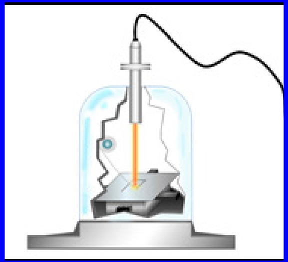

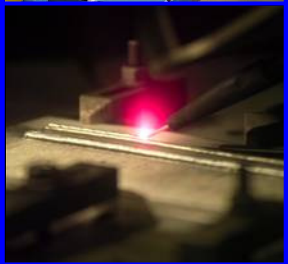
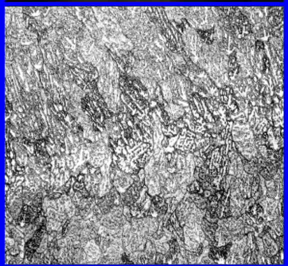


Electron Beam Freeform Fabrication: A Fabrication Process that Revolutionizes Aircraft Structural Designs and Spacecraft Supportability

Karen M. B. Taminger
NASA Langley Research Center

ARMD Technical Seminar on May 22, 2008

LaRC EBF^3 Team

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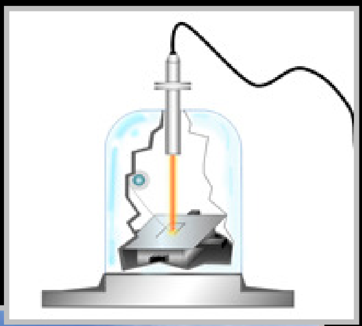
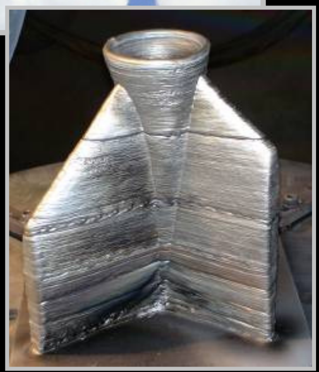
Partnerships
- Susan Cooper

Outline

- Technology inception
- Characterization
- Technical challenges
- Current applications
- Influence on future designs
- Supportability in space

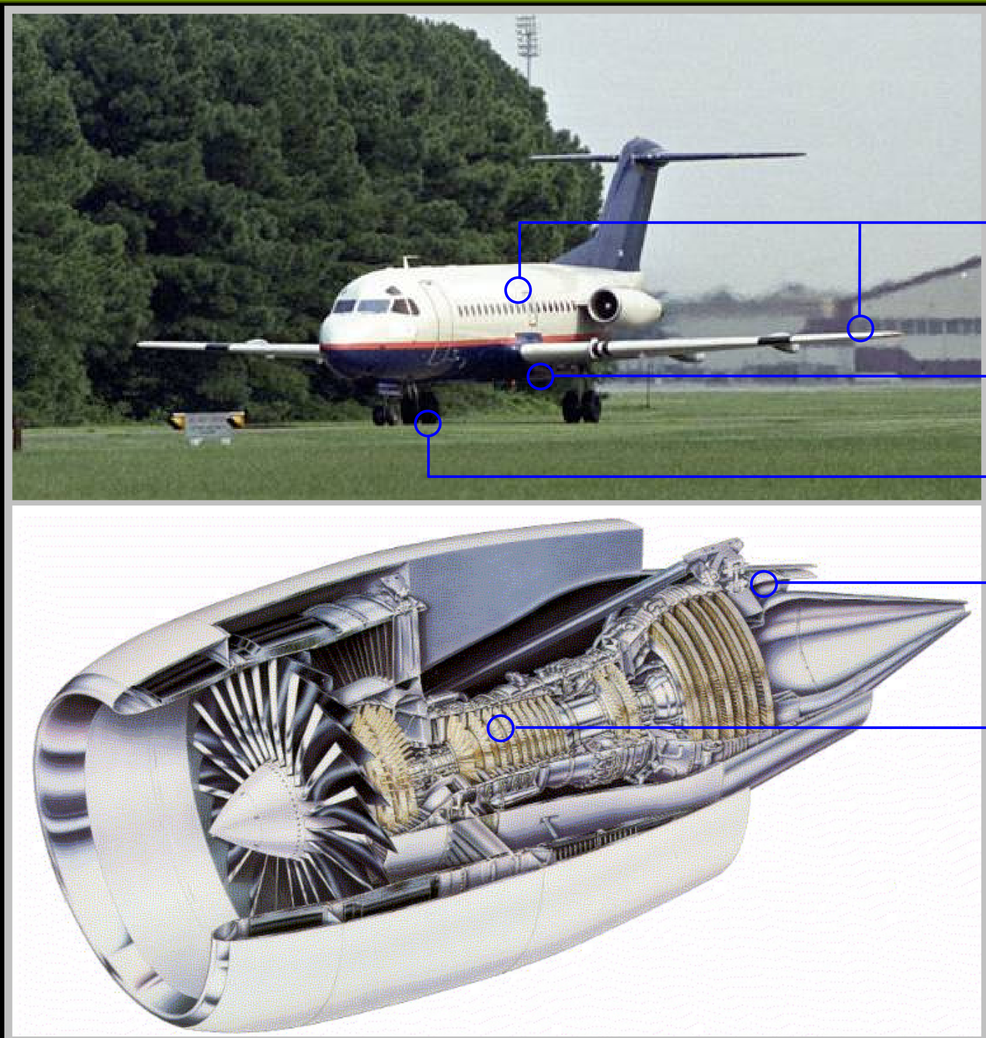
Outline





- **Technology inception**
  - **Motivation**
  - **EBF^3 process description**
  - **Benefits**
- Characterization
- Technical challenges
- Current applications
- Influence on future designs
- Supportability in space

Structural Metals in Aircraft



Motivation

- New metals technology
  - Efficient, lightweight structures
  - Cost-effective
  - Enable new alloys
- Disruptive technology

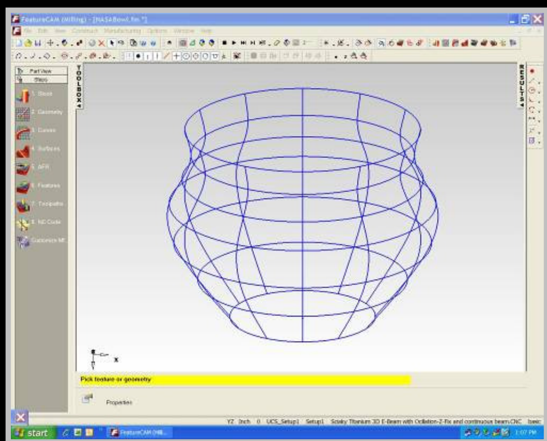
Metal Deposition Processes

Laser		E-Beam
5-10%	Energy efficiency	95%
Continuous gated pulsed	Beam control	Continuous, rastered
Mirrors or fiber optics	Beam delivery	Magnetically steered
Inert gas	Environment	Vacuum
Powder, 5-85%	Feedstock efficiency	Wire, ~100%
0.5-9 lb/hr	Max dep. rate	> 30 lb/hr

EBF^3 Core Technology

- Rapid metal fabrication process
  - Layer-additive process
  - No molds or tools
  - Properties equivalent to wrought
  - Demonstrated on Al, Ti, Ni, Fe-based alloys

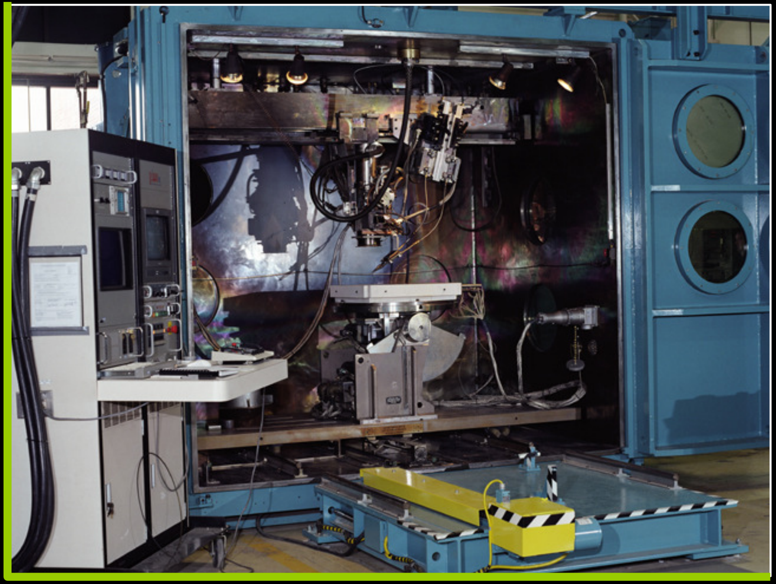
EBF^3 Process



- Slice CAD drawing
- E-beam creates melt pool
- Add wire to pool
- Translate layer-by-layer

LaRC EBF^3 System #1

- 42 kW gun
- 60 kV max
- 6-axis positioning

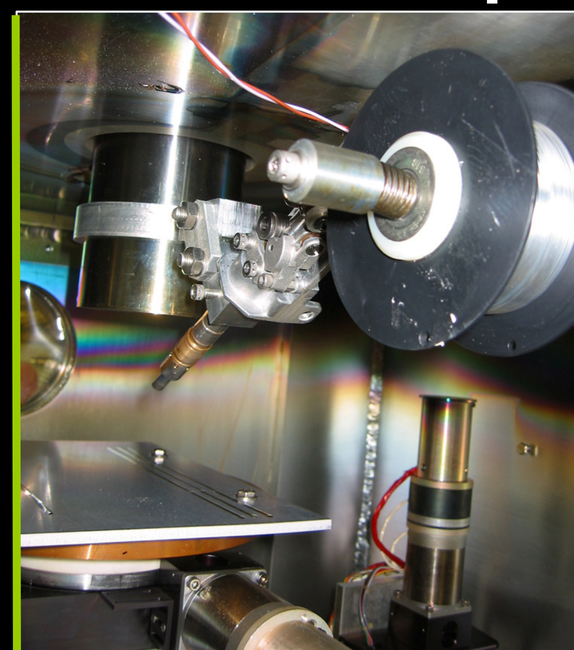


- 78” x 108” x 100” vacuum chamber
- 24” x 48” x 60” build envelope

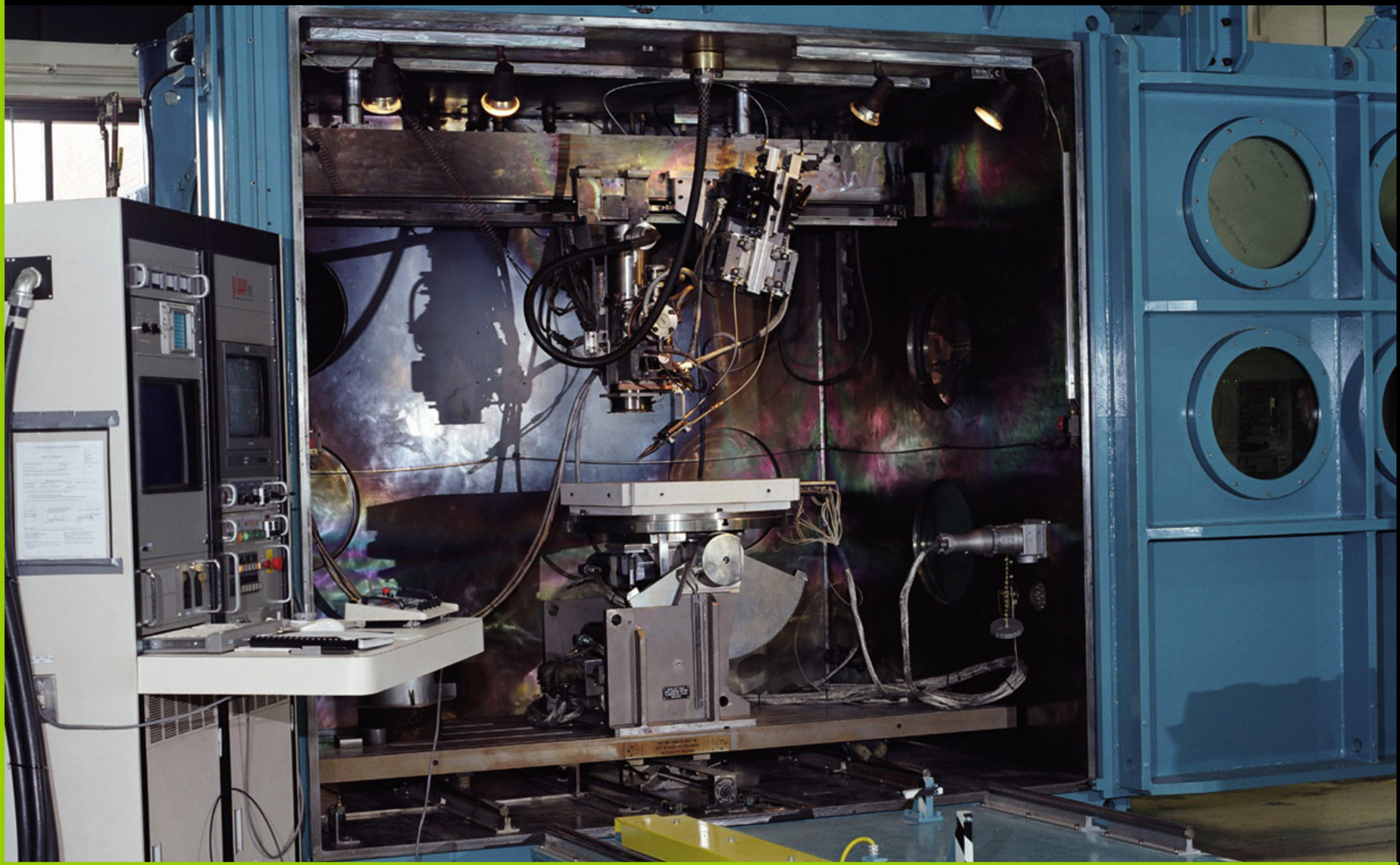
LaRC EBF^3 System #2

- 3 kW gun
- 30 kV max
- 4-axis positioning

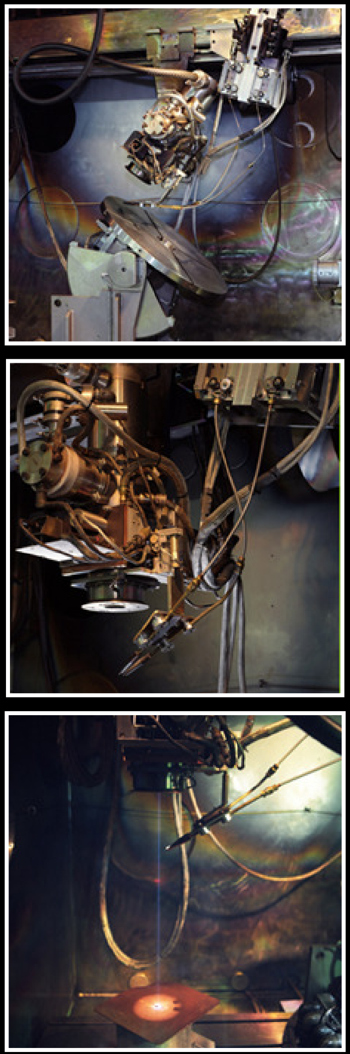
- 36” x 36” x 36” chamber
- 12” x 12” x 8” build envelope



