Results from Testing of Two Rotary Percussive Drilling Systems

Kristopher Kriechbaum, Kyle Brown, Ian Cady, Max von der Heydt,
Kerry Klein, Eric Kulczycki, Avi Okon
Jet Propulsion Laboratory, California Institute of Technology
E-mail: kristopher.l.kriechbaum@jpl.nasa.gov

ABSTRACT

The developmental test program for the MSL (Mars Science Laboratory) rotary percussive drill examined the effect of various drill input parameters on the drill penetration rate. Some of the input parameters tested were drill angle with respect to gravity and percussive impact energy. The suite of rocks tested ranged from a high strength basalt to soft Kaolinite clay. We developed a hole start routine to reduce high sideloads from bit walk. The ongoing development test program for the IMSAH (Integrated Mars Sample Acquisition and Handling) rotary percussive corer uses many of the same rocks as the MSL suite. An additional performance parameter is core integrity. The MSL development test drill and the IMSAH test drill use similar hardware to provide rotation and percussion. However, the MSL test drill uses external stabilizers, while the IMSAH test drill does not have external stabilization. In addition the IMSAH drill is a core drill, while the MSL drill uses a solid powdering bit. Results from the testing of these two related drilling systems is examined.

INTRODUCTION

Collection and analysis of samples from the surface and subsurface is a main focus of current and upcoming missions to Mars. MSL is required to obtain samples of Martian rocks and analyze them using on-board science instruments. The sample acquisition tool of the MSL rover is a rotary percussive drill using a full face powdering bit and external stabilizers. The drill is mounted to the end of a ∼2 m long 5-DOF manipulator that provides the preload to hold the stabilizers in place on the rock. Future drills may also be percussive because of the lower weight on bit (WoB) required for effective drilling as compared to rotary drag drilling. Bit wear from use of percussion is also reduced, which allows for more drilling depth per bit.

Integrated Mars Sample Acquisition and Handling (IMSAH) is a technology development task focused on designing an end-to-end system capable of acquiring cores from Martian rocks and preparing them for potential return to Earth (Backes 2010). The current conceptual design of the IMSAH subsystem uses a rotary percussive coring drill. The IMSAH drill would also likely be mounted on the end of a 5-DOF manipulator. However, the rover and robotic arm are expected to be closer to the size of the Mars Exploration Rovers than that of MSL. In order to reduce mass and requirements on the rover system, the current IMSAH baseline design does not have external stabilizers, nor does it have an independent feed actuator. It may utilize a passive spring-based mechanism which the manipulator arm could compress against the rock surface to provide WoB. It is assumed that both the arm and the drill actuators could not be driven simultaneously. Thus the drilling would cycle through (re)applying WoB with the arm, locking the arm joints, and drilling.

Other shallow drilling tools have been developed for potential future missions (Zacny et al. 2008; Mukherjee et al. 2006). The low-force sample acquisition system (LSAS) drill from Alliance Space Systems can collect powder samples of up to 1 cm^3 from depths of up to 2cm (Stanley et al. 2007). The Corer-Abrader Tool and the Mini-Corer from Honeybee Robotics are both rotary drag coring tools. The Ultrasonic/Sonic driller/corer from JPL creates fine powdered cuttings and can also create cores (Bar-Cohen et al. 2001).

Rigorous testing is important for several reasons. Experience with dry drilling at this scale is very limited. Most terrestrial drills use fluids for cuttings removal, and WoB is not limited by drilling from a low-mass rover. Modeling the mechanics of rotary percussive drilling is still an active research topic (Han et al. 2005; Han et al. 2006). Data collected during testing can be used to help refine design requirements such as rotary torque or impact energy needs for a flight tool. Finally, early testing allows for verification of possible implementation approaches.

This paper is organized as follows: Section 3 describes the drilling systems used to perform the testing. Section 4 discusses results from the testing of these two rotary percussive drills. Section 5 gives a summary of the test results and possible future directions.

TEST HARDWARE OVERVIEW

The Testbed 3 (TB3) drill is a brassboard-level prototype that was used to test implementation approaches and verify functional requirements for the different mechanisms of the MSL drill. The Mini-TB3 drill used some components from the TB3 drill, with a key difference that the Mini-TB3 drill has been adapted to create cores instead of powder. Mini-TB3 is currently being used to test possible approaches for the IMSAH coring drill.

Testbed 3 Drill

The TB3 drill has four primary functions. The linear feed mechanism applies and controls WoB. The spindle mechanism provides the torque to rotate the bit on the surface of the rock and move cuttings up the drill bit flutes. The percussion mechanism provides the percussive impacts to break the rock. Finally, the chuck mechanism allows for bit changeout. For ease of use the chuck on the TB3 drill is operated manually, not with an actuator. The TB3 drill also has a pair of external stabilizers that are connected via a linkage. The drill is mounted at the end of a 5-DOF manipulator that is ~2 m in length. Figure 1 shows a photograph of the Testbed 3 drill preloaded against a rock.

