ADDITIVE MANUFACTURING OF TITANIUM ALLOYS

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Based on a paper by B. Dutta and F.H. (Sam) Froes
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OUTLINE

- Cost of Titanium Components
- Cost Breakdown of Titanium Components
- Overview of Additive Manufacturing (AM)
- Part Building Technology
- Comparisons of Technologies
- Titanium Applications
- Remanufacturing
- Microstructure and Mechanical Properties
- Economics of (AM)
- Developing Techniques
- Conclusions

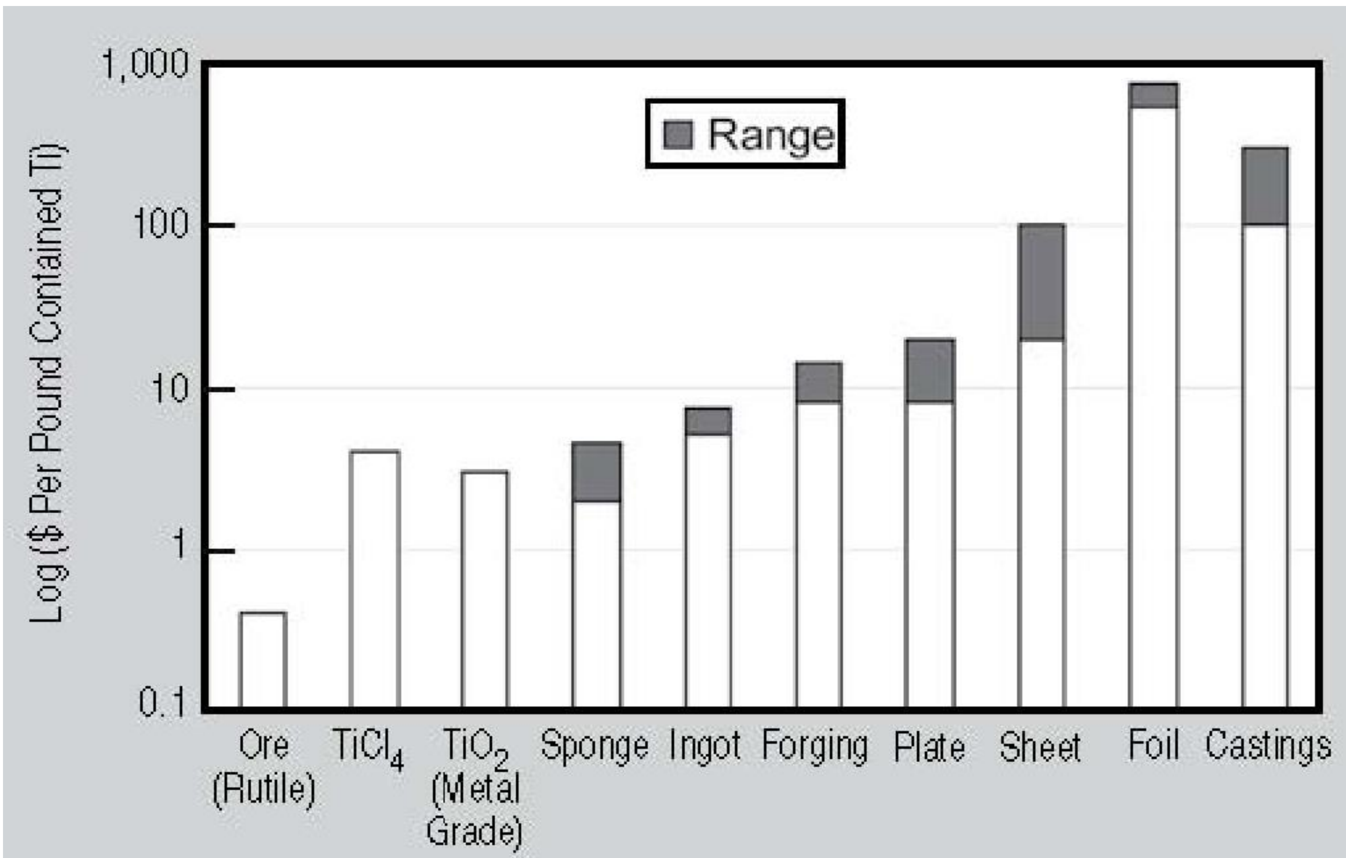
Cost of Titanium/ Comparisons

Item	Material ($/pound)		
	Steel	Aluminum	Titanuim
	0.02	0.01	0.22 (rutile)
Metal	0.10	1.10	5.44
Ingot	0.15	1.15	9.07
Sheet	0.30-0.60	1.00-5.00	15.00-50.00

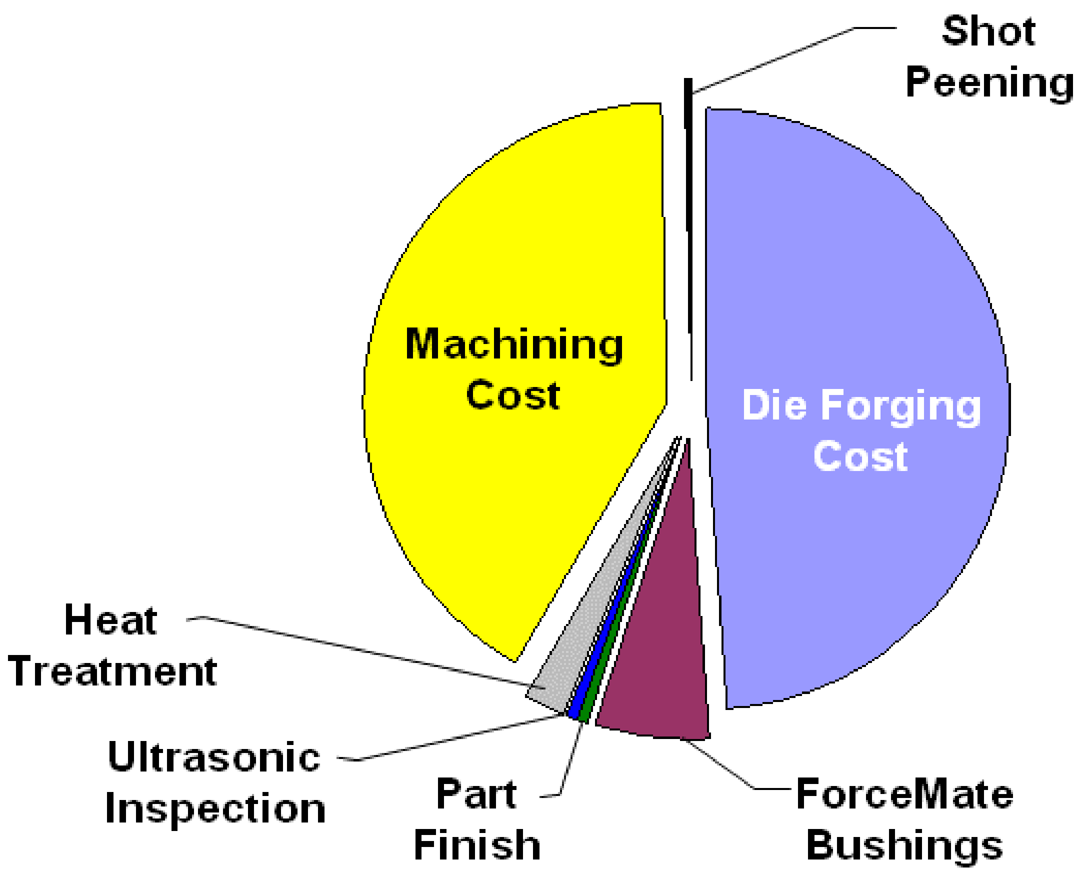
Metal Consumption

Structural Metals	Consumption/year (10^3 metric tons)
Ti	50
Steel	700,000
Stainless steel	13,000
Al	25,000

Cost of titanium at various stages of a component fabrication.

