Fabrication Capabilities Utilizing In Situ Materials

Carole A. McLemore[1], John C. Fikes[2] and Charles A. Darby[3],
National Aeronautics and Space Administration/Marshall Space Flight Center (MSFC), Huntsville, Alabama, 35812

James E. Good[4]
Teledyne Brown Engineering, Huntsville, Alabama, 35805

and

Scott D. Gilley[5]
Tec-Masters, Inc., Huntsville, Alabama, 35806

The National Aeronautics and Space Administration (NASA) has a Space Exploration Policy that lays out a plan that far exceeds the earlier Apollo goals where landing on the moon and taking those first historic steps fulfilled the mission. The policy states that we will set roots on the moon by establishing an outpost. This outpost will be used as a test bed for residing in more distant locales, such as Mars. In order to become self-sufficient, the occupants must have the capability to fabricate component parts in situ. Additionally, in situ materials must be used to minimize valuable mission upmass and to be as efficient as possible. In situ materials can be found from various sources such as raw lunar regolith whereby specific constituents can be extracted from the regolith (such as aluminum, titanium, or iron), and existing hardware already residing on the moon from past Apollo missions. The Electron Beam Melting (EBM) process lends itself well to fabricating parts, tools, and other necessary items using in situ materials and will be discussed further in this paper.

I. Introduction

NASA's Space Exploration Policy outlines returning to the moon with plans to stay for an extended period of time in addition to other goals. Fabrication capabilities will be critical in order for the inhabitants to be self-sufficient and even more critical in future missions to Mars. Specifically, the fabrication technologies will support habitat structure development, tools and mechanical part fabrication, as well as repair and replacement of ground support and space mission hardware (such as life support system components, vehicle hardware, and also crew systems). NASA/Marshall Space Flight Center is supporting the development of fabrication technologies through the In Situ Fabrication and Repair (ISFR) project activities and is working in conjunction with the In Situ Resource Utilization (ISRU) project led by NASA/JSC to provide the capability to "live off the land". The ISFR element supports the entire life cycle of Exploration and mission success by: reducing downtime due to failed components; decreasing risk to the crew by recovering quickly from degraded operation of equipment; improving system functionality with advanced geometry capabilities; and enhancing mission safety by reducing assembly part counts of original designs where possible. These benefits become even more significant as space exploration turns its attention towards Mars.

---

[1] Project Manager, ISFR/ISRU/Dust, Exploration Advanced Capabilities Office, VP33.
[2] Deputy Project Manager, , ISFR/ISRU/Dust, Exploration Advanced Capabilities Office, VP33.
[3] Lead Systems Engineer, Project Engineering Branch, ES11, AIAA Senior Member.
[4] Fabrication Technologies Engineer, Aerospace Systems, M/S 60.
[5] Fabrication Technologies Team Lead, Advanced Technology and Space Programs Directorate, Teledyne Brown Engineering M/S 60.

The ISFR element performed a trade study and determined the Electron Beam Melting (EBM) process as the most viable system for in situ fabrication. This paper addresses EBM fabrication capabilities with an emphasis on the ability to use in situ materials (i.e., lunar regolith) as a viable feedstock. In lieu of lunar regolith, lunar simulant, developed and managed through MSFC, is used as feedstock.to represent the regolith. This research and technology development must answer several questions. Can the lunar regolith be used to make functional parts? How much strength can be expected from such a part? Will the raw regolith require a binder material to be added to improve the strength characteristics? Will extracted metals from the regolith be a viable byproduct material for fabrication? These are questions that have not been answered, but are critical as we plan to inhabit the moon and explore Mars. Additionally, provisioned feedstock will also play a vital role, especially initially as the crew inhabits the moon and prior to any mining and processing of regolith. In consideration of this, the ISFR element has concentrated on high demand materials such as titanium and aluminum. This material processing development will be discussed in the paper. Results of testing recently conducted by the ISFR element will go far in answering the above questions and concerns. These assessments will be presented, and subsequent conclusions will be made.

