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Coring basalt under Mars low pressure conditions

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Abstract

Background: Future exploratory drilling on Mars will ideally employ drill bits that are capable of penetrating any terrain from hard rocks such as basalt to ice or ice-bound soils. Candidate drill bits include diamond impregnated or surface-set types, and bits with large individual cutters, typically made of polycrystalline diamond or tungsten carbide composites. Each has disadvantages, but bits with large individual cutters seem more likely to be capable of improvement. Drilling in hard rocks poses difficulties for these bits, so we have investigated their performance in basalt. Basalt rock was chosen as it is the most prevalent type of rock found on the surface of Mars, and any future drilling mission to Mars will probably encounter basalt while drilling a hole (even if drilling basalt was not the mission objective). It is also one of the hardest types of rock, which makes the design of a Mars drilling system very challenging, especially because a lander or a rover will be constrained to low mass and limited power.

Method: Custom designed core bits with discrete cutters (Polycrystalline Diamond or PDC elements) were used to drill high strength basalt rock under conditions of low temperature and pressure appropriate to Mars. The experimental arrangement allowed for remote control of the weight-on-bit and the rotational speed of the drill string. Acquired data included weight-on-bit, rotational speed of the drill, reaction torque, drilling power, penetration rate, bit temperature and the temperature of the drilled formation.

Conclusion: Penetration in the basalt was initially rapid, but increasing wear required progressive increases in the applied weight-on-bit to maintain the rate of penetration. Eventually, the wear was so great that penetration could not be maintained with 500 N, the maximum weight that can reasonably be expected on a small exploration vehicle (~150-200 kg). In the present case, for a core bit with an outside diameter of 38 mm and an inside diameter of 25 mm, the wear limit was reached after a depth of five centimeters had been penetrated. Additional penetration to a depth of over 15 cm was possible only after increasing the Weight on Bit to 950 N. The drilling power was in the range of 100 W. Improvements in drilling performance could potentially be achieved by reducing the bit diameter, changing the bit design and replacing a PDC cutter with a more wear resistant material. The bit performance has also been modeled, and a consistent explanation for the bit behavior was found.

Introduction

Interest is increasing in being able to drill exploration boreholes on Mars. With the large range of possible landing sites and the uncertainty in the drilling location there is a need to find a drilling system, and particularly a bit type, that will be able to penetrate a wide range of materials. This is so even if the drill is mounted on a rover, that will allow the drill to be moved and the drilling site to be selected with some care, since even if the surface features of the drilling site can be examined closely, there will be no way of knowing what lies below the surface. Because of the low temperatures and low pressures on the martian surface, it is almost certain that the drill will have to operate without the benefit of liquid, and perhaps even without gas flow for cuttings removal and cooling.

Among the harder materials that may be found on the martian surface, basalt is one of the most common. For example the surface rock coverage (largely basalt) at the Viking 1 and Viking 2 landing sites were 6.9% and 17.6%, respectively (Golombek and Rapp 1997). Thus, it is likely that any drill will encounter basalt, ranging from small pebbles to large boulders at or below the surface, depending on the location. In addition, drilling and sampling basalt might be a mission requirement. Ice and ice-bound soils may be encountered, and so a capacity to drill these materials will also be required. In order to save weight and complexity in the drilling equipment, it will clearly be of interest to have one drilling system and one drill bit type to drill all materials. Preservation of volatiles might be another requirement of drilling on Mars, and this will add considerable complexity and challenge. Conserving volatiles, however, was not a prime goal of the present study.

Types of drill bits

At present, it is likely that the drill will be required to recover cores, and so a coring bit will be required. For a small bit of at most a few tens of millimeters in diameter, this precludes the choice of a roller-cone bit in favor of one with fixed cutters. Current fixed-cutter bits for coring hard rocks such as basalt include diamond-impregnated and diamond surface-set bits, in which many generally rounded and more or less randomly placed diamonds project out of the surface of a metallic matrix (Figure 1). Such bits operate by a crushing and grinding action, and produce very fine cuttings. Clearance between the bit face and the rock is small, so if large or sticky cuttings are produced, such bits can easily become choked. This is particularly so if ice is encountered, and it is commonly found that such bits become "glazed" by an accumulation of melted and re-frozen ice and cuttings on and around the cutting structure, reducing the rate of penetration to near zero.

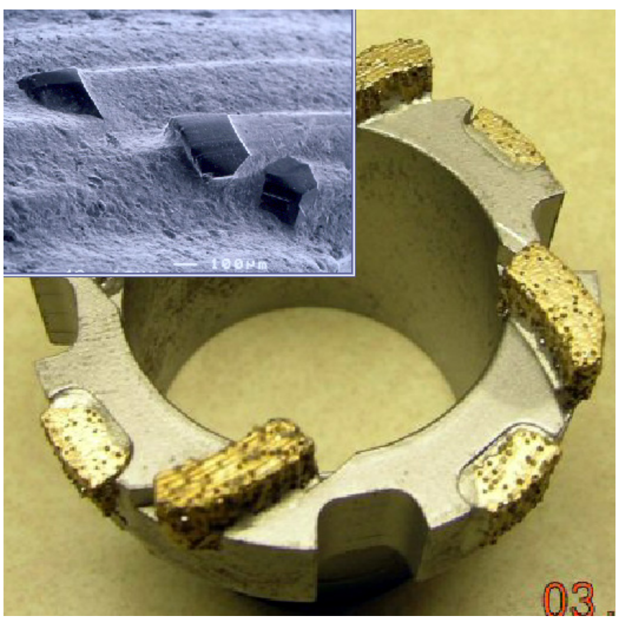

Figure 1. Coring bit with four diamond impregnated segments placed in so-called 4-wing configuration. An insert shows a scanning electron micrograph of one of the segment's surface with three diamonds clearly protruding above the metal matrix. The diamonds are approximately 350 μm in diameter (figure1.jpg).

