Experimental investigation of crack formation in rock mass under impact fracture by a hard indenter

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Experimental investigation of crack formation in rock mass under impact fracture by a hard indenter

LV Gorodilov and VP Efimov*

Chinakal Institute of Mining, Siberian Branch Russian, Academy of Sciences, Novosibirsk, Russia

E-mail: *efimov-pedan@mail.ru

Abstract. The technique for determining geometric parameters of cracks formed in rock mass under penetration of a hard tool is presented. The results of rock fracture as impact craters and main cracks formed in a marble block after penetration of a wedge-shaped steel tool are discussed. The photographs of the craters and polished sections of drill cores are given.

1. Introduction

Impact fracture of rocks is a method of wide application in mineral mining in destruction of rocks by hammers, in breaking of oversizes, or in rotary–percussion drilling. Although the process remains of concern as judged by numerous experimental and theoretical investigations undertaken, the problem of quantitative description of impact fracture and efficient calculation modeling for predicting its results is far from being solved up to the resent moment. Intrinsically, failure mechanics has initiated a new school on contact failure named Indentation Fracture in the English-language literature. The difficulty of the research consists in extreme concentration of all processes that result in failure. This means that origination of cracks in the conditions of complex stress state deserves close attention. Rather strongly localized volume of material under an indentation tool, being in plastic state due to high compressive stress, is large relative to an incipient crack in the beginning of the process and turns out to be small at the stage of the main crack development. Consequently, the contact failure models embrace both plastic and elastiplastin deformation of a medium under an indenter, as well as brittle crack formation and propagation. Modeling contact interaction using elastic solutions is classic, and such solutions are available in educational books (Hertz contact, Boussinesq problem). Modeling of plastic contact for a wedge was started in [1] and was extended in [2] with regard to strengthening of material under static indentation. Various aspects of rock fracture under indentation of hard tools are discussed in [3–6].

Models of contact-induced fracture verified experimentally in static or dynamic indentation tests. Results of fracture under indentation of a hard tool (indenter) in rocks are mostly estimated by geometrical parameters of a formed crater. The crater is formed either due to plastic deformation of rocks directly in the zone of contact, or due to rock disintegration while edge cracks develop from the contact zone and expose. It is found [4, 7–10] that a system of cracks originates under contact fracture, and the sizes and orientations of the cracks depend on the properties of rocks and on the parameters of indenter (geometrical sizes, weight, pre-impact velocity). Furthermore, axial cracks under a wedge open and grow under loading, and edge cracks propagate under stress relaxation. Under repeated impacts, the developed cracks can exert considerable influence on development of a new system of cracks. Dimension of the plastic deformation zone can be estimated by measuring the indentation depth (crater) whereas determination of penetrated cracks under the wedge impacts is experimentally difficult. When studying formation of cracks under indentation of a tool to small samples of rocks, alongside with parameters of a crater, some information can be obtained by visual inspection (exposure of some cracks on the sample surface), ultrasonic sounding or simply saw cutting. In a full-scale experiment, when the listed approaches are impracticable in view of the large dimensions of samples, it seems acceptable to carry out core sampling at the fracture point and, then, to process cores by sawing or polishing. Such procedure is described in [11]. This study aims to improve the procedure in terms of cores taken at the repeated impact point in a marble block.

2. Description of the experiment scheme and results

The method of impact action on a marble block is in detail presented in [12]. A tool was a blunt wedge with a length of 30 mm and an angle of 60°. Rock mass was represented by a marble block 0.95×0.95×1.5 m 4000 kg in weight. Operation of an impact machine was simulated by a pendulum hammer (Figure 1), which allowed varying blow energy and blow structure by changing weights in the piston–impact tool system. In the tests, piston *4* was brought to a wanted velocity to interact with impact tool *5* pressed to marble block *1*. Then, the pre- and post-impact velocities of the piston were determined using a light sensor composed of two laser–photodiode pairs with an amplifier, arranged immediately at the point of the piston and impact tool interaction to record in turn the moments when beams were intersected by the front face of the piston.

The impact process was studied using vibrator inverters AP 33 installed in the impact tool and in the piston; the signals were transferred from the inverters, via amplifiers Bruel&Kjaer 2651, to AD converter L-Card E-440 and, then, to PC for processing in PowerGraph 3.3. The impact tool was also equipped with variable inductance velocity transducer IDS-2.

