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On the critical failure mode transition depth for rock cutting with different back rake angles

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ABSTRACT

The failure mode of rock under cutting exhibits a ductile-brittle transition as the depth of cut increases. The critical transition depth, beyond which energy consumed in brittle fracturing surpasses the energy consumed in plastic flow, is the key to differentiating between the ductile and brittle cutting modes and therefore is an important parameter to optimise tool design and operational parameters to meet specific application requirements. This critical failure mode transition depth depends not only on rock properties but also on cutting operational parameters, in particular, the back rake angle. In this work, a series of rock cutting tests were performed to investigate the influence of back rake angle on the critical failure mode transition depth. Size effect law is employed first to identify the critical transition depths, which are then compared with values derived from the analysis of specific cutting energy. It is found that the critical failure mode transition depth increases with the back rake angle. This suggests that the brittle fracture failure induced at large depth of cut can be inhibited by increasing the back rake angle. Cutting at a small back rake angle, on the other hand, is desirable if minimisation of the cutting energy is required in the application.

1. Introduction

Understanding the interaction between rock and a cutter is important for many rock engineering applications, including exploration drilling, tunnelling, mining, stone sawing and polishing (Buyuksagis, 2007; Che and Ehmann, 2014; Franca, 2011; Gong et al., 2016; Kahraman, 2002; Li et al., 2001). The cutting process involves removing a fraction of rock material with a cutter being driven across rock surface at a prescribed velocity while penetrating into the rock at certain depth, see illustration in Fig. 1. This penetration depth is referred to as the depth of cut, d.

It is well known that there exist two different failure modes in rock cutting, namely, ductile and brittle failure modes (Huang et al., 2013; Nicodeme, 1997; Richard, 1999; Richard et al., 1998; Zhou and Lin, 2013) and both failure mechanisms in general coexist in any cutting operation (He and Xu, 2015a). In shallow cutting, the ductile failure mode dominates, which is characterised by crushing of particles in the vicinity of the tip of the cutting tool and shearing of rock grains in front of the tool (see Fig. 2a and b). Brittle failure mode dominates at greater cutting depths with energy dissipated mainly in creating macroscopic cracking surfaces ahead of the cutting tool (see Fig. 2c and d). Therefore, a critical transition depth emerges where the failure of rock in cutting changes from ductile-dominated to brittle-dominated failure as the depth of cut increases.

The failure mode transition has been an active research topic in rock cutting mechanics, e.g., (Huang et al., 2013; Nicodeme, 1997; Richard, 1999; Richard et al., 2012, 1998; Zhou and Lin, 2013, 2014). Most of these studies focused on linking the critical failure mode transition depth with the mechanical properties of rock such as opening-mode fracture toughness, K_{IC}, uniaxial compressive strength, σ_c, and tensile strength, σ_t. For example, Richard et al. (1998) proposed the relationship between the critical failure mode transition depth, d_c, and rock properties as $d_c \propto (K_{IC}/\sigma_c)^2$. This relationship was later confirmed by discrete element numerical simulations in Huang and Detournay (2008) where d_c is further linked to an intrinsic length scale, $l_i = 1/\pi(K_{IC}/\sigma_c)^2$.

However, to our best knowledge, the effect of some operational parameters such as cutting velocity and back rake angle on the failure mode transition phenomenon has rarely been explored. Recent experimental observations suggest that the critical failure mode

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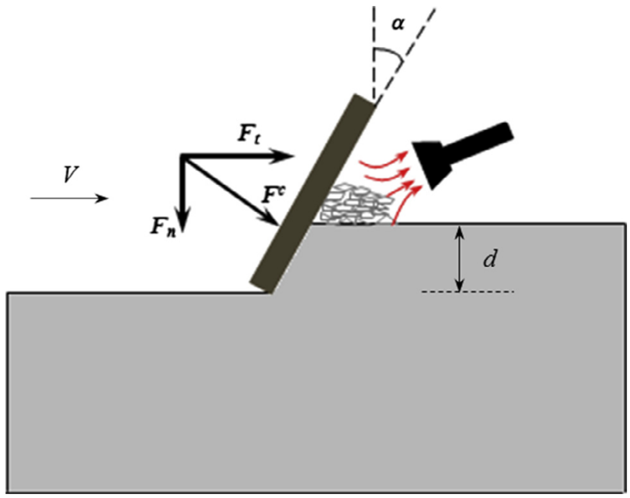

Fig. 1. Schematic representation of a cutting test with an inclined cutter. The inclination of cutter with respect to the normal to the top surface of rock is the back rake angle α. F_t and F_n are the tangential and normal component of the resulting cutting force F^c.

transition depth is dependent not only on rock properties but also on the operational parameters. It was found that the cutting velocity in the range of 4–20 mm/s has little impact on failure mode transition while a larger back rake angle tends to make the failure mode transition shifted to a greater depth of cut (He and Xu, 2015b). Despite this, the reliability of the specific energy model used to derive the critical failure mode transition depth needs to be improved.

