Electron Beam Additive Manufacturing of Aluminum Derived from a Lunar Highlands Regolith Simulant X. Walls[1], A. Ellery[2], S. Sarafan[3], J. Gholipour[4], K. Marczenko[5], P. Wanjara[6]. [1]Carleton University, Department of Mechanical and Aerospace Engineering. 1125 Colonel by Drive, Ottawa, ON, Canada. K1S 5B6 and National Research Council of Canada, Aerospace Research Center, 2107 chemin de la Polytechnique, Montréal, QC, Canada. H3T 1J4; e-mail: xavierwallsperez@cmail.carleton.ca. [2]Carleton University, Department of Mechanical and Aerospace Engineering. 1125 Colonel by Drive, Ottawa, ON, Canada. K1S 5B6; e-mail: alexellery@cunet.carleton.ca. [3]National Research Council of Canada, Aerospace Research Center, 2107 chemin de la Polytechnique, Montréal, QC, Canada. H3T 1J4; e-mail: Sheida.Sarafan@cnrc-nrc.gc.ca. [4]National Research Council of Canada, Aerospace Research Center, 2107 chemin de la Polytechnique, Montréal, QC, Canada. H3T 1J4; e-mail: Javad.GholipourBaradari@cnrc-nrc.gc.ca. [5]Carleton University, Department of Chemistry. 1125 Colonel by Drive, Ottawa, ON, Canada. K1S 5B6; e-mail: katherinemarczenko@cunet.carleton.ca. [6]National Research Council of Canada, Aerospace Research Center, 2107 chemin de la Polytechnique, Montréal, QC, Canada. H3T 1J4; e-mail: priti.wanjara@cnrc-nrc.gc.ca.

Introduction: As space agencies and private-sector initiatives plan extended missions to the Moon and beyond, in-situ resource utilization (ISRU) becomes a crucial strategy for sustaining operations without depending on Earth-based supply lines. Transporting large quantities of materials to the lunar surface is prohibitively expensive due to launch costs and payload limitations. Therefore, developing methods to harvest and process local resources offers substantial logistical and economic benefits.

Lunar regolith, particularly from the highland anorthositic regions, is rich in aluminum-bearing minerals, mainly anorthite ($CaAl_2Si_2O_8$). It is possible to sustainably extract silica (SiO_2) and alumina (Al_2O_3) from $CaAl_2Si_2O_8$ using an acid leaching method with hydrochloric acid (HCl) [2]. Afterwards, Al_2O_3 can be electrochemically reduced to metallic Al using calcium chloride ($CaCl_2$) as the electrolyte [3,4] (i.e., approach based on the Fray Farthing Chen (FFC) Cambridge process [5]). Inert electrodes can be used to release O_2, critical for a sustained presence on the Moon. The resulting Al from the electrochemical process can be formed into a wire spool to be used as a viable feedstock for electron beam additive manufacturing (EBAM) on the Moon.

EBAM offers several advantages for the lunar environment [6]. Because EBAM inherently relies on a high-vacuum chamber and a network of vacuum lines and diffusion/turbo pumps, the natural vacuum environment on the lunar surface potentially reduces the complexity of maintaining stable electron beam conditions. EBAM is also an energy-efficient manufacturing process where the electron beam is used for localized melting, minimizing heat loss and leveraging on the high vacuum environment for the rapid heat transfer from electrons into the metal. Additionally, Al extracted on-site can be processed into feedstock for its use in the EBAM process. The directed energy deposition approach using EBAM reduces energy and material waste while enabling near-net-shape production, critical when resources are limited. Moreover, the process is highly scalable, allowing for the manufacturing of small components or large structures as needed.

This study presents the results obtained from EBAM of an Al wire produced through a multi-step process: the extraction of Al_2O_3 from $CaAl_2Si_2O_8$, the electrochemical reduction of Al_2O_3 to metallic Al, and the processing of the produced Al into a wire feedstock.

Materials and Methods:

Beneficiation and Acid leaching Pre-processing.

A lunar highlands simulant (LHS-1) was magnetically beneficiated to remove any Fe-rich material. The beneficiated simulant was leached in a concentrated HCl solution (38%) at 94°C for 4 hours. The supernatant solution was separated from the remaining precipitate using a centrifuge. The solids were dried at 150°C for an hour and were analyzed for the presence of SiO_2. The supernatant solution was sparged with HCl gas, forcing the precipitation of aluminum chloride hexahydrate crystals ($AlCl_3 \cdot 6H_20$) (ACH). The ACH was separated from the remaining supernatant using a centrifuge and calcined at 250°C for two hours followed by 800°C for two hours.

Electrolysis of Al_2O_3 to metallic Al.

