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A study on rock cutting efficiency and structural stability of a point attack pick cutter by lab-scale linear cutting machine testing and finite element analysis

Jin-Young Park[a], Hoon Kang[a], Jae-Wook Lee[a], Jong-Hyoung Kim[a], Joo-Young Oh[a], Jung-Woo Cho[a,*], Jamal Rostami[b], Hyun Deok Kim[c]

[a] Daegyeong Regional Division, Korea Institute of Industrial Technology, Daegu, Republic of Korea
[b] Department of Mining Engineering, Colorado School of Mines, Golden, CO, USA
[c] Department of Electronics of Engineering, Kyungpook National University, Daegu, Republic of Korea

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ABSTRACT

A lab-scale linear cutting machine was manufactured to investigate the rock-cutting mechanism and a range of design factors of point attack pick cutters. Tests were performed on three samples with different strengths, and measured cutting forces were used to calculate the specific energy, an indicator of cutting efficiency. We proposed design conditions such as cut spacing, depth, skew angle, and attack angle for the cutting head to achieve efficient rock cutting while minimizing specific energy. In addition, the structural stability of the pick cutter and holder with respect to skew angle was analyzed. The relation between structural stability and durability is discussed in terms of the resultant force and skew angle. A series of finite element analyses explored the structural stability of the pick assembly. The results indicated two sites of concentrated stress that depend on the skew angle and can accelerate undesired abrasion of the pick, and a positive skew angle appears advantageous in terms of both cutting efficiency and structural stability.

1. Introduction

Automated construction and mining processes are becoming attractive in the Republic of Korea as labor costs rise. The design and manufacture of roadheaders for rock excavation is also appealing for construction and mining. The arrangement of pick cutters on the cutting head is the main task in roadheader design, because it is the main determinant of the machine's performance. To understand the rock cutting mechanism and evaluate the key parameters in cutting head design requires linear cutting machine (LCM) tests of pick cutters or field tests for a full cutting head. However, few studies or experiments have investigated pick cutters or cutting head design in the Republic of Korea.

A roadheader's performance varies with the properties of the rock it cuts, and also depends on design parameters such as the dimensions and geometry of the pick cutter, tip radius, number of pick cutters, operating load (vertical force and torque), rotation speed, cutting depth (d), cut spacing (s), attack angle (θ_{at}), and skew angle (θ_{sk}).[1–3] Pick cutter design is similar to the design of a tunnel boring machine's (TBM) disc cutters, as the cutting performance varies particularly with the cutting depth and cut spacing among the design parameters.

Previous works related to mechanized excavation tools (e.g., TBM disc cutters and pick cutters) include the following. Full-scale LCM tests by Bilgin et al.[4,5] revealed that the cut spacing and cutting depth are the main factors influencing cutting efficiency. Gertsch et al.[6] investigated the forces acting on the disc cutter under a series of spacings and penetrations for TBM performance prediction, and Balci et al.[7] studied the correlation between a full-scale rock cutting test and a small-scale test. Chang et al.[8] conducted a LCM test to construct a performance prediction model for a TBM cutting granitic rock, and Cho et al.[9] investigated the optimum cutter spacing of TBM disc cutters thorough LCM tests and numerical simulations. However, these previous studies focused on the effects of well-known factors (i.e., rock properties, cut spacing, and cutting depth), whereas pick cutters differ from TBM disc cutters in that the skew and attack angles also influence the cutting performance. Several researchers have reported that heating of the tip of the pick cutter during rock cutting resulted in abrasive wear.[2,10,11] Li et al.[12] noted failure modes such as the bit falling off, pick loss, and wear of the tip. Shao et al.[13] proposed SMART*CUT technology to alleviate wear at the tip of a pick cutter. Others[14–16] have reported the effects of the skew and attack angles on the rotational performance or

* Corresponding author.
E-mail address: chojw1665@kitech.re.kr (J.-W. Cho).

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Table 1
Uniaxial compression test results.

Specimen class	Size of core specimen D × L (mm)	Uniaxial Compressive Strength, *UCS* (MPa)
Low	53.4 × 127.3	21
Moderate	53.4 × 127.8	41
Medium	53.4 × 126.4	57

cutting force of the pick; however, the currently available results and discussions are not sufficient to predict the general cutting performance of pick cutters or to design the cutting heads of excavating machines. Furthermore, it has been reported that a pick cutter and holder are more structurally stable when the attack angle and the resultant force angle are equal.[17–19] However, there is a lack of studies on the structural stability of a pick cutter with respect to changes in the skew angle.

A full-scale LCM testing is the most reliable approach for determining the optimal design conditions of the cutting heads of rock excavation machines (e.g., TBMs, roadheaders, continuous miners),[4–9,14–16,20–23] a full-scale LCM is costly to manufacture, and it is time consuming to collect and place the required full-scale rock samples. Therefore, lab-scale LCM testing was developed to investigate the rock-cutting performance of a single pick cutter.[24]

This paper reports the results of lab-scale LCM tests that investigated the cutting performance of a pick cutter and suggests desirable design parameters for roadheaders. The cutting force (F_c), including the normal (F_s), drag (F_d), and side (F_s) forces, was measured for each sample with the variables set as five design parameters: attack angle, skew angle, cutting depth, cut spacing, and uniaxial compressive strength (*UCS*) of the sample. The measured cutting forces were used to obtain the specific energy (*SE*), as a measure of cutting efficiency, and the resultant force angle (θ_{re}), to estimate the structural stability of the pick cutter and holder. The analysis results yield the desirable design ranges and working conditions of the pick cutter, so as to improve the cutting efficiency and enhance the durability of the cutting head of a roadheader.

