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Numerical simulation of the stress-strain state of a coal seam caused by an explosion of a blast-hole charge with an annular gap

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Abstract. The computer simulation of the propagation of a blast wave generated by various explosives is carried out. The simulation used numerical methods to solve dynamic problems in the mechanics of a deformable solid, which allow one to investigate the development of waves during the explosion of charges of various shapes at different speeds of detonation of explosives and various conditions of placement of charges in the hole. The novelty of the research is related to analysis of conditions for the formation of a tensile pulse, which determines the opening of natural and induced defects in a zone remote from the explosion (from 20 to 100 radii of charge), which is known as the zone of explosive pre-fracture.

1 Introduction

Sudden outburst of coal and gas is one of the most catastrophic gas-dynamic phenomena in coal seams [1]. It manifests itself in spontaneous instantaneous destruction of a part of the coal seam near the mine workings, throwing of the destroyed coal into the worked-out space and enhanced gas emission. “Shock blasting” mode of the edge part of the coal seam is often used among the various measures used to reduce the risk of sudden outburst of coal and gas emission [2].

Shock blasting can either provoke gas-dynamic destruction of a part of the coal seam in the form of local outburst (but this removes the factor of instantaneity) [2, 3], or to create conditions for the quiet degassing of the coal seam and the subsequent reduction of the probability of coal and gas emissions [4-6].

The ambiguous effect of the explosive impact on the gas-saturated coal seam has not yet received a theoretical explanation and the mechanism of its action is not clear, but to study its impact on the coal seam, various studies are being undertaken.

The aim of this work is to study the impact of the blast wave on the most dangerous coal containing natural methane (up to 90%) in a dissolved state inside the coal substance. This coal does not contain macropores and initially is not permeable. Macropores and induced microcracks are developed under technogenic impact on coal. Dissolved methane is released by the diffusion mechanism in these pores and microcracks,. Then free methane

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is actively involved in the destruction of coal. The paper investigates the conditions of microcrack formation in the coal under the action of the blast wave. Our study may help in developing shacking blasting technology in coal mines.

2 Simulation of the action of an explosive wave

Under some simplifications, the conditions for the formation of tensile stresses in the blast wave, which determine the disclosure of natural and induced defects in the zone remote from the explosion, were investigated. The blast waves in coal mines are not shock one, so the stress wave in a continuous homogeneous elastic medium was considered in the simulation. The wave is caused by a sharp increase in the pressure of gaseous explosion products in the explosive chamber or well.

2.1 Calculation method

The studies started analytically for the spherical explosive chamber and described in [7] were continued numerically with the help of computer simulation of dynamic processes based on a combination of the finite element method (FEM) and the smoothed-particle hydrodynamics (SPH) method [8].

The advantage of the SPH method is the ability to calculate displacements with arbitrary deformations while maintaining the advantages of the Lagrangian approach. The SPH method is the method in which the material is divided into particles, for each of which the mass, density, position, velocity and stresses are known at any time. Derivatives included in the equations of mechanics are calculated using spline interpolation, in accordance with which each particle is an interpolation point at which the parameters of the deformable medium are known. The numerical solution in the whole integration domain is obtained by means of interpolation functions for which these particles are interpolation nodes. Thus, the computation of gradients reduces to the analytic differentiation of smooth functions.

A useful quality of the SPH method is the ability to represent the destruction of the material in a realistic form without additional conditions and without compromising the ability to perform further calculations. As soon as under the action of tensile stresses the condition of the particle exit beyond the neighborhood defined by the smoothing radius is satisfied, the interaction between neighboring particles disappears. Thus, the destruction of the material is numerically modeled.

The mesh-free basis of the Lagrangian SPH method eliminates the computational constraints on the significant deformations of the medium that naturally occur during detonation of explosives and the expansion of detonation products. Repeated comparisons of the results of computer modeling with experimental data and with calculations carried out by other methods [9-11] showed that the computational approach allows us to accurately investigate the explosive deformation and destruction of the rock mass and to obtain reliable results. A difference of results did not exceed 10%.

2.2 Wave stress calculations

The computational approach allowed for the conditions of spherical and cylindrical symmetry to take into account more adequately the detonation of explosives and design features of the charges used in practice. In the carried out calculations, the pictures of dynamic stresses in the blast holes and in the solid medium were obtained, the main attention was paid to the analysis of the tensile impulse in the blast wave in the area far from the explosion. This area is remoted from the center of the blast hole at a distance of more than twenty of its radii.

