Electron Beam Additive Manufacturing:
State-of-the-Technology, Challenges & Opportunities

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Direct Digital Manufacturing Workshop | Solomons, MD | May 11-12, 2010

Electron Beam Freeform Fabrication (a.k.a.: EBF^3, EBFFF, EBAM)

- Electron beam deposition with wire feed
- High deposition rates, large part sizes
- Near-net shape with finished machining

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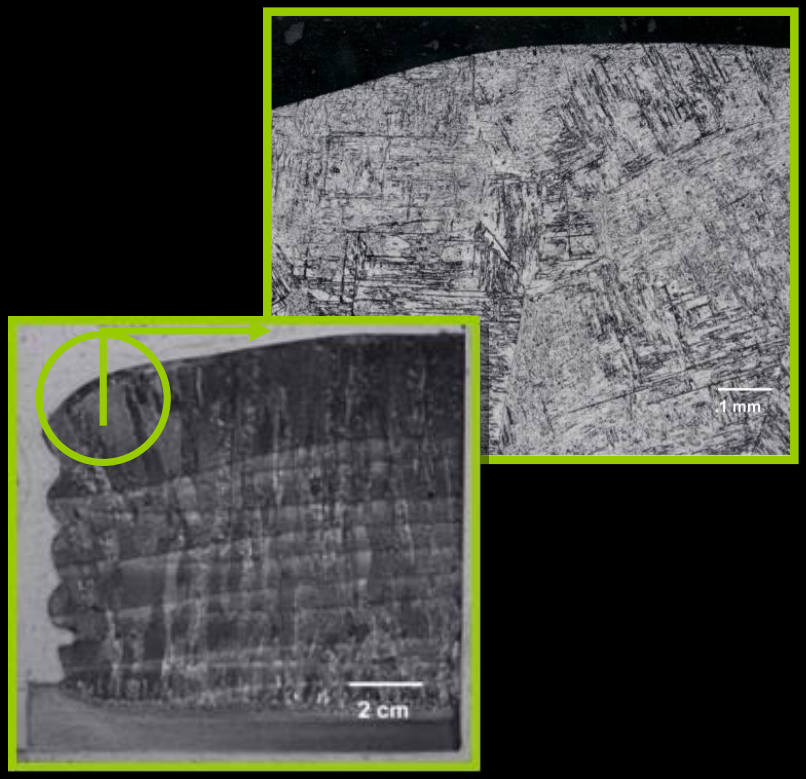
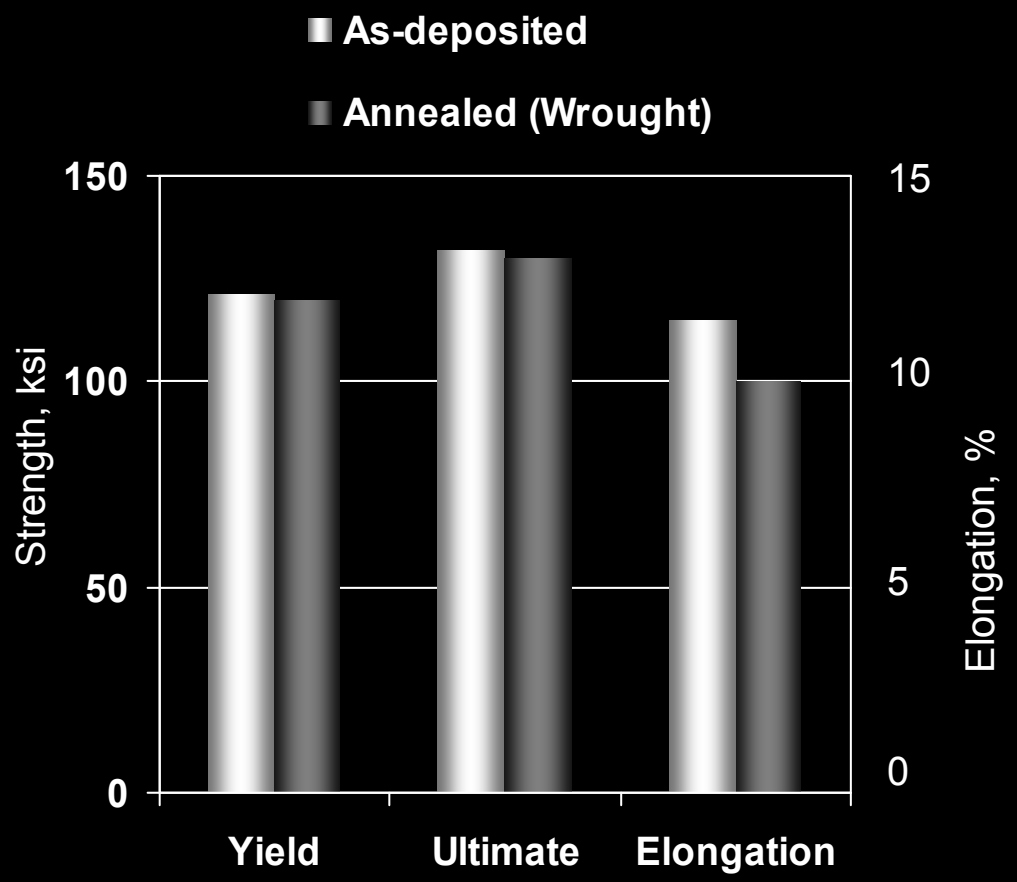
Ti-6Al-4V Processed by EBF^3



