LUPIN
Executive Summary Report

ESA Contract 4000133993/21/NL/GLC

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1 INTRODUCTION

1.1 Scope

The **LUPIN** project, '**Lu**nar Lithogra**p**hy Manufactur**in**g', was conducted under ESA contract No. 4000133993/21/NL/GLC 'Adaptation of Lithography - Based Ceramic Manufacturing (LCM) to process lunar regolith and optimization of the process steps for the Moon environment and reduced logistics' in the frame of the 'OSIP Off-Earth Manufacturing and Construction Campaign-Study Scheme'.

This document is the Executive Summary Report of the **LUPIN** project, and it provides a conclusive description of the project objectives and achievements. Hereby, only a general overview of the project's activities is given. For more details, the Final Report of the project is available, illustrating all the necessary information[HSF-OHB-RP-0001].

1.2 Application

Nowadays, human Moon exploration, and the consequent desire to establish a permanent settlement on its surface, represents one of the most fascinating challenge to face. The permanent presence of a human outpost very far from Earth raises the problem of the huge amount of payload required for the settlement, as well as the need of rapid and in-time supply of material and spare parts useful for all the activities carried out in-situ, including the realization of medicals tools and patient-specific back-up implants. Additive Layering Manufacturing (ALM) can give an answer to this problem, but its combination with ceramic material arises some issues. Thus, Lithoz introduced a new methodology, called Lithography-Based Ceramic Manufacturing (LCM), where the ceramic powder is distributed in a photocurable monomer formulation in presence of a photoinitiator.

ESA has awarded a General Studies Programme activity, under Contract 4000133993, to the **LUPIN** Consortium (Lithoz GmbH and OHB System AG under the coordination of the latter) to evaluate the feasibility and implementation effort required in adapting LCM to process lunar regolith in the lunar environment, in view of the permanent and sustainable presence of a human outpost on the Moon with a reduced logistic demand, consequently released from onerous and not always timely terrestrial supplies.

2 REFERENCES

2.1 Applicable Documents

This document shall be read in conjunction with documents listed hereafter, which form part of this document to the extent specified herein. In case of a conflict between any provisions of this document and the provisions of the documents listed hereafter, the content of the contractually higher document shall be considered as superseding.

Table 2-1: Applicable Documents

AD	Doc. No.	Issue	Title
[AD01]	HSF-OHB-RP-0001	01	LUPIN Final Report

It should be noted that all requirements listed in the documents of Table 2-1 are applicable unless noted otherwise or exceptions are identified and agreed.

2.2 Reference Documents

The following documents contain additional information that is relevant to the scope of this document.

Table 2-2: Reference Documents

RD	Doc. No.	Issue	Title
[RD01]	Idea_I-2020-00924_2nd_Round_Adaptation	01	Proposal LUPIN
[RD02]	HSF-OHB-MN-0004	01	KoM Minute of Meeting
[RD03]	HSF-OHB-MM-0007 LUPIN PM1	01	Progress Meeting 1
[RD04]	HSF-OHB-MM-0009 LUPIN PM2	01	Progress Meeting 2
[RD05]	HSF-OHB-MM-0011 LUPIN PM3	01	Progress Meeting 3
[RD06]	HSF-OHB-MM-0012 LUPIN PM4	01	Progress Meeting 4
[RD07]	HSF-OHB-MM-0015 LUPIN PM5	01	Progress Meeting 5
[RD08]	Cheibas et all	01	Additive manufacturing of functionally graded materials with in-situ resources

RD	Doc. No.	Issue	Title
[RD09]	HSF-OHB-TN-0009	01	LCM feedstock material preparation for Lunar Environment
[RD10]	HSF-OHB-TN-0010	02	LCM printer adaptation
[RD11]	HSF-OHB-TN-0011	01	LCM post processing assessment
[RD12]	HSF-OHB-TN-0012	01	LCM end-to-end process to support a Moon base implementation

2.3 Abbreviations & Nomenclature

For all terms, definitions and conventions used, if available.

Table 2-3: Abbreviations & Nomenclature

Abbreviation	Meaning
LCM	Lithography-based Ceramic Manufacturing
ALM	Additive Layer Manufacturing
ESA	European Space Agency
GSP	General Studies Programme
FFF	Fused Filament Fabrication
CAD	Computer Aided Design
CI	Configuration Item
AD	Applicable Document
RD	Reference Document
LCA	Life Cycle Assessment
LHS	Lunar Highlands Simulant
KoM	Kick-off Meeting
DMD	Digital Micromirror Device
LED	Light-Emitting Diode
SLA	Stereolithography

3 LUPIN PROJECT EXECUTIVE SUMMARY

3.1 Study Framework

Ceramic materials are extensively used in a vast number of technological processes and in Space applications. Their outstanding characteristics, including corrosion resistance, the ability to withstand very high temperatures, as well as their exceptional mechanical properties like hardness, stiffness and wear resistance make them ideal for the use in demanding environments such as furnaces, heating units or in chemical reactors. There is also an increasing demand for high-performance ceramics for medical applications such as tooth- and bone-replacement materials or in artificial hip-joints (Schwentenwein Martin, 2020).

