SIMULANT AND ENVIRONMENT REQUIREMENTS FOR ISRU MANUFACTURING TECHNOLOGY DEVELOPMENT.

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Introduction

This work examined the importance of simulant type, atmosphere, and ambient hydration in the development of energy-based additive manufacturing technology, specifically using lunar simulants and a concentrated solar simulator to perform tests. Optical and discrete element models of the test setup were developed. Ultimate strength testing of over 40 samples was conducted. Qualitative effects of changing process parameters were explored. Based on statistical analysis of test results, recommendations to the aerospace community on the importance of simulant choice, testing within a vacuum chamber, and pre-drying simulant were made.

Motivation

In the last five years, space resource utilization has moved from science fiction to international mandate. New technologies for volatile extraction, construction with native materials, and mineral excavation are being actively developed through international partnerships by public and private entities. As the aerospace community continues to develop space resource utilization technology, more and more new technology will go from the conceptual stage to the lab testing stage of development. Testing is expensive and time consuming, and poor results can cause technologies to be quickly written off in this era of accelerated program schedules and tighter budgets. Worse yet, inaccurate results can make technologies appear to work for ISRU when they could not succeed in the target environment. Since no lab conditions can perfectly replicate space environments such as the lunar surface, it will become increasingly more important to determine the degree of fidelity necessary for a given test plan.

Work conducted by groups such as the Center for Lunar and Asteroid Surface Science at the University of Central Florida has helped classify and rate regolith simulant based on several planetary bodies (Taylor, 2010), but the points of required fidelity in chemistry and granular mechanics of processes concerned with the melting of regolith differ from the customary geotechnical evaluation markers used in the field. Additionally, environment plays a large role in the success of any energy based manufacturing process (additive manufacturing is particularly susceptible to oxidation and thermal variation) but thus far little work has been done to quantify environmental effects in ISRU technology development. This work seeks to help the space resources community better evaluate regolith simulant and testing environment choices to improve the rate of technology development and the eventual outcomes.

Concentrated Solar Regolith Additive Manufacturing

The process of choice for evaluation in this work was concentrated solar additive manufacturing of lunar regolith. A 1kW solar simulator and two types of regolith simulant (JSC-1A and LMS-1) were used in and out of vacuum. JSC-1A was chosen because it is the most characterized and widespread lunar mare simulant currently available, while LMS-1 was chosen because it allegedly has a higher mineralogical fidelity than JSC-1A. The concentrated solar melting process was chosen because of its likelihood to be one of the first ISRU technologies tested in-situ and because it allows for realistic evaluation of melting physics. Some techniques such as selective laser melting have such as small spot size that phenomena such as outgassing are difficult to observe during testing.

Power at the spot was set between 30-40 W/cm^2 in order to ensure full melting but avoid ablation/explosive spalling. Melting was observed at as low as 12 W/cm^2 while the aforementioned explosive processes have been observed in concentrated solar regolith tests under both atmospheric and vacuum conditions at irradiance of as little as 100 W/cm^2 (Dreyer et al, 2016). Preparing samples at a slightly higher irradiance allowed for direct observation of phenomena such as partial sintering, outgassing, and melt pool sizing.

