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Fibrous Habitat Structure from Lunar Basalt Fibre

Hanna Läkk[a]*, Jürgen Schleppi[b], Aidan Cowley[c], Lauren Vasey[d], Maria Yablonina[d], Achim Menges[d]

[a] *ESTEC, European Space Agency, Keplerlaan 1, 2201 AZ Noordwijk, the Netherlands,* hanna.lakk@esa.int, advenit.makaya@esa.int
[b] *Institute of Mechanical, Process and Energy Engineering, Heriot-Watt University, Edinburgh Campus, EH14 4AS Edinburgh,United Kingdom,* js79@hw.ac.uk
[c] *EAC, European Space Agency, Linder Höhe, D-51147 Cologne, German,* aidan.cowley@esa.int
[d] *Institute for Computational Design and Construction, University of Stuttgart, Keplerstrasse 11, 70174 Stuttgart, Germany,* lauren.vasey@icd.uni-stuttgart.de, maria.yablonina@icd.uni-stuttgart.de, achim.menges@icd.uni-stuttgart.de
* Corresponding Author

Abstract

Most of the current state-of-art in-situ resource utilization (ISRU) technologies for planetary manufacturing of habitats and other civil engineering structures focus on the automated additive construction (AAC) systems. AAC enables the usage of a variety of materials found locally in a low-fidelity large-scale compressive structures. Different methods exist from slurry extrusion to sintering to melting techniques, with varying levels of difficulty, costs and technological readiness. However, when using additive construction methods in space environment a number of challenges arise, such as construction in a vacuum or low atmosphere as well as under reduced or zero/ milli-gravity. To bypass many of these issues the usage of in-situ produced fibres in manufacturing processes might provide a potential alternative to additive construction technology.

The objective of this study is to identify and develop promising fabrication methodology for a fibre based in-situ robotic fabrication process for potential use in a lunar habitat as an alternative to existing additive manufacturing technologies. One of the key advantages of using fibres in construction is a higher-fidelity of the manufacturing process due to the use of continuous filament and minimization of powders and liquids. It also enables the possibility of orienting and locating each fibre in the structure allowing local differentiation of material properties, and manufacturing of not only compression but also tensile structures.

The first part of the study discusses the production method of a basalt fibre from lunar regolith using microwave furnace. Loose regolith that is deposited into the furnace is melted under a number of microwave heaters and transported to a bushing, from where the fibres are extruded. The material properties of the fibres are specified through mechanical and thermal testing. The application of these fibres in a schematic robotic fabrication process of a habitat structure is discussed in the second part of the study. This construction sequence begins with a manufacturing of flat two dimensional frames which are then bent into position to act as a support and scaffold for the rest of the structure.

Keywords: basalt fibre, fibrous structure, computational design and simulation, robotic manufacturing, ISRU, space architecture

Acronyms/Abbreviations
AAC – Automated additive construction
ESA – European Space Agency
ESTEC – European Space Research and Technology Centre
ACT – Advanced Concepts Team
EAC – European Astronaut Centre
ICD – Institute for Computational Design and Construction
ISRU – Is situ resource utilization
AM – Additive manufacturing
FDM – Filament deposition modeling
JSC-1 – Lunar regolith simulant
JSC-2A – Lunar regolith simulant
MLS-1 – Lunar regolith simulant
MLS-2 – Lunar regolith simulant
SLM – Selective laser melting
LFA – Laser flash annealing
SSI – Space Studies Institute

1. Introduction

The current project was initiated by the Advanced Concepts Team (ACT) at ESTEC/ European Space Agency (ESA) in September 2017 in the framework of Ariadna study. Ariadna is a mechanism for collaborative research projects between ACT and academia [1]. The Advanced Concepts Team is part of the ESA's Directorate of Technical and Quality Management (TEC-SF). It is an inter-disciplinary research team that studies novel scientific and technological concepts that are of strategical importance in the long term planning of the Agency. The project was set up in collaboration with the European Astronaut Centre (EAC) and the Institute for Computational Design and Construction (ICD) at the University of Stuttgart. The EAC provides training facilities for European and international partner astronauts and is divided into six parts, such as Astronaut Training, Space Medicine, Astronaut Management, Human Exploration of the Moon as part of the Spaceship EAC initiative and Communications [2]. The ICD is dedicated to the research of computational design and computer-aided manufacturing processes in architecture, with a particular focus on robotic manufacturing methods [3].