EBF^3 Demonstration



Benefits of EBF^3



- Near-net shape
  - Minimize scrap
  - Reduces part count
- Efficient designs
  - Lightweight
  - Enhanced performance
- Complex unitized components
  - Integral structures
  - Functionally graded materials
- "Green" manufacturing
  - Minimal waste products
  - Energy and feedstock efficient

Ti Processing Steps

Conventional

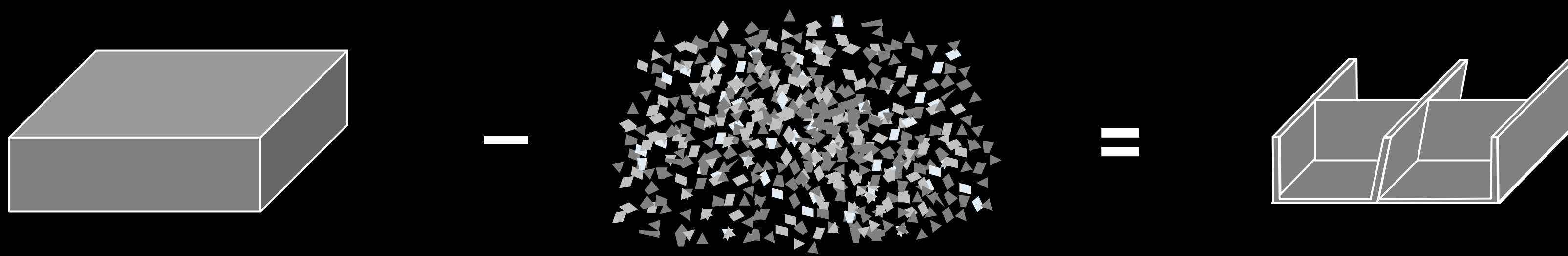
1. $TiCl_4$
2. Sponge
3. Refine
4. Ingot
5. Forge
6. Billet Slab
7. Forge
8. Pre-form
9. Form
10. Mill Product
11. Machine
12. Final Product

Direct Fabrication

1. $TiCl_4$
2. Powder
3. Wire
4. EBF^3
5. Machine
6. Final Product

EBF^3 Saves Resources

Conventional Machining:

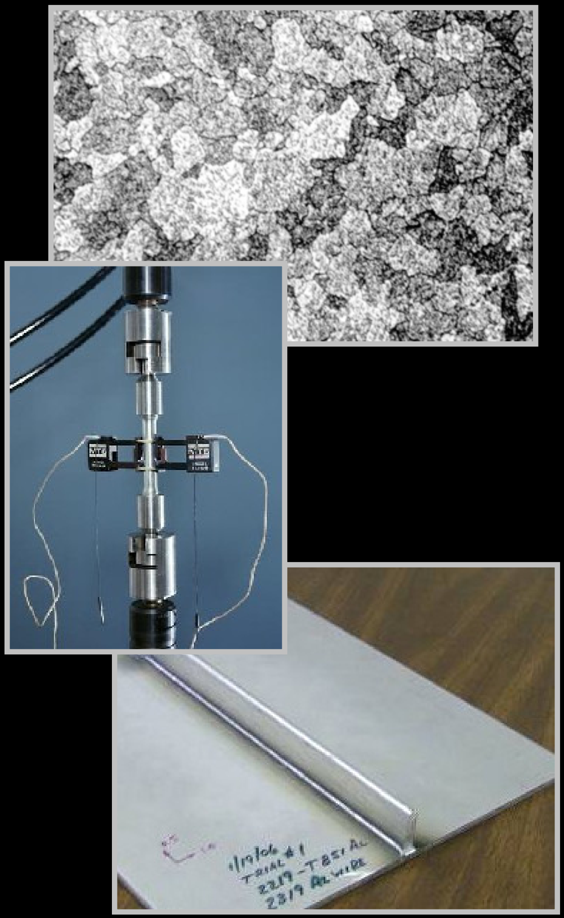


3000 lbs. 2850 lbs. 150 lbs.

Additive Manufacturing via EBF^3:

100 lbs. 100 lbs. 50 lbs. 150 lbs.

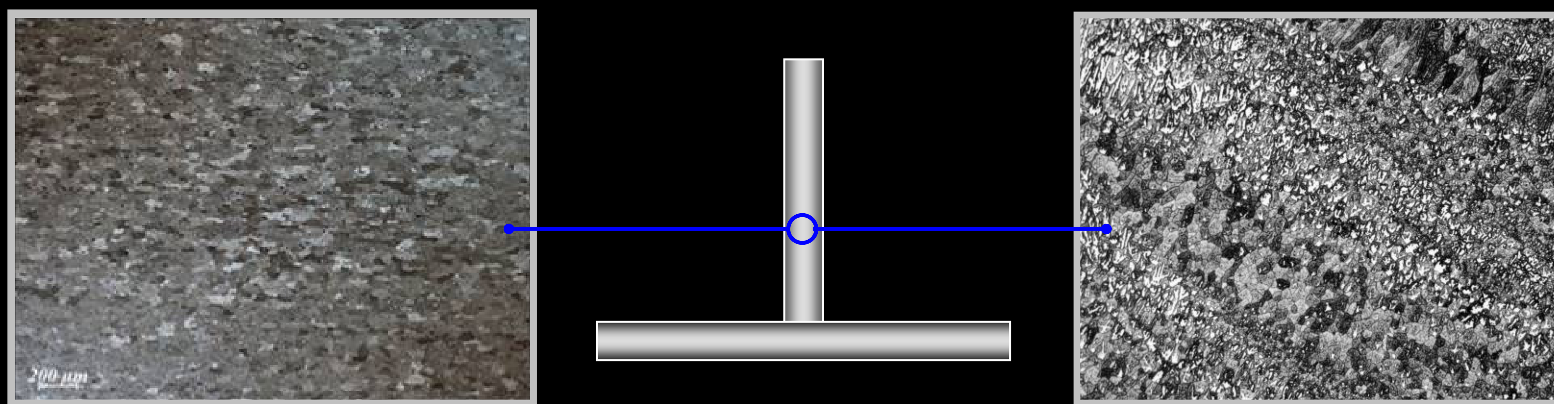
Outline



- Technology inception
- Characterization
  - Microstructure
  - Mechanical properties
  - Structural integrity
- Technical challenges
- Current applications
- Influence on future designs
- Supportability in space

2219 Al Microstructure

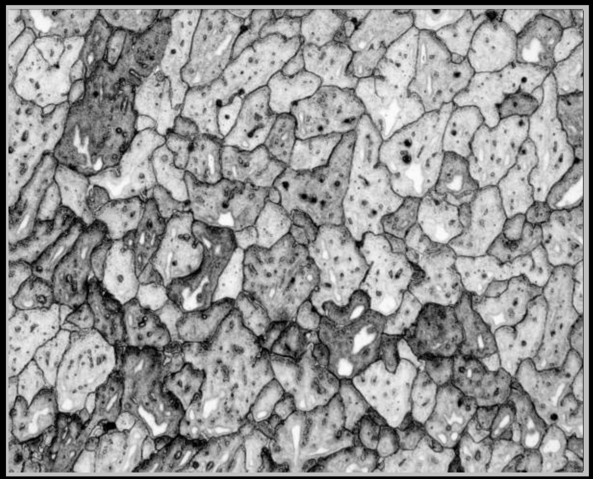
Machined from plate | **Built by EBF^3**



