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Rock cutting characteristics on soft-to-hard rocks under different cutter inclinations

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1. Introduction

Rock drilling and cutting is essential in the mining industry. Rock characterisation and classification methods have been proposed to assess drilling or cutting performance.[1–5] However, a generalised method to relate rock characteristics to rock cutting performance has not yet been developed. This is due to the complexity of interactions among the variables involved in the cutting process encompassing not only rock properties, but also the nature of cutting. Cost-effective drilling is achievable by allocating the available gross energy towards the cutting action and, at the same time, reducing systematically that energy consumed in frictional processes inherent to tool-rock interactions. A set of optimum drilling parameters (i.e. the optimum weight and torque on the bit) is essential to produce the optimum drilling rate and attain higher efficiency. In this instance, extra energy may be required if the weight and torque on the bit are significantly different from their optimum values making the drilling process less efficient.

Several attempts have been made to assess drilling performance by correlating different rock properties with the drilling rate. For instance, rock texture, grain size, Unconfined Compressive Strength (UCS), Mohs hardness and rock mass structural parameters have been used to build a number of drillability indices.[1,3,6] However, not only rock properties, but also different sets of drilling parameters (weight and torque on the bit) and drilling techniques have an impact on the drilling performance and efficiency of the process as noticed in Refs. 7–10.

Through tool-rock interaction laws, it was found that Specific Energy (SE) accounts for both the energy consumed in rock cutting and the energy consumed in friction between the tool and the rock or in mechanical energy losses outside the rock.[7,8] The concept of specific energy (SE) in rock drilling was introduced by Teale [7] as the work done to excavate a unit volume of rock. In this manner, the cutting response of PDC (Polycrystalline Diamond Compact) bits derives from a combination of two major actions[8]: i) a pure cutting action and ii) a frictional action due to the cutter wear-flat area. The energy consumed in a pure cutting action of rock is measured by the intrinsic specific energy (ε) attainable at the cutting point.[8,9,11,12] The magnitude of the intrinsic specific energy depends entirely on the nature of the rock,[7,8] the surrounding pressure on the rock surface[13] and the drilling technique being used.[9,11,12] Quantities of consumed energy higher than the intrinsic specific energy represent the energy consumed by frictional processes.

The intrinsic specific energy (ε) quantifies the maximum cutting efficiency associated with the optimum cutting force[8,9,11,12] and it has become useful to estimate rock strength. In this regard, it has been found that ε approximately equals to Unconfined Compressive Strength (UCS) of rock in drilling experiments with PDC bits[9] and roller-cone bits.[11] In addition, this finding has been supported by a significant number of cutting tests with a single

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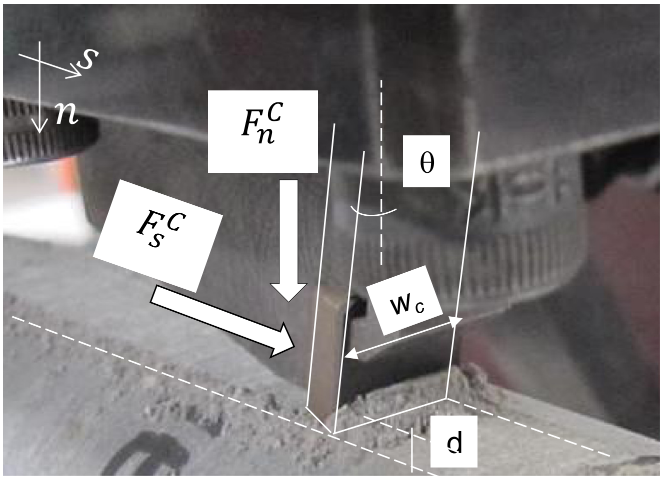

Fig. 1. PDC cutting test at shallow depth of cut.

PDC cutter when the back-rake angle of the cutter (θ) is 15°,[14] see Fig. 1 for the definition of back-rake angle.

A literature survey indicates that there are very few studies on effect of cutting parameters on the intrinsic specific energy value. To investigate the magnitude of the intrinsic specific energy and its relation with the geometry of the cutting and peak strength of rock, cutting experiments with a single PDC were carried out on different rock types at different back-rake angles, i.e. θ of 15°, 30° and 45°. Additionally, the stress-strain parameters of the rocks were obtained by performing a series of uniaxial compressive tests.