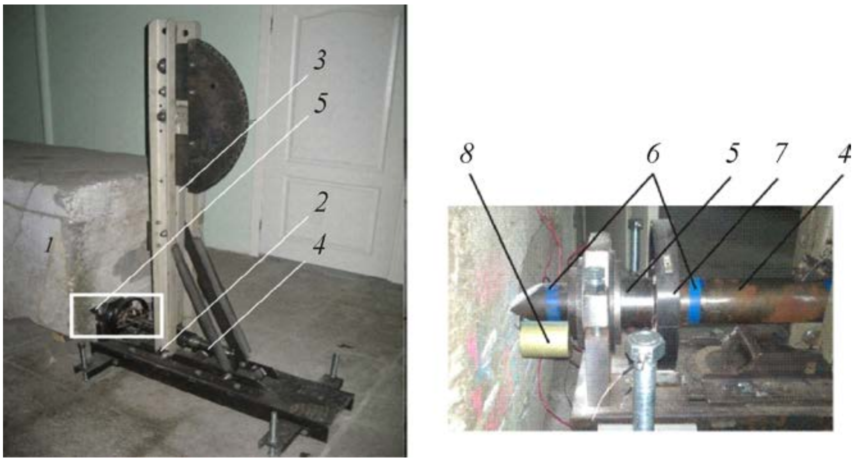

Figure 1. Experimental design: *1*—marble block; *2*—supporting frame; *3*—pendant; *4*—piston; *5*—impact tool; *6*—acceleration sensor; *7*—optical velocity sensor; *8*—variable inductance velocity transducer IDS-2.

During the tests, geometrical parameters of craters were measured and cores were taken using diamond-coated drill bits MATRIX with diameters of 33 and 55 mm. Coring leaves a ring slot wit a clearance of 2 mm. Cores were separated from the block using the method of slotting using plastic material, developed at the Institute of Mining, SB RAS [13]. A layer of plasticine 3–5 mm thick was placed on the bottom of the core slot, then a knockout with an end anvil was inserted in the slot, and a blow was delivered on the anvil. As a rule, after that, a transverse crack was formed, and the core was separated along the plane of the slot bottom.

Figure 2 gives photographs of the marble block surface before coring, after core removal and the core taken using the drill bit with the diameter of 30 mm. Then the cores were sawed and polished on the axial plane being perpendicular to the wedge tool plane.

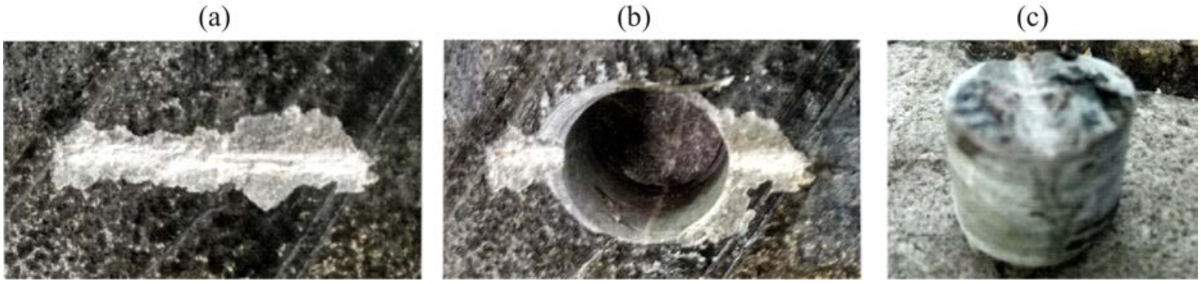

Figure 2. (a) Surface of marble block after wedge indentation; (b) core removal; (c) core.

On the polished surface of the cores, visible are cracks both existing in the block and formed by the wedge tool. Figure 3 offers photographs of the cut sections of the cores, and it is seen that it is rather difficult to determine the length of a crack induced by the impact against the background of the existing fracturing of natural stone.

For example, Figures 3a and 3c show almost an ideal picture—the impact-induced crack merges with none of the natural cracks, and is easy to measure its length. The situation is different in Figures 3b, 3d and 3e—it is very difficult to distinguish a small wedge-induced crack against the main crack exposed on the surface after the impact. In this case, the information recorded during the tests may be helpful. For instance, records of accelerometer installed in the tool display some special features during crack growth.

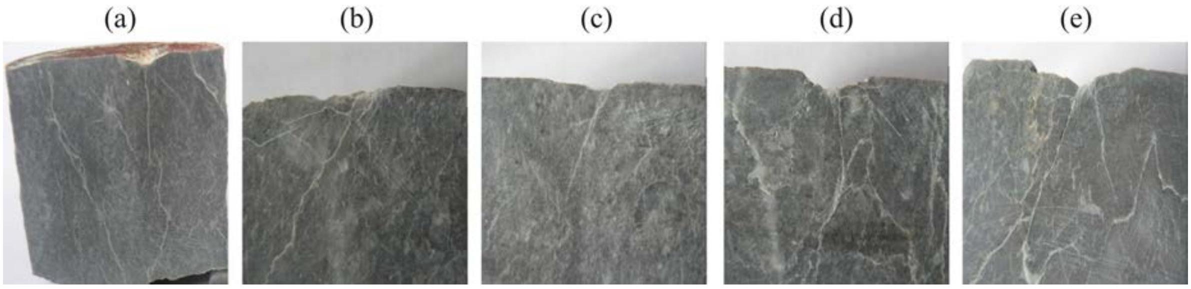

Figure 3. Photographs of polished sections of cores after impacts with an energy, J: (a) 68 (sample blow); (b) 33.6; (c) 68.7; (d) 132.5; (e) 140 (total energy of blows).