The drill bit for TB3 uses a full-faced, sleeved auger. The cutting portion of the bit is created from a COTS bit that is machined down to the appropriate geometry. The fluted portion of the bit is inside a sleeve. This allows the auger to carry cuttings up the sleeve into the sample collection chamber. The drill can penetrate up to 5-6 cm depending on the geometry of the rock surface. Very little of the cuttings material from the upper 1.5 cm of the hole is colleced. After that depth, the sleeve is fully engaged in the drill hole and the cuttings travel up the auger into the sample collection chamber. The outer diameter of the cutting tip is approximately 16mm. Figure 2 shows a cross section of the TB3 bit and the path the collected cuttings take into the sample chamber.

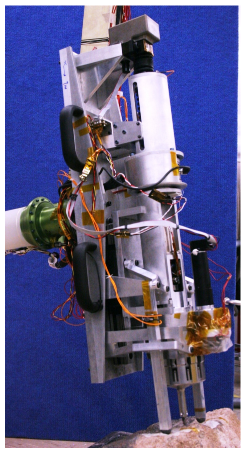

FIG. 1. TB3 preloaded against a rock.

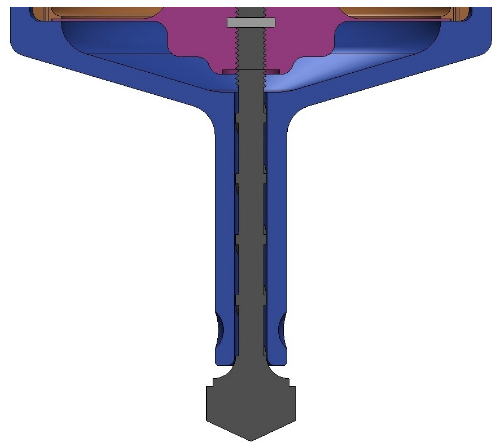

FIG. 2. Cross section of the TB3 bit.

The drill contains a single-axis force sensor to measure WoB. There is also a 6-axis force/torque sensor between the end of the arm and the drill to measure preload and reaction forces while drilling. The voice coil percussion mechanism has a linear potentiometer mounted to the moving mass to give high-rate position information. Position information is differentiated to get velocity, which is then used to calculate the energy of the free mass at impact. A typical test consists of preloading the stabilizers against the rock, performing the hole start routine, and drilling the hole to full depth. While preloading, an attempt is made to line up the drill axis with the surface normal of the rock. A target WoB is set for each hole, and the feed rate is adjusted to maintain that WoB. We also collect current and speed data for the spindle and current data for the voice coil.

Mini-TB3 Drill

The functionality of the Mini-TB3 drill is very similar to that of the TB3 drill. The Mini-TB3 drill uses the same mechanisms for the rotation, percussion, and the chuck functions. However, the linear feed mechanism is different. In the current IMSAH baseline architecture, both the arm and the drill could not be driven at the same time because of system-level constraints. However, an actuated arm of the scale and strength required to manipulate Mini-TB3 does not currently exist. As a compromise, Mini-TB3 was mounted to a smaller robotic arm-like fixture that was created from aluminum tubing and commercially available fittings. The linear feed is still provided by an actuated linear stage, but when the drill is running the linear feed motor is not used. The inherent springiness of the arm-like fixture itself is used to maintain WoB. The approximate stiffness of the arm-like fixture in the direction of the drilling axis is 30 N/mm. Figure 3 shows a photograph of the Mini-TB3 drill and the arm-like test fixture.

The bits used on Mini-TB3 are custom made by the Relton Corporation. The outer diameter of the bit is approximately 21 mm and it creates a core that is approximately 10 mm in diameter. There is free space inside the bit for a sample tube, breakoff, and retention mechanisms. As the core is drilled, it goes directly into the sample tube. At the system level, it is easier to handle and manipulate a sample tube of known size than it is to handle a core of unknown dimensions or that is broken into pieces. However, Mini-TB3 has neither breakoff nor retention mechanisms. Figure 4 shows a cross section of the bit used on Mini-TB3.

The Mini-TB3 drill is mounted on a six-axis force/torque sensor. It is primarily used to measure WoB, but the other channels are also recorded for possible analysis. Data collected from percussion and rotation is the same as that which is collected from the TB3 drill. A test of Mini-TB3 consists of alternating back and forth between applying WoB and operating the drill. The length of time the drill is operated depends on the rock being drilled. Softer rock requires less time than harder rock before the springiness of the fixture has driven the drill as far forward as it can and there is no further rock that the drill is touching. The drilling cycle times range from 2-10 seconds.

