Research Campaign:
The Sciences of Space Manufacturing

A campaign of fundamental, computational, and applied sciences underpinning and advancing manufacturing outside of Earth's gravity

Primary author

Ian Hanson
(256) 544-5278
NASA Marshall Space Flight Center
ian.m.hanson@nasa.gov

Co-Authors (listed alphabetically):

Robert Biggs, Lockheed Martin Space
Joshua Fody, NASA Langley Research Center
Ed Glaessgen, NASA Langley Research Center
Brad Kinsey, University of New Hampshire
Douglas Matson, Tufts University
Ranga Narayanan, University of Florida
Adrian Radocea, Varda Space Industries
Brodan Richter, NASA Langley Research Center
John T. Roth, University of New Hampshire
Michael SanSoucie, NASA Marshall Space Flight Center
James Stott, NASA Marshall Space Flight Center
Louise Strutzenberg, NASA Marshall Space Flight Center
Peter Voorhees, Northwestern University
Ulrike Wegst, Northeastern University

Introduction

The expansion of manufacturing into the reduced gravity environments of space and other worlds creates both the need and opportunity for greater scientific understanding. Development of space infrastructure and the constant push of human exploration back to the Moon and beyond require this new industrial revolution – manufacturing with scale and responsiveness beyond the limits of rocket fairings and launch schedules in a novel design language. Great science accompanies great industrial change. This pattern repeats throughout history prominently since the industrial revolution – the field of thermodynamics and a host of novel precision tools trace their inspiration to Watt's practical and applied work to increase the efficiency of the original Newcomen steam engine.

Space manufacturing encompasses manufacturing during exploration in distant spacecraft, on the lunar surface as well as closer to home in orbit around the Earth. For exploration and lunar habitat applications, space manufacturing provides flexibility and logistical benefits. Missions gain flexibility with the ability to manufacture parts and tools on demand and logistical benefits from the mass savings once when the mass of the total manufacturing platform adds up to less than the stowed parts they replace. The first on-demand manufacturing systems already provide novel capability to the ISS (International Space Station) and have already produced over 200 tools and parts [1]. For lunar development and work in Earth's orbit, space manufacturing allows scale – the fabrication and assembly of structures far too large or fragile to launch from the surface. In time, the commercialization, industrialization and democratization of space requires all manner of space manufacturing from polymers and glasses to composites and circuitry. These endeavors require not only novel forming and joining technologies, but ultimately also the ability to mine, refine, manipulate, recycle, and shape useful parts from scrap, space debris, regolith, or asteroids. All of these processes – the full breadth of space manufacturing – share the same fundamental phenomena. This fundamental and applied scientific work accelerates development of these manufacturing processes in deep space, in orbit and in Earth-bound for-space applications simultaneously.

Space manufacturing is not a relocation of manufacturing – it's a reinvention. On-demand additive manufacturing and recycling systems produce parts with materials properties and geometries fundamentally different than traditional subtractive manufacturing systems. Developing exploration manufacturing platforms capable of creating useful spares requires host spacecraft and habitat systems designed specifically to accept these on-demand manufactured parts. Therefore, the manufacturing system as well as the entire spacecraft and habitat system require novel designs accommodating the manufacturing processes that create them. Existing engineering handbook properties lose relevance in this design environment, warranting a new design space of materials and processes custom to reduced gravity environments to empower growth. The current manufacturing design language grew from a rich but extensive decades- to centuries-long history of Edisonian engineering technology iterations – a history we do not have the time to repeat. This campaign supports the science needed to translate and rewrite this design language, but accelerated by computational methods freed from the pace of microgravity demonstrations and physical testing, especially considering the restrictions of work in reduced gravity.

In this campaign white paper we propose expanding research into fundamental properties relevant to the development of useful material properties and adapted manufacturing processes for use outside of the Earth's gravity, translating this understanding through the support and development of computational methods predicting behavior from atomic through macroscopic scales, and partnering with nascent public and government engineering efforts to steer our efforts toward their engineering outcomes and collect scientific data on their engineering technology demonstration hardware.

Phenomena of Interest

Space manufacturing began as early as the 1970s in Skylab [2]. Limited access to space held back the development of microgravity manufacturing technologies [3]; however, the completed work revealed many important phenomena requiring changes in how we can manufacture without gravity. In some cases, these changes pose significant obstacles to the development of robust practices. In other cases, the differences of the space environment open unique process windows or capabilities that would also create economic benefit for economies back on earth [4,5].