1.1 Study motivation

Developing necessary technologies for in-situ resource utilization (ISRU) is the key for long-term exploration, broadening the extent of space activities and enabling settlements in space. The majority of research studies related to ISRU are looking into various Additive Manufacturing (AM) technologies based on regolith feedstock. AM provides different methods for the construction with regolith from extrusion to sintering and melting techniques [4]. These methods, however, face special challenges when applied in space environment. Construction in a vacuum or low atmosphere, under reduced or zero gravity and extreme temperatures sets its limitations on many of the AM techniques. While it has been successfully proven that it is possible to use filament deposition modelling (FDM) process in zero-gravity to manufacture small elements, such as crew tools and parts for life support systems [5], the AM technologies for powder or liquid resin systems could be problematic due to cloud-forming of regolith and spherical droplets of a binding liquid due to lack of atmosphere and low or lack of gravity.

Therefore the most promising methods for processing regolith into a structural material in space to date propose using solar, laser and microwave sintering [6][7][8][9][10][11]. A study has shown, however, that 3D printing with raw regolith comes with issues related to thermal stresses and variation within the regolith feedstock [12]. Another limitations of regolith structures produced by additive manufacturing is their low tensile strength due to the structure and layering of the material, making them fit for compressive loads only. Therefore, when using pure regolith the number of shapes and sizes the structure can take is limited.

To bypass many of these issues related to 3D printing with regolith the current study proposes a robotic manufacturing process using lunar basalt fibre feedstock to manufacture fibrous habitat structures. The autonomous manufacturing of fibrous structures has a number of important advantages compared to additive manufacturing with regolith when constructing habitats or other surface structures:

- A fibre based process enables the possibility of orienting and locating each fibre in the structure to allow local differentiation of material properties
- Better control of the manufacturing process due to the use of continuous filament and absence of powders and liquids, therefore higher-fidelity process
- Fibres can be successfully used in compression and bending-active structures through the use of additives as well as in tension active structures; therefore, larger variety of applications, for example pressure vessels which cannot be produced with additive manufacturing techniques
- Fibrous materials are highly formable which allows production of complex shapes in response to unique performance criteria or site conditions
- Fibre based or composite fabrication methods have demonstrated production of light-weight structures, important where large-scale, material efficiency, or mobility is needed
- Possibly better performance in response to thermal stresses

Basalt fibre, very similar to glass fibre, is a good candidate for use in lunar construction due to a number of beneficial properties [13]:

- Basalt-based materials are environmentally-friendly and not hazardous
- Simpler manufacturing process than that of a glass fibre due to less complex composition
- High strength and high modulus with excellent shock resistance
- Similar mechanical properties than glass fibres
- High chemical durability against the impact of water, salts, alkalis and acids
- High service temperature

In fact, many previous studies have shown that the fibres produced in lunar environmental conditions, such as high vacuum and low-gravity, may have higher tensile strength compared to those produced on Earth. This is due to two reasons. First, the materials on the Moon are known to be extremely anhydrous and hydrolytic weakening process will be inhibited in vacuum [14]. The other aspect is the lack of ferric oxide (Fe_2O_3) in lunar soil which is considered as contaminant to high-strength glass products [15]. Therefore it is suggested that lunar glass products could be competitive with, or even superior to, metals extracted from regolith, with considerably less processing effort.

1.2 Study structure and aims

The study is divided into two parts which run parallel to each other. The first part of the study focuses on the development of the manufacturing process for a lunar basalt fibre and the characterisation of the sample material related to its mechanical and thermal properties. The material study is done in collaboration with Spaceship EAC and Materials and Processes Section (TEC-MSP) at ESTEC/ ESA. The second part of the study looks into the application of lunar basalt fibre in robotic manufacturing process of a fibrous habitat structure and is carried out under the lead of ICD, University of Stuttgart (Fig. 1).

1.2.1 Lunar basalt fibre production

The first stage of the material study focuses on the manufacturing and testing of the material on a single fibre level. The basalt fibre samples are produced for initial testing using lunar regolith simulant. The tests determine the mechanical and thermal properties of the fibres. Later, an automated extruder will be developed which would convert raw lunar regolith simulant feedstock into fibres by controlling the conditions of the drawing process. The fibres produced will be again tested for their mechanical and thermal properties. The main aims of the first stages of material study are:

- Impact of variation of regolith feedstock composition on the fibres (including varying simulant regolith used)
- Impact of dopant material inclusion on the mechanical and thermal properties of the fibres
- Understanding of the critical process parameters (e.g. fibre pull rate, extrapolated mass to product metrics, etc) on the production of fibres

The second stage of the material study will focus on the fibre-resin matrix system on a composite level. The samples are fabricated by combining basalt fibre and matrix into a composite structure to test the influence of fibre orientation and the type of resin on the mechanical and air permeability properties of the composite. The composite samples are fabricated using layers of continuous fibre with specific orientation which are sealed with sprayed chopped fibre. Two different resin systems are used for the comparison. The aims for the second stage of the material study are:

- Impact of the fibre orientation on the mechanical and air permeability properties of the composite
- Impact of the type of resin on the mechanical and air permeability properties of the composite
- Impact of the composite layup structure on the mechanical and air permeability properties of the composite

1.2.2 Robotic manufacturing of fibrous habitat structure

In phase 1, precedent research will be conducted to summarize existing proposals for lunar in-situ fabrication, as well as to synthesize existing work in mobile robotics, computational design, and fibre-based robotic fabrication methods for potential implementation. Key constraints will be identified to be considered in the production and development of a fibre-based robotic fabrication methods for the Moon (radiation protection, impact protection, and necessary functional criteria). A conceptual design phase will assess which types of fabrication methods (robotic weaving, fibre extrusion) are feasible given existing constraints and the resulting types of structures that they can create. Particular consideration will be given to methods which minimize additives (such as resin), and processes in which it is feasible for the robot to execute the process autonomously or semi-autonomously in low gravity conditions. Potential site criteria will be identified for situating the fibre-based construction.

From this analysis, schematic proposals for in-situ fibre-based construction processes would be developed based on their viability. Initially, concepts for fabrication processes will be investigated digitally using computer aided design software, physics based or FEA simulation tools, and kinematic solvers which reveal functional limitations of a robotic setup or process. Initial designs concept models can be generated in order to estimate load bearing capacities utilizing simulation and finite element software.

In phase 2 and 3, the conceptual fabrication process and necessary hardware to enable the process will be investigated through a series of experiments. This phase will include end-effector and mobile robot development. During this phase, concepts will be investigated through small scale prototypes produced with custom end effectors on industrial robots, or small, mobile robots developed with task specificity. Computational workflows will be developed that generate the robotic toolpaths or robotic behaviour based on a particular unique site condition as well as structural viability.

The expected result of this study will be a developed concept for an in-situ robotic fabrication process for fibrous based construction. Important process considerations will be documented and described. Success of hardware, sensors, or computational process in enabling the fabrication method will be described. Mechanical properties of prototypes produced, when verified through experiments and testing, will be recorded and documented.

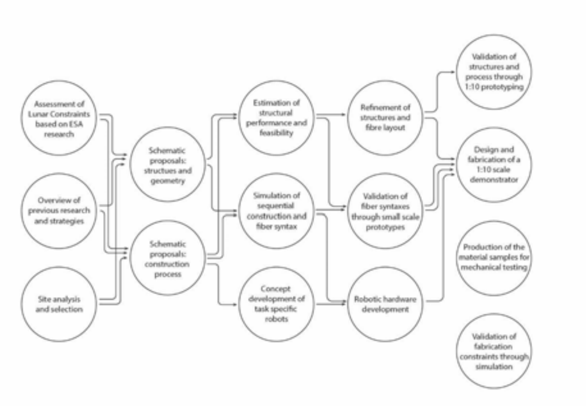

Fig. 1. Study structure of robotic manufacturing of fibrous habitat

2. Precedent research

The current section is divided into two main parts. The first focusses on the precedents on the material level by discussing previous work in lunar glass/ basalt fibre production. The second part handles the precursors for robotic manufacturing of fibrous structures. To our knowledge there exist no previous studies on robotic manufacturing of fibrous habitat structures in space, which is why the chosen precedents focus on Earth applications.

2.1 Studies about in-space manufacturing of glass/ basalt fibre

Research into in-space fibreglass production started in late 1970's. A number of studies conducted since then describe a set-up for the fabrication process of fibres, whereas the focus on the characterisation of extruded fibre properties is limited. To that end, Ho and Sobon [16] presented a conceptual design for fiberglass production systems in both lunar and space environments. The feedstock would come from the by-products of aluminium and titanium extraction which would include anorthite ($CaAl_2Si_2O_8$), slag from aluminium made up of 75% SiO_2, 15% Al_2O_3 and 10% CaO + MgO, and CaO from titanium. They proposed melting the mixture by solar energy in a multifurnace of a lunar plant. According to their estimations the solar concentrator would generate 1880kW of power and that the systems would reproduce about 90 times their total mass in fiberglass in 1 year.

Mackenzie and Claridge [17] did preliminary experiments on melting of oxide mixtures corresponding to the chemical composition of Apollo 11, 12 and 16 lunar soil samples. They used specially designed furnace to produce glass wool from regolith simulant.

Lewis and Taylor [18] describe in their study a fabrication process of a minimally processed composite material derived from Apollo 16 regolith simulant. The proposed composite is three phase: glass, metal and vacuum. The fibreglass threads are clued together by metal, with the in-between spaces 'filled' with vacuum. The metal would be made sticky through free surfaces, which would be created and maintained in high vacuum. The fibre extruder was built to draw 30 km of 30 µm diameter fibre from the reservoir, metal coat it with calcium and wind around a collecting reel.

