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Independent analyses of cutting and friction forces applied on a single polycrystalline diamond compact cutter

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ABSTRACT

This paper presents an analysis of the excavation forces involved in the cutting action and in the friction of a cutter/rock contact. A vertical lathe-type device provided data on the forces applied on a single cutter under dry excavation conditions. A cutting device was used to perform cutting experiments with unworn and worn cutters. A tribometer was used to perform friction tests on the cutters wear flat previously realized with the vertical lathe. The experiments display results conform to the literature as the non-dependence of the cutting coefficient to the rock properties. Then, this study focuses on the cutting forces and explains that these forces include a component of rock shearing and impact friction. The impact friction is induced by the interaction between ejected rock particles and the cutting active area. The evidence of this impact friction is then brought by the formation of an eroded zone on the cutting active area.

1. Introduction

The drilling industry mainly uses two families of tools: roller cone bits for the hardest rock formations and drag bits in softer rocks. Because of their great excavation performances, drag bits have an increasing market share reaching more than 60% in 2014 and estimated at 80% in 2020 [1]. During excavation, drag bits operate by shear mode and are mostly damaged by abrasion [2]. Therefore, the increase in market share is also explained by the progresses made on materials and mechanical studies to assess their wear resistance.

Drag bits are formed by tens of polycrystalline diamond compact (PDC) cutters. These bits have a specific design allowing a homogenous distribution of stresses and wear on the cutters [3]. Consequently, laboratory experiments are often performed on a single cutter. This strategy is also justified by the accurate control of experimental conditions and the easier interpretation of mechanical data obtained with a single cutter [4]. In this way, Fairhurst and Lacabanne [5] first decomposed the forces applied on a single cutter as cutting forces and friction forces. The cutting forces are applied on the cutter front active area. The friction forces appear between the cutters and the rock when a significant wear flat is formed at the cutter tip [6]. These authors introduced then strong hypotheses as the independence between these friction and cutting forces. Detournay and Defourny [7] also assumed that, at the beginning of a test, before the formation of a wear flat, the forces applied on the cutter are equal to the cutting forces. Since, the single cutter approach and these hypotheses are broadly used to asses cutters quality [8]. Thereby, the study of cutter/rock interactions decomposed at the cutter active areas can bring new developments for the understating of drill bits excavation and wear performances.

The aim of this work is to study independently the cutting and the friction components applied to a single cutter. First, experiments equivalent to the excavation conditions but in dry conditions were performed to highlight the results obtained with the independence hypothesis. Then, cutting tests with different cutter wear flats, cutting depths and rocks were carried out to study the cutting forces. Finally, friction tests without penetrating the rock were done to only measure friction forces applied between cutters with different wear flats and rocks.

2. Single cutter/rock contact

The PDC cutters used in this study are cylindrical with a diameter of 13.4 mm and a height of 10 mm. They are formed by a tungsten carbide-cobalt substrate surmounted by the PDC part. The thickness of this PDC part is 2 mm. The PDC part has a chamfer