Surface Tension and Other Weak Interfacial Phenomena

Absent gravity, surface tension and related forces dominate practical manufacturing tasks in ways difficult to predict based on terrestrial experience. The microgravity environment challenges common understanding regarding the formation and distribution of porosity, the function of lubricants, material segregation within a liquid or melt, and the ability to manage small particles from machining, wear, fretting, surface breakdown and exfoliation. Mastering this understanding not only mitigates problems in these areas, but also opens up new possibilities for containerless processing, novel functional gradient materials, and chemical processing optimized for space – replacing methods that currently depend on gravity distillation and burn-off. This topic also addresses safety concerns regarding the grouping of gas molecules into asphyxiating pockets or the flammability and explosion hazards of dusts.

Heat Transfer

Thermal transfer through and between various structures and phases of materials departs significantly from processing norms when performed in space. Gravity-driven convection dominates thermal transfer in many manufacturing systems on Earth. While large-scale heat removal concerns for basic process control and quenching could be described as engineering problems, heat transfer differences alter processes down through to the atomic scale affecting phase transformation, precipitate evolution, flow stress dependence, and solidification dynamics. For example, a study of crystal growth in soluble salts such as (NH2CH2COOH)3H2SO4 (TGS) found that the absence of gravity-driven thermal convection inhibited and complicated desired growth rates [6]. Detailed study of heat transfer across multiple length scale regimes benefits a wide variety of processes, leading to understanding of the origins of materials properties dependent on the subtleties of material morphology, crystal habit, and microstructure. Advances in the solution space may yield new heat pipe and radiator technologies, novel thermally-controlled processing for custom microstructures related to case hardening or directional solidification, and other tailored microstructures.

Extreme Environments and Non-Equilibrium Processing

With abundant hard vacuum and extreme low temperatures, space processing entails non-standard starting and rest conditions. The palette of materials property data available to engineers for work in space environments fails to cover the expected space manufacturing and service environment for many alloys, polymer systems and composites. Other challenging environments of space manufacturing can include hard radiation, no electronic ground, atomic oxygen corrosion in low Earth orbit, and lunar dust. The extension of manufacturing off the ground requires a similar departure of our understanding further from properties evaluated at room temperatures, ambient conditions, and standard pressure.

In addition to exploring phenomena related to a new set of common equilibrium temperatures, pressures and gravity environments, discovering materials characteristics in these conditions also supports on-demand manufacturing processes. For example, simulations of metallic additive manufacturing (AM) require accurate high temperature material properties because most of the consequential physics defining microstructure and defect formation takes place in and around the melt pool. However, a lack of accurate temperature-dependent material property data near and above the melting temperature for relevant metal alloys inhibits useful simulations [7,8]. Furthermore, investigating the extreme temperature, solvent, or stress gradients imposed by AM processing provides insight into non-equilibrium reactions and the properties of the metastable materials they produce [9].

In addition to progress towards new materials, an improved understanding of non-equilibrium processing advances the critical and costly field of quality control and certification connected to all manner of space manufacturing. Current NASA certification standards for additively manufactured safety-critical crewed flight vehicle parts specify significant production controls and post-processing steps, often requiring 100% volumetric inspection of every part [10]. Inherently variable as-built material properties, particularly from additively manufactured parts, drive these requirements, adding inspection time and costs which inhibit the more widespread adoptions of additive manufacturing by industry. The more that we do to accurately predict processing outcomes, the more accurately we can make microstructure, defect, and stress predictions that ultimately achieve high resolution property predictions resulting in safer, more predictable parts requiring fewer inspections, process controls and post processing steps.

Avenues of Progress

The campaign targets three areas that individually merit attention, but together comprise an organized and purposeful focus on space manufacturing. The foundational work element executes various investigations of fundamental microgravity materials science and collects thermophysical data with precision suitable for modeling inputs. The computational materials science efforts apply these data and discoveries in models for materials design and manufacturing applications following best practices for establishing collaborative infrastructure and robust verification and validation. Thirdly, a partnership and community team engages government and commercial engineering projects to both align scientific objectives to real-world challenges and to partner with hardware developers to augment engineering technology demonstration hardware to also generate scientific output.

Foundational Work

Foundational Work comprises two families of projects supporting the larger goals of the campaign – the continuation and expansion of fundamental microgravity materials science and the collection of thermophysical materials property data with fidelity required to serve as inputs to computational efforts. Neither of these represent a major new direction, but both require renewed urgency and acceleration to satisfy the intended role of science in the support of space manufacturing.