Magoffin and Garvey [15] report on the progress of producing glass samples and fibres from simulated lunar soil provided by Space Studies Institute (SSI) of Princeton using a 75 kW thermal solar concentrator. They were able to produce 9 m long fibres with different fibre diameters. Tensile tests on a 25 µm fibre indicated approximate strengths of 5000 kg/cm² (70 000 psi).

Smith and Workman [19] used MLS-1 and MLS-2 regolith simulants in comparison to E-glass in their study. A reduced gravity fibre pulling apparatus was developed in order to study the effects of gravity on fibre formation. They were successfully able to produce E-glass fibre in simulated zero, high and lunar gravity environments. The final fibre diameter was affected by the g-loads by increase in diameter when the g-load increased. They also found that while MLS-1 had poor fibre forming properties, the MLS-2 doped with 8 wt% boric oxide (B_2O_3) was an optimal mixture for producing continuous high quality fibres, with a minimum diameter of 7.5 µm.

Tucker and Ethridge [20] had similar results in their fibre study to Smith's and Workman's. They used MLS-1 and MLS-2 simulants to extrude the fibres. They found that only MLS-2 doped with boric oxide was able to form continuous fibres, with an average diameter of 45 µm. The mean tensile strength of the fibres turned out to be 60 000 psi with a standard deviation of 17 500 psi. In the study of the effects of lunar gravity on fibre formation they concluded that gravity plays a role in crystallization and final fibre diameter.

In their later study, Tucker et al. [21] used JSC-1 simulant to produce lunar fibreglass for the reinforcement of lunar concrete. The simulant was able to form continuous fibres which were coated with a polyamide solution to protect the fibres from degradation and maintain the mechanical strength.

Ray et al. [22] described the properties of JSC-1A simulant in their research. He discovered that the simulant easily forms fibres and other glass products when melted and cooled at nominal rates between 50 and 55 °C/min. In addition, the coefficient of thermal expansion of the glass measured is in close agreement with that of alumina or yttria-stabilized zirconia (YSZ), which makes the glass suitable for use as a coating and sealing material on these ceramics.

Pico et al [23] were able to produce their own lunar simulants ITALUS-1 and ITALUS-2 for the study by melting commercial basalt together with some additives. The simulants were melted in a monofilament spinning machine and the fibre was extruded from the crucible. They found that ITALUS-2 was able to form more stable fibres than ITALUS-1. The diameter of the drawn fibres was 16.7 μm.

2.2 Concepts for robotic manufacturing of fibrous structures

Existing fibre based composite fabrication production methods in the aerospace and automotive industries primarily utilize moulds and other types of formwork, enabling the repeatable of production of identical components [24][25]. In contrast to other industries, architecture is a field which requires a high degree of customizability and site specificity, making mould based, repetitive processes inapplicable. Ongoing research at the University of Stuttgart by the ICD and ITKE with partner institutes has demonstrated that fibrous based construction processes can have several advantages over other production methods, particularly as viable construction strategies for a lunar environment. These demonstrators have shown that fibrous based material systems can be extremely lightweight and structurally performative. They also exhibit a low material packing volume, and the processes can be capable of a high degree of automation and customizability (Fig. 2.).

Particularly relevant for this study, are precedent demonstrators in fibre winding: where resin infused carbon and glass fibre rovings are incrementally wound around an initial minimal boundary formwork to make highly differentiated and structurally performative structures. In ICD/ITKE research pavilion 2013/2014, a series of fibre composite components were wound in between two reconfigurable steel end-effectors [26][27] and then assembled manually. A component based approach would be difficult to be applied in space because the complex tectonics between components require extreme dexterity and are ill suited therefore to automated production scenarios, where the robot must be able to achieve its task relatively autonomously with minimal troubleshooting.

In contrast, The ICD/ITKE Research Pavilion 2016-17 was achieved through a multi-robot fabrication process which resulted in the production of a single continuous long span composite cantilever. In this case, multiple robotic systems could interface, communicate, and collaborate to create a seamless fibre laying process. In the specific experimental set-up, two stationary industrial robotic arms with the strength and precision necessary for fibre winding work are placed at the extremities of the structure, while an autonomous, long range but less precise UAV is utilized to pass the fibre from one side to the other [28]. Additional investigations in custom bespoke robots attest to the importance of expanding the constraints of single robots through collaboration. In the Mobile Robotic Fabrication Eco-System project, three robots of two different types were deployed on-site to wind a large scale tensile filament structure, working in a team and counteract each other's limitations [29].

