At the frontier of in-space production: Harnessing microgravity for manufacturing

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ABSTRACT

Since the dawn of human space exploration, there have been dreams of manufacturing products in space of such quality and novelty that they improve life on Earth. And over the past 50 years, microgravity research has demonstrated that in-space production may outperform terrestrial processes in the manufacturing of some materials. The introduction of commercial launch service providers and orbital laboratories will open the door to realizing these dreams by reducing logistical costs and providing dedicated manufacturing facilities in space.

In this paper, we define some of the physical and biological effects of microgravity and opportunities that this unique environment offers. We present a brief history of in-space production and three exemplary test cases: crystal production, organoids and microphysical systems, and complex solidification. With these microgravity effects and opportunities now coming into focus, we near a new frontier that realizes the dream of producing superior products in space.

Keywords: space, manufacturing, microgravity, crystal

1 INTRODUCTION

As engineers and scientists design, improve, and optimize materials and manufacturing processes, they have many variables to fine tune (e.g. temperature, pressure, flowrate, concentration, etc.). Rarely is gravitational acceleration considered. In fact, it is nearly always assumed to be constant with small corrections depending on altitude or latitude. This “constant” force has been leveraged for many industrial processes, particularly for density-driven segregation in separation processes such as distillation, liquid-liquid extraction, or liquid melt purification.

However, many industrial processes are designed to mitigate the detrimental effects of gravity. For example, the size of crystalline particles and colloids can be limited by gravitational sedimentation. Soft and biological materials may collapse under their own weight, necessitating additional supports or scaffolding. Density-driven segregation may induce undesired phase segregation. Each of these effects represents manufacturing obstacles that must be overcome, and the corrective actions often introduce additional consequences in the form of reduced product quality, increased labor or processing time, and increased manufacturing costs.

Decades of research have explored the fundamental physics of energy and material interactions when gravity is removed. The International Space Station (ISS) now has more than 20 years of continuous human habitation supporting space-based research. Commercial launch capabilities have opened the door to consistent and cost-effective access to space. The reduction in launch costs, combined with future commercial platforms and stations capable of supporting manufacturing in space, allows engineers and scientists to treat gravity as a variable to aid in the creation of novel manufacturing modes.

This paper outlines opportunities for the in-space production of materials and biomaterials on the ISS and beyond. A brief introduction to physical and biological processes in the absence of gravity is provided, followed by a brief history of in-space manufacturing and exemplary areas for advancing in-space production.

2 PHYSICS AND BIOLOGY IN MICROGRAVITY

The removal of gravity has some obvious effects on physical and biological phenomena and many underlying, cascading effects. One obvious physical phenomena is the absence of density-driven separation and sedimentation, which allows surface forces to dominate. This means that multiphase fluids are dictated by the surface energies and surface tension of the phases present.

This has a significant effect on multiphase materials such as foams, emulsions, and gels. The mesoporous structure of multiphase materials like aerogels and bijels may be improved by eliminating density-driven phase separation. In addition, complex solidification dynamics involving multiple components are improved by suppressing density-driven segregation in materials like complex glasses, metallic glasses, and high-entropy alloys.

Microgravity also significantly affects the physics of heat and mass transport by suppressing buoyancy-driven (natural) convection. This eliminates a source of mixing in fluids and creates a diffusion-limited regime. Heat transfer is reduced in the near absence of natural convection, and the reaction kinetics are slowed due to the diffusion-limited transport.[1]

Space-based manufacturing can leverage the suppressed natural convection in processes and materials that necessitate thermal or concentration gradients. In addition to controlled kinetics in the diffusion-limited regime, fluid processing hindered by turbulence may be improved by operating without natural convection-driven mixing and turbulence. This is exemplified in Figure 1, which shows that crystals can grow larger and of higher crystalline quality in the absence of convection-driven eddy currents and sedimentation.

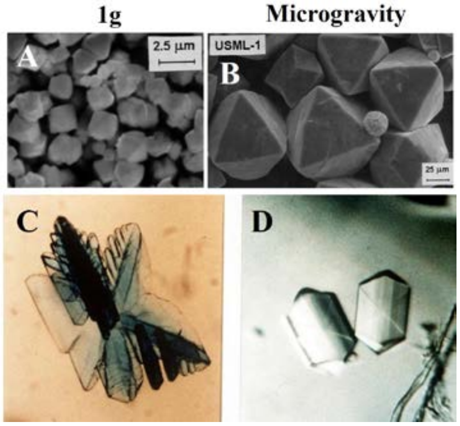

Figure 1: A-B) Zeolite crystals grew larger and with fewer defects in microgravity (B) relative to 1g terrestrial samples (A). C-D) Isocitrate lyase protein crystals grown on Earth (C) suffered from convection currents adversely affecting crystalline quality compared with crystals grown in microgravity (D). Images courtesy of NASA.