- Large columnar grains grow epitaxially from substrate
- Forms typical alpha-beta lath structure within grains



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

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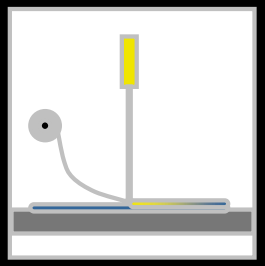
History of EBF³ Development

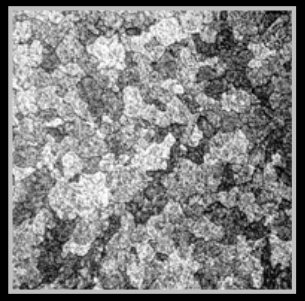
Technology Inception



Define EBF³ system specs

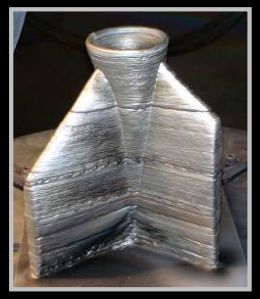
EBF³ system installed at NASA LaRC

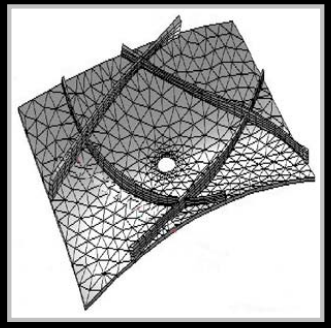
Technology Maturation



EBF³ process understanding

Increasing part complexity





Unitized & graded structures

2001 2002 2003 2004 2005 2006 2007

2003 2004 2005 2006 2007

Design portable EBF³ system

Integrate prototype portable EBF³ system

Microgravity testing

Patent on portable EBF³ concept issued 1/07

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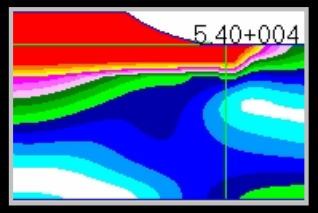
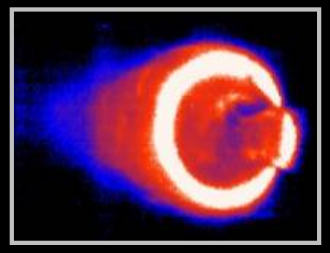
Future of EBF^3

