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An experimental study of the effect of back rake angle in rock cutting

Iman Rostamsowlat[a,b,*], Thomas Richard[c], Brian Evans[a]

[a] Deep Exploration Technologies CRC, Department of Petroleum Engineering, Curtin University, Kensington, WA 6151, Australia
[b] Rock Properties & Drilling Mechanics Groups, CSIRO Energy, Perth, Australia
[c] Epslog SA, 69 Jean Street, Hamilton Hill, 6163 WA, Australia

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ABSTRACT

The objective of this paper is to investigate the influence of the rake angle on the magnitude of the intrinsic specific energy and the inclination of the force acting on the cutting face of a Polycrystalline Diamond Compact (PDC) sharp cutter while tracing a groove on the surface of a rock sample. An extensive and comprehensive set of cutting experiments was performed on a wide range of quarry rock samples using a state of the art rock cutting equipment (Wombat). The results conform with the previous studies by other researchers; the intrinsic specific energy is in good agreement with the uni-axial compressive strength of the rock samples when the cutter is positioned at back rake angles between 5° to 20°. New results on a few rock samples were also obtained by performing novel experimental tests at very large rake angles ($\theta > 70°$) as well as negative rake angles, showing that the intrinsic specific energy increases dramatically once the back rake angle exceeds 75°. Results also indicate that the decrease of the apparent interfacial friction angle with increasing back rake angle seems to follow a "universal trend" weakly dependent on the rock sample.

1. Introduction

Polycrystalline Diamond Compact (PDC) bits have been used in the petroleum drilling industry since 1973. Unlike tricone bits, which indent the rock with a crushing force, PDC bit cutters machine out the rock surface and cause rock failure by a shearing action.[28] Rock cutting is one of the most important processes involved in the mechanical excavation and drilling of rock, which have both been research topics of particular interest in the areas of civil, mining, and petroleum engineering over the past decades. A drill bit is a collection of cutting elements (cutters) whose rake angles can vary from cutter to cutter.[1–4]

It is generally accepted in the literature[5–10] that the force acting on a single cutter is governed by the coexistence of two independent processes: (*i*) a "frictional contact" process mobilised across the wear flat, and (*ii*) a "pure cutting" action in front of the cutting face. This study focuses on the pure cutting process where the term "pure" means that all the energy is devoted to remove the rock material and no energy is dissipated by the frictional contact process.

Rock cutting can be characterized by two main failure modes (depending on the depth of cut) that take place ahead of the cutting face: (*i*) a ductile regime (with depth of cut typically less than 1 mm[11]) which is characterized by the de-cohesion of the constitutive matrix and grains of the rock with grains and powder accumulating progressively ahead of the cutter, and (*ii*) a brittle regime (at larger depth of cut) which is associated with the propagation of macroscopic cracks at the tip of the cutting tool.[11–15] In the case of ductile regime, work performed by the cutter is proportional to the volume of rock being removed, which leads to a linear relationship between the cutting force and the cross-sectional area of the groove traced by the cutter.[7,12] The two cutting force components F_{cn} and F_{cs}, normal (subscript n) and parallel (subscript s) to the velocity vector $\boldsymbol{v}$ (see Fig. 1), respectively, can be written as:

$$\begin{cases} F_{cn} = \zeta \varepsilon A_c \\ F_{cs} = \varepsilon A_c \end{cases} \quad (1)$$

Here, ε is the intrinsic specific energy (defined as the minimum energy to remove a unit volume of the rock with the unit of stress MPa[16]) which increases with increasing back rake angle (θ) but correlates very well with the uni-axial compressive strength (q) of the rocks for rectangular cutter (for $\omega \simeq 10-20$ mm where ω is the width of cutter) when the back rake angle (θ) is in the range of 10° to 20°.[11,12,17–21] The back rake angle or θ is defined as the angle between the normal to the cutting surface (k) and the velocity vector, and A_c is the cross-sectional area of the groove traced by the cutter ($A_c = \omega \times d$ for a rectangular shaped cutter where d is the depth of cut). The number ζ is given by:

$$\zeta = tan\ (\theta + \psi) \quad (2)$$

* Corresponding author at: 26 Dick Perry Avenue, Department of Petroleum Engineering, Curtin University, Kensington, WA 6151, Australia.
E-mail addresses: iman.rostamsowlat@gmail.com, iman.rostamsowlat@postgrad.curtin.edu.au (I. Rostamsowlat).

