JASMAC

Conference of the Japan Society of Microgravity Appllication

OS2-11

月面でのその場資源利用に向けたレゴリス系融体の電解試験および熱物性計測

Electrochemical and thermal measurements of regolith-based melts for in-situ resource utilization on the Moon

鈴木祐太 [1*]、小畠秀和 [1]、後藤琢也 [1]、田中聖也 [1]、福中康博 [2]、石川毅彦 [3]、小山千尋 [3]、行松和輝 [3]
Yuta SUZUKI[1], Hidekazu KOBATAKE[1], Seiya TANAKA[1], Takuya GOTO[1], Yasuhiro FUKUNAKA[2] , Takehiko ISHIKAWA[3], Chihiro KOYAMA[3], and Kazuki YUKUMATSU[3]

[1] 同志社大学，Doshisha University
[2] 京都大学，Kyoto University
[3] 宇宙航空研究開発機構，Japan Aerospace Exploration Agency

* Correspondence: yusuzuki@mail.doshisha.ac.jp

1. Introduction

To realize sustainable human activities on the Moon, it is essential to establish in-situ resource utilization processes on the lunar surface. Lunar regolith, composed of metal oxides[1)] as shown in Table 1, can be reduced to obtain valuable metals and oxygen. Electrochemical processes, which are driven by electrical power, offer the advantage of not requiring the transportation of reducing agents such as carbon from Earth to the lunar surface. As part of research on the reduction of lunar regolith using electrochemical processes, several research groups have reported experiments on the electrolytic recovery of metals from molten regolith[2-4)]. This method offers advantages in terms of ease of procurement on the lunar surface and simplicity of electrolyzer setup. However, there are concerns regarding the tendency for the melt composition to become imbalanced as electrolysis progresses, leading to an increase in the melting point and viscosity.

Table 1. Typical range of weight fractions of principal metal oxide components in lunar regolith[1)] .

Components	SiO_2	FeO	Al_2O_3	CaO	MgO	TiO_2	Na_2O
Lunar regolith	43–47%	5–16%	13–27%	10–15%	6–11%	1–4%	< 1%

Here, we propose an electrolytic melt with a new composition consisting of a mixture of lunar regolith and a fluoride salt[5)]. Compared to a melt containing sole molten lunar regolith, a system mixed with halide salts has physical properties that are advantageous for electrolysis, such as a lower melting point and viscosity. In this study, CaF_2 is used as the halide salt. CaF_2 can be obtained from fluorapatite, which is a lunar mineral and exists in concentrations of 3.0-3.8 wt.%[6)]. Therefore, it is possible to construct an electrolytic melt that is more suitable for electrolysis using only minerals found on the Moon. This study investigated the fundamental electrochemical behavior aimed at recovering metals from lunar regolith using electrochemical processes, and discusses plans for thermal property measurements using the electrostatic levitation furnace (ELF) in the Kibo module of the International Space Station (ISS).

2. Experiments

FJS-1, which has a composition similar to that of the excavated samples from Apollo 14, was used as a lunar regolith simulant for the experiment. The composition of the metal oxides that make up FJS-1[7)] is shown in Table 2. The melting point of the FJS-1 and CaF_2 mixture was measured using TG-DTA. Electrochemical measurements were performed using a three-electrode system, and the metals obtained by electrolytic reduction were analyzed by SEM and EDS. As a test using a levitation device, a gas jet-type levitation test was conducted on spherical samples after laser heating.

Table 2. The weight fractions of metal oxide components in FJS-1[7].

SiO_2	Al_2O_3	CaO	FeO	Fe_2O_3	MgO	Na_2O	TiO_2	K_2O	P_2O_5	H_2O	MnO
49.1	16.2	9.1	8.3	4.8	3.8	2.8	1.9	1.0	0.44	0.43	0.19

3. Results and Discussion

TG-DTA and electrochemical measurements clarified the fundamental thermal and electrochemical properties of FJS-1 and CaF_2[5]. The differential thermal analysis curves measured for various compositions of FJS-1 and CaF_2 found that the eutectic temperature was 1275 K at FJS-1:CaF_2=90:10 wt.%, which is lower than the melting point of FJS-1, 1393 K. Furthermore, electrochemical measurements also revealed the reduction behavior of FJS-1:CaF_2=80:20 wt.%, demonstrating that Al and Si derived from FJS-1 can be recovered by electrolysis.

In a levitation experiment on the ground, we conducted a levitation experiment of molten regolith simulant using a gas jet levitation device heated by a semiconductor laser. It has been confirmed that melting and levitation without sample volatilization is possible. We also conducted similar tests using CaF_2-containing samples and investigated the deliquescence of each sample.

The results of this research project will provide knowledge that will contribute to the establishment of a unique lunar resource utilization process and contribute to the realization of manned activities on the Moon.

References

1) G. H. Heiken, D. T. Vaniman, B. M. French, Lunar Source Book, Cambridge University Press, 1991.
2) K.D. Grossman, L. Sibille, E. Bell, E. Petersen, J.A. Toro Medina, H. Williams, T. Newbold, K. Zacny, I. Bates, GaLORE (Gaseous Lunar Oxygen from Regolith Electrolysis): Technology Advances for a Cold-Walled Molten Regolith Electrolysis Reactor, in: ASCEND 2021, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2021. DOI: 10.2514/6.2021-4019.
3) S.S. Schreiner, L. Sibille, J.A. Dominguez, J.A. Hoffman, A parametric sizing model for Molten Regolith Electrolysis reactors to produce oxygen on the Moon, Advances in Space Research 57 (2016) 1585. DOI: 10.1016/j.asr.2016.01.006.
4) A.H. Sirk, D.R. Sadoway, L. Sibille, Direct Electrolysis of Molten Lunar Regolith for the Production of Oxygen and Metals on the Moon, ECS Trans 28 (2010) 367–373. DOI: 10.1149/1.3367929.
5) Y. Suzuki, S. Tanaka, T. Goto, Thermal and Electrochemical Properties of a Mixture of Lunar Regolith Simulant (FJS-1) and CaF_2, Planet. Space Sci., 266 (2025) 106177. DOI: 10.1016/j.pss.2025.106177.
6) L.H. Fuchs, Fluorapatite and other accessory minerals in Apollo 11 rocks, Proceedings of the Apollo 11 Lunar Science Conference 1 (1970) 475.
7) H. Kanamori, S. Udagawa, T. Yoshida, S. Matsumoto, K. Takagi: Properties of Lunar Soil Simulant Manufactured in Japan, in: Space 98. American Society of Civil Engineers, Reston, VA, , (1998) 462. DOI: 10.1061/40339(206)53