Automated Rock Thin Section Device for Space Exploration

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***Abstract* — We are developing a device for automated production of rock thin sections in a space environment. A rock thin section is a rock ground to 30 microns thickness and a polished surface finish. Analysis of rocks in thin section is a powerful tool for understanding the origin and evolution of rocks on earth. Identification of mineral fractions, rock microtexture, and mineralogy allows rock type to be determined. Properly prepared thin sections can be analyzed by a number of microscopic techniques (optical, SEM, electron microprobe, etc.) some of which are already in development for space exploration. The research effort (Automated Rock Thin Section Device, ARTS) is focused on major hurdles to realize the device. Major functional subsystems will be developed to TRL-3. We are focusing our efforts on the development of mechanisms for automated handling of a variety of samples and their cutting and polishing to thin section quality. Sections will be evaluated with standard geological techniques available at the Colorado School of Mines and elsewhere. We are developing a generalized sample manipulation system for preparing thin sections of a variety of sample types, including: arbitrary rocks of up to ~8cm characteristic dimension, cores of >1cm diameter, rock fragments, regolith, and dust. Team member Honeybee Robotics is developing a precision rock grinding device for grinding rocks to thin section quality. In this year, the first year of development, we are developing thin section surface roughness requirements for analog Lunar and analog Martian rocks, acquisition of analog rocks, methods of manipulation of rocks and cutting to a pre-form for fine grinding/polishing, and approaches for grinding and polishing to thin section.**

I. INTRODUCTION

Petrographic thin sections have been in use for more than 150 years [1] and are fundamental to the study of rock samples using the petrographic (polarizing) microscope. Thin sections are traditionally used to identify minerals and their structural aspects (cleavage, fractures, mineral zoning) rock microtextures that indicate the mode of formation of the rock (igneous, metamorphic, sedimentary). In recent decades, polished thin sections and grain mounts have been the preferred form of sample preparation for electron microprobe and other types of microscopic chemical analysis, allowing geometrical factors to be eliminated from the interpretation of spectroscopic data.

A thin section, along with chemical analytical data for a rock on the Moon, Mars, other planetary body, an asteroid, or comet would remove much ambiguity from interpreting the geological history of the sampled site. For example, the composition of the lunar mare regolith, the underlying basaltic rock, an impact melt breccia made from the local regolith, or impact glass made by melting the regolith may be quite similar, but the materials can all be distinguished using a petrographic thin section. The use of a polarized light microscope allows optical characteristics of minerals and their identification and, to some extent, mineral composition. However, unpolarized light microscopy can allow some mineral, texture and structure, plus some mineral identification to be made. If microprobe instruments are carried, mineral composition can also be determined.

The preparation of thin sections has traditionally been an art rather than a science, with the most difficult handwork problems being the mounting of the sample and the determination of thickness (30 microns) of the section. The 30-micron thickness was chosen because most common minerals (e.g. silicates) are transparent at that thickness, while a few minerals (e.g. ilmenite, spinel, sulfides) are opaque. The polarizing microscope allows the birefringence of minerals to be utilized as a means toward mineral identification. A petrologist handy with the petrographic microscope can rapidly identify minerals partly because of the standardized thickness and interference colors related to birefringence. Part of the art of thin section preparation has been the skill of the preparer in judging the thickness of the slice, commonly done by looking at the section in the polarizing microscope for interference colors that are related to the thickness of known mineral grains. However, rocks with totally unknown mineralogy were more difficult to grind to the correct thickness. Precise measurements possible today allow this to be automated.

The automated thin sectioning device has a range of applicability to future missions to all planetary bodies with direct access to the surface and sub-surface. The *Solar System Exploration Roadmap* [2] identified several technology priorities for Solar System exploration. In the area of Science Instruments *in situ* sensing was rated among the "highest priority". The development of sample acquisition and sample preparation systems was identified as needed for *in situ*

This work is funded by the NASA PIDDP program, grant number NNX06H15G, technical officer Johnathan A. Rall, PIDDP Discipline Scientist.

sensing. The rating of "highest priority" identifies new developments that are required for all or most roadmap missions. Sample acquisition, handling, and preparation was identified as highest priority because for many roadmap missions sample return is impractical at this time (Venus, Europa, Titan, and Enceladus). Several Mars Exploration Payload and Analysis Group (MEPAG) [3] objectives would be addressed by an automated thin section device. Many of the MEPAG goals also have analogs to surface investigations on other planetary surfaces [4]. Such as: "II. Understanding processes and history of climate on Mars", "III. Determine evolution of the surface and interior of Mars", and "IV: Prepare for human exploration". A cursory description of MEPAG investigations that would be addressed include: investigations of dust, aqueous weathering products, sedimentary processes, mineralogical composition, and regolith formation and subsequent modification, weathering and diagenetic processes. The "Lunar Surface Exploration Strategy Lunar Exploration Science Working Group" (LExSWG) [5] noted that identification of rock texture and grain sizes of highland rocks, cratered and basin ejecta, and lunar volcanic origin to 50 µm resolution would be desirable. The recent report *The Scientific Context for Exploration of the Moon: Interim Report* from the Space Studies Board [6] listed mineralogical identification by *in situ* instruments among landed implementations for achieving science goals of improved understanding of lunar crust, volcanism, and polar regolith.

