SUB-SURFACE CRACKS DUE TO DISC CUTTER SPACING FOR IMPROVED ROCK BREAKAGE AND GROUND CONTROL

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ABSTRACT

The importance of using disc cutters for rock excavation is reflected by their wide application in hard rock cutting machines such as tunnel boring machines and raise borers. The forces involved in the cutting process are those due mainly to thrust and rolling forces and are greater than that required by cutting picks. An interesting feature of cutting with discs is the formation of surface crushing, fracture and sub-surface chipping and primary crack formation. Experimental, as well as analytical, work has been carried out to determine the optimum spacing between the disc cutters to control primary crack orientation. Wedge bit indenters were used to simulate disc cutters. The paper concludes by proposing a new approach to rock excavation by hybrid cutting based on controlling the primary crack orientation.

INTRODUCTION

One of the key factors in minimising haulage separation during the heading development in tunnelling operation is the quick crivage of the heading and the speedy installation of supports. In coal mines today, the common method of heading development is by using heading machines of various configurations. The rate of the heading advance depends on the machine head and cutter tool designs. Faster cutting rates can be attributed to sharp tools and their patterns on the cutting head. Considerable power can be saved by understanding the nature of the cutting tool attack on the rock, the nature of rock breakage and sub-surface cracks developed as a result of tool attack.

Rock cutting using disc cutters are mainly used on hard and abrasive rocks. The type of machines associated with disc cutters are mainly TBM's and raise borers. The application of the disc cutters for coal mining has not been widely accepted although attempts have been made in Poland and Russia (Logov, Gerike and Raskin, 1989) to mount discs on shearer drum as shown in Fig. 1.

Fig. 1 Shearer drum fitted with disc cutters (Logov, Gerike and Raskin, 1989)

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11th International Conference on Ground Control in Mining, The University of Wollongong, N.S.W., July 1992.
The magnitude of the forces required to excavate rock using disc cutters are markedly different to that of pick cutting. According to Roxborough and Phillips (1975), cuttings by discs require thrust and rolling forces about 35 and 5 times higher respectively than that required for picks under the identical conditions. Rock cutting by discs involves rock surface and sub-surface chipping as well as the formation of primary cracks extending deeper in the rock. The depth of the primary crack development depend on the type and strength of the rock cut.

Sub-surface crack interaction (sub-surface chipping) between adjoining disc cutters has been regarded as the most damaging fracture process in disc cutter cutting. A large number of experiments have been undertaken to investigate the mechanism involved (Miller, 1974, Ozdemir, 1975, and Roxborough, 1981). One of the purposes of the investigation was to select the optimum spacing between adjoining disc cutters as it bears a close relationship to cutting efficiency. Cutting performance and therefore operating costs, are closely related to this factor.

Whereas sub-surface chipping has received significant attention from investigators, primary crack development involved in disc cutting (which propagates mainly downward into relatively large depths) has largely been ignored. The reasons may be that these cracks are generally not visible from the rock surface.

Primary cracks were found to interact with each other in the case of indexed indenters (Lindqvist, 1984). The outwardly directed primary cracks were observed on the rock sample cut by a triple tungsten carbide kerf cutter. A stress field due to two-indentations (point loads) was calculated from the Boussinesq solution. The results indicated that the directions along which the maximum tensile stress act are close to the direction of the outwardly directed primary crack, observed experimentally.

This study implied that there may be possible way to control primary crack behaviour, and thus improve rock cutting performance. The study reported was rather preliminary, requiring further investigation on the controlled experimental condition and theoretical analyses.

Howarth (1988) examined experimentally, the length of primary cracks caused by sharp and blunt disc cutters. He found that the length of primary cracks caused by a sharp disc cutter was approximately 78 mm or approximately 26 times the depth of cut. The lateral extent of the cracks developed as a result of indentation by the blunt disc cutter was approximately 23 mm or roughly 13 times the depth of cut. However, Howarth did not examine the orientation and inclination of the primary cracks and their interactions with other primary cracks generated by the adjacent disc cutters.

