LEMON
Executive Summary Report

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1 INTRODUCTION

1.1 Scope

The Lemon project, '**L**ithography M**e**tal **Mo**o**n**', was conducted under ESA contract No. 4000134145/20/NL/GLC. The project explores how to adapt Lithography Metal Manufacturing (LMM) to process scrap metal with lunar regolith contamination in a 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.

This document is the Executive Summary Report of the **LEMON** 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 [RD06].

1.2 Application

One of the major challenges in implementing and maintain a permanent Moon base is the need for a constant input of consumables including not only food/water/oxygen for the crew but also provision of module elements, power generation, module interior fittings, laboratory resources, medical facilities etc. All these needs require a major logistics implementation when they have to be transported from Earth. The possibility of reducing this Earth dependency by making maximum use of both existing lunar surface materials and re-cycling of lunar base materials will represent the only programmatic solution to assure a sustainable settlement.

In this framework, a novel lithographic printing technique (called Lithography-based Metal Manufacturing -LMM) for processing metallic powders will be an asset to pave the way in this direction. In contrast to the currently predominantly used powder bed fusion (direct metal laser melting) techniques, this process uses a paste/suspension as feedstock and, hence, does not rely on the use of highly-spherical gas atomized powders. This will enable the utilization of recycled powders from scrap metals that are available at Moon bases and provides higher flexibility in accepting raw material with poor quality and purity.

LMM can be used as a complimentary technology to other AM-solutions, such as Direct Metal Laser Sintering, as it also represents a great advantage when focusing on smaller, more complex parts, which require a high feature resolution and improved surface quality. The process can be used to directly produce parts in a small-scale series or to manufacture prototypes to mitigate risks on the final production.

To achieve this goal, in the frame of LEMON project, Incus tested if recycled metal powder can be printed, with lunar regolith simulant contamination, while maintaining a proper part quality. Additionally, a green binder has been developed and the pre- and post-processing steps were optimised, leading firstly to ASTM printing and testing and subsequently to selection, printing and testing of different demonstrators for future lunar applications.

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]	ESA-TECSF-SOW-018347	1.1	STATEMENT OF WORK "Discovery: Permanently Open Announcement of Opportunity"

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]	HSF-OHB-TN-0008	01	Scrap metals as processable material for LMM (TN1 – WP200)
[RD02]	HSF-OHB-TN-0013	02	Sintering process adaptation for LMM (TN2 – WP400)
[RD03]	HSF-OHB-TN-0015	01	Process adaptation test plan (TP1 – WP300)
[RD04]	HSF-OHB-TN-0014	02	Samples characterization test plan (TP2 – WP400)
[RD05]	HSF-OHB-TN-0016	02	Sample characterization and process sustainability (TN3 - WP400)
[RD06]	HSF-OHB-RP-0011	01	LEMON Final Report

2.3 Abbreviations & Nomenclature

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

Table 2-3: Abbreviations & Nomenclature

Abbreviation	Meaning
AD	Applicable Document
ALM	Additive Layering Manufacturing
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
CI	Configuration Item
DLP	Digital Light Processing
DMLS	Direct Metal Laser Sintering
ESA	European Space Agency
FFF	Fused Filament Fabrication
GD	Generative Design
LCM	Lithography-Based Ceramic Manufacturing
LMM	Lithography-Based Metal Manufacturing
MIM	Metal Injection Moulding
OSIP	Open Space Innovation Platform
RD	Reference Document
SLS	Selective Laser Sintering

3 LEMON STUDY OVERVIEW

3.1 Study Framework

The most diffuse process to realize high volume and complex parts in metal is the Metal Injection Moulding (MIM). The window of economic advantage in MIM parts lies in a combination of high design complexity and high production volumes for small-size parts, and the final products are used in a broad range of industries, including medical, dental, firearms, aerospace, consumer electronics and automotive applications.