In the following sections we review our research plan, rock requirements work, and progress on development of major device units: Rough Cutter, Adhesive and Support, Grinding and Polishing, and Dust Mitigation/Cross Contamination.

II. Research Plan

A. *Research plan:*

In any mission operational decisions would balance potential science return with technical risks and mission resources. High degrees of sample handling likely carry greater technical risks than sample comminution or unprepared sample analysis. Risk assessment can only be accomplished by a diversified investigation of thin section preparation techniques at an early stage of instrument development. We are studying the technically limiting steps to realizing an automated thin section device rather than develop a complete system. Specifically, we are focusing on: sample handling, adhesive and support application, cutting, grinding, and polishing. The major units of the device will be developed to TRL 3.

A complete automated thin section device would be capable of accepting a variety of sample types, manipulation and processing (rough cutting) of samples to a conforming structure for thin sectioning, thin section grinding and polishing stages, sample caching, and sample delivery to multiple science instrument platforms, with thin section petrology microscope analysis performed at intermediate grinding stages, and with cross and forward contamination safeguards. Fig. 1. shows a block diagram overview of a complete system concept. In this concept a unified grasping and transport mechanism would be used to deliver a sample between function components. Sample had-off between the manipulator and functional units would be eliminated to the maximum extent possible.

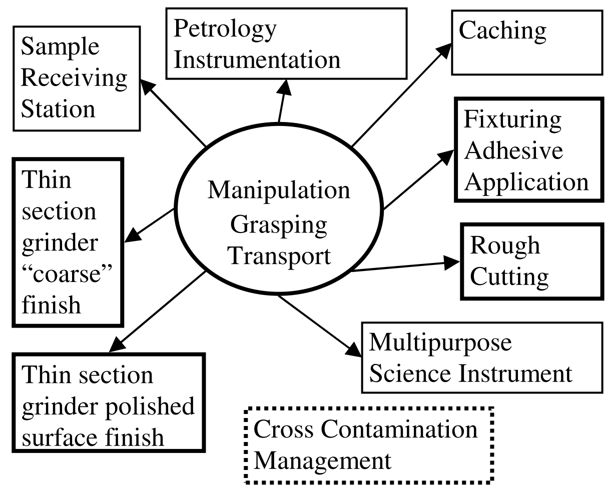

Fig. 1. System block diagram of a complete thin section device. Unified manipulation system would transport samples between several functional units: in bold: units we are developing/limiting steps; dotted box: trade study

We consider the following to be the major hurdles to realizing a thin section device for the space environment:

1) Reduction or elimination of consumables normally used in thin sections.
2) Cutting of an irregular sample to a workable size and shape, and fixturing of the sample: rock, rock core, regolith and dust.
3) Grinding and polishing of cut sample to finished thin section.
4) Cross contamination safeguards and removal of discarded cuttings and rock dust.

Work flow of a thin section device would follow the process outlined in Fig. 2. We are investigating methods to make thin sections of the follow classes of sample.

Class 1. Large rocks of arbitrary shape, ~8cm or less.
Class 2. Rock cores of >1cm diameter.
Class 3. Rock fragments (fragments too small for pre-form).
Class 4. Fine regolith and dust (grain mount).

Each of class of sample must be cut to a pre-form "tablet" shape, roughly, 20 mm x 20 mm x 5 mm. The final shape will be defined by engineering requirements of grasping, cutting, grinding, and polishing units. Class 1 and 2 samples would be cut down to the pre-form shape largely without significant volumes of epoxy, while Class 3 and 4 samples would begin with epoxy setting followed by cutting to the pre-form shape.

