Int. J. Rock Mech. Min.Sci. & Geomech. Abstr. Vol.32, No.8, pp.763-766, 1995

Technical Note

Physical Mechanisms of Hard Rock Fragmentation under Mechanical Loading: A Review

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1 Introduction

Rock indentation is the basic process in drilling and excavation by mechanical means. A sound understanding of rock fragmentation mechanisms will help in the design of mining tool and equipment to improve the mining and drilling efficiency. The physical mechanisms of rock fragmentation have been studied both by theoretical and experimental methods, e.g. Refs [1,2]. Here we review the results of a number of investigations in the area and consider diversity between them. The valuable reviews of rock indentation problems have been presented in Refs [3,5]. Lawn and Wilshaw [6] summarized the problems of microindentation in the ceramics, and some conclusions of the work can be extended to rocks. The paper seeks to collect the available data about the physical mechanisms of rock fragmentation and to determine the problems which are to be solved as well as to establish contradictory results.

2 Stages of rock fragmentation under indentation

It is well known that the process of rock fragmentation under indentation includes generally the following stages: build up of the stress field, formation of zone of inelastic deformation (or crushed zone), surface chipping and crater formation, and sometimes, formation of subsurface cracks [1,2].

Many investigators have observed the consolidation, deflection, surface deformation of rock before the fragmentation [7-10]. After that the surface destruction occurs [11-14],

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which leads to the formation of the layer of destroyed and , then, crushed rock between the tool and rock surface.

The next step is the formation of stable zone of inelastic deformation, and the circumferential crack.There are some disrepancy between data of different authors: some of them think that the zone forms before the formation of the cone crack and its formation results from the accumulation of crushed rock between the tool and loaded massif [11-13,15,16], other suppose that the formation of cone cracks precedes the formation of the zone of crushed rock [14,17,18]. Simultaneously, the crushing of rock in the zone occurs. Then, the subsurface (axial) cracks are formed. The cracks are initiated at the crushed zone and propagate in the direction of the resultant force [9,10,19]. One should note that the axial cracks have been observed only in brittle rocks, and never in plastic or porous rocks. Thereafter, the interior cone (i.e. the part of rock which is bounded by the Hertzian rock crack) is squashed, and the chipping of the rock occurs [9,10,20,21]. There are some discordance between the data of different authors in the point as well: some authors reason that the squashing of the interior cone occurs earlier and the chipping is caused just by the lateral pressure from the destroyed rock in the cone (the cone is supposed to expand after its destruction) [15,20,23]; others argue that the chipping leads to the squashing of the cone [18,24].

There are several proposals for the mechanism of chipping : first, the Hertzian cone crack changes its direction due to the change in the stress field (which is caused by the availability of this crack) and begins to propagate not from the free surface but towards the free surface [9]. That leads to the chipping. Second, the lateral cracks which are normal or inclined to the cone crack are formed, and the cracks propagate towards the free surface and determine the chipping [17,20,21,25].Third, the crushed zone transfers the load , the lateral load from the zone causes the build up of the stress field in the rest of massif, which leads to the formation of lateral cracks being initiated from the zone and propagating towards the free surface [15,23,26].

Simulating the process of rock fragmentation with the use of Boussinesque problem solution, Eigheles [20] and Shreiner[21] have recognized two mechanisms of rock fragmentation.The described above mechanism is supposed to assign only to brittle hard rocks.The plastic hard rocks are destroyed as follows. A zone of irreversible deformation is formed under the contact surface at a depth which is approximately equal to the radius of contact surface. The zone grows and takes a crescent form. Simultaneously,the rock in the zone is crushed.Then, the zone reachs the free surface and that leads to the chipping as well.In this case the cone crack forms as well but it remains rather small.

Eigheles[20] has shown that there are two zones of ultimate state: under the contact surface and at its contour. The growth of first zone leads to the formation of cone cracks, the growth of second one leads to the creation of a crescent plastic zone under the contact surface. The second zone has a dominant role in fragmentation of brittle rocks, the first zone does in fragmentation of plastic rocks.

After the chipping the crushed rock as well as the chips are removed, but part of it remains under the indentor and presents a nucleus of the next crushed zone [9,10,27].

3 Physical mechanisms of formation of crushed zone

It is well known that a zone of highly fractured and inelastically deformed rock is created beneath the indentor [1].

Paone and Tananand [28] have shown that the plastic deformation work in a hemispherical bit indentation varies directly with the volume of crushed zone. From 70fragmentation work is consumed just by the formation of the zone.