It is known that in the case of camouflet explosions of spherical and cylindrical charges in an infinite medium at the front of the wave, the radial and circumferential stresses are first compressive (here negative), but then become tensile (positive). Fig.1 shows graphs of the changes over time of the stresses σ generated by the wave during the explosion of the TNT charge at a detonation rate of 6930 m/s in a hole with a radius of r =2 cm. The stresses related to the maximum value of compression stresses in the hole (Q^* = 9.7915 GPa) are along y-axis, the time τ (in microseconds) from the moment of arrival of the blast wave in the considered point of medium is3 along the x-axis.

As can be seen from the figure, the largest value at the front of the wave has a tensile radial stress, in absolute units, the tensile value can be 300 MPa. The duration of the tensile pulse exceeds 20 μs, and at a point at a distance of 50 *r*, the tensile pulse is more longer (about 30 μm), although the magnitude of the tensile stresses there twice as less.

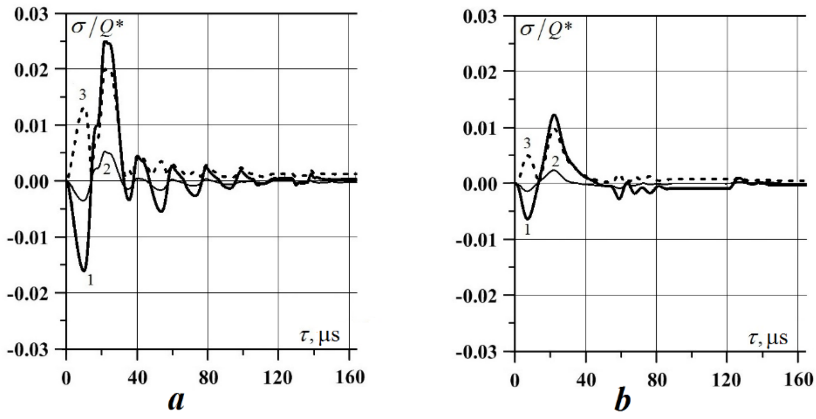

Fig. 1. Change of dimensionless radial (1), circumferential (2) stresses and von Mises stresses (3) in time τ at the front of the blast wave at distances from the center of the blast hole: ***a*** - 20 *r*, ***b*** - 50 *r*

Since the magnitude of the tensile stresses and the duration of the tensile pulse depend on the detonation velocity of explosives in the calculations, corresponding dependences were obtained for points located at different distances from the center of the hole (Fig. 2). It follows from the calculations that at a detonation velocity v exceeding 4 km/s, the magnitude of tensile stresses and their duration at the wave front are sufficient for the disclosure of natural and the formation of induced microcracks, as can be concluded from [7,12,13]. When the detonation velocity is less than this specified value, the tensile impulse becomes insignificant.

To assess the influence of design3 features of the explosive charges in the borehole calculations of the effect of the annular gap between the shell of the explosive device and the borehole wall by the amount of pulse stretching are carried out. The gaps between the shell explosive device and the wall of the well take place in practice, in particular when torpedoing coal seams. Sometimes the free space in the well is filled with inert material, such as water. Similar studies of the effect of the design features of the charges were carried out in [14].

Fig.3 shows the change in stresses at a point remote from the center of the blast hole at a distance of 20 *r*, at the arrival of the blast wave front for different values of air gaps Δ*s*. Fig.4 shows the dependence of the maximum radial stresses for different fillers of the annular gap.