II. Available In Situ Materials

Weight is a critical component of spaceflight. It must be minimized in order to provide the largest payload mass possible for cargo. This becomes even more critical as you travel further away from Earth. A one-way mission to Mars takes six months. Therefore, it is vital to take as much cargo in the way of consumables and hardware required to establish a base to exist day-to-day. As on Earth, hardware failures will occur. In order to repair the hardware, replacement parts will be needed. How will these parts be made available? The obvious method is to carry spares. Another method is to have the means to fabricate a replacement part. What parts will fail? That is difficult to predict since most of these parts will not have been used in these harsh environments for this long of a time. This would then seem to require spares for many component parts. Carrying a spare or spares for every single component that could fail is not feasible because the weight and volume required would be a huge penalty that would result in little, if any, room for the crew, necessary consumables, and scientific instruments on the vehicle. Figure 1 provides data on four Space Shuttle missions to the International Space Station depicting ascent spares and the associated volume required to store these spares. If the capability existed to manufacture these parts in situ, how much weight and volume could be eliminated from the overall payload? It could be significant depending on the payload and the specific mission. Using additive manufacturing techniques such as the Electron Beam Melting (EBM) process, the ability to fabricate many of the spare parts could be accomplished even by initially provisioning feedstock powders. An even more significant improvement would be the ability to use in situ materials in lieu of the provisioned powders.

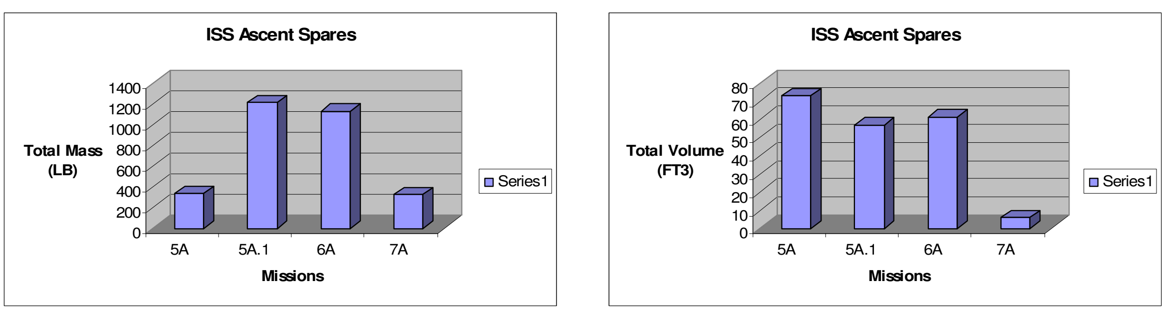

Figure 1. ISS Ascent Spares for Selected Shuttle-to-ISS Missions

These in situ materials can come in many forms. Raw regolith is a primary source of in situ material. MSFC has been investigating whether raw regolith can be a viable feedstock using the EBM fabrication process. Due to the nature of regolith, a binder material may need to be added to the regolith in order to achieve the best melt. As an alternative, metals that are bound in the regolith could be extracted and used as feedstock. The lunar regolith is a multi-component silicate rich in iron, aluminum, and titanium. The ability to pull out these materials from the regolith would eliminate the need to bring those materials from Earth.

The Exploration Systems Architecture Study (ESAS)[1], completed in November 2005, identified oxygen extraction as one of the three critical areas of lunar In Situ Resource Utilization (ISRU) that could provide significant benefits to future robotic and human exploration of the Moon. The EBM fabrication system can benefit greatly from specific oxygen extraction processes planned for the moon. One such process is the Molten Oxide Electrolysis (MOE) process. The MOE process eliminates the need for beneficiation as it uses raw regolith as feedstock that does not require any form of pre-treatment[2]. The process results in the production of oxygen and by-products which consist of metals that can be used in the fabrication of in situ component parts.

In the case of the lunar surface, in situ materials exist that are not found in or on other planetary bodies.. The Apollo Program ended in December of 1972, but there are still some artifacts on the moon from those missions[3]. The largest of these artifacts include portions of the six lunar modules, three electric Lunar Roving Vehicles, and an array of scientific instruments. In order to save payload weight on the return missions, the Apollo astronauts also left most of their cameras behind and only brought back the film. Obviously, these artifacts have historic significance and may be deemed “untouchable” to future visitors. Outside of this fact, this hardware is available for use, in situ, and could be recycled for use in another capacity.