Commercialization



Computationally guided process maturation

Closed loop control



Current Applications

First production parts on aircraft

Influence Future Designs

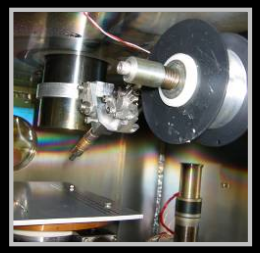
Selective reinforcement/ integrated sensors

2007 2008 2009 2010 2011 2012 2013 & beyond

Detailed property testing for certification

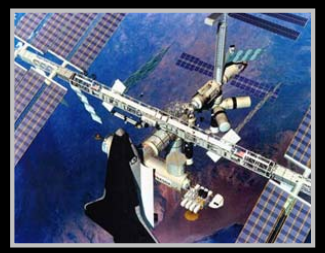
Process certified

2007 2008 2009 2010 2011 2012 2013 & beyond



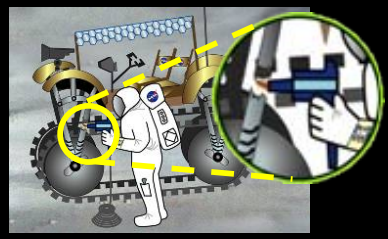
Retire prototype portable system

Next Gen EBF^3 lunar systems build and test



ISS demo of EBF^3 system

Lunar surface system demo



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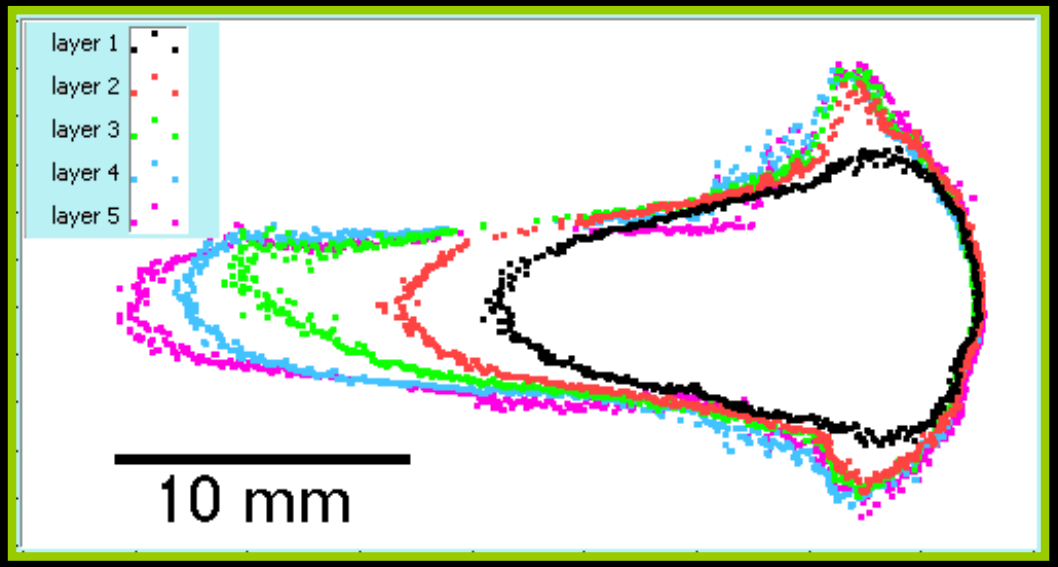
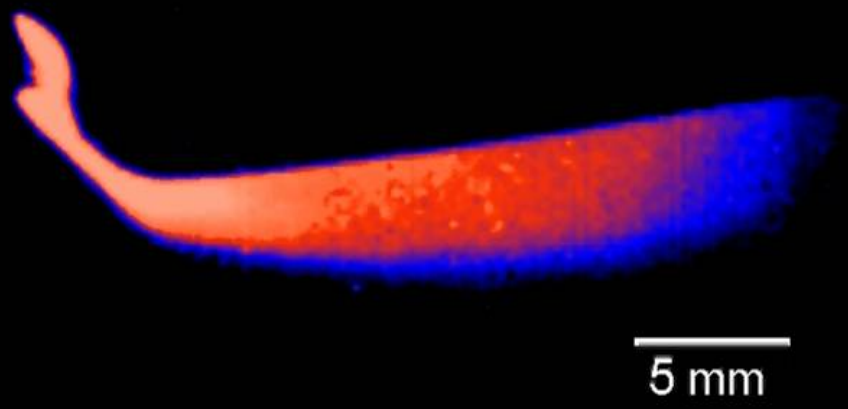
Need for Process Control