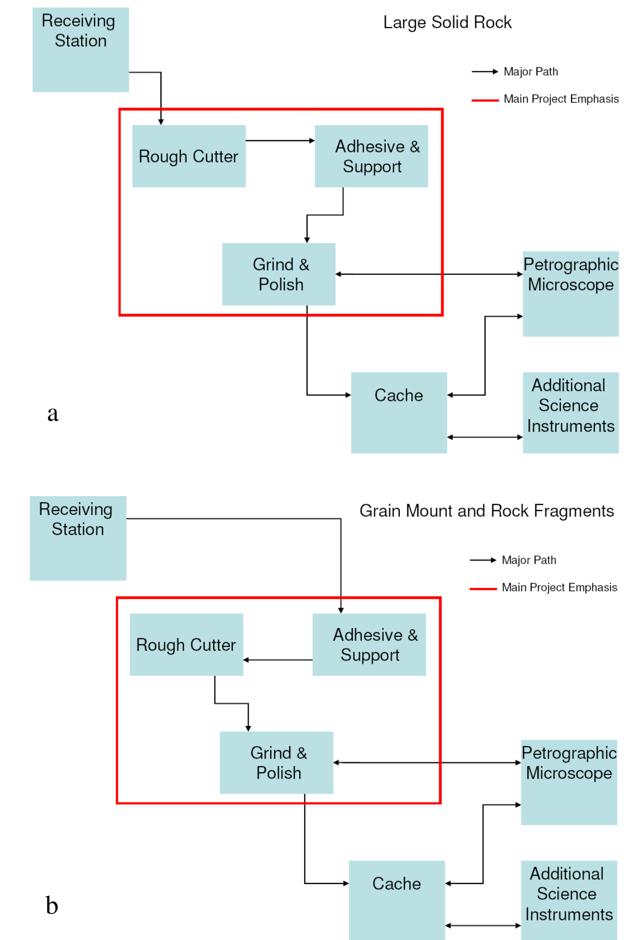

Fig. 2. Work flow diagram for large solid rocks, grain mounts, and fragments. A) Class 1 and possibly Class 2. b) Class 3, 4 and possibly Class 2.

III. Requirements

Rock hardness, grain size, and rock friability have significant impact on the outcome of thin section preparation, along with the specific grinding and polishing method employed. Traditional preparation is the natural starting point for determining final polished surface finish of a properly prepared thin section. We have evaluated the surface finish of polished and rough ground basalt thin sections prepared by traditional methods in the Geology and Geological Engineering Sample Preparation Laboratory at the Colorado School of Mines. Fig. 3. shows polished and standard thin sections surface finish of a basalt measured using a Wyko Optical Profiler. The standard thin section was prepared by grinding with 600 grit Silicon Carbide water slurry. The standard thin section is marginally adequate for petrographic analysis. A cover glass slide or additional polishing would typically be applied to this sample. The polished thin section was prepared with the 600 grit Silicon Carbide slurry followed by 0.3 μm Aluminum Oxide water slurry. The polished thin section is excellent for petrographic and SEM analysis. The mean surface roughness parameter of these thin sections is shown in Table I.

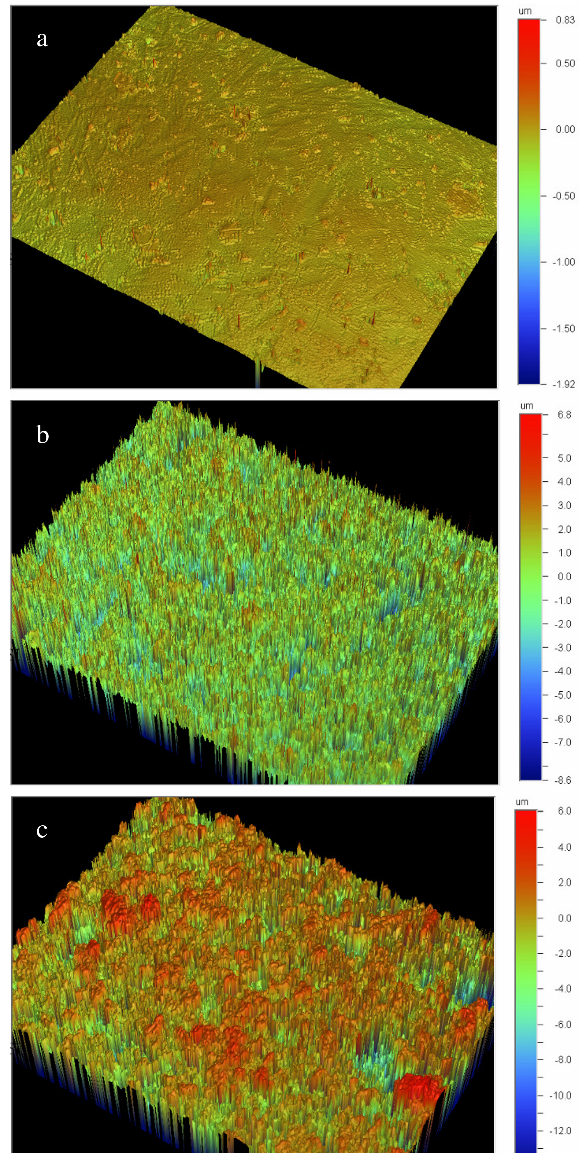

Fig. 3. Surface profiles of traditionally prepared a) polished basalt thin section, b) standard basalt thin section, and c) a RAT ground basalt sample. The area shown in each view is 0.75 x 1.0mm. The color scale is μm of surface depth.

