Topical: Using the International Space Station as a Testbed to Research 3D Printing of Foams

Alexander Blanchard | MSFC EM-04 | (207)-766-6482 | alexander.j.blanchard@nasa.gov
Dr. John Pojman | Louisiana State University | john@pojman.com

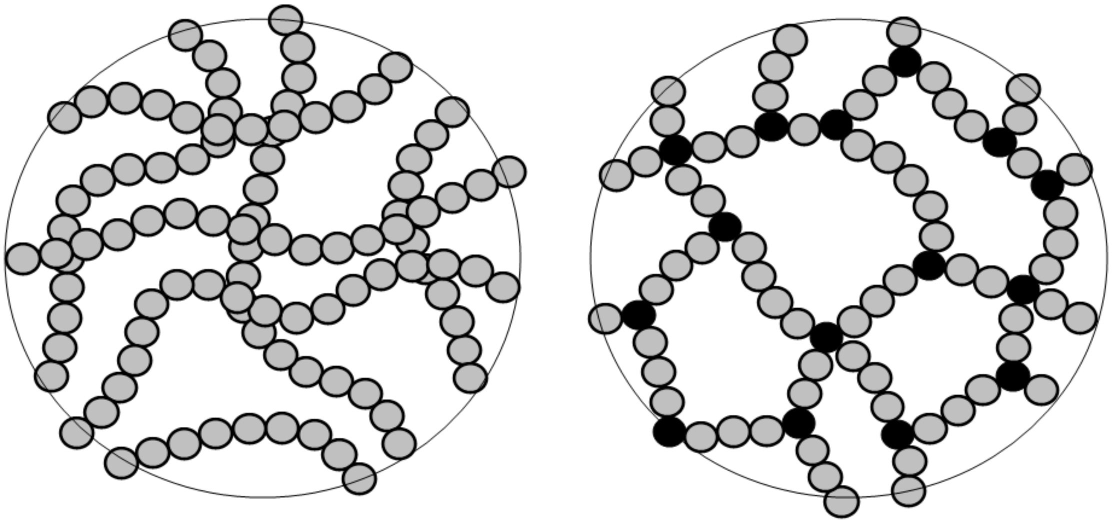
1. Introduction

Waste management on the International Space Station (ISS) poses similar problems in low Earth orbit as it does terrestrially. The confined space of the ISS magnifies the need for efficient waste handling. A build-up of waste on station would pose health and safety threats to crew on board limiting their capacity to work effectively, jeopardizing critical mission success. Currently, astronauts spend much of their time collecting trash into packages known as 'trash footballs' (Figure 1). These packages are loaded onto a designated vehicle destined either for safe return to Earth or disintegration upon re-entry into the atmosphere. Under the current paradigm, the ISS is constantly resupplied from Earth, however for long-duration missions and future habitation this logistical model is not feasible. Logistics reduction will be necessary in future missions making the need for on-demand sparing from all useable material a requirement.

Figure 1. Stowage bags in the Harmony node of the International Space Station. The bags, containing trash and excessed equipment, will be transferred to the docked Progress 45. spacecraft for disposal.
Photo Credit: NASA

Furthermore, the bulk of this waste is generated from packaging materials. These materials predominately consist of either foam used to prevent damage to items during launch or films used to bag items for storage. Of the two, foams represent a larger share of the packaging waste with some foams such as Zotek F30 contributing as much as 60 kg per launch.[1] Foams are of particular interest because in addition to representing a large share of waste volume per launch, they are not easily recycled due to crosslinking. Crosslinking occurs when two polymer chains are either chemically or physically connected with either covalent or ionic bonding. This restricts the movement of individual polymer chains affecting the rheology, melt processing, and mechanical properties. Crosslinked polymers are typically thermosetting polymers which harden irreversibly, making reprocessing difficult to achieve (Figure 2). This greatly restricts the availability of foams that can be recycled or reprocessed for use in additive manufacturing. Of particular interest is the additive manufacture of on demand parts and packaging consisting of foams that can then be recycled and reused.

If waste streams are diverted from disposal and instead converted into functional parts or tools, considerable amounts of time, energy, and money could be saved as well as significantly reducing logistical support. These capabilities could also extend beyond space applications. For instance, soldiers stationed in the battlefield may be able refabricate parts where resupply missions are too dangerous to execute.



Left: Linear polymer chains without crosslinking (thermoplastic polymer) Right: Crosslinked polymer chains (rigid thermosetting polymer)
Photo Credit: Wiki Commons

2. Investment Opportunities

To realize the full potential of recycling and reuse, funding must be focused on two main areas, namely: 1) investigating material properties and materials that lend themselves well to additive manufacturing, and 2) understanding and overcoming current additive manufacturing (AM) hardware and power limitations in low gravity environments. Although further advancements in AM will relinquish much needed crew time, maturing additive manufacturing materials will yield the greatest results as it allows for tailor-made materials for niche applications as specificity is increasing at a prodigious rate. Funding fundamental materials research will enable a future human presence on the Moon and beyond, in addition to growing the United States of America's economy while remaining dominant in the aerospace sector.

