Optimization of Energy Input in the Fracture Process of Rocks

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Abstract. The problem of energy input optimization during the fracture process of rocks is considered to be a part of fracture mechanics. For fracture prediction the incubation time criterion is used. The Hertz solution for the contact problem is applied for calculation of the contact forces. The estimation of energy necessary for strength pulse initiation during a single cycle of vibrational drilling is performed. The dependence of this energy on the loading pulse duration is investigated. The average breaking force is evaluated.

Introduction

At present vibrational drilling is one of the most prevailing ways of rock treatment [1]. The efficiency of the drilling process increases with the action of impact pulses combined with the translational and rotational motion of the drilling tool. In work [2] it is shown that there exists an optimal frequency of imposed vibrations, which significantly raise the fracture process efficiency. Impact pulses lead to high rates of loading. Therefore, it is necessary to take into account the dynamic properties of the treated rock for finding the optimum drilling technology mentioned above.

Analyzing the dynamic strength of different materials, one should note that the traditional point of view on this problem does not provide a satisfactory explanation of the observed phenomena. There are many experiments, which give evidence that in the case of high rate loading a material can withstand stresses significantly higher than in quasistatic loading. For the explanation of this ~~fact~~ there were attempts made to generalize the static fracture criterion for high rate loading. Therefore, the notion of the so-called dynamic strength of materials was introduced. Its value depends not only on the rate of loading but also on the impact pulse shape [3,4]. In practice the application of this generalized static fracture criterion is very difficult because it is impossible to make experimental measurements measure the dynamic strength for a wide multifold of impact shapes.

In the present work the fracture criterion based on the incubation time concept is used since it permits to predict a fracture for wide scale loading pulses with arbitrary shape [5,6,7,8]:

$$\frac{1}{\tau}\int_{t}^{t-\tau} dt' \frac{1}{d}\int_{0}^{d} \sigma(t',r)dr \le \sigma_c \ , \qquad (1)$$

where τ is the incubation time, d is the linear fracture size parameter, which is the characteristic of the scale level [9] and σ_c is the static strength of material. Applying this criterion to experimental results in dynamic fracture of rocks described in works [10] the parameters τ and d were determined for corresponding materials. Knowing the values of these parameters one can identify the threshold amplitude for load pulses of certain width.

For estimation of energy which is necessary for threshold impulse initiation in elastic media because of contact interaction, the Hertz problem is considered. The spherical solid particle in radius R and velocity V impacts the surface of the elastic half-space, in our case it is a rock. Using the motion equation of particle and quasistatic Hertz theory of impact it was shown [11] that maximum (radial) rupture stress in surface points can be evaluated as:

$$\sigma_r(V,R,t) = \frac{1-2\nu}{2}\frac{k\sqrt{h(t)}}{\pi R}, \qquad (2)$$

where $k = \frac{4}{3}\sqrt{R}\frac{E}{(1-\nu^2)}$, ν is Poisson ratio of elastic media, E is Young's modulus. The temporal dependence of penetration depth $h(t)$ can be properly estimated by following expression:

$$h(t) \approx 0{,}995 h_0 \sin\left(\frac{\pi t}{t_0}\right). \qquad (3)$$

The maximum depth of penetration h_0 and the time of impact t_0 are calculated by formulas:

$$h_0 = \left(\frac{5mV^2}{4k}\right)^{\frac{2}{5}} \text{ и } t_0 = 2{,}94\frac{h_0}{V}, \qquad (4)$$

where m is a mass of particle. It is supposed that the process of fracture is a penetration of the spherical particle into the elastic half-space. The kinetic energy of this particle can be compared with the energy necessary for the origin of rock fracture. Thus, it is possible to express the rupture stress as a follows:

$$\sigma_r(V,R,t) = \sigma_{\max}(V,R)\sqrt{\sin\left(\frac{\pi t}{t_0}\right)}, \qquad (5)$$

where $\sigma_{\max}(V,R) = \frac{1-2\nu}{2}\cdot\frac{k}{\pi R}\sqrt{0{,}34 t_0 V}$ is magnitude of rupture stress impulse.

Substituting the expression for tension stress (5) in criterion (1), the dependence of the threshold amplitude of fracture pulses from load duration can be calculated.

$$\sigma^*_{\max} = \frac{\sigma_c \tau}{I_{\max}}, \qquad (6)$$

where $I_{\max} = \max_t \int_{t-\tau}^{t}\sqrt{\sin\left(\frac{\pi t'}{t_0}\right)}dt'$ is a maximum of the integrated function of the pulse shape.

