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NASA's In-Space Manufacturing Project: Update on Manufacturing Technologies and Materials to Enable More Sustainable and Safer Exploration

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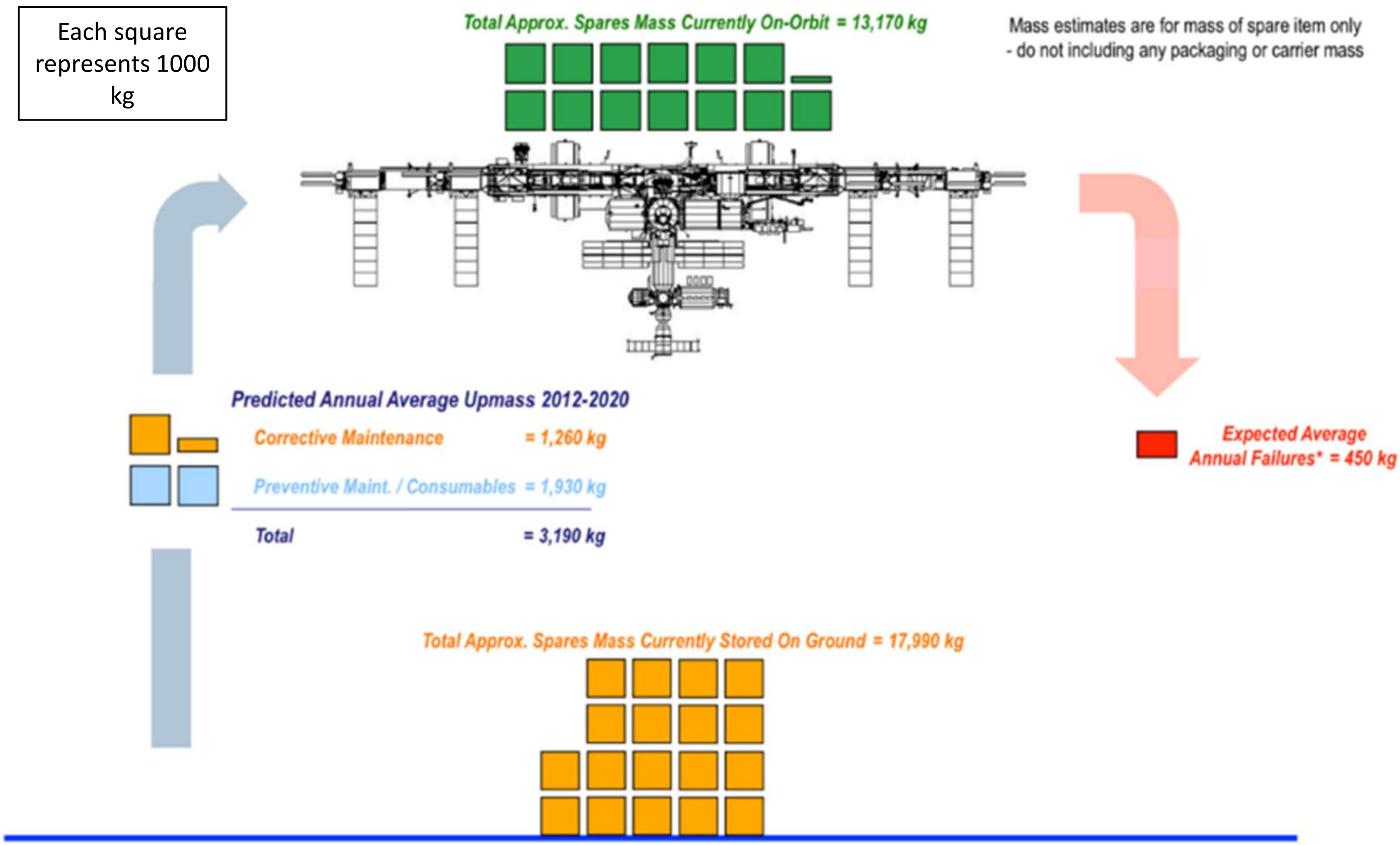
Why manufacture in space: The logistics quandary of long endurance spaceflight

