The problem of pore fracture growth in a marginal part of a gas-bearing coal seam

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Abstract. The model of geomechanic state of the coal massif inclosing in-seam working driven along a gas-bearing seam is introduced in the paper. The model is built on the basis of the fundamental concepts of deformable body geomechanics and elastic fracture mechanics. It suggests that the massif is in the state of plane deformation loaded with a stress gravity field. It is assumed that strength characteristics of a coal seam are less than the strength characteristics of the inclosing seam rocks but higher than the strength characteristics along their contact. Coulomb-Mohr and Mohr-Kuznetsov strength criteria are taken as the condition for appearing of inelastic deformation. In this connection, the problem of stress-deformable state of a coal rock massif appears to be an elastoplastic one. The pore gas pressure changes deep down the seam according to the hyperbolic tangent function. The model assumes that when setting the boundary condition on the seam contact with the side rocks the microfractures containing pore methane are oriented in the direction of a maximum principal stress.

1. Introduction
Geodynamic phenomena are referred to high-rate physical and mechanical processes that take place in rock massifs in mining areas. Rock bursts and sudden coal and gas outbursts are the most significant phenomena from the safety mining point of view. In spite of the fact that these phenomena are quite frequent in coal mines the existing prediction and controlling methods are not always effective [1-5] as this issue is still not well studied.

Contemporary concepts and notions on rock bursts and coal and gas outbursts are based on the hypotheses that they basically manifest in limited stressed marginal zones of coal seams. At present there are many theories that describe these types of geodynamic phenomenon [1]. However, due to the complexity of mathematical description of the processes that accompany these phenomena there is no unified theory on rock bursts and outbursts. It is important to note that the existing theories are unified in the fact that for estimation and description of these phenomena it is important to know the distribution character of the stress-strain state of a massif in marginal zones of a seam. The problem of a stress-strain state distribution usually reduces to defining bearing pressure parameters and they are the components of a stress tensor in marginal zones of a seam and the size of the inelastic deformation zones (limit stressed zones). It is rather a complex task, especially, if it is important to consider geological dislocations (faults) and the influences of other workings in calculating the massif.

It is known that in rock massifs as in any solid body there are always microfractures which being in the field of mechanical stresses can grow into macroscopic size [1]. Being a so called stress concentration source they become a reason for engineering structure distortions. In a rock massif,
especially while developing coal seams, free methane, that forms as a result of desorption due to the change of a stress state in zones of mining activity, enters into pores and microfractures under a certain pressure p. This fact can initiate in a coal rock massif a dynamic phenomenon in a form of broken coal and significant value of methane outburst into the working. Generally, the outburst is conditioned by the intensive growth of microfractures of significant values in border zones of a massif. Methane that occurs in microfractures, being under pressure, squeezes out the coal wall (curtain) which is situated between fractures (fracture) and a working face (side of the working).

2. Setting the problem and its solution
The problem on methane filled fracture growth consists of solving two sequential tasks. The first task is a problem of stress field construction in marginal zones of a seam. The second task is a problem of the fracture growth under the influence of methane in the field of defined stresses.

The first task is set as follows. In a rock massif modelled by the infinite plane there is an extensive rectangular-sectioned working with \( b \times h \) dimensions driven in \( H \) depth along the coal seam on all its thickness \( m \). The massif is loaded with a gravity pressure \( \gamma H \) up and down, and in the sides \( -\lambda \gamma H \) (\( \gamma \)– rock specific weight, \( \lambda \)– lateral pressure coefficient). Coordinate system \( y0z \) coincides with central axes of a working. As a working path along \( x \) axis prevails significantly over the sizes in \( 0yz \) plane than we may consider the rocks in its vicinity to be in a state of plain-strain deformation. It is also accepted that contractive normal stresses are positive and the stretching normal stresses are negative. Strength characteristics of a seam are less than strength characteristics of inclosing rocks but higher than strength characteristics along its contacting with the massif that is why limit stressed zones with \( L \) dimensions are formed in marginal seam zones of the working situated in a certain depth (figure 1).

![Figure 1. Calculating scheme of a task on a stress state of a massif with an in-seam working. 1 – a working, 2 – coal seam, 3 – limit stressed zones.](image-url)
The substitution of limit stressed marginal zone of a seam by normal and shearing (tangential) stresses acting in it as it is done in [6–8] allows reducing the problem on geomechanic state of a coal rock massif inclosing a coal seam with a working driven along it to an elastic boundary value problem. This problem can be solved with the help of boundary-element method [9–11].

The problem of methane influence on geomechanic state of a coal seam marginal zone is rather complicated and, eventually, does not have a conventional solution at present. In this connection when solving it the following suppositions are formulated: all the fractures in marginal zones are open and filled under the pressure with methane, the contact between their edges is impossible; normal to them together with the direction of the principal stress make an angle $\pi/2$ [1].