Figure 2a. The photo shows a bit with tungsten carbide (WC) cutters leaning 5º forward or having a 5º positive rake angle and held in place by a wedge and two set screws. The bit is a full faced bit with a centered WC spear point cutter (figure2a.jpg).

Figure 2b. The photo shows a bit with polycrystalline diamond compact (PDC) cutters leaning 15º backwards or having a 15º negative rake angle and held in place by two sets of wedges and set screws. The PDC cutter is made of a hard but brittle diamond layer (black and shiny layer) and a WC backing supporting the diamond layer. The WC backing is in direct contact with the wedge. In this particular design the PDC cutter has a serrated edge. The bit is a full faced bit with a centered WC spear point cutter (figure2b.jpg).

For drilling in soft rocks and ice, the choice is usually for bits with a few, deliberately placed sharp, chisel-like cutting elements, sometimes known as "defined edge cutters", (since the cutting surfaces are placed and oriented on the bit so as to collaborate by cutting specific parts of the hole bottom).

For ice and the softest rocks, the cutters are tilted so as to present a "positive rake angle" to the rock (Figure 2a). A positive rake angle makes for a very aggressive cutting action, but equally, because of the need for clearance below the cutter, it requires that the included angle at the cutter edge must be less than ninety degrees. (Included angle is the angle between the front face of the cutter and the face that passes over the newly-cut surface behind the cutter). Such cutters are necessarily much more fragile than those with a negative rake angle (Figure 2b), and so cannot be used for hard rocks, where a negative rake of a few degrees is common. Defined edge cutter bits with negative rake will penetrate ice, albeit more slowly than the more aggressive positive rake bits, and so are capable of cutting both ice and hard rocks.

Some further aspects of the problems of drilling in different possible martian terrains, and under martian conditions have been addressed previously by the present authors (Zacny and Cooper 2004; Zacny et al. 2004; Zacny and Cooper 2005; Zacny and Cooper 2006).

Selection of a drill bit

To develop a universal bit that can penetrate a wide range of materials, the choice would thus appear to lie between taking a diamond surface set or impregnated bit and modifying it so that it will not choke or glaze over when drilling ice, or taking a defined edge cutter bit and balancing the rake angle of the cutters so that it is sufficiently aggressive to penetrate soft rocks and ice, while at the same time being sufficiently robust to resist excessive wear or fracture when drilling hard rocks. Clearly, the abrasion and fracture resistance of the cutter material also play a part in this balance. At present, we see more potential in the latter approach in view of the continuing progress being made in synthetic diamonds of the PDC (polycrystalline diamond compact) type that are, along with tungsten carbide, typically used in defined edge cutters bits. The work described in this note is thus aimed ultimately at the development of a universal bit type that will make progress in all rock and soil types. Our specific point of attack has been to see if we can make a defined edge cutter bit that will be wear and fracture resistant while drilling in a hard rock such as basalt, as opposed to taking a diamond-impregnated or surface set bit and seeing if we can develop a variant that is resistant to choking.

PDC is generally considered to be too brittle for cutters this sharp to survive in applications involving the drilling of hard rock. Tungsten carbide cutters are tougher, and do not chip so easily as the diamond layer on a PDC cutter, and so they would be the preferred choice from this point of view. On the other hand, their resistance to abrasive wear is less than that of diamond. The practical choice, therefore, would appear to be between a PDC cutter with negative rake and a tungsten carbide cutter with positive rake. In such cases, the behavior of the two bits could be expected to be as indicated in Figure 3, in which the required power or weight on bit (WOB) needed to maintain a certain rate of penetration is plotted against the drilled depth. The bit with positive rake (tungsten carbide) initially performs better, but it wears at a greater rate and so, after a critical distance, it is overtaken by the PDC bit.

Thus, there exists a threshold depth, where the WC cutter will become so dull that it will require as much power and WOB as the initially more power "hungry" PDC bit (see Figure 3). The exact value of this critical depth will depend on the fraction of hard and abrasive rock encountered during drilling. For example, if a WC bit had to drill through surface basalt (a possible scenario for the lander mounted, deck deployable (not arm deployable) drill) it would most likely get dull within the first few centimeters.

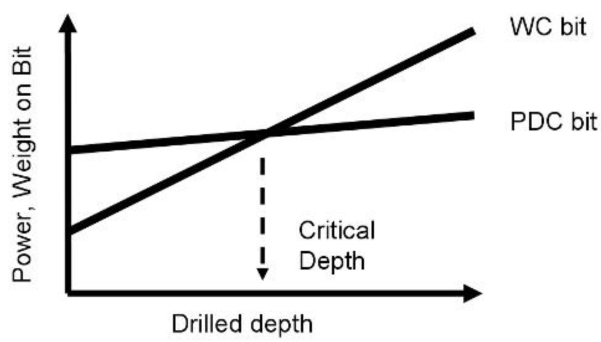

Figure 3. Hypothetical power and weight on bit (WOB) needed to maintain a certain rate of penetration as a function of depth for two types of cutter materials: polycrystalline diamond compact (PDC) and tungsten carbide (WC) (figure3.jpg).

