ADDITIVE MANUFACTURING OF FUNCTIONALLY GRADED MATERIALS WITH IN-SITU RESOURCES


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Digital Light Processing
Spark Plasma Sintering
In Situ Resource Utilization
Regolith

ABSTRACT

This study examines the additive manufacturing feasibility of functionally graded materials with in-situ resources. A potential application of the outcome is for aerospace components and space habitats. At first, compatible in-situ resources for functionally graded materials and additive manufacturing (AM) suitable processes are investigated. Then powder characterization of three lunar simulants is performed to evaluate them for the fabrication tests. The chemical compositions, particle shape and size distribution, and thermal characteristics of the powders were analysed. This paper is a part of an ongoing study, with a final aim to develop a functionally-graded composite at the level of concept validation and evaluate it for thermal and mechanical properties.

1. INTRODUCTION

Successful long-term space exploration missions must ensure a high level of security and safety against harsh environmental conditions, such as meteoroids, radiation, thermal cycles, abrasion, vacuum, etc. Space habitats are a prospect in these missions. The building materials must ensure indoor atmospheric and thermal control whilst protecting from the outer space environment [1]. Space habitat designers and researchers generally propose resilient structures with multi-layered solutions, e.g., Fig. 1 [2][3]. Multi-layering is reasoned by a multitude of factors: mission requirements (both of the habitat itself and the need for configuration variety), user demands, and destination.

To overcome these requirements, NASA has proposed a strategy for technological habitation to be accomplished in three phases [5]:

- Class I, pre-integrated hard shell module;
- Class II, habitats prefabricated and surface assembled;
- Class III, in-situ resource utilization (ISRU), derived structure with integrated Earth components.

The designs for Class II and III modules usually consist of an interior shell pressurized containment and an exterior regolith layer to protect from radiation, meteoroids, and thermal cycles [6][7][8].

Figure 1. Section of a cylindrical module [4]
Earth-constructed, Fig.2 [4]. Shells can be built from textiles (inflatable), alloys, composites, etc. The exterior cover is recommended to be in-situ additive manufactured with regolith, due to the abundance of the loose material on planetary surfaces [9][10].

1.1. Functionally graded materials

In a sustainable mission, the strategy for a Class III space habitat requires full integration of subsystems and fabrication with in-situ resources. However, current solutions make use of single-material manufacturing methods and regard regolith as an aggregate instead of a source for alloy extraction [2]. Even if resources are readily available for a Class III module multi-material fabrication, the construction methods are considered separate both for the interior and the exterior of the structure. Besides not exploring the full in-situ resource utilization (ISRU) potential, these fabrication methods might contribute to challenges regarding mismatch at the interface between materials, in terms of fretting wear, fatigue, fracture, corrosion, and stress corrosion cracking [13][14]. Functionally graded layers can serve as an optimal transition between two incompatible materials. They are designed with function or performance in a graduated morphology to achieve tailored features [15][16][17]. For example, a buffer layer at a ceramic-metallic interface improves compatibility by promoting stronger bonding between substrates and preventing delamination otherwise common in composites. Besides the benefit of improved mechanical behaviour, thermal properties can also be enhanced by a specific sequence of graded insulation layers [13][18]. Functionally graded materials (FGM) are considered advantageous in maximizing the capabilities of in-space resources due to their multi-material approach evaluated as high performance contrary to monolithic applications [19].

FGMs can be classified by four major distinct categories, namely: 1) volume fraction, 2) grain shape/size, 3) material fraction, and 4) orientation, Fig. 3. [21][22][24].

Metal-ceramic gradients have been widely studied in recent years because of their attractive properties. There are a multitude of graded material examples that have shown high-temperature stability, high hardness, corrosion resistance, and good versatility; such as aluminium-silicon carbide (SiC/Al); aluminium-aluminium oxide (Al-Al$_2$O$_3$); titanium-titanium carbide (TiC/Ti) graded composites; graded yttria-stabilized zirconia coatings and Al$_2$O$_3$ ceramic coating on AZ91HP Mg alloy [14][26][27][28][29][30][31][32][33][34].