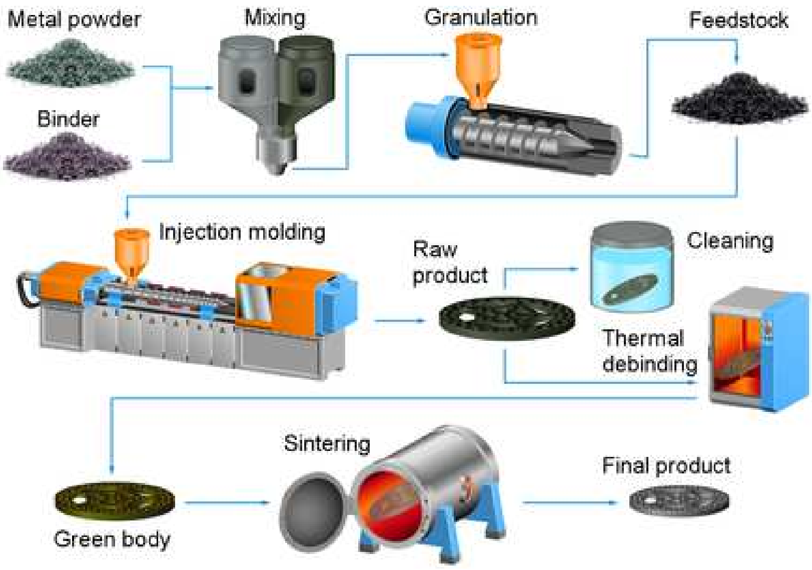

Figure 3-1: A schematic of the Metal Injection Moulding process.

The process, as represented in Figure 3-1, combines metal powders with polymers such as wax and thermoplastic binders to produce a feedstock mix that is injected as a liquid into a mould using a modified polymer injection moulding machine. The moulded "green part" is then cooled and ejected from the mould. Then, a portion of binder material is removed using solvent, thermal furnaces, catalytic process, or a combination of these methods. The resulting fragile and porous part is referred to as the "brown part". This "brown part" is then heated to temperatures near its melting point in a protective atmosphere furnace to densify the particles using capillary forces, in a process called sintering. The solid metal end-product has comparable mechanical and physical properties with parts made using conventional metalworking processes.

However, as the high initial costs of the injection moulding tool limit the field to high-volume applications, sinter-based Additive Manufacturing processes are looking to replace the injection moulding step of MIM by Additive Manufacturing the individual "green part". It is worthwhile to examine the manufacturing options for individual components using LMM technology. In addition to the economic aspects, however, time advantages or greater flexibility can also have an impact on the selection process of the manufacturing technology, where LMM technology has clear advantages over tool-based MIM technology (Metshape).

Lithography-based manufacturing methods fall under the ISO 52900 category vat-polymerisation. It allows the printing of many different materials with excellent surface properties. Metals, including non-weldable alloys, ceramics and polymers can be printed without the need for highly spherical gas atomised powders. Lithography-based manufacturing is also ideal to produce biomaterials. This versatility makes this method very suitable for a future lunar or Martian base. Thus, towards the desired degree of precision and performance, LMM is a remarkable option as it is widely discussed in the present study.

3.2 Scope, Main Objectives and Challenges of the LEMON Study

The aim of the **LEMON** (**L**ithography M**e**tal **Mo**o**n**) project is twofold: on the one hand, the goal is to demonstrate the feasibility of using the LMM technique with lunar regolith contaminated scrap metal 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 a lunar perspective, keeping account of all the difficulties that such a demanding and harsh environment poses.

LMM can be used as a complimentary technology to other AM-solutions, such as Direct Metal Laser Sintering, as it also represents a great advantage when focusing on smaller, more complex parts, which require a high feature resolution and improved surface quality. The process can be used to directly produce parts in a small-scale series or to manufacture prototypes to mitigate risks on the final production. Like other additive manufacturing processes, undercuts, cross bores or internal contour-adapted cooling channels are also possible.

In this frame, as a starting point, LMM process has been tested with lunar simulant, 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 LMM combined with lunar regolith feedstock deserves to be investigated is that if ALM as a general technology is already known to be resource-efficient, LMM is recognized to be a very materials- and energy-efficient variant of this family of technologies.

The overall project objective is to assess the feasibility to process Moon available scrap metals to achieve a high-quality final product via Zero Waste LMM process and optimize the binders' quantity and type to have a sustainable manufacturing chain.

The Figure 3-2 represents all the production elements and iterations to be assessed in the frame of the project. The goal of the LMM workflow is to produce ready-to-use components, without complicated post-processing and in a save and operator-friendly setup. Besides energy, the two consumables of the LMM printing process are the binder and the metallic powder. To setup a full recyclable workflow, both ingredients should ideally be reusable directly or after an effortless pre-treatment.

Figure 3-2: Zero Waste LMM Workflow.

3.3 LEMON Contribution to In-Space Metal Manufacturing and Roadmap

The innovation of the LEMON study is based on the advantages in reusing scraps metal and the high accuracy of the final production. Moreover, the process, which can also cope with lunar dust/regolith contamination, is versatile and can be applied to other materials group, not limited to the metals. This represents a significant step forward in the development of Off-Earth manufacturing capabilities. In fact, both the capability of express procurement on the Moon directly using available in-situ resources like scrap metals with lunar regolith contamination, and the possibility to make this process low resource- and low crew time-demanding are unprecedented and, therefore, on the other hand present several challenges that must be addressed, in particular when it comes to translating an existing and relatively well-known Earth application in lunar perspective, considering the peculiar environment characterized by reduced gravity level, significantly increased radiation exposure and challenging thermal management. Several challenges remain before the full potential of on-orbit manufacturing can be realized. The LMM will provide an innovative approach to the achievement of this goal, providing the possibility to print accurate and complex structures made of metals.