Note also, that it is unlikely that a full faced drill bit will get far in basalt (due to high stresses at the very center of a drill bit, which at this point moves only in a vertical direction). (Rotary percussive drilling as opposed to pure rotary drilling would be a much better choice in this case. However, rotary percussive drilling has other disadvantageous, high vibrations being one of them). On the other hand, a coring bit will most likely drill much deeper because of the peripheral placement of the cutters. Further, since a coring bit contacts the rock over only a fraction of the cross-sectional area of the hole (since the core is not cut), the available weight on bit is concentrated on the annulus being cut and so the load per unit of cut area is correspondingly greater.

Previous work

Thus far, the only tool that has successfully penetrated into basaltic rocks on Mars was the Rock Abrasion Tool on the Mars Exploration Rover Spirit (Gorevan at al. 2003). The RAT was designed to grind an area of approximately 45 mm in diameter and a few mm deep. The RAT on MER Spirit performed a total of 15 grinds in basalt, while the RAT on MER Opportunity has so far made twice as many grinds in sedimentary rocks (29 as of January 16th 2007), which are much softer than basalt. Although the grinding pads on the

Spirit RAT performed well in basalt, they are not made for drilling other formations, such as soils, ice, ice-bound soils etc. As discussed above, for these types of formation, chisel type cutters, such as Polycrystalline Diamond Compacts or the softer Tungsten Carbide are used.

Two teams (Swales Aerospace and Raytheon UTD) have also performed field coring in Columbia River basalt in Idaho Falls, ID in the winter of 2006. The Swales team penetrated 1.9 m in basalt (with an average power of 90 W) while Raytheon UTD team penetrated only 3 cm (with an average power of 60 W) due to problems with the auger choking (Hayati and Mukherjee 2006, Guerrero et al. 2006). The exact drilling parameters (bit torque, auger torque, weigh on bit etc.), drill bit size and bit type however have not been disclosed and in addition the formation strength is also an unknown making it very difficult to analyze and model the drilling performance. As will be shown in this manuscript, when drilling basalt or any other hard rock, it is not so much the power that is a limiting factor, but rather the required bit force (also called weight on bit). Thus, by leaving out the weight on bit data, the most important parameter is left out. The upper limit to the force that can be applied to the bit is the product of platform (or rover) mass times acceleration of local gravity (Mars in this case). Of course this assumes that the drill is positioned at the center of gravity of rover or lander. A safety factor would also need to be included, otherwise a rover or lander will be up in the air rotating around the drill.

There is also little literature that reports on laboratory drilling or coring of basalt in the context of Mars drilling. Tests with a PDC coring bit (OD of 35 mm and ID of 14 mm) in basalt of unknown strength revealed that even with a weight on bit of the order of 1000 N penetration was close to zero (Finzi et al. 2004). The authors also developed drilling or cutting numerical model based on the Nishimatsu cutting theory (Nishimatsu 1972). They found that the difference between the actual drilling data and the theoretical model was in excess of 100%. However, their model was developed for a cutter with a positive rake angle while the bit they used had a negative rake angle, making the results somewhat problematic.

Some tests were performed in another harder formation (Mafurite of unknown compressive strength) with a coring bit (OD of 19 mm and ID of 9 mm) having cutting teeth made of hard alloy steel. The penetration rate with 140-170 N weight on bit was found to be on the order of 4 mm/hr (Anttila 2004) suggesting that the prevalent drilling mechanism was grinding and not cutting.

The above literature survey suggests that there has been little research done in investigating drilling in basalt and no tests were done in drilling basalt under Mars environmental conditions. In addition, apart form a numerical model based on the Nishimatsu cutting theory which, was difficult to apply due to a number of parameters that had to be assumed (e.g. friction angle), no practical drilling equation was developed for drilling. In data for most tests a number of important parameters such as the rock strength were also left out.

This paper initially reports on unconfined compressive tests done on basalt rocks at various temperatures. It then reports on coring tests in the same basalt rock (unconfined compressive strength, UCS, of ~280 MPa under simulated martian atmospheric conditions. Finally, a drilling equation is derived, which models the drill bit behavior in basalt.

Experimental methods

Experimental equipment

The drilling test equipment included an instrumented drill press, a test chamber that housed the test sample (see Figure 4), signal conditioners, a digital display console, and a data acquisition and control system. The experimental arrangement allowed for remote control of the weight-on-bit (WOB) and the rotational speed of the drill string. Acquired data included weight-on-bit, rotational speed of the drill, reaction torque, (the last two being multiplied to obtain drilling power), depth of the bit inside the sample (converted to the penetration rate), bit temperature and the temperature of the drilled formation. Most of the tests were conducted under simulated Martian conditions of low temperature and pressure (inside the environmental chamber).

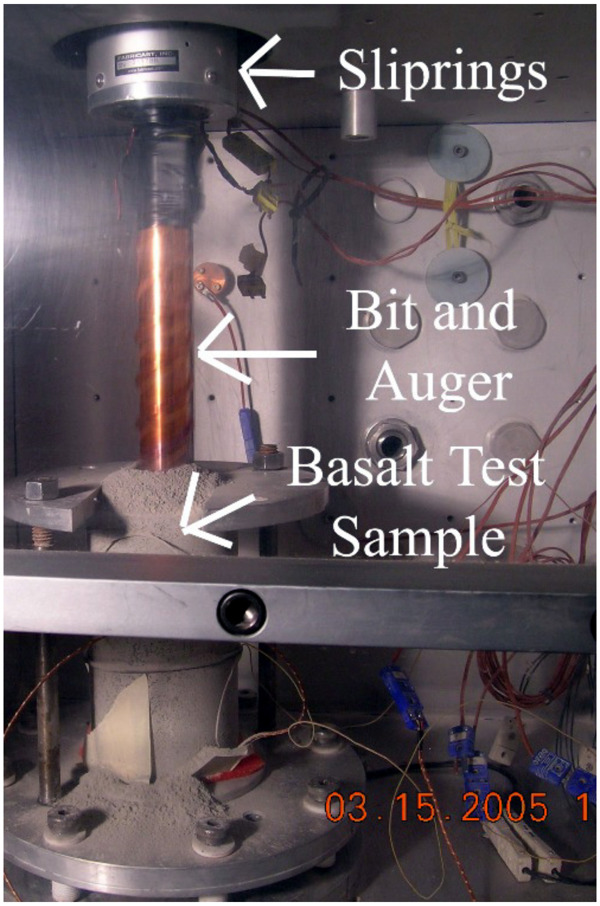

Figure 4. Experimental set up showing an auger with a coring bit inside the basalt rock sample (figure4.jpg).

