Microgravity Manufacturing: Extending Rapid Prototyping Past the Horizon

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Abstract

Over the last decade, rapid prototyping (RP) technologies have continued to advance in all aspects of operation and application. From continuously advanced materials and processes development to more hard-core manufacturing uses, the RP realm has stretched considerably past its original expectations as a prototyping capability. This paper discusses the unique applications for which NASA has chosen these manufacturing techniques to be utilized in outer space.

Background

Manufacturing capability in outer space remains one of the critical milestones to surpass to allow for humans to conduct long duration manned space exploration. The high cost-to-orbit for leaving the Earth s gravitational field continues to be the limiting factor in carrying sufficient hardware to maintain extended life support in microgravity or on other planets. Additive manufacturing techniques, or chipless fabrication, like RP are being considered as the most promising technologies for achieving in-situ or remote processing of hardware components, as well as for the repair of existing hardware. At least three RP technologies are currently being explored for use in microgravity and extraterrestrial fabrication.

Fused Deposition Modeling

Fused Deposition Modeling (FDM) is a rapid proto-typing process developed by Stratasys, Inc., which deposits a fine line of semi-molten polymer onto a substrate while moving via computer control to form the cross sectional shape of the part it is building. The build platen is then lowered and the process is repeated, building a component directly layer by layer. This method enables direct net-shape production of polymer components directly from a computer file. The layered manufacturing process allows for the manufacture of complex shapes and internal cavities otherwise impossible to machine.

The application of FDM to microgravity manufacturing has sustained the highest degree of preliminary testing thus far. A commercial FDM unit was first tested by rotating the system onto its side and successfully building parts, free hanging, against the pull of gravity. The ABS plastic components fabricated in this manner were comparable to parts fabricated in the upright position, which warranted further testing in the microgravity range. (*See Figure 1).*

Figure 1. The Fused Deposition Modeling process applied against gravity, on its side.

In light of those results, the FDM system was tested jointly by NASA s Marshall Space Flight Center (MSFC), Johnson Space Center (JSC) and the Milwaukee School of Engineering (MSOE) on board the NASA KC135 Reduced Gravity plane, and again yielded positive results. Seven geometries were successfully fabricated over a series of four flights, resulting in a total of approximately 1-hour of zero-g flight time on the system. In fact, it was found during the flight testing that part configurations that required supporting fixtures during normal operation could be constructed freeform, or without supports, which eliminated the need for scrap support materials.

The next step underway is to develop an FDM system to install on the Space Shuttle, in order to examine long-term microgravity operation characteristics and functionality. The current smallest commercial FDM system is still much too large and heavy for installation on a standard shuttle middeck locker rack. The largest attachment capability, the double adapter plate, will have to be used even with a smaller modified FDM system. Some necessary steps to acquire a flight-ready FDM system are as follows:

- Acquire candidate polymer hardware geometry currently stocked as spare parts on the space shuttle or station, and fabricate these designs using ground-based FDM systems with ABS plastic.
- Determine build time requirements for each component, in order to properly schedule parts to be built in space during a short duration mission.
- Determine maximum allowable factors for a space-based demonstration FDM unit, including weight and physical dimensions, environmental effects, i.e. toxicity, heat output and power consumption limits.
- Determine, from parts inventory and feasibility study, the maximum build envelope capacity of the reduced FDM system.

- Design and build part storage containers for safe return of test articles to Earth.
- Place the FDM demonstration flight unit in the queue for Space Shuttle flight experiments. The shuttle flight would accomplish or establish the following: demonstration of long duration flight operation of the FDM system, optimization of controls for astronaut friendly operation, allow for studying the effects of surface tension on build capability, build shuttle spare part geometries as fabricated on the ground for comparison and build microgravity-dependent part configurations to demonstrate advanced manufacturing.

Once a flight system is completed and is used to build parts during a mission, NASA must test components fabricated on the space shuttle for changes in mechanical properties, surface cohesion, layer-to-layer bonding and physical properties (porosity, density, dimensional stability, etc.)

NASA will benefit in a variety of ways from the successful completion of this project. First, fabrication of flight hardware spares in microgravity will lower flight weight, and particularly volume, due to excessive spares inventory. Second, the creation of new hardware, i.e. modified designs for other in-flight projects, will allow for innovation and optimization of flight experiments during a mission.

Selective Laser Sintering

Figure 2. A Selective Laser Sintering part just after fabrication.

Selective Laser Sintering (SLS) is a powder-based rapid prototyping process, which employs scanning laser technology to fuse the build material in the shape of the part cross-sections, one on top of the other. (*See Figure 2).* The current materials used with SLS include wax, polycarbonate, polyamide, nylon, polymer matrix metals and polymer matrix sand. NASA is exploring the possibility of using SLS based technology to form glass and structural materials from lunar and Martian soil, with the ultimate application being the fabrication of spacecraft glass, large lenses or mirrors, and even glass bio-domes directly on the surface of the moon and Mars using the existing soil. This would have a tremendous positive impact on colonization, as the build materials required would not have to be transported from the Earth.