For its part, ALM contribution to the Space field allows for weight and material volume minimization, which are, indeed, ideal drivers in costly products to be produced in low production volumes (Mellor, 2014), and at the same time it also increases the opportunity to apply novel strategies in the design activity by offering the opportunity to manufacture products with minimal weight, solving material distribution problems by means of topology optimization (Brackett, 2011).

When dealing with ceramic materials, Additive Layer Manufacturing and in particular the Fused Filament Fabrication (FFF) technology, which has been proved to be capable to provide a significant added value to Space exploration, are not recommended because the resulting printed ceramic parts lack the mechanical properties of conventional manufactured counterparts, mainly due to the insufficient densities or the rough surfaces of the sintered parts, and, moreover, they exhibit a pronounced anisotropy in density and mechanical properties. To overcome this shortcoming, Lithoz introduced a new methodology, called Lithography-Based Ceramic Manufacturing (LCM), where the ceramic powder is distributed in a photocurable monomer formulation in presence of a photoinitiator. This slurry is crosslinked upon irradiation of visible LED light to form parts made of ceramic filled composites (called “green bodies”) with adequate mechanical strength for further processing. This approach eliminates the handling of the fine powders, which enhances the work safety and allows the yielding of higher densities after sintering due to the improved powder compaction. The technology is based on different steps and pre- and post-processing equipment and procedures to produce 3D-parts directly from a Computer Aided Design (CAD) are required. Indeed, the feedstocks suitable for LCM processing are photocurable ceramic suspensions where the ceramic powder is homogenously dispersed in a liquid photocurable matrix. Its preparation is very delicate and it can strongly compromise the final printing result. The organic components of the matrix are based on acrylate and methacrylate chemistry and the photoinitiator-system is chosen in accordance to the wavelength of the LED-based light source. The suspensions have to be extremely homogenous and stable in terms of filler sedimentation to ensure proper processability and also the viscosity must be adjusted to match the working window of the system. Depending on the geometry of the desired green parts, different slurry systems are available, varying in filler content and crosslink density of the organic matrix in order to achieve sufficient mechanical green strength and green density, which are key requirements for producing dense, strong, and defect-free ceramic components. Furthermore, after the printing of the green body, a cleaning process made by means of a specific solvent, a subsequent drying process and a final thermal treatment, which comprises debinding (removal of photopolymer network binder) and sintering (densification of ceramics), have to be scheduled.

Thus, towards the desired degree of precision and performance, LCM is a remarkable option, as it is widely discussed in the LUPIN study. As a matter of fact, in literature LCM has been proved to show a significant control of the surface topography of ceramic parts, and the possibility to obtain design-controlled micro-structured surfaces with high-aspect-ratio micro-metric details in the development of two different micro-textured bio devices for cell culture testifies this (Adrián de Blas Romero, 2017).

3.2 Scope, Objectives and Challenges of the LUPIN Project

The aim of the **LUPIN** (**Lu**nar Lithogra**p**hy Manufactur**in**g) project is twofold: on the one hand, the goal is to demonstrate the feasibility of using the LCM technique with the lunar regolith as raw material, on the other hand the goal is to detail the effort required to adapt this process in order to make it suitable in the lunar perspective, keeping account of all the difficulties that such a demanding and harsh environment poses.

In this frame, as a starting point, LCM process has been tested with lunar simulant during the GSP project with Lithoz, showing the feasibility in processing the in-situ resources with parameters adjustment of the commercial machine. The initial idea was to conduct a dedicated study to assess each single process step and simplify some passages in the manufacturing, in order to make them fit for Moon environment.

The reason why LCM combined with lunar regolith feedstock deserves to be investigated is that if ALM as a general technology is already known to be resource-efficient, LCM is recognized to be a very materials- and energy-efficient variant of this family of technologies. The material efficiency of the LCM process is 90 % and it can be improved up to 95 %, while the energy efficiency is demonstrated by the fact that the process requires a power input of less than 500 W, bringing LCM closer to a ‘zero-waste’ process.

In the frame of making LCM end-to-end process feasible and sustainable in lunar perspective, the following objectives have been pursued:

- Modification on the printer for lunar environment and reduced gravity condition;
- Slurry preparation and binder optimization in Moon perspective;
- Post-processing simplification and synergies identification with other ALM technologies;
- Self-sustainability assessment of the process;
- Demonstrator parts manufacturing representative of a meaningful usage on the Moon;
- Applicability of LCM process to other materials;
- Identification of technological gaps to be filled to make the implementation feasible.

