Added Cutting Teeth to Promote Surface Crack Incisions for Cutting Sandstone

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Abstract

To promote surface crack incisions between indentations, we first prefabricated CCS (constant cross section) indenters and modified indenters by adding cutting teeth on the CCS indenters. The subsequent indentation tests, using the modified indenters and the CCS indenters, indicate that the modified indenters can effectively promote surface crack incisions, initiating from the contact points between the cutting teeth and the rock. In addition, the promoted surface crack incisions form more thick chips between indentations, whereas the consumed indentation energy of the modified indenters is close to that of the CCS indenter. Thus, the modified indenter can effectively promote indentation efficiency.

1 Introduction

Indentation tests, using conical, wedge-shaped and blunt indenters, have been extensively conducted to investigate the rock cutting mechanism. Rock chips and indentation forces, closely relating to indentation efficiency and tool wear, are two critical indexes. For the conical indenter, Dai et al. (2019) first tested the mechanical properties of the seafloor massive sulfides and then predicted the indentation force in the mining process. Similar numerical simulations by Li et al. (2017) indicated that tensile internal cracks are common in the cutting process. They further found that the increase in confinement elevates the cutting force. Wang et al. (2018) performed indentation tests in biaxial states and proposed that the confinement significantly influences chip formation and indentation force. Momber (2004) stated that the indentation force is nonlinear to the length of the crack, forming in the conical indentation. Second, for the wedge-shaped indenters, Huang et al. (1998) proposed that the increase in confining stress can significantly deflect the propagation direction of the internal crack (using the numerical method) and increases the indentation force. Chen and Labuz (2006) verified the results by conducting laboratory indentation tests. The numerical study by Zhu et al. (2016) indicated that the discontinuities may prevent the internal crack propagation. Haeri et al. (2014; 2016) theoretically analyzed the internal crack coalescence between two wedge-shaped indenters.

Compared to the conical and the wedge-shaped indenters, blunt indenters, including constant cross section (CCS) indenters, are more common in rock excavation machines. Additionally, blunt indenters may form more internal cracks between indentations. In the indentation process using the blunt indenter, a large crushed core first forms ahead the blunt indenter. With further increase in indentation depth, the crushed core expands and a plastic zone outside the crushed core forms. When the stresses at the outer rim of the plastic zone reach critical values, internal cracks initiate and propagate (Alehossein et al., 2000; Liu et al., 2019a). These internal cracks are critical to chip formation and closely relate to the indentation force. For instance, the 2-dimensional numerical study by Bejari et al. (2012) showed that joint planes in the rock affect the crack propagation, initiating from the adjacent plastic zones, and further influence the advance rate of the TBM. The 2-dimensional numerical studies (Liu et al., 2019b; Zhai et al., 2016) and the laboratory tests by Lin et al. (2018) properly verified the results. In addition, the recent numerical studies showed that the internal crack propagation closely relates to the fluctuations of the indentation force (Liu et al., 2018a; Liu and Wang 2018).

The above studies significantly contribute to understanding the internal crack propagation between indentations. Interestingly, Zhang et al. (2012) found that surface cracks, besides the internal cracks, frequently form in the indentation process. Recent, the indentation tests by Liu et al. (2016) and Han et al. (2017) showed that the incisions by surface cracks significantly affect chip formation between indentations. For example, the laboratory test by Liu et al. (2018a) showed that the internal crack (Figs. 1(a)) on the ABC plane (Figs. 1(b)) connected adjacent plastic zones. However, without sufficient incisions by the surface cracks, only two shallow and independent grooves formed and the rock between indentations remained relatively intact (Fig. 1(b)). Clearly, the rock breakage is insufficient because of the poor incision by the surface cracks. Liu et al. (2018a) found that many factors, including the ratio of spacing to indentation depth and the bedding plane orientation, may affect surface crack incisions. However, the method to promote surface crack incision lacks sufficient study. Fortunately, the recent study by Xiao et al. (2019) may shed some light on how to promote surface crack incisions. They applied the Vickers indenter (Fig. 1(c)) and surprisingly found that surface cracks frequently initiate from the junctures of the adjacent surfaces of the indenter (Fig. 1(d)).

Thus, to promote surface crack incisions between indentations, we first prefabricated the modified indenters, by installing Vickers indenter on the CCS indenter. Then, indentation tests, using the CCS indenters and the modified indenters, were performed to investigate the chipping characteristics and the indentation efficiency.