TABLE I
COMPARISON OF SURFACE ROUGHNESS

Sample	Ra (μm)
Basalt, polished thin section	0.03
Basalt, standard thin section	0.96
Basalt, RAT ground surface (different basalt from thin sections)	1.28

For comparison the profilometry results of a basalt ground using a RAT from Honeybee Robotics is shown in Fig. 3c. The mean surface roughness, Ra, of the RAT ground basalt is already on the same order as a standard thin section. The polished thin section exceeds the surface finish requirements for petrographic analysis. While the very fine surface finish of a polished thin section may not be achievable in a thin section device for space exploration, it is not necessary for basic petrographic analysis. We are examining surface finish of the thin sections produced by our systems and traditional methods to determine minimum surface finish requirements for successful petrographic analysis. To the extent possible, we will test system components using mars, lunar, and other roadmap mission destination analog rocks and regolith.

IV. ROUGH CUTTING

Once a rock has been selected for examination, the first step in the process of generating a thin section is to extract a "tablet" from the sample. This process requires that the sample be cut in three orthogonal directions. Traditionally, this process is done using a rotating cutting wheel (disk or blade) with diamond embedded in a brass matrix. However, this is not the only way to cut rock. For example, in quarries rock slabs are cut using wire cable saws (long steel wire ropes with embedded abrasive) that are drawn through the rock over long distances. In the semiconductor industry, silicon and sapphire are cut using steel wire coated with embedded diamond. The cuts are straight and smooth with very little kerf. In this project, a decision was made to evaluate both the cutting wheel and the cutting wire approaches so that the advantages and disadvantages of each approach could be evaluated.

A. Comparison of Cutting Methods

Table II gives a weighted comparison of the two methods. The number in parenthesis are relative weighted values of each attribute for each of the two cutting methods, on a scale of zero (0) to five (5) scale, with five being the best. An itemized listing of the pros and cons of each method follows.

<u>Diamond Wire vs. Cutting Wheel for Tablet Generation</u>

Diamond Wire Pros:

- Low applied cutting force
  - Low contact force required (~20 N)
  - Reduced fixturing requirements (low draw force cutting).
  - Reduced power consumption
- High degree of controllability
  - Easily modify tension/velocity
  - Able to control system with many different instrumentation methods.
- Small Cutter Footprint
  - Small kerf → reduced dust generation
  - Reduced friction → decreased conductive heat transfer/thermal stress
- Produces a "Linear Cut"
  - Diamond wire produces straight cuts
- Cutting wire can cut in planes that are orthogonal to the "normal cutting plane"
  - Can do with a single axis what would require 2 axes using a cutting wheel.
  - Wire can be plunged to a certain depth, and translated, a cutting wheel would require a second axis to produce similar cut.

Diamond Wire Cons:

- Requires instrumentation to control cutting. At a minimum, the capstan system requires a measure of capstan rotation, and wire tension. (Cutting wheel requires force applied).
- Possibility of wire break must be addressed
- Wire wear rate must be quantified.

Cutting Wheel Pros:

- Higher reliability
- Higher total volume of cutting media.
- Simpler control (only contact force required)

Cutting Wheel Cons:

- Higher power requirements.
- Larger kerf → more dust generation.
- More heating during cutting.
- Requires more degrees-of-freedom to cut in multiple planes, relative to wire.
- Wheel diameter determines size of sample that can be cut

TABLE II: CUTTING METHOD ATTRIBUTE COMPARISON

Attribute	Diamond Wire	Cutting/Grinding Wheel
Overall Size	(4)	(2)
Kerf	(5) Small approximately 1/10th that of wheel cutter	(2) Equal to wheel thickness +
Dust generation	(4) Minimal	(2) Significant
wear rate	(3)	(5)
Predicted reliability	(3)	(5)
Maintainability	(2) Reel replacement system will be complex. Rewiring mechanism also complex	(4) Simple tool changer design could allow for replacement of wheel
Overall System Inertia	See Overall Size above. 2 reels, or 2 pulleys plus capstan	Blade Thickness/Diameter
Minimum Power Requirement	Low draw force (5)	Larger torque motor required (3)
Axis required for "straight cut"	(4)	(3)
Orthogonality of cut	(3)	(4)
Flexibility of Cut Depth	(5) Wire pulleys can be adjusted for different size rocks	(2) No flexibility, only able to cut to wheel radius - needed shaft clearance
Thermal buildup in machine	(5) Wire has small mass, low repeated contact time, minimal thermal buildup	(3)
Ability to cut orthogonal to cut plane	(4)	(0) not possible

Since the cutting wheel method has been widely used and is relatively well understood, the initial focus of this research has been on evaluating the use of diamond wire as a new alternative method for rock cutting for thin section tablets. This is motivated by its promise for lower weight, greater flexibility and lower power requirements.