Consider the physical mechanisms of the formation of the zone and its shape. Shreiner [21] has reasoned that under the contact surface the zone of ultimate state of material is created and the plastic deformation of material initiates in the zone. Then,the zone of plastic shears grows and form a plastic half-sphere under the contact surface.

Artsimovich[10] noted that the contours of the crushed zone conform to the lines of maximal tangential stress. Brezhnev [29] has shown that the crushed zone boundary is determined by the isolines of maximal tangential stresses from the sides and by the isolines of the maximal normal stress from below. He supposed that the rock is failed by the action of normal (tensile) stress but only in the points in which the strength of rock is reduced due to microdefects caused by shears (i.e. by maximal tangential stresses).In several works, one supposed that the crushed zone is formed due to the shears over the slip lines [14,16]. In cutting the crushed zone has a shape of wedge [12,13] Mavlutov[27] noted that the crushed zone under loading behaves as qasi-liquid in the presence of water, and as the free-flowing bulk material when dry.

Among the causes of the formation of crushed zone which have been suggested by different authors, one should note the following: the state of confining pressure under the contact surface [20]; accumulation of destroyed rock in contact area provided it is not removed [7].In cutting, the zone is formed at rather high ratio between the depth of cut and the width of cutter [12] or at rather high ratio between tangential and normal cutting forces [7], or when the friction between crushed particles exceeds the friction between the particles and the cutter face [11].

One should note that there are investigations in which the zone is not considered as some separate body which interacts with tool and the rock massif, but only as the zone of high density of microcracks [24,30].

4 Mechanisms of chipping and crack formation

Consider the zone which contains a number of macrocracks but is not crushed. It is well known that the Hertzian cone crack which divides the loaded rock into the interior cone and the rest of massif [2] , is formed under indentation of axisymmetric bodies. The crack is formed by the action of tensile stress. Some investigators [1,6,9] noted an availability of subsurface(axial), circumferential,lateral cracks etc.

The chipping of rock is caused by interaction between as-formed zone of crushed material, the cone,tool and all massif.The energy needed for chipping is about 5-10Almost all energy is spent by the formation of the interior cracks (mainly,the crushed zone).

Artsimovich [9] noted that after the formation of the crushed zone the cracks are formed in points of maximum of tensile stress, and, then, propagate by the lines of maximal gradient of tangential stress.In Ref[18] the authors noted that the chipping proceeds when the depth of cone crack becomes so large that the rock/indentor friction stops to hinder the transverse deformation of the cone. Eigheles [20] has shown that the chipping occurs once the interior cone fails: the failure of the interior cone leads to the increase in the lateral pressure between the cone and the rest of massif, and then to the build up of tensile stress and the the propagation of lateral cracks.

Swain and Lawn [25] have schown that after the formation of the crushed zone,cone crack and penny-shaped median cracks , lateral cracks which inititate at the crushed zone and propagate to the free surface , are formed.The lateral cracks are formed just during unload.

Andreyev [31] studied theoretically the impact loading, and concluded the the crack trajectory conforms to the line of gradient of maximal tangential stress.

Protassov [15] has noted that the elastic energy which is accumulated in the crushed zone exceeds some limit the zone is expanded , form a secondary circular crushed zone, and that leads to the chipping.

Some authors supposed that the propagation of cracks which initiate in the crushed zone is stimulated by the ingress of the crushed rock (powder) into the cracks [12,13].

There are some disrepancy between data of different authors as relating to the mechanism of chipping : some of them suppose that the chipping crack is a tensile crack [7,20,30], others think that it is a shear or mixed mode crack [23,33]. Moscalev et al.[11] have shown that the character of the chipping crack depends on the ratio between the maximal tangential stress and the tensile strength of rock, but for the most of rocks the tensile crack causes the chipping. Cherepanov [34] has supposed that the chip formation in cutting is caused by the shear crack propagation.

5 Influence of rate of loading, shape of indenter and cutting conditions on the mechanism of rock fragmentation

The principal method of studying of rock fragmentation is the vertical indentation of axisymmetric indentor with constant velocity. But in drilling the rock/tool interaction proceeds most commonly by impact or cutting; the tool shape is more often nonsymmetric.