3. Precedence to Research 3D Printed Foam Objects

Foams are ubiquitous in the world around us; they are present in aerospace applications the auto industry, foods, cosmetics, and everything in between. Solid foams form when gas is trapped in a liquid medium that undergoes a phase transition to a solid. An example of foam is when the addition of a surfactant such as soap lowers the surface tension of the surrounding fluid and allows for bubble formation when the solution is agitated.[2] Sometimes foam is produced when two chemicals are combined to produce a gas in large quantities within a liquid medium, for example, when diisocyanates and polyols combine to form polyurethane foam.[3] Another common method is the addition of a blowing agent that will release gas when activated by an external force (usually with heat or UV light) within a material undergoing a phase transition, such as a liquid polymer cooling to become a solid.[4] As the polymer solidifies the gas bubbles become trapped resulting in foam. A variety of blowing agents can be chosen depending on the chemical system; some examples include azodicarbonamide and sodium bicarbonate.

Surprisingly, foams behave very differently in microgravity than they do here on Earth. Terrestrially, the bubbles produced that will ultimately become foam will rise to the surface of the liquid medium due to their natural buoyancy while the denser fluid begins to sediment to the bottom. Then, as the liquid percolates between the bubbles and begins to settle towards the bottom, the bubbles become increasingly thinner until eventually, they burst. Another phenomenon that is occurring during liquid sedimentation is coarsening. Coarsening arises when the mean number of bubbles decreases while mean bubble size increases. During coarsening, larger bubbles form at the expense of smaller bubbles as bubbles coalesce into ever increasing sizes. As bubbles become larger and more buoyant, they rise displacing surrounding fluid, increasing the rate of sedimentation and coarsening. However, bubbles formed in microgravity tend to be extremely stable due to the lack of fluid sedimentation that is seen here on Earth.[5] With the lack of sedimentation, the bubbles are not as thin and are not compressed due to the force of gravity. A recent experiment on the ISS saw the formation of bubbles within pure water.[5] The added stability of bubbles found in microgravity will also influence bulk foaming behavior because as fewer bubbles collapse back into solution, a large increase in bubble formation can be observed.[5] Furthermore, it is possible to produce foams with larger bubbles with enhanced uniformity.[5]

One of the traditional challenges with human spaceflight past low Earth orbit is that long duration missions will have limited storage for items and equipment needed to sustain life on another planet. Current constraints for on demand manufacturing require that the printed part be no larger than the build volume of the printer. Traditional techniques for the manufacture of a part larger than its build volume requires the manufacture of several smaller parts that are then joined postproduction. A team of researchers at the University of San Diego have recently demonstrated the addition of blowing agents into resin for stereolithography (SLA) 3D printing that allows for a part to be expanded up to 40 times its original volume after heat activation. To accomplish this task, the researchers placed four constraints on the blowing agent, namely: 1) the polymer resin must have a quick cure time, 2) the decomposition of blowing agent must be above the glass transition temperature (T_g) yet below the melting temperature (T_m) to assure that the printed part can undergo deformation without melting, 3) it must be soluble in the monomer, and 4) it must not crosslink. The researchers chose SLA over Fused Deposition Modeling (FDM) for its ability to produce high fidelity parts.[6] Previous attempts to produce FDM filament capable of producing foam parts has thus far been limited to intercalating a dissolvable solid homogeneously throughout the filament which is dissolved after production.[7,8] However, FDM technology is well-suited for a much larger array of materials and material systems than SLA because materials selection is not limited to those that cure rapidly when exposed to light. Moreover, FDM is the primary 3D printing technology on the ISS. Thus, there is a need to build objects larger than the build-volume given the limited space available on future missions and FDM is well positioned to take advantage of future materials research that could make this a possibility.

4. Outcomes

Terrestrially, gravity is omnipresent often convoluting the observation of physical phenomena; however, microgravity poses its own unique challenges. On Earth, convection is the result of differing densities between two liquids or gasses whereby the denser of the two sinks and the lighter one rises, resulting in mixing. In microgravity, there is not a density difference which mitigates buoyancy driven convection, therefore convection resulting from differences in interfacial tension (Marangoni convection) will predominate.[9]Materials processing in the absence of buoyancy driven convection may allow for the manufacture of high-quality materials that are not possible here on Earth. Therefore, the author suggests the use of the ISS as a test bed to study filaments used in FDM printing to produce foams for niche applications and allow for the ability to print parts larger than the original build volume.