2. MATERIALS AND METHODS

This research is focused on the feasibility of ISRU via manufacturing of FGMs for a Class III space habitat. Because the study is considered for human space exploration, the Moon is selected as a strategic location in terms of planetary surfaces. The reasoning is based on Earth’s proximity to the Moon, as the closest and most reachable terrestrial body in case of emergency evacuation and supply. It is proposed that initial research for technology and human life support systems can be performed on a lunar habitat. Then the transfer of knowledge can be considered in future missions for other terrestrial bodies [2].
The primary resource for ISRU on the lunar surface is regolith, i.e. the layer of unconsolidated mineral of thickness between 3 - 20m atop the lunar surface, consisting of fine-grained particles and rocks [35]. The constituents of the lunar soil are comprised of silicate (plagioclase, feldspar, pyroxene, olivine) and oxide minerals (ilmenite, spinel) [36][37][35]. Other possible materials present in small quantities are volatiles (water, OH, H, C, N, F, S, Cl), however accurate soil composition will differ depending on the sampling location (Mare, Highlands) [38][39].

2.1. Metal extraction from regolith

To effectively locate, process, and utilize native resources is an essential mining requirement for lunar base operation. The lunar soil is abundant in metals such as silicon, aluminium, iron, titanium, and magnesium. Iron metal has potential structural purposes, while aluminium can be used as a coating metal, or rocket fuel [2]. The metal extraction methods from minerals are pyrometallurgy, electrometallurgy, and hydrometallurgy. In each discipline, the reduction of each component to its elemental form must have a process reactant that can be recycled indefinitely, be suited for lunar surface conditions, and consume minimal water [40]. Silicon, aluminium, and glass can be refined using fluorine, in a multi-stage reduction process that separates and purifies the elements. Oxygen is a by-product in this refining process, which is a high-priority resource for human life support or rocket fuel [38]. Molten salt electrolysis (Metalysis-FFC) technique has been tested on a lunar simulant JSA-2A to process metal alloys as products. The method produced three dominant distinct alloy groups, Al/Fe alloy, Fe/Si alloy (sometimes with the inclusion of Ti or Al), and Ca/Si/Al alloy (sometimes with the inclusion of Mg). Depending on the feedstock, Metalysis-FFC has the potential to produce specially-design alloys from refining of lunar regolith [41].

The extracted lunar resources considered for a gradient in the current study are titanium, titanium alloys, steel, magnesium, aluminium, and aluminium alloys. The primary criteria for material selection are simulant compatibility with the metal or alloy in particle size distribution, density, and thermal properties.

Additive manufacturing (AM), also known as 3D-printing, can be used for FGM fabrication in a gradient from a) metal to a regolith simulator, or b) alloy to a regolith simulant, see Fig. 4. Similar to ceramic reinforced metal matrix composites (MMC), the chosen metallic substrate will be dispersed in the regolith matrix, a technique that may contribute strengthening to the additive manufactured regolith [42].

2.2. Additive manufacturing

Current FGM fabrication methods can be classified as thin-film or bulk fabrication. Thin sections/coatings have the advantage of being less time consuming, for which fabrication processes such as physical/chemical vapour deposition are generally applied [43]. Bulk FGMs are more demanding and commonly use conventional powder metallurgical technologies [44][24]. In this study, which focuses on the application of FGMs for components or a space habitat, bulk manufacturing techniques that could be considered include material extrusion [45][46][47], light polymerisation [48], spark plasma sintering [49], powder bed [50][51][52] and powder fed techniques [53][42][54]. The selection between AM and conventional methods depends upon technique viability for processing both ceramic and metal/alloy powders, suitability for microgravity, and resultant mechanical properties post-fabrication. Subsequently, the following methods are considered herein: (i) Spark Plasma Sintering (SPS) is selected due to the higher powder densification in the sintering technique, essential for building reliable structural components [49]; and (ii) Digital Light Processing (DLP) as this method works both with ceramic and metal powders whilst being suited to a microgravity environment [55].
An overview of the different promising consolidation techniques suitable for ISRU, as well as their advantages and disadvantages, is given in Table 1. It must be noted that none of the following studies have been conducted with genuine lunar regolith, rather with a variety of Earth-manufactured simulants. Thus results are expected to be partially dependent on the simulant properties and also on the chosen lunar environment for some early studies.

