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Additive manufacturing of physical assets by using ceramic multicomponent extra-terrestrial materials

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ABSTRACT

Powder Bed Fusion (PBF) is a range of advanced manufacturing technologies that can fabricate three-dimensional assets directly from CAD data, on a successive layer-by-layer strategy by using thermal energy, typically from a laser source, to irradiate and fuse particles within a powder bed.

The aim of this paper was to investigate the application of this advanced manufacturing technique to process ceramic multicomponent materials into 3D layered structures. The materials used matched those found on the Lunar and Martian surfaces. The indigenous extra-terrestrial Lunar and Martian materials could potentially be used for manufacturing physical assets onsite (i.e., off-world) on future planetary exploration missions and could cover a range of potential applications including: infrastructure, radiation shielding, thermal storage, etc.

Two different simulants of the mineralogical and basic properties of Lunar and Martian indigenous materials were used for the purpose of this study and processed with commercially available laser additive manufacturing equipment. The results of the laser processing were investigated and quantified through mechanical hardness testing, optical and scanning electron microscopy, X-ray fluorescence spectroscopy, thermo-gravimetric analysis, spectrometry, and finally X-ray diffraction.

The research resulted in the identification of a range of process parameters that resulted in the successful manufacture of three-dimensional components from Lunar and Martian ceramic multicomponent simulant materials. The feasibility of using thermal based additive manufacturing with multi-component ceramic materials has therefore been established, which represents a potential solution to off-world bulk structure manufacture for future human space exploration.

1. Introduction

Mankind has always envisioned conquering space, “the final frontier” as acclaimed by many science fiction novelists and aspiring scientists. Setting the first human in orbit around Earth was only the beginning [1]; a few years later a number of manned and unmanned missions had managed to establish human presence on the moon [2], land robotic missions on planet Mars [3,4] and, very recently, visit an actual comet (67P/Churyumov–Gerasimenko) [5]. Although a reduction in manned space missions has been the status quo for the past few decades, it now seems that a new age of space exploration is at the doorstep and major space agencies have announced their plans towards realising this new age by gradually re-advancing from Low Earth Orbit (LEO) missions to the Moon and later onto the planet Mars [6,7].

The benefits of establishing a human outpost off-world (i.e., the Moon) are multifold, with the most valuable asset being the gathering of data and attaining knowledge on off-world survival with the chance to develop strategies to retain human presence in space and reach even further to other planetary bodies (i.e., Mars). In order for this step of human colonisation to become a reality, engineers back on earth are assigned the highly challenging task in finding efficient and cost-effective ways to build structures that will be able to support life and scientific activity whilst resisting Martian/Lunar environmental threats such as micro-meteoroid impacts, solar and cosmic radiation, intense temperature loads, etc. Numerous studies are available in the literature proposing and engineering ways in fabricating habitats by either dwelling caves underneath the surface or via the concept of In Situ Resource Utilisation (ISRU) to use indigenous materials, readily available onsite to build such habitat structures [8–10].

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Table 1
Composition (wt.%) of the major constituents in the JSC-1A Lunar regolith simulant and JSC-Mars-1 Martian regolith simulant.

Chemical compound	Lunar regolith simulant (Orbitec, 2005)	Martian regolith simulant (Orbitec, 2008)
Silicon dioxide (SiO_2)	46–49	34.5–44
Titanium dioxide (TiO_2)	1–2	3–4
Aluminum oxide (Al_2O_3)	14.5–15.5	18.5–23.5
Ferric oxide (Fe_2O_3)	3–4	9–12
Iron oxide (FeO)	7–7.5	2.5–3.5
Magnesium oxide (MgO)	8.5–9.5	2.5–3.5
Calcium oxide (CaO)	10–11	5–6
Sodium oxide (Na_2O)	2.5–3	2–2.5
Potassium oxide (K_2O)	0.75–0.85	0.5–0.6
Manganese oxide (MnO)	0.15–0.20	0.2–0.3
Chromium III oxide (Cr_2O_3)	0.02–0.06	–
Diphosphorus pentoxide (P_2O_5)	0.6–0.7	0.7–0.9

Table 2
Process parameters used during the experimental procedure.