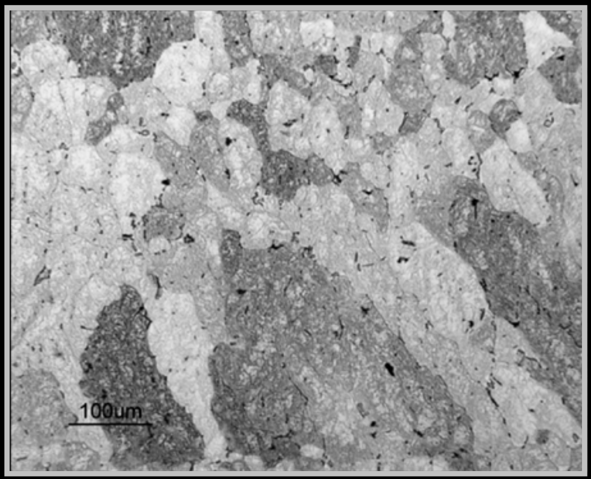
0.01 in | 0.01 in

2219 Al EBF³ Microstructure

As-deposited



T6 Condition

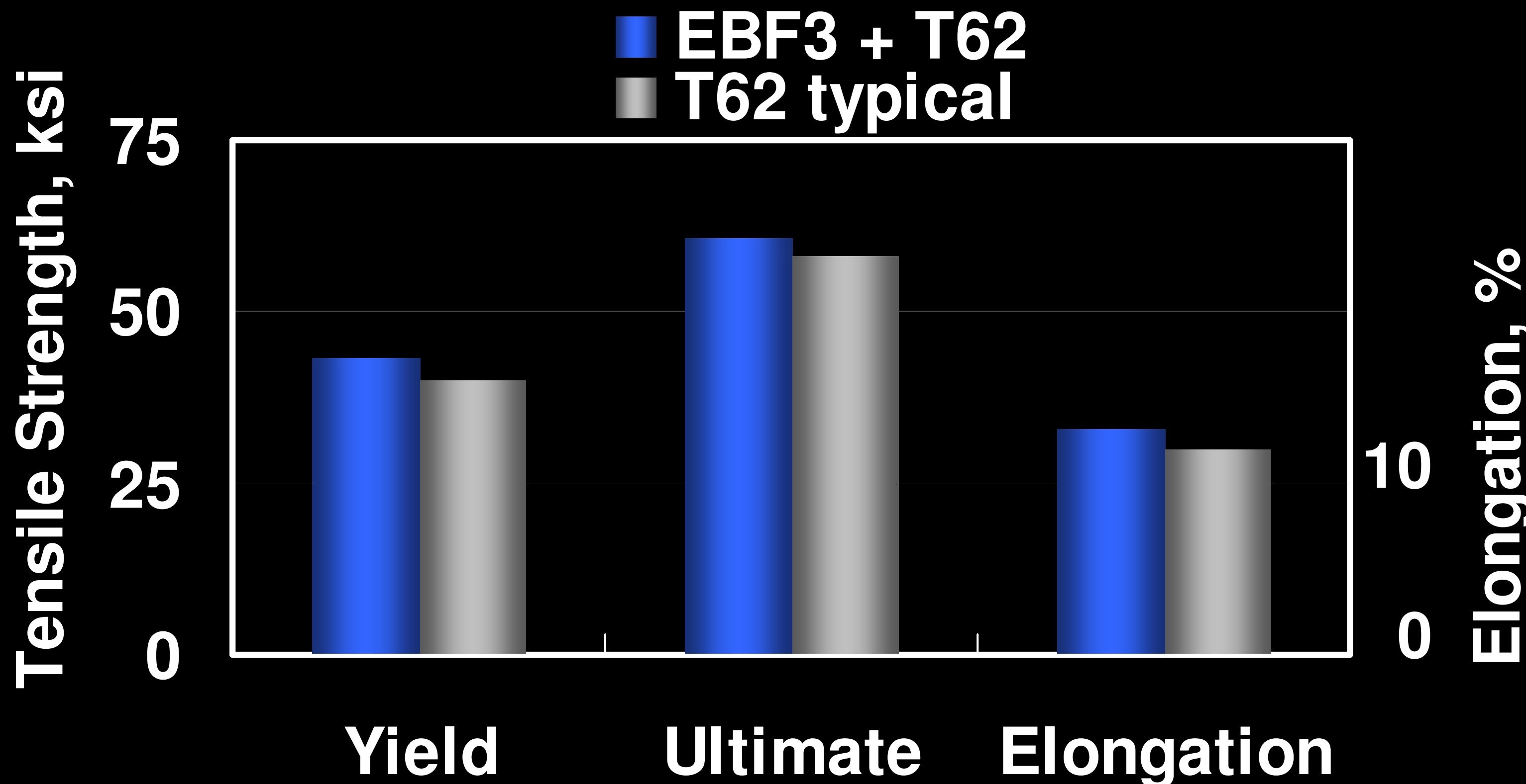


0.004 in

Rapid cool cast:
- Cu segregation
- Dendrites

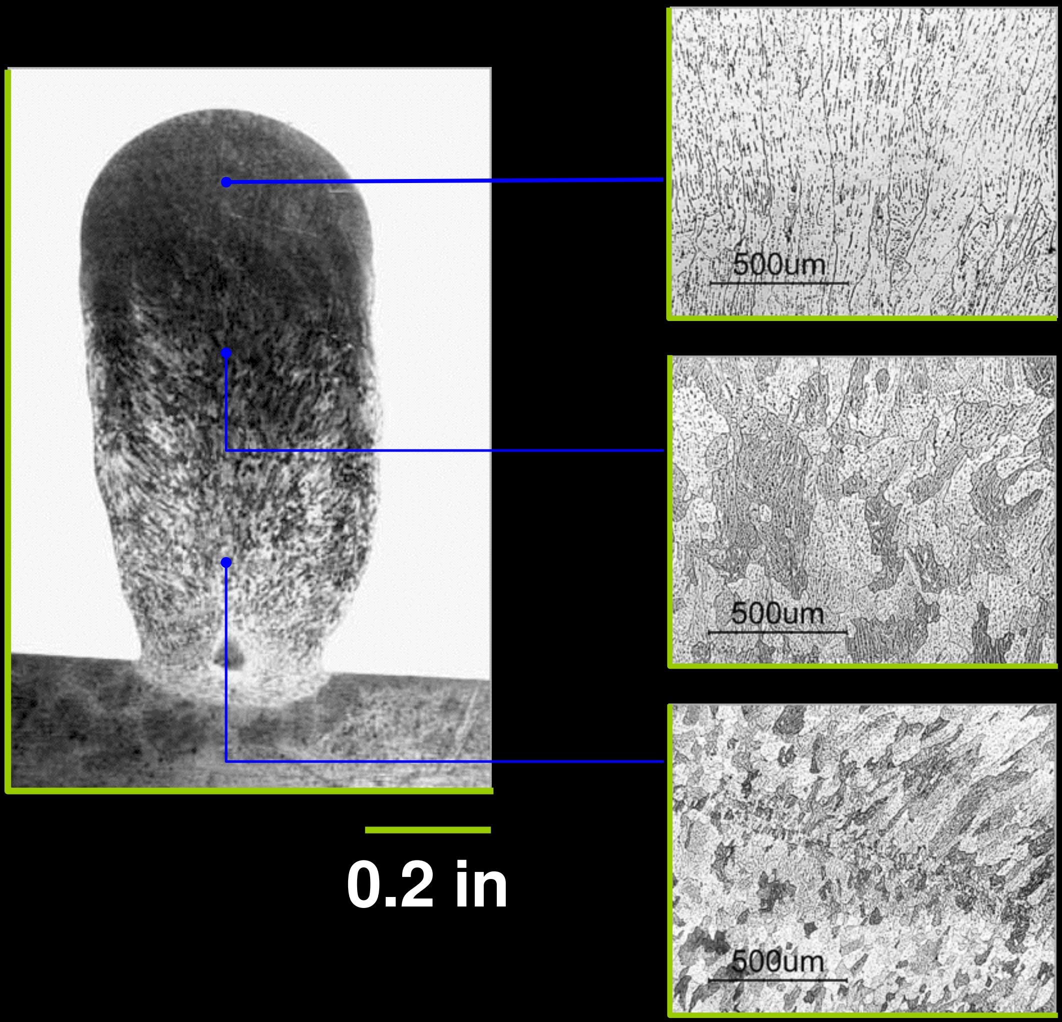
Transformed:
- Grain boundaries retained