B. Creating a specimen table from a rock sample with Diamond Wire

The process of cutting a specimen tablet consists of the following: Fixture the rock in a "vise" in the proper orientation to allow a tablet to be cut from it at the location and orientation (pose) desired (as dictated by the exploration geologists or other science officer, or rover onboard program).

Fig. 4 shows a concept for the initial staging of a rock sample in preparation for its being slabbed to produce a tablet. The rock is placed in a special "vice" that has passive compliant fingers which individually contact the rock sample and apply force. The matrix of fingers is used to stabilize the rock in spite of its asymmetric shape. There will be limits to the size and shape that can be stabilized but in general the vise will be capable of holding a variety of samples. One of the benefits of the wire cutting technique is the low draw force required, thus making the sample retention system requirements less stringent.

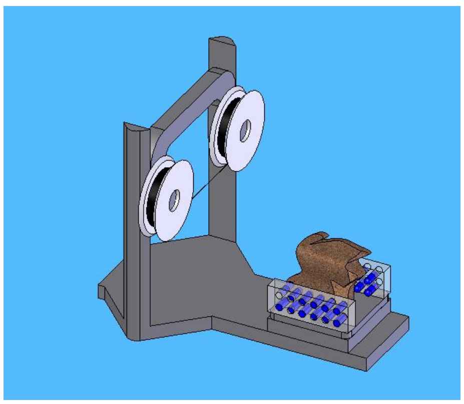
Fig. 4. Rock sample gripped in vise

In Fig. 5 the vise has been indexed into position below the diamond wire cutter, here portrayed as a set of spools (reels), but it could also be a single capstan arrangement.

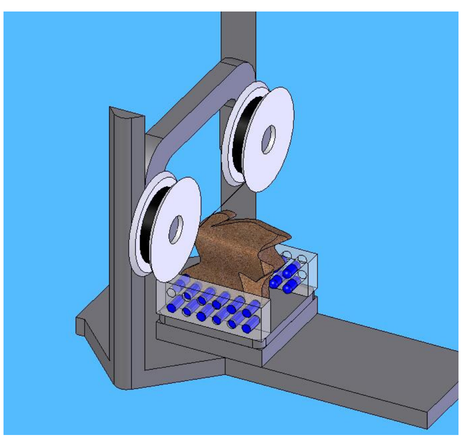
Fig. 5. Rock sample positioned below wire cutting mechanism

In Fig. 6, the two dimensioning cuts have been completed as well as the rough surface cut of the top face of the tablet. Note all of these cuts can be accomplished without having to reorient the sample. In Fig. 7, the sample has been rotated 90 degrees about the vertical axis so that the two orthogonal depth cuts can be made.

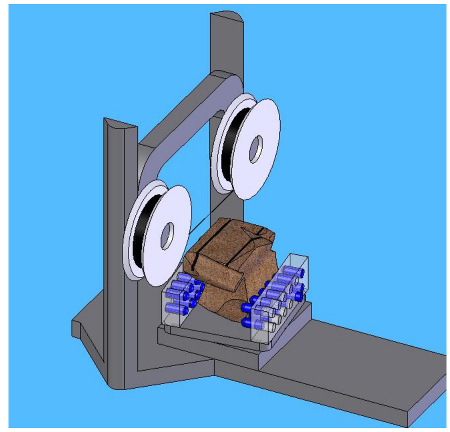
Fig. 6. Two depth cuts and facing cut have been completed

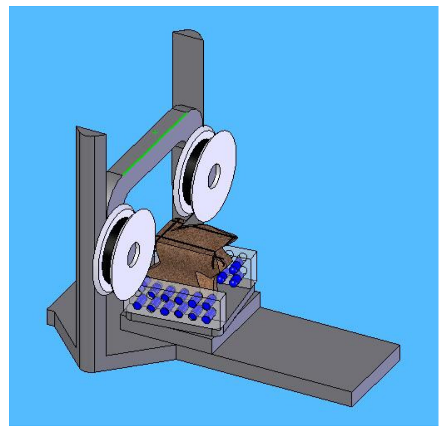
Fig. 7. Sample is rotated 90 degrees in preparation for orthogonal depth cuts

As shown in the Figs. 4-7, two parallel depth cuts and one surface cut can be completed before the sample has to be reoriented (no re-fixturing required). The two orthogonal depth cuts are completed and then the lower face cut is executed without having to do any more reorientation. The shorter (full-through) cut should be saved for last since the potential for vibratory excitation of the sample is thus minimized. The important characteristics of these cuts are: straightness, flatness, and smoothness. The use of the diamond wire cutting technique facilitates this simplified manipulation of the sample. It also minimizes the kerf and dust generated, and reduces the power required.