2. Rock cutting mechanism

Rock cutting induces two modes of failure in the rock depending on the depth of cut, d, which are plastic yielding and fracture mode of failure.[14–16] At relatively shallow depths of cut, plastic yield mode of failure is dominant and material failure is governed by yield strength (i.e. strength-related failure mechanism). On the other hand, when the depth of cut is relatively deep, fracture mode of failure dominates and therefore material failure is governed by its fracture properties (i.e. fracture-related failure mechanism). In these instances, UCS and fracture toughness, K, become relevant to characterise plastic yield and fracture mode of failure in cutting, respectively.

Lin and Zhou[15,16] demonstrated that rock cutting is well described by Bazant's size effect law (SEL) for quasi-brittle materials, such as concrete and rocks.[17] SEL is expressed as a function of the nominal stress $\sigma_N = \left(F_s^C\right)_{peak}/w_c d$ and the depth of cut, d, where $\left(F_s^C\right)_{peak}$ is the peak cutting force and w_c is the cutter width, see Fig. 1 for the geometry and nomenclature of the cutting test. In the case of rock cutting, they found that linear elastic fracture mechanics (LEFM) is relevant asymptotically to cutting data when cutting is relatively deep. In the present study it is anticipated that the cutting experiments were carried out at depths of cut smaller than 0.5 mm in compliance with plastic yield mode of failure.

3. Experimental study

A series of uniaxial compressive tests and cutting tests using a single PDC (Polycrystalline Diamond Compact) cutter were carried out. Uniaxial compressive tests were conducted at The University of Adelaide and cutting tests were performed at the Australian Resource Research Centre (ARRC) CSIRO-Perth facilities. The experimental work details are summarised in Table 1.

Table 1.
Experimental program.

Test type	Rock name	Rock type	Rock source	Number of tests	Total tests
PDC Cutting	Tuffeau	Limestone	France	15	45
	Mountain Gold	Sandstone	Australia	15	
	Hawksbury	Sandstone	Australia	15	
	Brukunga	Phyllite	Australia	15	
	Mantina	Basalt	Australia	15	
Compressive loading	All above	All above	France, Australia	3, 4 or 5 per rock	26

3.1. Rocks investigated

Rock types including limestone (Tuffeau), sandstone (Mountain Gold, Hawkesbury), phyllite (Brukunga) and basalt (Mantina) were investigated. The rocks were sourced from several mines and quarries in France and Australia. Table 2 lists the rocks investigated and their physical and mechanical properties including grain size, uniaxial compressive strength (UCS) and Young's modulus (E) on average. The rock samples correspond to fine grain size having densities ranging from 1.5 to 2.7 g/cm^3 and uniaxial compressive strengths ranging from 9 to 249 MPa.

3.2. Uniaxial Compressive tests

To study the stress-strain characteristics of the rocks under uniaxial compressive tests, in total 26 samples were prepared from coring rock blocks listed in Table 2. The diameter of cores was 42 mm and their aspect ratio (the ratio diameter to length) was maintained at 2.4. Visual inspection shows that sample diameters were more than 10–20 times bigger than rock grains size. Each rock was tested at least three times and consistent results were obtained from UCS tests on each rock.

Axial and lateral deformations induced by axial load on the rock samples were measured locally by either: i) a pair of axial and lateral strain gauges (FLA-30–11 and FLA-10–11 manufactured by Tokyo Sokki Kenkyujo Co.) attached directly to the surface of the rocks in axial and lateral directions, respectively, or ii) direct-contact axial and lateral extensometers (632.12F20-series manufactured by MTS Systems Co.). In addition, the axial deformation was measured externally by a pair of LVDTs (Linear variable displacement transducers). Local measurement devices are free from bedding errors[18] and therefore, in this study, local axial and lateral deformations measured were used.

Axial deformation feedback signal was used to control the axial loading keeping a constant axial deformation rate equal to 0.04 mm/min. For this purpose, a closed-loop servo-controlled loading machine stiff enough to allow the elastic energy not to accumulate in the testing machine was used. The testing machine has a loading capacity of 1000 kN. In all the tests, no additional friction-reducing layers in contact between the specimens and the loading platen were used. In this case, the platen was in direct contact with the specimens.

3.3. Cutting tests with a single PDC

In total 45 PDC cutting tests were carried out on the rocks to investigate the magnitude of the intrinsic specific energy, ε. The tests were conducted following a standard practice suggested by Richard et al.[14] The cutting device used in this experiment was