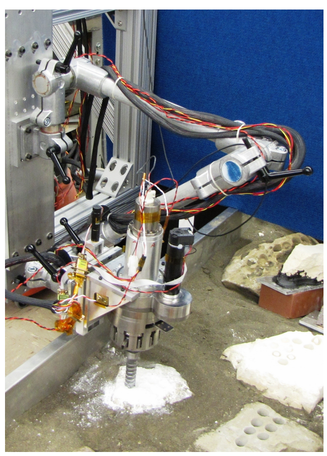

FIG. 3. The Mini-TB3 drill and arm-like fixture.

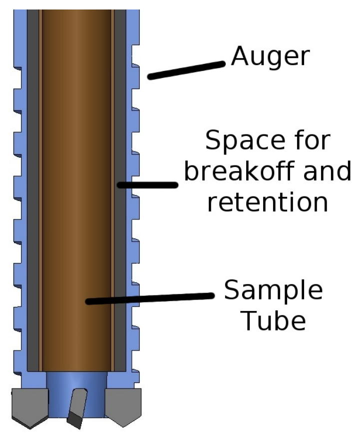

FIG. 4. Cross section of the coring bit used on Mini-TB3.

TEST RESULTS

Because TB3 is a full face drill that creates only powder, more tests were performed on the hardest rock of the test suite, namely the MMS basalt. If the drill has enough percussive energy to break the hardest rock, any softer rock will follow. However, when trying to create a core, it is not clear if a single level of percussion will work. The percussion level would again be set by the hardest rock, but it is possible that this high level of percussion could destroy the softer rocks. The TB3 linear feed is controlled to try and maintain a constant WoB. Because the current design of the IMSAH core drill would use a passive spring-fed mechanism that is reset by the arm to provide linear feed, the WoB is always decreasing during a drilling cycle. Finally, TB3 testing all took place before the IMSAH project had even started. Lessons from TB3 testing were used to craft tests for Mini-TB3.

Testbed 3 Results

A suite of 5 different rocks was chosen by the MSL science team to test the TB3 drill. These are Belleville basalt, Mojave Mars Simulant (MMS) basalt (Peters et al. 2008), vesicular basalt, volcanic breccia, and kaolinite. Each rock was chosen to pose different difficulties for the drill. The rock used for most testing was the MMS basalt. Belleville basalt has a higher UCS than MMS basalt, and volcanic breccia is a highly heterogeneous rock. Vesicular basalt was chosen because of the likelihood that it could cause high vibrations, and kaolinite is a soft clay mineral.

Hole Starting

The capability of the MSL robotic arm allows for a preload on the stabilizers of 300 N. All TB3 tests used a preload of 300 N on the stabilizers. We saw some alleviation of preload during testing, especially as the hole was being started and when the drill axis (and rock surface normal) was not aligned with gravity. Possible explanations for this include percussion-induced vibrations of the drill and bit walk. Bit walk is caused by the lateral forces created when the bit is in uneven contact with the rock. In preliminary tests, this slippage caused high sideloads on the bit. As the hole was drilled deeper, this sideload created high torques on the bit which caused the spindle to stall. We devised a hole start routine that minimizes the possibility of bit walk and thus reduces the likelihood of high sideloads deeper in the hole. The hole start routine is as follows:

1. Apply a low WoB (nominally 60N). Note the linear feed position. Call this position *A*.
2. Turn on percussion without rotation for a short period of time.
3. Retract the linear feed.
4. Turn the rotary stage a small amount, nominally 15°. Return the feed to position *A*. Return to item 2 until the rotary stage has gone through a half rotation. Only a half rotation is needed because the bit is symmetric.
5. Rotate at a low rotary speed while percussing for a small number of rotations. Return to item 1. Continue until the desired starter hole depth is reached.

We used the hole start routine until a depth of 5-6mm was reached. At that depth the full face of the bit is in contact with the rock and the rock surface is clear of any protrusions that could cause an off-axis torque on the bit.

Drilling Angle

Primary performance parameters for the MSL and the TB3 drill are rate of penetration and collection efficiency. The MSL rover is required to obtain samples drilling straight ahead while parked on a 20° slope. We performed testing at angles from 0° (vertical) to 110° (drilling upwards) with respect to gravity. Table 1 shows the average collection efficiency and rate of penetration (ROP) at increasing angles. All of these tests were performed with 80 N WOB. Collection efficiency is defined as $m_{collected}/m_{possible}$, where $m_{collected}$ is the mass of sample collected in the bit, and $m_{possible}$ is the total mass of rock drilled (calculated from volume removed and rock density). Note that we assume sample collection does not start until the bit sleeve is fully in the borehole, so we subtract the first 1.5 cm of depth from the hole when calculating $m_{possible}$. The decrease in collection efficiency

TABLE 1. TB3 performance in MMS basalt.

