Engineering, Operations & Technology
Boeing Research & Technology

Additive Manufacturing in Aerospace; Examples and Research Outlook

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National Academy of Engineering

Frontiers of Engineering 2011, Additive Manufacturing

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Introduction and Content

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Aerospace's stringent requirements and need for weight reduction provide the context for developing AM to the level of robustness established by traditional manufacturing methods.

- **Introduction to Aerospace Requirements for Additive Manufacturing**
- **Use of Additive Manufacturing in Aerospace**
- **Examples of Aerospace-Driven Research in AM**
- **Current Area of Development**
- **Moving Forward**

Brett Lyons

- Material and Process Research Engineer, Composite Processes Group
- Focus on Additive Manufacturing (Selective Laser Sintering) and composite tooling (soluble mandrels and rapid tooling)
- Masters in MechE from Michigan, staff research technician at UofM 3D Lab prior to Boeing (5 years), Formula SAE Race Car Team
- Free Time:日本語, martial arts, photography, RC planes

Aerospace Requirements for Additive Manufacturing

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Stringent requirements in insure safety push understanding of materials

United State's Federal Aviation Regulations, Title 14, Section 25, Subpart D, Subsection 25.605;

"The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must (a) Be established on the basis of experience or tests; (b) Conform to approved specifications (such as industry or military specifications, or Technical Standard Orders) that ensure their having the strength and other properties assumed in the design data; and (c) Take into account the effects of environmental conditions, such as temperature and humidity, expected in service."

Reference that shows commercial aircraft weight sensitivity[1]

"Removing just one pound of weight from each aircraft in American's fleet would save more than 11,000 gallons of fuel annually"

AA flies 619 aircraft therefore 1 pound weight reduction on just one aircraft yields

- **114 pounds of fuel burn reduction annually, 2850 pounds over an aircraft's service life**
- **$55 per year fuel cost reduction, $1375 of increased revenue for a plane's service life**

[1] American Airlines "Fuel Smart" program literature: http://www.aa.com/i18n/amrcorp/newsroom/fuel-smart.jsp

Material behavior must be fully understood, to high levels of confidence, for even the simplest component:

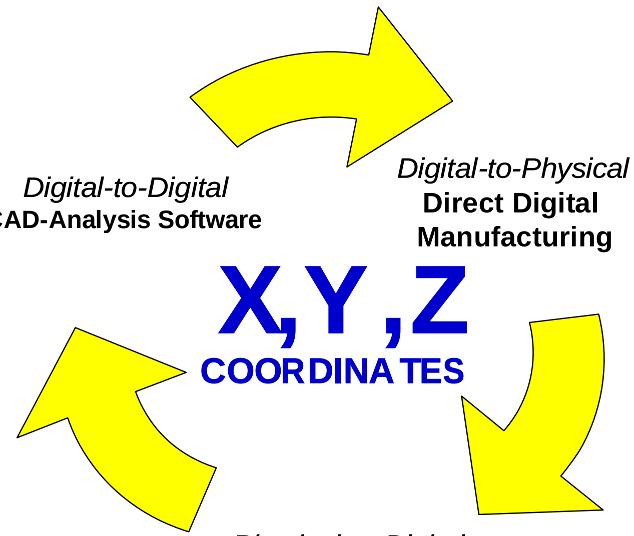
- **strengths under the full range of possible temperature and environmental conditions (-65F to >300F, humidity)**
- **mechanical fatigue, creep**
- **use temperature under load, survival temp ranges, thermal fatigue**
- **several tests of flammability**
- **smoke release and toxicity**
- **electric and thermal conductivity**
- **multiple chemical sensitivities**
- **radiation sensitivity, in a wide range of the spectrum**
- **appearance under a wide range of lighting conditions and through service life**
- **processing controls and inputs**
- **Cost, sustainability of material supply, and recyclability after service life**

