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Assessing the efficiency of carbide drill bits and factors influencing their application to debris-rich subglacial ice

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ABSTRACT

When drilling into subglacial bedrock, drill operators commonly encounter basal ice containing high concentrations of rock debris and melt water. As such conditions can easily damage conventional ice drills, researchers have experimented with carbide, diamond, and polycrystalline diamond compact drill bits, with varying degrees of success. In this study, we analyzed the relationship between drilling speed and power consumption for a carbide drill bit penetrating debris-rich ice. We also assessed drill load, rotation speed, and various performance parameters for the cutting element, as well as the physical and mechanical properties of rock and ice, to construct mathematical models. We show that our modeled results are in close agreement with the experimental data, and that both penetration speed and power consumption are positively correlated with drill speed and load. When used in ice with 30% rock content, the maximum penetration speed of the carbide bit is 3.4 mm/s with a power consumption of ≤0.5 kW, making the bit suitable for use with existing electromechanical drills. Our study also provides a guide for further research into cutting heat and equipment design.

1. Introduction

Earth's ice sheets and subglacial environments possess a rich record of past climate that, owing to its inherent inaccessibility, has yet to be fully understood. In recent years, there has been growing interest in drilling to the ice–bedrock interface to obtain samples of subglacial bedrock directly, thereby providing much-needed information on landscape formation and evolution, ice–bedrock interactions, ice sheet formation, glacial dynamics, and climate change (Hansen et al., 2010; Popp et al., 2014). Consequently, researchers in several countries are actively developing drilling equipment that can penetrate both glacier ice and the subglacial bedrock surface. The process is complicated, however, by the complex geologic conditions in the basal reaches of ice sheets (Fountain et al., 1981; Herron and Langway, 1979). For instance, past drilling programs in Greenland and Antarctica reported drift sheets and abundant debris-rich ice in this zone (Bolshiyanov et al., 1990; Kudryashov et al., 1993), with alternating hard and soft layers where ice is at or near the pressure-melting point. As a result, drilling operations in these environments commonly experience both low drilling efficiency and an elevated risk of complications, thus requiring additional power.

Standard cable-suspended electromechanical drills employ the weight of the cutting tool to generate drill load, which is typically 1.5–4 kN, with a rotation speed of 50–200 rpm (Augustin et al., 2007). Given these relatively low values, this approach provides limited power for cutting, since a sizeable amount of the power supply is utilized for chip removal. The situation is further complicated when drilling in ice–rock mixtures, because the elevated hardness and abrasiveness of debris-rich ice means conventional drill bits are easily damaged. To address this shortcoming, several researchers have tested carbide, diamond, and polycrystalline diamond compact (PCD) drill bits for penetrating basal ice and the test effects were not bad (Cao et al., 2014; Popp et al., 2014).

For example, in 1988 a Russian team used a KEMS-112 electromechanical drilling tool equipped with a conventional SA-1 carbide

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drill bit (inner diameter: 93 mm; outer diameter: 112 mm) to core Vavilov Glacier, where they encountered debris-rich ice at 459.33 m depth. During penetration of the bedrock, the number of cutting teeth was reduced by half to decrease the requisite drill load. The cutter load then was increased to 1.2 kN, resulting in a penetration rate of 1.6 m/h with an average round-trip length of ~0.37 m, and the collection of 2.15-m-long cores of debris-rich ice (Bolshiyanov et al., 1990; Stiévenard et al., 1996; Talalay, 2011).

In a lab-based experiment, a team from Ohio State University used a drill head with tungsten carbide inserts to core alternating layers of clean ice and ice-cemented limestone particles. To reduce wear, the cutting blade was assigned slant and relief angles of 20° and 5°, respectively. According to Zagorodnov et al. (2005), the maximum penetration speed in the sheer ice was 1.6 mm/s, while that in the debris-rich ice reached 2 mm/s at 0.26 kW of power.

The NEEM project began in June 2009 with the objective of extracting an ice core from northwest Greenland. On 26 July 2010, the drill reached bedrock at 2537.36 m depth, having passed through a 2-m layer of basal ice containing granitic debris. After a few more runs, no penetration was made, and the drilling was terminated when the cutters were damaged (Popp et al., 2014).

Alongside the field and lab experiments described above, numerous researchers (e.g., Talalay, 2003; Azuma et al., 2007; Green et al., 2007; Cao et al., 2015a,b) have modeled the drilling and cutting characteristics of specific electric mechanical drills. While these simulations provide valuable guidelines for further research into drilling efficiency, we note that they focused on pure ice and thus provide little insight into drilling debris-rich ice.