Problem:

Melt pool changes with temperature from one layer to the next

Current Solution:

Monitor melt pool size as indication of temperature for process control

Required Work:

- Complete integration of sensors into control system
- Refine control logic to correct for other process anomalies (wire irregularities, change in direction)

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Loss of Al in Ti-6Al-4V

Problem:

Al loss in Ti-6-4 due to melting in vacuum (function of temperature & pressure)

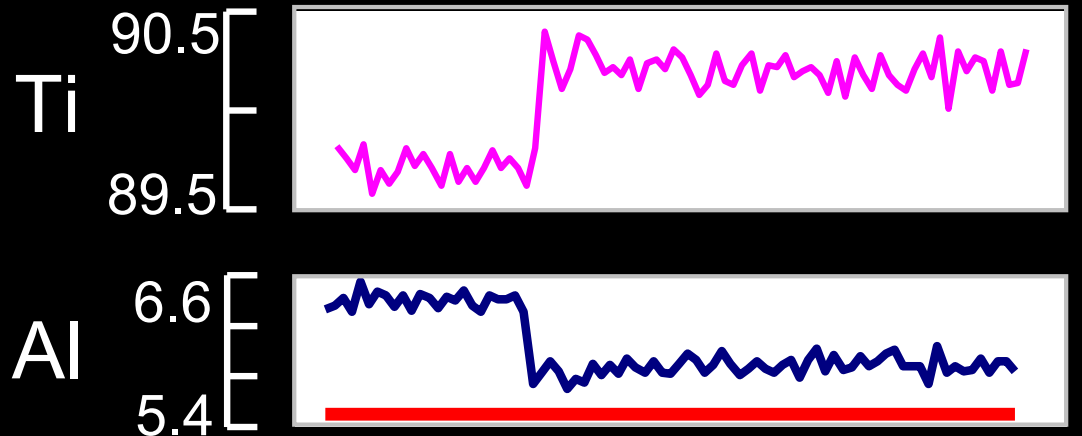
Current Solution:

↑ Al in wire composition

↓ thermal input

Required Work:

- Quantify losses at standard operating parameters to ensure consistency
- Process development to reduce Al loss by reducing thermal input



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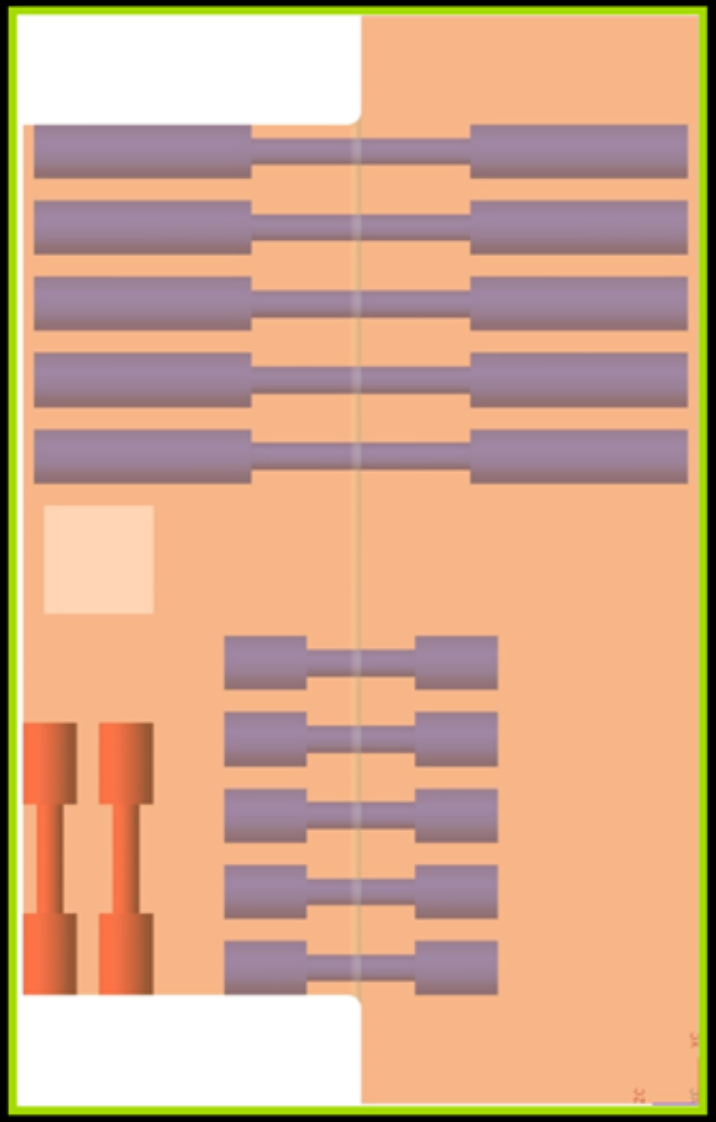
Certification & Repeatability



