INVESTIGATION OF MACHINING METHODS OF ROCK SAMPLES IN LUNAR VERTICAL HOLES AND LAVA TUBE FOR UZUME PROJECT. K. Furutani[1] and J. Haruyama[2], [1]Toyota Technological Institute, 12-1, Hisakata 2-chome, Tempaku-ku, Nagoya 468-8511 Japan, furutani@toyota-ti.ac.jp, [2]Institute of Space and Aeronautical Science, JAXA, 1-1, Yoshinodai 3-chome, Chuo-ku, Sagamihara, Kanagawa 252-5210 Japan.

Introduction: When data acquired by KAGUYA were analyzed, large vertical holes were discovered on the Moon surface [1]. In addition, the data analyzed further suggested that each of them is a part of lava tubes extending horizontally [2]. Although the objective will be mainly observations in the first step of UZUME (Unprecedented Zipangu Underworld of the Moon Exploration) project for explorations of the vertical holes, inspection technologies including machining methods for a preprocess will be demanded in later steps. In this report, machining devices are introduced and troublesome phenomena during machining in vacuum are discussed.

Examples of Machining Devices: Although many machining devices for lunar, planet and asteroid explorations have been proposed, few have been tried to use in high vacuum [3, 4]. Augers [5] are not preferable for sampling hard rocks which possibly crop out on the wall and floor of the lava tubes. A roughness below 50-100 μm is preferable for X-ray fluorescence [6]. The consumed energy restricts the removal rate. Because solar cells can provide low peak power, secondary batteries are needed. Table 1 shows comparisons of machining method for lunar explorations.

Impact (percussive). Figure 1 shows an example of impact type crusher driven with a solenoid [3]. A small sample can be also broken out from a large rock. Tough and hard materials such as tungsten carbide is used for tools to bear large impulsive force. Debris should be promptly removed by shifting machining position [3] or brushing to avoid absorbing the impulsive force. Rocks has larger compressive toughness than share one. The lateral impact applying the share stress can smoothen the waviness as well as the debris [7]. The device should be mechanically isolated to avoid exciting the instruments.

Ultrasonic vibration. Because the energy conversion efficiency of ultrasonic transducers is not generally so high, a bolted-Langevin transducer (BLT) is often used at a mechanical resonance frequency. An aluminum horn is attached to an end of the BLT to amplify the vibration for machining rough surface [8]. A vibrator with a free mass has been proposed [9] to avoid varying resonance frequency by pressing the device onto a rock. These restrict the device length.

Grinding wheel. Although a grinding wheel has many cutting edges [10] and the machining force does not pulsate, the grinder often chatters in the case of holding with a flex arm. The debris are easily loaded on a rigid grinding wheel by the electrification.

Wire-sawing. Diamond abrasives are electroplated with nickel on a thin carbon steel wire. The interior of a rock sample can be directly observed after wire-sawing. Figure 2 shows a wire-sawing machine [4]. A saw wire is reciprocally fed with two reels. Figure 3 shows examples of wire-sawing in vacuum at 10^{-3} Pa. The cutting depth was saturated due to the adhesion of nickel for fixing the diamond abrasives on the saw wire. A through system has been proposed and tested only in air [11].

Applicable range of surface roughness. Figure 4 shows the ranges of surface roughness before and after machining. The surface can be smoothened by grinding and wire-sawing even though the initial surface is very rough [4]. A holding device for a crude rock sample such as a vise for odd shapes is also a key component.

Table 1 Comparisons of machining method (A: excellent, B: good, C: fair, D: poor)

	Impact (normal) [3]	Impact (lateral) [7]	Ultrasonic vibration [8]	Ultrasonic vibration with free mass [9]	Grinding wheel [10]	Wire-sawing [4]
Roughness	B	B	A	C	A	A
Machining time	B	C	C	B	A	B
Size and weight	B	A	B	B	C	C
Consumed energy	A	A	B	B	C	C
Heat generation	B	B	B	B	C	B
Vacuum compatibility	A	A	A	A	B	B
Simple structure	B	A	A	C	C	D
Duration	B	C	B	B	C	A
Overall	Component inspection	Structure observation	Component inspection	Rough sampling	Precision observation	Precision observation of interior

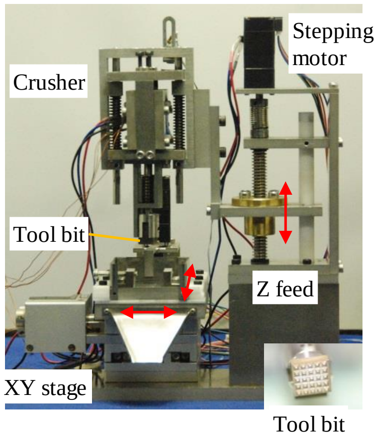

Fig. 1 Impact type crusher [3]