The SLS technology is probably the most versatile rapid prototyping process on the market as far as polymer materials capability. SLS is largely researched for advanced materials capability in academia, including direct metal sintering, direct ceramic powder sintering, and composite material RP development. Some preliminary studies have been conducted at various universities on the formation of glass using laser sintering technologies, using sand or lunar simulant. MSFC currently houses world-class experience in the formation of glass from lunar soil, and the intent of this study is to draw on that capability along with the in-house rapid prototyping expertise.

The next step will be to determine the feasibility of rapidly prototyping structural components using SLS and lunar soil simulants as a build material. Studies must be conducted to determine laser power requirements for small-spot glass formation, layer-to-layer bonding characteristics, and the effects of scaling up the process for large-scale component fabrication.

Successful determination of sintering parameters will lead to materials properties testing and International Space Station flight experiment development and demonstration. Power sources to be considered are laser and focused solar energy. A KC135 Reduced Gravity demonstration will proceed the space station flight to determine the feasibility of using this process in a low-gravity environment.

Laser Engineered Net Shaping

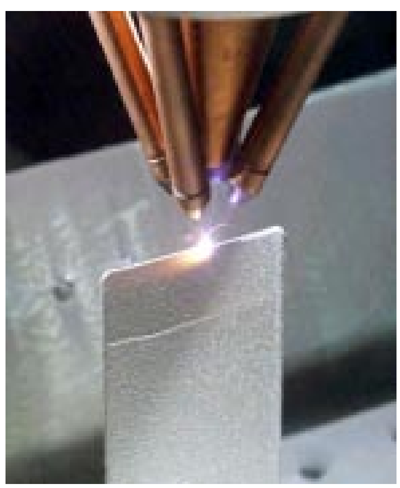


Figure 3. The Laser Engineered Net Shaping process during operation.

Laser Engineered Net Shaping (LENS) is a new rapid prototyping process developed by Sandia National Laboratories and marketed by Optomec Design Company, which sprays a fine line of metal powder into a moving, focused laser, building a component directly layer by layer. *(See Figure 3).* This method enables direct near-net-shape production of metallic components directly from a computer file. The layered manufacturing process allows for the manufacture of complex shapes and internal cavities otherwise impossible to machine. NASA will exploit the benefits of the LENS technique to quickly and inexpensively produce replacement components or repair broken hardware in a space shuttle or space station environment.

The LENS technology has been in operation for a very short time, although it has been tested against the pull of gravity by one of the current users of the system. In this application, the LENS head was placed on a multi-axis robotic arm, which allowed for the fabrication of part components even in upside-down situations. Additions were made to the system to keep powder overspray from accumulating on the laser lens, which would also be necessary in a microgravity environment. The next step will be to build a smaller, simpler LENS system in order to proof the feasibility of operation in a microgravity environment. As in the FDM process, there a various steps to accomplish a flight-ready LENS-type system, including:

- NASA must acquire candidate hardware component geometry currently stocked as spare parts on the space shuttle or station, and fabricate these designs using a ground-based LENS system with a suitable metal, i.e. stainless steel or aluminum.
- Determine maximum allowable factors for a space-based demonstration LENS unit, including weight, size and power consumption limits.
- Determine, from parts inventory and feasibility study, the maximum build envelope capacity of the reduced LENS system, in addition to most suitable build materials for microgravity, powder reclamation capability, and part removal from platen options.
- Fabricate a LENS demonstration flight unit.

After a flight unit is prepared, NASA must conduct flight feasibility studies using the NASA KC135 Reduced Gravity Flight Test and analyze the parts fabricated in Reduced Gravity Flight Test for consistency with ground-based fabricated components to determine if any modifications will be required prior to shuttle flight. NASA will then place the LENS demonstration flight unit in the queue for Space

Shuttle flight experiments, finally to test the components fabricated on the space shuttle for changes in mechanical properties.

NASA will benefit in a variety of ways from the successful completion of the LENS project. First, fabrication of flight hardware spares in microgravity will become a reality. Second, the repair of damaged or broken components may also be accomplished without affecting the materials properties of the repaired component. In addition, preliminary NASA studies of LENS-fabricated components have confirmed that the mechanical properties are actually stronger than wrought-annealed properties. This will lead to the use of more economical materials for higher performance applications.

NASA s advanced LENS system for use on space station will utilize an incorporated vision system for component inspection and selective repair, multiple build materials capabilities to meet various processing needs, low power (i.e. diode laser) consumption with maximum output, 100% powder reclamation capability and an integrated platen/part separation system. NASA is also currently pursuing development of hand-held LENS repair units for the regeneration of damaged spacecraft hulls during space flight. These systems will smart scan spacecraft hull surfaces for micro-meteorite damage detection and repair, using advanced digital imaging and void recognition software, and will selectively repair defects with parent material either manually or remotely by computer. Finally, large orbiting LENS systems are foreseen for major repair and overhaul requirements, in addition to in-situ fabrication of metal hardware from lunar, asteroid, or Martian soil. *(See Figure 4).*

Figure 4. A concept of a Martian rover duplicating itself from the Martian soil.