In Figure 3-3, a preliminary display of potential demonstrator parts obtained via lithography metal manufacturing is reported, showing the high relevance of this project in the perspective of life support systems for a future lunar crewed self-sustainable outpost. In the same Figure, are reported other possible demonstrators, qualitatively proving how the LMM process can ensure that the 3D-printed components maintain the same functionality, exhibiting high level resolution and accuracy.

Figure 3-3: Potential lithography metal manufactured 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. 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.

Thus, the utilization of the Moon seems to be the next logical step in implementing the global strategy for human exploration of the Solar System. The key to a sustainable human presence on the Moon is the ability to manufacture necessary structures and spares in-situ and on-demand, becoming in this way independent from Earth dependence. In the following scheme, the expected roadmap for LEMON project has been reported.

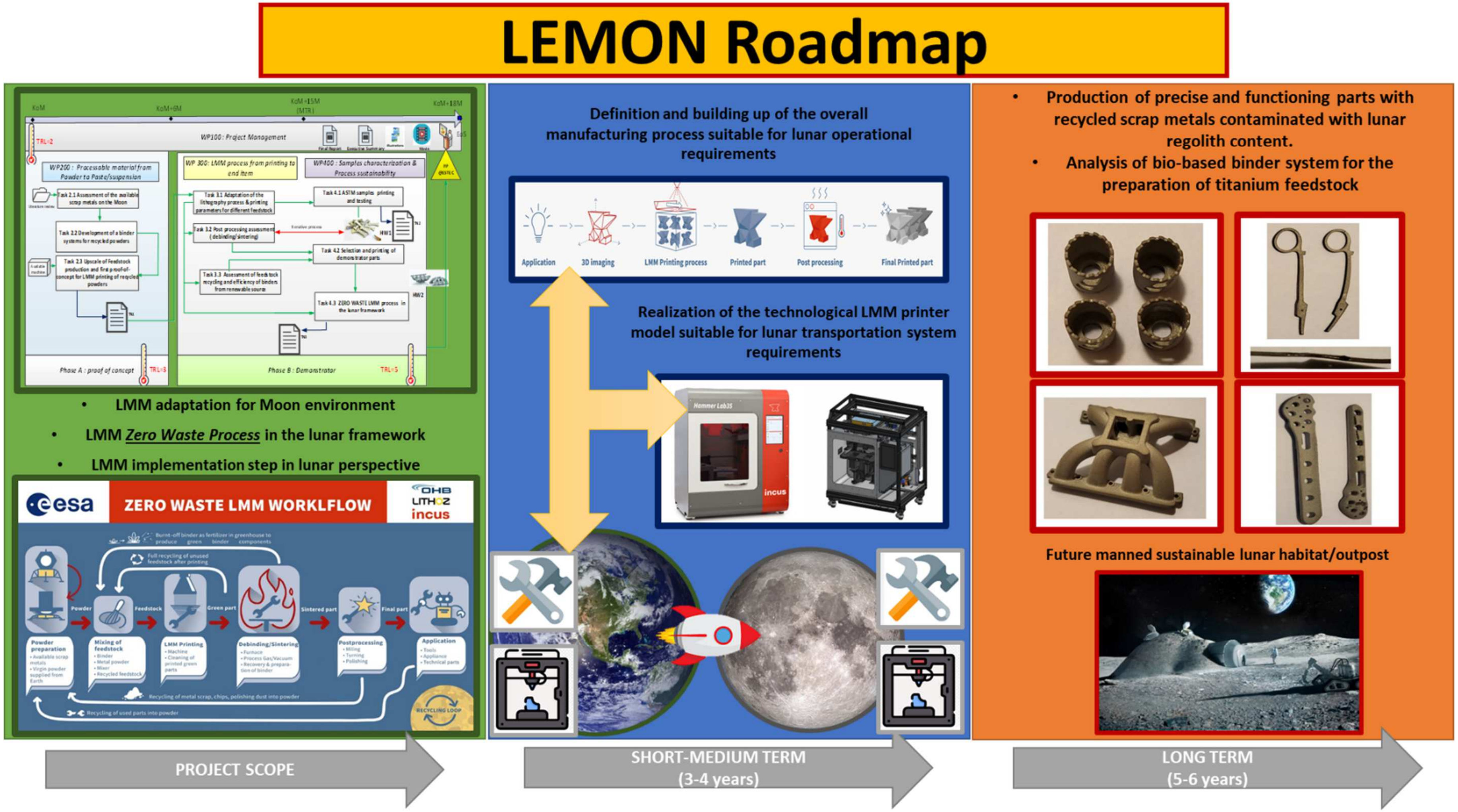

Figure 3-4: LEMON expected roadmap.