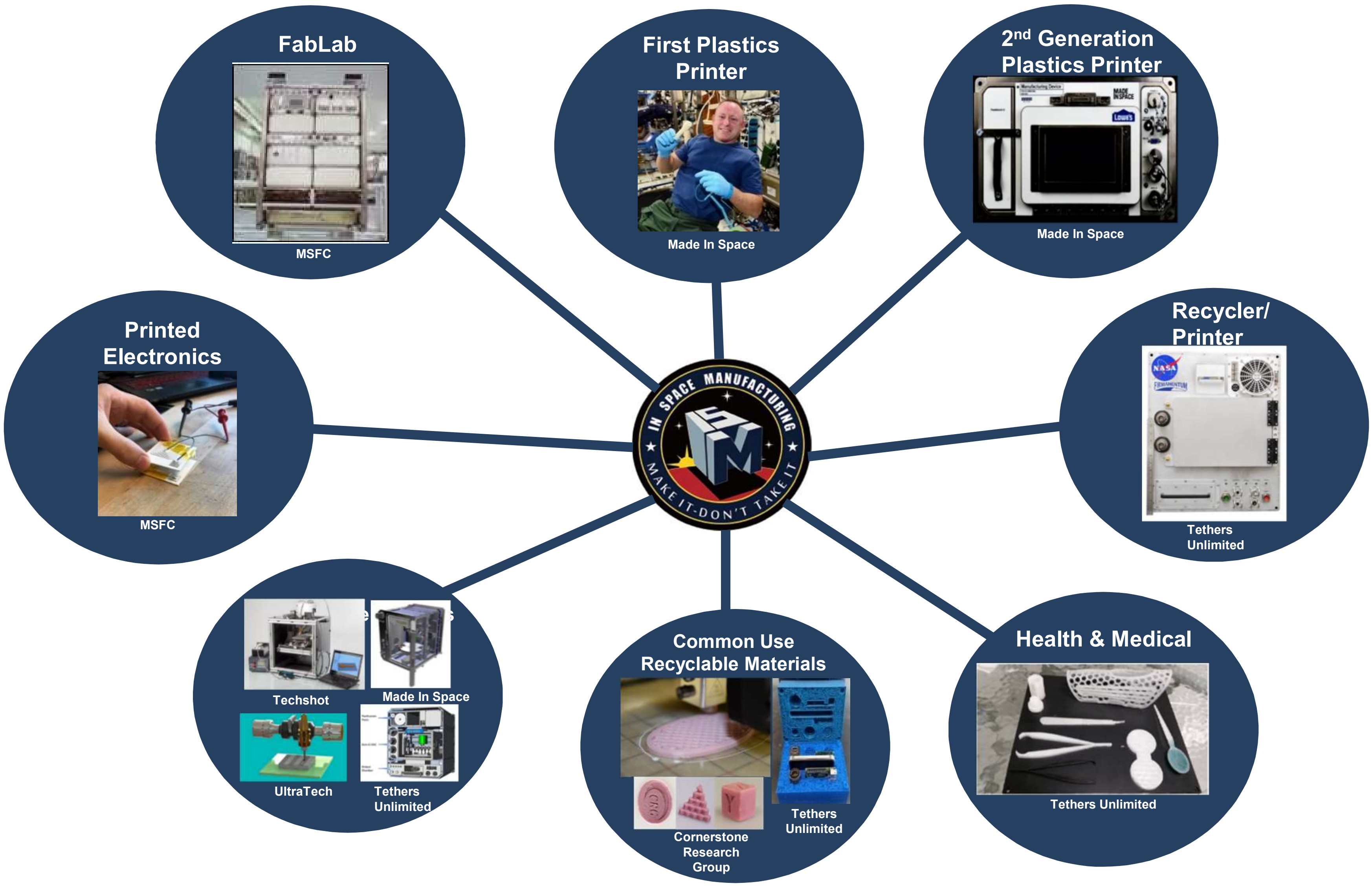


- Based on historical data, 95% of spares will never be used
- Impossible to know which spares will be needed
- Unanticipated system issues always appear, even after years of testing and operations

* - Based on predicted MTBFs

Image credit: Bill Cirillo (LaRC) and Andrew Owens (MIT)

In-Space Manufacturing (ISM) Project Portfolio



In-space manufacturing of polymers

- **3D Printing in Zero G Technology Demonstration Mission**
  - Small Business Innovative Research (SBIR) contract with Made in Space, Inc.
  - Printed 55 parts of Acryonitrile Butadiene Styrene (ABS) from 2014-2016
  - Printer operates in Microgravity Science Glovebox (MSG)

- **Additive Manufacturing Facility (AMF)**
  - Multimaterial commercial facility for polymer printing from Made in Space, Inc.
  - Printed over 100 mechanical test coupons (flight and ground-produced specimens)

- Computational models of fused filament fabrication (FFF) processes for polymer printing (work performed at NASA Ames Research Center) have not predicted significant impacts on FFF with variation of the gravity vector

3D Printing in Zero G Technology Demonstration mission printer in Microgravity Science Glovebox

