FFC CAMBRIDGE PROCESS WITH METAL 3D PRINTING AS UNIVERSAL IN-SITU RESOURCE UTILISATION

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ABSTRACT

We examine the use of the FFC Cambridge process in conjunction with additive manufacturing as a potentially universal approach to deep in-situ resource utilisation on the Moon. FFC Cambridge process offers the means to reduce a wide range of metal oxides to extract reduced metal form. 3D printing offers the means to fashion that feedstock into a diverse range of products including structures, motors and electronics. Such capabilities introduce the possibility of manufacturing entire robotic machines from lunar material.

1. INTRODUCTION

Although in-situ resource utilisation (ISRU) has yet to be deployed in support of space missions, it has been actively proposed as a means to reduce the costs of human missions. If resources can be extracted locally from the Moon – our current focus – then these resources do not require launch and delivery from Earth. In particular, consumables including water have been of interest because they are a major resource and their extraction involves minimum processing. Hence, the high degree of interest directed towards the discovery of water ice at the lunar poles. A human requires a minimum of 4.4 kg of water per day (including 2.5 kg for imbibing), 0.9 kg of oxygen per day and 0.7 kg of dehydrated food per day. If water were available for consumption and electrolysis for oxygen, this would save 5.4 kg per astronaut per day (almost 2 tonnes per astronaut per year). Water at 5.6 ± 2.9% concentration (plus H_2S, ethylene, CO_2 and methanol) was detected by LCROSS (lunar crater observation and sensing satellite) mission (2009) in an impact plume generated by a Centaur rocket stage from the Cabeus crater. However, water and oxygen recovery through ECLSS (environmental control and life support system) would alleviate this requirement enormously. Electrolysis of water may be achieved within an electrolytic fuel cell - LH_2/LOX offers the prospect for locally derived propellant and oxidant which may be used for local transport or for launch from the lunar surface. Regenerative fuel cells that utilize hydrogen and oxygen derived from lunar resources offer the possibility for the high capacity storage of energy with high efficiency. The electrolyzed products of water – oxygen and hydrogen – will require liquefaction and cryogenic storage. In-situ liquid oxygen production is particularly of interest because over 80% of the propellant/oxidiser is oxygen.

Over 20 different processes have been proposed for extracting oxygen from lunar minerals but only 8 are favoured to exhibit simplicity, low energy consumption, readily available feedstock and minimum Earth-imported reagents: vapour pyrolysis, hydrogen reduction of glass, molten silicate electrolysis, fluxed molten silicate electrolysis, ion plasma pyrolysis and ilmenite reduction by H_2, CO and CH_4 [1]. Lunar ilmenite $FeTiO_3$ in particular, constituting 10-20% of lunar mare basalt, has been proposed as a source of oxygen. However, the requirement for fuel/oxidiser may be substituted with solar-electrical power while the latter requirement could be relaxed significantly by exploiting electromagnetic launcher technology. We proffer a view that extraction and consumption of consumables wantonly wastes finite and valuable resources which can be largely substituted using closed ecological life support systems (CELSS), solar-electric energy and electromagnetic launchers. All these technologies may be supported by deep ISRU.

We define the extraction of consumables with minimum processing as shallow ISRU and it serves primarily to support human missions. Deep ISRU involves the more challenging problem of extracting resources from a raw state requiring a considerable amount of processing. This requirement for extensive processing of raw materials differentiates deep ISRU from shallow ISRU. The purpose of deep ISRU is to create physical infrastructure on the Moon that may be built and serviced robotically and/or with human involvement. In the context of deep ISRU, we consider one of the most important factors is to minimise the infrastructure required to extract materials from lunar resources.

Simultaneously, the material set extracted must provide full functionality for a diverse range of applications required for the construction of infrastructure. One step in this direction involves 3D printing of compressive structures on extraterrestrial bodies [2] such as contour crafting [3] and D-shape [4].

