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Design and testing of coring bits on drilling lunar rock simulant

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Abstract

Coring bits are widely utilized in the sampling of celestial bodies, and their drilling behaviors directly affect the sampling results and drilling security. This paper introduces a lunar regolith coring bit (LRCB), which is a key component of sampling tools for lunar rock breaking during the lunar soil sampling process. We establish the interaction model between the drill bit and rock at a small cutting depth, and the two main influential parameters (forward and outward rake angles) of LRCB on drilling loads are determined. We perform the parameter screening task of LRCB with the aim to minimize the weight on bit (WOB). We verify the drilling load performances of LRCB after optimization, and the higher penetrations per revolution (PPR) are, the larger drilling loads we gained. Besides, we perform lunar soil drilling simulations to estimate the efficiency on chip conveying and sample coring of LRCB. The results of the simulation and test are basically consistent on coring efficiency, and the chip removal efficiency of LRCB is slightly lower than HIT-H bit from simulation. This work proposes a method for the design of coring bits in subsequent extraterrestrial explorations.

Keywords: Lunar regolith coring bit; Bit geometric optimization; Lunar rock drilling; Drilling behaviors

1. Introduction

Drilling and coring have traditionally been part of a commonly employed method in geological engineering, and are employed in extraterrestrial explorations because of the capability of chip conveying without the need for additional liquid. After performing laboratory analyses of native samples returned from celestial bodies, explanations about the origin and evolution of the earth, planets, and even the solar system may be understood (Duffard et al., 2011; Zacny et al., 2011). From the 1960s, the United States and the former Soviet Union have successively landed on the moon, and have obtained approximately 380 kg of lunar regolith samples (Barsukov, 1977; Taylor, 1975). Recently, China has also planned a lunar sample-and-return mission, called the Chinese Lunar Exploration Program (CE), to acquire the lunar regolith 2 m beneath the surface employing a coring bit jointed with a hollow auger (Duan et al., 2014; Tian et al., 2015). According to the lunar regolith data announced by the National Aeronautics and Space Administration (NASA), lunar regolith components having a variety of shapes are widely distributed on the lunar subsurface, and include types such as granular soil and rock block (Allton, 1989; El-Khayatt and Al-Rajhi, 2015). General failures typically experienced during the drilling process mainly include (a) choking due to the soil chips and (b) blockages due to the hard rock (Carrier et al., 1991; Tian et al., 2012). As the guiding component of the drill auger, the drilling behaviors are strongly related to the coring bit geometries. Thus, for

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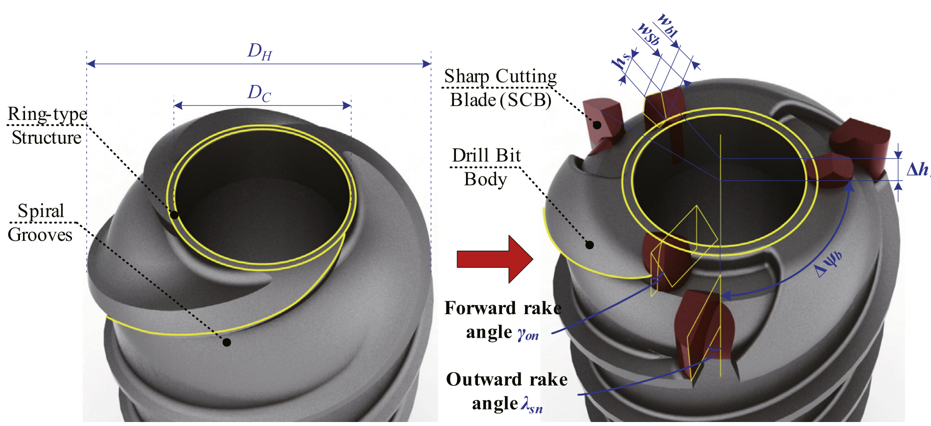
the CE program, a good coring bit should (1) convey lunar soil chips without the aid of lubricants or flushing fluids, (2) achieve good drill-core recovery, and (3) break through the lunar rock block with the drillability above VI (Deng et al., 2013; Shi et al., 2014).