Using the expression (6), it is possible to graph the dependence of the threshold amplitude $\sigma^*_{\max}$ on impact duration t_0 (Fig.1). It has been done for sandstone which has the follow strength parameters: $\sigma_c = 31{,}18$ MPa and $\tau = 54$ mcs.

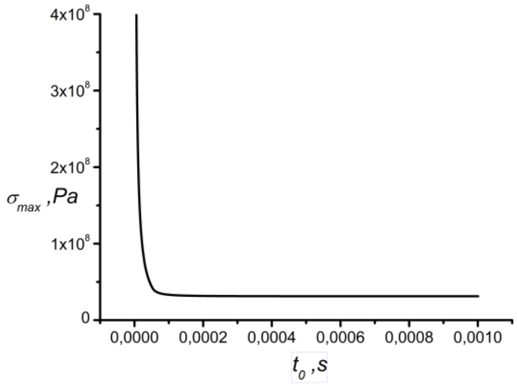

Fig 1. Dependence threshold pulse amplitude on the fracture load duration for sandstone

Using equations (2)-(5), it is possible to express the kinetic energy of the particle in terms of duration t_0 and amplitude $\sigma_{\max}$ of the tensile pulse which originated in the media after collision:

$$\varepsilon = \frac{mV^2}{2} = k_1 \cdot \frac{t_0^3 \sigma_{\max}^{\frac{13}{2}}}{\rho^{\frac{3}{2}} E^4}, \qquad (7)$$

where $k_1 = \frac{2}{3}\frac{\pi^5}{(2{,}94)^3}\left(\frac{5(1-\nu^2)}{4}\right)^4\left(\frac{6}{5(1-2\nu)}\right)^{\frac{13}{2}}$ is a non-dimensioned coefficient and ρ is the density of the particle. The value of the parameter ρ depends on the depth of separated layers in the material. By substituting the threshold amplitude of the fracture pulse into equation (7) the dependence of the energy spent on fracture versus impact duration can be calculated. The graph of this dependence is shown in Fig. 2. It was calculated for sandstone and all necessary data for this material is given in work [10]:

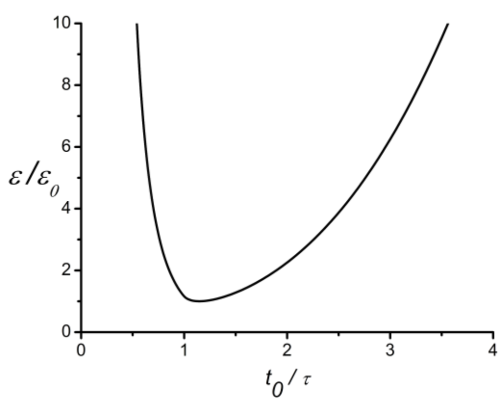

Fig 2. Dependence of the energy spent on fracture versus impact duration

It is demonstrated that there is an optimal duration of the threshold fracture pulse which requires for its initiation a minimum quantity of energy. The same dependence was observed for fracture of the media with cracks [12]. The existence of energetically optimal duration of the threshold pulse allows to explain the decrease of the contact forces in the process of vibrational fracture of the rocks.

The dependence of the static fracture force on the width of the separated layer Δ can be estimated with the relation of the contact force P to the contact area radius a:

$$a = \left[3 \cdot P \cdot \left(1 - \nu^2\right) \cdot \frac{R}{4 \cdot E}\right]^{\frac{1}{3}}$$

Assume the separated layer width Δ is in proportion to the contact area radius: $\Delta = k(\Delta) \cdot a$, where $k(\Delta)$ is a coefficient of proportionality. Thus, the static fracture force can be evaluated by the following expression:

$$Pc(\Delta) = \frac{4}{3 \cdot \left(1 - \nu^2\right)} \cdot \frac{E}{R} \cdot \left(\frac{\Delta}{k(\Delta)}\right)^3 \tag{8}$$

Young's modulus and Poisson ratio have the following values for sandstone: $E = 62 \cdot 10^9$ Pa, $\nu = 0.3$. Suppose the static force $Pc = 500$ N is required for separation of the layer with thickness $\Delta = 10^{-2}$ m (radius $R = 5 \cdot 10^{-3}$ m). Thus, using equation (8) the value of the coefficient $k(\Delta) = 33$ can be calculated. The obtained dependence of a static fracture force on width of separated layer is shown on Fig. 3.