Instrumented, high temp mechanical test cell

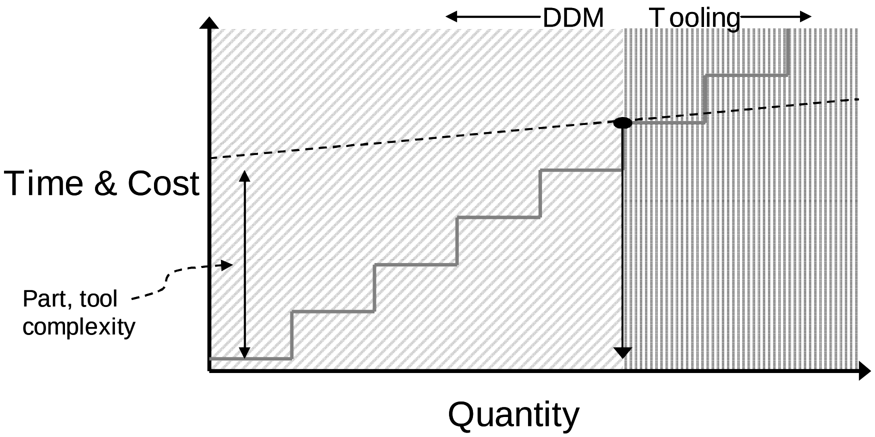
Examples of flammability test coupons

Why Aerospace is Interested in Additive Manufacturing

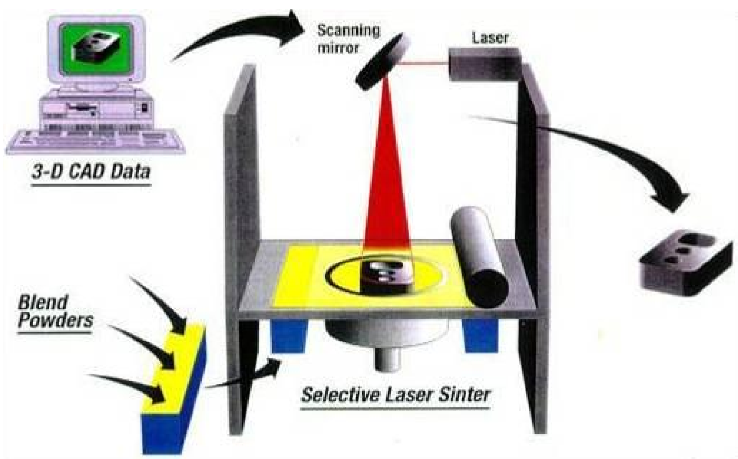
Digital-Physical Loop



Flexible Manufacturing



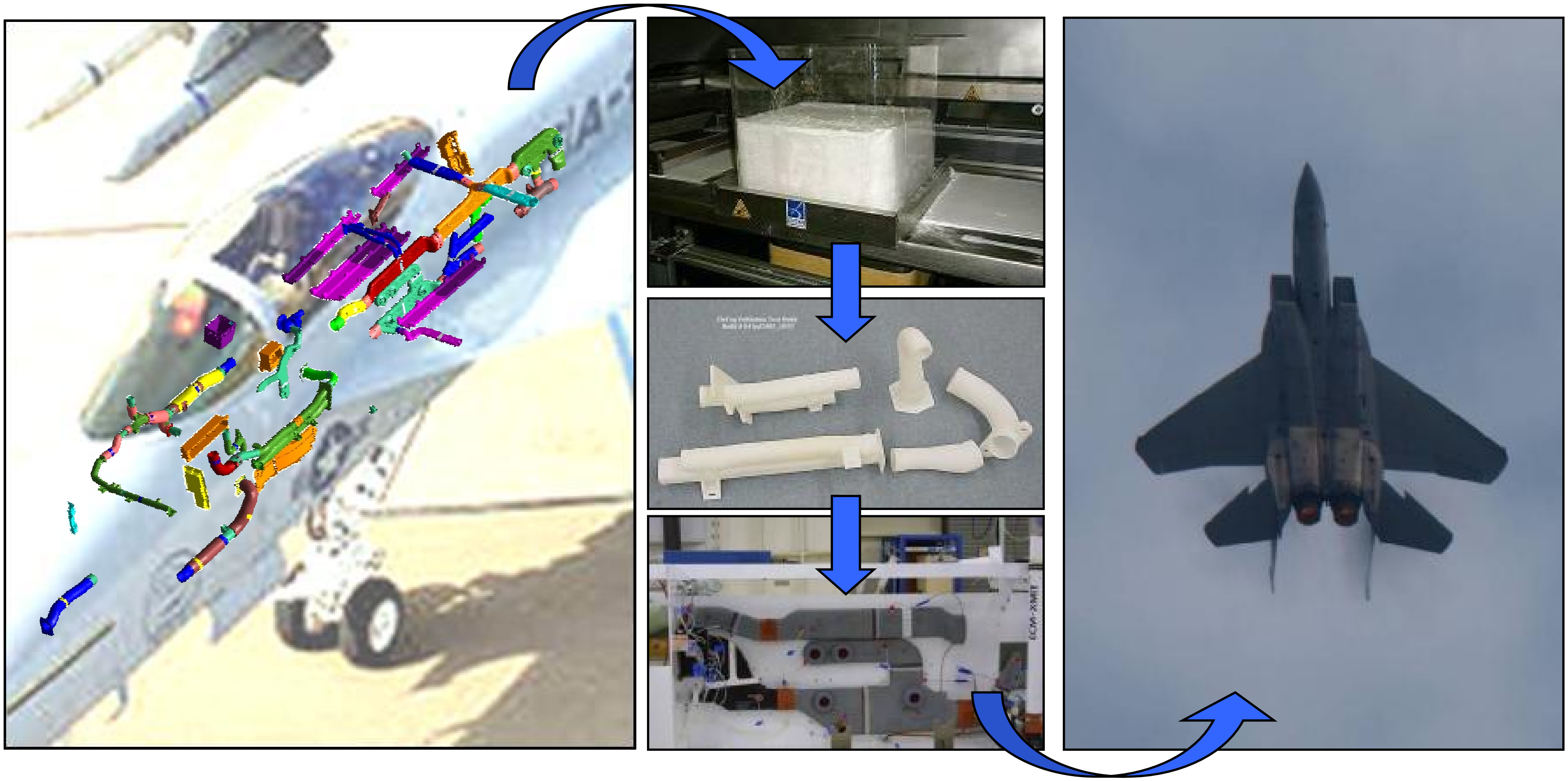
Viable Processes, Complex Geometry



Selective Laser Sintering (SLS)

Use of Additive Manufacturing in Aerospace

The Boeing company has been utilizing SLS for flight hardware in regular production since 2002, for both military[2] and commercial[3] programs



[2] Hauge R., Wooten J., Rapid Manufacturing: an industrial revolution for the digital age, Chapter 15, Page 233, John Wiley & Sons Ltd., UK, 2006

Use of Additive Manufacturing in Aerospace