3.3 LUPIN Contribution to In-Space Manufacturing

In Figure 3.1, a preliminary display of the Lithoz potential lunar regolith-made demonstrator parts is reported, showing the high relevance of this project in the perspective of life support systems for a future lunar crewed self-sustainable outpost. With refer to other different materials, in the same Figure are reported other possible demonstrators, qualitatively proving how the LCM process can ensure that the 3D-printed components maintain the same functionality, exhibiting high level resolution and accuracy.

Figure 3.1 – Potential lunar regolith (on the top) and different materials (on the bottom) demonstrator parts for life-support systems in a future lunar outpost.

Regardless of the material used as feedstock, it is clear that the possibility to manufacture functional multi-articulated mechanisms in a single step without the need for post-manufacturing assembly is very attractive for Space applications. In fact, the fabrication of complex and multi-articulated mechanisms is often seen as a time consuming and demanding process and it is next to impossible in a Space environment using conventional manufacturing techniques, which are often limited to simple mechanisms that require complex assembly.

Finally, on a long-term time scale, a permanent use of this technology is envisioned for the development of an entire Off-Earth Manufacturing outpost in the frame of a lunar base. Such a base will provide among others:

- in-situ surface exploration to determine material composition and lunar chronology;
- remote seismic exploration of lunar interior to determine physical structure;
- assessment of lunar surface/near surface resources for human exploitation;
- testing of technologies for human exploration of the Solar System.

In the following scheme in Figure 3.2, the expected roadmap for LUPIN project has been reported.

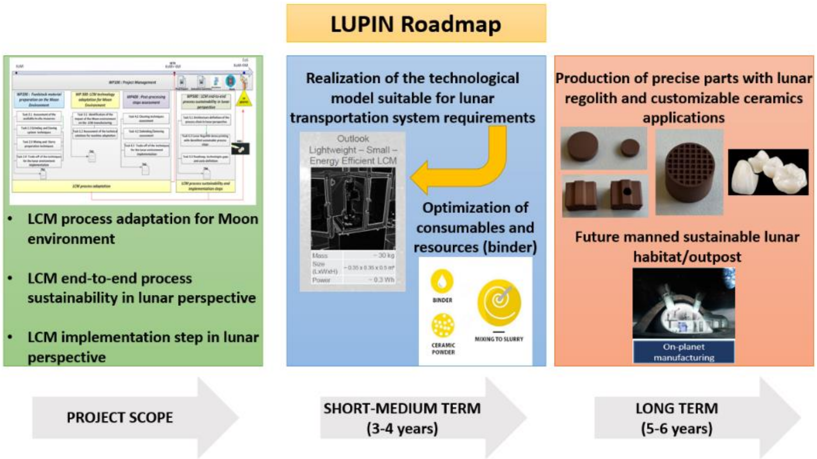


Figure 3.2 – LUPIN expected roadmap.

4 LCM TECHNOLOGY ASSESSMENT

4.1 Lunar Regolith Simulant Selection and Preparation

In the frame of the project, particular attention has been paid to the application of the LCM to in-situ material on the Moon, such as lunar regolith. However, due to the limited availability of original lunar soil, the current study was conducted considering as lunar feedstock the LHS-1 (Lunar Highlands Simulant) developed by CLASS Exolith Lab.

The LCM suspensions have to be extremely homogenous and stable in terms of filler sedimentation to ensure proper processability, and also the viscosity must be adjusted to match the working window of the system. Therefore, the ceramic/regolith particles size distribution is a key aspect for the manufacturing. The lower the average size of the particles, the better the homogeneity of the suspension. In order to reach this result, a planetary milling machine has been used for sieving and grinding procedures, followed by a manual chopping of the dry powder cake.


LHS-1 Lunar Highlands Simulant | Fact Sheet
March, 2019

Simulant Name: LHS-1 Lunar Highlands Simulant
Simulant Type: General Purpose
Reference Material: Generic Highlands Soil
Bulk Density: 1.30 g/cm³
Particle Size Range: 0-1 mm
Mean Particle Size: 94 microns

Mineralogy
Weight percent, as mixed.

Plagioclase	74.4
Glass	24.2
Basalt	0.5
Ilmenite	0.4
Pyroxene	0.3
Olivine	0.2

Bulk Chemistry
Weight percent, as measured by XRF.

SiO_2	44.18
TiO_2	0.79
Al_2O_3	26.24
Cr_2O_3	0.02
FeO_T	3.04
MgO	11.22
MnO	0.05
CaO	11.62
Na_2O	2.30
K_2O	0.46
SO_3	0.10
Total	100.0

Particle Size Distribution
Apollo data has been adjusted to remove the >1 mm fraction.

Reflectance Spectrum
Data coming soon.

Figure 4.1 – LHS-01 data sheet.

4.2 LHS-1 Suspension Preparation

After the grinding and sieving of the regolith powder performed at the Aalen University, the LHS-1 powder has been dispatched to Lithoz GmbH for the 3D-printing process. As it can be seen in Figure 4.2, the final ceramic/regolith slurry was obtained by mixing the ceramic/regolith powder with the proper binder matrix.