Basalt rock test sample

For drilling tests, a basalt rock sample was acquired from a local stone dealer. The rock originated from China and no record of its physical properties was available. Therefore, an X-ray diffraction analysis was performed, which revealed that the rock consisted of anorthite (~55%), enstatite (~27%) and diopside (~18%).

To determine a value for the unconfined compressive strength (UCS), five samples were prepared and tested at the University of California, Berkeley concrete testing facility. The cylindrical samples were 56.5 mm in diameter and 144.5 mm in length, giving an aspect ratio of 1:2.56.

The effect of temperature on the strength of rock was found by others to be significant (Heins and Friz 1967; Mellor 1971). Since the drillability of the rock is inversely proportional to its strength (Paone and Madson 1966), it is expected that the temperature will in turn affect the efficiency of the rock breaking process. Heins and Friz (1967) found that the strength of an oven-dried basalt rock increases by 50% when cooled down to -196 ºC. This temperature dependency on the strength of rocks was also confirmed for other rock types by Mellor (1971).

Since the Martian surface is very cold (the mean martian surface temperatures is approximately -63 ºC), it was necessary to determine the UCS of basalt at low temperature. In addition, to confirm the observations of Mellor (1971) and Heins and Friz (1967) (i.e. to determine the dependency of the strength on the temperature), the UCS test was performed at room and elevated temperatures. Two samples were tested at -100 ºC and at room temperature, while only one sample was tested at 100 ºC.

The cold specimens were placed in a freezer at -80 ºC and then soaked in liquid nitrogen at -196 ºC. During the test, the sample was placed inside dry ice (at -79 ºC). A thermocouple was attached to the sample's side to monitor the temperature during the test (Figure 5). It took approximately five minutes for the load to reach the breaking strength of the rock and in this time the temperature of the sample increased from -110 ºC to -100 ºC.

Figure 5. Test specimen inside the uniaxial test fixture. The top surface of the sample projects above the upper slab of dry ice (figure5.jpg).

The hot specimen was initially placed inside an oven at 280 ºC for 24 hours. The sample, however, cooled down in the time it took to place it inside the test fixture and load it to failure. The temperature of the inside of the fractured core was measured within a minute after the fracture and it was found to be approximately 100 ºC.

In all tests, a loading rate of 2.3 kN/sec was used. The mode of failure in all tests was 'coning' (Figure 6) accompanied by an internal disintegration of the rock, which is considered to be indicative of a valid test (Hawkes and Mellor 1970).

Figure 6. Conical fragments of basalt after unconfined compressive strength test (figure6.jpg).

Figure 7 summarizes the Unconfined Compressive Strength (UCS) of basalt as a function of its temperature. Assuming that the relationship between the strength of the rock and its temperature is linear, the strength of the rock can be approximated by the best fit line, i.e. equation (1). Note that this equation is only valid for the temperature range used in the actual tests. This is because the strength of rock below -120 ºC, as found by Mellor (Mellor 1971), actually decreases with a further drop in temperature.

$$UCS\ (MPa) = -0.22 * T\ (°C) + 282 \qquad (1)$$

Another way of expressing the thermal strength dependency of the rock is to use the temperature coefficient, defined by equation (2), (Mellor 1971). The temperature coefficient for basalt in the current tests was calculated to be 0.1, which is very close to that obtained by Mellor (1971) of 0.09 for Tholeiitic basalt in the Brazil test. Other researchers, however, found the temperature coefficient to be 0.18 for 3-point bending (Heins and Friz 1967), 0.22 for the Uniaxial Compression test (Kumar 1968) and 0.2 also for the Uniaxial Compression test (Podnieks et al. 1968).

$$Temp.\,Coeff.\left(\frac{\%}{°C}\right) = \frac{\Delta\sigma * 100}{(\bar{\sigma}\ for\ \Delta T) * \Delta\sigma} \qquad (2)$$

where,

- $\Delta\sigma$: Range of strength values.
- ΔT : Temperature range.

- $\overline{\sigma}$ *for* ΔT : average strength for the temperature range

Several proposals have been considered to try to explain the dependence of the strength of rocks on temperature but none have been very successful (Kumar 1968; Podnieks et al. 1968; Heins and Friz 1967). One of them is derived from two thermal strain effects (Mellor 1971). The first effect is based on the idea that as the temperature is lowered, the interatomic spacing in the crystal lattice should decrease and in turn cause an increase in the interatomic forces and thus the elastic moduli. This explanation, however, cannot explain such a large increase in the rock strength for the given change in the temperature. The second effect is based on the difference in the expansion coefficients of the constituent minerals, which should create differential strain between adjacent crystals once the temperature is changed. However, this differential strain would most likely weaken the rock by introducing more cracks and by extending the existing ones. This is because, according to the Griffith theory, the strength of a material is inversely proportional to the square root of the length of the largest crack inside the material (Griffith 1921).

