstrated to lead to a perceptible change in the structural state of carbon (cementite) in steel.

1. Introduction
Explosive hardening is currently one of the most promising ways to improve the stress-strain behavior of steel [1]. The use of blast treatment coupled with advanced methods of modelling the blast propagation conditions in steel workpieces of complex geometry can be expected to accomplish the objective of hardening steel workpieces of complex geometry, such as rails. It is important to note that, apart from controlling the phase and structural state of steel and strengthening it, blast treatment helps, at the same time, to control the magnitude of internal stresses that exercise a noticeable impact on the stress-strain properties and service characteristics of rail steels [2].

The purpose of this study is to provide computer simulation and to analyze the impact of blast treatment on steel hardness and wear resistance.

2. Materials and methods
U8A Russian industrial steel (Fe – balance, 0.76%C, 0.27%Si, 0.23%Mn, the Russian analog of W108 steel by AISI) was the object of the study. The initiation site was placed on an attachable wheel. Test modes differed in the supporting plate thickness as well as the content and density of its material.

The finite-element analysis using ANSYS Workbench 19.2 was used to simulate the blast propagation within the steel workpiece. For computer simulation purposes, Steel 4340 behavior was used for the steel; Adiprene behavior, for the supporting plate; and Octol behavior, for the explosive. Detonation of a steel cylinder placed on a concrete support (CONC140MPA) was simulated. The values of the supporting plate density (\(\rho\)), its thickness (\(\delta\)), and shear modulus (\(G\)) were varied during the tests. The Johnson-Cook model was used in solving the problem [3].

A Leica DM IRM metallographic microscope was used to study the steel microstructure. HVS-1000 and Rockwell durometers were used to measure microhardness (HV) and Rockwell macrohardness (HRC). A Buehler Auto Met 250 honing machine was used to test abrasive wear resistance. Weight loss
over a given time interval was used as a measure of wear rate. A Sartorius CPA 225D analytical balance was used to take mass measurements. The structural condition of carbon in steel was studied through the internal friction method using the inverse torsion pendulum in the continuous heating mode at the rate of 10 °C/min and at a frequency of 9 Hz according to the technique [5]. Research was performed on cylindrical samples with a diameter of 19.8 mm and a height of 11 mm that were cut from the original or blasted workpiece. This cutting-up layout allowed for thorough studies of the impact of nonuniform blast propagation throughout the workpiece. Those samples were primarily selected for research, where the simulation results demonstrated the greatest changes in properties.

3. Experimental results

Analysis of the stress-strain properties distribution along the workpiece demonstrated no noticeable hardening in most of the cylinder. The maximum deformation and flow stress are observed near the explosives area (Figure 1). These values decrease with distance from the explosives area in all directions.

Figure 1. Distribution of plastic deformations (a) and flow stress (b) along the cylindrical workpiece made of U8A steel. Case of loading without a supporting plate

Figure 2. Distribution of plastic deformations (a, c) and flow stress (b, d) along the cylindrical workpiece made of U8A steel. Case of loading with a supporting plate of δ=2 mm, ρ=1.73 g/cm³, G=3.309 MP (a, b) and a supporting plate of δ=4 mm, ρ=1.32 g/cm³, G=2.206 MPa (c, d)

The blue-colored rectangular region in Figures 1b, 2b and 2d is a concrete support where a steel cylinder placed.
While modelling blast treatment, the thickness and density of the supporting plate were varied (Figure 2). Analysis of the simulation results demonstrated that the maximum plastic deformation (6.01%) is achieved during explosive hardening of the workpiece when the supporting plate has a thickness of $\delta=1$ mm, density of $1.32 \, \text{g/cm}^3$, shear modulus of $G=2.206 \, \text{MPa}$, while the maximum flow stress ($941.4 \, \text{MPa}$) is observed when these parameters are at $\delta=2$ mm, $\rho=1.73 \, \text{g/cm}^3$, $G=309 \, \text{MPa}$. The optimal ratio of the maximum flow stress ($916.1 \, \text{MPa}$) and plastic deformation (5.78%) is achieved with the supporting plate of $\delta=4$ mm, $\rho=1.32 \, \text{g/cm}^3$, $G=2.206 \, \text{MPa}$. Aggregation of the computer simulation results suggests that an increase in the supporting plate thickness and a decrease in its density can lead to hardening of the steel workpiece. Notably, the flow stress in each of the scenarios increased by about 1.1 times, which indicates a slight hardening of the material in certain areas of the cylinder.

