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Characteristics of cutting behavior of a pick cutter in hard rock

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ABSTRACT

The pick cutter is one of the most common cutting tools for the mechanical rock excavator. It has been shown that pick cutters can be used efficiently in soft and moderate rocks. Recently, a roadheader is considered as an excavation method in various tunnel and underground space development projects planned in Korea. In the applications, major potential problems are the decrease in cutting performance in hard rocks and the excessive wear of a pick in abrasive rocks. In order to assess the applicability of pick cutters in abrasive hard rocks, this paper performed the linear cutting machine (LCM) test using a pick cutter for hard rock specimen. The cutter forces and specific energy were obtained from the LCM tests. The results indicated that excessive cutter forces and specific energy will be required to break the hard rock. Also, additional problems related to the wear of a cutting tool and the mechanical stability of a pick holder were observed in the LCM test. Based on the results, this paper discusses the possible problems when the pick cutters are applied to hard rock formation and the major issues to be addressed in the future.

1. INTRODUCTION

Mechanical excavation has been widely used in civil and mining projects, and

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demand for this method is rapidly increasing due to its numerous advantages in terms of safety, stability, high advance rate, less environmental impact over the drill and blasting method. Various types of mechanical excavators (e.g., TBMs, roadheaders, longwall shearers and trenchers) with mounted cutting tools (e.g., disc cutter, pick cutter and drag bit) can be used to excavate rock mass (Jeong and Jeon, 2018). Recently, Roadheader is considered as an excavation method in various tunnel and underground space development projects planned in Korea. In the applications, major potential problems are the decrease in cutting performance in hard rocks and the excessive wear of a pick in abrasive rocks.

In order to assess the applicability of pick cutters in abrasive hard rocks, this paper performed the linear cutting machine (LCM) test using a pick cutter for hard rock specimen. The cutter forces and specific energy were obtained from the LCM tests, and the cutting characteristics of pick cutter in hard rock was investigated.

2. TESTING CONDITIONS

2.1 LCM system

The LCM system has been widely used to evaluate the cutting performance of cutting tools such as TBM disc and pick cutters (Chang et al. 2006; Cho et al. 2010; Park et al., 2018; Jeong et al., 2020). The system has advantages in terms of the use of a real range of cutting forces and determination of the design parameters of mechanical excavators. The LCM system used in this study has a 20-ton loading capacity and can provide sufficient stiffness for a pick cutter during the linear cutting test. The cutter forces in three directions (normal, cutting and side force) were measured using a load-cell at a sampling rate of 20 s^{-1}. The detailed information of the LCM was well-described in the previous study (Jeong and Jeon, 2018; Jeong et al., 2020). The conical pick was selected as heavy type pick to have cuttability for a hard rock.

2.2 Rock specimen

The gneiss specimen was cut to the dimension of 300 mm × 300 mm × 200 mm for the test. There is no significant discontinuity in the rock specimen, and it was assumed as the intact rock specimen. The mechanical properties of the rock are presented in Table. 1. Based on the classification system for strength of rock by ISRM, the rock specimen can be considered as extremely hard rock. Before the cutting test, rock specimen was preconditioned with a couple of preliminary cutting to simulate the damaged rock surface in actual excavation. After preconditioning works, the LCM tests were done under given cutting conditions.

Table 1. Mechanical properties of rock specimen used in this study

Density (g/cm^3)	Uniaxial compressive strength (MPa)	Brazilian tensile strength (MPa)	Young`s Modulus (GPa)	Poisson`s ratio

2.62	245.01	11.19	33.65	0.22

2.3 Cutting conditions

The depth of cut and cut spacing are important cutting parameter of a pick cutter. In this study, the cut spacing was fixed as 12 mm, and the depth of cut was considered as 4 levels. The two cutting angles of a pick, i.e., attack and skew angles were set as 45° and 5°, respectively. The direction of skew angle was negative; thus, the direction of pick was toward to the previous cut line. The definition of skew angle was followed by the previous study (Park et al., 2018; Jeong et al., 2020). The cutting speed was applied as 20 mm/s. As previous studies have shown, the cutting speed affects neither cutter forces nor specific energy (Copur et al., 2017). It was assumed that the cutting speed does not affect the cutting performance of a pick cutter. The cutting distance was 200-250 mm for all cutting conditions, and at least five cutting lines were made for each case.