Ultrasonic Object Consolidation

Ultrasonic Object Consolidation (UOC) is an exciting new metal rapid prototyping process developed by Solidica, Inc. in Ann Arbor, MI. The UOC process is a low-heat, low-energy material joining technique that shows the highest promise for fabricating aluminum or titanium hardware in microgravity. The process works on the same principal as solid state welding currently used in electronics manufacturing. Two thin layers of material are brought into contact under pressure, and are then submitted to ultrasonic vibration between them (on the order of a few microns). The rubbing action causes the oxide layers of each material to break away, exposing two atomic-clean metal surfaces to each other, causing a solid-state weld. Figure 5 demonstrates the UOC process.

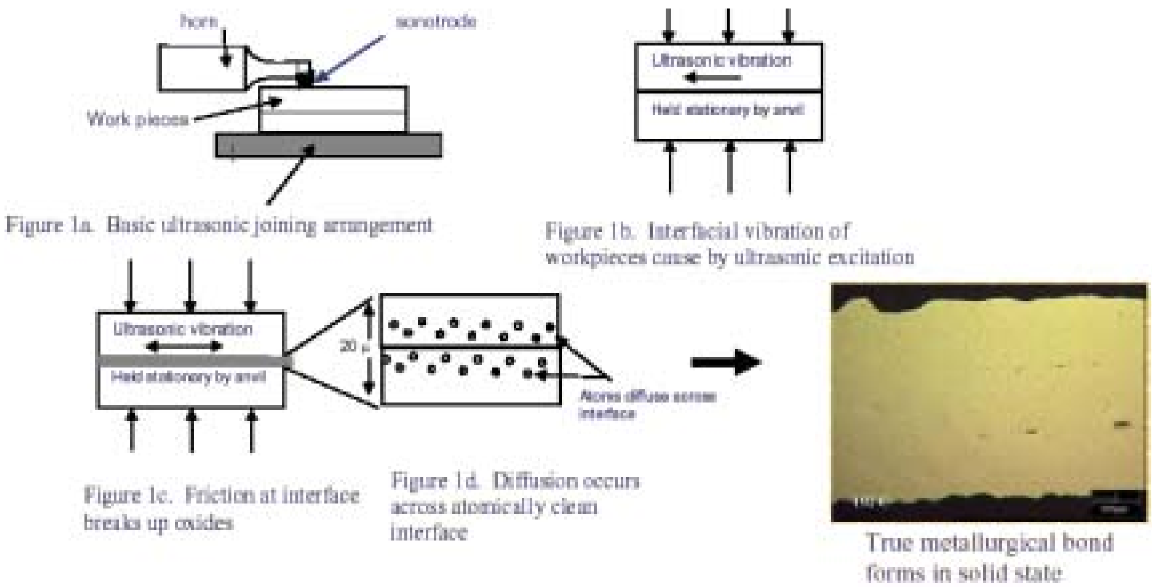


Figure 5. A Description of the Ultrasonic Object Consolidation (UOC) process from Solidica.

The amount of heat generated is negligible, and the energy and forces required to make a bond on thin material are very low as well. NASA/MSFC is currently working with Solidica to develop a machine based on this principal that will potentially be adaptable to use in microgravity. The main issues to be addressed for adaptation will then be system size (volume), and the noise/vibration effects.

Laser Engineering Net Shaping

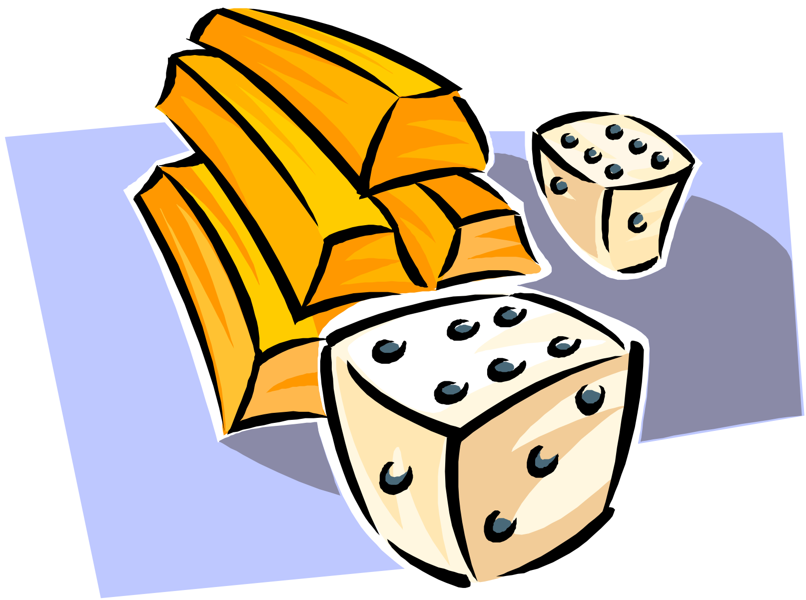
- Task- Present some of RP Lab's findings and experiences with this technology.
- Standards- The audience; Experiment the variables of this machine s operation.
- Conditions- 45 minutes, lecture and Power Point presentation in classroom environment.