Fig. 2. Precedent examples of fibrous based fabrication methods for differentiated and lightweight structures. From upper left, clockwise. ICD/ITKE Research Pavilion 2013/2014. ICD/ITKE Research Pavilion 2014/2015, Mobile Robotic Fabrication Eco-System by Maria Yablonina of ICD, ICD/ITKE Research Pavilion 2016/2017.

One complication of adapting existing fibre winding strategies to in-situ space construction is that these examples are partially porous, and therefore unsuitable to withstanding high internal pressure. Thus, there is incentive to combine them with other systems with integrated membranes and foils acting as integrated envelopes. For example, for the production of ICD/ ITKE Research Pavilion 2014/2015, an ETFE pneumatic membrane was inflated, and through a sensor guided robotic extrusion process, was gradually reinforced with pre-impregnated carbon fibre until it became a stable shell, capable of withstanding high compression and bending forces [30].

While this fabrication process additionally has potential, one complication is getting the robot into the pneumatic, and developing an airlock where the robot could freely navigate between the interior and exterior. In addition, the production of the membrane structure would need to be produced ahead of time. Therefore, additional strategies for creating an enclosed surface, where a fibre scaffold is then covered with a layer of chopped fibres, are being investigated as a means to create an envelope capable of withstanding high amounts of pressure.

Adapting these strategies to a low gravity environment on the moon necessitates careful consideration on how the processes will be impacted by low gravity. Because these processes are tension active, the relative effect of the lack of low gravity is determined to be minimal, and can be replicated by manipulating the self-weight of the material, physically or in a simulation environment. This is an advantage over other additive fabrication processes, where adhesion and friction between the components due to gravity aids the process.

3. Building a habitat on the Moon

In the beginning of the project the location for the habitat was discussed, together with the environmental factors on the Moon. The location and the environment determined the functional requirements for the habitat structure which are described below.

3.1 Moon environment

The most obvious environmental factors to consider on the Moon are extreme temperatures, low gravity (about 16.6% of Earth's gravity) and a very thin atmosphere. Due to the lack of atmosphere, the temperatures on the Moon range between -150°C and +100°C at non-polar regions, and between -50°C (lit areas) and -200°C (dark areas) at polar regions.

In addition, other important factors determine the lunar environment. The lack of a magnetic field means that the Moon is constantly exposed to galactic cosmic radiation (GCR), solar winds and solar particle events (SPEs). The GCR can damage DNA and increase the risk of cancer, neurological disorders, cataracts and non-cancer mortality risks. Therefore, a shielding must be present to protect humans from this ionizing radiation.

Micrometeorite impacts are considered a medium-high risk. It is estimated that micrometeoroids of about milligram mass should be expected to strike lunar features as large as facilities and equipment almost yearly. Impacts by smaller objects will be more frequent, and by larger objects rarer. Although having an extremely high-velocity, the chance of micrometeorites directly hitting the astronauts is very small and the damages to habitats and infrastructure can be minimised. It is suggested that 2-3 millimetres of composite material is relatively effective in shielding against damage by micrometeoroids in the milligram mass range.

3.2 Habitat location

Three potential sites were initially considered for the habitat location: a lunar crater, a lava tube, and the moon surface. The lunar crater was selected because it minimized extra supporting structures, and also minimized the amount of time robots would need to manipulate the local topographic condition by removing or pushing around regolith. The thermal regulating capacities of surrounding regolith were also considered to be highly advantageous.

It should be noted that with further development, and with additional earth moving robots, these construction methods and structures could also be built with a pre-existing flat topographic condition.

3.2 Functional requirements

Due to the time constraints of the study it is assumed that the proposed robotic technology will function in the Moon environment without any adjustments. The required habitat structure should hold 4 bar of air pressure (safety margin for textile structures) and have a minimum of 300 m3 habitat volume (equivalent to accommodating crew of 4). Simplified environmental conditions, including only lunar gravity, temperatures, depending on the location, and vacuum, are considered as design constraints.

4. Methods

4.1 Basalt fibre production from lunar regolith simulant

For the current study on fibre manufacturing JSC-2A regolith was chosen as a feedstock. JSC simulant is a basaltic ash with a composition similar to many terrestrial basalts. JSC simulants are known to be most similar to the mare soils of the Moon in major element composition when compared to other simulants. Lunar soil, however, contains no water and has low abundances of volatile oxides such as Na_2O. In addition, lunar rocks were formed in highly reducing environments and contain iron only as $Fe2+$ and FeO [31]. It is also shown that the JSC simulant has good glass forming properties, making it an excellent candidate for fibre drawing [32].