Every major manned space program since Apollo involved microgravity science work – the science forms a through line connecting all major space exploration including Skylab, Spacelab on the shuttle, Soviet/Russian work on Mir, and diverse projects on the ISS. Similarly, several terrestrial and space-based facilities work year-round to collect precision thermophysical data without the interference of gravity, including the Japan Aerospace Exploration Agency (JAXA) Electrostatic Levitation Furnace (ELF) and the European Space Agency (ESA) Electromagnetic Levitator (EML) both currently operating on the ISS. These ISS materials science facilities continue as microgravity workhorses but face fundamental limitations in utility and longevity when compared to the range and quantity of work ahead. To reach the goals of this campaign, microgravity science and the collection of high-precision thermophysical data requires a purposeful and proactive shift toward free-flyer science missions.

Decreasing launch costs together with the standardization and further miniaturization of robotic satellite technology removes cost and risk from free-flyer research programs – following a trend already seen in the proliferation of CubeSats [11] which are often capable of recording or transmitting data [12-15]. Free flyers can operate robotically, which is necessary especially for research with potentially hazardous experiments unsuitable for the ISS. Chinese and Russian programs regularly employ free-flyers to accelerate their microgravity and space capabilities using crafts such as the SJ-10 or the FOTON-M4 spacecraft. [16-20].

Not all microgravity research requires a trip to orbit. Terrestrial support includes research performed in levitators, drop towers, parabolic flights, sounding rockets, and suborbital flights. These platforms offering compromised microgravity or microgravity durations counted in seconds reduce risk, provide screening for more involved experiments and themselves support robust discovery with lower costs than orbital research. Other microgravity manufacturing science suitable for terrestrial work include studies on inspection techniques using material returned from microgravity processing and studies for screening experimental material for factors such as heterogenous nucleation tendencies, defect-dependent mechanical properties, and sensitivity to impurities or contamination.

This campaign supports the expansion of existing microgravity research programs at NASA centers throughout the Decadal Survey term. Envisioned work begins immediately continuing on the ISS platform, with aggressive near-term development and planning for the transition to free-flyer and potentially commercial orbital research platforms as the ISS wanes as the preeminent microgravity research destination [21]. In the medium and long term, basic research continues, but in a path more strongly correlated with manufacturing partnership objectives – focusing on materials systems, energy input sources, and scales more relevant to problems uncovered during engineering efforts. For the handling and dissemination of generated data, the campaign could employ the expertise at the National Institute of Standards and Technology (NIST), building on their experience with the Materials Genome Initiative (MGI) and preserving a legacy of value to projects extending far past this decadal term [22]. These foundational efforts squarely fit the role of government to support industrial development in ways too costly or time-consuming for commercial enterprise to engage. Stretch goals may include developing technologies to addresses gaps in current free-flyer capabilities such as the currently limited ability to return intact experimental materials to the surface.

Computational Materials Science

The *Computational Materials Science* thrust of the campaign aligns with the goals and objectives in the MGI Strategic Plan of the National Science and Technology Council (NSTC), executed in agreement with the vision and path forward described in "Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems" [23,24]. These source documents outline a steep challenge, and as a subset of their overarching goals the campaign intention simultaneously follows prior successes and models new approaches for the larger initiative. While the larger MGI may struggle with the creation of a unified materials innovation infrastructure, organizing the equivalent for only the parties pursuing microgravity materials science presents far fewer problems. Similarly, rather than needing to address all 118 gaps identified in the Vision 2040 document, this campaign seeks only to address a narrow set specific to microgravity science in order to draw participation from and provide inspiration to the larger computational materials science community. Prominently, this includes a robust program of verification experiments – a modeling effort without access to verification through physical experiments cannot thoroughly iterate and improve – and the expertise to provide this support already exists within NASA.

The computational element of the campaign stands out for the breadth of involvement. A sustained university research grant program throughout the campaign draws in fresh ideas while fulfilling MGI goals of training the future workforce. With the collaborative environment and a shared code database, the government-coordinated modeling program lowers the barrier to entry for university groups that may not have a strong existing computational materials science program. Graduates from these programs benefit from diverse experiences, allowing a transition into government programs, work with commercial hardware integrators, or other elements of the cyber-physical-social ecosystem established in this program.