… the environment these SLS components function in is challenging:

Video: 60 seconds Aboard The Ike (Boeing Media, for Public Presentation)

Use of Additive Manufacturing in Aerospace

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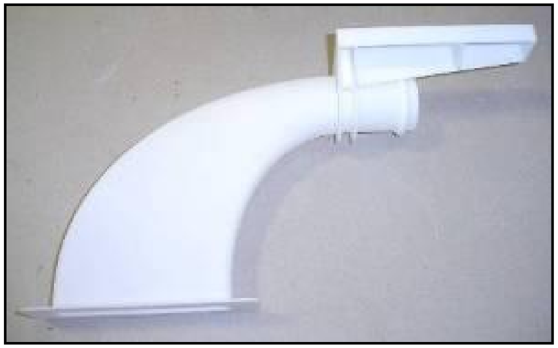
- **Organic Growth of SLS within Boeing Commercial[3], spec based growth**
- **787 was first program to utilize in BCA; weight and assembly benefits**

[3] Lyons, B., Deck, E, Bartel, A, Commercial Aircraft Applications for Laser Sintered Polyamides, SAE Technical Paper 09ATC-0387,

Examples of Aerospace-Driven Research in AM

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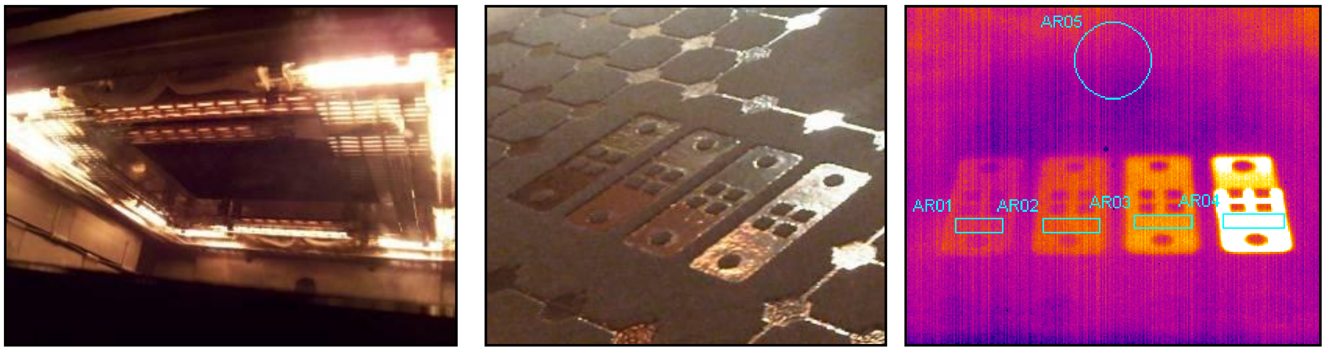
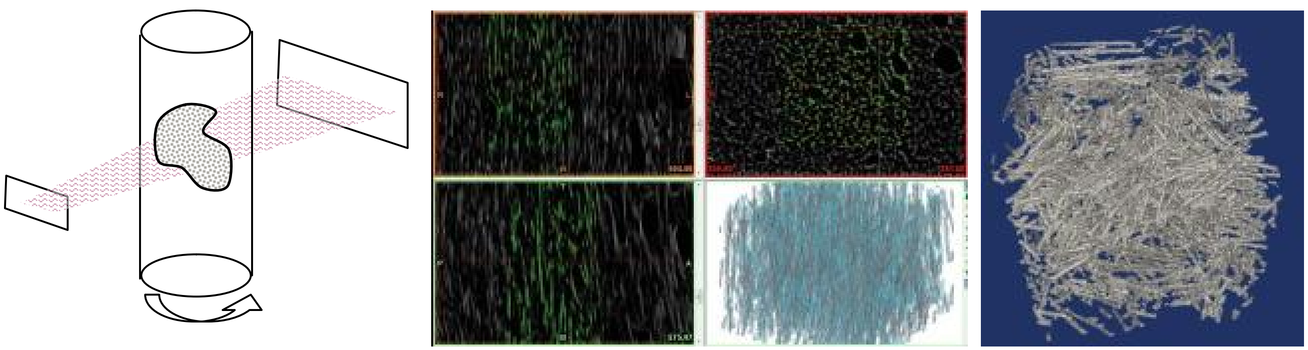
Aerospace is driving needs for AM improvement in process control, materials and inspection