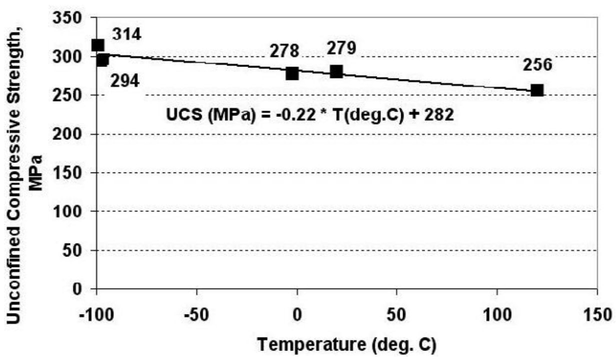

Figure 7. Unconfined compressive strength of basalt as a function of the rock temperature (figure7.jpg).

Since Martian rocks are very cold, it is therefore expected that the drilling effort (energy required to drill a volume of rock) and the required weight on bit will be higher. There is no doubt that drilling process itself will warm up the rock (thus making a rock easier to drill), however, sampling protocols will require the increase in rock temperature to be kept low (in order to preserve a sample in its original state) and this probably will be achieved by temporarily stopping the drilling process and allowing for a bit to cool down.

Drilling with a PDC bit

As mentioned before, for drilling hard rocks, diamond impregnated bits are commonly used on Earth. However, they are not effective for drilling ice or ice-bound soils, and their rate of penetration in soft rocks is much less than that of chisel-type bits using discrete cutters with either a positive or negative rake angle. The purpose of the test, therefore, was to determine whether a chisel type bit, with discrete cutters, such as a PDC bit, which is normally used in softer rocks, soils and ice, could effectively cut basalt. If PDC bits were to be found effective in hard rocks, then diamond impregnated bits would not be needed any more. In turn, only one bit, i.e. a PDC type bit would be required on Mars. Such a bit could, therefore, penetrate not only ice and ice bound soils, but also very hard rocks, such as basalt. Note that, for terrestrial drilling operations, PDC bits are not normally used in basalt because of their high ratio of cost to wear rate. For terrestrial drilling, lives of at least tens of meters are expected, and even thousands of meters are attained with PDC bits drilling petroleum wells in shales and clays. However, in the context of drilling on Mars, cost is a lesser consideration, and, at least in the near future, hole depths are not expected to be more than a few meters.

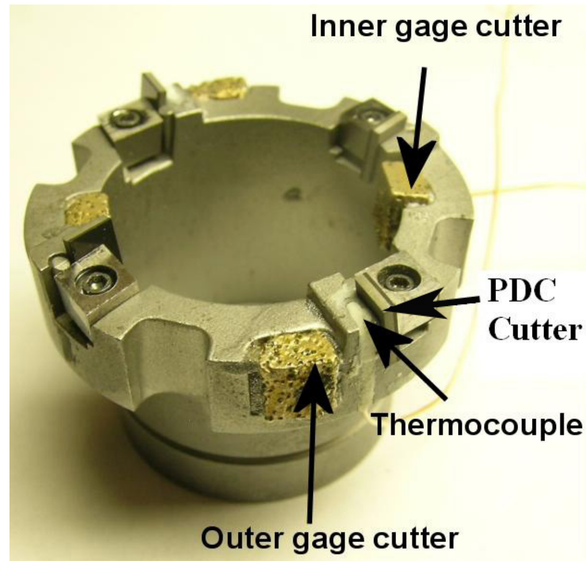

Figure 8. PDC coring bit used for drilling into basalt. PDC cutters were placed at 10° negative rake angle. Also shown are diamond impregnated gauge cutters for maintaining an outer diameter and an inner diameter of a hole and a location of a thermocouple (figure8.jpg).

The test was performed in basalt under Martian conditions, with a PDC cutter set at a negative 10º rake angle as shown in Figure 8. The bit also include diamond impregnated gage cutters on its inside and outside walls for maintaining the gage diameter of the core and the hole respectively. Figure 9 shows drilling data such as the power, the rate of penetration, the torque and the specific energy (the energy required to drill a unit volume of rock) as a function of rotational speed in rpm. The weight on bit was maintained at 900 N. The test showed that PDC type cutters can effectively drill hard rocks such as basalt for a short time with limited penetration depth. Initial penetration rates as high as 40 cm/hr were achieved with a power of 70 W or less. The specific energy was found to be lowest for a rotational speed of 150 rpm, indicating that this is the optimum rotational speed, given the set of experimental conditions (WOB, bit type, and rock type).

Figure 10 shows one of the PDC cutters after the drilling test in basalt. Note the extent of the wear flat area, which is approximately 0.2 mm thick (the diamond layer is 0.5 mm wide). Taking into account the geometry of the cutter, the extent of the wear flat area, and the value of the applied WOB, the pressure applied by the cutter on the surface of the

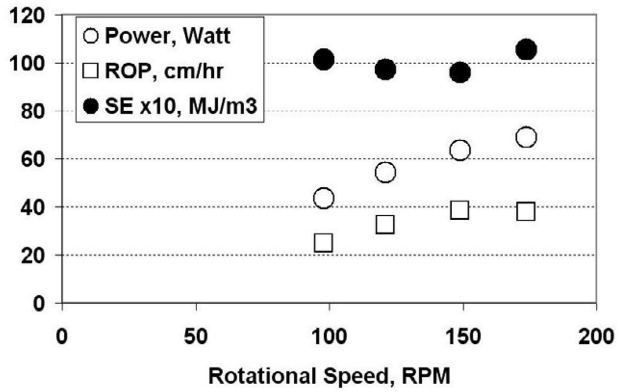

Figure 9. Drilling data (power, rate of penetration and specific energy) as a function of rotational speed for the PDC bit drilling basalt (figure9.jpg).