Figure 4 presents records of two close-energy blows. By oscillogram *3* of the piston velocity and by oscillogram *1* of the piston acceleration, it is clear that the second blow is more intensive than the first. The fundamental difference of the blow is observable in oscillogram *2* recorded by the acceleration indicator installed on the impact tool. The record of the tool acceleration in penetration is approximately similar in case of both blows. Then, the record represents a so-called “tail” that is a signal generated by a growing crack. Under blow *1*, the “tail” is at the level of noise, which is indicative of the fact that no large crack is generated by this blow. Blow *2* produces a high-amplitude “tail,” which implies grow of a large crack under the wedge tool. These records allow a qualitative conclusion to be drawn on initiation or propagation of a wedge indentation-induced crack. This makes it possible to eliminate inference on a long induced crack in case of a low energy blow and to treat such crack as existing, or to assume a short crack as a blow-induced event. Close inspection of the magnified polished sections brings the same conclusion. In the latter case, the color of a fresh crack differs slightly from the old crack color.

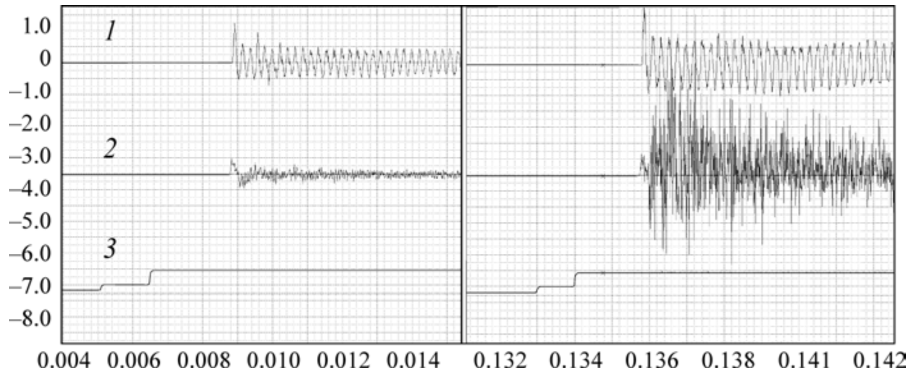

Figure 4. Acceleration oscillograms of piston (*1*), wedge tool (*2*) and light sensor (*3*).

Merging of fresh and existing large cracks (Figure 3a) complicates determination of length of the wedge-induced crack. In this case, the new crack length is assumed as an average length of the cracks measured on the two halves of the core. In Figure 3e, there is one more obstacle for determination of an induced crack length. At a small angle to the core axis (an extension of the blow direction line), two main cracks propagate with opening visible when magnified. In this instance, the crack length was taken as the maximum values of measurements on the two halves of the core.

Geometrical parameters of craters, measured before coring, were used to plot the relationship of the crack length, crater depth and blow energy (Figure 5).

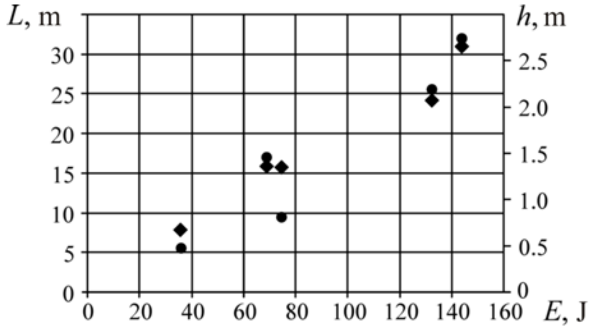

Figure 5. Relationship between crack length, crater depth and energy of blow.

In Figure 5 the characteristics of the external and internal fracture of the marble block under impact. Apparently, there is direct correlation between them, and the scatter of points on the flat is higher for the measured cracks than for the formed craters. Off the general tendency of proportional increase in the fracture characteristics with the blow energy is only a single point at which the total blow energy is ~ 74.4 J. An explanation is that the length of the induced crack in this experiment is assumed to be the thickness of shatters along the impact line as the core has fallen apart during coring. Naturally, this is a rough low estimate. One the objectives of this study is determination of fracture characteristics after multiple impacts and comparison with the fracture characteristics after a unit impact. To this effect, the points on the flat in Figure 5 are grouped by pairs at the two-fold and four-fold energies of unit impact. Nothing can be said about the double blow, for the core has disintegrated. In case of the quadruple blow (total blow energy ~ 144.1 J), fracture efficiency is higher in case of the multiple blows than under unit blow (energy ~ 132.4 J) approximately of the same energy. This proves the conclusion drawn in [8].

3. Conclusions

In the experimental investigation of impact-induced fracture of rocks by a hard indenter, the procedure of core sampling, sawing, polishing and inspection makes it possible to obtain quantitative characteristics of induced cracks—length and path.

The test results show rock fracture under impacts by the piston–wedge tool system is mainly governed by the impact energy transferred to rocks. The integrated recording of the impact action process and fracture parameters inside and outside a rock block offers the required information for proper modeling impact fracture.

Under multiple blows at the same point, fracture efficiency is higher as against unit blow in case that the total energy of multiple blows is equal to the unit blow energy.

Acknowledgements
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