4.1.1 Concept for in-situ production of basalt fibre

The process of lunar fibre production would be similar to basalt fibre production on Earth. To potentially consider basalt fibres as a resource in the in-situ manufacturing, the fibre extrusion process should be controlled and automatized (Fig. 3). The aim is to achieve a continuous basalt fibre production process which allows for winding up fibres onto rovings. These can then be used in robotic manufacturing of habitats and other structures. The ultimate process could look like:

1. Gather regolith
2. Melt regolith in furnace
3. Draw melt through a bushing with multiple nozzles

4. Fibre coating
5. Wind yarn on rovings

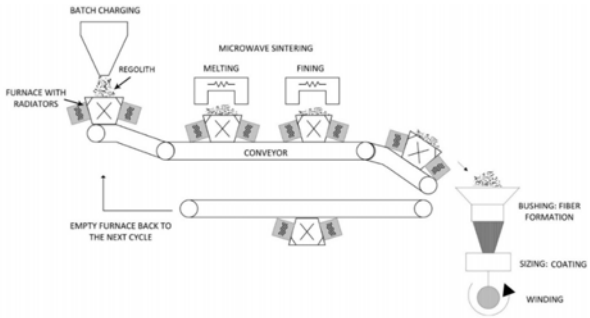

Fig. 3. Proposed lunar basalt fibre plant by F. Spina

4.1.3 Preliminary method for basalt fibre production

Preliminary tests were conducted to determine process parameters such as temperature, speed and crucible materials. The preliminary setup is depicted in Fig. 4 and shows how fibres were manufactured by casting molten regolith from a platinum crucible into a graphite mold. First about 100 gram JSC-2A regolith simulant where entered into a platinum crucible, which was then entered into an electric heated furnace. The regolith was heated from 20 °C until 1550 °C within 15 minutes until it was removed from the furnace. Next, the molten regolith was cast from the platinum crucible into the graphite mold until enough material had gathered in it and the temperature had dropped enough to form an "anchor". The actual fibres were created by steadily drawing the platinum crucible away from the mold until the temperature at the edge of the crucible drops close to solidification temperatures (approx. 1200 °C) and causes the fibre to snap. The speed with which the crucible was moved varied in-between 0.5 m/s to 2 m/s, where an increase in speed led to a decrease of fibre diameter and vice versa. However, the fibre diameter is not only dependent on the speed but also on the temperature of the regolith at the point in time when the fibre is being drawn. Hence further experiments will need to determine the ideal processing temperatures, speed and cooling times.

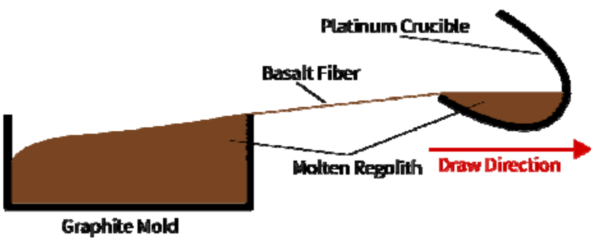

Fig. 4. Preliminary setup for regolith simulant fibre production

4.2 Robotic manufacturing of fibrous structure

Design and scientific development for viable structures and construction methods are currently being carried out in two stages: one through digital design studies, which utilize physics engines to simulate fibre to fibre interaction and physical manipulation. Structural feasibility and production constraints can be verified in this initial design phase, where the exact sequence of each fibre path can be roughly simulated to guarantee collision free movement between the robots and fibres in the scene.

Physical prototyping is used to validate these designs and processes on multiple scales. Small scale prototypes are being used to test the fibre to fibre interaction and construction sequences of design iterations. After initial prototyping on a small scale, larger prototypes are being wound with industrial robots, custom hardware, and mobile robots at a scale of 1:10, described in fabrication setup.

4.2.1 Digital design development methods

Not all surfaces can be fabricated using a fibre winding fabrication process, thus using a set of computational methods for deriving valid forms and their fibre syntaxes is an important step in initial design and concept development.

To computationally derive valid surfaces, it is possible to loft straight lines between minimal boundary curves, a technique used extensively in previous projects resulting in hyperbolic surfaces. A second set of valid structures can be considered where the first fibre layer is composed of initially straight lines, and subsequent layers are used to incrementally tension and pull down this initial integrated formwork. This strategy has been implemented previously, in ICD/ITKE Research Pavilion 2016/2017.

A third technique can be applied where an initial surface is derived through a process of dynamic relation. An approximate fibre syntax order can then be derived by combinatorically generating and analysing all fibres: fibres that produce ridges above the relaxed surface (i.e. local high points) need to be eliminated, and the remaining fibres then need to be placed sequentially where fibres high above the surface are placed first. This process does not always yield a valid result, but does enable the consideration of a greater of design space of possible fibre wound geometries, resulting in schematic structures which must be further refined by considering other constraints and performance criteria.

4.2.2 Preliminary concepts for structures and fabrication sequence

The main concept for the structure emerged by considering the range of possible windable geometries with the constraints of the potential sites: a minimal surface hyperbolic can be created over a crater site where compressive arches at the boundary can serve to lift the surface for inhabitation (Fig. 5).

