ADDITIVE MANUFACTURING OF IRON AND STEEL ALLOYS DERIVED FROM LUNAR REGOLITH: TESTS ON REDUCED SIMULANT AND ANALOG ALLOYS

P. E. Corwin[1] [1]Colorado School of Mines, Center for Space Resource, 1500 Illinois St., Golden CO, 80401, pecorwin@mines.edu

Introduction: The reduction of lunar regolith for in-situ resource utilization (ISRU) has been studied since shortly after samples were returned from the Moon [1-3]. However, most laboratory work has focused on the extraction of oxygen for propellant and life support, with limited work on the characterization, purification, or properties of the produced metal alloys. Under a Post-Phase II NASA SBIR, Pioneer Astronautics' Moon to Mars Oxygen and Steel Technology (MMOST) is currently developing a system for extraction of iron and oxygen from lunar regolith using hydrogen reduction. This presentation focuses on the work at Colorado School of Mines (CSM) to characterize the iron or steel product produced from the MMOST system and to develop the processes needed to convert them to useful components.

Characterization and Analogous Alloy Selection: Samples of reduced iron were taken at several steps in the process. Metallurgical samples were mounted, polished, and etched to examine microstructure. Samples were also examined under scanning electron microscope to observe and characterize inclusions found within the sample. While terrestrial minerals are not precise matches to lunar minerals, the samples were found to be close to pure iron, with little to no silicon within the metallic material. Iron oxide inclusions were observed within the sample but were small and disperse enough to not lead to negative effects in downstream processing.

To increase the quantity of material available for testing, a series of material analogs were selected of varying fidelity. It is likely that alloying elements commonly used by the steel industry will not be available on the Moon within the near-term. As such, steel alloy analogs were selected to minimize alloy content. Commercial ER70S-2/3 welding wire is somewhat available and has some of the lowest alloy content among commercial wire. This alloy was selected for process development of the additive manufacturing equipment.

For a closer analog, a hot briquetted iron (HBI) product was selected for melting and wire drawing at CSM facilities. This product does not contain the manganese or silicon found in commercial steels and should provide a closer chemical match to the iron produced by MMOST. This material will be used to develop the wire drawing parameters and further refine the additive manufacturing process. The work to convert this to a suitable feedstock is currently ongoing. Although outside the scope of this presentation, material produced by MMOST will be carried through the full process, from raw iron product though manufactured component.

Production and Testing of Additively Manufcatured Samples from Analog Alloys: Wire Arc Additive Manufacturing (WAAM), a type of Directed Energy Deposition (DED) was selected to produce samples. A Universal Robots UR10E 6-axis robot arm, integrated by THG Automation, was used for builds throughout the work. The advantage of a multi-axis robot arm, as opposed to a simpler gantry system, is two-fold. First, it allows for a more flexible build area, allowing the robot to build parts larger than the arm itself. Secondly, the wrist rotation of the robot allows for non-vertical build angles, enabling complex builds and overhangs without the need for repositioning the component mid-build.

Simple walls have been the primary focus as they provide an efficient way to maximize sampling and characterize the material. Walls up to 11cm tall, 23cm in length, and 2cm thickness were successfully produced from commercial alloys. Off-angle testing was conducted and, at time of writing, had produced horizontal walls up to 4cm tall. Work is ongoing to test samples for porosity, mechanical properties, and microstructure. G-code integration is currently underway and has produced components up to 10cm in the major direction.

References: [1] Kesterke D.G. (1970) *US Dept. of the Interior, Bureau of Mines,* 7578. [2] Gibson, M.A. and Knudsen, C.W. (1985) *Lunar and Planetary Institute* p. 543-550. [3] Sanders, G.B. and Larson, W.E. (2013) *Journal of Aerospace Engineering,* 26, p. 5-17.