What It Is

- YAG Laser
- Controlled Environment (Argon)
- X,Y,Z= +/- .0005
- Two feed hoppers (bi-metal capable)
- Gas pressure feed with wheel pick up.

What It Isn t

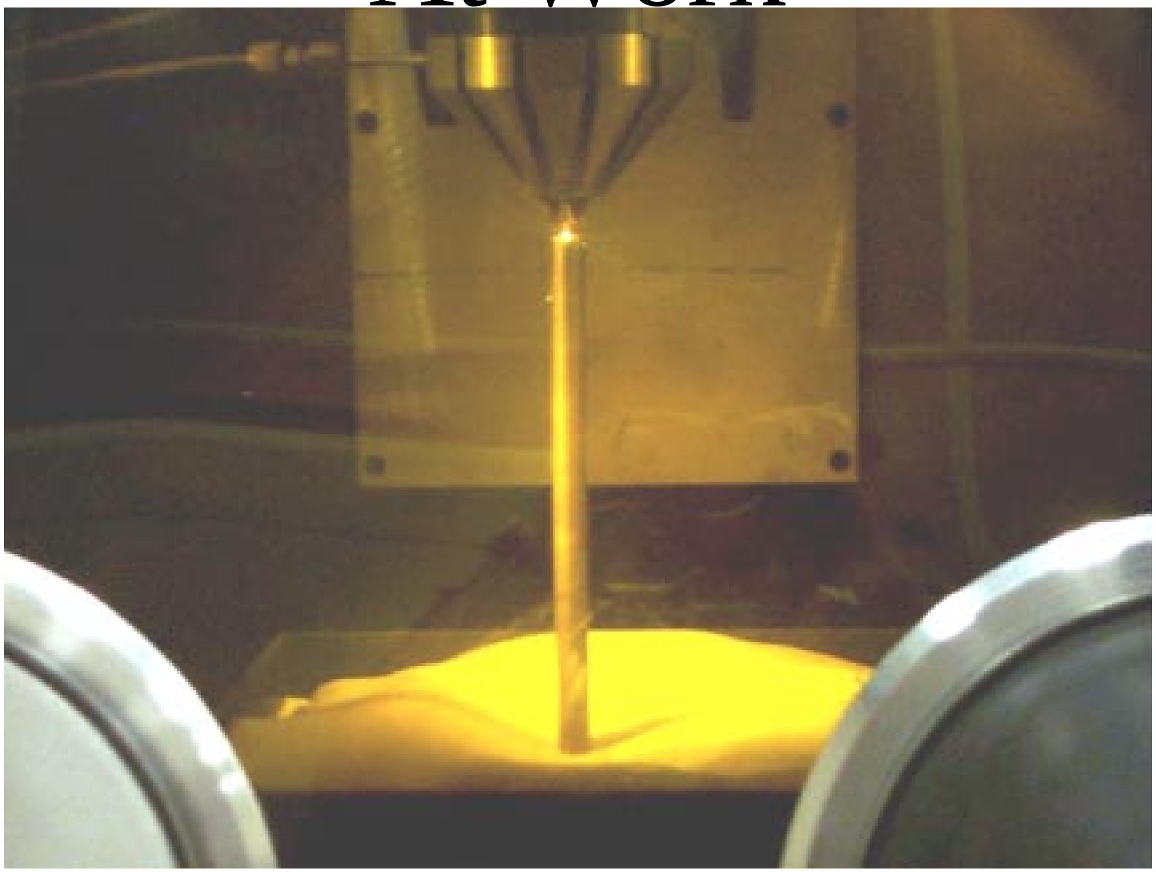
- Perfected
- 100% Efficient
- Maintenance Free
- Cheap
- Real Smart