Angle	Collection %	ROP (mm/min)
0°	83	4.5
45°	55	5.0
90°	46	12.2
110°	46	9.3

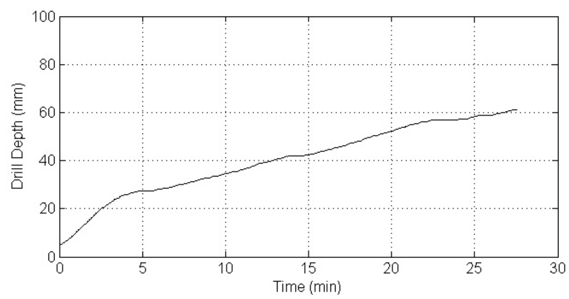

FIG. 5. Kink in ROP during a vertical test.

is clear as the drilling angle with respect to gravity is increased. As the angle increases, the cuttings can more easily fall out of the hole between the sleeve and the borehole. The lower ROP of the 0° and 45° tests can be explained by poor cuttings removal. Figure 5 shows a depth vs. time plot for a vertical test. At a depth of around 25mm (∼4 min) the ROP greatly decreases. As the hole is drilled, the cuttings have two paths to follow - out onto the rock surface or up through the auger sleeve. As the auger sleeve enters the hole, the path out onto the rock surface is reduced and there is very little to push the cuttings out through this path. When drilling horizontally and upwards, the cuttings can flow out under the force of gravity. The difference in ROP between the 90° and 110° tests can be explained by a difference in impact energy. All tests at 0°, 45° and 90° had an average impact energy of .7 J. The tests performed at 110° had an average impact energy of .6 J.

Mini-TB3 Results

The rock suite chosen for Mini-TB3 testing is different than that used for TB3 tests. The rocks used for Mini-TB3 tests are MMS basalt, volcanic breccia, siltstone, Santa Barbara limestone, and kaolinite.

Hole Starting

The range of WoB for Mini-TB3 testing was 20 N - 50 N. At these lower WoBs the effect of bit walk is noticeably less, even without external stabilizers. The only special thing we do to start a hole is drill the first 5-6mm at 20 N WoB. If future testing finds cases where side loads can develop, autonomous re-centering algorithms could be used (Hudson et al. 2010).

Core Integrity and ROP

A key question to be answered with the Mini-TB3 testing is whether or not a single impact energy can be used to successfully core all rocks of the test suite. The quality of a core is subjective. If only powder or rock chunks are obtained, then the stratigraphy of the rock will have been lost. If the core is obtained in segments and discs the science return is still likely acceptable. However, a core in multiple pieces makes the breakoff and retention functions more difficult. Table 2 summarizes Mini-TB3 ROP in all the rocks of the test suite. All tests presented in the table used impact energies of .35-.45 J, WoB of both 20 and 40 N, and rotary speed of 350 rpm. Total drilling power was less than 100 W for all tests. Over 2/3 of the power is used for percussion, which is not optimized for the low impact levels we tested at. Thus far, little effort has been spent on optimizing the bit geometries for cuttings removal.

TABLE 2. Mini-TB3 performance in all rocks.

Rock	Average ROP (mm/min)
SB Limestone	29
Kaolinite	21
Siltstone	8
Volcanic Breccia	5.8
MMS Basalt	3

As expected, the MMS basalt and volcanic breccia had the lowest ROP as they are the hardest rocks. The limestone and kaolinite were soft and easy to drill. The siltstone was in the middle. The average quality of the core obtained from each rock varied. Figure 6 shows photographs of a few representative cores. The Santa Barbara limestone produced the most consistent cores. The core was either full-length and attached to the parent rock or broken into a few long pieces. The kaolinite either stayed in a single piece on the parent rock or broke into pieces on the order of 1 cm. This depended on exactly which kaolinite rock we drilled, illustrating the wide variation of rocks of the same type. MMS basalt and volcanic breccia broke into long segments and discs. Core quality of the siltstone is the lowest. We drilled the siltstone at high and low impact energies, various rpms, and without a sample tube to allow more clearance inside the bit. All tests produced thin discs that are 3-8mm thick as shown in Figure 6.

FIG. 6. Representative Santa Barbara limestone, siltstone, and MMS basalt cores.

CONCLUSIONS

We have presented results obtained during the testing of two different rotary percussive drilling systems. The results of TB3 drill testing were used to inform the design of the MSL powdering drill. We developed a reliable hole starting routine, and found that the drill could still collect sample even when drilling upwards with respect to gravity. The Mini-TB3 results are being used to further the design of the IMSAH coring drill. Mini-TB3 testing has shown that starting a hole without external stabilizers at low WoB is not an issue. Work remains to optimize the design to create the best core quality. Creating a good core is more difficult than creating powder. Designing a dry drill for shallow surface access is still a difficult problem.

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