In 1976, the stair-type coring bit was utilized in the unmanned Luna-24 sampling mission launched by the former Soviet Union (Pitcher and Gao, 2015). The bit was embedded with eight columnar cutting blades, with the main task being to break through the lunar rock block. During the lunar soil drilling, the chips were gradually accumulated near the bit body, and were eventually removed by the auger spiral groove with the increasing drilling depth. Recently, the Northern Centre for Advanced Technology (NORCAT) developed a dry drill bit for NASA's moon polar exploration program (Bar-Cohen and Zacny, 2008). The screw grooves were dug on the drill bit body to remove the polar lunar soils, and the diamond grits were impregnated on the helical surface to deal with the rock. In the field test, the drill bit penetrates the loose lunar soil simulant at a lower weight on bit (WOB), and comminutes rocks such as basalt and anorthosites. In addition, the Jet Propulsion Laboratory (JPL) introduced a rock-coring bit for the Mars Sample Return (MSR) mission in 2012 (Hudson et al., 2010; Kriechbaum et al., 2010). The bit inlaid four tungsten carbide cutting blades on the top plane for rock breaking, and the radioactive grooves that are connected to the auger were excavated along the blade rake face to contain the rock chips. Because the objects being drilled are Mars rocks and the drilling depth is only 50 mm, the drilling loads caused by chip accumulation can be omitted (Mattingly and May, 2011; Klein et al., 2012). Besides, some other sampling devices have been developed to acquire the lunar surface regolith in recent years. The typical one is the rigid-flexible link combined lunar sampler, which is mainly composed of three rigid rotational links and one flexible shrinking link (Ling et al., 2014). The difference of this sampler compared with coring method is the sampling objective which is the multi-point loose soil on lunar surface. The sampling volume is much more than coring method, and the sampling peak power is no more than 6 W which is far less than drilling.

The theory of rock-cutting load prediction can be traced to Merchant's model, which proposed the metal-cutting theory in rock-cutting processes with properties of plastic material, and was based on the Coulomb criterion and the shear plane assumption (Che et al., 2012a). Then, Nishimatsu proposed a formula for the cutting force in rock cutting by using a wedge-shaped tool based on the Mohr criterion of failure and the specific stress distribution assumption (Che et al., 2012b). Detournay and Defourny built the cutting force models (D-D model) of the drag bit for both sharp and worn cutters, and which was based on the intrinsic specific energy and a quantity with dimension of stress. To obtain an accurate prediction of the rock-drilling response, Detournay differentiated between three successive regimes, namely the dominance of frictional contact, the cutting depth, and hole-bottom poor cleaning (Detournay and Richard, 2008; Perneder et al., 2011).

In summary, the features of lunar soil convey are determined by the drill bit body, and the blade shape affects mainly the rock-drilling performance. Recently, the Research Center of Aerospace Mechanism and Control developed a helical-type drill bit body (HIT-H) for lunar soil coring. The spatial helix grooves combined with the ring-type soil coring isolated structure are employed on the HIT-H bit, which improves the performance in terms of both conveying the soil chips and drill-core recovery in lunar soil sampling (Zhao et al., 2016a). With the purpose of design a coring bit which the drilling feature includes smooth chip conveying, high drill-core recovery and low rock drilling load, the LRCB is developed based on the HIT-H bit body. In this study, we focus mainly on the parametric design of LRCB cutting blades. We assume the Coulomb-Mohr criterion and compact core, and we establish the interaction model between the lunar rock simulant and the LRCB. Meanwhile, we analyzed the variations in the drilling loads derived from the blade shape



(a) HIT-H bit (b) LRCB

Fig. 1. 3D view of spiral helix bit (HIT-H) and LRCB.

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