However, we propose that mongrel metals extracted by the FFC (Fray Farthing Chen) Cambridge process provide a more flexible alternative for both compressive and tensile applications. The FFC Cambridge process is part of the broader Metalysis process which includes feedstock design, post-cleaning, etc. The implementation of 3D printing provides for the monolithic construction of secondary structure such as support brackets and even mechanical joints. It has been proposed that electromechanical components such as electronic circuitry, computer processors, actuators, sensors, etc may be inserted automatically during structural fabrication to enable automatic manufacture of robotic systems [5]. This presupposes the import of such mechatronic components from Earth. However, we are not merely concerned with in-situ sourcing of structures but also such mechatronic components. All machines comprise of a power source for energy (electrical energy generation system), actuators to generate motion (electric motor), mechanisms to shape the output (gearing system), and a control system to monitor performance and adjust the actuator input (control electronics). Hence, from mechatronic components, it is feasible to construct mining robots in-situ [6]. We assume resource acquisition by bucket wheel scooping of lunar regolith, followed by comminution and electrostatic/magnetic beneficiation. Some materials may require access to NiFe asteroid material from crater regions [7]. We must define the basic categories of materials that we require to support a lunar infrastructure:

(i) metals for tensile structures and electrical conduction
(ii) ceramics for compressive structures and electrical/thermal insulation
(iii) glasses for thermal insulation, electrical insulation and structural reinforcement
(iv) plastics for flexible electrical insulation
(v) volatiles for fuel and reagents

Of particular interest is the provision of mechatronic systems as well as static structures which require specific in-situ materials:

(i) Extraction of lunar volatiles for the production of fuel/propellant and silicone plastics/oils
(ii) Extraction of iron alloys for structure and electric motors
(iii) Extraction of Al metal for structure and electrical wiring
(iv) Extraction of Si and SiO_2 for alloying, ceramics and silicones

We impose a philosophy of maximising leverage from in-situ resources as a context for investigating the FFC Cambridge process. The two lunar minerals on which we have focussed are anorthite (common in the highland regions) and ilmenite (common in the maria regions). From these two minerals, an entire suite of metals can be extracted in alloy form, or if subjected to prior purification methods, in pure form – Al, Ca, Si from anorthite and Fe and Ti from ilmenite in alloy forms, or pure Al from alumina, pure Ti from rutile and pure Si from silica.

2. WHY ELECTROLYSIS?

Practical problems with thermochemical reduction of ilmenite are several [8]. Hydrogen reduction of ilmenite is severely degraded by the formation of H_2S by the 0.5% traces of FeS typical in lunar soil. Pre-oxidation by roasting to release SO_2 invokes more complex processing. Vacuum pyrolysis requires very high temperatures of ~2000-3000^{o}C generated by solar furnace, microwave heating, electron beams, etc to vaporise the mineral [9]. Furthermore, experimental Fresnel lens-based solar furnaces at 1300-2000^{o}C for vacuum pyrolysis yield oxygen from lunar regolith but do not fully reduce metal oxides [10]. Electrolysis of lunar material offers several advantages over chemical processes, including, principally, the lack of requirement for reagents imported from Earth. Molten basalt [11] or molten regolith [12] may be subjected to electrolysis. Another benefit of electrolysis over techniques such as carbothermic reduction is a reduction of impurities in the products. There is a salutary lesson from aluminium. On Earth, Al is extracted from bauxite through two stages. The Bayer process purifies Al_2O_3 in bauxite by dissolving it in NaOH at 150-200^{o}C ($Al_2O_3 + 2NaOH \rightarrow 2NaAlO_2 + H_2O$) which is supersaturated ($NaAlO_2 + 2H_2O \rightarrow Al(OH)_3 + NaOH$) followed by heating in excess of 1000^{o}C ($2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O$). Direct carbothermal reduction of alumina with other reductants requires extremely high temperatures of ~2000^{o}C rendering it infeasible. To reduce energy requirements, it is necessary to dissolve minerals in an electrolyte. The Hall-Heroult process is the second stage that extracts Al from Al_2O_3 electrolytically. Hall-Heroult electrolysis reduces Al_2O_3 dissolved in molten cryolite (Na_3AlF_6) mineral to reduce its melting point of 2072^{o}C to 1000^{o}C: $Al_2O_3 + 3/2\ C \rightarrow 2Al + 3/2\ CO_2$. Electrolysis yields Al at the cathode and CO_2 with the consumption of the graphite anode (although the CO_2 can be recovered and conserved). Cryolite would have to be imported due to the paucity of Na and F in lunar sources.