V. Adhesive & Support Application

Traditional thin section preparation requires several consumable materials (microscope slides, epoxies, grinding paste, and cover glass slide) and multiple handling steps. Adaptation of the thin section into the space environment will require simplifying sample processing without significantly sacrificing section quality. To reduce consumables we are investigating the following:

1. Polishing to sufficient surface finish such that a cover slide is unnecessary.
2. The "self supported" thin section.

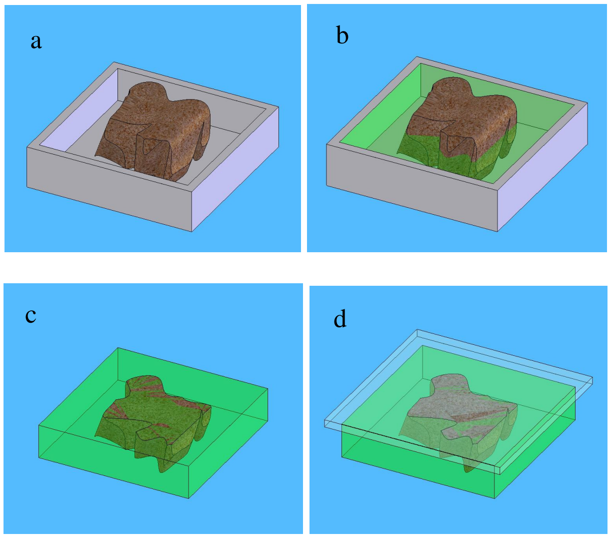

Fig. 8. Conceptual preparation of adhesive and microscope slide to a rock fragment: a) rock fragment in the adhesive mould, b) adhesive dispensed in mould, c) fragment and adhesive cut to tablet, d) a microscope glass slide applied.

Fig. 8. shows the steps for adhesive application to a rock fragment and a microscope slide. The rock fragment is inserted into an adhesive application mold. Adhesive is then dispensed into the mould and set. UV activated epoxy is a possible adhesive. The adhesive/sample is removed from the mould and cut in the rough cutter, facing one side. On the faced side a microscope glass slide is adhered by additional epoxy.

To further reduce consumables we propose the concept of a "self supported" thin section pre-form as shown in Fig. 9. The self supported thin section would eliminate the glass slide and depending on the fracture toughness and consolidation of the rock sample may eliminate or reduce the volume of epoxy needed. The central thin section region (~1cm^2) would be supported by surrounding rock left intact in grinding and polishing phases of preparation. The rock profile would transition from thick wall to thin section gradually to minimize strain through the transition. The thick wall provides a gasping surface for handling of the sample and support to the thin section. The rock may need added strength for the thin section to survive caching, especially if poorly consolidated or highly fractured. A thin layer of adhesive applied to the back before thin section cutting would provide strength if needed.

The self-supported concept can be extended to rock fragments, regolith, and dust samples by immersion of the sample in an adhesive mold, matching the "table" pre-form prior to thin section grinding. Such samples would be primarily supported by adhesive, hence "fixtured" by adhesive as shown in sequence in Fig. 8.

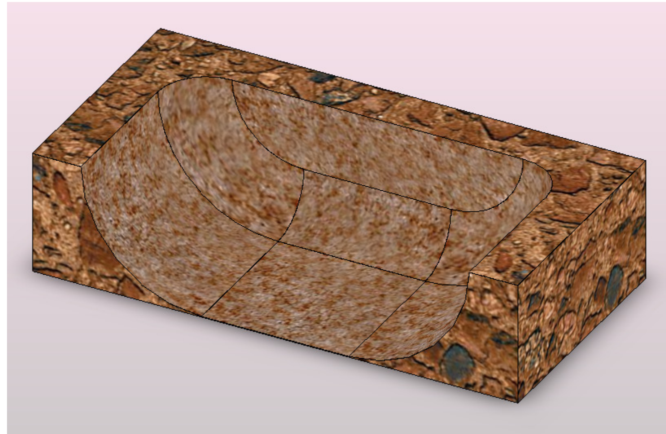

Fig. 9. Cross section of self-supported thin section concept.

VI. Fine Grinder and Polisher

There are at least two fundamental differences between producing thin sections on extraterrestrial bodies and producing thin sections on Earth. The first one involves robotic grinding and polishing as opposed to this process being done by a qualified thin section expert, and the seconds one is dry grinding as opposed to wet grinding and polishing on Earth.