Higher strength polymer feedstock development

- Development of feedstocks compatible with fused filament fabrication systems
  - Target property thresholds approach those of Aluminum alloys

Actuated Medical Inc. (AMI) SBIR (now in phase II)

- Carbon fiber reinforced PEEK (poly ether ether ketone) feedstock for 3D printing of medical devices and parts with strength requirements beyond those of traditional thermoplastic compositions
- Retrofit kit for standard desktop printers to enable printing of this feedstock in commercially available systems
- Laser-assisted heating following layer deposition significantly reduces anisotropy in the printed part

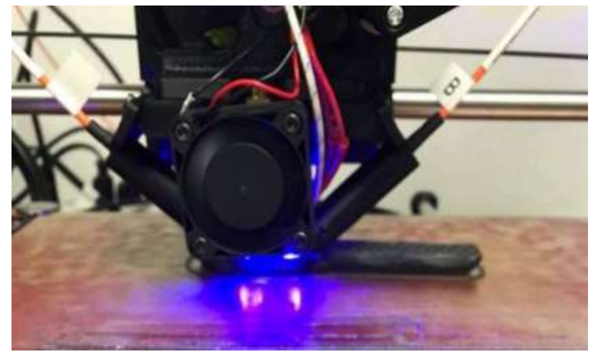


Image from Actuated Medical, Inc.

Geocomposites SBIR (now in phase II)

- Dual nozzle fused filament fabrication for printing of matrix with continuous fiber reinforcement
- Material strengths for some configurations are greater than 200 MPa in tension

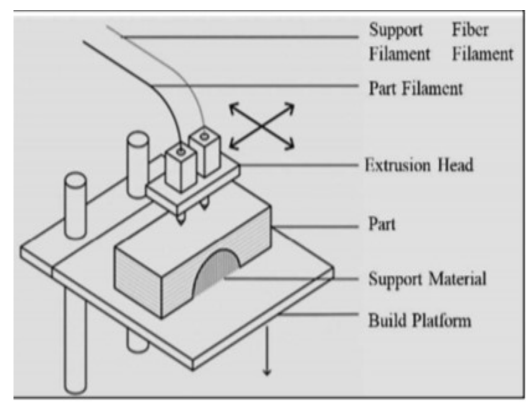


Image from Geocomposites

Recycling

- Recycling is critical to reducing logistics requirements for space missions and closing the manufacturing loop. ISM focuses on technologies to enable reuse of plastics, metals, and packaging materials.

- ISM manufacturing technology development for recycling capabilities

  - **ReFabricator payload from Tethers Unlimited, Inc. (TUI)** installed on International Space Station in early 2019.
    - capability to recycle printed polymer parts into filament feedstock for further manufacturing

  - **Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA), a ground based prototype system in development from TUI,** can process virgin or metal scrap material into ingots
    - Debris from machining of metal to fabricate a part is collected and can be used for further ingot manufacturing

ReFabricator (image from TUI)

Enabling Technologies for the Recycling Ecosystem

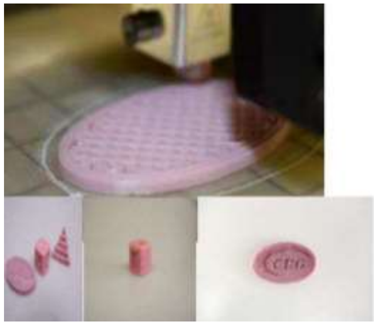
- ISM also has the goal of developing recyclable packaging materials and sustainable approaches which enable a recycling ecosystem for ISS.

  - **Polyethylene based thermally reversible material** can be processed into films and foams and recycled into filament for 3D printing (Cornerstone Research Group)

  - **Customizable, Recyclable ISS Packaging (CRISSP)**
    - Polymer 3D printed foams with custom infills engineered for specific vibration attenuation properties (Tethers Unlimited, Inc.)

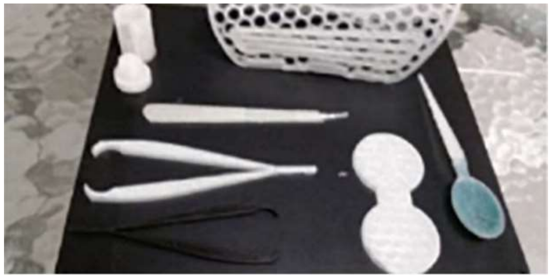
  - **ERASMUS is a multimaterial recycling capability** with an integrated dry heat sterilization chamber for polymer parts (Tethers Unlimited, Inc.)