Table 1. Overview of advantages and disadvantages of consolidation techniques suitable for ISRU

<table>
<thead>
<tr>
<th>Consolidation technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Extrusion</td>
<td><strong>Sulfur Concrete</strong> [56][46]</td>
<td>• Feasibility of extraction of S from ores</td>
</tr>
<tr>
<td></td>
<td>• Ease of manufacturing</td>
<td>• Low impact resistance</td>
</tr>
<tr>
<td></td>
<td>• Presence of FeS on the Moon</td>
<td>• Relatively high rate of sublimation of S</td>
</tr>
<tr>
<td></td>
<td>• Cheap process</td>
<td></td>
</tr>
<tr>
<td>Power Bed Fusion</td>
<td><strong>Selective Laser Melting (SLM)</strong> [57][58]</td>
<td>• Slow process and poor surface finish</td>
</tr>
<tr>
<td></td>
<td>• Can produce high quality components in low to medium batch quantities</td>
<td>• Residual stresses (cracking)</td>
</tr>
<tr>
<td></td>
<td>• Good repeatability</td>
<td>• Porosity (requires post-processing)</td>
</tr>
<tr>
<td></td>
<td>• Full design flexibility</td>
<td>• Lack of knowledge about the interaction between laser and ceramics</td>
</tr>
<tr>
<td></td>
<td>• Low waste compared to conventional casting techniques (no machining)</td>
<td>• Powder sieving or crushing required</td>
</tr>
<tr>
<td></td>
<td>• Production of nearly fully dense parts</td>
<td>• Powder heterogeneity causes variations in energy density</td>
</tr>
<tr>
<td>Additive Manufacturing</td>
<td><strong>Solar Sintering</strong> [59][60]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Use of solar light source, more stable on the Moon</td>
<td>• Difficulty when sintered under vacuum</td>
</tr>
<tr>
<td></td>
<td>• No need of binders</td>
<td>• Low mechanical properties</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Poor bonding between successive layers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Difficult to balance sintered and molten phases</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• No prediction on the equipment lifetime</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Few investigations carried out on this technique</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>D-shape Process</strong> [61]</td>
<td>• Large printer must be brought to the Moon</td>
</tr>
<tr>
<td></td>
<td>• Allows large-scale manufacturing in one single printing process</td>
<td>• Use of an inorganic binder and an ink</td>
</tr>
<tr>
<td></td>
<td>• No need of sieving or crushing of the lunar regolith</td>
<td>• Large quantity of binder</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Low shape accuracy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Multistep process lasting several hours</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Photopolymerization</strong> [62][63]/Digital Light Processing (DPL) [48][55]</td>
<td>• Requires specific polymeric resins and additives</td>
</tr>
<tr>
<td></td>
<td>• Good surface finish</td>
<td>• Time demanding (multistep process lasting several hours)</td>
</tr>
<tr>
<td></td>
<td>• More accurate and complex shape can be produced by this technique</td>
<td>• Expensive process</td>
</tr>
<tr>
<td></td>
<td>• Can produce small parts with high precision but also large parts whilst</td>
<td>• Difficult to achieve high density</td>
</tr>
<tr>
<td></td>
<td>maintaining high precision</td>
<td>• Complex curing process and complex kinetics</td>
</tr>
<tr>
<td></td>
<td>• No mould required, only a CAD model</td>
<td>• Smaller (down to nano) particle size is preferred</td>
</tr>
</tbody>
</table>
### Spark Plasma Sintering (SPS) [64][49]
- Microstructure control due to low temperature and short time
- High density due to higher heating rate and pressure than other techniques
- Dissimilar materials can be sintered
- Fast and FGMs can be produced
- Cost of SPS is 50 – 80% lower than other conventional sintering techniques
- Temperature of 900°C enough for sintering lunar regolith
- Good mechanical properties
- Only simple symmetrical shapes can be prepared
- Expensive DC generator required
- For very small powders (less than 100 nm), significant temperature gradient can lead to non-uniform densification
- Sieving or crushing required for lunar regolith
- Limited to simple shapes