Similarly, the absence of sedimentation allows cell cultures to remain suspended in solution to form 3D structures rather than loose cell aggregates that fall out of solution. In a related fashion, soft, low-density materials can be reproducibly grown in microgravity as opposed to terrestrially, where their delicate structures collapse under their own weight. Thus, the printing of 3D human tissues may be improved in the weightlessness of microgravity. This could be extended to intricate and delicate 3D printed polymer or metal parts, or even large structures like satellites or arrays with designs that could not be supported on Earth or survive launch forces.

In microgravity, it is possible to minimize or even eliminate the contact of fluids and materials with the walls of a containment vessel. This can reduce heterogeneous nucleation for more controlled crystal growth and avoid crystal formation for glasses like bulk metallic glasses.[2] Containerless processing can also prevent undesired effects from surface energies, contamination, or other effects from the containment vessel.

Microgravity also affects cellular physiology and gene expression, altering an organism's phenotype.[3] Simulated microgravity has been shown to accelerate microbial metabolism, alter the population dynamics of microbial ecosystems, and reduce the lag time associated with the production of useful chemical and biological byproducts.[4] Thus, microgravity may provide pathways to the use of microorganisms as living foundries for in-space biofabrication.

3 HISTORY OF IN-SPACE PRODUCTION

When the United States launched its first space station, Skylab, into low Earth orbit in 1973, there were aspirations of producing new materials that would be improved by manufacturing in microgravity.[5, 6] Arguably, the first in-space production occurred just a few years prior in 1969 when Soviet cosmonauts conducted the first welding in space on Soyuz 6. Thus Skylab was equipped with a materials processing facility to explore the potential of microgravity to produce novel and higher-quality materials.

These early experiments on Skylab demonstrated the capability of microgravity to improve crystal quality and size.[6] Through vapor-phase growth, GeSe crystals grew to 20 mm in microgravity, exceeding the size of terrestrial crystals by an order of magnitude, as shown in Figure 3A. Melt growth of InSb crystals in microgravity exhibited an order-of-magnitude reduction in crystal defects due to the absence of convection currents and container wall interaction during crystallization. These and other experiments on Skylab and the Soviet Salyut and Almaz space stations provided the proof of principle that materials production could be improved through microgravity.

The development of the space shuttle by the United States and the Soviet/Russian space station, Mir, provided additional opportunities to explore and demonstrate in-space production. The U.S. National Institute of Standards and Technology (NIST) partnered with NASA to produce polystyrene beads, later called "space beads," to be used as calibration standards. The beads were produced on space shuttle Challenger in 1983 and exhibited superior particle sphericitiy, narrow size distribution, and particle rigidity due to the absence of gravity during production. The 10-µm

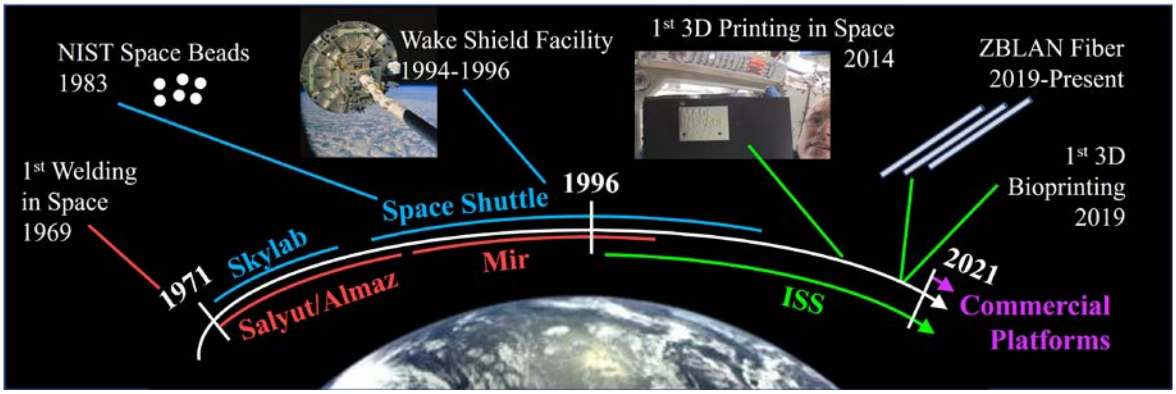

Figure 2: Select examples of in-space production over the last 50 years with spacecraft and space stations that enabled the research. Inset images courtesy of NASA.