Autonomous grinding and polishing will involve grinding a rock tablet to the thickness of approximately 30 microns and then using a polishing section (if necessary) to obtain a surface roughness of approximately 1 micron or better. The quality control on Earth is performed by a thin section expert (the technician inspects the thin section under optical reflective and transmitting microscopes), whereas on an extraterrestrial body, this would have to be performed via actual measurement of the rock thickness and the surface roughness.

On Earth, cutting fluids are widely used to assist with various grinding, drilling, and machining processes by removing newly formed debris and cooling the tool and the material. Also, abrasive powders made from Silicon Carbide or Aluminum Oxide can be mixed with water to create a slurry for producing a polished finish. However, lubrication will not be available when performing the same processes on most extraterrestrial bodies. This is because the transportation of fluid will be prohibitively expensive and most atmospheres or lack of it (vacuum) will not support fluids (at low pressures fluid will turn into solid or gas, depending on temperature). Because of the limitations discussed above, a dry process for creating thin sections is being investigated.

A. Approach for Testing Concepts

Initial brainstorming sessions lead to the development of a number of different grinding concepts. These concepts were narrowed down to two that are commonly used in grinding processes on Earth. These are plunge grinding and side grinding. The abrasive wheels used to test the two grinding methods are shown in Fig. 10.

Fig. 10. Cylinder and Straight style grinding wheels.

During initial testing, these wheels were used in a standard surface grinder. The goal was to determine the achievable surface finish as a function of diamond grit size within the abrasive wheel.

As an initial mock-up for grinding a thin section, a sample of basalt was cut into a tablet and epoxied to a ground stainless steel bar as shown in Fig. 11. These steel bars were then mounted to the vice of a Brown & Sharpe surface grinder. The grinder allowed the sample to be held rigidly (via a magnetic table) to a three degree of freedom platform. The off the shelf grinding wheels shown in Fig. 10, were mounted to the surface grinder and were used to grind the rock tablets. The surface roughness of the ground rock tablet was then assessed using a hand held Hommel T500 profilometer and the results are tabulated in Table 1. It can be seen that the surface roughens of ~ 1 micron may be achieved with a grit of 180 or better. A wheel with this grit might be also used for a grinding process. (Note that the results for the electroplated diamond wheel are misleading since this type of wheel needs to be broken-in to achieve optimum performance). It is therefore conceivable that grinding a rock tablet to a thickness of 30 microns and surface roughness of ~ 1 micron might be possible with a single abrasive wheel.

Fig. 11. Basalt rock tablet mounted to Ground Stainless Steel Bar.

TABLE III

SURFACE FINISH FOR VARIOUS COTS GRINDING WHEELS

Wheel Type	Grit	Wheel Description	Ra. (μm)
Cylinder	100	Electroplated Diamond Coated	1.7-2.5
Cylinder	320	Electroplated Diamond Coated	3.0–3.5
Cylinder	150	Resin-bond with synthetic diamond	1.2–1.4
Straight	150	Resin-bond with synthetic diamond	1.4
Straight	180	Resin-bond with CBN	1.3
Straight	600	Resin-bond with CBN	0.7-0.8

B. Model of Prototype

Given the encouraging results form the Brown & Sharpe surface grinder, it is highly probably that a smaller surface grinder could be a solution for this application. The grinder would have to operate autonomously (this would include autonomous grinding/polishing of a variety of rocks to a thickness of 30 to 38 microns and surface roughness of around 1 micron). This means that a quality control station will be necessary for measuring the rock thickness and surface roughness. Having these dedicated quality control stations will allow the system to account for inaccuracies caused by wheel wear and to some extent, system compliance. Also, a number of various types of grinding wheels could be tested and characterized throughout their life cycle.

A model of the prototype system is shown in Fig. 12. This system is comprised of three stations. These are the grinding/polishing station, thickness measurement station, and surface finish measurement station. The prototype system is also designed so that the grind station can be oriented to grind with either the cylinder or straight type grind wheels. The tablet holder is mounted to a load cell to provide information on the force with which the wheel is pressing against the rock and in turn the grind pressure. The load cell is mounted to a precision linear lift stage with a resolution of 0.2 microns. Finally, this stage is mounted to an X stage for tablet transfer between the stations and possible oscillatory motion (back-forth) during a grinding process.