Methane pressure changes smoothly according to a certain dependence [2, 3]. At the edge of the seam, it equals to atmospheric pressure and in a significant distance from it methane pressure reaches hydrostatical pressure of a liquid at this depth. Depending on gas-bearing capacity and permeability of a seam, the intensity of methane pressure growth can vary and in relatively close distance from the edge of the seam, it approaches to hydrostatic pressure value.

The function in a form of hyperbolic tangent can be used as analytical dependence that describes methane pressure change

$$p(y_1) = p_0 + (p_\infty - p_0) \tanh(t \cdot y_1),$$

where $p$ is methane pore pressure in a coal seam, $p_0$ is atmospheric pressure, $p_\infty$ is free methane pressure at the remote border, $y_1$ is a coordinate that is measured off from the edge of a seam ($y_1 = y - b/2$), $t$ is a parameter that reflects tangent curve (tangensoid) profile in equation (1).

As it is mentioned above, in coal seams, there are always fractures filled with pressured methane so, under certain conditions, they can grow. In this connection it is important to set physical and mechanical parameters of the medium which make the growth of gas-bearing fractures possible as their intensive growth, as a rule, brings about a sudden outburst.

As it is known, when theoretical analysis of strength problem and the problem of distribution of large displacement discontinuity in solid deformable bodies is done, thermodynamics universal equation is used. This equation can be applied to the body with a fracture, to both adjoin states of it: before and after its growth into a certain distance $\Delta l$. In quasi-static processes this equation is written as [12–14]

$$k_I^2 + k_{II}^2 = \frac{E \cdot P}{1 - \mu^2},$$

where $k_I$ is a stress intensity coefficient, conditioned by the influence of a normal (wedging) load $p_I$ at the edges of a fracture, $k_{II}$ is a stress intensity coefficient from the influence of tangential load $p_{II}$ also at the edges of a fracture, $E$ is a seam deformation modulus in a limit stressed zone, $P$ is a density of a surface energy which is necessary for the formation of a unit surface.

Coefficients $k_I$ and $k_{II}$, included into equation (2) are defined as following:

$$k_I = (p - p_I)(\pi d_0)^{1/2}, \quad k_{II} = p_{II}(\pi d_0)^{1/2}.$$  

In equation (3) $p_I, p_{II}$ are defined by the stresses acting at the “remote” border and in this case they are connected with the components of a stress field in the vicinity of the working and fracture angle $\theta$ to $y$ axis as follows [12, 14]

$$p_I = \frac{\sigma_z - \sigma_y}{2} + \left( \frac{\sigma_z - \sigma_y}{2} \right) \cos 2\theta + \tau_{yz} \sin 2\theta, \quad p_{II} = \left( \frac{\sigma_z - \sigma_y}{2} \right) \sin 2\theta + \tau_{yz} \cos 2\theta.$$
Substituting equations (3) into equation (2) allows defining methane pressure, which is called first critical pressure [12 – 14]

\[ p_1 = p_I + \left( \frac{E \cdot P}{\pi l_0 (1 - \mu^2)} - p_N^2 \right)^{1/2}, \tag{4} \]

where index 1 stands for the number of the first critical pressure.

Equation (4) defines the value of methane pressure in a fracture that corresponds to the beginning of its growth (fracture initiation). The pressure value during the growth of the fracture on a given distance is defined according to the equation of the second critical pressure \( p_2 \) (5), that corresponds to its sustainable growth and is determined from the formula [12, 14]:

\[ p_2 = \frac{\pi}{2 \arctg \left[ \frac{E \cdot p}{\pi (l - \mu^3)} - p_{Nl}^2 \right]^{1/2}} p_I + \left( \frac{E \cdot P}{\pi l (1 - \mu^2)} - p_N^2 \right)^{1/2}, \tag{5} \]

where index 2 stands for the number of the second critical (breakdown) pressure.

Below you may see the results of the research for geomechanical state of the rock massif inclosing gas-bearing seam and a working driven along it.

3. Computational experiment and the analysis of the received results

Computational experiment is carried on applying basic parameters of the massif and the working: \( H=800 \text{ m}, \gamma=25 \text{ kH/m}^3, \lambda=1; \) ultimate linear compression strength of a seam \( \sigma_0=10 \text{ MPa}, \) angle of internal friction of a seam \( \mu=20^\circ; \) cohesion coefficient and internal friction angle on the contact of a seam with a massif \( K'=0, \rho=10^\circ, \) \( h=m=3 \text{ m}, b=10 \text{ m}, p_0=0.1 \text{ MPa}, E=1000 \text{ MPa}, \mu=0.2, P=0.0087 \text{ MPa/m}. \) The values of \( \tau \) parameter that characterizes the profile (form) of methane pore pressure tangential curve equals to 0.4. The results are given in figures 2 – 5.