- **Process control: Multi-Zone heating, thermography**
- **Material Development: Flame Retardant Polyamide FR-106**
- **Inspeciton: Micro CT analysis[4]**



MZ heating (left), SLS part bed (center), same parts seen via infrared thermography during laser scanning (right)



Micro-CT inspection of AM materials; schematic (left), slide data (center), 3D reconstructed AM fibers (right)

[4] B. Lyons, Micro-Computed Tomography Inspection in Additive Manufacturing, 3DSUG Conference, April 6th 2011, Miami, Florida, ROI# BOE033011-226

AM material development; Unique challenges

- Thermoplastics typically processed with thermal and pressure inputs
- SLS currently only offers control of thermal input, within a bounded space
- 4D energy gradients and thermal history are severe
- Industry has become used to behavior of Polyamides in this process
- Large polymer company research just now beginning to allocate resources to AM

Material	Melt Temp °C	Glass trans. temp °C	Specific Heat J/g K	Heat of Fusion (100% crys.) J/g	Thermal conductivity W/m K	Thermal Expansion (ppm / Tg °C)	SG g/cc (crystalline)
PA	180-186	42-55	1.26	226	0.19	85	1.03
PAEK	300-375	145-165	2.20	130	0.26	60	1.30

Comparison of PA and PAEK material properties indicate different in processing requirements and component performance

Range of test parts from SLS process, shown in a variety of materials

Current Area of Development

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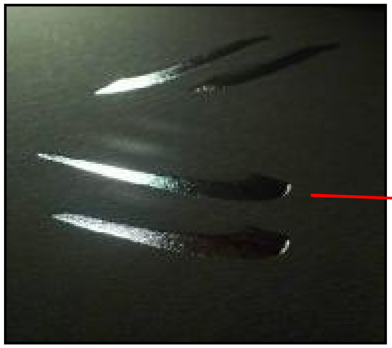
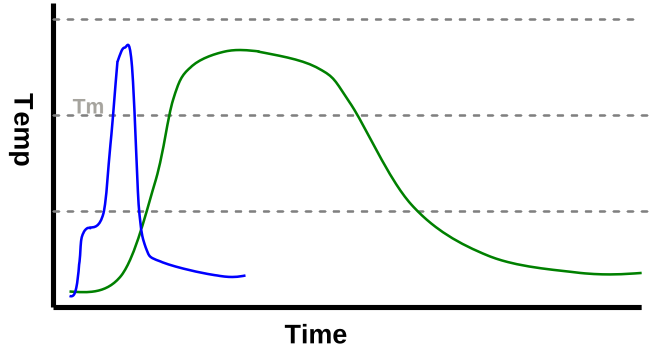
- **Consider Thermal Processing**
- **Layer-wise manufacturing induces severe and variable 4D energy gradients**
- **The processes are controllable, but new methods and approaches have been required**