diameter polystyrene spheres were sold to the public as Standard Reference Materials (SRM) 1960, making them the first commercial product manufactured in space.[7]

For more than 20 years, the ISS has been continuously inhabited by crews conducting research onboard the largest human-created structure in space. This research facility has served as the test bed for many in-space production trials, including the production of bulk metallic glass, artificial retinas, organoids, single crystal radiation detectors, and pharmaceutical formulations. Made In Space, which was acquired by Redwire in 2020, successfully printed the first object in space in 2014: a faceplate composed of acrylonitrile butadiene styrene. In 2019, for the first time, companies Techshot and nScrypt used their BioFabrication Facility onboard the ISS to 3D print using cultured human cells as bioinks.

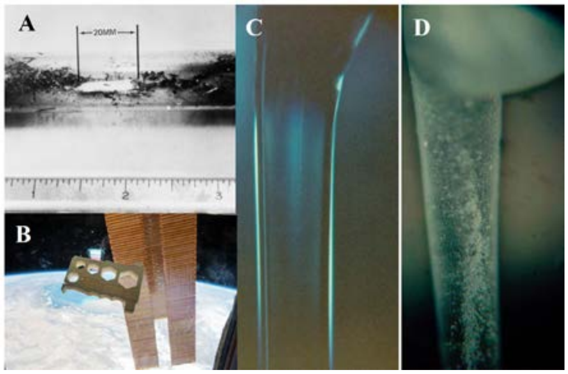

Figure 3: Examples of materials produced in microgravity. A) A 20-mm crystal of GeSe on Skylab. B) A tool that was 3D printed on the ISS. C-D) ZBLAN optical fibers drawn in microgravity (C) and on Earth (D), showing an absence of crystallization and surface defects in the microgravity sample. Images courtesy of NASA.

One notable commercial manufacturing development on the ISS has been the drawing of exotic optical glass fibers in microgravity. ZBLAN is a heavy metal fluoride glass with a broad transmission range. Replacement of traditional silica optical fibers with ZBLAN fibers could reduce attenuation in the infrared spectrum by orders of magnitude. However, terrestrial manufacturing of ZBLAN is plagued by crystallization and surface defects, which limit the predicted performance. Microgravity has been shown to reduce or eliminate crystallization by removing buoyancy-driven segregation and convection, as shown in Figure 3C.[8] Multiple commercial companies are currently pursuing ZBLAN fiber production on the ISS to manufacture fibers of superior optical quality for use on Earth.[9]

4 IN-SPACE PRODUCTION TECHNOLOGIES OPPORTUNITIES

Past research has demonstrated that there is great potential to manufacture products in microgravity that cannot be produced terrestrially. However, the economic value of manufacturing products in space is complex and requires more rigorous selection than terrestrial production. Two major considerations are the significant transportation costs of raw materials and final products, as well as the high costs and difficulty of remote operation.

With the addition of commercial launch services by SpaceX, Northrup Grumman, and soon Boeing and Sierra Nevada, the cost of transportation to low Earth orbit is rapidly decreasing. However, mass is still a significant consideration, as the cost to launch a kilogram to the ISS is currently greater than $23,000 USD.[10] Because of these rapidly falling but still significant transportation costs, in-space production requires a focused approach to identify scalable and sustainable manufacturing opportunities.

Three considerations are necessary for evaluating in-space manufacturing potential. (1) How many flights are required to prove the concept and fine tune the operating parameters? The best outcome will result from the ability to continuously test and iterate in space to eliminate additional launch costs and reduce timelines. (2) What is the product value per unit mass? Due to transportation costs, the initial focus should be on production efforts where the value ratio of the product to the mass of materials is high. (3) Is it possible to reduce transportation costs by sourcing raw materials in-situ? These materials could be waste streams or in-situ-sourced materials. Additionally, the products could be produced for use in space, further enhancing the value and eliminating the cost of delivery and return.