Figure 4.2 – Process chain for slurry preparation.

The development of a promising photocurable ceramic slurry requires the homogenous dispersion of ceramic/regolith particles in the raw organic binder. In this frame, the reduced gravity level can strongly enhance the process. The viscosity of ceramic slurry increases by adding the ceramic particles, hence processing of ceramic slurry becomes more challenging compared to pure organic binder. During printing process, the layer thickness should be greater than the particle size of regolith slurry in order to prevent defects such as surface deformations and cracks after thermal post-processing.

4.3 LCM printing process

The LCM process is typically carried out using a printer composed of a building platform, a vat, an optical system and a light engine (see Figure 4.3). First, the vat is filled with the photocurable ceramic suspension, then the building platform begins to move down into the suspension until the gap between the building platform and the vat is of a chosen value, typically between 10 and 100 µm. This gap, corresponding to the resulting thickness of the printed layer of the green body, is chosen according to the optical properties and photo reactivity of the ceramic suspension as well as the needed resolution of the printed part. Then, the photocurable suspension is cured selectively through a mask-exposure process from the bottom of the transparent vat. The light engine is based on light-emitting diodes (LED) with a wavelength of 460 nm, the optical system consists of a DMD-chip and a transmissivity optical device, the transparent vat is a layer-laminate (Glass–Polymer–Foil) and the building platform is made of glass–aluminium parts.

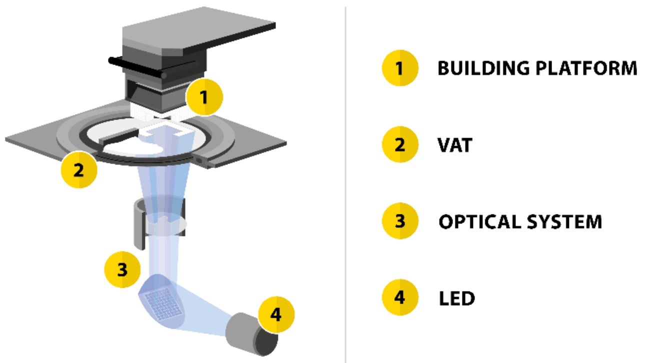


Figure 4.3 – LCM machine for ceramic 3D printing - main components.

4.4 LCM Post-Processing Assessment

LCM can be classified under Stereolithography (SLA) processes and, therefore, it can be considered as indirect additive manufacturing methods because the ceramic parts must undergo specific thermal post-processing treatments. Just like other indirect additive. SLA produces composite samples (“green body”) that basically consist of ceramic powder and organic binder. The organic binder is burned out and the ceramic particles are sintered to obtain the final ceramic parts. Among all, SLA-based manufacturing processes are the most conspicuous techniques, due to the high resolution of the surface with mechanical properties comparable to conventional ceramic manufacturing. In particular, LCM is based upon the concept of photopolymerisation, which means that the printed samples undergo thermal treatment in order to gain the final material characteristics as can been schematically seen in Figure 4.4.

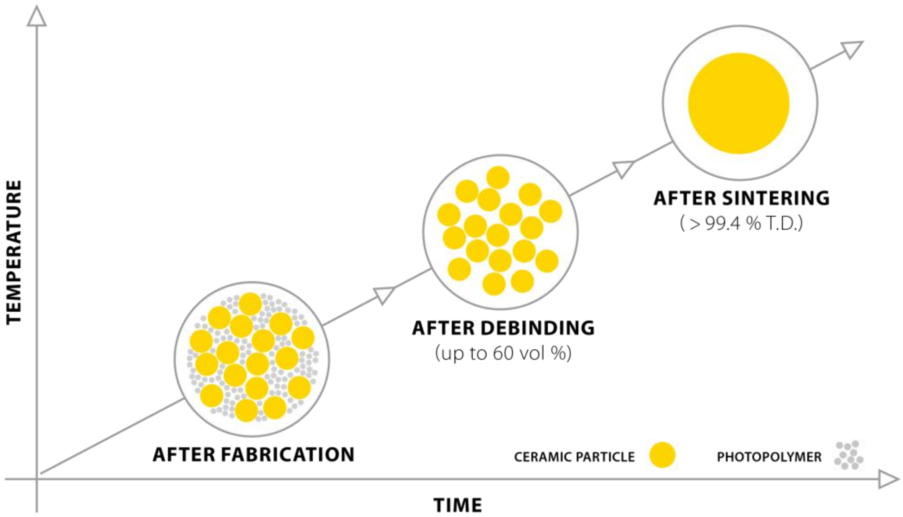


Figure 4.4 – Steps of thermal treatment after green body fabrication.