III. In Situ Material Processing

Marshall Space Flight Center performed an extensive trade study[4] covering all additive and subtractive manufacturing techniques. Using specific criteria centering on the ability to fabricate items using different materials with certain accuracies, a list of the best processes were assembled. Initially, these processes were not limited to metals or plastics, but instead included multi-materials. A process was ranked high if it could process metals and plastics and, especially, if there was a varied selection of metals and plastics. It became apparent that the processes that claimed to do all things did none very well. The conclusion was to concentrate on a type of material and determine the best possible way to process it. Another trade study was performed limiting the materials to just metals since the ability to fabricate metal parts proved to be of more value than plastic parts. This decision was made based on the relevance and abundance of each material in situ.

The new trade study, based on the ability to fabricate a suite of metal materials, also considered other factors such as accuracy, surface finish, and material properties. Upon weighing all criteria, the Arcam EBM process was selected as the fabrication technology to pursue. .The ability of the EBM hardware to process a wide range of materials, such as stainless steel, titanium, copper, aluminum, inconels, and others, was a deciding factor. Additionally, the electron beam melts the metal powder sufficiently to fabricate a fully dense part. The material properties documented in the literature exceeded those of cast material and were in line with wrought properties. The microscopy reported reflected good grain structure. and fatigue data was promising. Based on this data, MSFC invested in the acquisition of a machine (see Figure 2) in order to develop the technology for in situ manufacturing as well as nearer-term ground and flight applications.

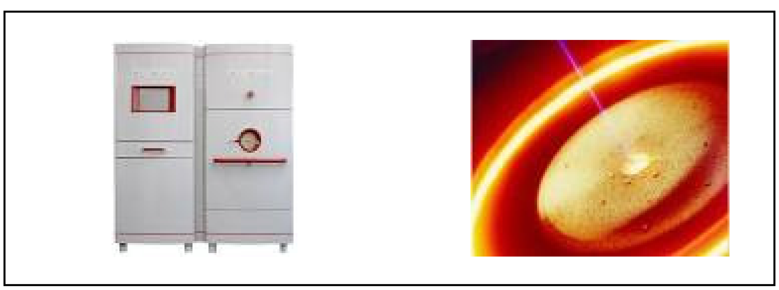

Figure 2. The Arcam S12 EBM Machine and the Electron Beam Material Interaction

Fundamentally, the EBM technology works by building up a three dimensional (3-D) component layer-by-layer. This is done by using an electron beam to successively melt the metal powder in an exact geometry for each layer, as defined by the computer model files. The computer files input is a 3-D CAD model which is pre-processed by slicing the model into thin layers. The metal powder is then melted within a vacuum environment which will eliminate any impurities such as oxides and nitrides. Once the part has been completed, the vacuum is removed and the part is cooled. The result is a net-shaped part ready for cleaning.

The electron beam is generated in an electron beam gun where the electrons are emitted from a filament which is heated to greater than 2500 degrees Celsius. The electrons are accelerated through the anode to half the speed of light. A magnetic field lens brings the beam into focus while another magnetic field controls the movement of the beam. When the electrons hit the powder, kinetic energy is transformed to heat. The heat, in turn, melts the metal powder.

While there are many advantages to using the EBM system to fabricate components, there are also some aspects that could be improved upon. The surface finish is similar to a casting; thus, the part may require some post surface finishing. Other metal additive systems are capable of better finishes. A better surface finish can most likely be achieved through improving or tweaking the machine process parameters and/or by performing a secondary finishing process. Additionally, the small build volume of the EBM machine limits builds to approximately 8”x8”x8”. The EBM manufacturer has recently developed a model of the machine that allows increased build height to approximately 15” while keeping the X-Y limits the same. Another configuration would allow for an approximately 13” X-Y limit while keeping the vertical measurement to 8”. Overall, the advantages of using the EBM system outweigh the disadvantages.

IV. MSFC Research Involving In Situ Fabrication

The lunar regolith contains metals such as aluminum, titanium, and iron that can be mined and extracted. Another viable feedstock is to use the raw regolith without any beneficiation. Preference would be to use the regolith as is for fabrication feedstock; however, more research must be done to determine if this is feasible. Early results show that the regolith will melt using the EBM process (see Figure 3), but analysis still needs to determine just how strong this fabricated material is after processing. MSFC is currently performing this work and will report the results as they become available. It is believed that the raw regolith will require a binder material in order to get the best possible melt and strength properties. Pure aluminum powder has been alloyed with the raw regolith (JSC-1A and LHT-2C simulants are currently being used in lieu of regolith for this investigation). Some of this material has been processed as shown below in Figure 4. Machine setting parameters such as current and voltage are being optimized while work continues to achieve the best method to alloy these materials.