We will present three exemplary test cases of products that are enhanced by manufacturing in space and are ripe for commercial in-space production.

4.1 Opportunity #1: Crystal Production

As discussed previously, the absence of buoyancy-driven convection and sedimentation can lead to significant improvements in crystal growth. These improvements include larger crystals, single crystal growth, and reduced defects and impurities. For inorganic materials, numerous examples have demonstrated improved crystal growth in microgravity. And for pharmaceuticals, protein structure and drug formulations that do not crystallize well terrestrially may crystallize in microgravity.[1]

In a recent study, Merck & Co. flew samples of its monoclonal antibody oncolytic, pembrolizumab (Keytruda®), to be crystalized on the ISS, as shown in Figure 4.[11] The result was better uniformity that could improve not only manufacturability but also the formulation of the final product. Improvements in uniformity represent a significant opportunity to harness microgravity for crystal generation and open the field to the production of therapeutic large biomolecule crystals and small molecule pharmaceuticals, as more then 90% of small molecule pharmaceutical products are crystalline.

For inorganic crystal production, opportunities exist to build on the demonstrations of past microgravity experiments. For example, zeolite crystals have been produced in microgravity of larger size and with reduced defects compared with ground controls, as depicted in Figure 1B. It is expected that that similar results could be achieved with metal-organic frameworks (MOFs). In addition, much work has been conducted on large single crystal growth of semiconductor crystals for sensors and detectors. Commercial trials are underway on the ISS to explore the manufacturing of single crystal optical components.

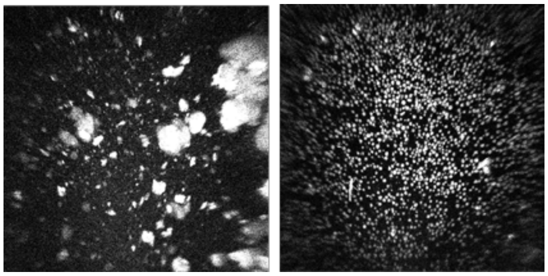

Figure 4: Ultraviolet images of pembrolizumab crystallized in a ground control sample (left) and microgravity sample (right). Adapted from Reichert *et al*.[11]

4.2 Opportunity #2: Organoids and Microphysiological Systems

Organoids, 3D self-organized tissues developed from stem cells to replicate some functions of human organs, have been widely adopted for research applications as "mini-organ" model systems for human disease. These cell assembly technologies, paired with microphysiological systems, or "tissue chips," small microfabricated platforms designed for the sustained culture of small tissue samples, can be scaled for throughput as viable models, with good reproducibility and lower cost points.[3, 12]

The pharmaceutical industry is beginning to look to organoids and microphysiological systems to develop tools that could help remediate risks involved in drug discovery and development. One issue is the morphological differences between terrestrial tissue cultures that are flat and the tissues found in organisms that have a 3D structure. Much of this difference is associated with the structural supports and process of development found in living systems. Early studies have shown that 3D organoids grown in microgravity better reflect the tissues they model. This could lead to improvements in the time to market and cost of future pharmaceutical products.[3, 13]

4.3 Opportunity #3: Complex Solidification

ZBLAN optical fibers are arguably the most mature in-space production technology. However, many other multicomponent materials and alloys can be improved by microgravity solidification. Much like ZBLAN, several high-entropy alloys have exhibited density-driven segregation of higher atomic mass constituents. Solidification of high-entropy alloys in microgravity may lead to improved homogeneity and performance. Similar opportunities may exist for complex ceramics as well.

Another advantage of microgravity production is the possibility for containerless processing. In the free-fall of low Earth orbit, melts may be suspended without contacting the containment vessels, which reduces both impurities introduction and homogeneous nucleation at the container surface. Containerless production of bulk metallic glasses has been demonstrated in microgravity with impressive results.[2] Similar opportunities may exist for complex glasses in which crystallization during terrestrial manufacturing hinders performance.

5 CONCLUSION

After more than 50 years of research in microgravity, we near the dawn of a new day in manufacturing: in-space production. Experiments onboard Skylab, Mir, and the ISS have demonstrated the superior performance of some products when produced in microgravity. And with new launch services and commercial platforms coming online, the time is ripe for new commercial ventures in in-space production. Engineers and scientists can now treat gravity as a variable to optimize manufacturing processes.

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