Unlike bauxite, lunar anorthite ($CaAl_2Si_2O_8$) requires prior conversion to Al_2O_3. The most commonly proposed approach to thermal processing of anorthite is vacuum distillation at near 2000^oC yielding $CaAlO_4$. Electrolysis involves the immersion of a cathode and anode held at a potential difference into a bath of molten silicate magma. Electrolysis of molten silicates deposits mixed metals dominated by iron at the cathode with the evolution of oxygen at the anode. The use of a fluoride flux reduces high temperature corrosion but imposes an imported reagent requirement. Magma electrolysis of molten lunar regolith however requires lower temperatures of 1600^oC to reduce metal silicates [13]. Anorthite may be electrolysed directly at 1600^oC to yield Al and CaO (quicklime). Quicklime mixed with water yields slaked lime $Ca(OH)_2$ useful for cement production. Similarly, for ilmenite, molten regolith electrolysis has been favoured as a means of oxygen production leaving a molten ferrosilicon "mongrel" alloy with dissolved metals. It requires significant amounts of energy but does not require beneficiation of ilmenite.

The FFC Cambridge process is an electrolytic technique that is highly diverse in its applicability – unlike most electrolytic techniques that are highly material specific and bespoke, FFC Cambridge process can be adapted to a wide range of materials and applications – it offers an unrivalled one process fits-all technique that lends itself to in-situ resource utilisation. It can reduce anorthite directly into its component metals at much lower temperatures. A sintered cathode of anorthite in molten $CaCl_2$ removes O to yield Al, Ca and Si provided the respective oxides are isolated beforehand. The required thermal heating to $900\text{-}1100^oC$ is modest but electrolytic energy is required to split all the anorthite components - Ca and Si are as desirable as Al (Ca is a better conductor than copper or aluminium). The $CaCl_2$ is recycled. It operates with consumable graphite electrodes or preferably non-consumable anodes. Acid leaching by HCl is a viable approach to reducing anorthite to SiO_2 (silica is scarce on the Moon but may be used as a ceramic, glass manufacture and/or reduced to silicon) while avoiding high temperatures but does require modest heating to accelerate the reaction:

$CaAl_2Si_2O_8 + 8HCl + 2H_2O \rightarrow CaCl_2 + 2AlCl_3.6H_2O + 2SiO_2$

The advantage of this approach is that it produces $CaCl_2$ electrolyte for the FFC Cambridge process – it represents a lunar analogue to the terrestrial recycling of $CaCl_2$ as a waste product of the Solvay process. This requires import of NaCl from Earth proposed as the salt contingency [14]. A similar notion proposed leveraging of aluminium, silicon, glass and oxygen from lunar resources by the import of KF from Earth which may be salt electrolysed into K and F [15].

3. FFC CAMBRIDGE PROCESS

The FFC Cambridge process is an electrolytic technique that can extract near pure metals from their oxide and silicate forms. It was developed as a replacement of the Kroll process to extract Ti from rutile (TiO_2). The Kroll process involves a series of processes – chlorination of rutile, reduction of titanium tetrachloride with magnesium, and electrolysis of magnesium chloride to recycle magnesium, yielding titanium sponge. The FFC Cambridge process however is a single electrolytic process in which molten $CaCl_2$ electrolyte permits the formation of $CaTiO_3$ as an intermediate species. Rutile feedstock is shown in Fig 1.