Problem:

Part-to-part and machine-to-machine variations limit repeatability

Current Solution:

Define tight process specification & conduct allowables testing

Required Work:

- Compare parts built on different machined with similar build parameters
- Beam probe analysis to monitor beam degradation with filament life
- Generate & maintain database with pedigree data from multiple deposition sites

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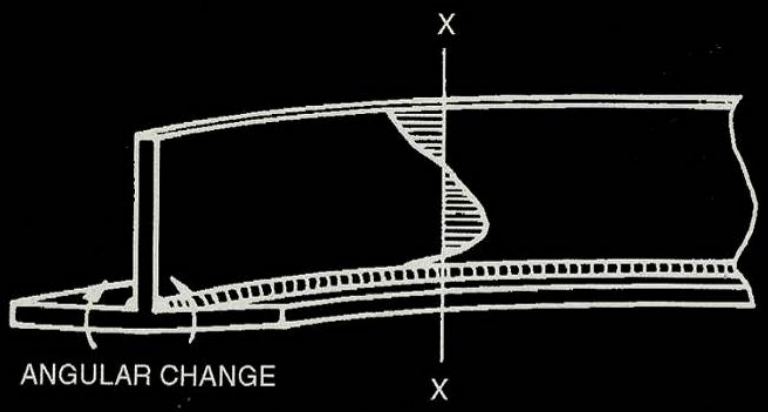
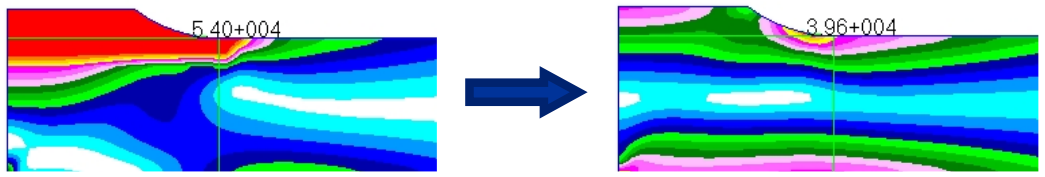
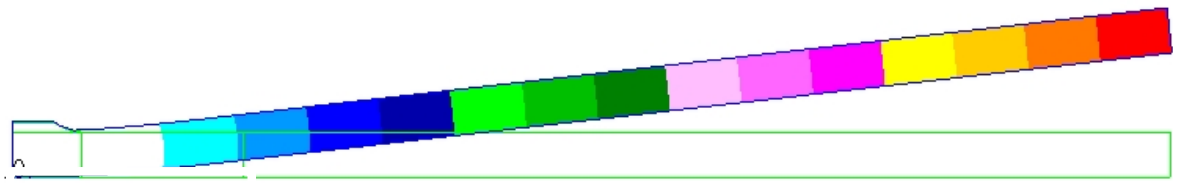
Distortion and Residual Stress