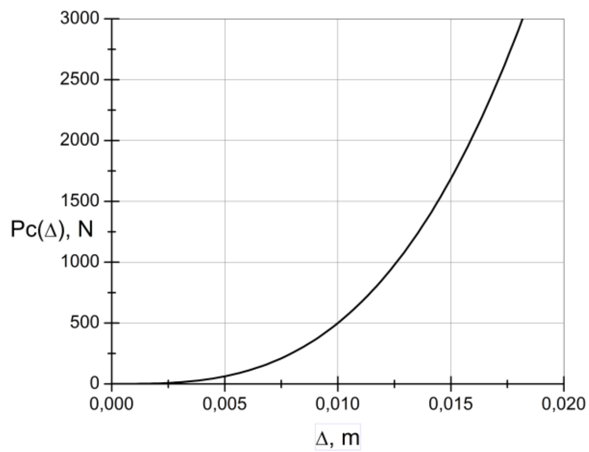

Fig. 3. Dependence of a static fracture force on width of separated layer

It is reasonable to suppose that the energy necessary for threshold pulse initiation equals to the work of the average breaking force. Hence, the average value of this force can be estimated by the following expression:

$$P_{fr} = \frac{\varepsilon}{d},$$

where d is a linear fracture parameter which is a characteristic of this scale level, for sandstone $d = 0.93$ mm. The increase of load duration leads to rise of the fracture force until it reaches the value of the static fracture force. This means that the load duration comes up to value t_0^* and material begins to take up the load like in a static case. The dependences of the average fracture force on load duration for different widths of the separated layer are shown on Fig. 4.

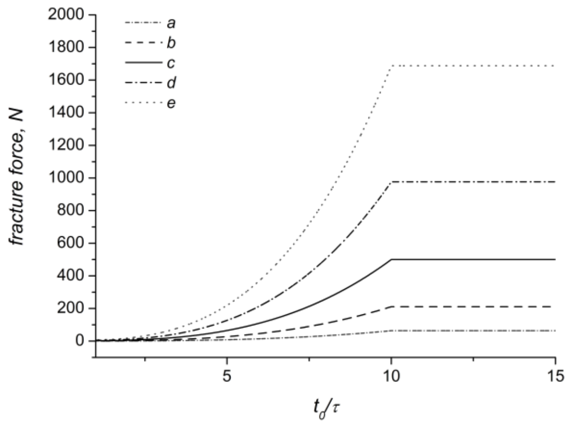

Fig. 4. Dependence of the fracture force on load duration for different width of separated layer Δ: *a*-5 *mm*,*b*-7.5 mm, *c*-10 mm, *d*-12.5 mm, *e*-15 *mm*.

The fracture load duration depends not only on the added oscillation frequency but also it depends on the feed rate of the tool. The feed rate growth leads to a decrease of the added vibration influence. When the feed rate reaches a certain critical value Wc and the tool is in a fixed contact with the treatment material, the fracture process approaches a stationary state. Assume that duration of the single load t_0 relates to feed rate W by the following equation:

$$t_0(W) = \frac{1}{2 \cdot f} + \frac{W}{Wc} \cdot \left(t_0^* - \frac{1}{2 \cdot f} \right) \tag{9}$$

Using equation (9) it is possible to graph the dependence of fracture force on the feed rate (Fig. 5).

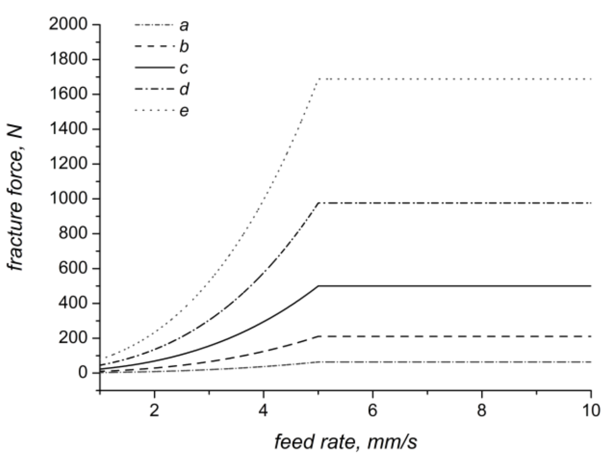

Fig. 5. Dependence of the fracture force on feed rate for different width of separated layer Δ: *a*-5 *mm*,*b*-7.5 mm, *c*-10 mm, *d*-12.5 mm, *e*-15 *mm*.

For calculation of this dependence the following parameter values were used: $W_c = 5$ mm/s and vibrational frequency $f = 5$ kHz.

Conclusion

Application of a structural temporal approach allows the ability of the energy input optimization in the fracture process of rocks to be shown. The addition of vibration-on the tool leads to a significant decrease of the fracture force. The suggested method permits a quantitive estimate of the fracture force for different feed rates of treatment.

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