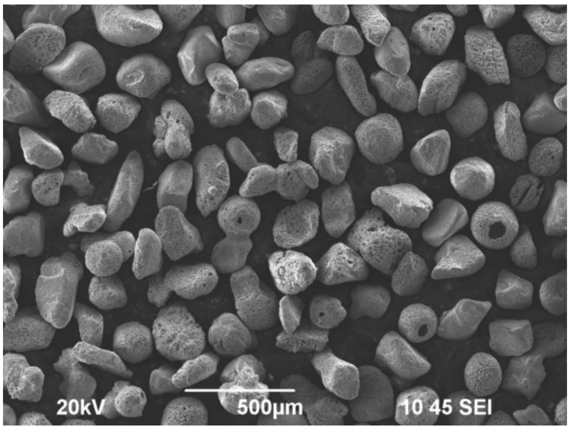

Figure 1. Synthetic rutile feedstock

The titanium powder output from such feedstock is shown in Fig 2.

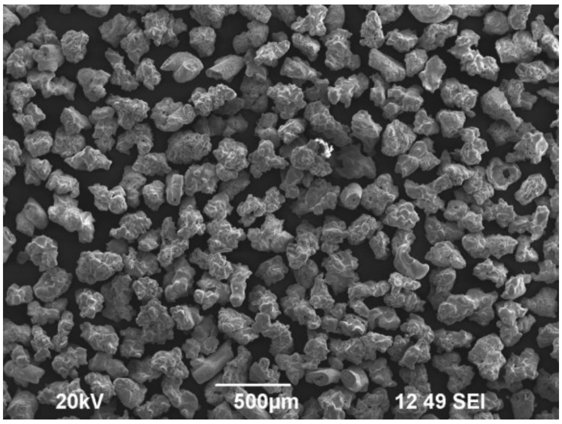

Figure 2. Titanium powder derived from synthetic rutile powder

The FFC Cambridge process has widespread applications as a universal chemical processing technique on the Moon:

(i) extraction of Al, Si, Ca and O_2 from lunar anorthite ($CaAl_2Si_2O_8$);

(ii) SiO_2 may be reduced by electrolysis in a molten $CaCl_2$ electrolyte at 850^oC with multiple metal wire electrode contact points in the bulk material supplying electrons [16];

(iii) extraction of FeTi amalgam and O_2 from lunar ilmenite ($FeTiO_3$) or alternatively, pure Ti from rutile TiO_2 resultant from hydrogen reduction of ilmenite at 1000°C;

(iv) reduction of wolframite to tungsten (or alternatively tantalum pentoxide to tantalum).

Ilmenite electro-reduction involves powdering the ilmenite to form the cathode. At the anode, O_2 is released to be recovered and stored. Applied to ilmenite ($FeTiO_3$), the final product is TiFe and $TiFe_2$ alloys releasing almost all oxygen from ore oxides. Since the process reduces rutile (TiO_2), over 99% of the oxygen can be recovered from ilmenite without chemical reductants. The inert anode may be constructed from ferrites (iron oxide with widespread electromagnetic applications) or cermet (nickel-ferrite mixture used for electrical components). The cathode is reduced into FeTi alloy sponge which is subject to crushing into a metal powder. In fact, multiple mixed oxides may be used simultaneously to create different alloys, e.g. SiO_2 to create silicon for magnetically soft silicon steel for use in electric motor cores. The production of silicon steel for motor cores is of particular interest here as this introduces the possibility of manufacturing electric motors in-situ. Another goal alloy is kovar, an alloy of Fe, Ni and Co (to replace copper conductors) with the Ni and Co sourced from NiFe asteroidal material located at certain lunar crater rims. The $CaCl_2$ electrolyte is recycled requiring only Cl import from Earth in salt form to replenish small losses. During electrolysis, metals or metal oxides are recovered at the cathode and oxygen at the anode.

4. ADDITIVE MANUFACTURING

A common approach to the execution of multiple manufacturing tasks is to develop specialized optimized machinery to achieve each individual task. This is not an option for planetary colonization in general and ISRU in particular where tasks may be unanticipated and require adaptability. 3D printing is however a highly versatile mode of manufacture that lends itself to adaptability. Of particular importance is that the FFC Cambridge process can produce metal powders (or wire) suitable as input to metallic additive manufacturing or powder metallurgy techniques to convert it directly into products. Fig 3 illustrates 3D printed test structures from Ti powder from the FFC Cambridge process.

