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Experimental study of force responses in polycrystalline diamond face turning of rock

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ABSTRACT

Polycrystalline Diamond Compact (PDC) cutters, as the most commonly used inserts for rock cutting/drilling processes, are drawing increased attention in manufacturing and petroleum engineering, driven by the necessity to elevate cutter and process performance. The knowledge of the force responses when using PDC cutters under various cutting conditions is an essential prerequisite for achieving this goal. In this paper, an experimental study of the force responses in face turning of rock is analyzed. A rock turning testbed that uses single PDC cutters is developed on a CNC turning center for measuring both thermal and mechanical responses at the rock–cutter interface in real-time. A $7 \times 3 \times 3$ full factorial design (rake angle $\times$ depth of cut $\times$ feedrate) was used for the experimental assessment of the process. A phenomenological force model based on the experimental data and the physics at rock–cutter interface was formulated. In model the actual oblique cutting process in the experiments was approximated by an orthogonal cutting configuration by analyzing force responses in a plane normal to the cutting edge of the PDC cutter.

1. Introduction

The use of Polycrystalline Diamond Compact (PDC) cutters, first introduced by General Electric in 1973 [1], and mounted on drill bit bodies, namely PDC drilling bits, has steadily increased in terms of the total footage of oil wells drilled worldwide [2] due to their high rate of penetration and long life. The shear cutting mechanism that characterizes the cutting mechanics leads to several times faster drilling speeds of the PDC bits as compared to traditional tri-cone bits [3]. However, PDC bits are very sensitive to the characteristics of the rock formation that they can drill. Generally, PDC cutters can cut only relatively soft rock formations, e.g., shales, soft and unconsolidated sandstones, carbonates, etc., but cannot effectively drill hard formations, e.g., granite, chert, pyrite, quartzite, conglomerate, etc. [4]. In order to improve the drilling performance of PDC bits, numerous research topics, including PDC cutter/bit material strengthening and profile optimization [5–7], wear and other failure prevention approaches [8,9], force response predictions [10–12], in-field process monitoring and dynamic process control [13–15], are receiving increased attention in both the manufacturing and petroleum engineering areas. A more comprehensive review of the related science and technology can be found in Refs. [16,17].

Among all of the above mentioned aspects, force response prediction, as the most straightforward method of indicating the performance of the PDC bits/cutters or the limitations of the drilling/cutting processes, has been highly emphasized by many researchers. The study of cutting processes performed with single PDC cutters leads to insights into the mechanisms of rock–cutter interaction, because they are generally conducted under relatively simple and undemanding environmental conditions in comparison to the complex cutting conditions in the field that are characterized by complex bit body structures and fluid conditions. Moreover, the force model of a single PDC cutter can be used for predicting the resultant forces that act on the whole PDC bit by integration of the force responses of the single cutters over the whole body of the PDC bits [18]. The study of the cutting action of single PDC cutters is possible based on mature cutting theories developed for other processes that are also performed with single cutters or inserts, e.g., metal cutting and mining. Due to the shear cutting mechanism of PDC cutters, a number of experimental studies to explore the shearing process mechanisms in rock cutting were conducted for the prediction of cutting forces acting on single PDC cutters. Gray et al. [19] conducted two-dimensional cutting tests on dry limestone samples at atmospheric pressure with a series of rake angles to capture the brittle failure mechanisms in rock cutting. The chip-generating cracks were found to have an initial orientation which is related to the applied resultant force. Fairhurst and Lacabanne have taken the frictional effect at the rock–cutter interface into account to describe the force response of drag bits [20]. Nishimatsu [10] formulated an analytical cutting force description in two-dimensional (2D) orthogonal

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rock cutting and experimentally found a linear relation between the rake angle and the mean friction angle on the rake face. More recently, Detournay et al. [21,22] developed a phenomenological force model (D-D model) for both sharp and worn cutters to describe the plastic model of rock failure.

In this paper, an experimental study is performed to investigate force responses in the three-dimensional (3D) oblique face turning process of rock performed with PDC cutters. Since the depths of cut to be used, compared to the cutter's diameter and the feedrates, are very small, the 3D oblique cutting configuration will be assumed to be a 2D quasi-orthogonal cutting configuration. Therefore, the measured force data (i.e., cutting, thrust and feed forces) in the oblique face turning process configuration will be suitably transformed to derive models for the cutting force (nominal cutting force) and thrust force (nominal thrust force) in the quasi-orthogonal cutting configuration. In this way, the complex oblique cutting configuration will be approximated by an orthogonal cutting configuration. The phenomenological force response model developed under this assumption establishes a relationship between the force responses and the rake angle, feedrate, and depth of cut. In addition, the force response of the PDC cutters will be considered not only at the rake face, in terms of the friction and compression forces, but also at the cutting edge in terms of the plowing force and at the flank face in terms of the friction and lateral interaction forces to be defined in Section 4.