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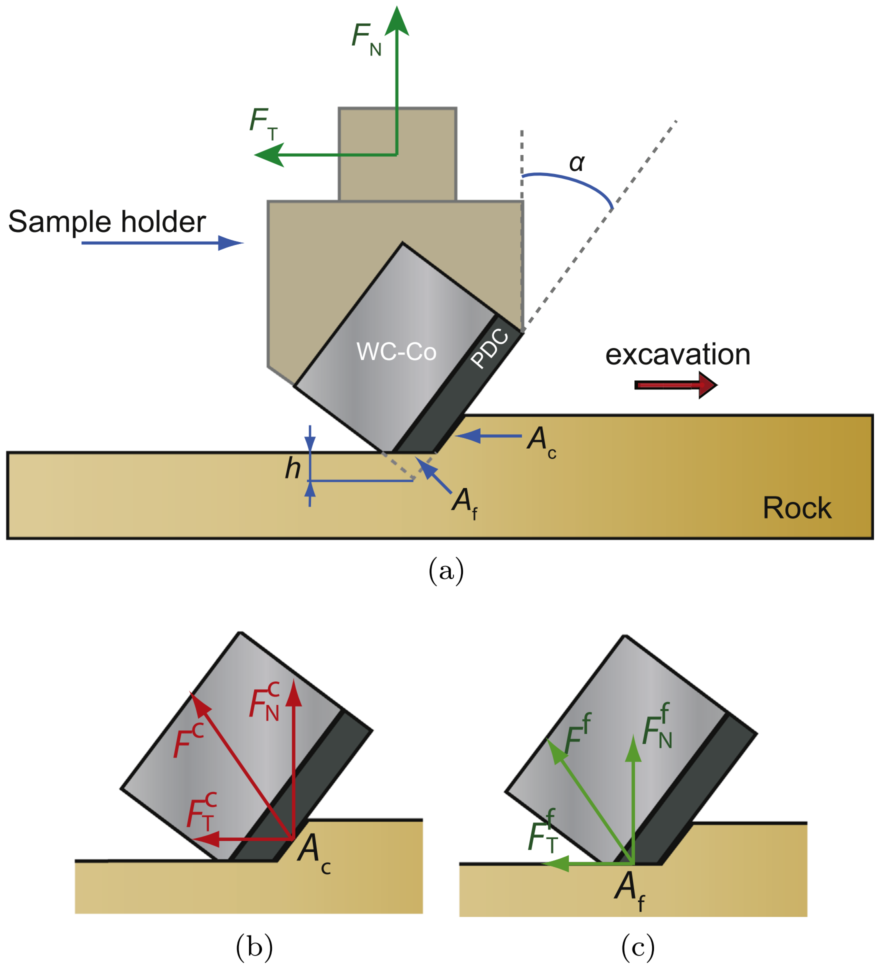

Fig. 1. Contact configuration of the vertical lathe: (a) overall cutter/rock contact model with F_N and F_T the applied forces, α the back rake angle, A_c the cutting active area and A_f the wear flat area; (b) cutting components F_T^c and F_N^c applied on A_c; and (c) friction components F_T^f and F_N^f applied on A_f.

of $45° \times 0.4$ mm. The PDC cutters have a coarse PDC microstructure with a mean diamond grains size of 17 ± 4 μm.

Concerning the single cutter contact mechanics, two main hypotheses are commonly used:

- The independence between the cutting components applied on the cutting active area A_c (Fig. 1b) and the friction components applied on the wear flat A_f (Fig. 1c);
- At the beginning of a test, the cutting is pure. The friction coefficient μ defined by friction components is equal to zero as there is no surface for the friction to be applied on.

These hypotheses can simply be expressed by two equations relating the overall forces applied to the cutter and the associated cutting and friction components:

$$\begin{cases} F_T = F_T^f + F_T^c = F_T^f + F_T(0) = \mu F_N^f + \varepsilon A_c \\ F_N = F_N^f + F_N^c = F_N^f + F_N(0) \end{cases} \quad (1)$$

The cutting forces are considered constant during excavation and proportional to the cutting active area A_c. The coefficient of proportionality is the intrinsic specific energy ε depending on rock mechanical properties. The friction increases with the wear flat formation as the load required to maintain the constant cutting depth increases. Accordingly, Detournay and Defourny [7] showed that a linear relation could be established between the transverse force F_T and the normal force F_N (with ζ the cutting coefficient defined by the cutting components):

$$F_T = \mu F_N + \varepsilon(1 - \mu\zeta)A_c \quad (2)$$

This linear law can also be expressed by relating the specific energy E (i.e. the ration between F_T and A_c) and the drilling strength S (i.e. the ration between F_N and A_c):

$$E = \mu S + \varepsilon(1 - \mu\zeta) \quad (3)$$

3. Experimental campaign

3.1. Excavation device

A vertical lathe-type device was used to realize dry excavation experiments. Cutters brazed on sample holders were adjusted downward on the lathe shaft. Ring-stone counterfaces were made of a manufactured mortar rock (1 m in external diameter, 0.5 m in internal diameter and 0.6 m thick with a density of 2150 kg m^{-3}).

The mortar has a homogeneous chemical composition (silica content of 60 wt.%) and mechanical properties (compressive strength of 48 MPa and young modulus of 78 GPa). The experiments were carried out using a normal load F_N ranged from 3000 to 5000 N, a back rake angle α of 15° and a mean cutting speed of 1.8 m s^{-1}. The cutting depth δ was maintained at 2 mm. The tests were conducted in atmospheric environment and no lubricant was added into the contact to significantly wear the PDC cutters. The experiments were conducted over an equivalent excavation distance of 8500 m. During these experiments, a wear flat area A_f is