This paper aims to investigate the effect of back rake angle on the transition of cutting failure modes. A series of cutting tests are conducted on two types of limestone and size effect law (SEL) is introduced into the analysis of the cutting mechanisms. The SEL derived failure mode transition depths are then compared with those derived from specific cutting energy analysis. The accuracy and reliability of SEL model and specific energy model are assessed by examining the cutting grooves.

2. Determination of the critical failure mode transition depth

Although there are extensive experimental and numerical studies reported on rock cutting processes, few of them deal with the reliable determination of the critical transition depth that quantifies the change of dominant rock failure modes during rock cutting. To deal with this issue, two different approaches are presented below, with one based on the size effect analysis and the other on specific cutting energy.

2.1. Critical transition depth prediction based on size effect analysis

It is well understood, in general, larger structures are more brittle than smaller structures (Van Mier, 2012) and there is a decrease in the nominal strength when the structure size exceeds a critical value. To capture the failure transitional behaviour for structure of varying sizes, Bažant proposed a size effect law (Bažant, 1984; Bažant et al., 1991) to model the blunt fracture behaviour in

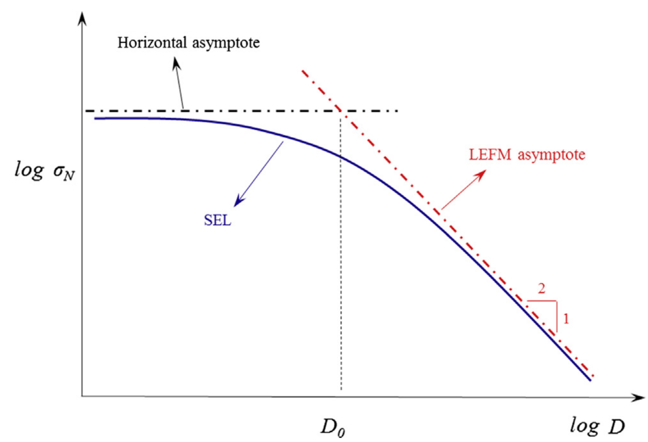

Fig. 3. Bažant's size effect law bridging between the strength asymptote and the LEFM asymptote.

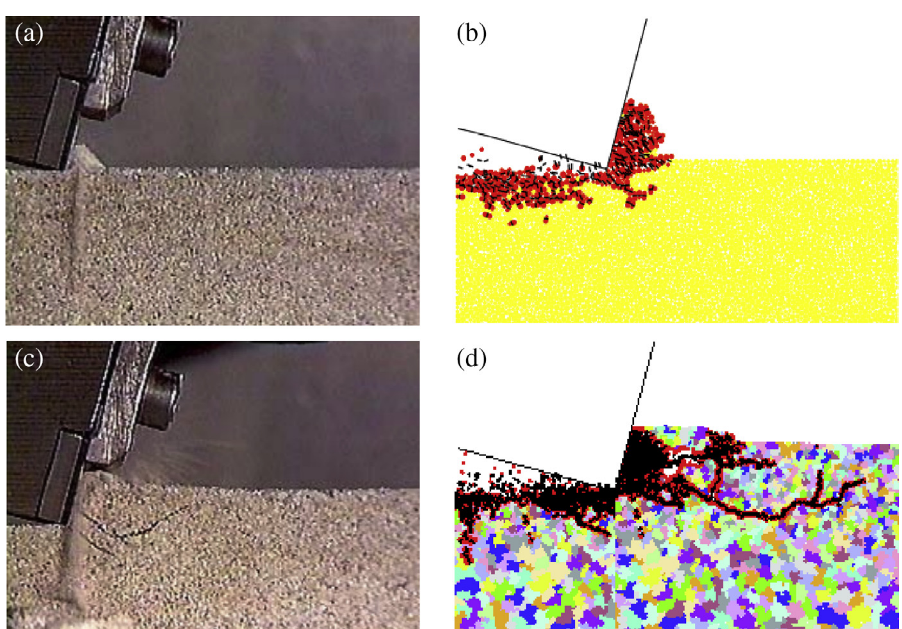

Fig. 2. Typical ductile failure mode of cutting in (a) test and (b) simulation and typical brittle failure mode of cutting in (c) test and (d) simulation. Results of experiment (left) and simulation (right) are reproduced after Richard (1999) and He and Xu (2015a), respectively.