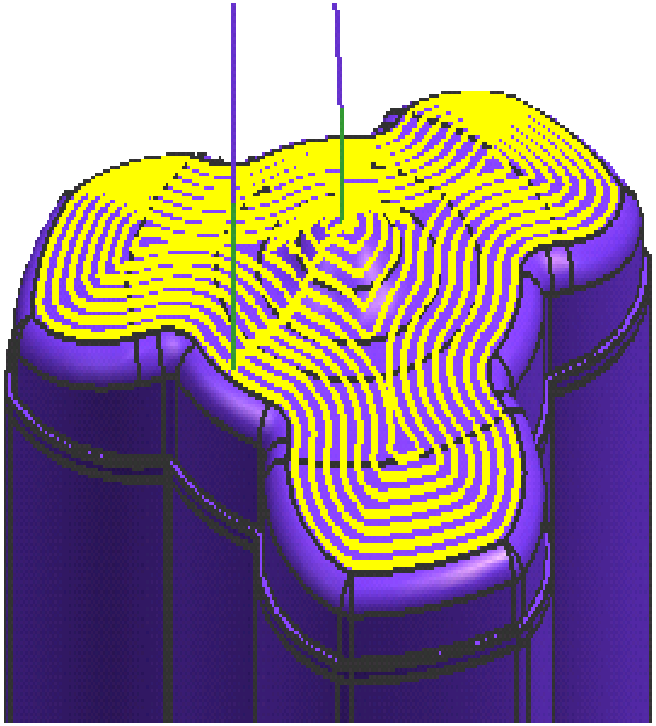


Boeing 787 side-of –body chord, manufacturing cost breakdown (courtesy Boeing).



Left: CAD model of the part and process head.

Right: Simulated toolpath for 5-axis deposition using DMDCAM software. Courtesy: DM3D Technology.



Part Building Technology

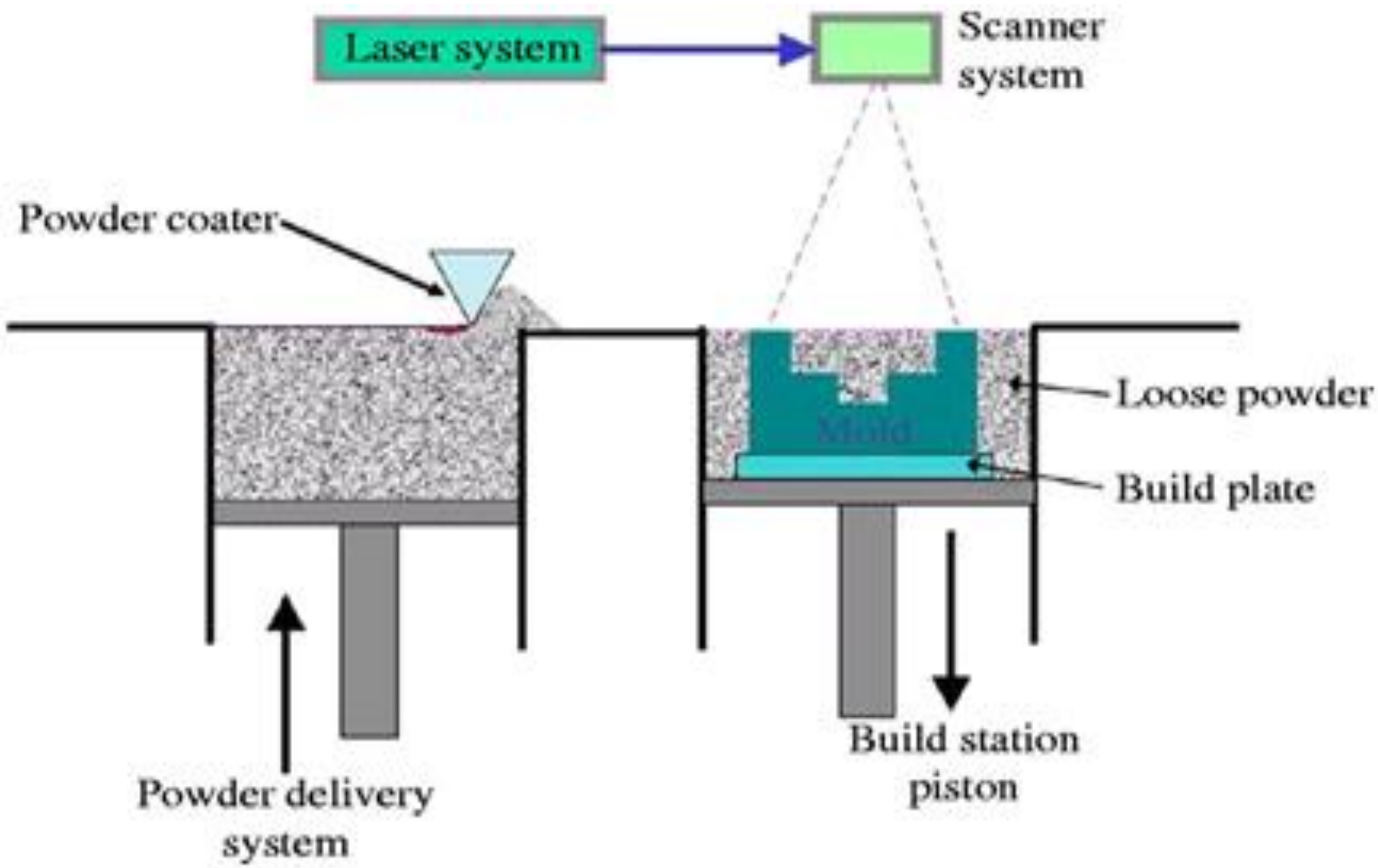
- Direct Energy Deposition (DED)
  - Large Build Envelopes
  - Add (Different) Material