4 LEMON TECHNOLOGY ASSESSMENT

4.1 LMM printing process

The LMM process was carried out using Hammer Lab35 printer (Figure 4-1).

Figure 4-1: LMM machine for metal 3D-printing.

A novel LMM process was developed by the founders of Incus and is based on the principle of photo polymerization, where metal powder is homogeneously dispersed in a light-sensitive resin and selectively polymerized by exposure to light. The Figure 4-2 represents the manufacturing flow, the LMM is a two-step process: the production of the green part and then post processing steps (debinding and sintering) to achieve the final metallic properties.

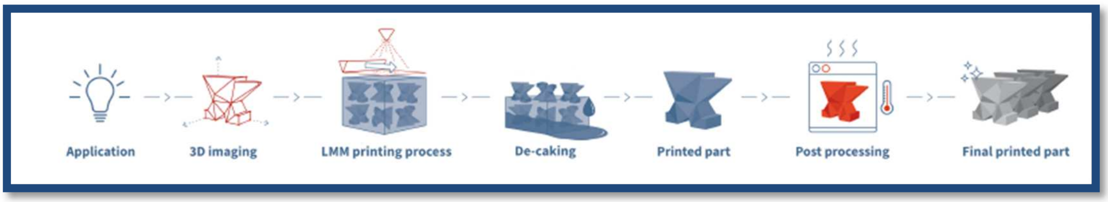

Figure 4-2: Lithography based Metal Manufacturing (LMM) process steps.

The Incus machine set-up is showed in Figure 4-3.

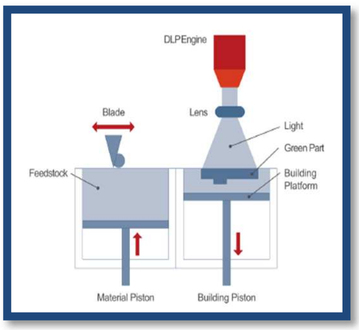

Figure 4-3: Incus machine set up.

4.2 Selection of virgin and recycled/mixed powder to check differences in printing behaviour

In the framework of the assessment of the current potential metal sources on the Moon and the materials used during the production of the current spacecraft generation, the selected materials to be used as metal powder for the study were: stainless steel, aluminium alloys and titanium. The standard photopolymerizable binder systems developed by Incus are versatile components for various metal powders which are commonly used in Metal Injection Molding. The optimal proportion of the powder with respect to the amount of binder depends on the different type of metal, powder particle size and distribution or particle shape. It is also desired to have as high metal content in the feedstock as technically possible, as it has positive effects on the physical properties of the final part after debinding and sintering. In the frame of LEMON project, feedstocks with different combinations of metal powders percentages and binder types, also considering regolith simulant contamination, were measured in terms of rheological behaviour. The depth of cure of the chosen formulations are tested in conjunction with the rheometer measurements. Various demonstration green parts were printed using the Ti and Al containing feedstock. Both the standard Ti TLS and the recycled Ti MW could be printed with the same process parameters. The microscopic evaluation of the green parts proved the previously established theory that the recycled powder has rougher particle surfaces. However, the definition of the printed green parts are excellent and small components, such as the example nozzles (Figure 4-4) were also possible to print with good quality.

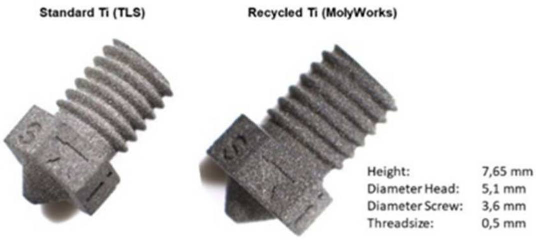

Figure 4-4: Ti green parts of small nozzles.

The amount of regolith, 10%$_{vol.}$ in the system was excessive and optimally should not be reached in the lunar production cycle. Furthermore, the regolith powder contains particles with diameters exceeding the printing layer thickness, causing surface defects on the green parts (Figure 4-5).

Figure 4-5: Ti green parts and the effects of the regolith contamination on the surface quality.