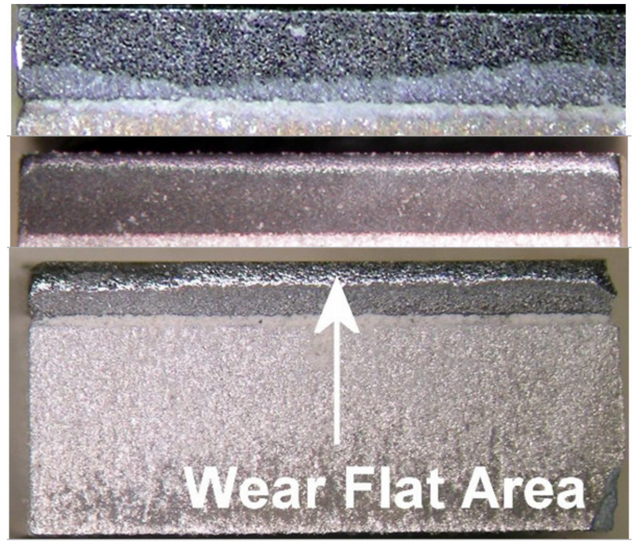

Figure 10. Photos showing progressive wear of the PDC cutting edge. The top cutter is new (figure10.jpg).

rock was calculated to be 320 MPa (see equation (3)). This is within the 15% error of the rock's Unconfined Compressive Strength of 280 MPa.

$$\sigma = \frac{WOB}{Area} = \frac{90kg * 9.8\frac{m}{s^2}}{4 * 3.5mm * 0.2mm} = 320MPa \quad (3)$$

Single Diamond Cutter for Drilling Basalt

Although PDC cutters initially achieved high penetration rates (see Figure 9), they soon developed wear flats (see Figure 10) and the WOB had to be adjusted to maintain an adequate penetration rate. Figure 11 shows results from one of the tests, where the WOB had to be increased to maintain the penetration rate. Initially, at a WOB value of 500 N, the rate of penetration was 40 cm/hr. However, as the wear flat developed, the rate of penetration dropped and so did the power (since the bit was cutting less rock). At the 241 sec time mark, the weight on bit was increased to 750 N, which resulted in a temporary increase in the rate of penetration and power. Soon, however, the rate of penetration dropped again and the weight on bit had to be increased one more time to 950 N (time mark: 661 seconds). Note that for the Martian lander/rover to be able to provide this kind of reaction force to the bit, it has to weigh at least 3 kN (300 kg) on Earth.

The total distance drilled by this bit during the test was approximately 5 cm, by which time the required WOB was becoming excessive. Ultimately, the bit was made to penetrate to a final depth of approximately 15 cm, but only after the weight on bit had been increased to 1000 N. Such a life would be considered inadequate even for a limited-depth Mars drilling operation. Since the PDC material was found not to have an adequate abrasion resistance, an alternative material was required. It has been known for centuries that diamond is the hardest material. Thus, if a single crystal diamond could be used instead of the PDC material, deeper holes could be drilled at high penetration rates. Single crystal diamond, however, shows a high anisotropy in its hardness. The hardness is greatest on the octahedral face, least on the cube, and intermediate on the rhombic dodecahedral face (cleavage is perfect on the octahedral face) (Kraus and Slawson 1939). The abrasion anisotropy in the diamond is not only a function of the crystal plane but it is also a function of the direction within the plane. For example, in the case of the dodecahedron plane, the relative grinding hardness along the hard direction is several hundred times that of the soft direction (Denning 1953). The large diamond hardness anisotropy was explained by calculating the surface energy of each of the planes.

Pfleider (1952) conducted a number of drilling tests, with cube and octahedral diamonds set at various angles. He concluded that a cube-shaped diamond set at 20º positive rake off the cube face gives the best performance and longest life. Although Long and Slawson (1952) suggested a crude way of orienting hard vectors in diamonds, with the advent of computer modeling, it is possible to determine the diamond orientation that would give good structural integrity combined with the longest life. Such a computer model of the diamond crystal was, for example, developed by Telling et al. 2000). Once the orientation is known, the crystal could then be shaped by diamond polishers. A drill bit with such single diamond crystal cutters (as shown in Figure 12) could then be used not only in hard formations, but also in ice and soil-ice mixtures.

Alternatively, continued progress is being recorded in improving the wear resistance of PDC. Clegg (2006) has reported results for drill bits using etched PDC cutting elements. He found that the wear resistance in laboratory tests was increased by 270%, while field test results showed an improvement of 43% in wear combined with an increase in the rate of penetration of 26%. At first sight, one might be inclined to attribute the smaller improvement in wear resistance under field conditions to the usual difficulties of transferring laboratory results to the field. However, a significant difference between the two test procedures was that the laboratory experiments were carried out without a cooling fluid around the cutters, while the field tests were done with the drill bits running in drilling mud. This may represent a critical difference from our perspective, because the essence of the improvement reported by Clegg was that etching the surface of the PDC to remove cobalt from the PDC near-surface region results in much reduced thermal degradation of the diamond material. When drilling under poorly cooled conditions (the laboratory tests) the temperature of the PDC would be expected to be much greater than under the liquid-cooled conditions of the field test. Hence, improvements to the thermal stability would have a greater effect under the laboratory conditions than in the field. If so, this is important in relation to drilling on Mars, since it is almost inevitable that drilling on Mars will be carried out in a dry environment without liquid cooling. Thus it is possible that the use of new, thermally-stable PDC materials will result in improvements in durability that are closer to Clegg's laboratory results than those found in the field tests.