2. Experimental setup and conditions for polycrystalline diamond turning of rock

2.1. Testbed configuration

A testbed was developed on an OKUMA CNC turning center whose general arrangement can be seen in Fig. 1(a). The experimental apparatus includes a three component KISTLER dynamometer (KISTLER 9256), a triaxial accelerometer (KISTLER 8692C5M1) and dual-mode charge amplifiers (KISTLER 5004) to measure and record cutting forces and vibrations. Signal acquisition is realized through LabVIEW® with a National Instruments data acquisition (DAQ) system (NI PCI-6259). Temperature measurements are performed with conventional K-type thermocouples attached to the rake face of the PDC cutter at approximately 2 mm from the cutting edge through a signal conditioner (OMEGA iDRN-TC). The spindle speeds in the testbed can range from 75 to 4200 rpm. The dynamometer can measure three-dimensional forces up to 10 kN, while the accelerometer can detect accelerations ranging from $-5g$ to $5g$ (g=9.8 m/s^2). The thermocouple can measure temperatures up to 1200 °C, which is far higher than the temperatures reached by diamond tools.

The PDC cutters used in this testbed are clamped by a tool holder system shown in Fig. 1(b). The rake angle of the cutter in the turning process can be changed by replacing the rake angle adjuster depicted in Fig. 1(b). At the present, the rake angle can be set to 10°, 12°, 15°, 17°, 20°, 22° and 25° by seven different rake angle adjusters. As shown in Fig. 2(a), the PDC cutters with a diameter of 5.6 mm provided by Diamond Innovations, Inc. have a 3 mm diamond layer on a 10 mm high tungsten carbide (WC) stud. The rock samples used in the turning tests are Indiana limestone cylinders with a 101.6 mm diameter and 101.6 mm length, as shown in Fig. 2(b).

2.2. Experimental procedures

As shown in Fig. 1, the x-direction denotes the cutting speed direction, the y-direction the thrust direction, and the z-direction the feed direction, respectively. When the turning tests are conducted, the PDC cutter, mounted on the machine's turret, will move along the feed direction with a specific feedrate. The cutting speed, along the x-direction, is provided by the rotation of the rock sample. During the turning tests, all the instruments (i.e., dynamometer, accelerometer and thermocouple) measure the desired thermal/

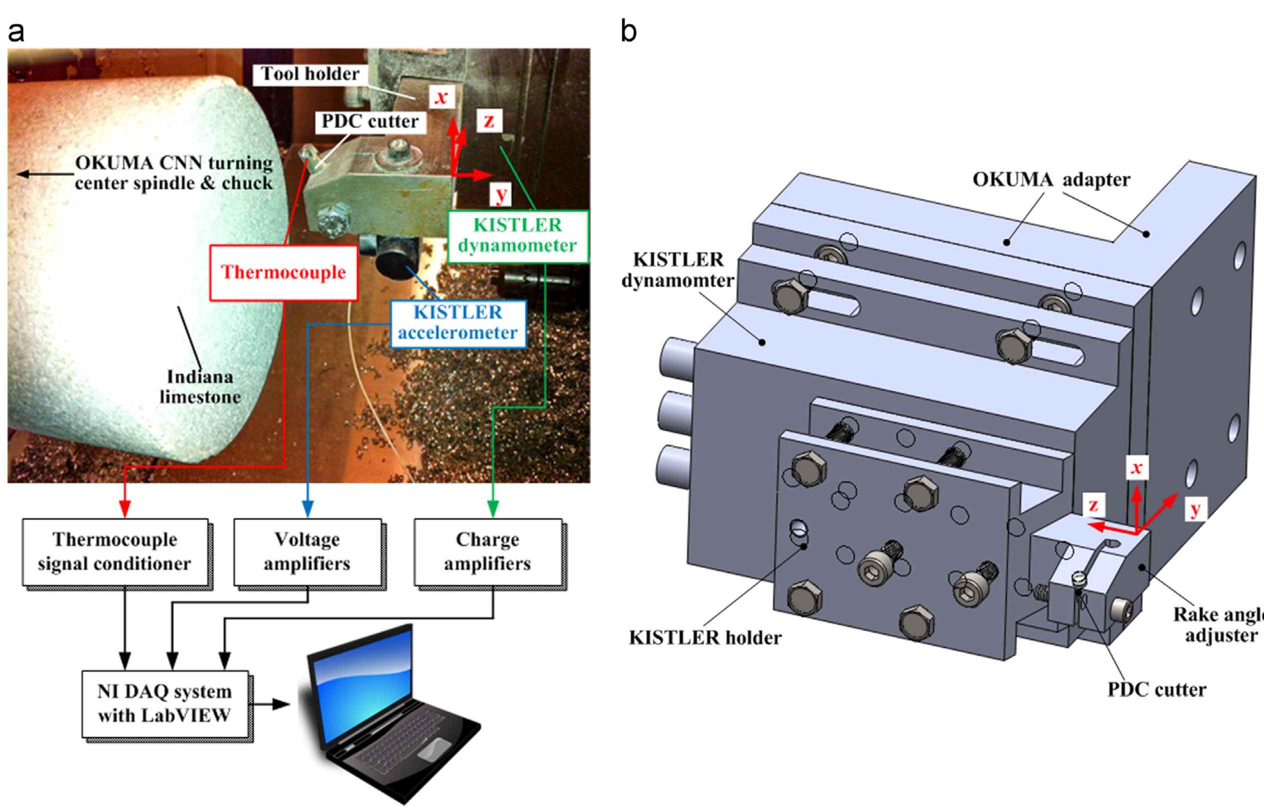

Fig. 1. Configuration of the polycrystalline diamond turning testbed: (a) dynamic turning testbed; and (b) tool holder system on the machine's turret.