The ISS provides a unique opportunity to study the addition of blowing agents into filament. With added stability and limited coarsening effects on bubbles afforded by microgravity in foaming systems similar to that observed on the ISS, it may be possible to produce rigid foam objects from FDM filament.[10] This could allow for a part to be printed that is substantially smaller than its final form. Once the part is printed the blowing agent could be activated either by heat or UV light to expand the part to many times its original size. Without buoyancy driven convection, longer set times are possible giving a wide range of polymer/blowing agent combinations allowing each part to be tailored to its application. Expandable printed objects could find use in a wide array of applications from habitat insulation to sleeping pads. Additionally, the lack of coarsening could yield foams with uniform pockets giving providing superior mechanical properties. This may also make it possible to produce traditional parts using less filament. Lastly, the addition of foaming agents in thermoplastics create foams without crosslinking so items made this way can be densified, melt processed, and extruded back into filament.

5. Conclusion

It is important to understand the phenomena of bubble formation as it relates to foaming in microgravity to not only enable future long-duration missions, but to provide valuable insights that lead to advanced materials of importance terrestrially. There are two principle driving factors behind these investigations, namely the reduction of buoyancy driven flow isolates the forces could allow for slow curing thermosplastics which are difficult to 3D print on Earth and the possibility of foams with enhanced physical properties. With the elimination of sedimentation, bubbles achieve greater stabilities than those observed on Earth allowing for more foaming behavior and uniform bubbles. Additionally, it has been shown that the addition of a blowing agent to SLA monomer on Earth can expand up to 40x its original volume.[6] Therefore, using the ISS to research the expansion of this technology into FDM 3D printing could enable reduced logistics and eventual colonization of Mars through the manufacture of spares and even habitats. The value of studying foams as it relates to 3D printing in microgravity cannot be overstated in terms of the benefit it will provide in helping us to understand this interesting phenomenon, providing a launch pad for future advanced materials development.

References

(1) Zapalac, Kris. Interview. By Michael Ewert. 25 October 2021

(2) Małysa, Kazimierz. "Wet Foams: Formation, Properties And Mechanism Of Stability". *Advances In Colloid And Interface Science*, vol 40, 1992, pp. 37-83. *Elsevier BV*, doi:10.1016/0001-8686(92)80071-5.

(3) Desai, Sonal et al. "Effect Of Polyols And Diisocyanates On Thermo-Mechanical And Morphological Properties Of Polyurethanes". *European Polymer Journal*, vol 36, no. 4, 2000, pp. 711-725. *Elsevier BV*, doi:10.1016/s0014-3057(99)00114-7.

(4) Quinn, Stephen. "Chemical Blowing Agents: Providing Production, Economic And Physical Improvements To A Wide Range Of Polymers". *Plastics, Additives And Compounding*, vol 3, no. 5, 2001, pp. 16-21. *Elsevier BV*, doi:10.1016/s1464-391x(01)80162-8.

(5) Langevin, Dominique. "Aqueous Foams And Foam Films Stabilised By Surfactants. Gravity-Free Studies". *Comptes Rendus Mécanique*, vol 345, no. 1, 2017, pp. 47-55. *Elsevier BV*, doi:10.1016/j.crme.2016.10.009. Accessed 26 Oct 2021.

(6) Wirth, David M. et al. "Highly Expandable Foam For Lithographic 3D Printing". *ACS Applied Materials & Interfaces*, vol 12, no. 16, 2020, pp. 19033-19043. *American Chemical Society (ACS)*, doi:10.1021/acsami.0c02683. Accessed 26 Oct 2021.

(7) Singh, Ashish Kumar et al. "Additive Manufacturing Of Syntactic Foams: Part 1: Development, Properties, And Recycling Potential Of Filaments". *JOM*, vol 70, no. 3, 2018, pp. 303-309. *Springer Science And Business Media LLC*, doi:10.1007/s11837-017-2734-7.

(8) Marascio, Matteo Gregorio Modesto et al. "3D Printing Of Polymers With Hierarchical Continuous Porosity". *Advanced Materials Technologies*, vol 2, no. 11, 2017, p. 1700145. *Wiley*, doi:10.1002/admt.201700145. Accessed 26 Oct 2021.

(9) Pojman, John A, and James Patton Downey. *Polymer Research In Microgravity*. American Chemical Society, 2001.

(10) Carpy, R et al. "Foam Generation And Sample Composition Optimization For The FOAM-C Experiment Of The ISS". *Journal Of Physics: Conference Series*, vol 327, 2011, p. 012025. *IOP Publishing*, doi:10.1088/1742-6596/327/1/012025. Accessed 26 Oct 2021.