The overarching goal of our investigation was to analyze the relative influences of sample shearing strength and cohesion, drill load and speed, and the friction coefficient between cutter and sample, in addition to other parameters, on penetration speed, torque, and power consumption when drilling debris-rich ice with a carbide cutter. We also sought to develop a numerical model, thereby providing a guide for further research into cutting heat and equipment design.

2. Modeling cutting mechanics of the carbide drill bit

Notation:

P_x — cutting force, N
P_y — axial pressure of cutter (a component of drill load), N
P_{load} — drill load, N; $P_{load} = m \cdot P_y$
α — rake angle of cutter
β — tip angle of cutter
γ — spiral angle formed by cutting
φ — shear angle
δ — friction angle between sample and cutter
θ — internal friction angle of sample
σ_s — compressive strength of sample, MPa
μ — internal friction coefficient of sample
τ_s — shear strength of sample, MPa
C — cohesion of sample, MPa
h — cutting depth, m
L — length of shearing plane, m
b — cutter width, m
F_1 — friction between cutter and cutting chip, N
N_1 — normal force between cutter and cutting chip, N
F_2 — friction of the cutter and bottom sample, N
N_2 — normal force between cutter and bottom sample, N
D_o — outer diameter of drill bit, m
D_i — inner diameter of drill bit, m
n — rotation speed of drill head, *rpm*
m — number of carbide inserts
M — torque moment of drill bit, N·m
P_i — power consumption of ice drilling, kW
P_r — power consumption of rock drilling, kW
v_i — penetration speed of ice drilling, m/h
v_r — penetration speed of rock drilling, m/h

Electromechanical rotary drill technology has been used extensively in the field of polar drilling. To improve drilling efficiency and facilitate the design of a more effective cutting apparatus, previous researchers (Talalay, 2003; Azuma et al., 2007; Green et al., 2007; Talalay, 2014; Cao et al., 2015a,b) have analyzed both the drilling process and the cutting mechanism of electromechanical tools, thereby laying the groundwork for further research into the drilling of debris-rich subglacial ice. This paper describes a carbide cutting model, shown in Fig. 1, where the rotary cutting process is simplified as a single shear plane model to analyze cutter stress. To make mechanical equilibrium analysis on the single cutter:

$$\sum F_x = F_1 \sin\alpha + N_1 \cos\alpha + F_2 \cos\gamma - N_2 \sin\gamma - P_x = 0 \quad (1)$$

$$\sum F_y = F_1 \cos\alpha - N_1 \sin\alpha + F_2 \sin\gamma + N_2 \cos\gamma - P_y = 0 \quad (2)$$

$$\tan\delta = \frac{F_1}{N_1} = \frac{F_2}{N_2} \quad (3)$$

From Formulas (1)–(3), N_1 and F_1 can be expressed as:

$$N_1 = \frac{[P_x \cdot \cos(\delta-\gamma) - P_y \cdot \sin(\delta-\gamma)] \cdot \cos\delta}{\cos(2\delta-\alpha-\gamma)} \quad (4)$$

$$F_1 = \frac{[P_x \cdot \cos(\delta-\gamma) - P_y \cdot \sin(\delta-\gamma)] \cdot \sin\delta}{\cos(2\delta-\alpha-\gamma)} \quad (5)$$

As the spiral drop angle formed by cutting is small, $\gamma \approx 0$ in the above formulas.

Using the chip as the object of interest, both the shear and compressive stresses on the shear plane can be obtained via stress equilibrium analysis. For example:

$$\tau_s = \frac{F_s}{L \cdot b} = \frac{F_1 \cdot \sin(\alpha-\varphi) + N_1 \cdot \cos(\alpha-\varphi)}{L \cdot b} \quad (6)$$

and

$$\sigma_s = \frac{N_s}{L \cdot b} = \frac{F_1 \cdot \cos(\alpha-\varphi) - N_1 \cdot \sin(\alpha-\varphi)}{L \cdot b} \quad (7)$$

where

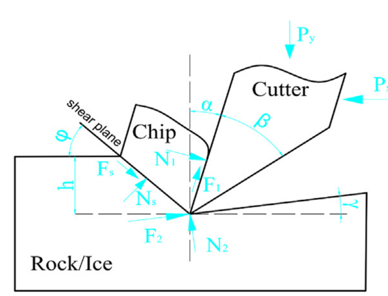

Fig. 1. Modeled cutting mechanics of a single cutter.