2219 Al Tensile Data



- EBF[3] tensile properties comparable to handbook data

Functionally Graded Al



0.2 in

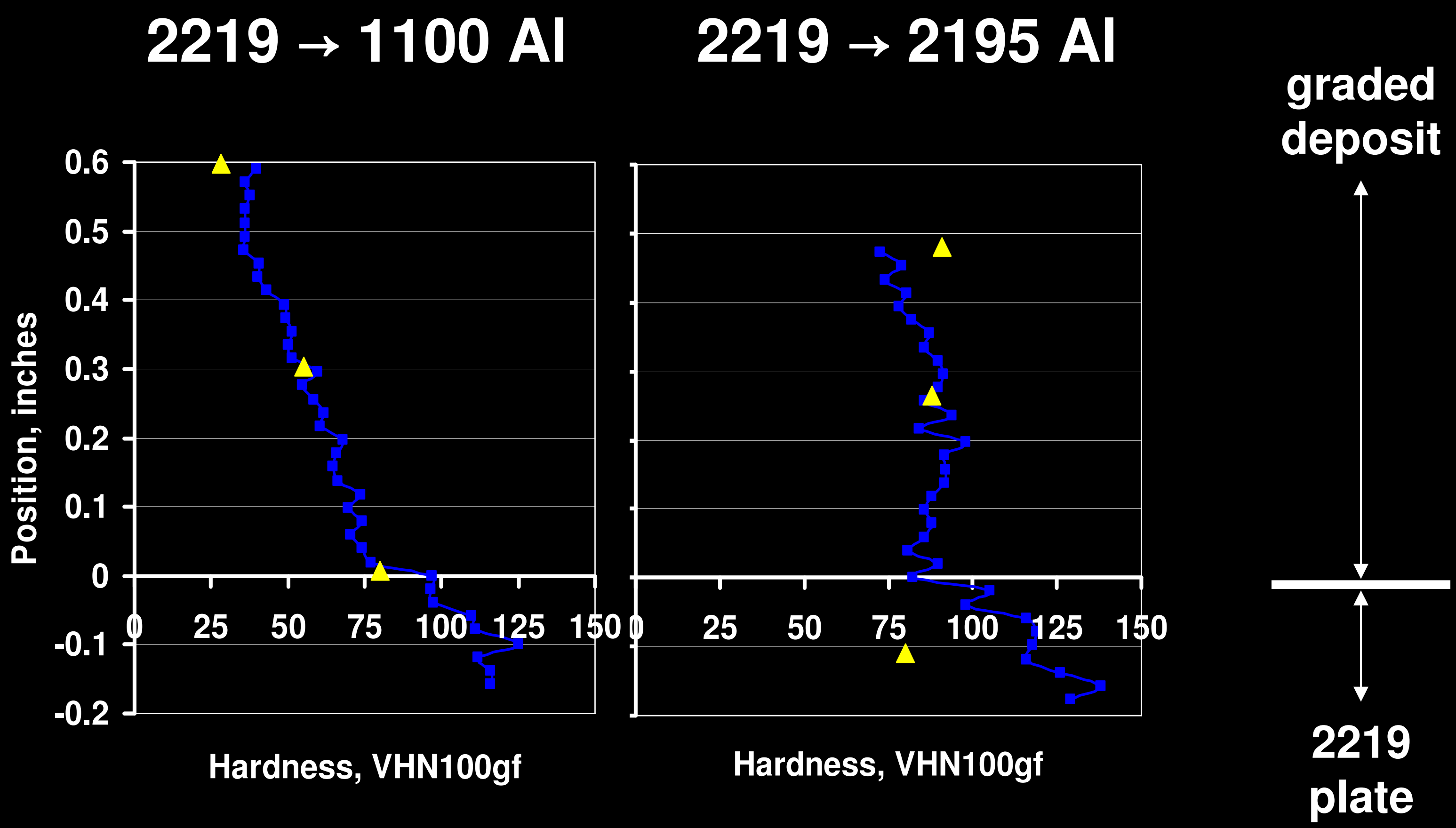
100% Pure Al

50% Pure Al +
50% 2219 Al

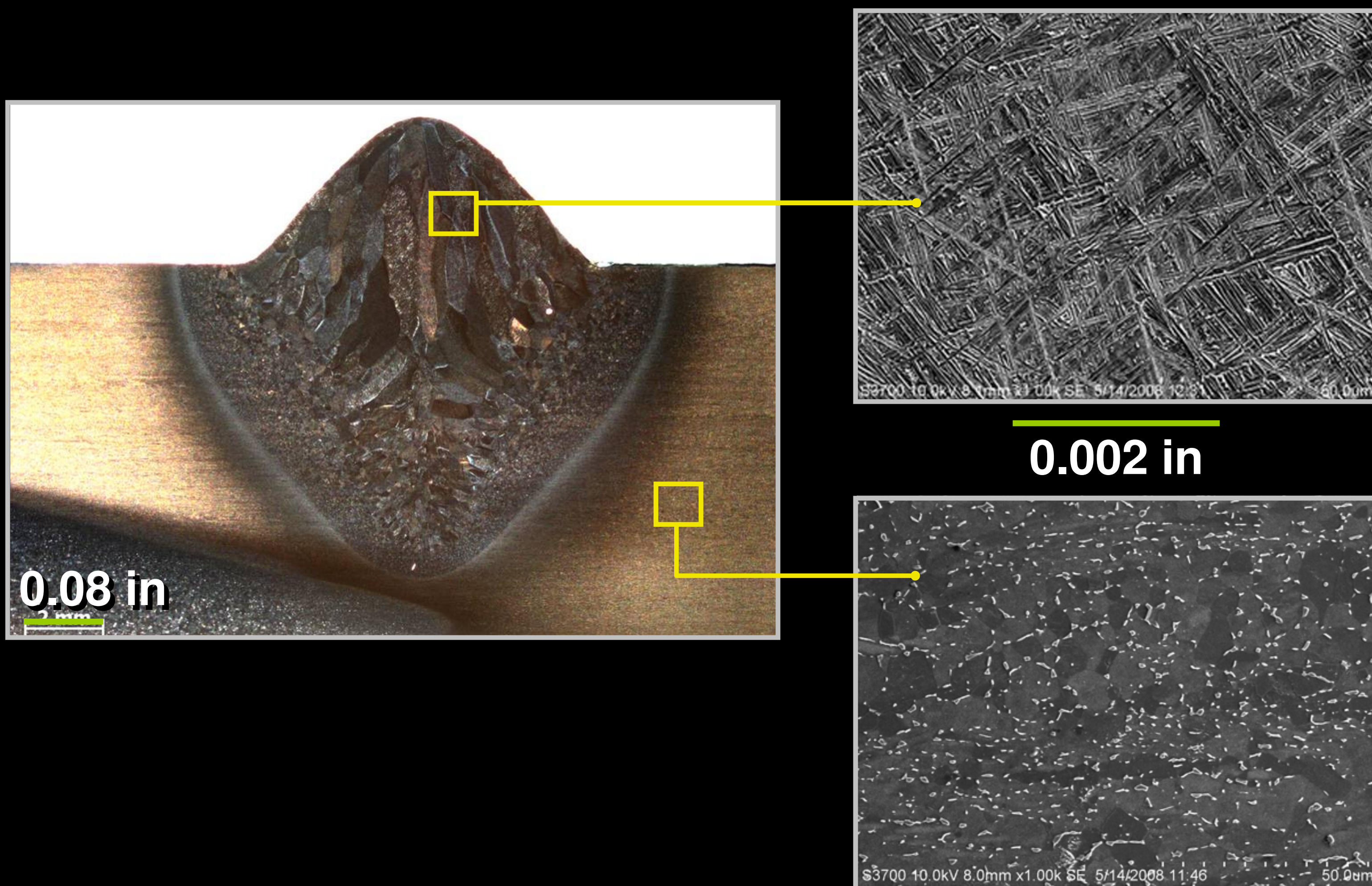
100% 2219 Al

0.02 in

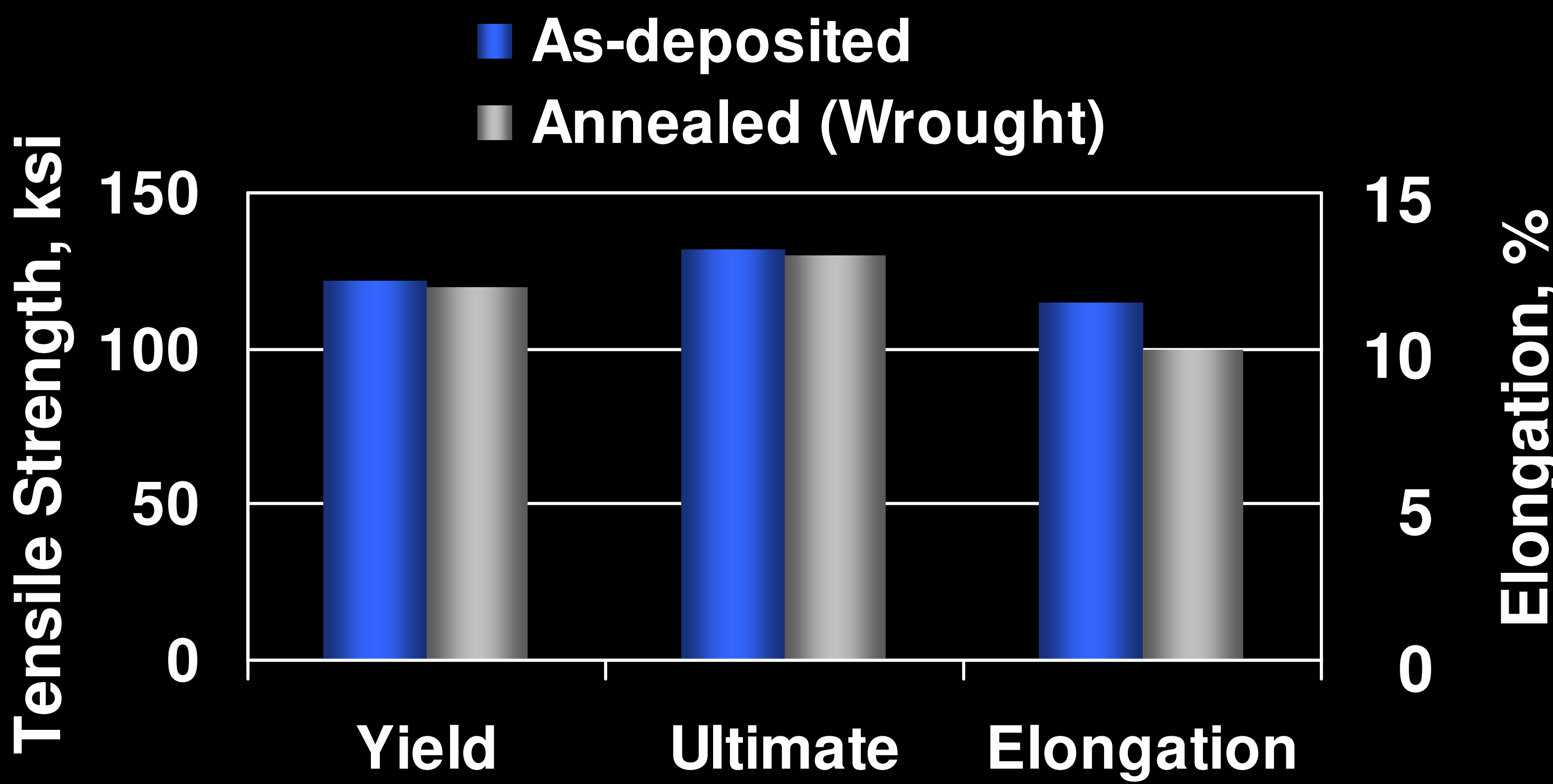
Graded Deposit Hardness



Ti-6Al-4V Microstructure



Ti-6Al-4V Tensile Data

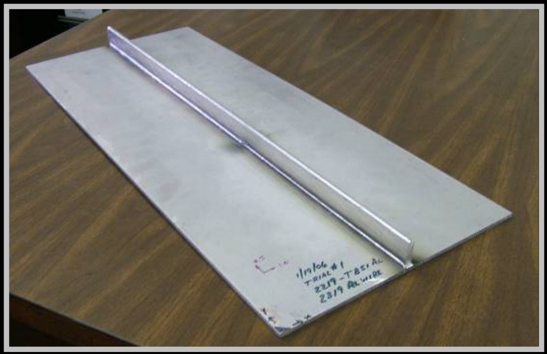


- EBF^3 Ti-6-4 equivalent to annealed wrought product

Unitized Structural Tests

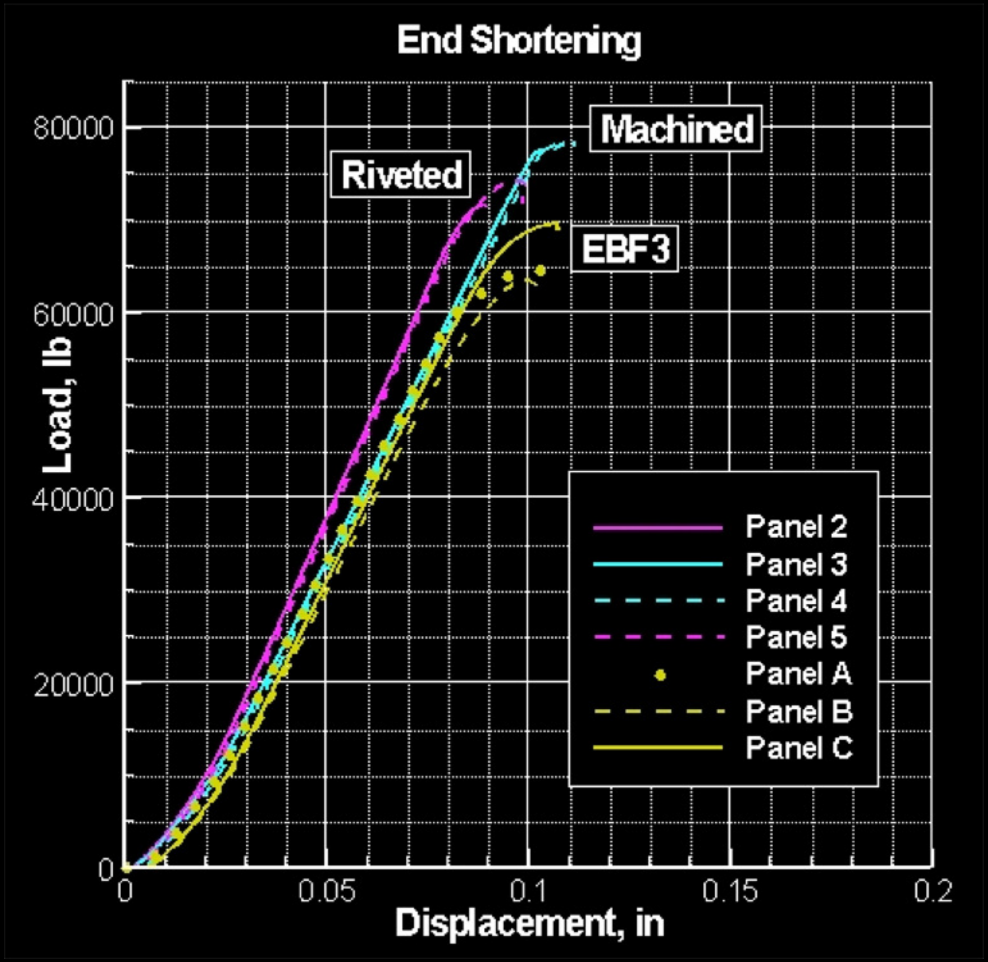
Uniaxial compression buckling tests

Machined | **Riveted** | **EBF^3**

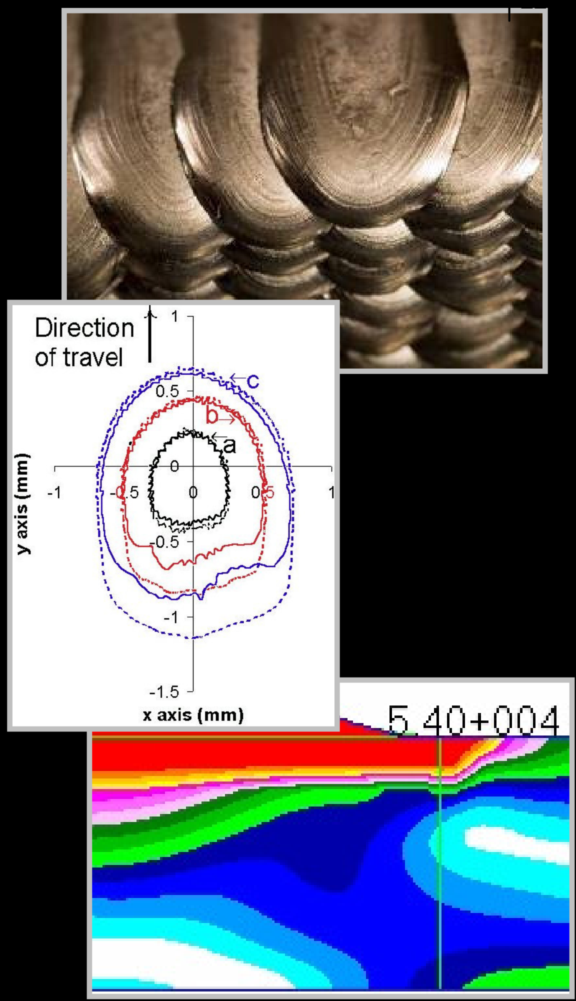


Structural Test Comparison

- EBF^3 panels 5% lower than machined
- Reduction due to distortion



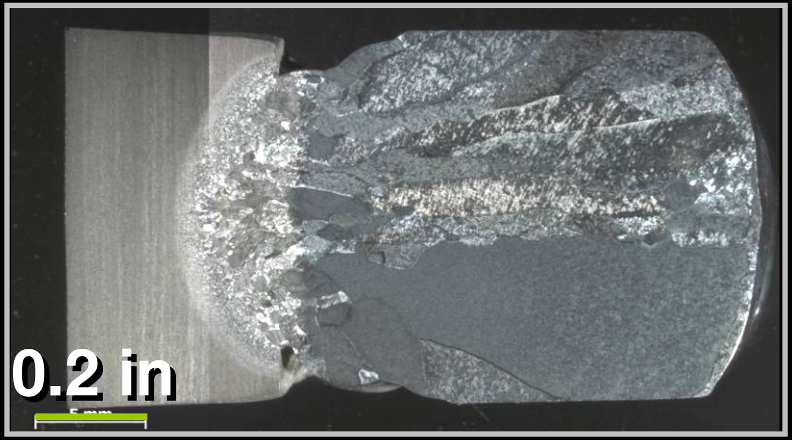
Outline

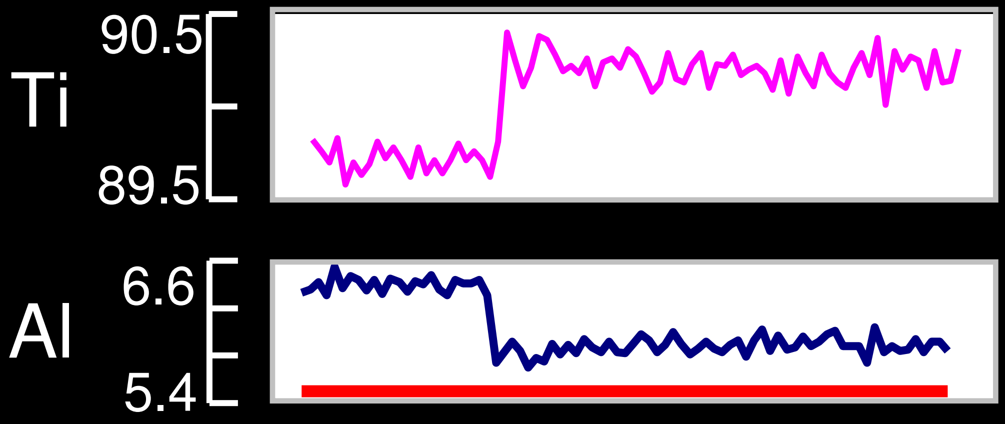


- Technology inception
- Characterization
- **Technical challenges**
  - Preferential vaporization
  - Process control
  - Residual stress
- Current applications
- Influence on future designs
- Supportability in space

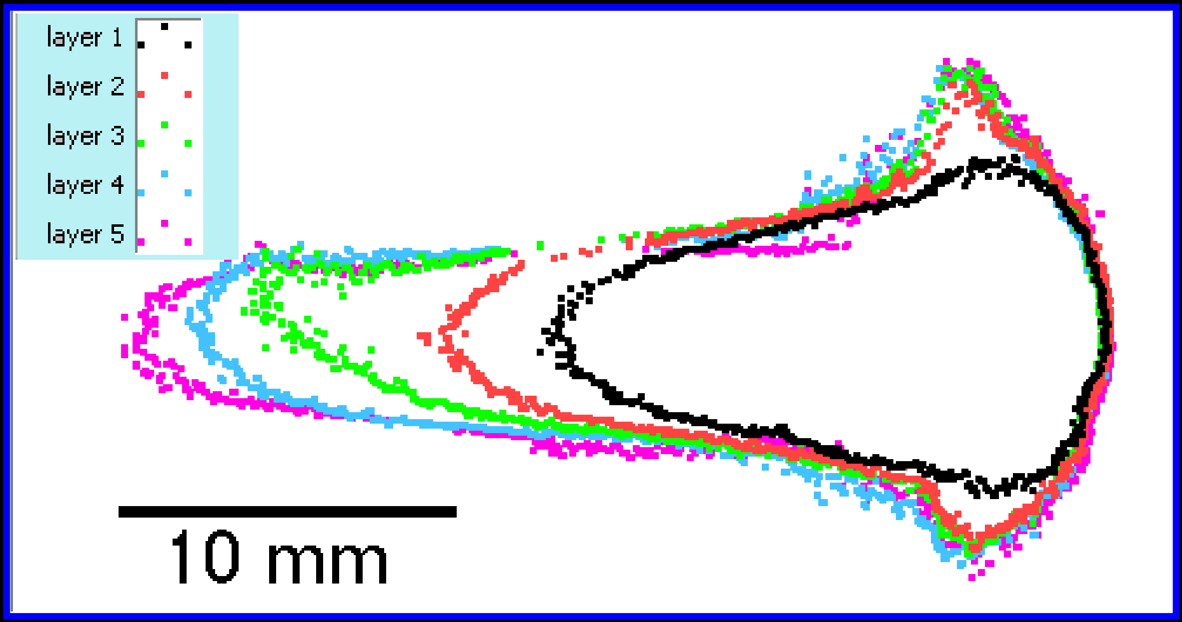
Loss of Al in Ti-6Al-4V

- Al loss in vacuum
- Function of temperature and pressure
- Process repeatability
- Issue with other alloys too