Modeling drilling performance

It is very difficult to model performance of the drill bits accurately. This is due to the existence of a number of parameters that need to be taken into account, and that, because of a lack of knowledge, must be estimated. For this reason, most of the drilling equations are semi-empirical. In this section, an attempt is made to model the drilling performance of the PDC bit using actual drilling data.

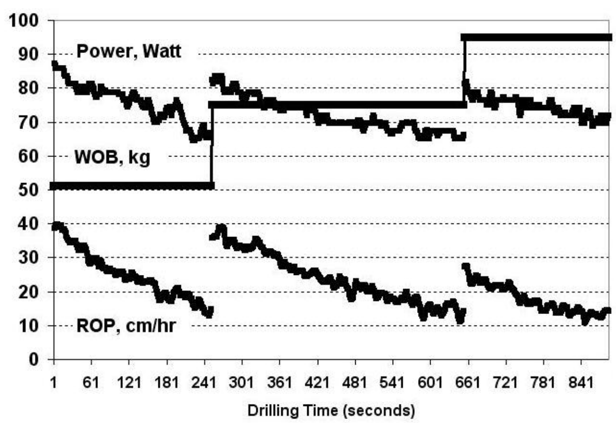

Figure 11. WOB needs to be increased in order to maintain the penetration rate (figure11.jpg).

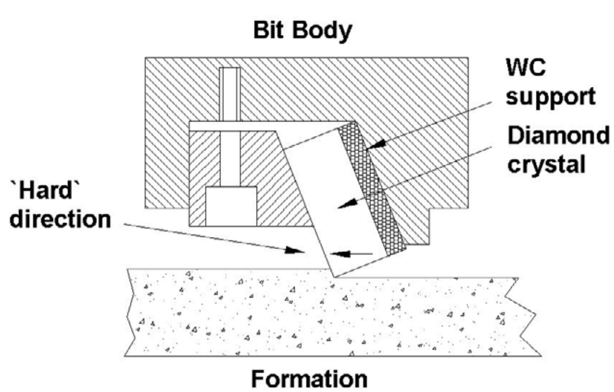

Figure 12. Proposed single diamond cutter placed at the negative rake angle (figure12.jpg).

The drilling power has two sources, i.e. the power to overcome the sliding friction and the power required to actually cut the rock. The power equation is therefore:

$$Power_{drilling} = Power_{cutting} + Power_{sliding} \quad (4)$$

The contribution of the friction to the total power is:

$$Power_{sliding} = (Torque)*\left(\frac{2\pi}{60}*RPM\right) = \left(\mu * WOB * \overline{R}\right)*\left(\frac{2\pi}{60}*RPM\right) \quad (5)$$

where, $\overline{R}$ is radius of the center of pressure of the cutting elements of the bit, which depends on the bit geometry and the distribution of cutters in the bit. Because of the small difference between the inner and outer radius of the cutters in a coring bit, $\overline{R}$, can be approximated by the average radius, i.e. $\overline{R} = (R_{Inner} + R_{Outer})/2$. Note that, in equation (5), the only unknown is the coefficient of sliding friction, μ.

The energy required to break a rock in rotary drilling is commonly taken to equal the unconfined compressive strength of the rock (work per unit volume = force per unit area), and amounts to supposing that a force corresponding to the unconfined compressive strength acts so as to sweep through the entire volume of rock to be destroyed. Thus the contribution of drilling (i.e. rock destruction power) to the total power budget is:

$$Power_{cutting} = Work_{per\ revolution} * \left(\frac{2\pi}{60}*RPM\right) \approx (UCS * Area * \delta)*\left(\frac{2\pi}{60}*RPM\right) \quad (6)$$

where,

- $Area = \frac{\pi}{4}\left(D_{Outer}^2 - D_{Inner}^2\right)$
- D_{Inner} = inner diameter
- D_{Outer} = outer diameter
- UCS = unconfined compressive strength
- δ = depth of cut per revolution
- RPM = rotational speed in revolutions per minute

Thus, the final power equation is:

$$Power_{drilling} = UCS * Area * \delta * \left(\frac{2\pi}{60}*RPM\right) + \left(\mu * WOB * \overline{R}\right)*\left(\frac{2\pi}{60}*RPM\right) \quad (7)$$

Estimating the coefficient of sliding friction. Figure 13 shows the power vs. rate of penetration for three different values of weight on bit, i.e. 500 N, 750 N and 950 N. The data were taken from the same test as reported in Figure 11. Since the power is directly proportional to the rate of penetration, it makes the analysis much easier. The two equations of the best fit lines are shown for the 50 kg (500 N) and for the 95 kg (950 N) cases only.

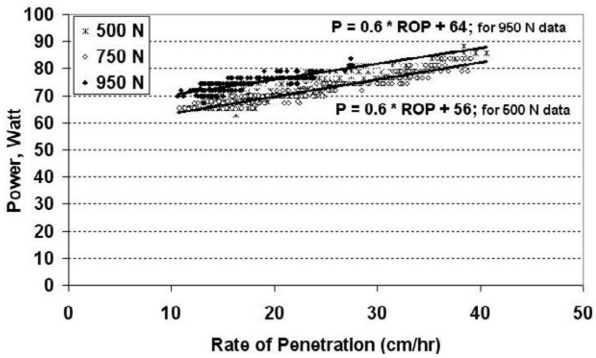

Figure 13. Power vs Rate of Penetration for the three different values of weight on bit (figure13.jpg).