### Vacuum Sintering [65]
- Sintered parts with low thermal conductivity
- Prevention of oxidization
- High weight loss increasing with temperature
- Presence of macro-pores, which can be controlled with sintering temperature
- Shrinkage dependent on the temperature

### Thermite reactions [66][67]
- Reduction of energy needed
- Limited equipment is required
- Quick reactions with smaller particles
- Addition of Al and other substances like Teflon
- Porous structures
- Little information about mechanical properties
- Sieving or crushing required for lunar regolith
- Deformation and surface cracking (even more with smaller particles)

## 3. PROCESS MATRIX CHARACTERIZATION

Due to the limited availability of original lunar soil, the current study is conducted with three regolith simulants: EAC-1A, LMS-1 (Lunar Mare Simulant), and LHS-1 (Lunar Highlands Simulant), (see Tab. 2 for composition). Selection of these simulants is based on resemblance to Apollo sample bulk chemistry, and mineralogical diversity of the location (Mare and Highlands) as also shown in Tab 2. LMS-1 and LHS-1 have been developed by CLASS Exolith Lab. The simulants were manufactured by combining both mineral and rock fragments (i.e. polyminerilic grains) for high-fidelity attributes [68]. EAC-1A lunar simulant was developed by the European Astronaut Centre (EAC) in Cologne. The powder was sourced from a commercial quarry in the Eifel volcanic region in Germany [69].

The considered processes, Digital Light Processing (DLP) and Spark Plasma Sintering (SPS), require characterization of the lunar simulant to determine and predict the fabrication behaviour. Bulk chemistry, particle shape, and size distribution are essential properties and have been investigated in this study for all three simulants.

### 3.1. Bulk chemistry and mineralogy

Apollo missions and robotic lunar landers are the benchmark for the development of LHS-1 and LMS-1 simulants. The reference materials for LHS-1 and LMS-1 simulants are the Generic Highlands Soil and High-Ti Mare Soil respectively, see Tab. 2, and Tab. 3. Lunar Highlands soils are predominantly comprised of anorthosite, a rock which is largely made up of plagioclase feldspar. Lunar Mare soils contains volcanic rock that erupted at the lunar surface and produced lava flows and pyroclastic deposits [70].
Table 2. Oxide composition of lunar simulants EAC-1A [71], LMS-1, LHS-1 [68], JSA-2A [71], and lunar samples Apollo 17 High-Ti Mare (71055) and Apollo Highland Average chemical composition [70].

<table>
<thead>
<tr>
<th>Units</th>
<th>EAC-1A (wt%)</th>
<th>LMS-1 (wt%)</th>
<th>LHS-1 (wt%)</th>
<th>JSA-2A (wt%)</th>
<th>Apollo 17 Highland (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>43.70</td>
<td>42.18</td>
<td>44.18</td>
<td>47.50</td>
<td>37.60</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2.40</td>
<td>4.62</td>
<td>0.79</td>
<td>1.50</td>
<td>12.10</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>12.60</td>
<td>14.13</td>
<td>26.24</td>
<td>15.00</td>
<td>8.74</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>-</td>
<td>0.21</td>
<td>0.02</td>
<td>-</td>
<td>0.42</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>12.00</td>
<td>-</td>
<td>3.50</td>
<td>21.50</td>
<td>5.90</td>
</tr>
<tr>
<td>FeO₁</td>
<td>-</td>
<td>7.87</td>
<td>3.04</td>
<td>7.25</td>
<td>-</td>
</tr>
<tr>
<td>MgO</td>
<td>11.90</td>
<td>18.89</td>
<td>11.22</td>
<td>9.00</td>
<td>8.21</td>
</tr>
<tr>
<td>MnO</td>
<td>0.20</td>
<td>0.15</td>
<td>0.05</td>
<td>0.18</td>
<td>0.22</td>
</tr>
<tr>
<td>CaO</td>
<td>10.80</td>
<td>5.94</td>
<td>11.62</td>
<td>10.50</td>
<td>10.30</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.90</td>
<td>4.92</td>
<td>2.30</td>
<td>2.75</td>
<td>0.39</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.30</td>
<td>0.57</td>
<td>0.46</td>
<td>0.80</td>
<td>0.08</td>
</tr>
<tr>
<td>SO₃</td>
<td>-</td>
<td>0.11</td>
<td>0.10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SrO</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.60</td>
<td>-</td>
<td>0.80</td>
<td>0.05</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>98.40</td>
<td>99.56</td>
<td>100</td>
<td>98.78</td>
<td>99.58</td>
</tr>
</tbody>
</table>