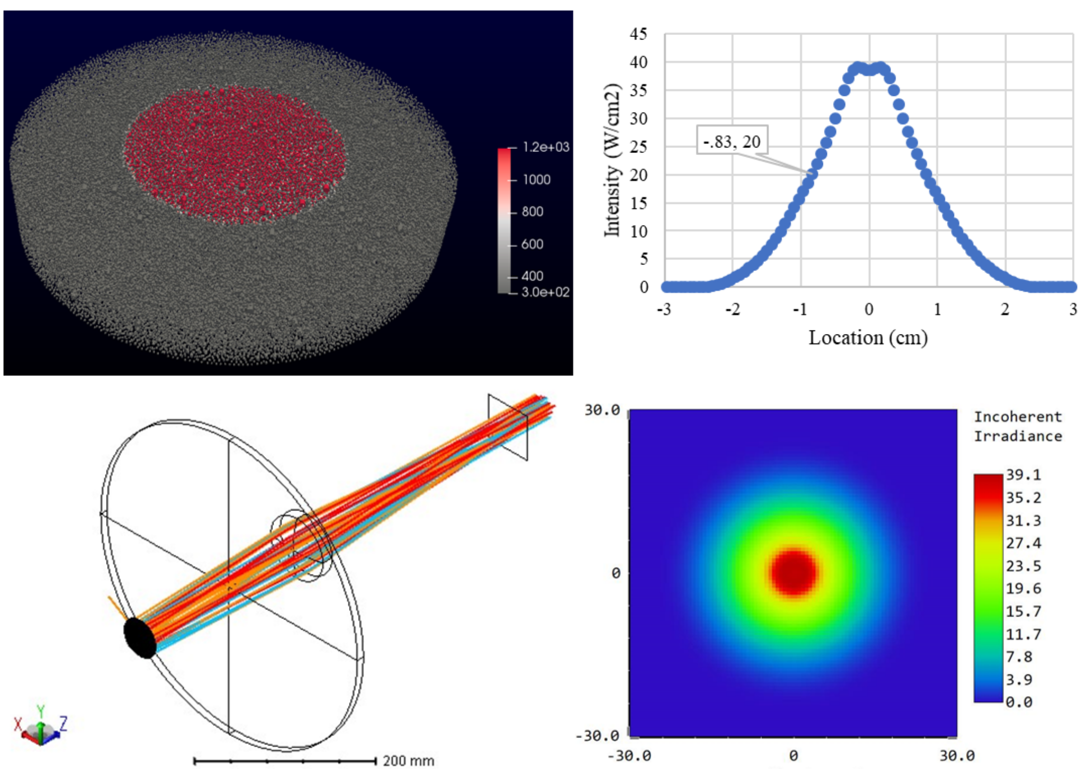

Figure 1: DEM and optical modeling. Top left: DEM heat transfer model (Kelvin). Bottom left: Zemax optical train. Top right: spot intensity and size, cross section. Bottom right: spot intensity and size (mm in the x and y) heat map.

Modeling

Before testing, modeling was conducted to determine spot size and thermal penetration. Optical modeling was performed in Zemax Optic Studio 16 and discrete element modeling (DEM) was performed in LIGGGHTS. The spot size and irradiance from Zemax was used as the thermal flux input parameters for the granular DEM. Lenses within the optical train of the system were modeled as BK7 glass and reflectivity of the internal mirrored surface was set to 100%. F, d, C wavelength presets were used to simulate visible light. Interesting results from this modeling include the closeness to measured intensity (at 32 W/cm2) and the surprisingly small modeled heat affected zone (as can be seen in white in Figure 1).

In the DEM software the initial temperature was set to 300K, irradiance at the surface was set to 30 W/cm^2 and the thermal and physical properties were set to those of basalt, including thermal conductivity, which was set to 1.1 W/mK because it was not possible to scale with time and individual grains have the thermal conductivity of solid basalt. Bulk JSC-1A in air has a thermal conductivity of around 0.2 W/mK (Yuan, 2011), and lunar regolith has a thermal conductivity around 0.015 W/mK (Keihm, 1973) in the porous surface layer. Lunar regolith is therefore an incredible insulator, so although the size of the modeled heat affected zone was surprising, the literature shows it is entirely reasonable.

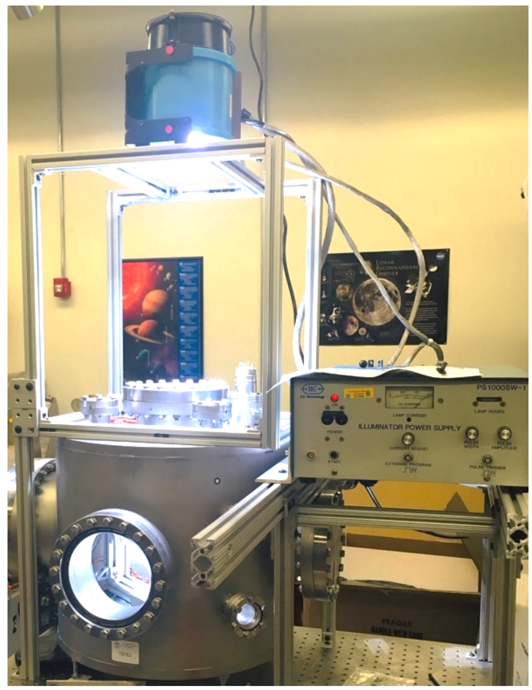

Figure 2: Test setup for sample preparation at the Colorado School of Mines including lamp, power supply, and chamber. Sample, optics, and pump not shown.