The simulation results indicated that thermal effects are insignificant, and that the local heating of the workpiece does not exceed 100°C. It should also be noted that heat tints, which could have signaled a noticeable temperature increase, were not observed on the surface of the workpiece.

Studies of the microstructures showed that, following blast treatment, U8A steel has a platelike pearlitic structure (with a varying dispersion of cementite plates) with areas of spheroidized pearlite. It has been established that explosive hardening leads to an increase in areas of microstructure with spheroidized pearlite. This structural feature can negatively affect the stress-strain behavior (lower hardness and wear resistance) [4]. In addition, chaotically directed "sharp" cracks can be spotted in the samples treated in Mode 1 (without a supporting plate). It should be noted that in case of blast treatment with a supporting plate, no cracks were found in the microstructure (see Figure 3).

The average microhardness of steel in its initial state was $\sim 2,100 \, \text{MPa}$. Microhardness in areas with a platelike pearlite structure is $\sim 2,500 \, \text{MPa}$, while areas of spheroidized structure have lower hardness of 2,100 MPa. Blast treatment does not result in a noticeable change in macrohardness and wear resistance of steel, yet it is accompanied by a slight increase in microhardness in the areas of platelike pearlite (up to $\sim 2,800 \, \text{MPa}$) and spheroidized pearlite (up to $\sim 2,300 \, \text{MPa}$). Maximum steel hardness was observed in the explosives area, i.e. where the blast wave impact was the greatest.

![Figure 3. Photos of No.1 samples microstructure in the initial state (a), after treatment without a supporting plate (b) and with a supporting plate (c)](image)

![Figure 4. Mass loss dependence of the duration of abrasive wear tests. In Figure 4:](image)

![Figure 5. Temperature dependences of the shear modulus and internal friction for U8A steel in its](image)
Mode 3 means the case of loading with a supporting plate of $\delta=2$ mm, $\rho=1.9$ g/cm$^3$, $G=2.758$ MPa. 0, 1, and 7 in diagram legend denote sample numbers in initial state and after blast treatment (with a supporting plate).

The distribution of macrohardness was fairly homogeneous in the cross-section of the workpiece for each of the blast treatment modes. The average Rockwell hardness is at 16-18 HRC. The distribution of macrohardness in the cross-section of the workpiece is fairly homogeneous, with a slight decrease by 2-3 HRC in the central part. Wear tests showed that the loss of mass for the U8A steel samples in the initial state and after blast treatment is greater than for samples of U8 normalized steel (see Figure 4). In addition, blast treatment did not result in any marked increase in wear resistance of the steel.

The studies of internal friction have shown that in the initial state there is a peak of internal friction at the heating temperature of $\sim 160$ °C, probably of a dislocation nature (Figure 5). Blast treatment results in an increase in internal friction, which is likely to be caused by an increase in the density of lattice dislocations. The internal friction and temperature dependence diagram clearly shows an intense Snoek-Köster peak at $\sim 270$ °C. The result indicates that blast treatment increases carbon concentration at the cores of lattice dislocations, which is likely due to the "withdrawal" of carbon atoms from the plates of Fe$_3$C cementite. This result is qualitatively well in line with the previously described effect of spheroidization and strain-induced dissolution of cementite plates in carbon steel [6].

4. Conclusions
It is shown that the explosive loading process leads to relatively insignificant plastic deformation and an increase in the flow stress of U8A carbon steel. The finite-element analysis demonstrates that deformation is uneven in the longitudinal and cross-section of the workpiece while increasing the supporting plate thickness and reducing its density leads to the hardening of the steel workpiece.

It has been established that blast treatment does not lead to a noticeable change in the parameters of the U8A steel microstructure but causes a slight increase in hardness in the areas of platelike and spheroidized pearlite.

The internal friction method demonstrated that blast treatment increases the concentration of carbon in the cores of lattice dislocations, which is likely due to the "withdrawal" of carbon atoms from the plates of Fe$_3$C cementite. This leads to their partial spheroidization and reduces the wear resistance of the steel. The process of spheroidization and strain-induced dissolution of cementite plates negatively affects wear resistance of carbon steel and "compensates" for a possible increase in wear resistance and hardness of carbon steel during its deformation hardening through blast treatment.
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