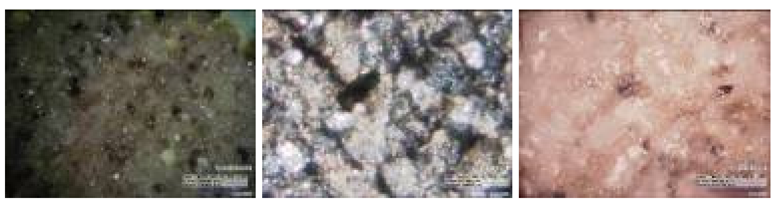

Figure 3. Sintered Lunar Regolith Simulant

Figure 4. Regolith trapped in Al (Alloy Mixture)

In order to validate the ability to process in situ materials, MSFC has invested in the development of material certification using aluminum in the EBM process. Aluminum can be extracted from the regolith and used in situ. Initially, aluminum powder or other types of metallic powder could be provisioned in case the infrastructure is not established to make in situ aluminum or other materials on the lunar surface. .It will be important to prove the EBM process functions properly in the lunar environment and can fabricate parts using these materials. Marshall Space Flight Center (MSFC) has initially worked with titanium as the primary material for the system. As a result, the process has been optimized and proven to be a viable material feedstock with the EBM hardware. Aluminum has also been used in the EBM, but the process has not yet been optimized to the point of producing end-use parts. MSFC will continue to optimize the aluminum process and make it a viable material for EBM processing. Aluminum and titanium are materials that are currently in demand in the aerospace industry. More interest is evolving in using these materials with EBM technology. The medical industry is another example of a group that has invested much time and money implementing the EBM process into their manufacturing capabilities. The use of this technology will provide credibility to the process and help gain acceptance as a viable manufacturing resource for in situ fabrication. With this in mind, MSFC is currently involved in the certification of the EBM process using specific materials in order to manufacture flight-qualified hardware. The EBM process can provide significant manufacturing capability to current MSFC programs as well as all manufacturing industries. As this technology evolves and gains acceptance, it will become a more mature technology for in situ fabrication.

Figure 5. Aluminum Alloys Fabricated Using the EBM Process (Fabricated at North Carolina State University (NCSU))

Much information in this area is shared through conferences, consortiums, and other outreach methods. MSFC is active in publishing papers and presenting at relevant conferences. Networking opportunities have resulted in MSFC collaborating and partnering with various groups interested in EBM technology as an additive manufacturing capability. These collaborations have resulted in good technology development activities and sharing of knowledge and experiences. MSFC has ongoing collaborative investments with The Boeing Company and North Carolina State University which has provided significant expertise and information to the in situ fabrication effort at MSFC.

V. Future EBM Plans at MSFC

Before taking our next step on the moon and actually incorporating in situ fabrication capabilities on the lunar surface, much work is still required. As mentioned previously, our goal is not to land on the moon or to take another "small step", but to inhabit the moon and establish a long-term base for an extended stay. For in situ fabrication, hardware designed and built on Earth must be designed with the specific purpose of maintainability and supportability by making parts capable of being repaired and/or replaced on the lunar surface. Considerations in hardware design include volume and mass restrictions in addition to power consumption. The hardware that does launch to the moon must be mass and power efficient. In terms of the actual in situ fabrication hardware that would reside on the moon, that must also be light in weight and not require a massive power supply. Commercial hardware, such as the Arcam EBM machine which MSFC is currently utilizing, cannot be flown as currently designed to the moon. It must be repackaged and redesigned to minimize weight and power. MSFC has done preliminary work on miniaturizing the EBM machine for remote manufacturing. This work will increase in priority as we get closer to 2020, the projected date for establishing an outpost on the moon.

In addition to sizing the fabrication hardware efficiently, it must become more robust and user-friendly. The machine must be closed loop and not require extensive knowledge by the astronaut in order to run the machine. One step in approaching this goal will be to incorporate an inspection station integral to the build. This station will inspect each layer as it is built. The benefit of such a station is that the build will abort once a layer is not recoverable or is out of specification. This will save time and material. Optimally, the system can make necessary adjustments to recover the build prior to exceeding the acceptable tolerance limits of the specification. These are development programs that will begin in the future as the priority increases and funding is available.