Consider some works in which the author consider an influence of the factors on the mechanism of rock fragmentation. In Refs [7,17], it was shown that the rock fragmentation in cutting proceeds just as it does in indentation of wedge indenter.The authors have made cutting and indentation tests on the marble. Artsimovich [10] has made the cutting tests on the marble as well as the simulation of elastic stress field, and concluded that the rock fragmentation in cutting is of a radically different kind from that in indentation. The difference consists in the following points: the crushed zone under the tool is inclined in the direction of cutting force; there is a zone of tensile stress behind the cutter. Mishnaevsky Jr [19] made the cutting tests on the glass , marble and limestone, and has shown that there are several features of cutting process, unlike the indentation:absense of Hertzian cone or circumferential cracks, and the availability of penny-shaped cracks lying in the plane that contains the cutting force vector.

In Ref [35] it has been shown that under dynamic loading at the loading rate 0.3...3 m/sek the rock is failed just as it does under static loading.

Pavlova and Shreiner[22] have established that aty dynamical loading the embrittlement of plastic rocks takes place, and they behave similarly to the brittle rocks. The brittle rock fragmentation proceeds at dynanic and static loading similarly.Artsimovich et al.[9] have shown as well that when the impact rate is no more than 8-10 m/sec the process of rock fragmentation under dynamic and static loading does not differ qualitatively.But the availability of the impact component (for example, in percussive-rotatory drilling) leads to increase in the depth of subsurface cracks.

Consider some data on the influence of indentor shape on the rock fragmentation process. In Ref [14] it was shown that the difference between the rock fragmentation under the indentation of spherical and cylindrical bits consists in that at the indentation of spherical bit the cracks are initiated in the centre of contact surface (not on the contour of contact surface).The prismatic bits are more effective for hard,viscous,non-cracked rocks, the cylindrical ones does for cracked , brittle, weak rocks. Zhlobinsky [23] concluded that the rock fragmentation proceeds most intensively when the hard brittle rock is loaded by spherical indentor, the hard plastic rock does by conical one, and the weak rock does by wedge-shaped one (just for static loading). At small impact force, the conical impactor is most effective(i.e. it makes the maximal crater at the same load). At great impact force, the most effective impactor is cylindrical.

Artsimovich [9] has made the indentation tests on the marble,granit and limestone with bits with right-angled section.He has shown that the nor Hertzian neither circumferential cracks are formed under the indentor.Cracks are initiated in the vicinity of small face of the indentor, grow and then form an large eliptic crack, which can be considered as corresponding to the cone crack in axisymmetric indentation.

Mishnaevsky [19] has made a vertical indentation of cutters into the inclined rock surface.In the tests , penny-shaped non-axisymmetric cracks, which looks like the cracks formed in cutting but differ from cone or circumferential cracks, were seen.

6 Conclusions

The review includes consideration of available data of physical mechanisms of hard rock fragmentation in drilling. One can conclude that the zone of crushed rock is of great importance in the rock fragmentation process. The main part of rock fragmentation energy is consumed just by the formation of the zone and rock crushing in it.The energy of rock fragmentation is the greater the greater the size of the zone. One can list the factors which determine supposedly the size of crushed zone (and, consequently, the energy consumption in drilling): availability of the confining pressure under the contact surface, relation between the depth of cut and the cutter width, friction between the crushed rock and cutter face and the internal friction of crushed rock, wedge angle of cutter and shape of indentor, possibility of accumulation of crushed rock between rock massif and cutter and removal of crushed rock, and so on.One can suppose that the sources of improvement of drilling tool are just in the control of the factors: reduction of internal or rock/tool friction by the corresponding chemical dopes into the water, corrresponding choice of shape of the bits to decrease the volume of rock under confining pressure, nonsymmetric shape of cutters to make easier the removal of crushed rock, use of narrow cutters ,etc. As for the mechanism of the formation of the crushed zone one can suppose that it is caused by the shears by slip lines under confining pressure.

Generalizing the above data, one can determine the optimal shapes of destructing elements for different types of rock: the cylindrical bits are most effective for brittle or quasi-brittle rocks (i.e. cracked rock or at high impact energy); the conical bits do for hard plastic rocks or at small energy of impact; the prismatic bits fit to the hard, viscous , non-cracked rocks.

Several suggestions about the possibility of the improvement of the drilling tool on the basis of the use of subsurface cracks were put forward: it was supposed that the cracks decrease the rock strength and make easier the rock fracrure in next loadings [10]; they bound the strained volume and decrease the triaxility of stress state, which leads to the reduction in the energy of drilling [9]; in cutting they can join together which leads to the spalling of the rock barriers between cuts without any additional energy consumption, and to the reduction

7 References

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