Fig. 1 Experimental set-up of the LCM test

2.4 Specific energy

The specific energy, defined as the required work to break the unit volume of rock can be calculated by Eq. 1. It is a representative index used to estimate the cutting efficiency of the cutting tools. In order to calculate the cut volume, all of the rock fragments including small particle and debris were collected after each cutting test.

$$\mathrm{SE} = \frac{F_c \times l}{V_{cut}} \quad (1)$$

where SE is the specific energy (unit: MJ/m^3), F_c is the mean cutting force of a pick cutter (unit: kN), l is the cutting distance (unit: mm) and V_{cut} is the cut rock volume (unit: m^3).

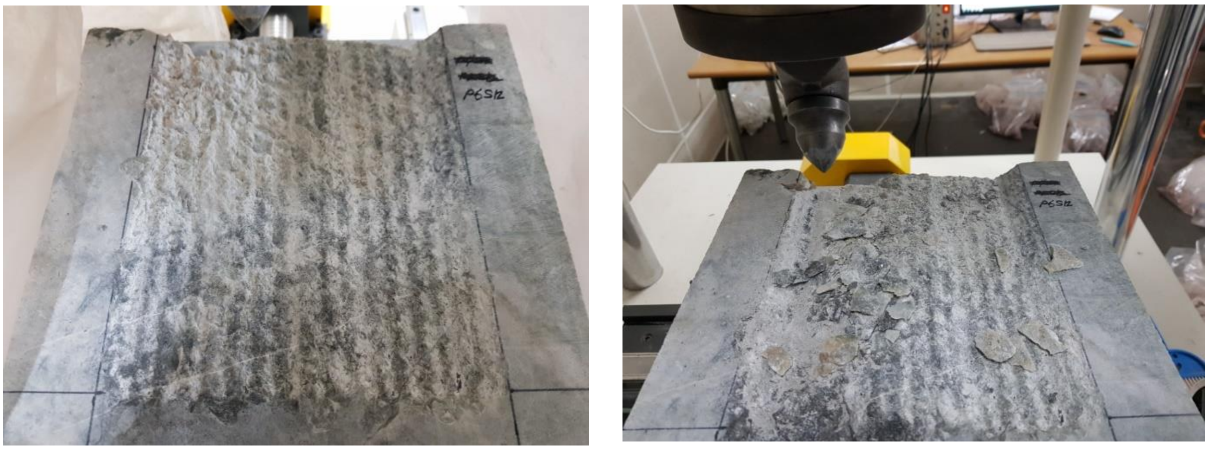


Fig. 2 Photos of cutting surface before and after the LCM test

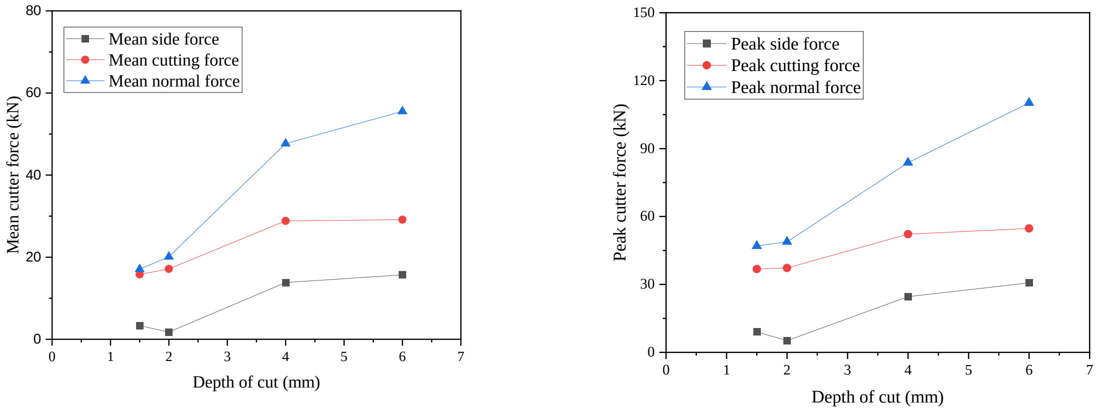
3. RESULTS AND DISCUSSION

3.1 Cutter forces

Fig. 3 shows the relationships between the mean cutter forces and the *s/d* ratio. The forces obtained during the cutting tests were averaged to estimate the mean cutter forces. The three force components linearly increased with depth of cuts. This trend is consistent with the results of previous studies (Bilgin et al., 2006; Jeong and Jeon, 2018; Park et al., 2018). In particular, both mean and peak cutter forces drastically increased at the 4 mm of depth of cut.