The electrolysis experiments were carried out in a kiln-type furnace. A stainless steel retort was placed in a heating chamber with an Al_2O_3 reaction crucible inside. The crucible was filled with pre-dried $CaCl_2$, obtained from the pre-processing of anorthite, and sealed with the electrodes suspended above the reaction crucible. The temperature was ramped up to 850°C, reaching the melting point of the $CaCl_2$ and maintained under an Argon (Ar) atmosphere for several hours to remove any residual H_2O absorbed during handling. Then, the temperature was increased to 950°C, at which point, the cathode, anode, and thermocouple were lowered into the molten electrolyte. The current was gradually increased in the cell and the reaction was carried out at a voltage between 3 and 4 V. The reactor was continually monitored to replenish the electrolyte as required. The reaction took place for 24 hours.

Forming of the produced Al into EBAM wire feed-stock.

Al produced from the electrochemical process was melted and fluxed with N_2. The slag on the surface was scraped off. Then, the molten Al was cast into a cylindrical mold and allowed to slowly cool down to room temperature. The Al ingot produced was cold forged by hammering to obtain a square cross section. Then, the sample was rolled several times until the cross section was small enough to fit into the drawing die. The tip was sanded and lubricated with a MoS_2 suspension. Finally, the sample was drawn several times until a cross-sectional diameter of 1.6 mm was achieved.

Wire-fed EBAM experiments.

Deposition trials were performed using a Sciaky W2000 EBAM machine. Different process trials were performed using a commercial Al wire spool to determine the best deposition parameters (voltage, current, beam focus, beam oscillation, scan speed, and wire feed rate). Once the process was stabilized, the electrochemically produced Al wire was tested in the EBAM machine. Small demonstrators were printed with the objective of showcasing the ability of this process to manufacture storage tanks for cryogenic material on the Moon. After printing of demonstrator parts, they were removed from the build plate using electrical discharge machining (EDM) followed by milling to net shape. The parts were then assembled using electron beam welding (EBW) that was also undertaken within the EBAM chamber.

Results:

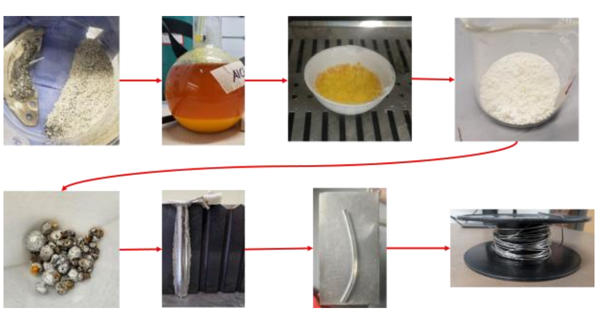

Figure 2. Main Steps to produce an Al wire from an LHS-1 simulant. Following the sequence indicated by arrows: 1. Beneficiation, 2. Leaching, 3. Separated ACH crystals, 4. Calcined Al_2O_3, 5. Electrochemically produced Al, 6. Casting, 7. Rolling, 8. Al wire spool after drawing.

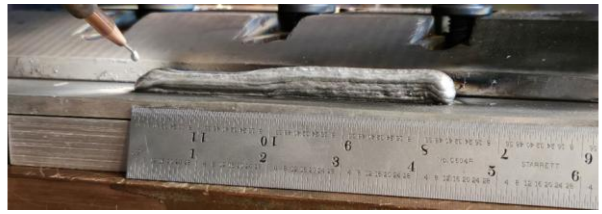

Figure 3. Deposition of Al wire. It was possible to successfully deposit 6 layers of material in a straight line, forming a wall-type structure.

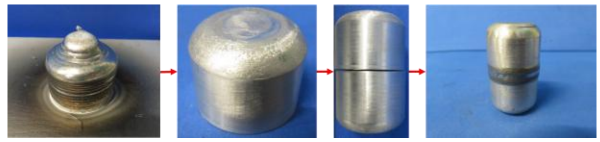

Figure 1. EBAM of tankage demonstrators. Following the sequence indicated by arrows: 1. Material as-deposited on the build plate (without post-processing). 2. Part removed from the build plate and machined to improve the surface finish. 3. Pre-weld assembly of two EBAM parts. 4. Finished demonstrator fabricated by EBW.

Conclusions: All the critical steps for the manufacturing of Al parts on the Moon have been demonstrated starting from obtaining the metal from natural resources up to the transformation of raw metal into functional parts. The main stages of the process can be summarized as follows:

1. Beneficiation	7. Casting
2. Leaching	8. Processing (Rolling and drawing)
3. Separation	9. Additive Manufacturing (EBAM)
4. Calcination	10. Post-processing (EDM+Milling)
5. Electrolysis	11. Joining (EBW)
6. Fluxing	

EBAM is a reliable option for manufacturing parts on the Moon. This process allows to reduce waste material, produce near-net shaped components and structures, and minimize energy consumption by localizing the energy in an electron beam.

References:

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