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Parametric study of rock cutting with SMART∗CUT picks

Wen Shao [a,b,∗], Xingsheng Li [b], Yong Sun [b], Han Huang [a]

[a] School of Mechanical and Mining Engineering, The University of Queensland, QLD 4072, Australia
[b] CSIRO Energy Flagship, PO Box 883, Kenmore, QLD 4069, Australia

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ABSTRACT

The severe abrasive wear of the current cemented tungsten carbide (WC) tools is a "bottleneck" that limits the usage of machinery in hard rock mines. To address this issue, a revolutionary thermally stable diamond composite (TSDC) based cutting tool, also called Super Material Abrasive Resistant Tool (SMART∗CUT) was developed by CSIRO. Before this novel tool is employed for practical rock cutting, the effects of the cutting parameters on the performance of the SMART∗CUT picks must be determined and the cutting forces of the picks have to be estimated as they directly affect the capability and efficiency of the selected cutterhead and hence the excavation machine. In this study, rock cutting tests based on Taguchi's L25 orthogonal array were conducted to analyze the cutting parameters. The signal-to-noise (S/N) ratios and the analysis of variance (ANOVA) were applied to investigate the effects of depth of cut, attack angle, spacing and cutting speed on mean cutting and normal forces during the rock cutting process. Empirical models for predicting the cutting forces on SMART∗CUT picks were developed using multiple linear regression (MLR) and artificial neural network (ANN) techniques. Parametric combinations for minimizing the cutting forces and the statistical significance of process factors were successfully determined by using the Taguchi technique. Good prediction capabilities with acceptable errors were achieved by the developed MLR and ANN models. However, the ANN models offered better accuracy and less deviation.

1. Introduction

Excessive abrasive wear of traditional refractory carbides, diamond impregnated metal matrix composites (DIMMC) or polycrystalline diamond compact (PDC) cutting elements has hindered the use of mechanical excavators as the temperature at the tool-rock interface could exceed 1300 °C when cutting hard rock (Boland et al., 2002; Li and Boland, 2005; Martin and Fowell, 1997). Hence, by changing the binder material from metallic cobalt to ceramic-based silicon carbide (SiC) during the sintering process, CSIRO (Commonwealth Scientific and Industrial Research Organisation) has explored a new diamond composite called thermally stable diamond composite (TSDC). The use of SiC as the binder material is beneficial to the mechanical stability of TSDC at high temperatures as it does not act as a catalyst for the decomposition of diamond to graphite even up to a high temperature of 1350 °C. CSIRO developed the SMART∗CUT (Super Material Abrasive Resistant Tool) rock cutting pick that has a TSDC cutting element bonded into the steel body of the pick using CSIRO's worldwide patented bonding technology. The successful development of the so called SMART∗CUT technology, indicates a great promise for the employment of these cutting tools in hard rock mines. The main advantages of TSDC-tipped SMART∗CUT picks are (a) good thermal stability, (b) high wear resistance and (c) the ability to mine harder deposits compared to point attack picks using tungsten carbide (WC) inserts (Li and Boland, 2005; Li et al., 2011; Shao et al., 2014). The previous research at CSIRO focused on the investigation of the wear characteristics of the solid, moulded TSDC cutting elements (Boland et al., 2002; Boland and Li, 2010; Li and Boland, 2005). It is evident that the wear resistance of TSDC elements was over one thousand times greater than that of cemented WC (Li and Boland, 2005). However, like other high wear resistance materials, the fracture toughness of TSDC is much less than that of WC. Therefore, the SMART∗CUT picks may not be directly applicable to the current cutterheads on mechanical mining machinery as they are all based on WC point attack picks that have different material properties and cutting geometries compared with such parameters required for TSDC-based picks (Li and Boland, 2005).

Before the employment of SMART∗CUT picks in a rock excavation machine, it is important to estimate the magnitude of cutting forces applied to the picks under different cutting scenarios, in

∗ Corresponding author at: School of Mechanical and Mining Engineering, The University of Queensland, QLD 4072, Australia.
E-mail address: shaowen_2013@163.com (W. Shao).

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order to calculate the cutterhead torque and cutter motor power for any set of geological formations, cutterhead design, and operational conditions of the machine (Goktan and Gunes, 2005; Yilmaz et al., 2007). Full-scale laboratory rock cutting tests are the most accepted, reliable and precise method that is needed to determine the cutting forces acting on an individual pick; the forces measured in these tests can be used as direct input into cutterhead design software to determine the capability and efficiency of the selected cutterhead and excavation machines (Balci et al., 2004; Copur et al., 2001; Hood and Alehossein, 2000; Rostami et al., 1994; Su and Ali Akcin, 2011; Tiryaki et al., 2010; Yilmaz et al., 2007). Moreover, excessive forces on the picks may result in premature fracture damage of the TSDC elements, damage the machine components and exceed the machine's torque and thrust capacities (Bilgin et al., 2006). Therefore, it is crucial to select the cutting parameters to minimize cutting forces.

In this study, the Taguchi method is initially employed to find out the critical cutting parameters that influence the rock cutting process. Then, multiple linear regression and neural network techniques are adopted to develop empirical models of the cutting forces on SMART∗CUT picks as a function of depth of cut (DOC), attack angle, pick spacing and cutting speed. The performances of these models are also discussed.