To be more precise, Lithography-based Ceramic Manufacturing (LCM) is a vat polymerization technique using light-emitting diodes (LEDs) as light source to cure the required area of a thin layer of photocurable ceramic slurry placed in the vat. Once the printing process is completed (see Figure 4.5 (a)), the samples should be removed from the building platform using a razorblade. Firstly, the green bodies need to be cleaned up with the aid of compressed air in order to get rid of the uncured slurry; secondly, the specimens are treated with an ethanol-based solvent using airbrush to remove the excess of slurry on the specimens' surface. Then, the green bodies are dried by using compressed and, finally, the cleaned parts (see Figure 4.5 (b)) are stored at 40 °C in a furnace before undergoing thermal post-process.

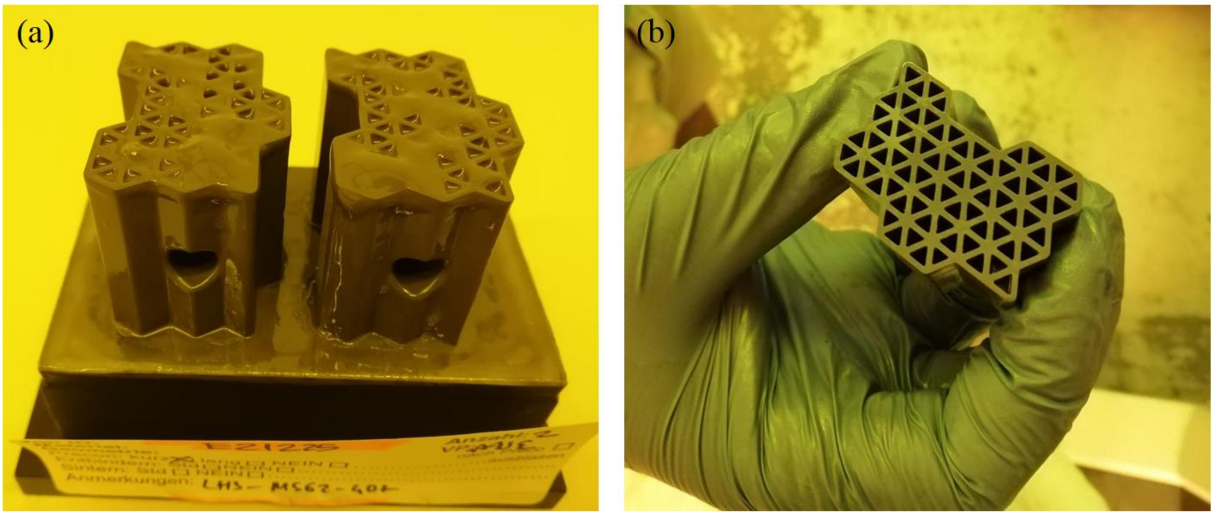


Figure 4.5 – Comparison of printed specimens before (left) and after (right) cleaning process.

Once the regolith samples were printed and cleaned successfully, the green bodies should be thermally treated in order to get the final ceramic product. The thermal treatment can be divided into two steps: debinding and sintering. Debinding occurs usually up to 600 °C in order to burn out the photopolymer network in green bodies. This stage is very critical in order to have defect-free samples. Considering that, the burn-out temperature profile should be adapted to the specific manufactured green body in the ongoing LCM process. Following debinding, the samples are sintered in order to gain the material characteristics such as density, microstructure, and mechanical strength. Depending on the ceramic type, the sintering process occurs usually above 1000 °C. Figure 4.6 depicts a comparison projection of before and after thermal post-process samples using green body samples such as screw, gear wheel, bio-screw and pipe bundle. The shrinkage was determined as 10.1 % and 16.0 % in the xy- and z-direction, respectively. The anisotropic behaviour of shrinkage can be explained by the typical layer-by-layer printing process characteristic of Additive Layering Manufacturing technologies.

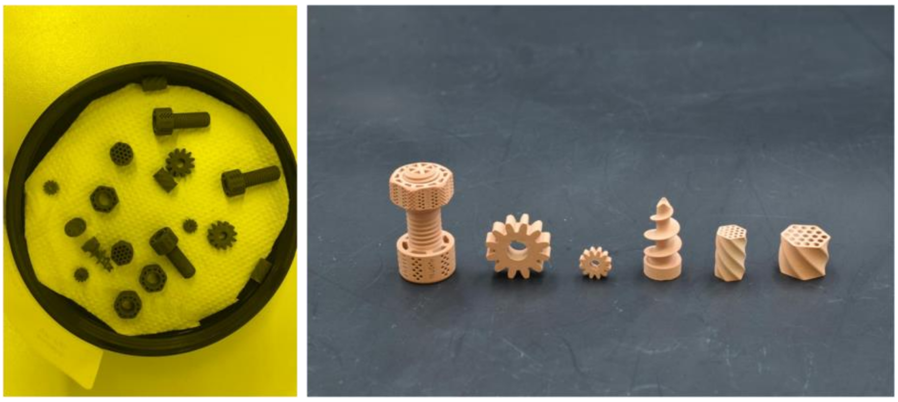


Figure 4.6 – Demonstrators fabricated using LCM process: green bodies (left) and sintered parts (right).