Partnerships and Community

The *Partnerships and Community* activities envisioned in this campaign organize, steer, and optimize the scientific work through close coordination with the broader government, academic, and commercial space manufacturing engineering community. In collaboration, for example, with engineering teams devising joining plans for orbital construction or demonstrating wire-fed metal AM processes, the foundational science priorities shift to collect data suitable for modeling the construction material systems and teams execute studies of melting and solidification relevant to AM energy sources used in these near-term microgravity technologies. The science stays agile, responsive to the most impactful engineering challenges. Similarly, as engineering programs mature toward technology readiness level (TRL) 5-6 and demonstration in a microgravity environment, the partnership leverage common goals to coordinate axillary data collection mission objectives to the orbital engineering technology demonstration platform, collecting precision microgravity data relevant to model validation and samples suitable for scientific analysis and the development of novel inspection techniques. This enhanced interaction paradigm applied to disparate engineering projects and the integrated computational microgravity science group behave similarly – driving the real-world applicability of model outcomes to engineering goals and reducing expensive engineering development iteration with predictive model output, benefitting both groups.

Conclusions

Unique mysteries of reduced gravity processing hold back the meaningful translation of manufacturing into space with the scale and efficiency needed to meet our exploration and development potential. Prior work in the space manufacturing environment revealed many unexpected disparities from traditional manufacturing due to surface interfacial effects, heat transfer, and non-equilibrium processing – this proposed campaign provides a mechanism for furthering understanding of those phenomena to enable robust space-based manufacturing of all types. This campaign coordinates and combines three complementary efforts to expand practical applied capabilities through advancing fundamental scientific knowledge, harnessing computational tools as knowledge multipliers, and creating social collaborative structure that engages human capital with efficiency and purpose.

Other national space programs understand the importance of this work. The ESA, JAXA, Chinese, and Russian space programs actively acknowledge the importance of developing capabilities for long-term presence in space, including those needed for manufacturing in space. The US must recognize this imperative and lead development of capabilities for space manufacturing. To meet this growing challenge, this campaign proposes the direct applied advancement of space manufacturing through three distinct, integrated *Avenues of Progress*. The first develops the *Foundational Work* that expands fundamental microgravity materials science alongside proliferating thermophysical materials property data – proactively ensuring these goals transition to new orbital capabilities without hiatus. This work enables and supports the *Computational Materials Science* element the campaign. In their most advanced form, *Computational Materials Science* tools holistically integrate manufacturing, materials, and design and unite materials science and engineering [25]. Achieving the potential of a computational scientific framework to solve engineering problems requires a similar integration of the practitioners of materials science and materials engineering into a symbiotic community. The steering, technology transfer, and socialization functions of the *Partnerships and Community* element form the center of the campaign. Together, these avenues provide a pathway enabling and accelerating space manufacturing for the decades to come.

References

[1] "Additive Manufacturing Facility (AMF)," accessed 15 December 2021. [Online]. Available: https://redwirespace.com/products/amf/.fac

[2] Witt, A. F., H. C. Gatos, M. Lichtensteiger, M. C. Lavine, and C. J. Herman. "Crystal Growth and Steady-State Segregation under Zero Gravity: InSb." Journal of the Electrochemical Society 122, no. 2 (1975): 276. DOI:10.1149/1.2134195

[3] Johnson, C. C., C. E. Wade, and J. J. Givens. "Space Station Biological Research Project." Gravitational and Space Biology Bulletin: Publication of the American Society for Gravitational and Space Biology 10, no. 2 (1997): 137-143. No DOI

[4] Giulianotti, Marc, Arun Sharma, Rachel Clemens, Orquidea Garcia, Lansing Taylor, Nicole Wagner, Kelly Shepard et al. "Opportunities for Biomanufacturing in Low Earth Orbit: Current Status and Future Directions." (2021). DOI:10.20944/preprints202108.0044.v1

[5] Scott, Troy J., and Nicholas S. Vonortas. "Microgravity protein crystallization for drug development: a bold example of public sector entrepreneurship." The Journal of Technology Transfer (2019): 1-20. DOI:10.1007/s10961-019-09743-y

[6] Aggarwal, Mohan D., Ashok K. Batra, Ravindra B. Lal, Benjamin G. Penn, and Donald O. Frazier. "Bulk single crystals grown from solution on earth and in microgravity." In Springer Handbook of Crystal Growth, pp. 559-598. Springer, Berlin, Heidelberg, 2010. DOI:10.1007/978-3-540-74761-1_17

[7] Mohr, Markus, and Hans-Jörg Fecht. "Investigating Thermophysical Properties Under Microgravity: A Review." Advanced Engineering Materials 23, no. 2 (2021): 2001223. DOI:10.1002/adem.202001223

[8] Mohr, Markus, Rainer Wunderlich, Rada Novakovic, Enrica Ricci, and Hans-Jörg Fecht. "Precise Measurements of Thermophysical Properties of Liquid Ti–6Al–4V (Ti64) Alloy On Board the International Space Station." Advanced Engineering Materials 22, no. 7 (2020): 2000169. DOI:10.1002/adem.202000169