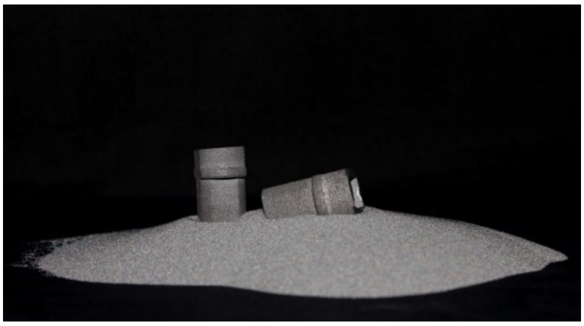

Figure 3. 3D printed structures from FFC Cambridge-derived Ti powder

3D printing permits the manufacture of structural designs that cannot be manufactured through subtractive techniques such as casting, milling, turning, forging or welding. It is reckoned that such subtractive methods require ten times as much material as that encapsulated in the final product. 3D printing involves building a 3D object layer by layer in plastic, metal or ceramic. Typical layer thickness is 20-100 µm. This allows the construction of complex shapes with complex internal geometries without specialised tooling. There is negligible material waste and component parts may be merged into monolithic structures reducing the requirement for assembly. Application to space and/or planetary environments is challenging as well as offering advantages: (i) lack of atmosphere makes powder vacuum weld into clumps; (ii) vacuum prevents oxidation during sintering/melting; (iii) low gravity may result in delamination between layers; (iv) low gravity reduces support structure requirements.

The two commonly adopted metal 3D printing techniques are: (a) selective laser sintering/melting (SLS/M) and (b) electron beam freeform fabrication/melting (EBF3). The latter is generally favoured because electron beams are more efficiently generated than laser beams. The concern over the use of powder required by SLS/M is moot in the context of robotic factory facilities on the Moon as there is an ambient gravity field (assistable by vibration) and there is no human infection issue in an automated factory environment.

The Renishaw SLM facilities in Kitchener Ontario offer 200 W and 400 W laser powder bed machines typically with a 70 µm laser spot size. They can deposit a range of metallic alloys. The machines can be fitted with a reduced build volume (RBV) to allow testing and parameter development on small quantities of powder. The manufacturing facilities of the National Research Council of Canada (NRC) include a Sciaky electron beam additive manufacturing (EBAM) system capable of depositing metallic materials in a vacuum operational environment using a wire feedstock. Specific advantages of the EBAM process are the relatively large build envelope, near 100% material efficiency of the wire-feed into the melt pool, and high bulk material deposition rates of 200-600 mm^3/s depending on feature size and material. Also, the build envelope of the EBAM, limited by the vacuum environment under terrestrial conditions, becomes infinite for in-space production. Previously micro-gravity testing of an EBAM system onboard NASA's reduced gravity aircraft demonstrated the deposition performance to be equivalent to 1G conditions. The next step for EBAM is logically to demonstrate the 3D printability of structural alloys developed on the basis of extraterrestrial resources so as to build the foundation of our understanding on their material characteristics and properties as well as assess their suitability for extraterrestrial construction and utilization. Essentially, only two processes – FFC Cambridge and metal 3D printing – are required to convert beneficiated raw metal material into final products. These two methods offer unprecedented capabilities in deep ISRU.

5. LUNAR ELECTRICITY GENERATION

On Earth, electrolysis is achieved through pure electrical sources – both thermal heating of the electrolyte and electrolytic circuit itself. The advantage of electrical heating is that it is not limited directly, unlike direct thermal heating. The generation of electrical energy from solar sources on the Moon is generally inefficient, particularly if generated from solar panels manufactured from lunar resources. To reduce electricity consumption, it is proposed that electrolysis may be implemented using solar furnaces to raise the temperature of the electrolyte thermally and electrical energy for the electrolytic reactions. Nevertheless, significant amounts of electrical power are required.