2. Experimental details

2.1. Full-scale linear rock cutting tests

As illustrated in Fig. 1, the linear rock cutting tests were conducted on the CSIRO's rock cutting planer. It consisted of a solid stationary main frame, a crosshead, a tri-axial force dynamometer and a cutting table (Fig. 2). The rock sample was mounted on the cutting table, and moved against the stationary cutting tool during the experiments. The cutting table and rock were driven horizontally by a hydraulic ram. The travelling stroke of the table was 3 m and its speed could be controlled from 0.1 to 3.0 m/s. The rock specimen was embedded in a steel tray which was rigidly secured to the cutting table. Both sides of the rock were also clamped to prevent from splitting when the cutting groove was near the edges of the rock block. This arrangement was able to accommodate rock blocks with dimensions of 450 × 450 × 1800 mm.

The cutting tool was adjusted both laterally and vertically, which allowed the cutting tool to be set to its required position relatively to the rock block. The setting of the cutting tool was manually driven by turning a handle (gears and screw system). Once the desired DOC (penetration) was achieved, the tool was secured into position using heavy screw threads and stops. An accuracy of 0.05 mm of penetration was achieved using a laser displacement sensor attached to the cutter assembly. A tri-axial dynamometer and data acquisition system were bolted to the crosshead to record the cutter forces. The data sampling rate was set as 3200 Hz. The control of linear rock cutting machine was carried out by a PC equipped with LabVIEW software and a National Instruments A/D card.

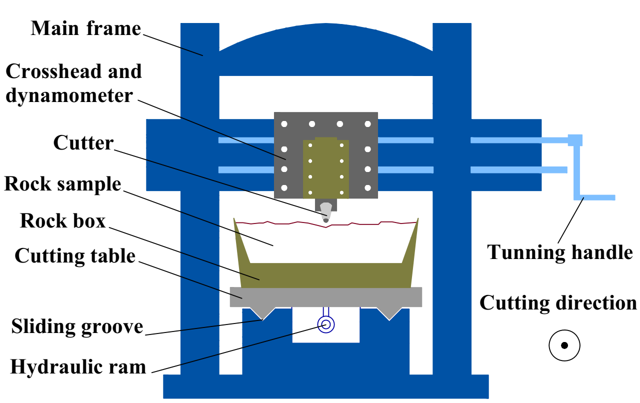

Fig. 1. Schematic view of the linear rock cutting planer.

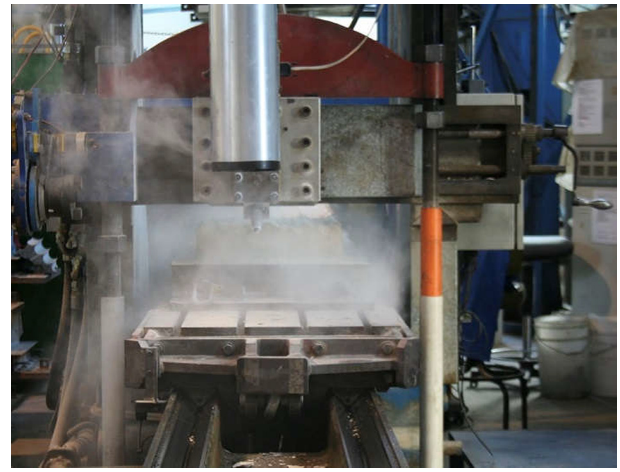

Fig. 2. Photograph of the linear rock cutting planer.

In this study, only the orthogonal force components F_c and F_n (cutting and normal forces) were taken into consideration for the cutting performance analyses because the magnitude of the sideway force F_s was always negligible compare to that of cutting and normal forces (Fig. 3).

2.2. Cutting tool

Fig. 4 shows the TSDC tipped SMART∗CUT pick developed by CSIRO, used as the cutting tool in all the tests. The pick had a gauge of 70 mm, flange diameter of 50 mm, shank diameter of 30 mm and tip diameter of 16 mm.

2.3. Rock sample and its properties

A block of Helidon Sandstone, collected from a local mining quarry near Brisbane Australia was used as the test sample; it had dimensions of 450 mm × 450 mm × 1700 mm. Its mechanical properties including density, uniaxial compressive strength (Fig. 5a), Brazilian tensile strength (Fig. 5b), Young's modulus and Poisson's ratio are given in Table 1.

Four core samples were prepared for the UCS and elastic properties tests. As can be seen from Fig. 6, the UCS values of the rock samples were consistent with an average UCS of 57 MPa. Fig. 7 shows the typical stress-strain curves of the core samples obtained from the elastic property tests.

2.4. Experimental design using Taguchi method

The Taguchi method is a popular and efficient experimental design technique to investigate how different parameters affect the mean and variance of a process performance characteristic. The approach can optimize performance characteristics by optimizing the settings of design parameters and reduce the sensitivity of system performance to environmental conditions and variations (Lin and Chou, 2008). The Taguchi method overcomes the limitation of full factorial design which has to test all the possible combinations of a process. A set of well-balanced experiments is organized by the manipulation of orthogonal arrays (OA), which