  - **Automated in-process quality control of recycled filament production** and polymer 3D printing (Cornerstone Research Group)



Thermally reversible polymers for 3D printing (Cornerstone Research Group)

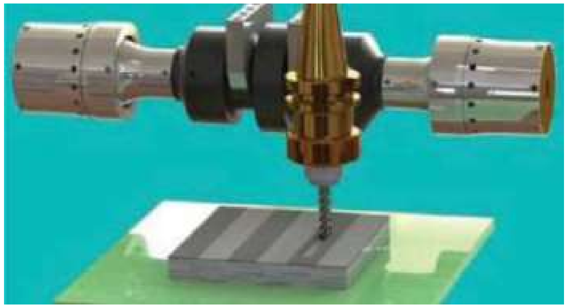
CRISSP from TUI



ERASMUS from TUI

Metal Additive Manufacturing for ISS (SBIRs)

- Challenges to metals fabrication in microgravity: power/volume/mass constraints, safety considerations, debris generation and control of debris (ex. machining), high temperature operating regimes for manufacturing and processing



Images from Fabrisonic

- **Ultra Tech Machinery and Fabrisonic are developing the ultrasonic additive manufacturing process for use on ISS**
  - Creates metallurgical bonds via acoustic energy imparted to adjacent layers of material using a sonotrode

Metal additive manufacturing for ISS

Images from Made in Space, Inc.

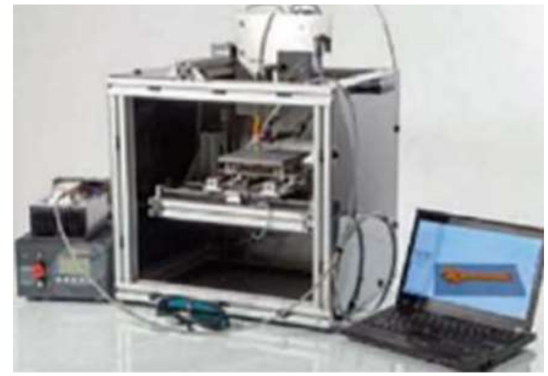


Image from Techshot, Inc.

- **Vulcan unit from Made in Space**
  - Derived from wire-fed welding process
  - Unit has multiple subsystems:
    - additive manufacturing unit (polymers and metals)
    - mill for finish machining
    - environmental control unit for debris capture
    - robotic capability for part manipulation

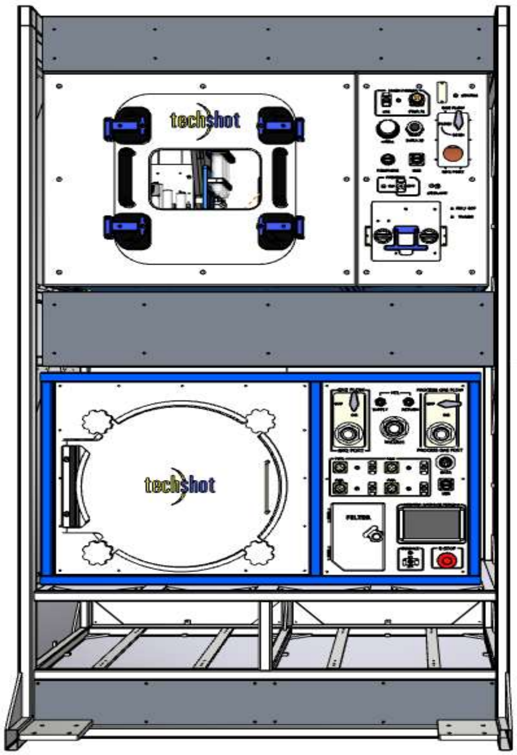
- **Sintered Inductive Metal Printer with Laser Exposure (SIMPLE) from Techshot, Inc.**
- Wire-fed additive manufacturing process for metals
- Uses inductive heating and operates in a vacuum
- Low power laser provides additional heating

Multimaterial Fabrication Laboratory

- Parallel efforts under a Broad Agency Announcement (BAA) to develop larger scale facilities for multi-material manufacturing (focus on aerospace metals) and inspection
- Systems must fit into an EXPRESS rack and are limited to peak power consumption of 2000 Watts, a weight of 576 lbm, and a volume of 16 cubic feet
- 18 month phase A efforts, focused on development of ground-based prototype systems and technology demonstration
- Phase A awards:
  - Techshot, Inc. (Greenville, IN)
  - Interlog (Anaheim, CA)
  - Tethers Unlimited (Bothell, WA)

Image of EXPRESS rack. Image from NASA.