[9] National Academies of Sciences, Engineering, and Medicine. frontiers of materials research: A decadal survey. National Academies Press, 2019. DOI:10.17226/25244

[10] NASA-STD-6030 Additive Manufacturing Requirements for Spaceflight Systems, Rev: Baseline, 21 April 2021 No DOI

[11] "NASA - CubeSats - CubeSats Overview", accessed 15 December 2021. [Online]. Available: https://www.nasa.gov/mission_pages/cubesats/overview

[12] Asphaug, E., Thangavelautham, J., Klesh, A., Chandra, A., Nallapu, R., Raura, L., ... & Schwartz, S. (2017). A cubesat centrifuge for long duration milligravity research. npj Microgravity, 3(1), 1-5. DOI:10.1038/s41526-017-0021-0

[13] Luna, Autumn, Jacob Meisel, Kaitlin Hsu, Silvia Russi, and Daniel Fernandez. "Protein structural changes on a CubeSat under rocket acceleration profile." npj Microgravity 6, no. 1 (2020): 1-6. DOI:10.1038/s41526-020-0102-3

[14] Schwartz, Stephen, Erik Asphaug, Jekan Thanga, Ravi Nallapu, and Leonard Vance. "An Ultra-Low-Gravity Centrifuge in Low-Earth Orbit." In European Planetary Science Congress, pp. EPSC2018-421. 2018. No DOI

[15] Lumpp, James E., Daniel M. Erb, Twyman S. Clements, Jason T. Rexroat, and Michael D. Johnson. "The CubeLab standard for improved access to the international space station." In 2011 Aerospace Conference, pp. 1-6. IEEE, 2011. DOI:10.1109/AERO.2011.5747232

[16] Li, Ning, Chengzhi Wang, Shujin Sun, Chen Zhang, Dongyuan Lü, Qin Chen, and Mian Long. "Microgravity-induced alterations of inflammation-related mechanotransduction in endothelial cells on board SJ-10 satellite." Frontiers in physiology 9 (2018): 1025. DOI:10.3389/fphys.2018.01025

[17] Hasan, Md Tawheed, Won Je Jang, Bong-Joo Lee, Kang Woong Kim, Sang Woo Hur, Sang Gu Lim, Sungchul C. Bai, and In-Soo Kong. "Heat-killed Bacillus sp. SJ-10 probiotic acts as a growth and humoral innate immunity response enhancer in olive flounder (Paralichthys olivaceus)." Fish & shellfish immunology 88 (2019): 424-431. DOI:10.1016/j.fsi.2019.03.018

[18] Hu, W. R., J. F. Zhao, M. Long, X. W. Zhang, Q. S. Liu, M. Y. Hou, Q. Kang et al. "Space program SJ-10 of microgravity research." Microgravity Science and Technology 26, no. 3 (2014): 159-169. DOI:10.1007/s12217-014-9390-0

[19] Borisenko, E. B., N. N. Kolesnikov, A. S. Senchenkov, and M. Fiederle. "Crystal growth of Cd1−xZnxTe by the traveling heater method in microgravity on board of Foton-M4 spacecraft." Journal of Crystal Growth 457 (2017): 262-264. DOI:10.1016/j.jcrysgro.2016.08.063

[20] Strelov, V. I., B. G. Zakharov, I. Zh Bezbakh, V. V. Safronov, B. V. Chernyshev, and I. N. Dutyshev. "Implementation of Temperature-Controlled Method of Protein Crystallization in Microgravity." Crystallography Reports 63, no. 1 (2018). DOI:10.1134/s1063774518010194

[21] NASA, “NASA Plan for Commercial LEO Development to achieve a robust low-Earth orbit economy from which NASA can purchase services as one of many customers: Summary and Near-Term Implementation Plans”, June 7, 2019. No DOI

[22] "NIST – Materials Genome Initiative – Materials Data Resources" accessed 15 December 2021. [Online]. Available: https://www.nist.gov/mgi/materials-data-resources

[23] Subcommittee on the Materials Genome Initiative, Committee on Technology of the National Science and Technology Council, “Materials Genome Initiative Strategic Plan”, November 2021. No DOI

[24] Liu, Xuan, David Furrer, Jared Kosters, and Jack Holmes. "Vision 2040: a roadmap for integrated, multiscale modeling and simulation of materials and systems." (2018). No DOI

[25] Allison, John. "Integrated computational materials engineering: A perspective on progress and future steps." Jom 63, no. 4 (2011): 15. DOI:10.1007/s11837-011-0053-y