Parameters	Value
Laser	Near-IR (NIR) Ytterbium fibre laser
Power (W)	5–50
Wavelength (μm)	1.06–1.09
Diameter of laser spot (μm)	80
Point distance (μm)	30–1000
Hatching space (μm) – (Overlap %)	52–80 (35–0%)
Exposure time (μsec)	100–1000
Thickness of powder layer (μm)	150–300
Velocity (mm/s)	Point distance/exposure time
Environment	Argon atmosphere
Temperature of substrate (°C)	200
Substrate material	Mild steel

Additive manufacturing, also known as 3D printing, is a novel range of advanced manufacturing techniques, that in combination with the ISRU concept could serve as a feasible solution to this significant off-world engineering challenge. To date only a limited number of research studies have been performed under this topic and most of the proposed approaches are facing significant challenges prior to any potential adoption [9,11–16].

In this paper a PBF process with a thermal energy source was investigated as to its potential as an off-world manufacturing solution to the aforementioned challenges. The PBF process was used to attempt to fuse together particulates of ceramic multicomponent materials that simulated Lunar and Martian regolith.

Although "regolith" is a terrestrial term, it is used to denote Lunar and Martian soil; soil is a pedogenic term used only in reference to Earth's geotechnical material [17] and refers to a complex layer of unconsolidated rock debris that have been derived by the fragmentation of the bedrock due to minor meteoritic impacts on the Lunar and Martian surfaces [18].

2. Materials and methods

2.1. Materials

The research presented, was carried out using commercially available simulants, developed in coordination with the Johnson Space Center at NASA and supplied by Orbital Technologies Corporation, Colorado, USA. The Lunar simulant JSC-1A has been characterized as a crushed basalt, rich in glass and oxidized forms of silicon, aluminum, iron, calcium and magnesium [19], with a composition matching actual lunar soil, but containing less material complexities due to it not having been exposed to "space weathering" conditions such as those explained in the introduction. [20].

The Martian simulant material JSC-Mars-1A consists mainly of palagonitic tephra (weathered volcanic ashes) and was mined on Earth in a cinder cone in Hawaii. The specific material was chosen due to the spectral similarities to the bright regions of Mars as measured by X-Ray Fluorescence (XRF) and Alpha Particle X-ray Spectrometer (APXS) analyses performed onboard the Viking landers, Mars and Spirit Rover. [21–23].

Although an accurate representation of the material gathered by Martian landers, it is important to note that the simulant material is not a de-facto standard (i.e., the whole of the Martian surface is not made of the same material) and therefore this work is specifically focusing on build material that is available at the various Martian lander sites. The following Table 1 consists of a representation of the chemistry present in both simulants.

2.2. Manufacturing equipment

Manufacturing experimentation was conducted using commercial AM equipment, a Realizer SLM100A Selective Laser Melting (SLM) machine (Realizer GmbH, Borchen, Germany). The SLM100A carries on board an Ytterbium fiber laser manufactured by IPG Photonics (IPG Photonics Corp., Oxford, USA) producing laser radiation of 1.06–1.09 μm wavelength, with a standard TEM_{00} Gaussian profile beam, of 50 W maximum power output and a 30–300 μm spot size. All manufactured samples were built on a mild steel substrate plate that was available with the machine together with applying constant heating at 200 °C. The following Table 2 states the process parameters used during the experimental procedure. An experimental study was followed in order for a suitable process parameter window to be identified that would allow the successful fabrication of multiple layered structures. The feedstock Martian material was screened in order to match the equipment's requirements, from a d (0.5):350 μm that corresponds to the as received powder particle size, to a d (0.5):70 μm, as measured through laser diffraction. A laser beam spot size of Ø80 μm was used and a minimum layer thickness of 150 μm was selected based on previous empirical data, in order to account for the poor packing density of the feedstock material due to its angular shape; as shown in the SEM images in Fig. 2