The feedstock with 50%$_{vol.}$ Al6061 was printed with the same processing parameters as the Ti TLS and Ti MW feedstocks. The produced green parts have excellent resolution and good surface quality (Figure 4-5). However, the debinding and sintering of the LMM-printing produced Al green parts is not an established process and the final parts currently do not reach desired industrial qualifications.

Figure 4-5: Al green parts.

5 SINTERING PROCESS ADAPTATION FOR LMM

5.1 Post Processing Assessment (de-binding / sintering)

Binder MB111 was not previously used for Titanium printing; therefore, an assessment of its debinding and sintering performance has been performed. The fabricated green part samples have been sintered and evaluated (particularly in terms of relative density and carbon content) by two service providers: Metshape GmbH and Element 22 GmbH.

Initially, green parts with 55%$_{vol.}$ commercially available titanium powder were fabricated and sintered.

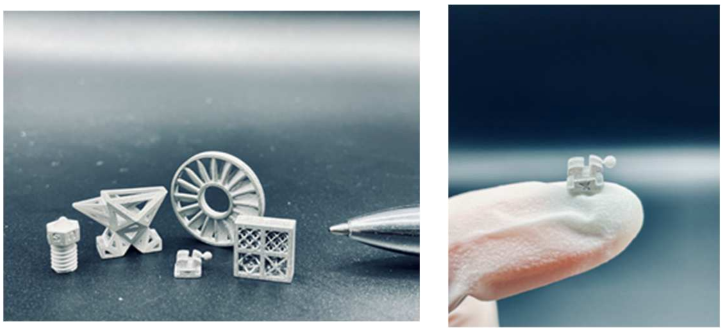

Figure 5-1: First sintering results with MB111 and standard, commercial Ti_6Al_4V.

Subsequently, other samples were printed using MB111 binder with 50%$_{vol.}$ of different powders: standard commercial Titanium (i.e., Ti reference), recycled Molyworks Titanium (i.e., Ti recycled), and recycled Titanium contaminated with 10% regolith added to the feedstock. Finally, an evaluation of samples printed with the P18 binder versus the ones printed using the MB111 binder has been performed.

The results of these tests clearly show that the final properties of the sintered parts significantly depend on the process parameters of the debinding and sintering.

6 ASTM TESTING

6.1 ASTM printing

Parts for mechanical testing were printed and sintered with the different feedstocks using TiB4 and P18 binders, commercial and recycled Titanium powder at different volume percentages, and also with 2% regolith simulant contamination.

Currently, there are no available ASTM standards for sinter-based metal additive manufacturing, therefore, parts and measurement standards were chosen according to the prior measurements' knowledge of Incus and Lithoz, respectively.

For the testing, the following samples were printed with all the previously mentioned feedstocks:

- Five pieces of 5 x 5 x 5 mm cubes and 10 x 10 x 10 mm cubes for sintering shrinkage characterization, respectively.
- Type 5A tensile test specimens according to the ISO 527 specification in two orientations. Built in Y direction ("laying"), parallel and 90 degrees rotated ("side standing") positions.
- Three-point flexural step samples according to the ISO 843-1 specification in two orientations. Built in Y direction ("laying"), parallel and 90 degrees rotated ("side standing") positions.

6.2 ASTM testing

In the framework of Task 4.2, the following tests on the feedstocks and the sintered parts have been conducted:

- Rheometry analysis of the fresh and recycled feedstocks.
- Sintering shrinkage evaluation.
- Tensile test measurement.
- Three-point flexural test measurement.

6.2.1 Rheometry analysis

Firstly, the freshly-mixed feedstock systems were measured. The results showed that utilizing recycled Titanium for the process increases the viscosity compared to the pristine powder charges. TiB4 have higher viscosity than the respective P18-based systems. Interestingly, by grinding the regolith simulant to the powder size distribution of the Molyworks Titanium powder, the viscosity does not get altered significantly with the contamination.

As the P18 system is not optimal to be used for Titanium debinding and sintering, feedstock recyclability analysation was performed only on the technically more promising TiB4 system. The rheometry measurements showed that the viscosity of the recycled feedstock containing commercial Titanium powder increases slightly.

The printability trials with recycled feedstock showed both with commercial and recycled Titanium five times full re-printability, so it can be stated that the viscosity changes do not affect significantly the process. With these results, it is verified that the TiB4 system can be used in a zero-waste circular economy environment.

6.2.2 Sintering shrinkage evaluation

There was no considerable change in the shrinkage characteristics on the two different sample sizes in the case of each feedstock.