Table 2. Results of cutter forces obtained from the LCM test

Depth of cut (mm)	Cutter forces (kN)					
	Mean			Peak		
	Side	Cutting	Normal	Side	Cutting	Normal
1.5	3.33	15.79	17.06	9.02	36.78	46.98
2.0	1.76	17.16	20.11	5.19	37.27	48.85
4.0	13.83	28.84	47.67	24.62	52.18	83.77
6.0	15.69	29.13	55.52	30.70	54.73	110.16

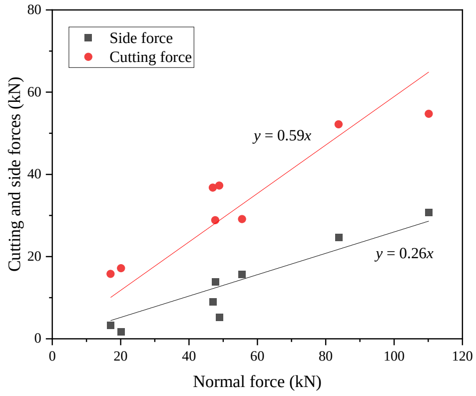


(a) Mean cutter force (b) Peak cutter force

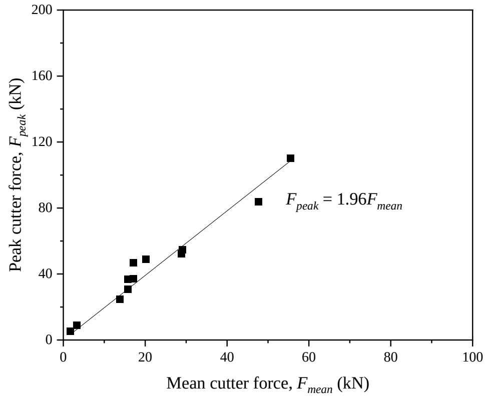
Fig. 3 Three directional cutter forces in the LCM test: (a) mean cutter force and (b) peak cutter force

Among the three force components, the normal force is larger than the cutting and side forces. Fig. 4(a) shows the ratio of the cutting and side forces to the normal force in different penetration depths. In this LCM test, the cutting and side coefficients are calculated as 0.59 and 0.26, respectively. The previous studies (Shao et al., 2014; Park et al., 2018) stated that the higher attack angle is more efficient in cutting hard rock formations. It means the proportion of normal force increases to cut the hard rock, then the higher attack angle is preferred to make the resultant angle equal to attack angle. The results obtained from this study indicated that cutting an extremely hard rock requires higher attack angle than 45° set in the LCM test.

In addition, Fig. 4(b) shows the relationship between the peak cutter force and mean cutter force obtained from this study. The ratio of peak force to mean force is considered as important parameter to assess structural stability of roadheader during rock excavation. In the previous study, the ratio was found to be around two to four (Bilgin et al., 2006; Choi et al., 2014; Jeong and Jeon, 2018(a), 2018(b)), and they noted that the ratio was affected by the mechanical properties (i.e., brittleness and mineral composition of rock). Although the cutting tests were conducted on extremely hard rock specimen, the ratio was found to be around two in this study. The result falls within the range reported in the previous studies. This result agrees well with previous findings (Jeong and Jeon, 2018(b)). They noted that the ratio of peak to mean cutting force affected the mechanical properties of rock, such as brittleness and mineral composition of rock rather than strength of rock.