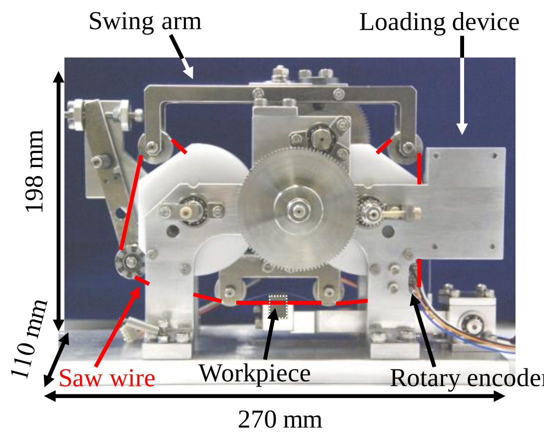

Fig. 2 Wire-sawing machine [4]

Phenomena during machining rocks in vacuum: A resin-bonded grinding bit was used in Rotary Abrasion Tool [10] cooled by convection of rarefied atmosphere on Mars. However, any coolant cannot be used on the Moon. The diamond abrasive carbonizes over 600°C. Phenolic resin used as a bond softens around 130°C. Therefore, the softening temperature of the bond restricts usable conditions. Though the softening temperature of electroplated nickel also used as a bond is higher than the resins, it often adheres on the rock during machining in vacuum [12]. The heat is also generated in actuators to drive the tool [3]. Because no convection is expected in vacuum, the heat should be conducted to the surface of the lava tubes through the housing.

SiO_2 contained in rocks generate electric charges under high stress due to piezoelectricity [13]. Even if a rock is initially neutral, both the positive and negative charges are generated when it is crashed [14] or rubbed [15]. The charged debris caused loading on the tool and wearing of components in the machining devices.

Though a machining device should be pressed on the rock over the reactive force, it is often hard to generate the pressing force by its weight due to the small gravity [16].

The status of the devices and systems should be monitored to solve these problems.

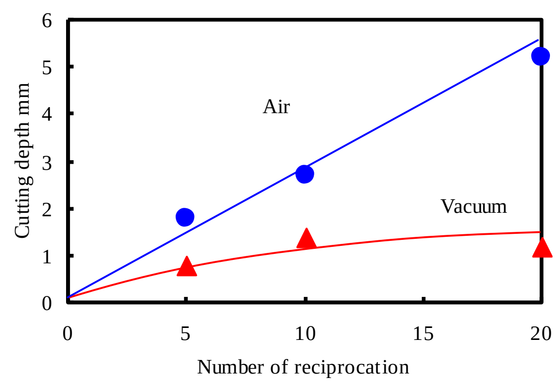

Fig. 3 Progress of cutting [4]

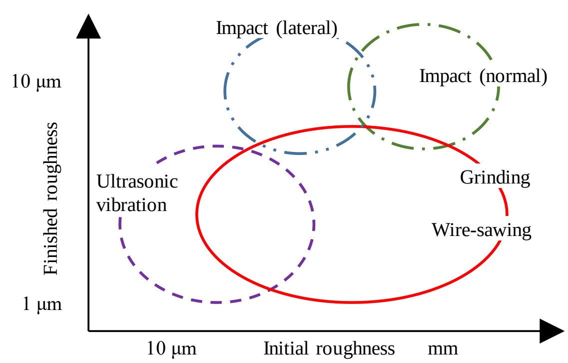

Fig. 4 Applicable range of roughness

References: [1] Haruyama J. et al. (2016) *Trans. JSASS, Aerospace Technol. Jpn. 14, ists30*, Pk_147-Pk_150. [2] Kaku T. et al. (2017) *GRL, 44, 20*, 10,155–10,161. [3] Furutani K. et al. (2017) *J. Rob. Mechatron., 29, 5*, 911-918. [4] Furutani K. et al. (2013) *Mater. Sci. Forum, 773-774*, 392-399. [5] Zacny K. et al. (2015) *46th LPSC*, 1614. [6] Maruyama Y. et al. (2008) *Earth. Planets. Space., 60, 4*, 293–297. [7] Furutani K. et al. (2016) *Int. J. Autom. Technol., 10, 4*, 533-539. [8] Tada K. et al. (2003) *47th Space Sci. Technol. Conf.*, 1489-1490. [9] Bao X. et al. (2003) IEEE Trans. UFFC, 50, 9, 1147-1160. [10] Gorevan S. P. et al. (2003) *JGR, 108, E12*, ROV9-1 - ROV9-8. [11] Paulsen G. et al. (2013) *Adv. Space Res., 51, 11*, 2181-2193. [12] Furutani K. et al. (2018) *33rd Ann. Meet. ASPE*, 273-276. [13] Bespal'ko A. A. et al. (2007) *J. Mining Sci., 43, 5*, 472–476. [14] Jakubiszyn S. et al. (1962) *J. Appl. Phys., 33, 7*, 2224-2226. [15] Tomizawa I. (1995) JGG, 47, 3, 313-324. [16] Jiang B. et al. (2017) *J. Terramech., 71*, 1-13.