This paper, therefore, examines experimentally and analytically the formation, orientation as well as inclination control of the primary cracks. Both the experimental and the analytical procedures used were described in detail by Guo (1990). In carrying out the tests, sharp single and bi-indenters were used. Tests were carried out statically because of the difficulty of simulating the actual cutting process using disc cutters in the laboratory. This difficulty was also highlighted by others when attempting the same (Howarth and Bridge, 1987)

**EXPERIMENTAL APPARATUS AND PRELIMINARY TESTS**

Fig. 2 shows the general set-up of the bi-indenter. The bi-indenter was made from two percussive chisel bits with tungsten carbide tips. The bits were-wedge shape set at an angle of 120°. The carbide tips were close to sharp. The bits were welded onto small steel blocks which were able to slide along the guiding channel at a specially made holder. In this way the spacing between the two bits was adjusted. By using only one bit on the holder,
Fig. 2 Bi-indentor arrangement

...a single indentation could also be performed. The holder was mounted onto a 500 kN Avery testing machine.

The rock specimens used were rectangular blocks of 300mm long x 200 mm high and 100mm wide. Only one side of each block was used for the indentation tests so as to avoid any possible interaction between different crack systems. Tests were conducted on sandstone (UCS 50 MPa) and marble (UCS 125 MPa). Initially, tests were conducted on a single indentation at various loads of 20 kN, 40kN, 60kN and 100kN. Then, the experiments were repeated under the same load using bi-indentors with the spacing between the bits set constant at 20 mm apart. The loading rate was maintained at 10 kN/min.

Following the tests, the rock specimens were cut by diamond saw to reveal primary crack systems. The cracks were highlighted by a blue dye mixed with a solution of araldite resin. The procedure for applying the dye consisted of heating the rock specimen in an oven to 100°C and then applying dye solution to the rock. Heating the rock assisted the penetration of the dye/araldite mixture into the crack surfaces and failure zones. A thin film was formed on the outer rock surface of the treated area. The time between the application of the dye and setting was between 30 min and one hour, depending on the composition of the dye/araldite mixture. The surface coat was subsequently removed by sanding down the rock surface thus highlighting crack formation as shown in Figs. 3 and 4. Fig. 5 represented assumed failure conditions under the indenter. Three significant features can be seen from these photographs. Firstly, fracture or crushed zones were found immediately underneath...
the tips of the indenters, the rock in this zone was intensively fractured. Secondly, two types of cracks were observed in both cases, these being lateral cracks which propagated roughly parallel to the rock free surface, or approached the surface, and thirdly, the primary cracks which propagated vertically downward or with some angle to the vertical. Both types of the cracks are initiated from the observed crushed zones. In terms of crack length, the primary cracks are more significant than the lateral cracks.

Lateral cracks which form sub-surface chips between the adjoining disc cutters have been observed and studied by many investigators (Miller, 1974; Ozdemir, 1975, and Roxborough, 1981). However, the primary crack or use of it has been ignored for disc cutting research in the past. In contrast to the observation that primary cracks penetrate into rock vertically along the direction of indenting in the case of a single wedge indenter, the primary cracks due to bi-indenters propagate into rock outwardly with some angle to the vertical. Tests on limestone and sandstone rocks showed that the angles between the primary crack propagation direction and the vertical are about 37°. This indicated that it is possible to control the direction of the primary crack propagation.

Based on the observations on the failure zone, it is assumed that the geometrical shape of these zones for the wedge type of indenters is close to a triangular shape as shown in Fig. 5. The material within the zone is in a compressive hydrostatic state, exerting a uniform pressure onto the surrounding virgin rock. The size of the crushed zone normally depends on the load or thrust applied to the indenters, and the rock properties such as hardness.

THE EFFECTS OF SPACING OF BI-INDENTER

A series of laboratory tests were undertaken to investigate the effects of spacing of the bi-indenters on the primary crack behaviour. Based on the assumptions made on the crushed zone, simplified computing models, as shown in Figs. 6 and 7, were constructed for the primary crack analyses for the single indenter and bi-indenters respectively were constructed. The crack analyses were carried out using the numerical technique developed by Guo, Aziz and Schmidt (1991 and 1992). The modelling of the primary crack propagation started with an initial crack of 5 mm in length. Fig. 7 shows the predicted crack propagation in the case of the single indenter. It is clear that the path of the predicted crack is in a close agreement with the crack observed in the tests.
The effect of spacing of the bi-indenters on the primary crack behaviour was modelled. A series of spacings i.e., 20mm, 40mm, 60mm, 80mm and 100mm were considered. Fig. 6 shows the predicted crack propagation paths for these spacings. As can be seen, outwards propagated primary cracks were predicted by the numerical model. The predicted primary crack propagation angle to the vertical is about 27°, in the case of 20mm spacing, which is less than that observed experimentally, i.e., approximately 37°. Fig. 6 also indicates that the direction of the primary crack propagation can be controlled, or at least partly controlled, by the spacing between indenters. As the spacing increases, the angle of the primary crack propagation to the vertical direction decreases. In the case with 100 mm spacing, the direction is close to the vertical, which implies that the interaction between each indenter of the bi-indenters has ceased.