To satisfy the necessary area, the structure would be constructed in a lunar crater with a diameter of approximately 30 to 35 meters, with a typical depth to diameter ratio of .12 to .17 [33][34]. Two flat composites would first be wound adjacent to this crater, and then subsequently bent into positon and secured with distributed composite screws into the edges of the crater. From here, additional reinforcement layers would stabilize the flexible bending active before a long span surface could be wound between the two arches at the perimeter. Layers of chopped strands of fibre in multiple directions would cover the scaffolding of previously laid fibres to create enclosure. The process could be repeated at a second height to create an interior cavity, or the surface could be covered with regolith for radiation and thermal protection.

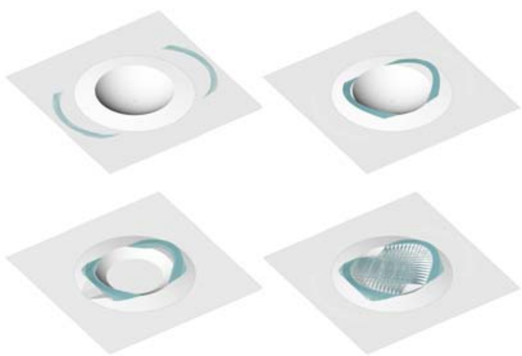

Fig. 5 Schematic concept for construction sequence

4.2.3 Fabrication process setup

Prototypes of the structure are being produced in a robotic lab at a scale of 1 to 10, where the diameter of the crater they represent is approximately 30 to 35 meters (Fig. 6). The fabrication process is combining existing infrastructure for fibre winding: including an industrial 6-axis KUKA KR 125/2, fibre-dip resin bath, with a custom developed end-effector for fibre winding.

Because of its low cost and availability as well as relative mechanical similarity to Basalt fibres, glass fibres are being used for early prototyping as a means to test and validate the fabrication process, construction sequence, and the resulting fibre to fibre interaction of physical prototypes. Because the structure is scaled down, certain constraints including robotic reachability can only be verified through simulations. Epoxy resin is currently being used as a matrix.

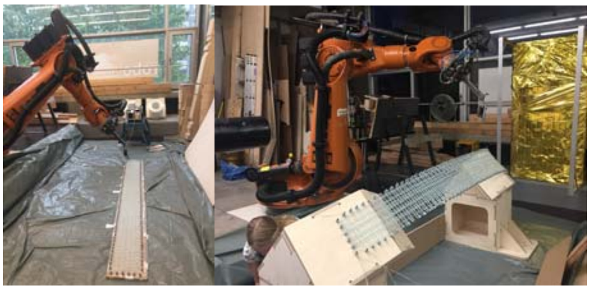

Fig. 6. Fabrication setup with 6-axis KUKA KR 125/2, fibre-dip resin bath, and 50k Glass rovings impregnated with HexionRIM135 Epoxy Resin.

5. Results

5.1 Basalt fibre production from lunar regolith simulant

Initial tests on fibre extrusion aimed to investigate fibre forming properties of JSC-2A regolith simulant, the effect of fibre drawing parameters on the fibre structure and the material properties of these fibres.

5.1.1 Characterization of basalt fibre samples

Scanning electron microscope (SEM) imaging (Fig. 7) of the snapped end of a basalt glass fibre manufactured from JSC-2A shows that one of the fibres has a diameter of about 150 µm. Despite the fibre appearing to have split when snapped, the overall surface of the fibre appears to be rather homogenous. What appears to be drops is residue from cleaning the fibre before entering it into the vacuum chamber of the SEM.

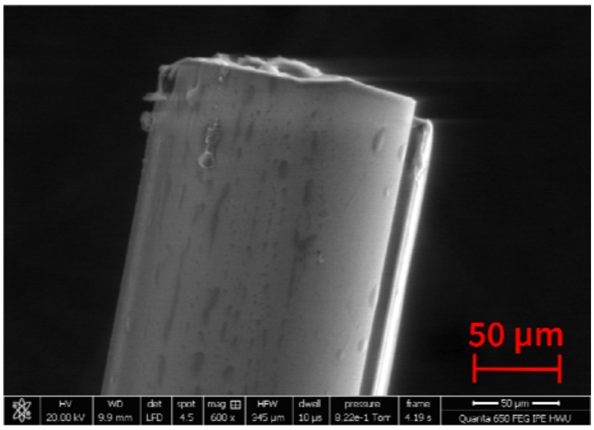

Fig. 7. Scanning Electron Microscope Image of the snapped end of a JSC-2A regolith simulant manufactured basalt glass fiber. Fibre diameter approximately 150 µm.