The difference in the power values at different WOB values with a consistent Rate of Penetration (ROP) can be attributed only to the change in the power component related to sliding friction. This is explained by the fact that with the rate of penetration remaining unchanged, the depth of cut must also remain unchanged, and in turn, the resistance from the rock ($Power_{drilling}$) as it is being drilled must be constant. (We do not expect there to be an influence here from the rate of deformation, since the rotary speed was held constant, but it is just possible that more heat was generated at the cutters under the higher weight conditions, and that, therefore, the rock was softer. This would have reduced the rock destruction component and therefore increased the frictional component further.) The coefficient of sliding friction, $\mu_{sliding}$, can then be calculated as follows:

$$Power_{(950N)} - Power_{(500N)} = 8\,Watt$$

$$= \mu_{sliding} * (950N - 500N) * \overline{R} * \left(\frac{2\pi}{60} * RPM\right) \quad (7)$$

where,

- 8 W is the difference in the power at the WOB values of 95 kg and 50 kg; (equations of best-fit lines in Figure 11)
- D_{Inner} = 25 mm
- D_{Outer} = 38 mm
- UCS = 300 MPa
- $\overline{R}$ = 16 mm
- RPM = 200

Substituting and solving equation 7 gives the coefficient of sliding friction, $\mu_{sliding}$, of 0.06. This value for the friction coefficient is indeed very low (for comparison the coefficient of friction of Teflon on Teflon is 0.04) but not impossible. PDC material is almost completely diamond (with a few percent of cobalt) and diamond is known to have a very low friction coefficient. For example, the coefficient of friction for a diamond stylus sliding on CVD (chemical vapor deposition) diamond can be as low as 0.04 in air and 0.001 in water (Tzeng 1993). Note also that in a separate set of friction experiments where a PDC bit was sliding on the surface of basalt rock at 100 rpm, a friction coefficient of approximately 0.075 was measured (Zacny and Cooper 2006). It is also quite plausible that very fine cuttings (majority smaller than 100 µm) generated during the drilling process provided a good lubrication at the bottom of a hole.

Calculating the depth of cut per revolution, δ and investigating accuracy of the drilling equation. The actual depth of cut per revolution, δ_{true}, can be calculated as follows:

$$\delta_{true} = \frac{ROP}{RPM} = \frac{20\frac{cm}{hr}}{200\frac{rev}{\min}} = 0.017mm \quad (8)$$

The depth of cut of 0.017 mm (17 µm) suggests that the main rock drilling mechanism was grinding and crushing, and not cutting.

A value of the depth of cut δ, can also be estimated from equation (6). Using a set of data points from Figure 11, in particular the WOB of 950 N, the ROP of 20 cm/hr, and the total power of 76 W. The power required to overcome friction resistance was found to be 18 W (Equation 5). Therefore, 76 – 18 = 58 W was attributed to the actual rock drilling. Substituting 58 W into equation (6) and solving for δ, gives the depth of cut of 0.016 mm, which is very close to the δ_{true} of 0.017 mm. This shows that equation (6) accurately models the drilling mechanics of a PDC bit under the set of drilling conditions used in the experiment.

Conclusions

In this work, we have investigated one possible approach through which may be developed a drill bit for martian conditions. The over-arching requirement is for a bit that will operate at low temperature and without liquid cooling. Beyond that, there is a desire to develop, if possible, a drill bit that is capable of penetrating the widest possible range of terrains that may be found on Mars. At present, it is likely that the choice will lie between a surface-set or impregnated diamond bit and a bit with larger, individual edged cutters. Current designs of the former type are inadequate for soft rocks or frozen soils, while bits of the latter type are easily chipped and/or wear too rapidly in hard rocks. We believe that there is greater scope for progress in improving bits with large individual cutters, so we have evaluated how such bits operate in basalt, the hard rock most likely to be encountered on the surface of Mars. In drilling basalt and other hard rocks, limiting factors are the ability of the cutter to penetrate the rock. In the present case, where penetration is principally by crushing and grinding, an ability to penetrate the rock amounts to having sufficient weight on bit to be able to reach the unconfined compressive strength of the rock over the area that contacts the rock, i.e. the wear flat. As the wear flat develops, the weight has to be increased progressively to maintain penetration until some limit is reached. Often, this occurs when the heat generated by the ever-increasing sliding friction causes overheating and rapid thermal degradation of the cutters. This does not appear to have happened in our case, possibly because of the low ambient temperature. In the context of drilling from an exploration vehicle on Mars, the most likely limiting factor will be the inability to apply sufficient weight on bit; temperature considerations are less likely to be important, and in any case, if thermal damage is a consideration, the rotary speed may be reduced without penalty. Alternatively, the current rapid progress in developing superior, more wear resistant diamond materials may allow the drilling conditions to be made more demanding, or alternatively, to delay the point at which the wear becomes enough to require a prohibitively high weight on bit. The drilling power required to penetrate basalt was found to be relatively low, in the range of 100 W, and therefore it is not a limiting factor in drilling basalt.

Further work must therefore concentrate on finding a drill bit design that can continue to penetrate at limited weight on bit. In the case of discrete, edged cutters, such as PDC elements, the search must move to materials with higher wear resistance. These may include improved "conventional" PDC, single crystal diamond, or cutters in which the PDC is overlain by CVD diamond. The latter may show less wear while still maintaining sufficient resistance to shock loading.

In this work, we have also developed and verified a drilling equation that can be successfully used to estimate the drilling performance of a PDC bits in hard formations.

Directory of supporting data

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