5 LUPIN EFFORT FOR LCM MOON SUITABILITY

The main objective of LUPIN was to elaborate a detailed and methodologic assessment on each element of the whole LCM process chain necessary to convert lunar regolith powder or ceramic powder into 3D-printed and sintered objects/components in the Moon environment. The presence of a furnace, with the slurry preparation and debinding procedure, and also the implementation of a cleaning subsystem, represent the main development challenges, which needed to be costed to allow having an integrated process in place on the Moon. Several adaptations and additional equipment need to be brought from Earth such as a furnace (for the thermal treatment consisting in both debinding and sintering steps), and a mixing system for the preparation of the ceramic suspensions obtained starting from the binder matrix and the powder. Moreover, it is clear that all the LCM facility has to be positioned in an enclosure isolated from the Moon environment in order to reduce its influence. The main elements assessed during the study are reported below and the technological gaps have been identified for each passage.

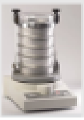
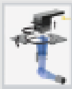
Process		Application/synergies with other AM
Grinding and sieving unit (for Regolith and porous ceramics)		The system need to prepare the powder for the slurry process. The machine is versatile and can be used on the Moon also for other purpose
Mixing system for the slurry		The system is needed as preparation step for the slurry.
Printing core part		Modified design to make the system compact and working under reduced gravity conditions
Cleaning step		Actually based on solvents. Recycling of the solvent or replace by gas flushing will be investigated
Debinding/Sintering		Post processing activities based currently on the furnace. The steps will be optimized and cross-checked for synergies with other AM process or alternative solution (e.g. microwave)

Figure 5.1 – LUPIN facility main elements and their application/synergies with other AM.

5.1 Impact of the Moon Environment on the Ceramic Slurry Mixing Process

The standard Lithoz equipment is not feasible for low-gravity experiments, which need extra cost and time. Indeed, open systems like to ones used for terrestrial applications require normal gravity to function optimally. For this reason, further experiments were done using centrifugal forces-based instrument to homogenize the final suspension. Regarding this, the low-gravity level has a strong beneficial effect on the mixing process, enhancing the uniformity of the slurry. The combination of centrifugal forces acts in different stages and allows very fast mixing throughout the beaker.

5.2 Impact of the Moon Environment on the LCM Dispensing and Coating Process

Before starting the printing process, the existing regolith slurry is filled into the LCM dispensing system. After starting the printing trial, the slurry is dosed with the aid of a dispensing system. The lithography-based ceramics manufacturing process is a layer-by-layer manufacturing process in which the slurry adheres to the surface of the vat after a thin-film coating has been carried out.

All the aforementioned components of the LCM facility (the building platform, the vat, the optical system and the LED light source) are not influenced by lunar environment. However, a more detailed assessment of the LCM process in terms of risks in the lunar environment showed that the open dispensing and coating unit for the suspension could cause problems in the lunar environment. Indeed, the open dispensing and coating unit are adapted to the Earth's gravity and would lose efficiency when operating in low-gravity.

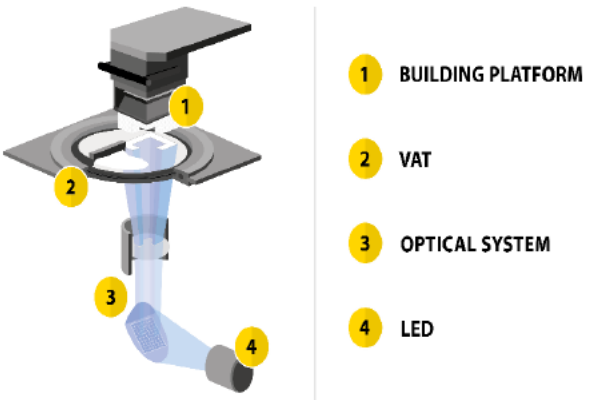


Figure 5.2 – LCM usual machine for Earth applications.

Table 5-1: Evaluation of the LCM process for a low-gravity environment

LCM- module	rating	comment
Ceramic Suspension	☺	sedimentation is reduced in low-G
Projection System	😐	-
Vat- & Separation System	😐	-
Building Platform	😐	-
Open dispensing & coating unit	☹	suspension dispensing and circulation at the doctor blade could be influenced by low-G
Concept of closed dispensing & coating unit	☺	suspension flow is easier regulatable @low-G
LCM- Process	😐	-
Photopolymerisation	😐	-
Debinding	😐	-
Sintering	☺	shrinkage is more homogeneous, less deformation @ low-G

☺	low-G has **positive** influence
😐	low-G has **no** influence
☹	low-G has **negative** influence

The issues with the open dispensing and coating unit in low-gravity environment have been solved by Lithoz with the ‘slot-die-head coating’ solution. This solution is established for the processing of ceramic slurries, and therefore – with small adaptions and testing – suitable for the LCM process.