Fig. 9 shows the normalised maximum tensile stresses at the crack tips as the cracks propagate. The normalised maximum tensile stresses decrease as the cracks propagate, which indicates that increasing loads needed to maintain the crack propagations, i.e., the crack propagations in all the cases are stable. It can be seen that, at the beginning of the propagation, higher normalised maximum tensile stress is observed in the cut with larger spacing, which indicates that the crack is easy to initiate (small load is required). Otherwise, a large load is required to initiate crack propagation.
However, as cracks propagate, the normalised maximum tensile stress decreases at a higher rate in the cut with a larger spacing. This implies that less load increase is required to maintain the crack propagation for the cut with a smaller spacing. In other words, once the crack propagation starts, for the same amount of load, the larger crack propagation can be achieved in the cut with a smaller spacing.

The above results indicate one very interesting finding for the first time in disc rock cutting studies, that is, it is possible to control the primary crack propagation in disc cutting by selecting the spacing between indexed indenters. The ideal rock cutting process can be achieved when the fragment formation (such as the fragment size and the load required) can be controlled. For example, more relatively large fragments and less small or fine fragments imply that the energy intensive process involved in the fine fragment formation is being minimised. This will not only improve the overall cutting efficiency but will also reduce the level of fine dust produced.
IMPLICATION OF THE CONCEPT FOR DISC ROCK CUTTING DESIGN

It can be imagined that some kind of fragment will be formed if primary cracks from two adjacent bi-indenters interact each other. If large rock fragments could be obtained, a method may be found which could lead to efficient cutting. Based on this idea, tests were designed to produce a triangular fragment between the two sets of bi-indenters as shown in Fig. 10. At first, bi-indenters are used to produce a pair of outwardly directed primary cracks in position 1, then, at position 2 at some distance away, bi-indenters were used to produce another pair of outwardly directed cracks with the aim of forcing the two adjoining cracks from the two bi-indenters to form a wedge-shaped rock fragment between them.

Based on the observations described above, the concept for an efficient cutting system is proposed. The basic action of this cutting system is to produce primary cracks in the first pass of the bi-indenters, and to produce the secondary crack in the successive path with another set of bi-indenters; the wedge fragment is then formed between the two passes. Finally, the drag pick is used to remove the fractured rock as shown in Fig. 12.

The cutting concept is a combination of disc cutting and drag-pick cutting. It is anticipated that this system will be more energy efficient for hard rock cutting over conventional disc cutting or drag pick cutting, not only because relatively large fragments can be produced, but also because this system combines the advantages of both tools. The disc cutter is used for the pre-fracturing of rock and the fractured rock is mainly removed by drag pick. Geier and Hood (1987) have demonstrated that pre-weakening a surface with parallel water jet slots reduces the mechanical specific energy when subsequently excavating the rock with drag picks. It is anticipated that overall energy usage and control of the level of dust produced can be improved with the proposed system. The proposed concept of hybrid cutting although similar to that proposed by Howarth (1988), is nevertheless based on the concept of controlled orientation of the primary cracks.

CONCLUSIONS

Based on the experimental tests, and supported by numerical modelling, the nature of rock chipping and primary crack formation and its orientation can be controlled with proper spacing of the disc cutters. Two types of cracks were identified with both single and bi-indenters (discs).

In the case of the single indenter, the direction of the primary cracks were vertically propagated, and in the case of the bi-indenters, the primary...
Fig. 11 Pattern of crack formation at various spacings between two adjoining bi-indenters.

Fig. 12 A concept of hybrid rock cutting system.
cracks propagated outwardly into the rock when the spacing was sufficiently small. In other words, the spacing between the indenter tips of the bi-indenters partly control the direction of the primary crack propagation. The interactions between the two bi-indenters are more apparent when the distances between the adjoining indenter tips, such as 30 mm and 40 mm, than when the spacing is larger, eg. 80 mm. Numerical approaches were found to be in general agreement with that observed experimentally.

Finally, a new concept of hybrid cutting, using disc cutters, has been proposed. This is based on the benefits of controlled primary crack orientation and the application of bi-discs.

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