Solar concentrators direct heat to their foci though the use of fibre optic cables alleviates this limitation somewhat in allowing thermal energy to be directed as desired – solar sintering is conducive to 3D printing architectures. Solar concentrators may also be used in conjunction with vacuum tube-based thermionic conversion to generate electrical energy [17]. Efficiencies of 20% are typical of Russian nuclear reactor thermionic conversion with T_C=1650°C at the cathode and T_A=650°C at the anode [18]. Thermionic conversion requires vacuum tube materials – glass, tungsten, nickel and kovar which can be sourced on the Moon. There are a number of potential improvements to thermionic conversion efficiency. The use of electric potential shaping can increase efficiencies up to 40% [19]. A second stage thermal electric conversion stage may yield up to 30% efficiencies [20]. Photon-enhanced thermionic conversion [21] adds a photovoltaic stage for up to 50% efficiencies that may be implemented with Se coatings or aluminium-doped haematite photocathodic coatings [22] (formed from ilmenite-derived iron heated in oxygen) or other photoconductive coatings. In-situ thermionic conversion approaches offer greater efficiencies than in-situ resourced solar cells [23, 24].

6. BROADER CONTEXT

The FFC Cambridge process combined with metal 3D printing is ideal for manufacturing structural elements from mongrel FeTi alloy. However, the in-situ manufacture of robotic systems requires the manufacture of electric motors, electronics and sensors from lunar material, often with very specific characteristics. For electric motors, we require magnetic material such as alnico (hard) and/or silicon steel (soft), conductive wiring of kovar or nickel, and insulating material configured in a complex structure. Fig 4 shows preliminary 3D printed electric motor designs.

Figure 4. Prototype 3D printed motor design

We have been developing a photolithographic method of printing the wiring to replace coils (Fig 5).

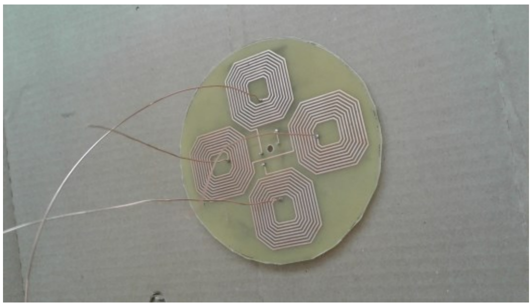

Figure 5. Photolithographically printed wire coils

We have been developing a method for 3D printing aluminium circuitry onto silicone plastic substrates (Fig 6).

Figure 6. Molten aluminium track on silicone substrate

Further developments have been made towards active electronics through vacuum tube-based neural networks to replace traditional computer architectures (Fig 7). Vacuum tubes are constructed from glass, tungsten, nickel and kovar – all derivable from lunar material.

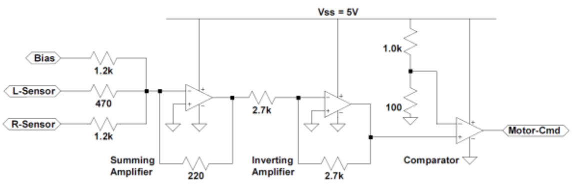

Figure 7. Analogue neural circuit as unit of computing

Once we have demonstrated full 3D printing of these components, we will have the elements required to 3D print robotic systems from lunar resources.

7. CONCLUSIONS

FFC Cambridge process in conjunction with metal 3D printing appears feasible. However, it produces oxygen for oxidant and mongrel alloys for structural applications. Structural applications will require by far the most mass of any lunar infrastructure. Hence, mass savings incurred by a lunar FFC Cambridge facility will be significant. The need for a multitude of specific materials for specific purposes (such as silicon steel for motors) suggest that FFC Cambridge process may supplemented with additional techniques to manufacture mechatronic components. In both cases, 3D printing offers a unique and versatile means of manufacture. Together, these techniques offer unprecedented capabilities for in-situ manufacturing of robotic machines.

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