Whit this solution some advantages for lunar applications arise:

- the dosage of the slurry can be controlled independently of gravity;
- the coating height can be adapted;
- due to the good wettability of the slurry on the vat, a thin film can be created in low-gravity.

5.3 Impact of the Moon Environment on the Sintering Technique

Up to now, all debinding and sintering processes have been conducted with gravity to fuse ceramic particles in order to obtain the final ceramic properties.
Gravity is an uneven load that affects sinter compaction, microstructure development, final properties, and dimensional uniformity. Earth-based sintering displays densification before deformation, however, short dwelling times (2h) demonstrated in this activity, would be profitable during sintering in Moon environments.
No sintering experiment has been conducted so far under low-gravity. Sintering experiments could provide information on whether uniform sintering is possible in low-gravity, in general the microstructure formation achieve high quality and purity when performed in microgravity (refer to proteins crystal growth or semiconductor manufacturing).

5.4 LCM Prototype fit for Moon Transportation System

The LCM Lithoz machine can be adapted according to the lunar transportation system availability in terms of mass and dimensions considering also the build volume requested. Lithoz has already built a prototype LCM machine (non-commercial) with reduced size and weight. The size of that machine is 50 x 50 x 100 cm and the weight is 60 kg.

Property	Value
Mass	60 kg
Size (LxWxH)	0.5 x 0.5 x 1 m^3
Power	550 Wh

Figure 5.3 – Prototype of LCM machine with reduced size and weight.

The technical prototype is technically similar to a LCM machine, but does not have the same usability or design as commercial 3D printers from Lithoz. This results in lower weight and dimensions, primarily due to different frame and housing. Lithoz can further reduce these factors to approximately a size of 35 x 35 x 50 cm with a weight of 30 kg. However, a large part of the machine size is due to the process chamber. The larger the process chamber, the larger the parts to be printed. Thus, it should be borne in mind that a reduction in size of the machine also has an influence on the size of the process chamber and, consequently, on the feasible part sizes.

6 PROCESS SUSTAINABILITY AND LIFE CYCLE ASSESSMENT

In order to get the maximum advantage from each of the ALM technologies proven suitable for Space applications, the self-sustainability of the entire process, along with a logistic relief related to a less pronounced resources demand (in terms of both Earth resupply and power and crew intervention for operations and maintenance) are crucial (Daurskikh, 2020). The key driver capability to make the lunar base implementation successful and self-sustainable is the possibility to have access to in-situ resources (lunar regolith) and recycle end-of-life items, converting them into raw material for 3D printers, thereby closing the material loop. In this frame, understanding if and how the LCM process proposed by Lithoz is suitable for processing feedstock material obtained by means of a recycled system is one of the critical and more challenging further steps in LCM technology implementation for future Space missions. Indeed, not only the recycling capability could lead to a significant save of materials and spare parts demand, but also it could mitigate Space debris, hence turning a problem into a valuable asset. In this frame, it has been estimated that the combination between in-situ manufacturing and recycling can lead to a 90 % reduction of the amount of resources that need to be transported to a Space destination (Owens, 2016).

For LCM printing, with lunar regolith simulant or other ceramics, it could be shown that 90 % or more of the suspension fed into the printer could be converted into green parts. Moreover, it was possible to demonstrate that printed green parts can be again recycled to use regolith or other ceramic powders as starting materials for feedstock preparation. This can be of relevance in case support structures need to be printed or if flawed green parts are produced. Moreover, this recycling step allows to reclaim the portion of suspension (approximatively 10 %) that is not converted into a 3D green part (losses can occur due to adhesion issues or during printed green parts cleaning procedures). The cleaning process itself was also investigated in detail. Here, special attention was paid to a solvent-free cleaning rout employing only pressurized air. Especially for simpler geometries without any channels or cavities, where all the part surfaces can easily be accessed from outside, this approach turned out to be very efficient. For more intricate and complex part designs, the additional use of a solvent was beneficial or even necessary. Recycling of used solvent could also be verified by a simple sedimentation process, by storing the used solvent in a container and let the particles settle over time. However, the development of a method for the collection of the solvent during cleaning was not a subject of this activity.

Using the brick design, which was also used as demonstrator (see Figure 5.1), as functional unit, a very basic life cycle assessment focused on the ALM process was performed. This model only considered the manufacturing of the parts without taking into account the production of raw materials, transport, or the end-of-life of the produced parts. The degradation products were calculated relying on full oxidation of the binder components as in the case under air environment, as no data on other relevant atmospheric conditions were available.