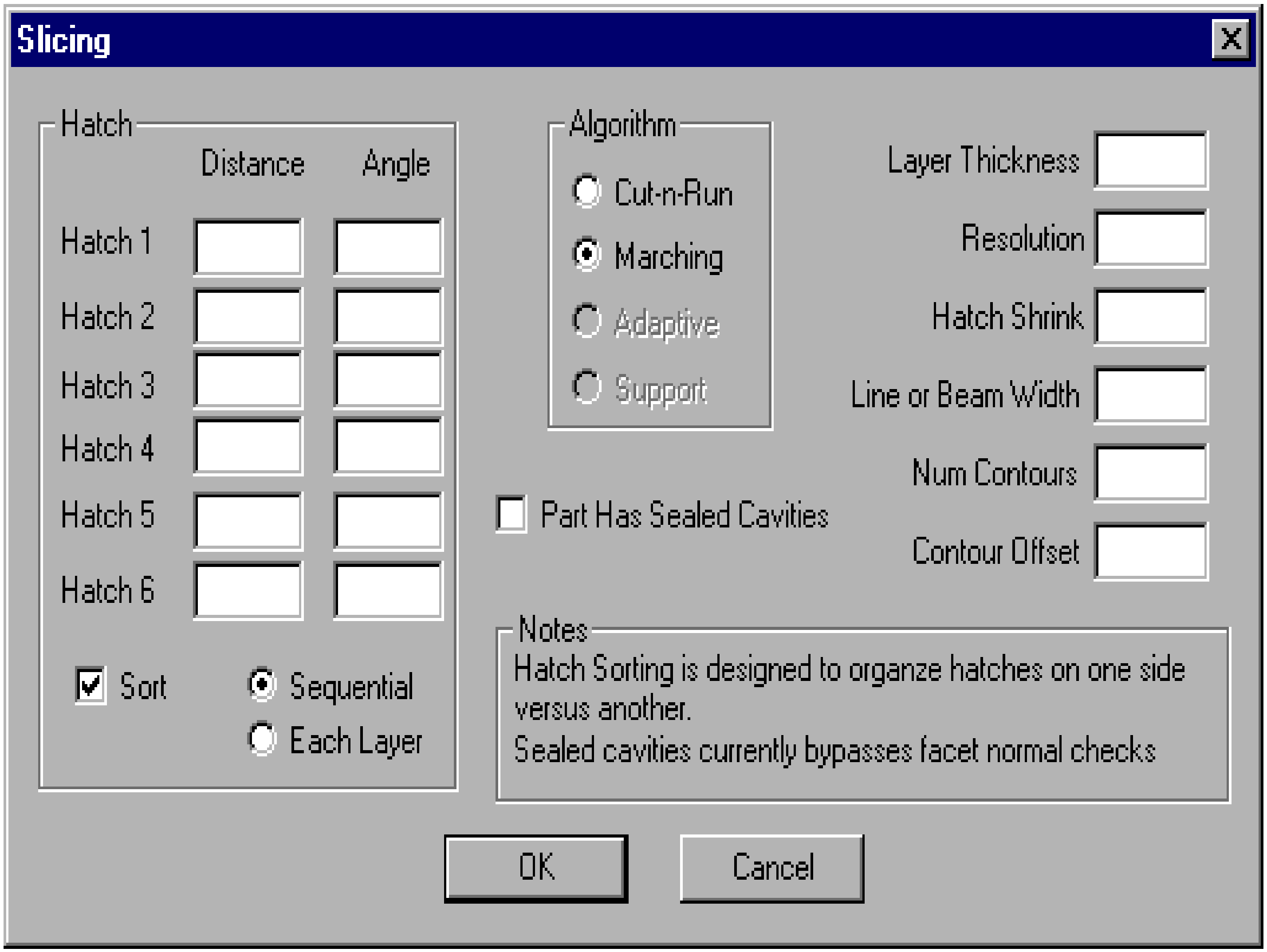
Our Machine

- LENS 750 by OPTOMEC
- 1999 Model
- Originally modified with powder recovery system & weld pool monitor (since removed)