(a) Cutting and side coefficients



(b) Peak and mean cutter forces

Fig. 4 The relationship between cutter forces: (a) cutting and side coefficients (b) peak and mean forces

3.2 Specific energy

The results of specific energy under different cutting conditions are summarized in Table 3, and Fig. 5 shows the relationships between the specific energy and the depth of cut. As reported in the previous study, the specific energy decreased with the depth of cut. However, the optimum value was not found because of the lack of testing data at the larger depth of cuts. The larger depth of cut was not considered due to the excessive cutter forces (above 10 tons at 6 mm of depth of cut). Based on the literature survey, the specific energy of pick for soft to medium rock (under 100 MPa) did not exceed tens of MJ/m^3. However, the results showed that the magnitude of specific energy exceeds hundreds of MJ/m^3. It indicated that the cutting extremely hard rock with conical pick is not efficient significantly. Despite its inefficient cutting performance, it is possible to break extremely hard rock using a conical pick. However, it is expected that roadheader experienced very low excavation performance under continuous hard rock formations due to the high level of cutter forces. Also, it should be noted that the result of this study is obtained from the single cutter. In real application, because many picks are in contact with the rock surface, it is high possibility to exceed the capacity (thrust and torque) of cutting-head. It is reasonable to temporarily operate under a low level of depth of cut.

Table 3 Result of specific energy obtained from the LCM test

Depth of cut (mm)	Cut spacing (mm)	s/d ratio	Specific energy (MJ/m^3)
1.5	12	8	453.67
2.0	12	6	388.05
4.0	12	3	365.09
6.0	12	2	264.33

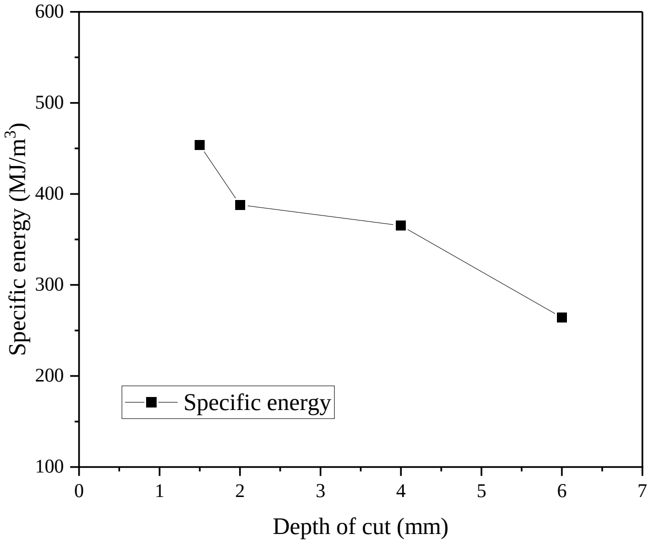


Fig. 5 The result of specific energy obtained from the LCM test

3.3 Cutting stability and wear of a pick

In hard rock excavation using roadheader, major potential problems are the decrease of cutting performance in hard rocks and the excessive wear of a pick in abrasive rocks. After the cutting tests, tip and body of pick was severely worn although the pick traveled only 10 m during total cases as shown in Fig. 6. This was judged to be due to high level of cutter force. The cutting performance of the pick is reported to decrease with cutter wear, while the picks should be replaced above certain limits. The frequent cutter replacement increases downtime and reduce excavation performance of the machine. It indicated that additional treatment or special materials with high wear resistance on the body and tip are required to excavate the hard rock formation.

Fig. 6 Excessive wear of pick after cutting

Fig. 7 shows the tearing in welding part between the pick holder and plate. It was judged to be because the cutting angle (skew and attack) was not optimized for the given rock condition. The structural stability of a pick is important consideration in pick cutting. The structural stability of pick is affected by the relationship between installation angle of pick and direction of resultant force. It is preferred to match the installation angle with the direction of resultant force. The mismatch of these angle can result in the additional load to a machine and other components of the cutting head.

Fig. 7 Tearing in welding part between holder and plate

4. CONCLUSIONS

This study tried to evaluate the cutting performance of pick under extremely hard rock, and to investigate the cutting characteristics of pick. In order to assess the applicability of pick cutters in abrasive hard rocks, the linear cutting machine (LCM) test was performed using a pick cutter for hard rock specimen. The results indicated that excessive cutter forces and specific energy will be required to break the hard rock. Also, additional problems related to the wear of a cutting tool and the mechanical stability of a pick holder were observed in the LCM test. The results of this study can be useful information when the pick cutters are applied to hard rock in the future.

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