Von Mises Stress Before & After Clamp Release



Distortion

Problem:

Temperature gradients induce residual stresses & distortion

Current Solution:

- Balanced deposition on both sides of baseplate
- Frequent thermal stress relief steps

Required Work:

- Post-deposition stress relief
- Modeling & validation of distortion & residual stress
- Process development to reduce distortion in one-sided deposits

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NDE Analysis of EBF^3 Parts

Problem:

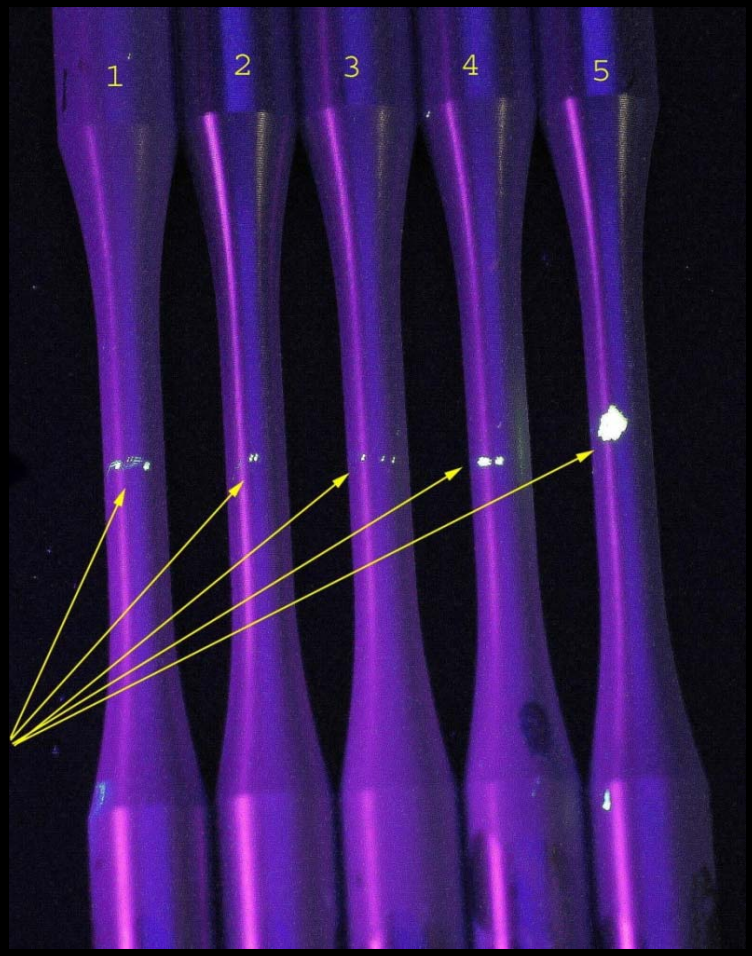
Irregular surface finish of as-deposited EBF^3 parts obscures NDE results

Current Solution:

NDE inspection after final machining

Required Work:

- NDE technique development to detect internal flaws without machining
- Process development to eliminate flaws
- Sensors incorporated into process control system to enable real-time NDE during deposition



Lack of fusion at substrate/ deposit interface

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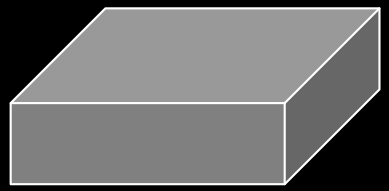
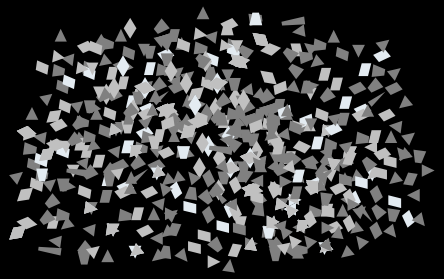
EBF^3 as a Green Manufacturing Process