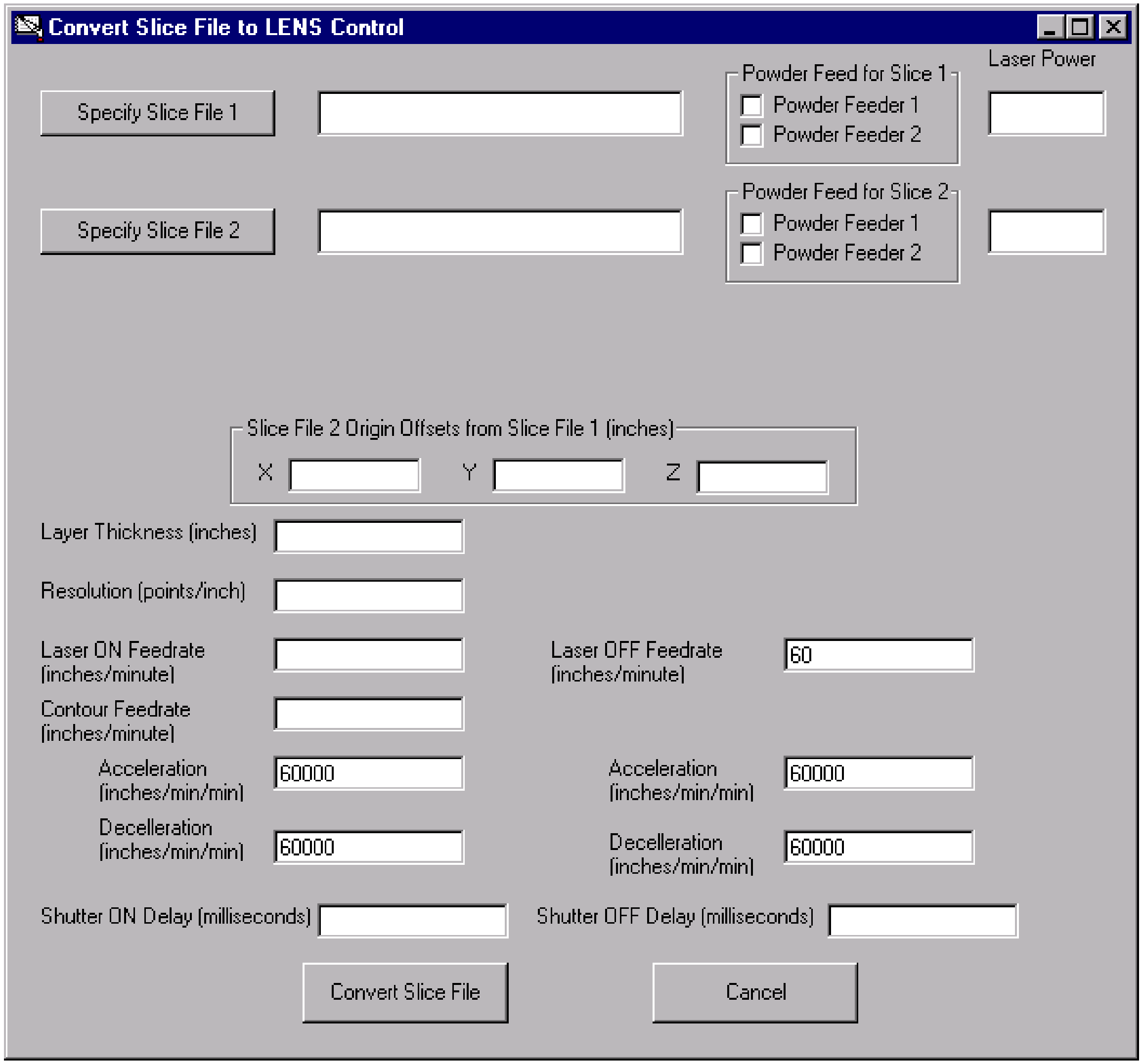
At Work



Screen 1- Variables



Screen 2- Variables



Considerations for Experiment Planning

Melting Temperatures of Constituents?

Oxidation & Effects?

Toxicity & Off-Gassing?

Spherical Diameter and Gradient?

Hydro & Feed Compatibility?

Materials We Have Tried-1

SS316 stainless steel	success
Inco718 (nickel based alloy)	success
Narloy Z (copper-silver alloy)+ Alumina Al2O3	didn’t deposit
Copper Chrome Niobium	didn’t deposit
Aluminum 2026	didn’t deposit
Inco718 + Alumina Al2O3 (mechanical mix)	deposit, but not homogeneous

Materials-2

SS316 + Alumina Al2O3 (new tricks)	success
Molybdenum-Rhenium	limited success
Nickel Aluminide	didn’t deposit
Copper Chrome Niobium (new tricks)	limited success
SS316 stainless steel	success
Inco718 (nickel based alloy)	success

Materials-3

Narloy Z (copper-silver alloy)	
+ Alumina Al_2O_3	didn't deposit
Copper Chrome Niobium	didn't deposit
Aluminum 2026	didn't deposit
Inco718	
+ Alumina Al_2O_3 (mechanical mix)	deposit, but not homogeneous

Materials-4

SS316 + Alumina Al2O3 (new tricks)	success
Molybdenum-Rhenium	limited success
Nickel Aluminide	didn’t deposit
Copper Chrome Niobium (new tricks)	limited success

Laser Engineered Net Shaping Materials Status

- The initial mechanical properties tests are back
- Both Inco718 and SS316 LENS processed samples had, as advertised, better than wrought properties
- An extensive study will now be kicked in, to include 4 materials and 4 parameters, with a larger sampling of parts in each category.
- Will include strength, ductility, toughness and fatigue, with Ti and Al.

Material	Yield (ksi)	Ultimate (ksi)
LENS SS316	**58**	**120**
Wrought SS316	*40*	*85*
LENS Inco718	**190**	**215**
Wrought Inco718	*158*	*194*