The practical implications of this may be of the highest importance to lunar ISRU activities related to any thermal processes. Heat can be continually dumped into the lunar surface, melting a layer of a few millimeters thick without touching the layer below it or even partially sintering the grains around it beyond a few centimeters. Any larger scale melting activities such as molten regolith electrolysis or manufacturing processes such as casting and 3D printing will require mechanical mixing of heated regolith with fresh feedstock to get beyond this millimeter thickness limit. Regolith will release its heat to space through radiation before it will spread to surrounding grains, but molten regolith in stored containers could serve as a heat storage tank for surviving the lunar night or for operations in the permanently shadowed regions.

Test Setup and Materials

A total of over 50 tests were conducted, including 10 of each of the following categories: JSC-1A samples prepared in air, JSC-1A samples pre-dried and prepared in vacuum, JSC-1A samples not pre-dried and prepared in vacuum, and LMS-1 samples not pre-dried and prepared in vacuum. Testing was performed within a vacuum chamber from the Kurt J. Lesker Company using a 1kW xenon arc lamp from ILC, as can be seen in Figure 2. Before the lamp was activated in vacuum tests, samples were kept in vacuum until the chamber reached below 100mTorr. Samples were heated for a total of at least 3 minutes then allowed to cool before being taken out of the chamber. Because outgassing was so prevalent in the materials, sometimes an extra few seconds was added to the 3 minutes to allow a bubble within the sample to pop and for the sample to return to a minimum density. This outgassing is likely due in part to inter-granular water release, but in larger part due to oxygen evolution from lower melting point end members such as potassium oxide. During testing the vacuum pump was continually activated. While the light was activated, pressure within the chamber would jump by between 30 and 150 mTorr. Dried samples were dried in a vacuum oven at over 375K for 24 hours, then sealed in a mason jar. All tests were conducted in Golden, Colorado, which is a comparatively highly dry environment.

Several line tests and 2D layer tests were also performed by placing motors below the samples and melting the regolith in a line or snake pattern. The purpose of these tests was to determine process parameters for additive manufacturing. While it was determined that a feed rate of 0.5 cm/min was appropriate for JSC-1A at the given irradiance, inconsistencies and low strength in the samples led researchers to believe that direct concentrated sunlight may not be the most appropriate technology for additive manufacturing. Of potential greater use would be to beneficiate and mix regolith with a feed stock of lower melting point (such as EPDM plastic) and print using an FDM style apparatus, as is being developed by the SwampWorks team at NASA Kennedy Space Center (Mueller, 2018).

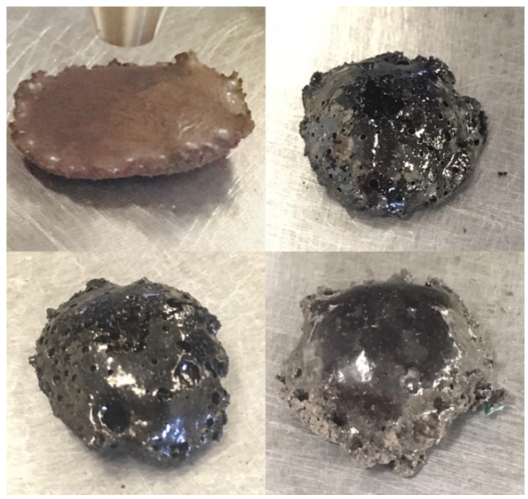

Figure 3: Clockwise from top left: JSC-1A melted in air, pre-dried JSC-1A melted in vacuum, non-dried JSC-1A melted in vacuum, LMS-1 melted in vacuum.

Strength Testing

As seen in Figure 3, the results of strength testing are highly dependent on simulant material and atmospheric conditions. The most interesting result is the extreme variability of the JSC-1A samples prepared in air. It has an ultimate strength range from the low side of the JSC-1A prepared in vacuum to the high side of the LMS-1 prepared in vacuum. The in-air samples have a variability in density from around 1.5 to 3.75 g/cm3 where every other sample group has a range of less than 1g/cm3 from lowest to highest.