During the time MSFC was deciding which additive process met the criteria for powdered-metal fabrication, another study MSFC performed looked at materials that were prevalent in failed components from the International Space Station (ISS), the Space Shuttle, and the Russian Mir Space Station. Some of these materials included Al 6061 and Al 7075, SS316L, Inconel 718 and Inconel 625, and titanium. As stated before, aluminum alloys are currently being developed to use in the EBM at MSFC. MSFC will determine the order of importance for new material development to use with the EBM process. This decision will be based on current program needs within MSFC and the candidate material that will be most used in hardware on the moon. Again, funding will dictate the timing of the development effort.

Current users of the EBM process are aware of the rough surface finish from the as-built part. As the surface finish is improved directly with the machine, the time required to post-process the part will decrease. This is especially important for titanium parts which are traditionally rough on finishing tools. MSFC has gained experience from industry research that can be applied to the in-house machine. Improved parameter settings are expected to provide a smoother surface finish as will the EBM hardware modifications that have been aforementioned. MSFC plans to develop these techniques in the near future. Additionally, other new technologies are being developed by industry to improve the finishing capability of hard metals such as titanium. Abrasive flow operations have been developed and show promise. MSFC, either in house or through collaboration, will invest more on developing technologies, including abrasive flow and other secondary finishing processes, especially those that will benefit in situ fabrication.

VI. Conclusion

Long-term stays on the lunar surface, and especially missions to Mars, will require astronauts to be self-sufficient for safety's sake, not to mention be a wiser use of vehicle upmass. Crews traveling to Mars will not have the luxury of another vehicle being available to quickly deliver replacement equipment or unforeseen replacement parts. The capability to fabricate parts in situ is an absolute must. This begins with identifying the process to perform the task and identifying the feedstock needed for fabrication. In this case, the EBM process fulfills the criteria with the ability to use provisioned materials, and ultimately utilize the lunar regolith, as is, or after a beneficiation or extraction process.

Now is the right time to test and ensure the EBM system can process expected in situ materials such as the "raw" lunar regolith and/or the metals that comprise it such as aluminum and titanium. MSFC is currently performing the work that will provide an answer to the question, "Can we fabricate parts using in situ materials on the lunar surface?" The value of this effort is increased by the knowledge that this manufacturing process can provide a significant contribution to existing systems as well as newly-designed hardware in the way of reduced weight, reduced part count, and faster turn-around of parts (i.e., labor savings).

The challenges that MSFC and others face in this area include certifying the EBM process for different materials to produce structural integrity parts, incorporating closed-loop feedback systems for part quality assurance, improving surface finishes, and packaging the fabrication hardware to be smaller, lighter, easier to use, and less power hungry. Current efforts at MSFC[5] have shown great promise that technology exists to fabricate components using in situ materials on the lunar surface. The future will require that we improve on the technology and develop a more robust system, but early results have shown that we have made a great start here on Earth to achieving the ability to "live off the land" on the moon and other planetary bodies such as Mars.

Acknowledgments

Portions of this work were performed in support of the George C. Marshall Space Flight Center under the Teledyne Brown Engineering Systems Development and Operations Support (SDOS) contract (No. NAS802060) and with the support of The Boeing Company in St. Louis, Missouri, and North Carolina State University in Raleigh-Durham, North Carolina.

References

[1] Stanley, D., Cook, S., and Connolly, J., "NASA's Exploration Systems Architecture Study," NASA TM-2005-214062, November 2005.

[2] Curreri, P.A., Sen, S., and Sadoway, D.R., "Process Demonstration For Lunar In Situ Resource Utilization – Molten Oxide Electrolysis," NASA TM-2006-214600, 2006.

[3] Heiney, A., "Apollo's Lunar Leftovers," http://www.nasa.gov/missions/solarsystem/f_leftovers_prt.htm, June 28, 2004.

[4] Howard, R., Patterson, B., Gilley, S., and Kennedy, J., "Fabrication Technology Options Trade Study," Teledyne Brown Engineering, 480RPT0190, 2004.

[5] Marshall Space Flight Center, In Situ Resource Utilization website, http://isru.msfc.nasa.gov