7 DEMONSTRATOR PARTS

Demonstrator parts have been realized according to the customized process, in particular for the slurry preparation (binder types and proportion) and for the required post-processing steps. The selection of the demonstrator parts has been and will be in the future coordinated with ESA to be representative of a meaningful usage on the Moon (e.g. heating system, electrical insulator, medical applications, etc.). Demonstrator parts have been printed as proof of evidence of the achieved quality, trading a conventional process flow with simplified/alternative choices. In Figure 7.1, some demonstrator parts printed with the Lithoz LCM process using LHS-1 can be observed. The following parts have been sintered at 1100 °C with a dwelling time of 2 hours:

- 6x small bricks (compression test, thermal testing on demonstrator) sized 17.5 x 12.0 x 14.0 mm^3 (length x width x height);
- 1 x mesh filter structures sized Ø = 12 mm & height = 10 mm, with a pore sized 1 mm.

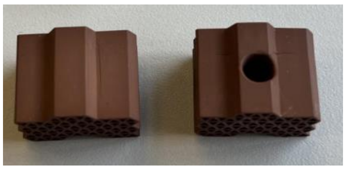


Figure 7.1 – Demonstrators parts realized (filter mesh on the left, brick on the right).

What has been concluded in this project after the realization of the aforementioned demonstrator parts is that the LHS-1 lunar simulant samples can be fabricated using LCM technology, reaching a wall thickness of up to 6 mm during thermal post-process treatment in order to obtain crack-free samples. Thus, it has been concluded that LCM process can be considered feasible in processing lunar regolith highly complex samples with high quality in terms of both resolution and accuracy.

Moreover, the intended goal was to show that LCM was able to cover a wide size range of final parts, at the same time exhibiting a significant and profitable flexibility in the materials to be processed. ESA agreed to assess the possibility to characterize the printed samples for thermal proprieties (e.g. linked to the function of thermal application) and specific function (e.g. torque for the screws). These extra activities could be carried out at ESA, to be confirmed after internal discussion.

In addition to the demonstrator parts previously showed, another set of testing items has been manufactured for further characterization at ESA/ESTEC on the thermal conductivity:

- 5 samples for laser flash apparatus (LFA) d=6 mm and h=1.5 mm;
- 5 samples for hot disc d=10 mm and h=2.5 mm.

However the potential application of the LCM are not limited to the lunar regolith processing, but to several ceramics type. In the view of long-term presence on the Moon and need of in situ components made of ceramic the process can cover biomedical applications as well as critical components such as impeller, drilling head or heat sink.

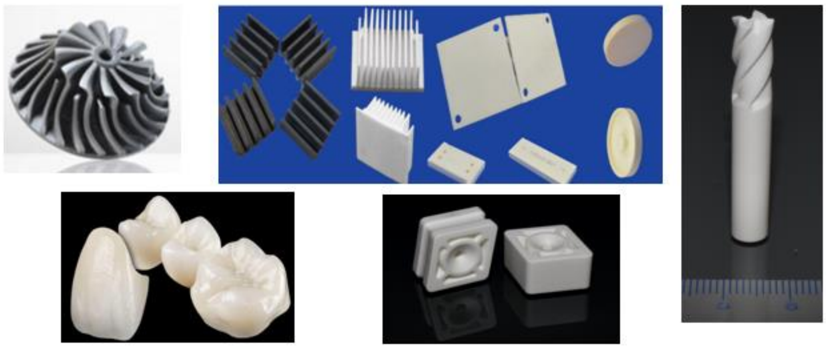


Figure 7.2 – Future likely ceramics demonstrator parts.

7.1 Applicability of LCM Process to Other Materials

After the assessment of the manufacturing process, the applicability to other materials, despite the regolith ceramic, has to be evaluated. This investigation will exploit the advantage of the lithography in building highly accurate parts to enhance the portfolio of products for the Off-Earth Manufacturing. It is worthwhile to mention that in the view of a manned Moon base, the possibility to print with ceramics for biomedical applications is crucial to provide precise, bio-compatible or even bio-resorbable parts to support medical treatments. Typical medical applications for 3D printed ceramics would be in the dental field or as a bone substitute material like implants (either bio-resorbable or non-resorbable).

Figure 7.3 – Ceramics material portfolio for LCM.

Lithoz 3D printing systems can process not only ceramic suspensions, but also metal suspensions, plastic suspensions or unfilled photosensitive resins are possible to be processed. The special vat construction makes it possible to process all kind of photosensitive low, normal and high viscosity materials with the known high accuracy and quality. Lithoz is specialized in adapting the 3D printer on the customer needs. Lithoz can adapt the printer size, the process chamber (e.g. closed system) and the required software features. Furthermore, it can provide different light sources (DLP, laser or other), wavelength (UV, near UV or visible light), and the related photosensitive binders. Finally, Lithoz developed a multi-materials 3D printer to combine different ceramic materials or material classes (ceramic – metal or different composites for solid state batteries, functional materials etc.) with each other.

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