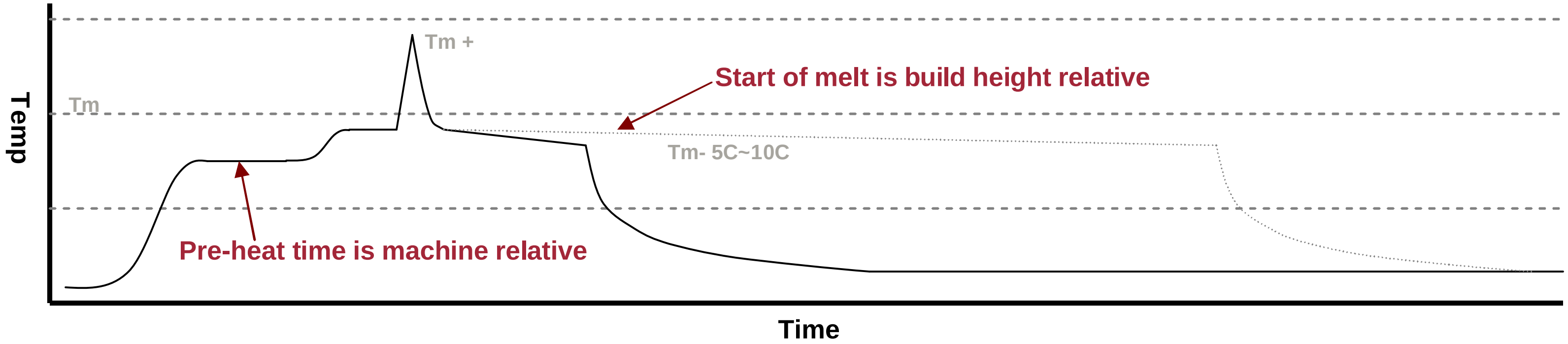


Qualitative differences in thermal processing profile

•Injection molding (left in blue)

•Autoclave (left in green)

•SLS (below in black)



Moving Forward

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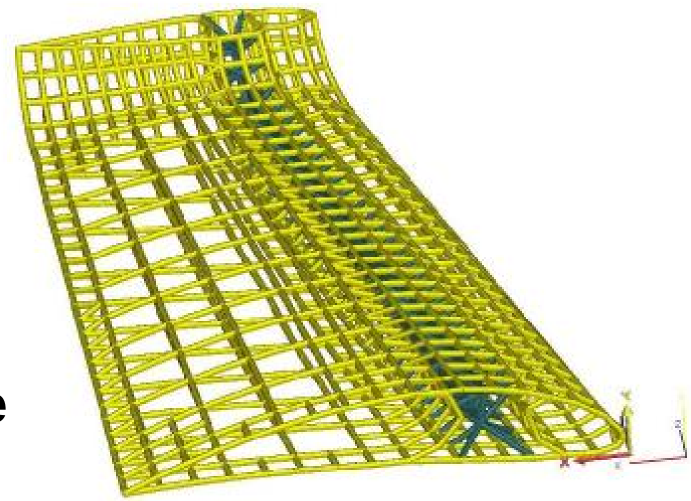
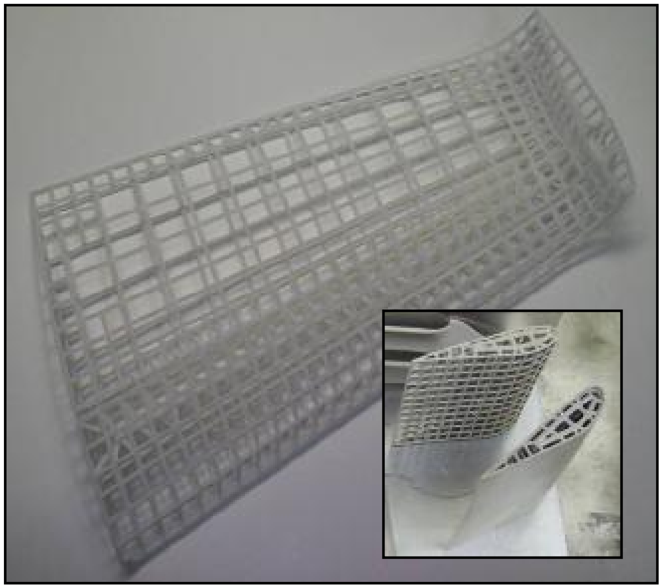
- New materials are becoming available for AM processing
- Benefits of AM will be extended beyond current applications with new materials
- Patent system and excessive litigation, have slowed development in AM
- These technologies are viable in high labor cost nations, even in the face of competition
- AM equipment needs to become more robust, look to CNC and injection molding history
- Analysis methods need to grow with new geometric capabilities





Thank you for your time, to our host Google, and to NAE for the opportunity to participate in FOE.

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