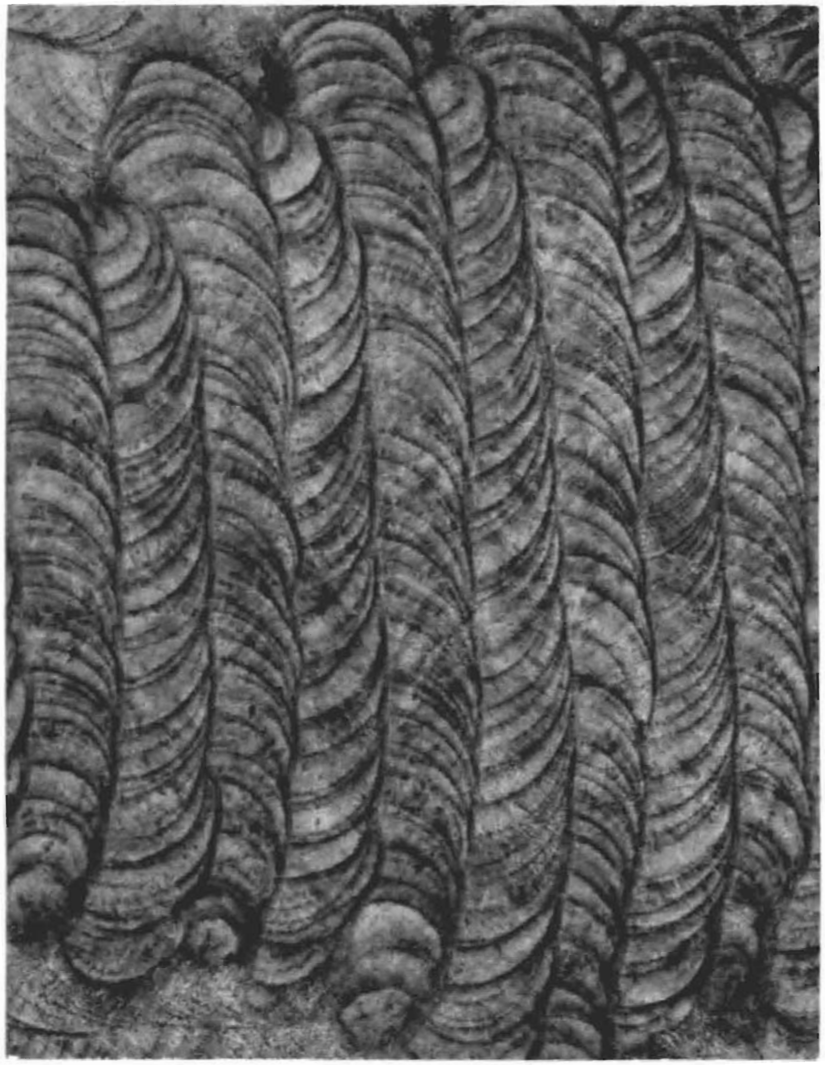
Wrought vs. Deposited

MSFC Laser Engineered Net Shaping Materials Properties

	Yield (ksi)	Ultimate (ksi)
Stainless Steel 316	**58**	**120**
Wrought SS316	*40*	*85*
Inconel 718	**190**	**215**
Wrought Inco718	*158*	*194*