Table 3. Summary of the EDX spot collection count for each lunar regolith simulant for EAC-1A [72] and Mineralogy Weight percent, as mixed for LMS-1 and LHS-1 [68].

<table>
<thead>
<tr>
<th>EAC-1A</th>
<th>LMS-1</th>
<th>LHS-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>(wt%)</td>
<td>(wt%)</td>
<td>(wt%)</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>17</td>
<td>32.8</td>
</tr>
<tr>
<td>Glass</td>
<td>-</td>
<td>24.5</td>
</tr>
<tr>
<td>Basalt</td>
<td>-</td>
<td>19.8</td>
</tr>
<tr>
<td>Ilmenite</td>
<td>-</td>
<td>11.1</td>
</tr>
<tr>
<td>Pyroxene</td>
<td>22</td>
<td>7.5</td>
</tr>
<tr>
<td>Olivine</td>
<td>14</td>
<td>4.3</td>
</tr>
<tr>
<td>Iron Oxide</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>Other</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>74</td>
<td>100</td>
</tr>
</tbody>
</table>
3.2. Particle size distribution

Lunar regolith was found to have log-normal size distribution with mean diameters typically between 45 μm and 100 μm, although particles can be as small as 10 nm [73][74]. Fig. 5 shows particle size data on the three selected as received simulants.

![Particle size distribution graph](image)

**Figure 5.** Average particle size distribution for EAC-1A [75], LMS-1, and LHS-1. Apollo data has been adjusted to remove the >1 mm fraction [68].

The particle size range for EAC-1A is 0.02 - 2000 μm [75]. The particle size range for LHS-1 and LMS-1 simulants is <1 μm – 1000 μm. The Mean Particle Size is 94 μm for LHS-1 and 63 μm for LMS-1 (Fig. 5). In all three simulants there is a significant fraction of large grains (>1mm), which is problematic for additive manufacturing. Thus, for the selected technique in this study, first a sieving or crushing process will be required to remove the greater fraction. Once processed in this way, further investigation into the size distribution of the simulant will be employed to assess potential sintering characteristics.

3.3. Particle shape

The particle shape has great influence over the flow and packing behaviour of powders, which affects in turn the properties of the consolidated material. Lunar particles are irregular in shape and have high cohesion in comparison to terrestrial materials, due to the environmental factors of the lunar surface; as a result, lunar regolith is highly abrasive (Fig. 6) [76]. This abrasive property is difficult to simulate using Earth material, which should be taken into account during this feasibility study. From initial observations, LMS-1 and LHS-1 particles exhibit larger particle elongation and lower circularity than EAC-1A. Quantitative shape analysis using image analysis software will be required to fully understand the expected behaviour of the powder under processing.

![SEM images](image)

**Figure 6.** SEM images for EAC-1A (a) [75], LHS-1(b), and LMS-1 (c) [68].

3.4. Bulk density

Most AM techniques involve the loose deposition of one material layer over another one. For this reason, *poured bulk density* was measured instead of *tapped density*. Poured density is useful in this study to determine the quantity of material required for the manufacturing process. Measurements on lunar soil samples, namely Apollo 14 and Apollo 15, have revealed bulk densities that vary from a minimum 0.87 g/cm$^2$ to a maximum 1.89 g/cm$^2$. The reason for this variation is related to specific gravity, re-entrant intra-granular voids, particle shape, particle size distribution, and surface texture [77].