6.2.3 Tensile test measurement

During the measurements, high deviation levels could be experienced, which caused by non-uniform pore structure in the final parts. This shows that the developed sintering curve is a sub-optimal process for the wall thickness of these parts. Furthermore, the elongation (E) properties are poor, especially in the case of the P18 system. The improvements of the binder components from the P18 to the TiB systems, indeed, show potential to reach component quality of on-Earth industrial standards using recycled Titanium powder charges with further development efforts. This evaluation comes from the high Young modulus results of the TiB4-recycled Titanium system, which imply that the stress characteristics of the produced parts are closer to the metal injection molded Titanium parts, before the early fracture. However, the regolith contaminated samples currently are too brittle to conduct the measurements and gain valuable results. The brittleness comes from the non-uniformity of the parts, as the regolith simulant behaves as the crack propagation site for the fracture mechanics.

6.2.4 Three-point flexural test measurement

The results showed that the printing orientation has not a considerable effect on the part strength post-sintering. The parts produced from the P18 based feedstocks showed high level strength, close to the metal injection molded Titanium parts standards according to literature. According to this result and the tensile test measurement results of the P18-based system, the increased carbon content in the sintered parts does not substantially diminish the mechanical properties in the level as originally expected. The TiB4 system with reference to Titanium powder showed lower strength results. However, if recycled Titanium (MW) is used, the 3P-bending strength interestingly reaches similar levels as the P18 system. However, adding the regolith simulant contamination to the system introduces inhomogeneity, which negatively affects the fracture mechanics, resulting in the fact that the mechanical properties of these parts in this measurement is poor, similarly to what happens during the tensile test.

7 DEMO PART SELECTION AND PRINTING

7.1 Demo part printing

For the desired potential out-of-Earth applications, the following parts have been selected as demonstrators:

- Circular saw.
- Drill bit.
- Medical equipment parts (surgical clamps and bone plates).
- Swagelok fitting.
- Small exhaust manifold.

These parts could be used on a possible scenario of a Moon base, with the possibility to be 3D-printed, in order to have dedicated ad-hoc components or replacing damaged parts in situ.

Concerning one of the research activities on the Moon, the possibility to perform soil sampling would be of interest. Therefore, one of the selected demonstrator parts was a circular saw sample with a 10 mm diameter. As the previous part, common-used drill bits are consumable components that are typically susceptible to degradation, thus, the next demonstrator decided to be produced was a drill bit part. Other parts that might be useful on a future Moon base would be medical equipment parts, such as surgical clamps and bone plates. Therefore, these two parts were chosen as demonstrators as well. Finally, one possible field of application for the LMM process would be fluid transfer components on-site. For this reason, a commercial Swagelok fitting and a small exhaust manifold have been selected.

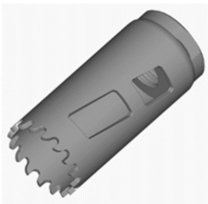

Figure 7-1: Demonstrator parts: circular saw sample.

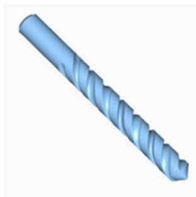

Figure 7-2: Demonstrator parts: drill bit.

Figure 7-3: Demonstrator parts: surgical clamps and bone plates.

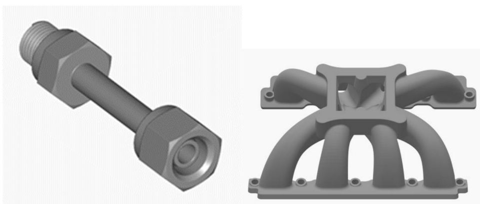

Figure 7-4: Demonstrator parts: Swagelok fitting and a small exhaust manifold.

7.2 Demo part printing

In order to print the demonstrator parts, the optimal print parameters, determined during Task 3.1 of the project for both the TiB4 system and the regolith simulant contaminated feedstocks respectively, were used. As the mechanical properties of the P18 based system were worse compared to the TiB4 counterparts, only TiB4 was chosen as binder component to produce the demonstrators. The samples were produced using the feedstocks of commercial TiB4, the TiB4 with 55%$_{vol.}$ recycled Titanium (MolyWorks) and 2% regolith simulant contamination.

The sintering process for these parts were the same as it was determined during the binder development. However, it is important to note that during the parts manufacturing processes on-Earth, the debinding and sintering is altered according to the desired part geometries and attributes, such as wall thickness, weight, and surface area. Furthermore, unique geometries necessitate uniquely designed sintering support structures to avoid deformation due to non-uniform shrinkage. As well as the desired parts must be designed with the manufacturing and the sintering processes in mind.