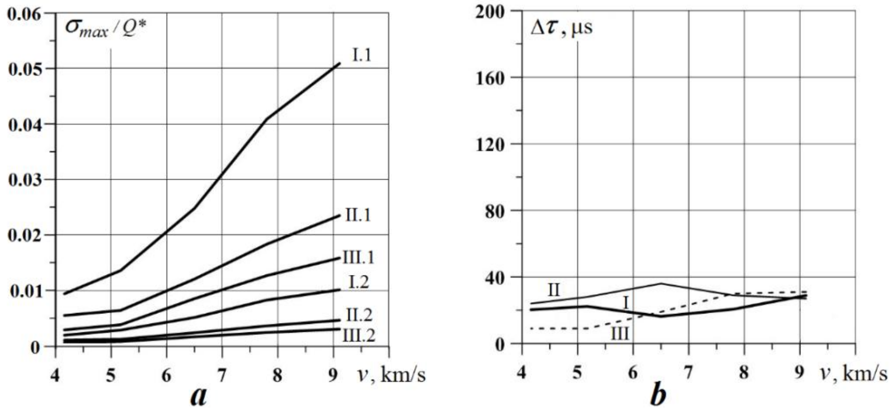

Fig 2. The dependence of the parameters of the tensile pulse at the wave front on the detonation velocity v at points at a distance: 20 r (I), 50 r (II), 75 r (III): ***a*** - the dependence of the maximum values of radial (1) and circumferential (2) tensile stresses; ***b*** - the dependence of the length of the pulse duration of tensile stresses $\Delta\tau$

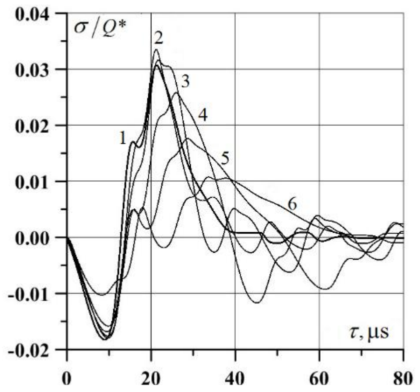

Fig. 3. Change of radial stresses depending on the time elapsed from the moment of arrival of the blast wave to a point at a distance of 20 r for different values of the air gap Δs: 1 - 0 (without a gap), 2 – 0.25 cm, 3 – 0.5 cm, 4 – 1 cm, 5 – 1.75 cm, 6 – 3 cm

Fig.4 shows the change in stresses at a point remote from the center of the blast hole at a distance of 20 r, at the arrival of the blast wave front for different values of air gaps Δs. Fig.5 shows the dependence of the maximum radial stresses for different fillers of the annular gap.

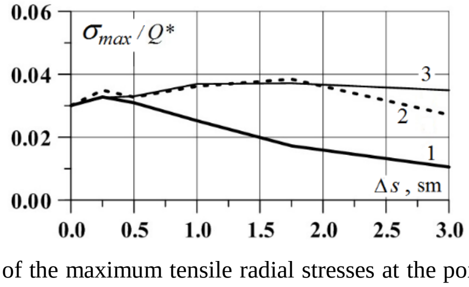

Fig. 4. Dimensionless values of the maximum tensile radial stresses at the point at a distance of 20 r from the wall of an explosive well depending on the magnitude of the gap Δs and filled it with an inert material: 1 - air gap 2 - the gap filled with sand, 3 - gap filled with water

3 The main results of the simulation

When using explosives with a detonation velocity of more than 4 km/s, the duration of the tensile pulse exceeds 15 μs, and the magnitude of the pulse can reach 300 MPa. Given that the inertial time of the dynamic fracture of many materials is evaluated in the order of 10 μs, we can conclude that when the explosive impact on coal seam with the use of explosives of high detonation velocity in the outburst-prone coal is possible disclosure of the natural and the formation of new micro-defects.

At a detonation velocity of less than 4 km/s, the development of induced cracks in the zone far from the explosion is impossible. In this case, according to the general ideas about the explosion in the rock formation of separate radial cracks is possible. These cracks develop from the blast hole into the depth of the rock mass under the action of the gaseous products of the explosion.

In practice, the technological gap between the well wall and the charge when using detonation explosives does not prevent the formation of a tensile pulse in the blast wave, and the water as a filler increases the amplitude of the tensile stresses.

We used these calculations as the basis for our studies of the regularities of filling of the induced microcracks free methane and the transition of these cracks in non-equilibrium state with the possibility of dynamic development and subsequent coal macrofracture in the form of outburst [15-17].

4 Conclusion of the technological orientation

The use of explosives with different detonation velocity can be quite an effective way to control the state of the coal seam by the crack-formation factor. When using explosives with high detonation velocity, it is possible to artificially provoke an outburst of coal and gas. When using explosives with a low detonation velocity, it is possible to obtain a mode of quiet degassing of the coal seam. This conclusion is independent of the design of the explosive charges used.

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