Poured bulk density was measured for simulants EAC-1A, LMS-1 and LHS-1 in accordance with ASTM D7481-18 (Standard Test Methods for Determining Loose and Tapped Bulk Densities of Powders using a Graduated Cylinder) [78]. For each simulant, three 100 g powder samples were poured into a 100 mL graduated cylinder and levelled; Eq. 1 was used to calculate density $\rho$, where $m$ is the mass of the sample (g), and $V$ is the untapped volume occupied by the simulant (cm$^3$):

$$\rho = \frac{m}{V}$$

(1)
Three measurements were carried per sample, with results derived from the mean. In comparison with lunar samples, the simulants exhibit similar poured bulk densities of 1.50g/cm$^3$ for EAC-1A, 1.60g/cm$^3$ for LMS-1 and 1.61g/cm$^3$ for LHS-1.

3.5. Thermal analysis

Regolith is a multi-constituent aggregate consisting of several mineralogical components. It is useful to understand the thermal behaviour of these components in order to estimate appropriate processing temperatures. A technique coupling Thermogravimetric Analysis (TGA) with Differential Scanning Calorimetry (DSC) was used to identify thermal transition temperatures for each sample. Using a calibrated Mettler Toledo TGA/DSC 3+ instrument, all three simulants were heated from room temperature to above 1400°C at a rate of 10K/min for EAC-1A and LHS-1 samples and a rate of 50K/min for LMS-1 sample. The tests were performed under an argon atmosphere with a constant gas flow of 70 ml/min. Additionally, a blank curve was obtained under the same conditions as each sample, in order to account for buoyancy and the effects of the instrument. Fig. 7 shows DSC curves normalized to sample temperature for EAC-1A, LMS-1 and LHS-1 simulants. All three samples exhibit transformations in the 1100 - 1350°C region. This is consistent with the melting of basalt, ilmenite and glass [59][79] which are present in the given simulants in varying quantity, see Tab.3. The exhibited thermal behaviour may also be attributed to the melting or partial-melting of plagioclase. In lunar regolith the plagioclase is assumed to be of the high-Ca type anorthite which has a melting temperature around 1550°C. However the presence of Na$_2$O oxide in the bulk chemistry suggests plagioclase may have undergone partial melting, as the plagioclase solidus temperature is known to decrease with increasing sodium content [80][81]. Thus, at sintering temperatures in the range 1250 - 1350°C or above, some regolith melting should be expected.

From the TGA results, the following values of mass loss were recorded, in the temperature range [30,
1350°C. When heated above 1350°C, mass losses of 0.97% for LMS-1, 1.07% for LHS-1 and 2.75% for EAC-1A were observed. These losses can be attributed to loss of water and the release of other volatiles at higher temperatures. To emulate lunar surface conditions most effectively, simulants should be furnace dried to remove volatiles before processing.

4. DISCUSSION and CONCLUSION

Powder characterization was performed on three lunar simulants to determine the feasibility of additively manufacturing and FGM. Metal oxides have been identified in the lunar regolith, which implies that in-situ extraction of metal is plausible. The compatibility of a gradient from metal to lunar simulant should be further investigated. Powder characterization of regolith simulant provides insight on how to fabricate the gradient. Based on this study, the following consolidation techniques were selected: additive manufacturing via DPL and conventional bulk consolidation via SPS. These techniques are suitable for both ceramic and metal powders and thus FGM. It was also found that prior to consolidation, the simulant powder requires preparation, particularly sieving and crushing due to the large particle size. The expected manufacturing challenges will be regarding mismatch in coefficient of thermal expansion and material composition behaviour during sintering. Optionally, crack prevention and delamination can be investigated to prevent parts failure and poor bonding between substrate materials.

To conclude, FGMs have a great potential for in-situ manufacturing on the lunar surface. It should be noted that while this study is focused on the space habitats, other aerospace components can also be considered. Future work will focus on further characterisation of lunar simulant and development of a thermal model of the FGM powder consolidation, to employ the selected bulk consolidation techniques for production of FGM material.

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