Figure 2 shows the dependency graphs of some researched parameters along \( VA \) line (figure 1). Numbers 1 and 3 are the curves of normal \( \sigma_1 \) and tangent (shearing) \( \tau_1 \) stresses in limit stress (plastic) zones, numbers 2 and 4 are the curves of these stresses in elastic zones. Curve 5 is a graph of variance for methane pore pressure. Graph 6 according to equation (4) corresponds to \( p_{Nl}, \) and it is built when \( l_0=0.05 \text{ m}, \) and a gas-bearing fracture (fractures) is directed along primary stresses \( \sigma_1, \) that act in a coal seam roof.

As it follows from figure 2 maximum bearing pressure equals to 1.816 \( \gamma H, \) and the size of a limit stressed zone \( L \) equals 5.55 \text{ m}. It is also seen from the figure, critical pressure curve 6 is situated higher than critical pressure curve 5. As the ordinates of a methane pressure graph are less than the ordinate of a critical pressure graph then the growth of gas-bearing fracture is impossible.

As the ordinates of graphs 5, 6 (figure 2) at the area of a seam with 3 m size adjacent to the side of the working differ from each other less than in other areas, then it is logically to suppose, that the fracture growth will primarily take place in that very area of a seam which is called border zone of a coal seam. In this connection the results of the researches about the condition of a coal seam with gas-bearing fractures in its border zones are introduced below.

In figure 4 a the graphs of variance for methane pore pressure (curve 5) and the first critical pressure (curve 6) along the coal seam roof are built, and in figure 4 b the graphs of these parameters are built along the horizontal axis of a seam. In calculations, the following is set: \( l_0=0.3 \text{ m}. \)

The analysis of the graphs shows that in the second case when the distance from the working face deep into the seam is over one meter, methane pressure in a fracture on its axis reaches the value of the first critical pressure and, consequently, the growth of the fracture in this area of the seam is possible.
Along the coal seam roof, the critical pressure everywhere prevails over methane pore pressure and this is the reason why the growth of the fracture is impossible.

![Graph of variance for some researched stress parameters along a coal seam roof](image1)

**Figure 2.** The graphs of variance for some researched stress parameters along a coal seam roof.

![Normal stress curves along a seam roof](image2)

**Figure 3.** Normal stress curves along a seam roof.

In figure 5 the graphs of pore and the first critical pressures when \( l_0 = 0.6 \) m are built. As it follows from figure 5 a, under such length of the fractures the graphs along the seam roof are tangential only in one interval (\( y = 6.8 \) m) and this is the reason why the growth of the fracture in this area is possible. The graphs of pressure distribution along the seam axis are tangential in two points (\( y = 5.7 \) m, \( y = 6.3 \) m). At this area methane, pressure prevails over the first critical pressure and, consequently, the growth of the fracture (fractures) must take place.
Figure 4. Graphs of methane pore pressure and the first critical pressure in a border zone of a seam. $l_0=0.3$ m.

Figure 5. Graphs of methane pore pressure and the first critical pressure in a border zone of a seam. $l_0=0.6$ m.

In conclusion, it should be noted, that the presented material is limited by the results of gas-bearing fracture growth directed only along the primary stresses $\sigma_1$. According to the results of the research when the direction of the fractures is different the probability of their growth decreases drastically. As the direct axis of a seam is a line of symmetry then vertical stresses $\sigma_z$ along it coincide with primary stresses $\sigma_1$. That is why only vertical fractures on $y$-axis were considered.

Within the contact of a seam with the roof rocks beside vertical normal stresses there are also tangent (shear) stresses. In this connection, the direction of primary stresses $\sigma_1$, together with positive direction of $y$-axis make an angle differing 90 degrees. Consequently, a favorable condition for
growing of fractures in a coal seam roof is their inclined direction that also coincides with the direction $\sigma_1$. This direction was considered in the calculations.

4. Conclusions
1. The developed model of geomechanic state of a massif inclosing an in-seam working provides the researches of a coal seam stress state and allows forecasting the growth of the fractures filled with pore methane.
   2. Distribution of vertical normal stresses in a seam roof and in its axis is not equal: in a roof on, a major part of a stressed zone, the stress values prevail over their values along the seam axis, and only on a rather small area, which is situated near the border of the working, stresses along the axis are higher than in the seam roof.
   3. The growth of gas-bearing fractures in unbroken seam with limit stressed marginal zones at the sides of a single working is possible only in limited cases. Firstly, the fractures should be directed along principal stresses $\sigma_1$, secondly, they should have rather large sizes and thirdly, the graph of pore methane pressure must be rather steep.

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