Conventional Machining:



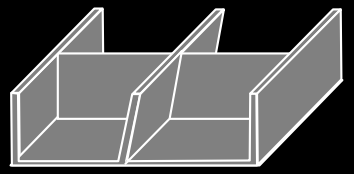
3000 lb.
forged billet

–



2850 lb. chips

=



150 lb. finish
machined part

20 : 1
buy-to-fly

Additive Manufacturing via EBF^3:

200 lb.
rolled sheet

+

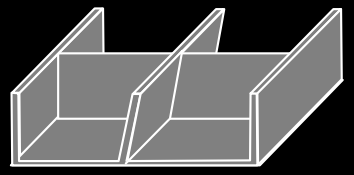
100 lb.
wire

+ EBF^3

–

150 lb.
chips

=



150 lb. finish
machined part

2 : 1
buy-to-fly

***EBF^3 saves significant resources over current methods*:**
raw materials, energy, fewer chemicals (cutting fluids), lead time = cost

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Repair via EBF^3

Opportunity:

Repair capability for large damaged parts that are irreparable by current technologies

- High value components (new or damaged in service)
- Reduce lead time to repair

Required Work:

- Tolerance control (residual stress, distortion)
- Material condition (HAZ, heat treat)
- Repair design (programming, stress analysis)
- Qualification (MRB)

* LM Aero ADP currently has three such parts and seeks funding to develop the technology

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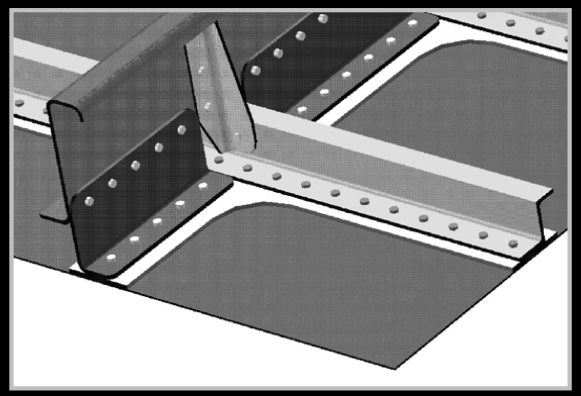
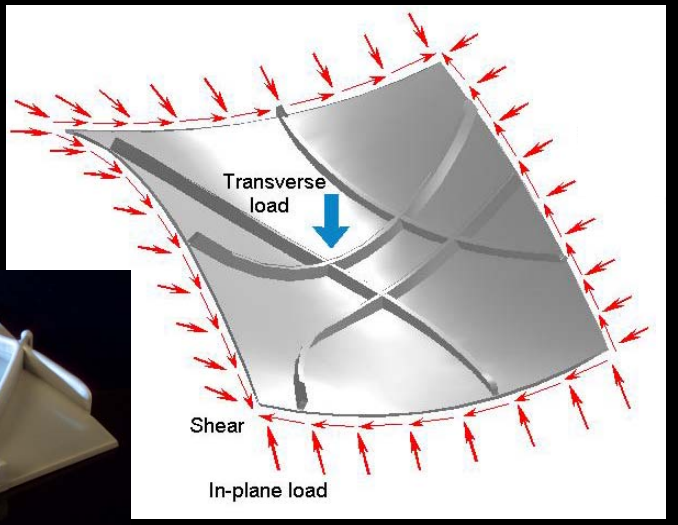
Novel Structural Designs

Designed for Assembly



Assembled from many discrete components

Designed for Performance



- Freeform fabrication of unitized structure allows use of functionally graded, locally controlled features
- New structural design & analysis tools allow concept development of structures with contoured stiffeners that follow load paths
- New manufacturing process coupled with novel structural analysis and design enables performance enhancements and reduced cost, weight

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EBF^3 Far Term Possibilities

- Complex geometries not possible with conventional processes
- Integrated multi-functional components
- Functional gradient materials
- Selectively reinforced metals
- Controlled microstructures
- Integrated sensors