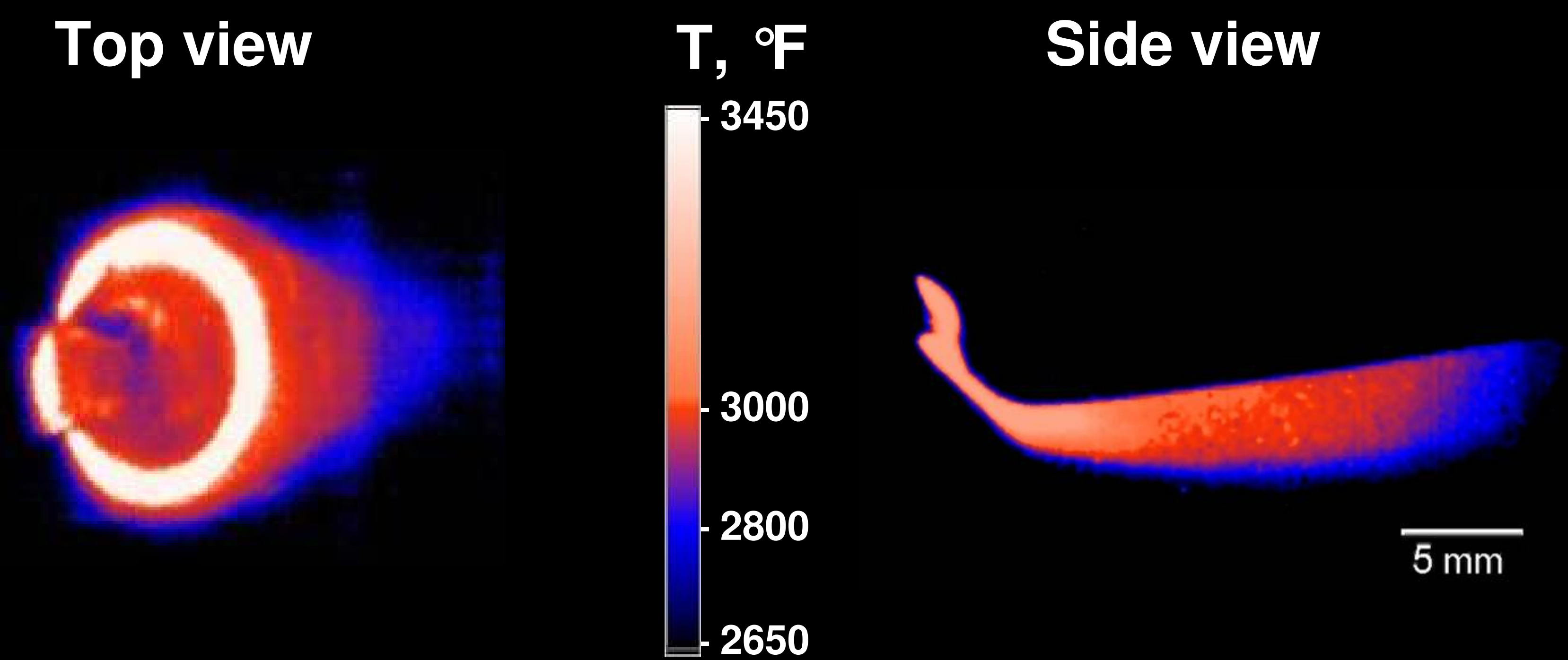


Need for Process Control



- Melt pool changes with temperature
- Monitor for process control

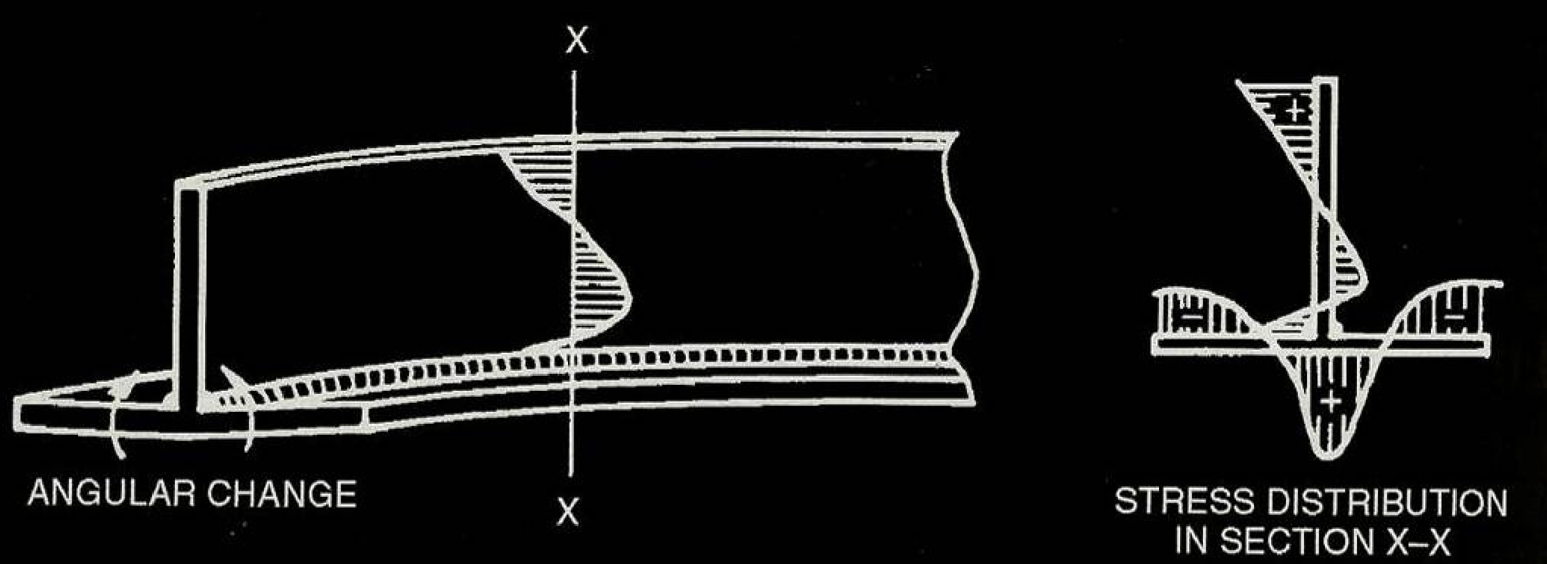
Thermal Imaging of EBF^3



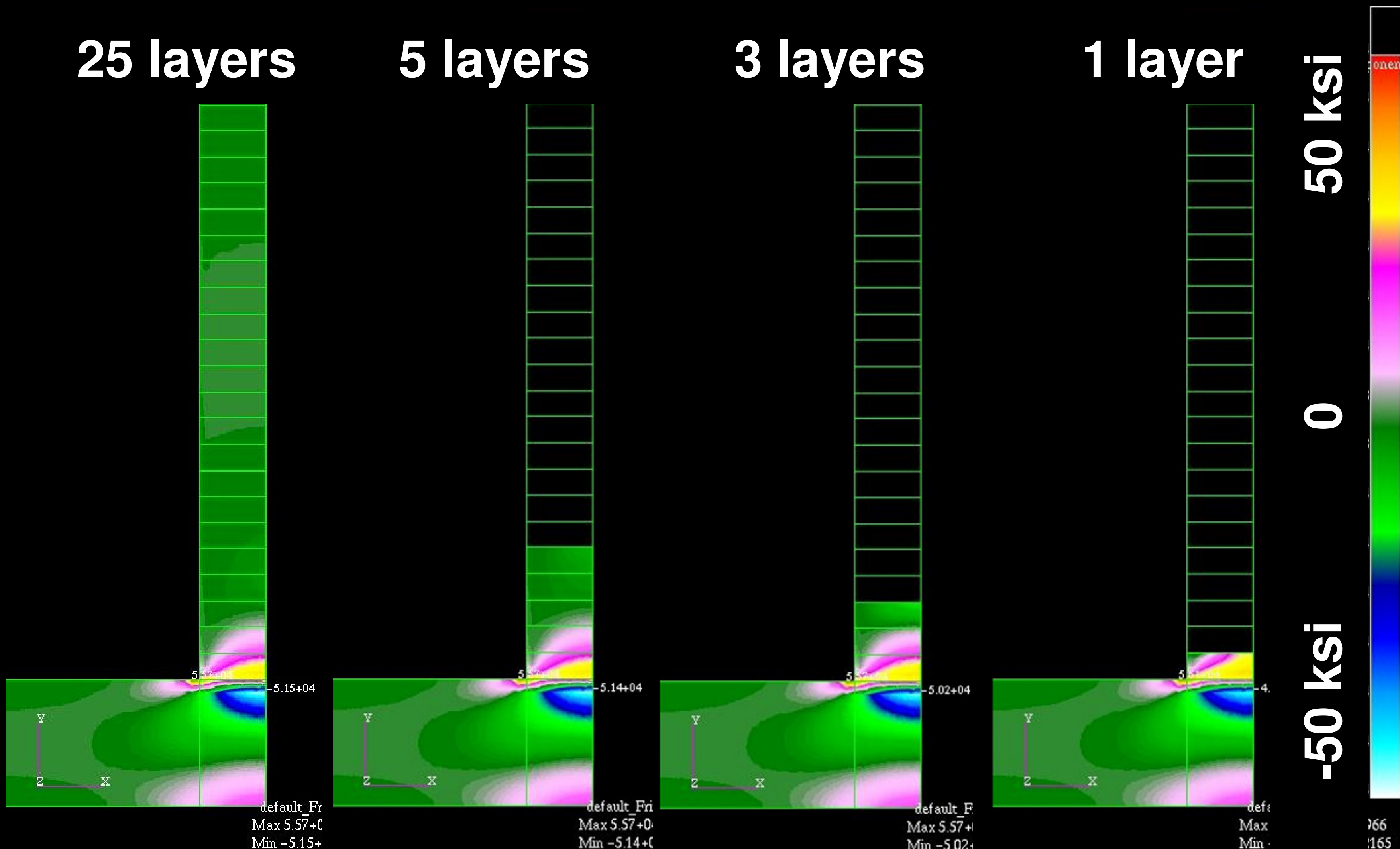
- Closed loop process control
- Collaboration with L-M and UTSI

Thermal Residual Stresses

- **Localized heat induces distortion and residual stress**

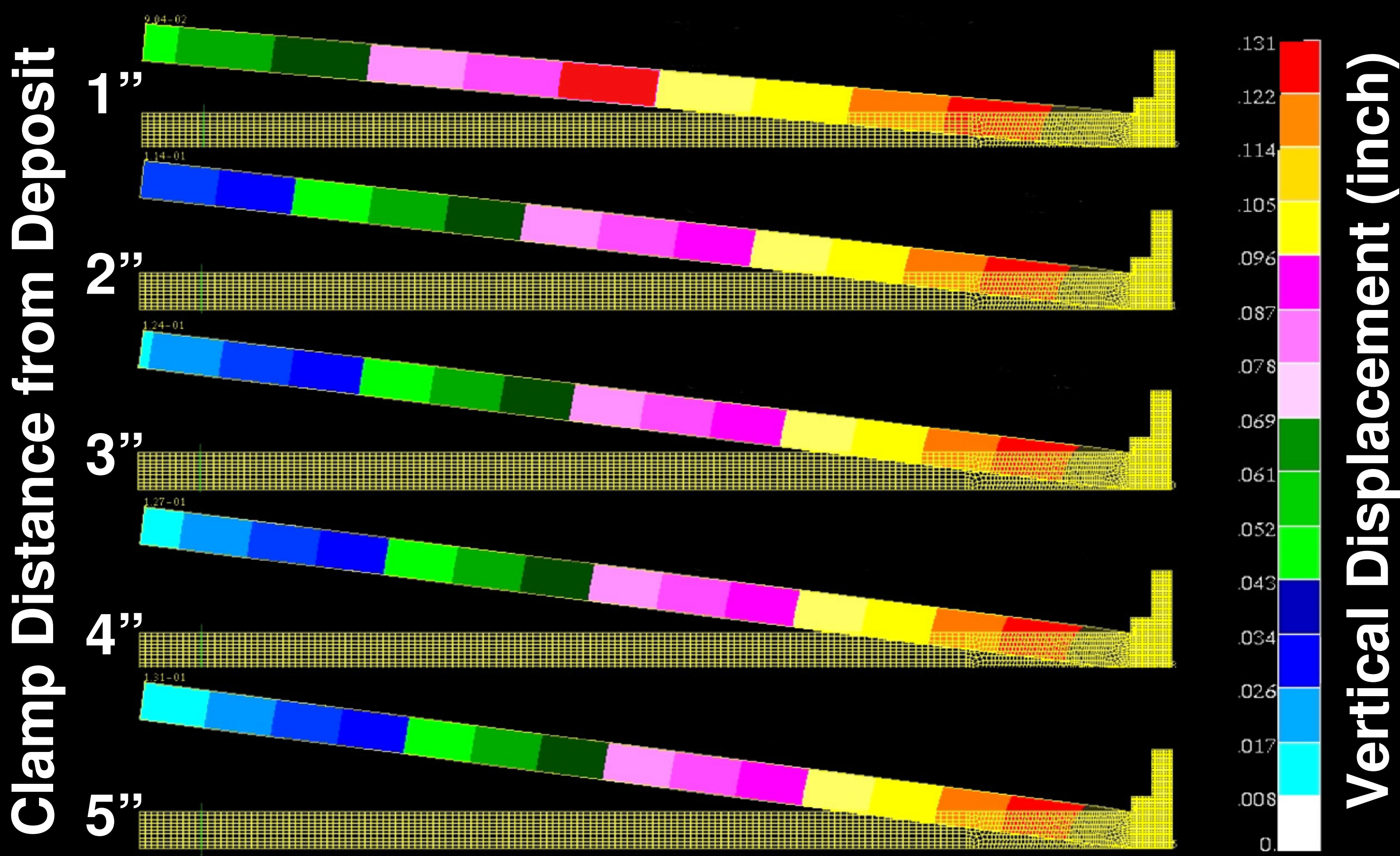


Residual Stress Distribution



http://www.nasa.gov

Baseplate Distortion



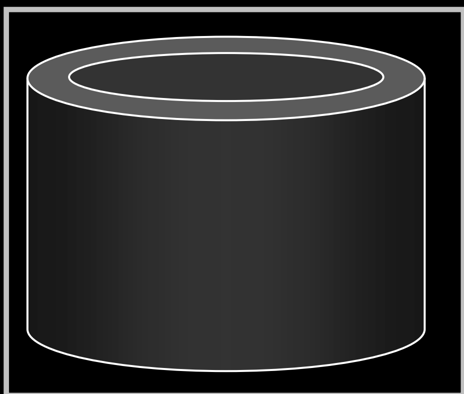
NASA-Industry Alliance

- **Joint-funded alliance**
  - Boeing
  - Lockheed-Martin
  - Spirit AeroSystems
  - NASA
  - AFRL
- **Develop process standards**
- **Catalyze growth of supply web**
- **NASA lead**
  - Public benefit without private preference

Outline

- Technology inception
- Characterization
- Technical challenges
- **Current applications**
  - Replace existing parts
  - Potential industries
- Influence on future designs
- Supportability in space

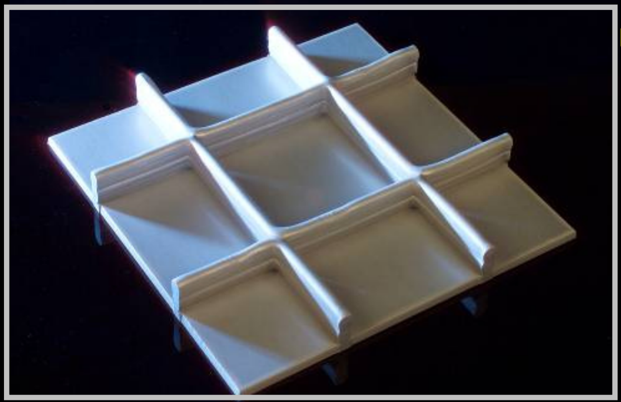
Add Details onto Forgings

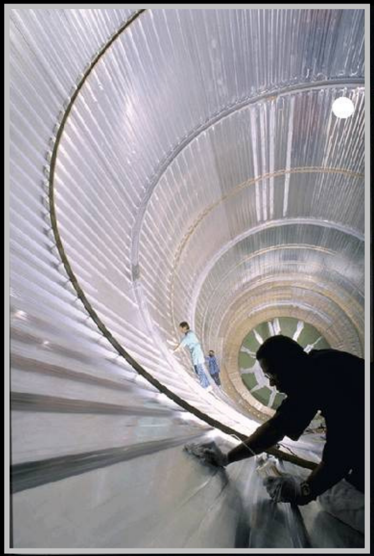


- Add features onto simplified preform
- Reduces billet sizes and buy-to-fly ratio