There are significant differences between both the densities and ultimate strengths of LMS-1 and JSC-1A samples prepared in vacuum. If LMS-1 is truly a higher fidelity simulant, this indicates that lunar regolith will be a better construction material in both strength and porosity than what may be indicated by tests done with JSC-1A.

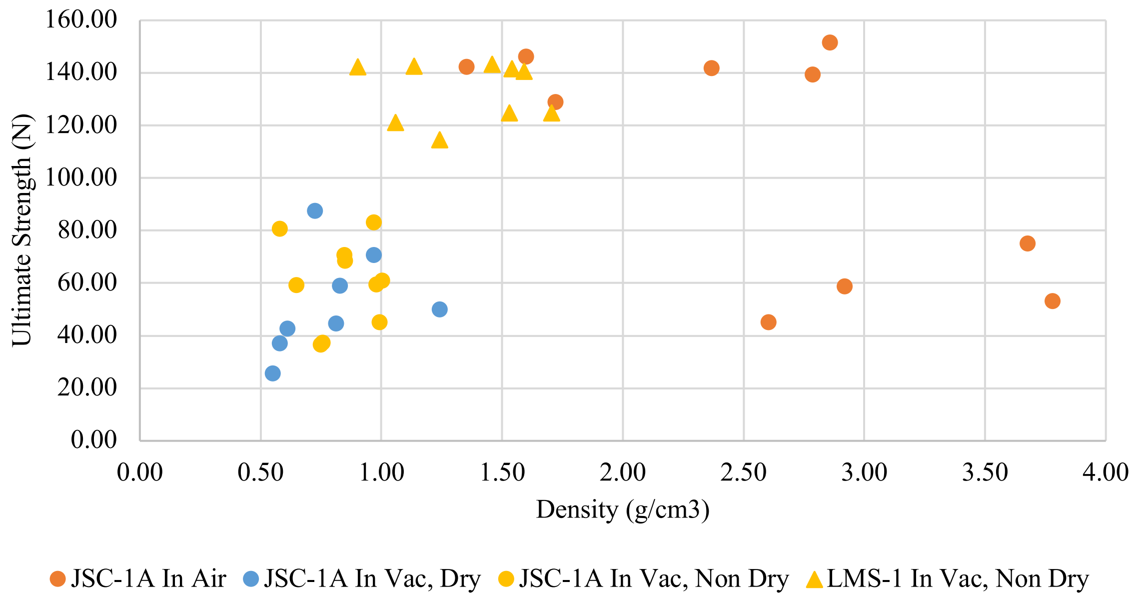

Figure 4: Ultimate strength test results. Note the high variability in samples prepared in air, difference in ultimate strength between JSC-1A and LMS-1, and the low difference between samples pre-dried and non-dried.

Finally, as can be seen in Table 1, there is very little difference between dried and non-dried samples. This may be due to the low percentage of water in the soil (estimated at <<1% of the total weight of the sample), or it may be due to the inability to release water trapped within grains. If this is the case, it may not be experimentally feasible to totally remove water from samples before testing. However, since there has been vapor water transport over the surface of the moon in the course of the last 3 billion years, there may be precedent that small amounts of inter-granular water also exist on the lunar surface. Uncorrupted samples from the lunar surface in the next decade will shed much light on this issue.

Table 1: Fundamental data points in the test matrix.

Material	Atmosphere	Pre-Drying	Mean Density (g/cm^3)	Min Density	Max Density	Mean Strength (N)	Min Strength	Max Strength
JSC-1A	Air	No	2.57	1.35	3.78	108.1	45.1	151.4
JSC-1A	Vacuum	No	0.84	0.58	1.01	60.1	36.5	83.0
JSC-1A	Vacuum	Yes	0.79	0.55	1.24	52.0	25.48	87.35
LMS-1	Vacuum	No	1.35	0.90	1.70	132.9	114.7	143.4

Conclusions

Basic simulant and environmental requirements for ISRU manufacturing technology were developed, namely:

A) The expense and difficulty of melting regolith in vacuum is justified due to the extreme variability in both strength and density when samples are prepared in air.
B) Higher chemical fidelity simulants are justified over more common simulants such as JSC-1A due to a significant difference in their strength and density.
C) Pre-drying samples does not appear necessary at this time, but further exploration of the topic is merited.
D) The extremely low thermal conductivity of regolith can be used to the community's advantage when planning missions, but must be considered when developing regolith melting ISRU technology.

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