Thermal characterisation of regolith simulant fibres will be undertaken in due course. In the interim, an acceptable analogue for the thermal behaviour of these materials can be found in melted regolith simulant samples. As part of previous ESA work, we have an understanding of the thermal characteristics of processed regolith material. In these experiments, regolith simulant material representing Mare, low Titanium context material (JSC-1) was processed using a Selective Laser Melting (SLM) additive manufacture process. Samples produced thusly would have undergone a transition into a glass melt state, homogenously similar to a glassy fibre. To produce these samples, the incident laser power was set at 50 W, scan speed of 0.08 m/s and a hatch distance 200 µm and the layer thickness value at 500 µm. Samples produced from these runs had a density of 2.35 g/cm3.

Subsequent to the production of these samples, Laser Flash Annealing (LFA) and thermal diffusivity measurements were taken. Diffusivity values between 0.6 and 0.65 mm2/s were observed at room temperature, decreasing to 0.6 mm2/s for 150˚C. Specific heat capacity of the samples was found to be 0.7 J/(gK) [35].

5.2 Robotic manufacturing of fibrous structure

The conceptual studies can be evaluated by the degree to which they satisfy the functional requirements presented in portion. In addition, the extent to which the structures and process fabrication constraints, are satisfied through the process simulation and analyses.

Additional aims are to minimize additional additives and hardware as well as to guarantee robustness and redundancy at the level of the structure and robotic system. The structural load bearing capacities can initially be estimated due to the similarity to known structural typologies with demonstrated performance, including arches and hyperbolic shell structures. In addition, the structure seems to windable, although particular attention now must be paid to the particular order the fibres will be placed.

The robotic setup has successfully enabled the production of a two dimensional composite strip, which was elastically bent into shape in preparation for subsequent reinforcement fibre layers. The resulting increased elastic stiffness can be verified just from empirical observation: the bending active is more resistant to deflection after being bent into position, then it is when flat and unconstrained.

6. Next steps

The next steps in material study related to single fibres aim to build an automated extruder for fiber drawing with controlled environment and parameters, so that the quality of extruded fibers can be improved and fibers with smaller diameter can be drawn ranging between 10-20 µm. These fibres have to be mechanically tested to determine the material properties.

On a composite level the following steps lead to fabricating composite samples with different resin systems and fiber lay ups. Industrially manufactured basalt fibres, more similar in mechanical properties to the fibres to be produced out of regolith simulant, will be used to produce these small material samples. The mechanical properties of the produced samples need to be tested and verified: this will necessitate a spectrum of material samples, produced with a variety of both anisotropic and isotropic fibre layouts, and with a variety of resin types representing the various options. These material samples will then be tested for their compressive, tensile, and bending behaviour through the following tests and fed back into the design process. Ideally the ability of these surfaces to handle pressure will also be addressed.

In the next steps of the research a detailed robotic fabrication sequence is to be further developed and tested to realize the presented construction. To ensure a fully automated construction process, a heterogeneous team of construction robots is proposed which would include two types of locomotion systems and various material manipulation effectors. The locomotion systems are classified into two types: environment locomotion systems, designed to navigate the lunar surface and the slopes of the crater, performing initial stages of construction; and material locomotion systems, designed to move along the material itself, performing further stages once the primary bending active elements are erected.

In the first stages of the process soil moving machines are to be deployed to prepare the site for the next stages. Once the site is prepared, a winding robot would be deployed to fabricate flat fibre sheets that will then become the bending active elements of the structure. Once the sheets are produced, cured, bent and anchored, a smaller material locomotion robot will be deployed. This machine will move along the length of the bending active elements. Two of these smaller locomotion units deployed on opposite sides of the crater together form a base for a cable robot that would perform the winding sequence, creating the surface between the bending active supporting arches and re-anchoring the bending active to resist an overturning moment.

7. Conclusions

The current collaboration project aims to identify and develop promising fabrication methodologies for a fibre based in-situ robotic fabrication process for potential use in a lunar habitat as an alternative or addition to existing additive manufacturing technologies. The study is divided into two parts that run parallel to each other. The first part focuses on the material development on a single fibre and composite level. In that part, JSC-2A lunar regolith simulant was successfully used to manually draw basalt fibres with different diameters. SEM images showed fairly homogenous surface of the 150 µm fibre and the thermal properties were derived from an acceptable analogue from an ongoing ESA GSP study.

The second part of the study focuses on the application of these fibres in in-situ robotic manufacturing process of fibrous habitat structures. So far, the computational design methods for process simulation and analysis have been tested by fabricating physical small scale and 1:10 scale prototypes. A two dimensional composite trip was successfully fabricated by 6-axis robotic arm and bent into shape for the preparation following reinforcement layers.

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