2. LCM tests

2.1. LCM testing system and pick cutter

Given the difficulty in extracting natural rock samples of the required strengths, cement mortar samples (300 × 200 × 200 mm) were cured for around 1 month to produce three types of sample corresponding to low-, moderate-, and medium-strength rock.[25] Uniaxial compression tests confirmed their strengths (Table 1).

In previous studies,[7,26] the maximum drag force (F_{d_peak}) and normal force (F_{n_peak}) while cutting a hard rock to a depth of 8 mm were measured to be 15 and 10 kN, respectively. The lab-scale LCM system uses a new method to measure the cutting forces (Fig. 1(a)).[24] The system consists of four frames to support the cutting load of the samples. The cutting depth and skew angle can be adjusted using a hydraulic cylinder and a plate located on the top, respectively. The attack angle is controlled by changing the plate, onto which the holder can be welded at an angle of 45° to 60°. A sample is placed on a sliding table located at the bottom, which is actuated horizontally by the hydraulic cylinder. This allows the linear cutting of the sample. Four single-axis

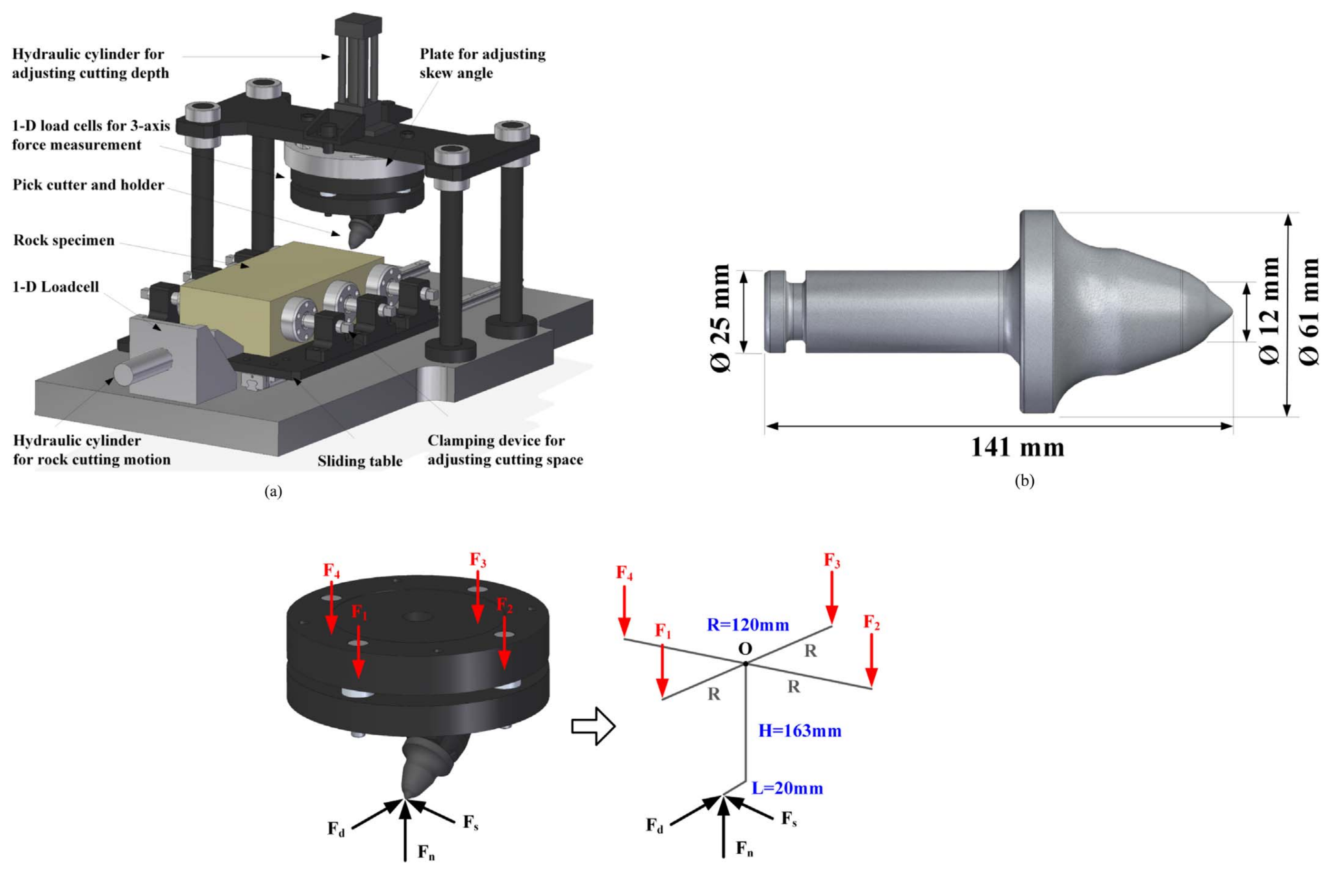

Fig. 1. Linear cutting machine and pick cutter. (a) Lab-scale linear cutting machine. (b) Point attack pick model T1 (by Kennametal Inc.). (c) Diagrams of the cutting forces acting on measuring device (left) and force vectors on the 3-D coordinates (right).[15].