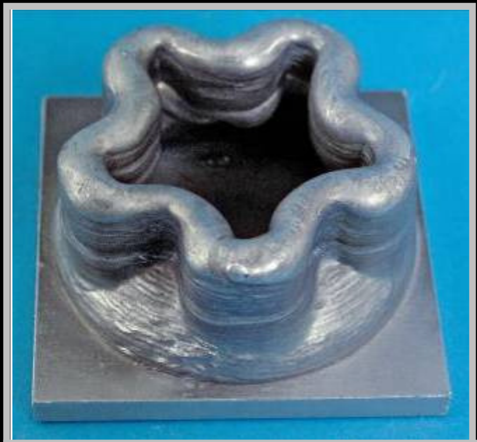
Cryotank Concept

- Form cylinder
- EBF^3 stiffeners
- Tailored stiffener arrays





Complex Shapes

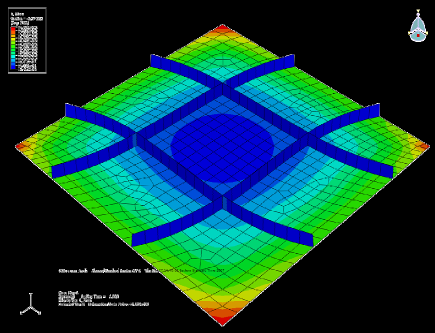


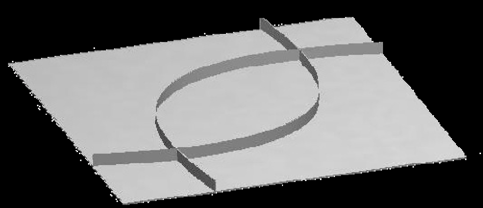
- Build entire part
- Unitized structures
- Allows internal cavities

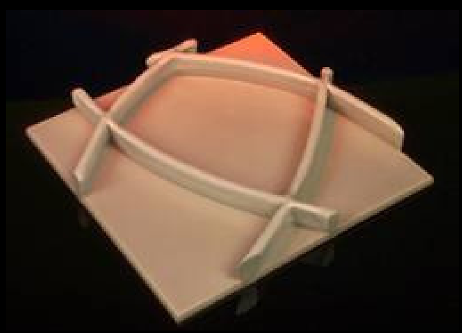
Potential Industries

- Aerospace
- Tool & dies
- Automotive
- Medical implants
- Sporting goods
- Repairs in remote locations

Outline

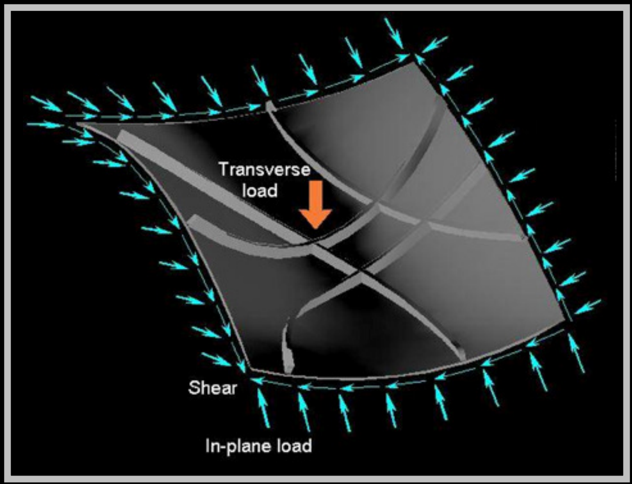






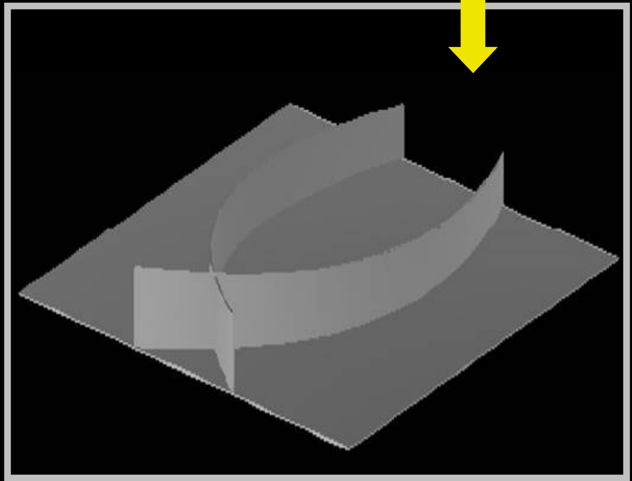
- Technology inception
- Characterization
- Technical challenges
- Current applications
- **Influence on future designs**
  - New unitized structural designs
  - Functionally-graded structures
  - Integrated systems
- Supportability in space

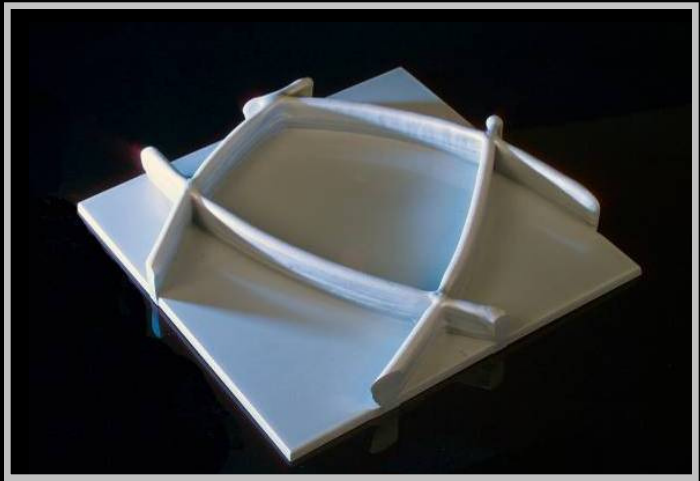
Novel Structural Designs



Curved stiffeners can be optimized for:

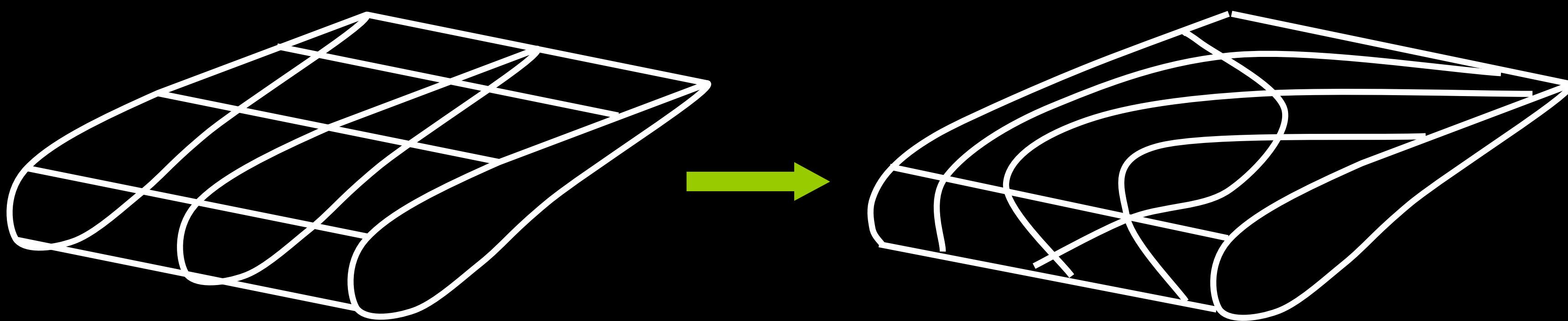
- Performance
- Low weight
- Low noise
- Damage tolerance





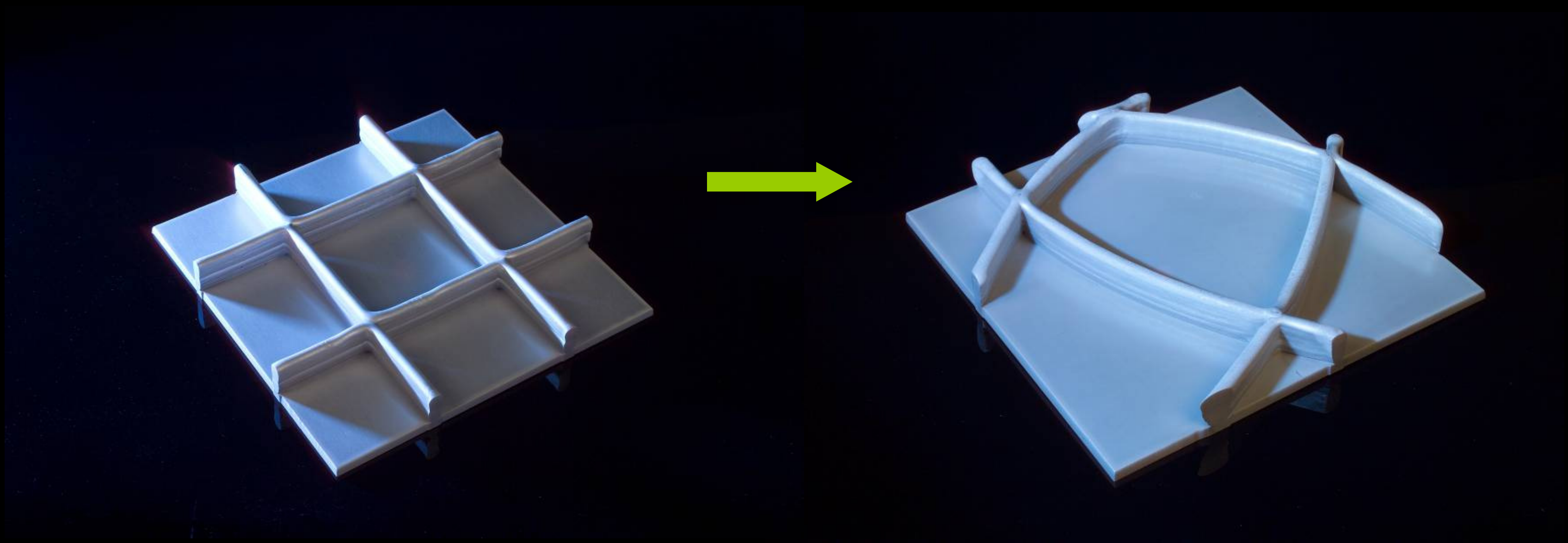
Aeroelastic Tailoring

Monocoque wing → Coupled bending-torsion wing



Design for Acoustics

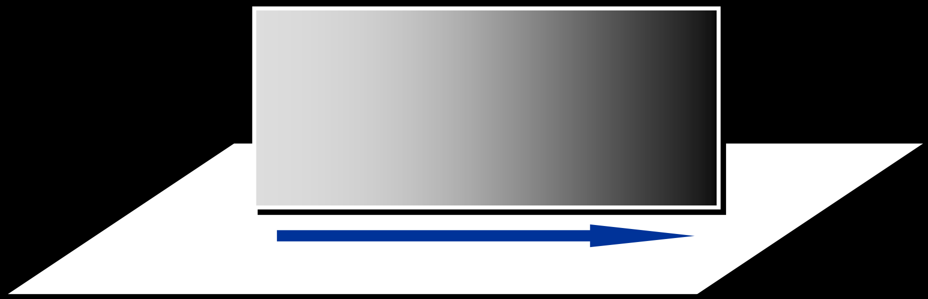
- **Optimize stiffeners to tailor natural resonance frequencies**



Functional Gradients

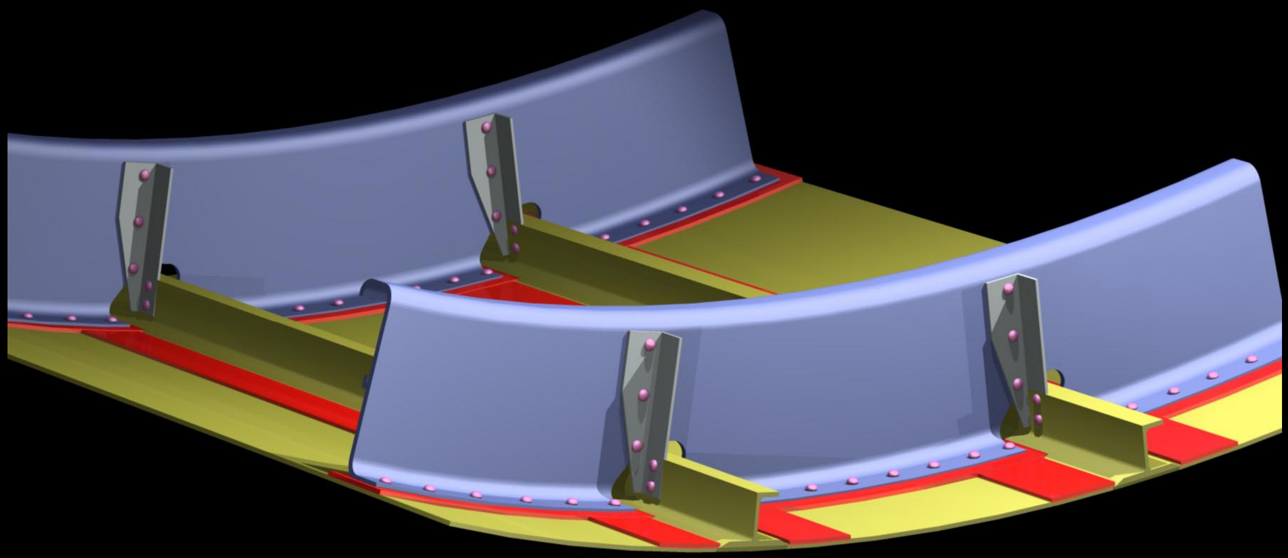
Locally control:

- Chemistry
- Microstructure
- Properties



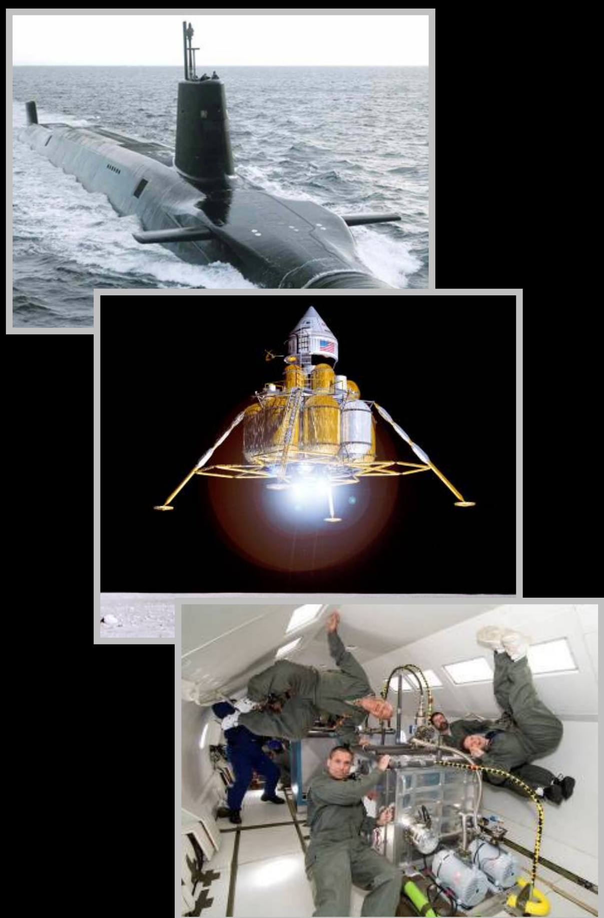
Integrated Systems

- Sensors for health monitoring
- Selective reinforcement



"Large Panel Validation of Advanced Metallic and Hybrid Structural Concepts for Next Generation Transport Aircraft," R. J. Bucci, et. Al., AeroMat 2007

Outline



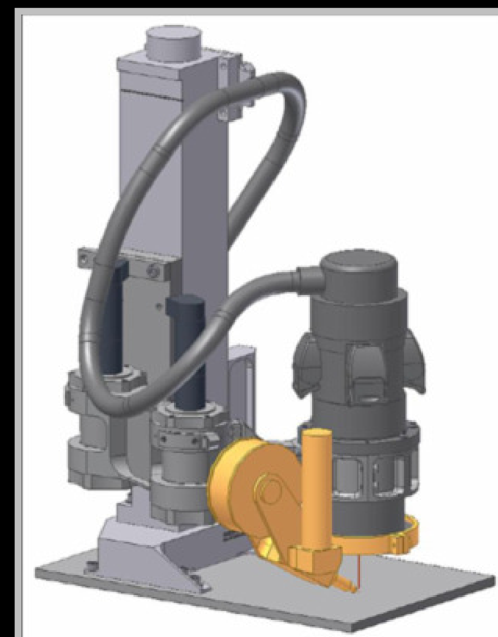
- Technology inception
- Characterization
- Technical challenges
- Current applications
- Influence on future designs
- **Supportability in space**
  - In-space repair
  - EBF^3 in 0-g
  - Space applications

Need for Supportability

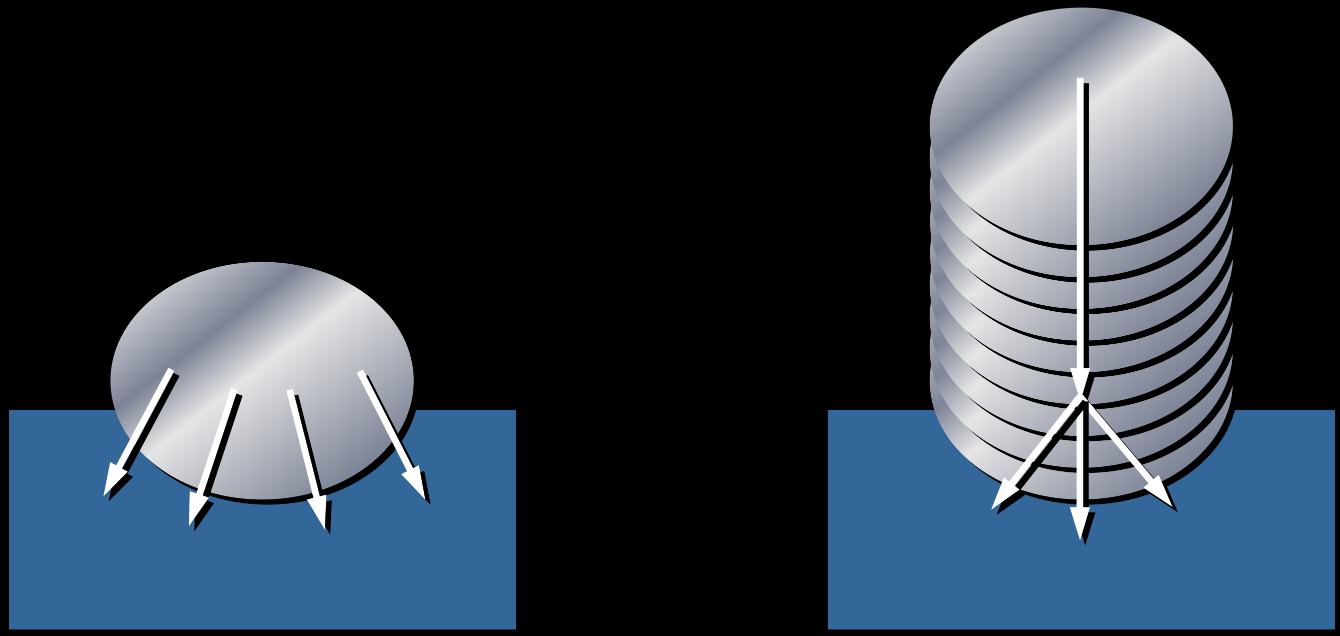
- Long duration missions
- Support autonomy
- Minimize resupply from Earth
- Fab or repair parts
- Enhances mission success

System Evolution

Ground-based: 100,000 lbs. → **Portable: 1,800 lbs.** → **Space-based: (concept) <100 lbs.**



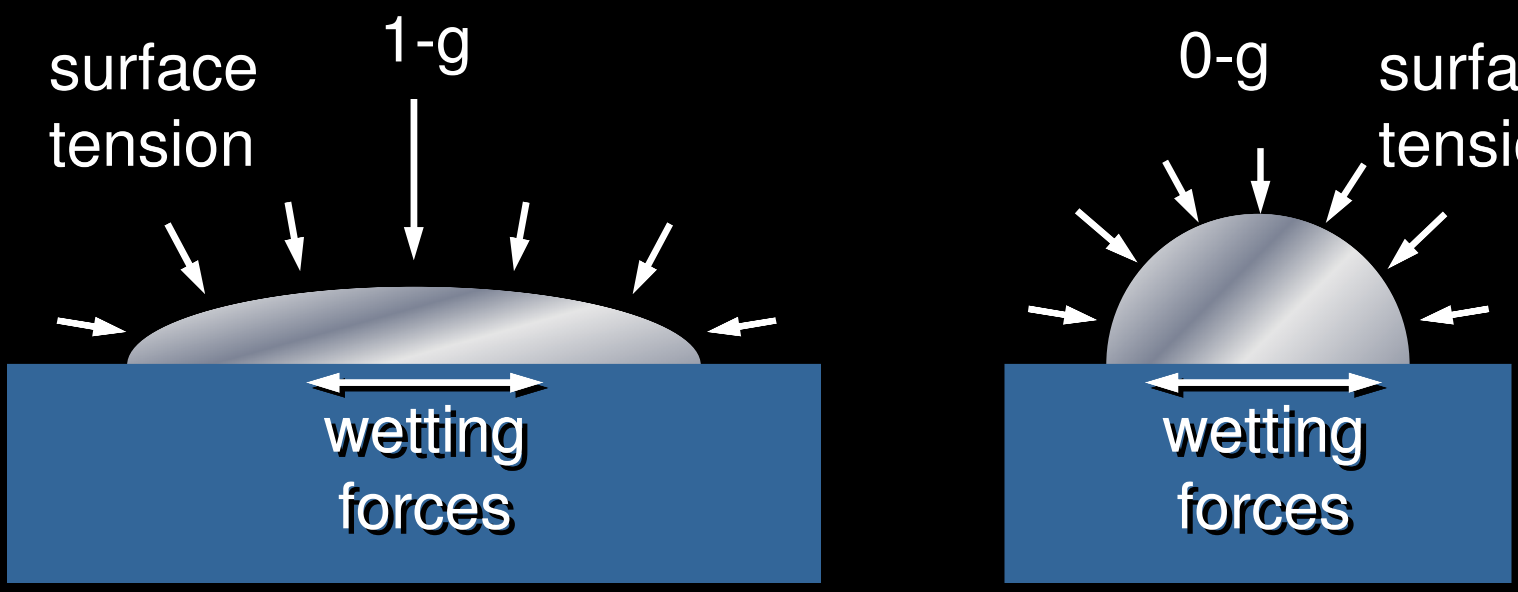
Height vs. Cooling Path



- Cooling path influences temperature

Gravity vs. Surface Tension

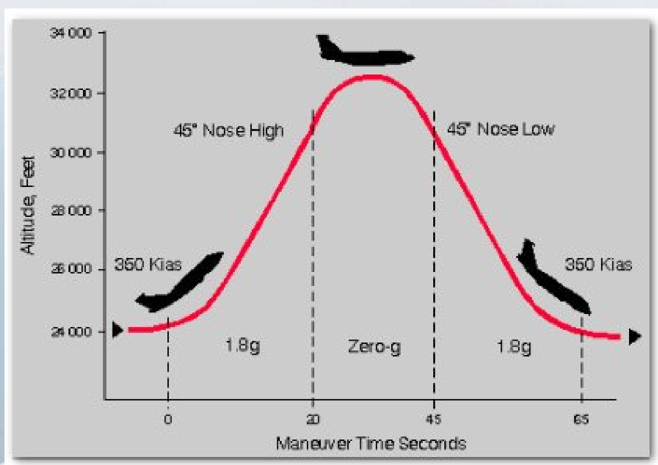
Equivalent droplet volumes



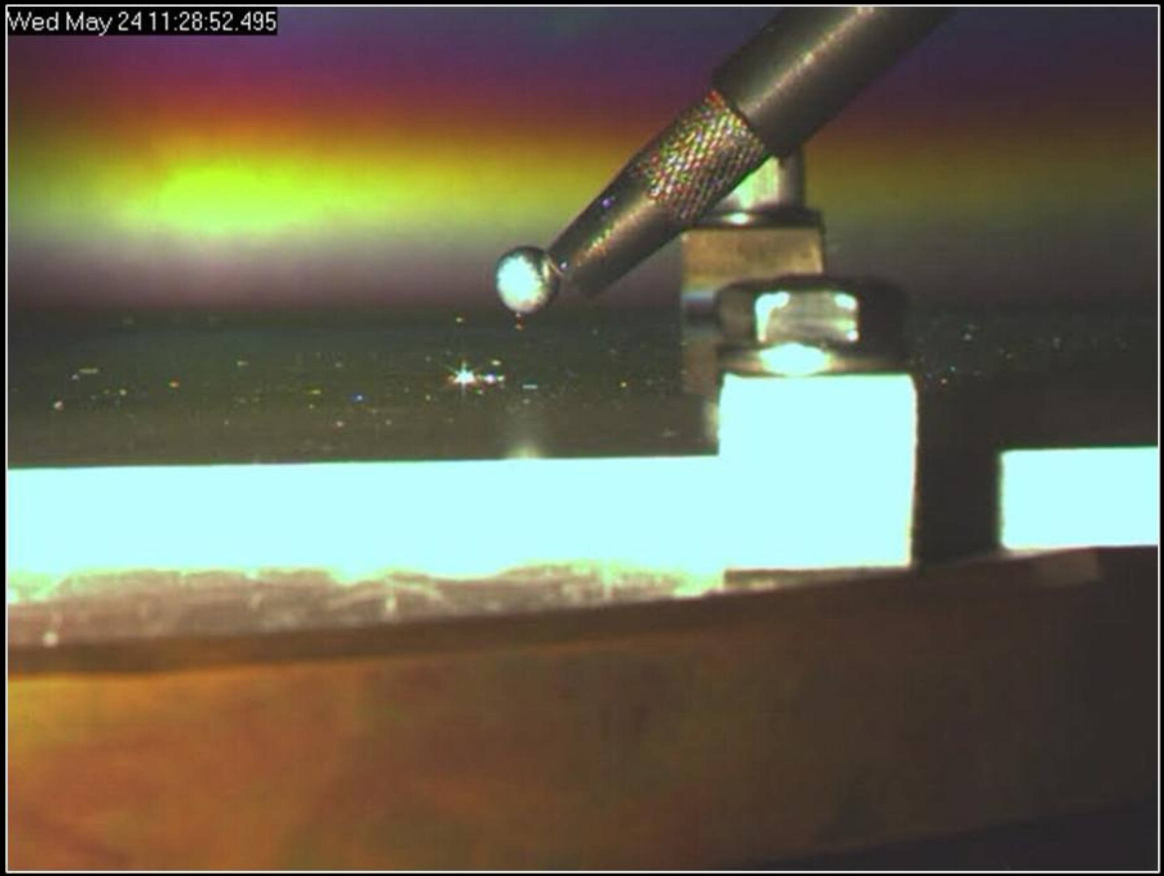
- **In 0-g, surface tension dominates**
- **Function of temperature**

Microgravity Testing

- **NASA JSC's C-9**
  - **15-20 sec. at 10^{-2} g**
  - **1.8 g pullout**
  - **40 per flight**