Multimaterial Fabrication Laboratory



Techshot rendering of Multimaterial Fabrication Laboratory system, which includes capabilities for printing of metals, postprocessing of material, and dimensional inspection. Image from Techshot.

Empyrean Fabrication Laboratory concept rendering. Rack includes a robotic arm capability, control systems, and part inspection. Image from TUI.

Printable Electronics

- A manufacturing capability for electronics will be needed to fabricate, assemble, and repair electronic parts on the long duration, long endurance missions NASA will pursue in the post-ISS era
    - Historically, many ISS system failures are electronic in nature

- **ISM is developing new on-demand printing and packaging technologies for next generation flexible, wearable sensor devices** which can be used in crew health monitoring applications (radiation exposure, carbon dioxide levels, cortisol, respiration)

- Other sensor applications include habitat monitoring and vehicle structural health monitoring

- Additional developments with on-demand printing capabilities include energy storage and power generation

Image of cortisol sensor (coin shown for scale)

First-generation CO_2 sensor

ISM Design Database

The ISM project currently has a database of candidate parts for In-Space Manufacturing which originate from:

- ISS databases cataloging part failures and problem reporting
- Heritage environmental control and life support systems (ECLSS)
- ISS medical toolkit manifest
- Intravehicular Activity (IVA) Government Furnished Equipment (GFE) Flight Crew Equipment (FCE) manifest
- In the next year, the database will also expand to include heritage spacesuit components

A NASA Space Technology Research Fellowship (NSTRF) student is using ISS and ISM databases to develop a systems modeling framework for assessing the utility of a manufacturing process in various mission scenarios

Multi-Purpose Precision Maintenance Tool

Description

Author/Origin: Robert Hillan, Future Engineers Challenge

Relevant Mission: Future Engineers Space Tool Design Competition

Date Added: June 20, 2016

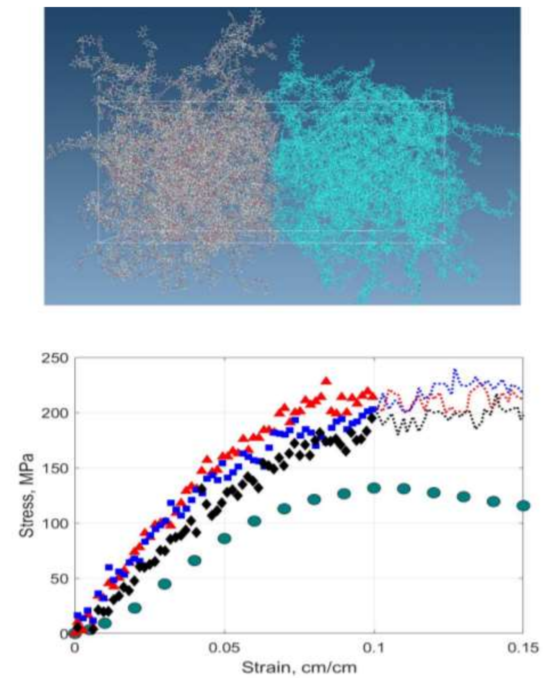
Keywords: International Space Station, ISS, Tools

GitHub Repository: Multi-Purpose Precision Maintenance Tool

Example of a part database entry from the NASA Ames Research Center 3D Resources website: https://nasa3d.arc.nasa.gov/

Computational Modeling

- The NASA Ames Research Center physics-based modeling group has provided analysis and modeling support of In-Space Manufacturing since 2014.
- Work includes:
  - Development and validation of computational models to support understanding of processes in zero-G environment
  - Elucidation of specific features of materials manufactured in micro-gravity that are distinct from earth-processed specimens
  - Enabling of physics based analysis of the ISM payloads before launch
  - Clarification of possible gaps in experimental performance
  - Support of verification and validation of parts manufactured in-space



Fully atomistic model of interface in ULTEM 9085 (polyetherimide/polycarbonate blend). Model (top) was used to predict the stress strain curves in the bottom plot. Image from NASA Ames Research Center.

Summary

- In-space manufacturing represents a suite of manufacturing technologies available to crew on long duration missions to reduce logistics and provide a capability for on-demand repair and replacement.
- ISM requires integration with space systems designers early in the development process.
- To make use of ISM, systems must be designed for accessibility and maintainability.
- The ISM design database activity will be used in part to define the "what we make" of ISM and will be a key driver for requirements of ISM platforms going forward.

"Every revolutionary idea seems to evoke three stages of reaction:

1. It's completely impossible.

2. It's possible, but it's not worth doing.

3. I said it was a good idea all along."

-Arthur C. Clarke