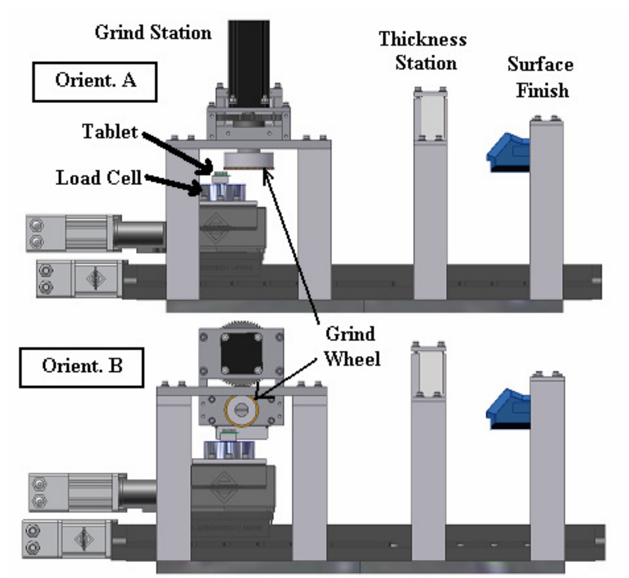

Fig. 12. Automated Thin Section Prototype showing two orientations of grind wheels and various stations.

C. Self Supporting Sample Concepts

The most important development centers on the system and method for producing self supported thin sections. If a technique and design for grinding self supported thin section is shown to be successful, this would potentially eliminate the need, at least for certain rock types, for using adhesive for mounting samples to glass slides. Not only is epoxy an expendable resource, but also requires additional mechanical actuators for applying it to the rock tablets. Also, most epoxies are organic, which would produce a cross contamination concern.

There are a few concepts which will be tested. One of them is shown in Fig. 13. The idea presented by this concept would first involve clamping the tablet to a steel or aluminum holder. Next, an appropriately shaped grinder would grind a “boat” shape into the center of the tablet, leaving the rest of the sample in-tact. A solid window made from a transparent to light and hard material, will be embedded, or bonded to the steel or aluminum holder. This is required to provide support for the sample during the grinding process and to provide a place for illuminating the tablet during petrographic analysis. Once documented, the tablet can be disposed of, and the holder can be reused.

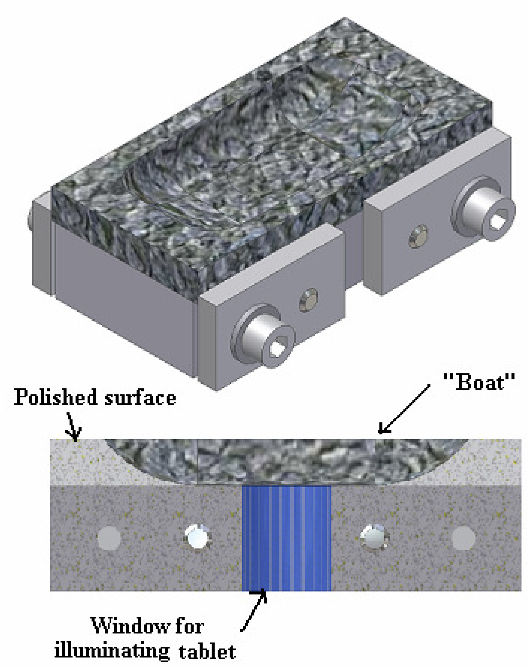

Fig. 13. Concept for Testing Self Supported Thin Section.

VII. Dust Generation, Mitigation, and Cross Contamination

Cross contamination safeguards and removal of discarded cuttings and rock dust was identified as a major hurtle for this device development work. The final device would likely contain several sealed sections to isolate rough cutting, adhesive application, and grinding/polishing units from each other and isolate the entire sample handling device from the rest of the rover (or lander). Sealing of sensitive mechanisms like gearboxes, lead screws, motors, etc. from dust are also needed. The starting point for future development of practical dust mitigation and cross contamination prevention technologies is the characterization of dust generated in the cutting, grinding, and polishing systems developed. A series of dust size measurements for different loading conditions, samples, etc. will be made. The information gathered will feed into future or current sample handling technology development projects.

VIII. Conclusion

Traditional thin section preparation is more an art than a science. Preparation is labor intensive with multiple handling steps, several consumables, and requires tending by a preparer skilled in the geological sciences. As on earth, a thin section of a sample acquired on another planetary body would be useful for the identification of minerals and their structural aspects (cleavage, fractures, mineral zoning) and rock microtextures that indicate the mode of formation of the rock (igneous, metamorphic, sedimentary). The Solar System Exploration Roadmap identified *in situ* Science Instruments development as an area of “highest priority”. Among *in situ* instrumentation, sample acquisition and sample preparation was specifically identified as enabling for missions to locations where sample return is impractical. The Automated Rock Thin Section device development is advancing the technology of sample handling and sample preparation for space exploration.

In this paper we have reviewed our research plan, rock requirements work, and progress on development of major device units: Rough Cutter, Adhesive and Support, Grinding and Polishing, and Dust Mitigation/Cross Contamination. We are focusing our efforts on major technical hurtles with the goal of raising the TRL level of each major unit to TRL 3.

Acknowledgment

We gratefully acknowledge the assistance of Dr. Rongjie Song for preparation of the profilometry data.

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