The circular saw parts in all feedstock cases showed post-sintering deformation. As this deformation is not uniform and parts with circular bores can be exhibited, the error is related to sintering shrinkage. During the densification process, the high, but thin wall contorted due to the gravitational effects, which caused elliptical shape of the bore in the final parts.

Figure 7-5: Demonstrator parts printing: circular saw parts in all the different feedstock cases.

The drill bits were also deformed, the parts were not linear. The reason for this is the parts' dragging caused by the shrinkage on the surface of the ceramic plate on which the parts stand during the entire sintering process. This, together with the high thickness of the bits, cause the curving of the part.

Figure 7-6: Demonstrator parts printing: drill bit parts in all the different feedstock cases.

Surgical clamp was printed as a two-part system to allow the movement of the clamp post- sintering. The same longitudinal deformation occurred in the case of the drill bit has been experienced also in these parts. Furthermore, the hole, where the two halves of the clamp should interconnect, showed the gravitational effect and deformed to the point of not serviceable.

Commercial Titanium | Recycled Titanium (MW) | Recycled Titanium (MW) with 2% regolith contamination

Figure 7-7: Demonstrator parts printing: surgical clamp parts in all the different feedstock cases.

The bone plates showed good geometrical stability after sintering. This is caused by the fact that the parts are not flat, so the previously mentioned dragging effect on the sintered plate is not that much pronounced or even absent. The only point in question in these parts is the black discoloration visible on the surface. That surface carbon build up is a known issue in Titanium sintering, and it is caused by the interaction of the Titanium and the support aluminium oxide surface.

Commercial Titanium | Recycled Titanium (MW) | Recycled Titanium (MW) with 2% regolith contamination

Figure 7-8: Demonstrator parts printing: bone plate parts in all the different feedstock cases.

During the printing of the commercial Swagelok fitting, it was discovered that the area between the body and the fitting nut is too small for the process in the original STL. Therefore, the part in this current design is not applicable for the LMM process. The part was only printed with the commercial Titanium and the recycled Titanium feedstock; regolith contaminated parts were not produced. In this sample the difference in the sinterability of the two powders can be visible, as the commercial Titanium powder-based specimen cracked during the sintering, while the recycled Titanium powder-based not. However, similar dragging-related strong shrinkage deformation can be seen.

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Commercial Titanium

Recycled Titanium (MW)

Figure 7-9: Demonstrator parts printing: Swagelok fitting parts in all the different feedstock cases.

The exhaust manifold part is designed with LMM printing and the sintering process in mind, thus the part geometrically stable, did not show unexpected or unwanted deformation. This shows that already in the design phase the manufacturing process must be taken into strong consideration.

Commercial Titanium

Recycled Titanium (MW)

Recycled Titanium (MW) with 2% regolith contamination

Figure 7-10: Demonstrator parts printing: exhaust manifold parts in all the different feedstock cases.

Based on this work, it can be concluded that: the bone plate and the circular saw are close to final application, in this case slight sintering improvements and support changes would provide good parts. However, the material properties in the current state would not allow usability of these parts. The Swagelok fitting replacement would have high potential too with design iterations. At the current stage, the exhaust manifold is the only suitable part for the current technology readiness level, as it is not a load-bearing application, and therefore the poor mechanical properties would not negatively affect the practicability.

8 ZERO WASTE LMM PROCESS ON THE MOON

8.1 Impact on the LMM Terrestrial Machine Design

The lunar environmental conditions influence the design of any mission aimed for the surface of the Moon in various ways and to different degrees. This is not different for the Hammer Lab35 printer and its operability. The specific consequences are described in this section.

The biggest challenge for the design is the thermal environment as all parts of the printer will be affected. The very low temperatures will compromise any standard lubrication of the linear units and other moving parts (particularly in combination with vacuum). All materials also become more brittle, especially plastics, which reduces the structural strength. Furthermore, the large temperature differences during day and night as well as between the sun-exposed and sun-hidden sides will introduce stress to the structure due to thermal cycling. This affects also the accuracy of the printer. The thermal expansion coefficient of the materials has to be matched to reduce those problems.

Because the vacuum does not allow for convective cooling, all electronics would require dedicated temperature control systems to avoid overheating but also to prevent too low temperatures when the printer is not in operation. Additionally, outgassing would be a problem for the electrical and optical systems.

Electrical devices also are predominantly affected by radiation and need to be designed accordingly. Furthermore, lunar dust could create shorts and damage the electronics and all mechanisms and moving parts need to be protected from contamination. This requires that the whole printer is sealed.