2 Test Methodology

2.1 Laboratory preparation

According to the previous studies (Han et al., 2017; Liu et al., 2018a), the CCS indenters and the modified indenters (composing of the CCS indenter and the cutting teeth) were prefabricated (Figs. 2(a) and 2(b)). These indenters were made of high stiffness steel (heat treated) to obtain comparable tests results. Figure 2(c) shows the cross section of the CCS indenters. The cutting tooth was a half of the Vickers indenter, installed on the main body (Fig. 2(d)). The cutting tooth consisted of the holding part (preventing shear failure of the cutting teeth) and the cutting part (directly acting on the rock surface). Green sandstone and Shandong sandstone specimens with the length,the width and the height of 200 mm, 200 mm and 100 mm, respectively, were indented in the present article. According to previous studies (Han et al., 2017), the size effect is negligible. Table 1 lists the basic mechanical parameters of these specimens.

Table 1 Basic mechanical parameters of the specimens

	Uniaxial compression strength (MPa)	Elastic modulus (GPa)	Poison's ratio	Density (g/cm ³)
Green sandstone	65.2	23.2	0.21	2.51
Shandong sandstone	54.7	19.5	0.25	2.47

2.2 Test specifications

The previous studies reported that the constant stress (Han et al., 2017; Liu et al., 2016) and the constant stiffness boundaries (Xia et al., 2018; Entacher et al, 2014) are feasible to investigate the rock cutting process. Thus, in the present article, the specimens were first cast in steel moulds with high stiffness for 28 days to provide a constant stiffness boundary (Fig. 2(e)). According to the previous indentation tests (Liu et al., 2018a), the spacings between indenters were 65 mm and 75 mm. Table 2 lists the corresponding indentation depths. In total, 26 indentation tests were performed using the WAW-600 testing system. In the indentation process, the indentation force and depth were recorded every 0.5 second. For the UCS testing, ISRM standard suggests that the test time ranges from 5 to 10 min (Aliabadiana et al., 2019). Thus, the constant indentation rate was 1.2 mm/min. The indentation ceased when the indentation depth reached specific values.

Table 2 Test specifications

Rock samples	65mm	75mm
Spacing		
Green sandstone	7.5 mm, 8.5 mm, 9.5 mm, 10.5 mm	8.5 mm, 9.5 mm, 10.5 mm
Shandong sandstone	7.5 mm, 8.5 mm, 9.5 mm	9.5 mm, 10.5 mm, 11.5 mm

3 Laboratory Results

3.1 Chip formation

The chip mass between indentations is a critical index determining indentation efficiency (Han et al., 2017; Liu et al., 2018a). Figure 3 shows the chip formations for the spacing of 75 mm. The horizontal and vertical directions are defined as X and Y directions, respectively. When the indentation depth was 8.5 mm, two small chips, denoted by the red dash lines, formed by the CCS indenters (Fig. 3(a1)). According to previous studies (Liu et al., 2016; Liu et al., 2018a), these thin chips with relatively even surfaces (Fig. 4(a1)) may form by shear failure. For the modified indenters with the same indentation depth and spacing, two surface cracks, initiating from the contact points between the cutting teeth and the rock (denoted by blue triangles), incised the rock between indentations (Fig. 3(b1)). Additionally, the uneven outline of the typical chip indicates that tensile failure may be responsible for the chip formation (Liu et al., 2016; Liu et al., 2018a) (Fig. 4(b1)). Besides, similar small chips formed near the indentations. For the CCS indenter, with the increase in indentation depth, larger chips near indentations formed (Figs. 3(a1) and 3(a3)). Similarly, these chips may result from shear failure (Figs. 4(a2) and 4(a3)). For the modified indenters, severer surface crack incisions, initiating from contact points between cutting teeth and rock, generated. The thick chips with uneven surfaces indicate that tensile failure dominates in the chipping process (Figs. 4(b2) and 4(b3)). For the Shandong sandstone with the spacing of 75 mm, similar phenomena occurred (Figs. 3(c1)~(c3) and 3(d1)~(d3)). Additionally, several irregular surface cracks,

resulting from the increased indentation depth and reported in previous studies (Liu et al., 2016; Liu et al., 2018a), incised the rock for the CCS indenters (Fig. 4(c3)). For the spacing of 65 mm, similar chipping phenomena occurred (Figures not shown). The above descriptions clearly indicate that the added cutting teeth significantly promote surface crack incisions between indentations. In addition, the promoted surface crack incisions are beneficial to the tensile chipping between indentations. These incisions may contribute to rock chipping. However, this inference needs further verification.