316-A AS FAB. LONG 25X

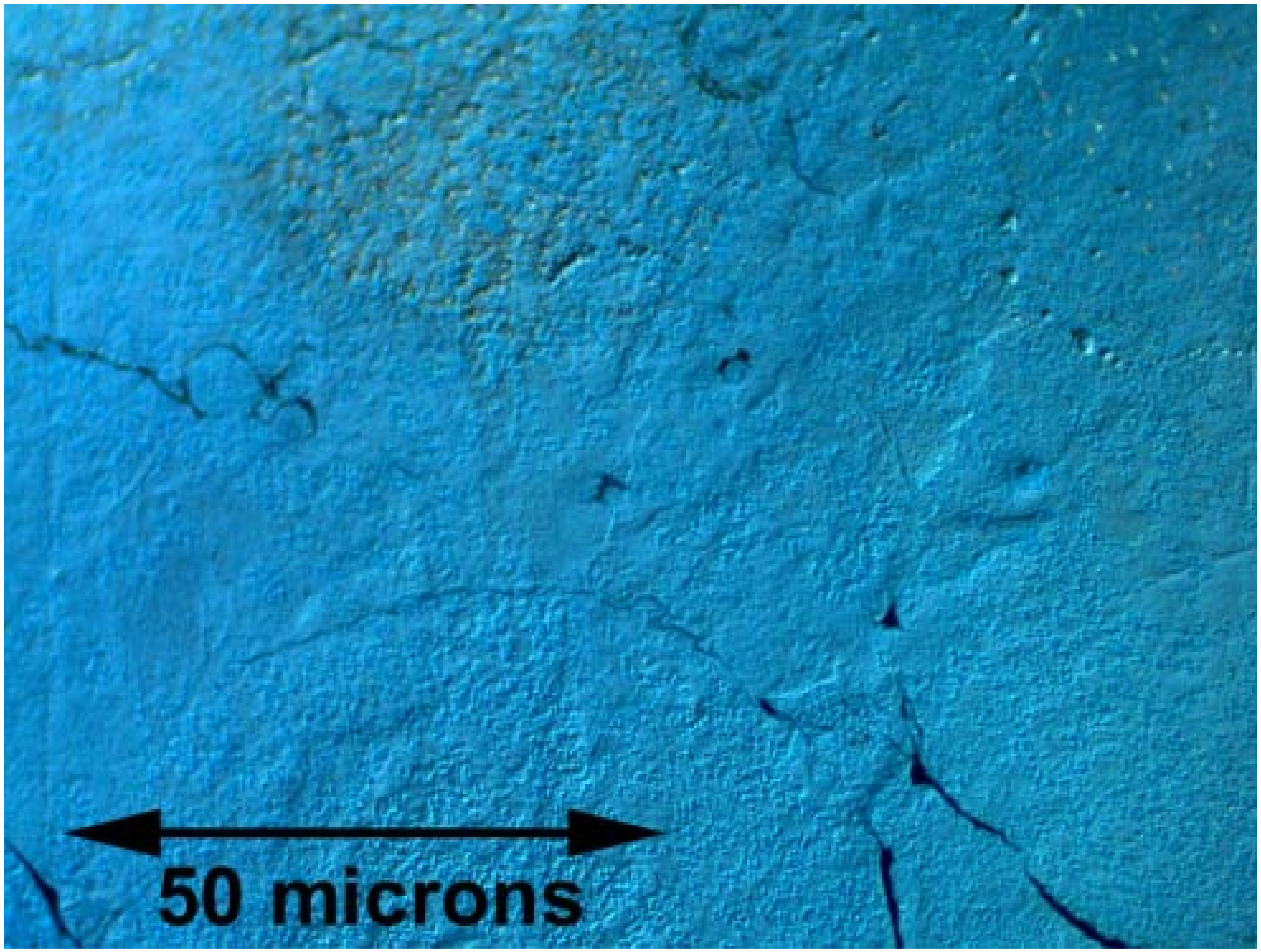
718-A AS FAB LONG 25X



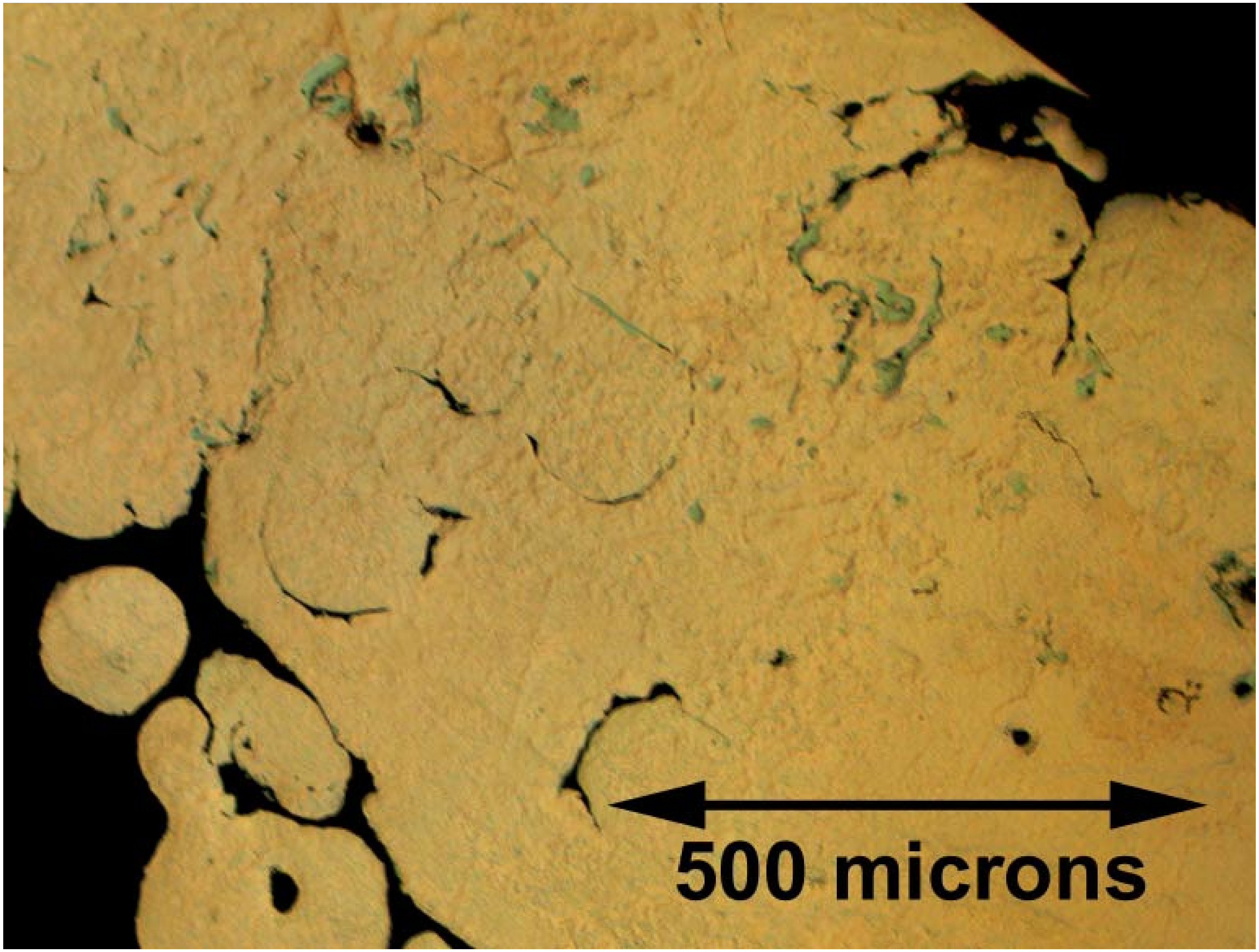
316-A AS FAB TRAN 25X

718-A AS FAB TRAN 25X

Nickel Based Powder



Copper Based Powder



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