However, not only the design of the printer is affected by the lunar environment but also the feedstock and the operation. If it is too hot, the feedstock becomes liquid and runs down from the material piston. Cold temperatures are not so much of an issue, but the thermal knife might need to be heated more to reach the desired viscosity of the feedstock to apply a new layer. The vacuum would actually be beneficial to the feedstock quality as it prevents air bubbles but would also have a non-uniform temperature in the print chamber as consequence. Additionally, the current layer couldn't be cooled with an airflow, but this might not be necessary anymore. The low gravity could cause the first few layers to warp up on the outside. It would also be unavoidable to have dust inside the print chamber, which could reduce the print quality.

Another aspect that will be influenced greatly by the vacuum is the usability of the printer. As explained before, LMM is a two-step AM-method. The green parts need to be cleaned and sintered after the print is completed. While these steps are easily done inside a laboratory, they will be more complicated with a space suit and extra-vehicular activities are (at least for now) always critical situations.

To summarise, because a sophisticated thermal control system is needed, a higher power input is required and the necessary shielding and sealing will make the printer more complex and heavier.

Three different possible scenarios for LMM facilities location on the Moon are discussed: on the surface of the Moon, inside a sheltered environment and in a habitat. It is evident that the preferred scenario to perform these kinds of activities is the third one which offers Earth-like operational conditions, that can significantly reduce the modifications to apply to the LMM process in a future lunar framework.

8.2 Printer Customisation

Beside all the challenges that the harsh lunar environment poses to a manufacturing process, the printer still has to survive the transport to the Moon. This means that mainly the weight and volume of the printer need to be reduced and it must be ensured that the launch loads do not cause any damage.

The printer also needs to be tested on a system level which, for example, would include a full vibration analysis dependant on the exact launcher used.

8.1 Future Challenges

8.1.1 Manufacturing

Before a modified version of the Hammer Lab35 can be used on the Moon, many other different aspects need to be considered first, apart from the changes to the printer itself.

The LMM process is still relatively new and more knowledge is necessary on how the various process parameters affect different materials. For this, test prints with a mix of different alloys and even of different metals should be done. Related to this, the regolith contamination should be further investigated. Accordingly, the binder formulation needs further evaluation to optimise the print process. Additionally, the base components for the binder should be organic so that optimally waste products from the food production cycle could be used.

Because LMM is a multi-step AM process, the debinding and sintering also need to be improved. Temperature and time have a great influence on the part quality and need to be controlled accordingly in the harsh and challenging lunar environment.

8.1.2 Recycling

Before a component can be printed, the raw material needs to be acquired first. A first problem is the collection of scrap material. The location of most anthropogenic objects on the Moon is well known, but the retrieval might be challenging because most of them are far from the South Pole.

Then, once the scrap parts are collected, they need to be ground and processed into powder. To produce a good quality powder for AM, the exact metal or alloy needs to be known. However, this is not always possible and becomes even harder when FGMs, composites or components with integrated electronics are considered.

9 CONCLUSIONS

The use of local lunar resources as well as the recycling of old spacecraft are essential for a sustainable and Earth-independent Moon base. Lithography-Based Metal Manufacturing is one Additive Manufacturing (AM) technique that offers many advantages in this regard because the metal powder does not need to be as ideal as with other manufacturing methods. Additionally, lithography-based manufacturing also can be used to print ceramics, polymers and biomaterials.

Through this project, it was proven that the LMM technology is able to use recycled powder sources for the feedstock material. Furthermore, contaminations for the powder sources are manageable, especially from the perspective of the printing process. During the earlier stage, Titanium as the material focus has been chosen, because of the availability of fully recycled grades in the Earth environment. This material shown technical difficulties during the sintering process, which resulted in poorer than expected mechanical properties of the fabricated parts. However, these material-related challenges can be solved with further research and development efforts, and the sintering process for Titanium will allow to reach the desired properties. Furthermore, it is expected that further developments in metal recycling technologies will open the avenue to metal materials with more settled sintering processes, such as recycled stainless steel.

The effects of the lunar environment on the Hammer Lab35 printer from Incus are various and differ in their severity. The vast temperature fluctuations, the vacuum and the dust have the greatest effect, but the influence of radiation and, to a lesser degree, meteoroids and seismic activity should not be forgotten. To avoid a complete redesign, it was decided to assume a use inside a habitat module. This means that only the launch requirements are of importance as the environment in the habitat would be comparable to the one on Earth and the reduced gravity negligibly influences the design and printing process. Therefore, mainly the size and mass of the Hammer Lab35 should be reduced and the structural integrity of all components during launch ensured.

With those aspects in mind, as well as the future challenges presented in the last chapter, upcoming research and development will be able to carry on and open up further the way towards a sustainable, manned settlement released from costly and not always timely Earth dependency.