The previous studies indicated that the chip mass (or the groove volume) can characterize the rock chipping degree (Han et al., 2017; Liu et al., 2018a). Thus, in the present article, the chips between indentations were collected and weighted (Fig. 4(c)). In Fig. 4(c), CCS, M, G and S denote the constant cross section indenter, the modified indenter, the green sandstone and the Shandong sandstone, respectively. In addition, 65 and 75 denote the spacings of 65 mm and 75 mm. Similarly (Liu et al., 2016; Liu et al., 2018a), the increase in indentation depth increases the chip mass. For the same spacings and indentation depths (except the relatively small indentation depths), chip masses caused by the modified indenter are larger than those by the CCS indenter. Thus, with the surface crack incisions in Figs. 3, we can conclude that the modified indenters can effectively promote surface crack incisions and further increases chip masses. Nevertheless, whether the modified indenters can promote indentation efficiency needs further analysis, because indentation efficiency is determined by the chip mass and the indentation energy (Eq. 1).

$$SE = \frac{W}{M} \quad (1)$$

Where SE, W and M are the specific energy, the indentation energy and the chip mass, respectively.

3.2 Indentation force

Figure 5(a) shows the typical indentation forces for the Shandong sandstone specimen with the spacing of 65 mm. Similarly, the indentation forces first increase with the increase in indentation depth, and then fluctuates (Liu et al., 2016; Liu et al., 2018a). These fluctuations may relate to the crack propagation in rock specimens (Liu et al., 2018b). More importantly, the close curves of the CCS indenters and the modified indenters show that the increased contact area by the cutting teeth may slightly increase indentation force. By integrating the indentation force and the indentation depth using Eq. 2, the consumed energies clearly show that the increase in indentation depth significantly increases the indentation energy. Additionally, the consumed energies of the CCS indenters and the modified indenters for the same spacing and indentation depth are close. Thus, the increased contact area by the cutting teeth may slightly affect the indentation energy.

$$W = \int_0^d F(d) dd \quad (2)$$

Where $F(d)$ and d are the indentation force and the indentation depth, respectively.

3.3 Indentation efficiency

According to the chip masses and the consumed indentation energy, Fig. 6(a) depicts the specific energies, using Eq. 1. Clearly, most specific energies of the modified indenters are lower than those of the CCS indenters. In other words, the modified indenters consume less energy than the CCS indenters for the same chip mass. In addition, according to Eq. 3, the further analysis in Fig. 6(b) clearly indicates that the promotion ratio ranges from -0.27 to 0.69 with an average value of 0.27. Thus, we can infer that the modified indenter can significantly promote indentation efficiency.

$$I_{SE} = \frac{SE_{CCS} - SE_m}{SE_{CCS}} \quad (3)$$

Where I_{SE} , SE_m and SE_{CCS} are the promotion ratio of indentation efficiency, the specific energy of the modified indenters and the specific energy of the CCS indenters.

4 Conclusions

The laboratory tests using the CCS indenters and the modified indenters show that the added cutting can promote surface crack incisions. The further analysis of the chip mass indicates that the degree of the surface crack incisions positively relates to the chip mass. In addition, the modified indenters consume approximately the same energy (for the same indentation depth and spacing) as the CCS indenters consume. Thus, the modified indenters can promote indentation efficiency.

Declarations

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Figures

Figure 1

Crack propagation by indentations and the Vickers indenter (Liu et al., 2018a; Xiao et al., 2019): (a) is the internal crack propagation on the ABC plane after indentations, (b) is the morphology of the indented rock, (c) is the Vickers indenter and (d) denotes the surface cracks formed by the Vickers indenter.

Figure 2

Indenters: (a) and (b) are the CCS indenters and the modified indenters, respectively, (c) is the cross section (A-A) of the CCS indenter and the main body of the modified indenters, (d) denotes the specifications of the cutting tooth and (e) is the indentation model.

Figure 3

surface crack incisions when the spacing is 75 mm: (a1)-(a3) are the surface crack propagation in green sandstone caused by the CCS indenters; (b1)-(b3) are the surface crack propagation in green sandstone caused by the modified indenters; (c1)-(c3) are the surface crack propagation in Shandong sandstone caused by the CCS indenters; (d1)-(d3) are the surface crack propagation in Shandong sandstone caused by the modified indenters

Figure 4

Typical chips and chips mass: (a1)~(a3) and (b1)~(b3) are typical chips and (c) is the weighted chip masses

Figure 5

Typical indentation forces and the indentation energies

Figure 6

The specific energy and the promoted indentation efficiency ratio: (a) is the specific energy and (b) is the promoted indentation efficiency ratio