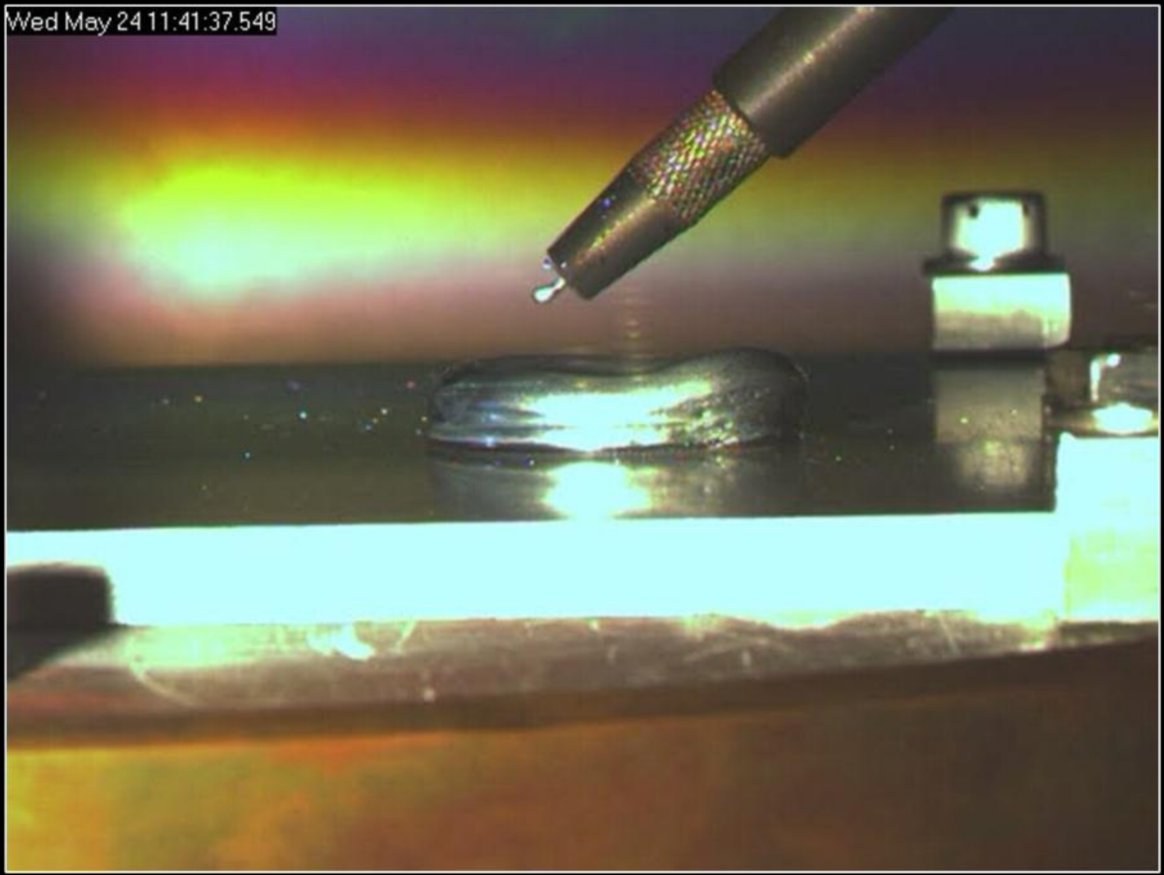


Successful 0-g Deposits



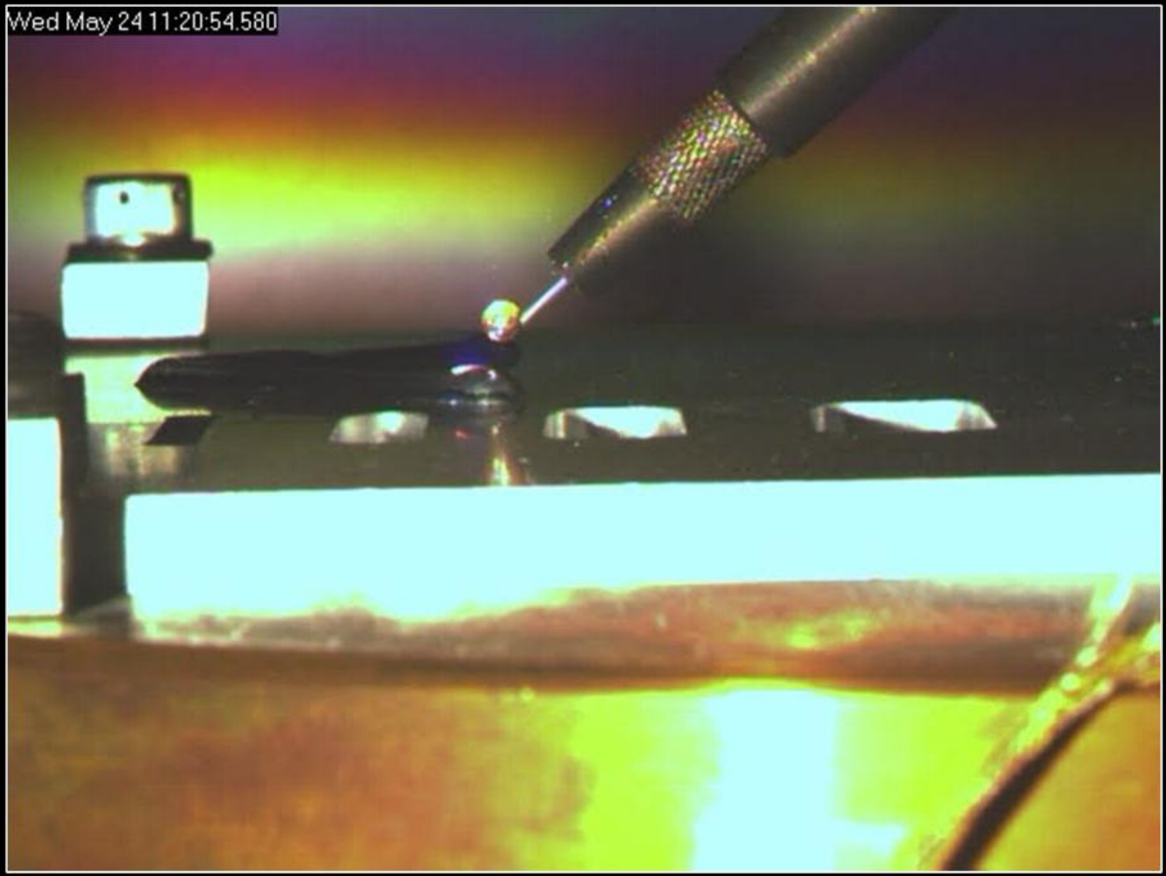
- **Wetting forces attract molten pool**

Successful 0-g Deposits



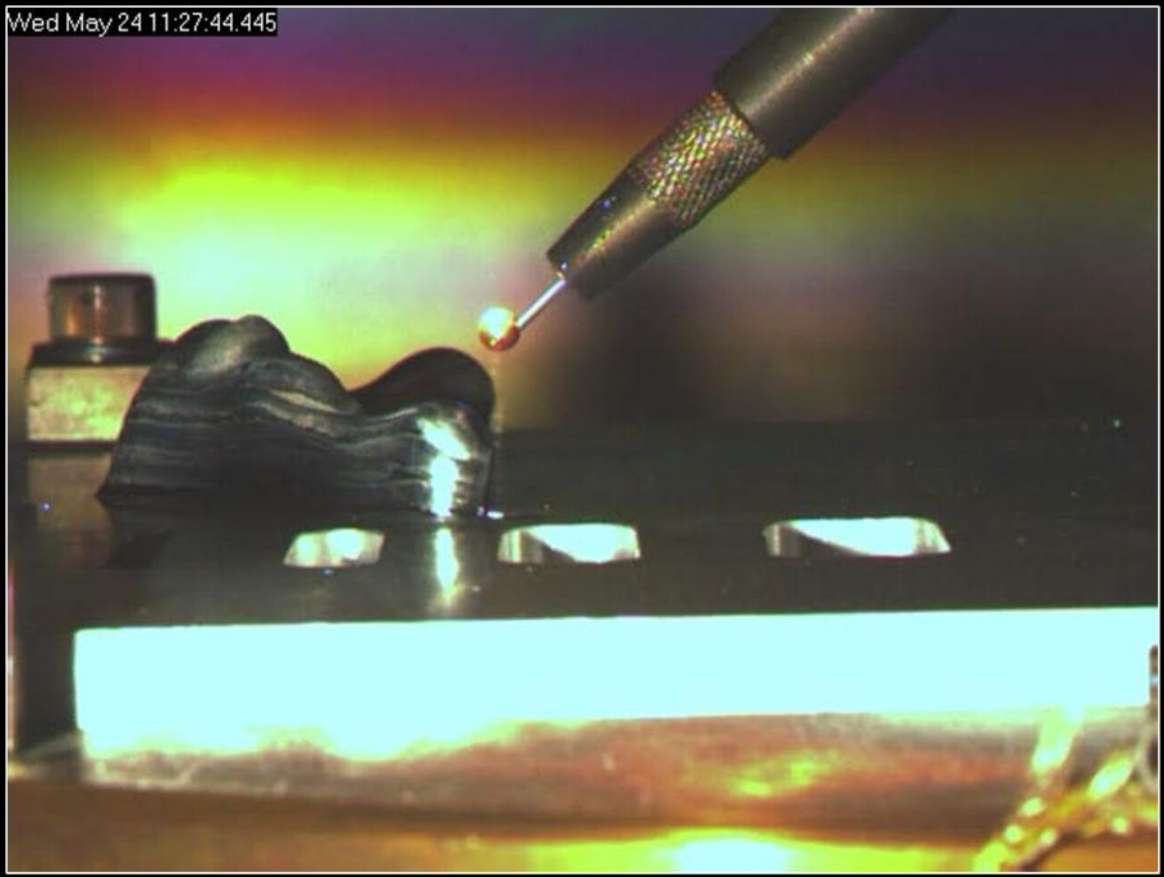
- **0-g deposit comparable to 1-g**

EBF^3 in 0-g



- **Surface tension dominates in 0-g**

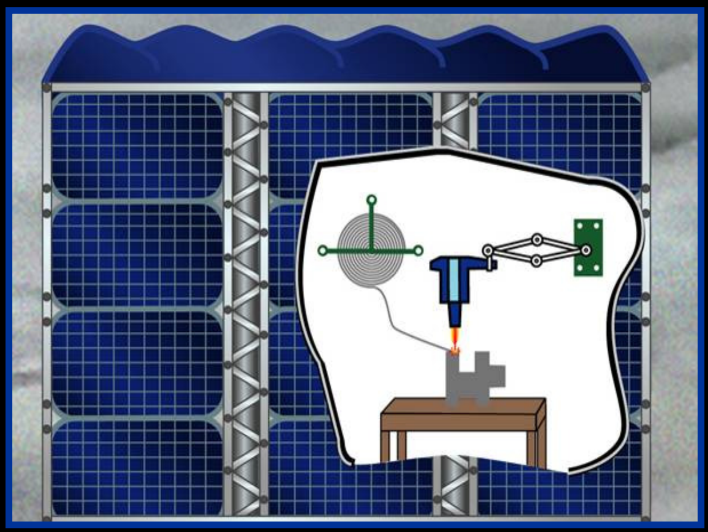
Learning in 0-g



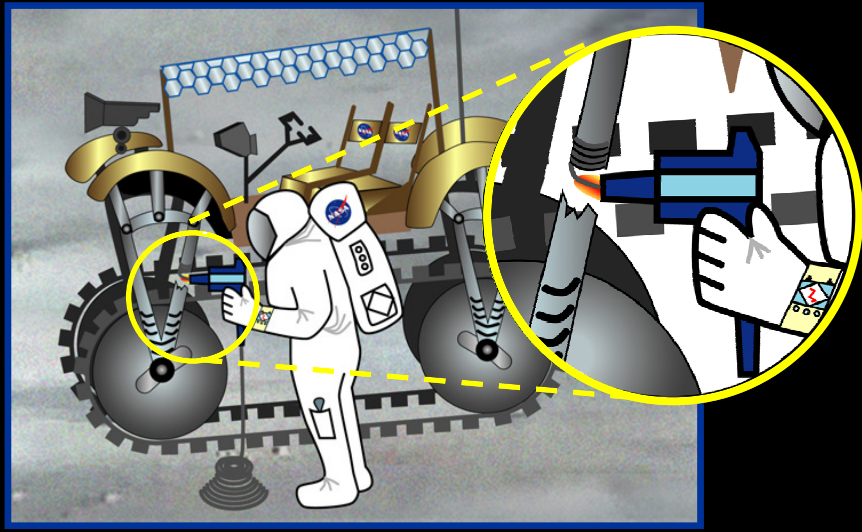
- **Height control required in 0-g**

Lunar Surface Repairs

- **Concept to support long duration human exploration missions**



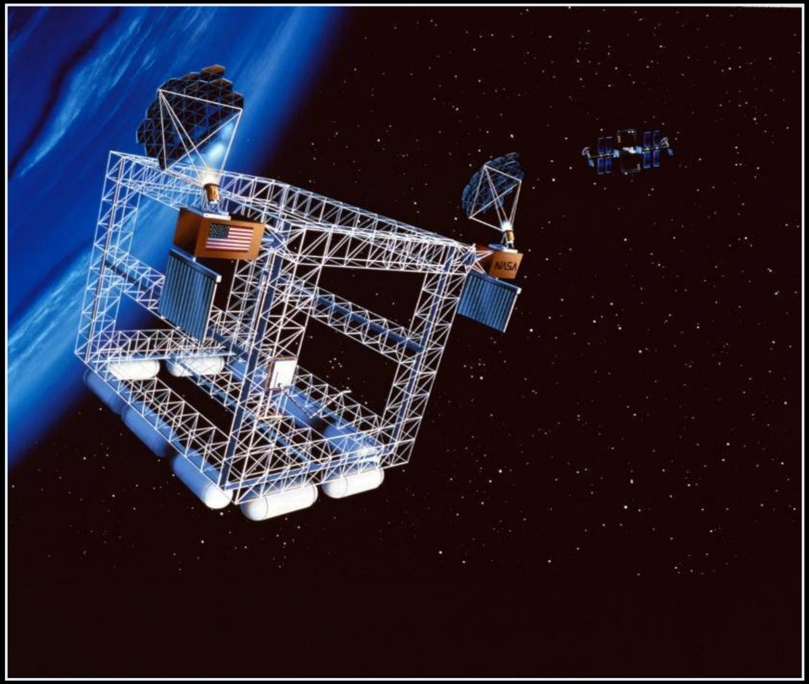
Automated



Hand-held

On-Orbit Assembly

- **Concept for fabrication of large space structures**



Remote Terrestrial Repairs

Similar self-supportability needs on Earth:

- **Navy ships**
- **Army supply in-theater**
- **Remote science bases**

Summary

- Led by LaRC since inception
- Disruptive technology
- Cross-cutting:
  - Aeronautics
  - Space
  - Other industry sectors
- Enables new structural designs
- Demonstrated in 0-g for use in-space

EBF^3 Timeline