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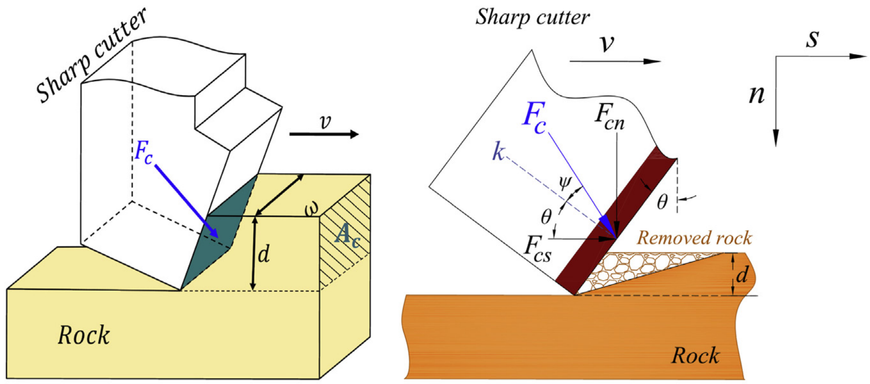

Fig. 1. Schematic of force components acting on a sharp cutter.

where ψ is the interfacial friction angle which is found independent of the depth of cut for a given back rake angle. However, experimental observations[12,22] suggest that the interfacial friction angle is predominantly affected by the back rake angle; an increase in the back rake angle leads to a decrease of interfacial friction angle. Results suggest that the failed materials mostly flow upward at small rake angle but as the back rake angle increases, backward flow of material increases at the expense of the upward flow due to the presence of a zone of dead material (or build-up edge BUE) at the cutting edge, leading to an overall rotation of the resulting cutting force with respect to the normal to the cutter. Although research efforts[21–24] have been devoted to the study of the cutting response of sharp and blunt cutters, to the best knowledge of authors, no work has been dedicated to capture the evolution of the cutting response of a sharp cutter at negative back rake angles and as the back rake angles approaches 90°.

In the present paper, we present, analyze and discuss the results of tests carried out with a sharp cutter at different back rake angles but also on a wide range of sedimentary rock samples with the intention of exploring the effect of rock material on the relation between the interfacial friction angle and the back rake angle. Furthermore, on a few rock samples, the back rake angle was varied from a negative value (cutter inclined backward with respect to the direction of cutting) to the highest possible forward inclination allowed by the equipment, up to nearly 85°, with the intention of capturing the transition from a cutting (uncontained failure) to a contact (contained failure) process as the cutter forward inclination increases. For this purpose, an extensive series of laboratory cutting experiments was conducted on thirteen different rock samples (clastics and carbonates) on a state of the art rock cutting laboratory equipment using a tailored designed cutter holder with adjustable rake angle.

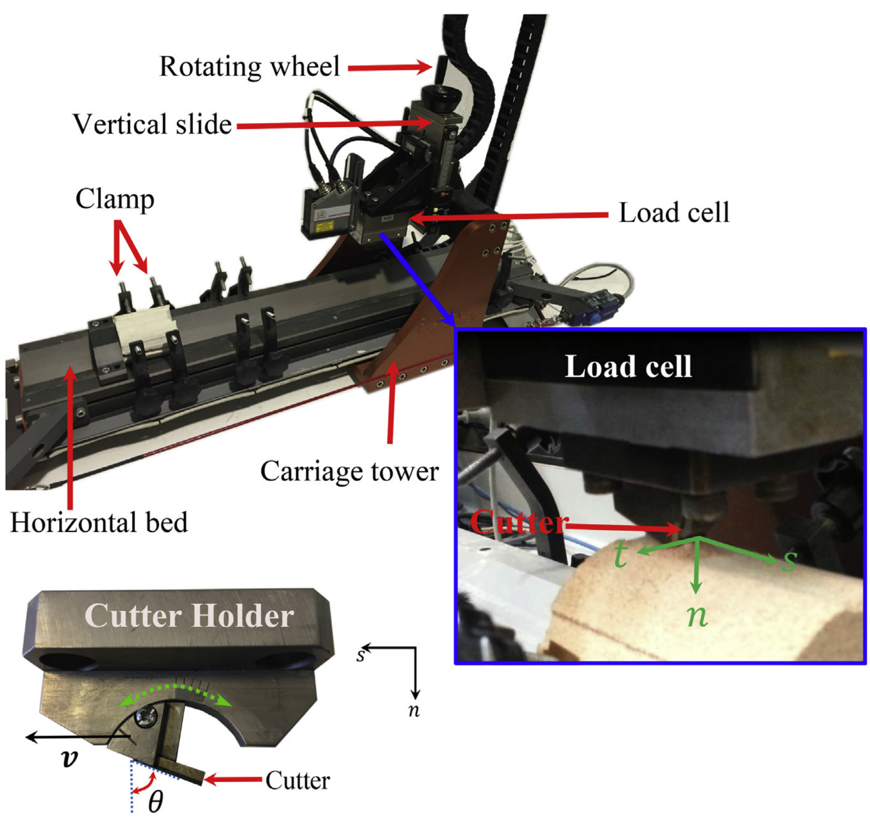

Fig. 2. Wombat parts and cutter holder.