- Powder Bed Fusion (PBF)
  - Complex Features
  - Hollow Cooling Passages

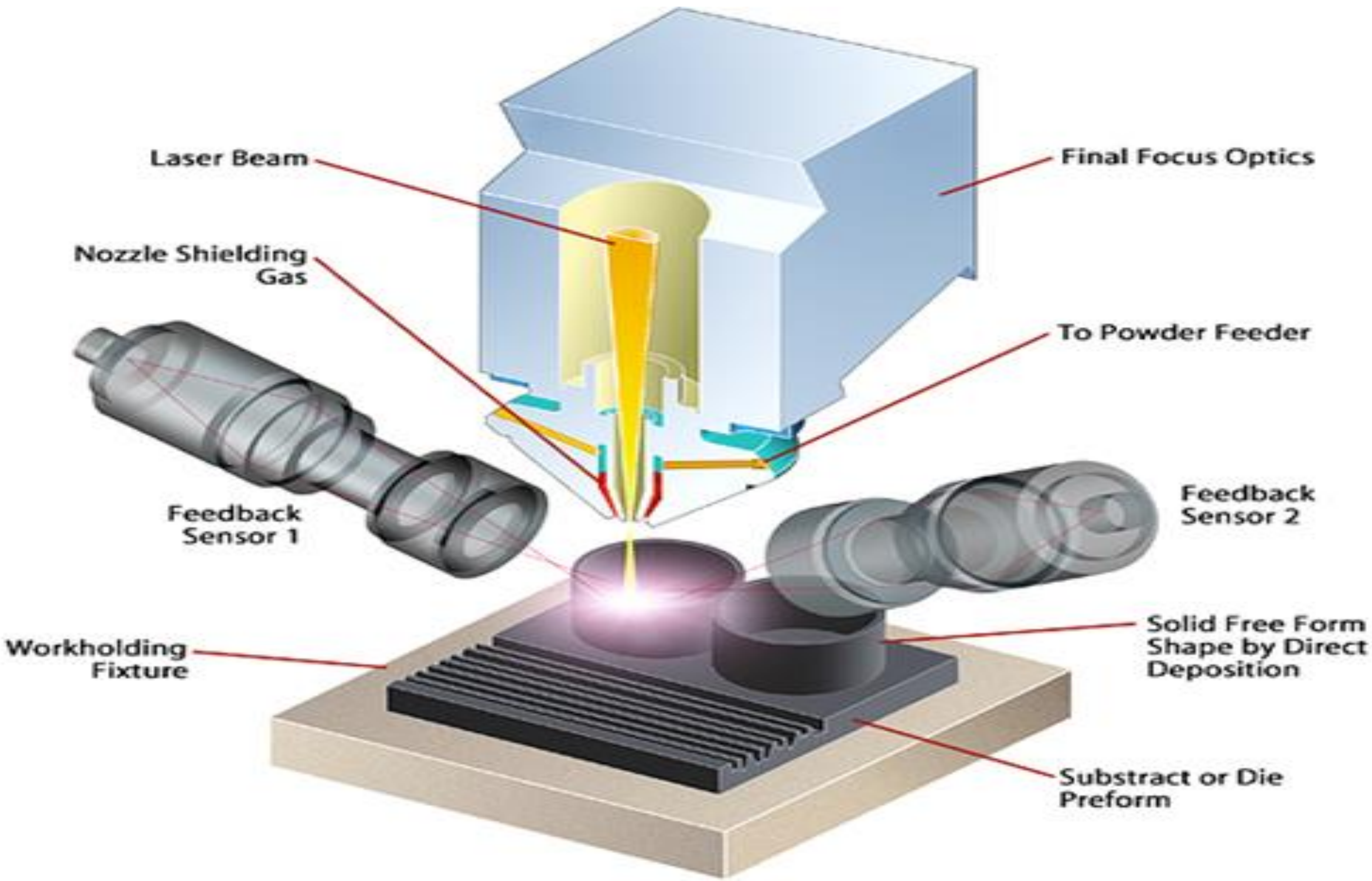
Heat Source Atmospheres

- Laser
  - Inert
- Electron Beam
  - Vacuum

AM Category	Technology	Company	Description
Directed Energy Deposition (DED)	Direct Metal Deposition (DMD)	DM3D Technology LLC (formerly POM Group)	Laser and metal powder used for melting and depositing with a patented closed loop process.
	Laser Engineered Net Shaping (LENS)	Optomec Inc.	Laser and metal powder used for melting and depositing.
	Direct Manufacturing (DM)	Sciaky Inc.	Electron beam and metal wire used for melting and depositing.
Powder Bed Fusion (PBF)	Selective Laser Sintering (SLS)	3D Systems Corp. (acquired Phoenix Systems)	Laser and metal powder used for sintering and bonding.
	Direct Metal Laser Sintering (DMLS)	EOS GmbH	Laser and metal powder used for sintering, melting, and bonding.
	Laser Melting (LM)	Renishaw Inc.	Laser and metal powder used for melting and bonding.
	Laser Melting (SLM)	SLM Solutions GmbH	Laser and metal powder used for melting and bonding.
	LaserCUSING	Concept Laser GmbH	Laser and metal powder used for melting and bonding.
	Electron Beam Melting (EBM)	Arcam AB	Electron beam and metal powder used for melting and bonding.



Schematic showing powder bed fusion technology.



Schematic showing Direct Metal Deposition (DMD) technology

Comparison of Various Technologies

Item	Laser based PBF (Ex: DMLS)	Electron beam based PBF (Ex: EBM)	Laser based Directed Energy Deposition (Ex: DMD)
Build envelop	Limited	Limited	Large & flexible
Beam size	Small, 0.1-0.5 mm	Small, 0.2-1 mm	Large, can vary from 2-4 mm
Layer thickness	Small, 50-100 μm	Small, 100 μm	Large, 500-1000 μm
Build rate	Low, cc/h	Low, 55-80 cc/h	High, 16-320 cc/h
Surface finish	Very good, Ra 9/12 μm, Rz 35/40 μm	Good, Ra 25/35 μm	Coarse, Ra 20-50 μm, Rz 150-300 μm, Depends on beam size
Residual stress	High	Minimal	High

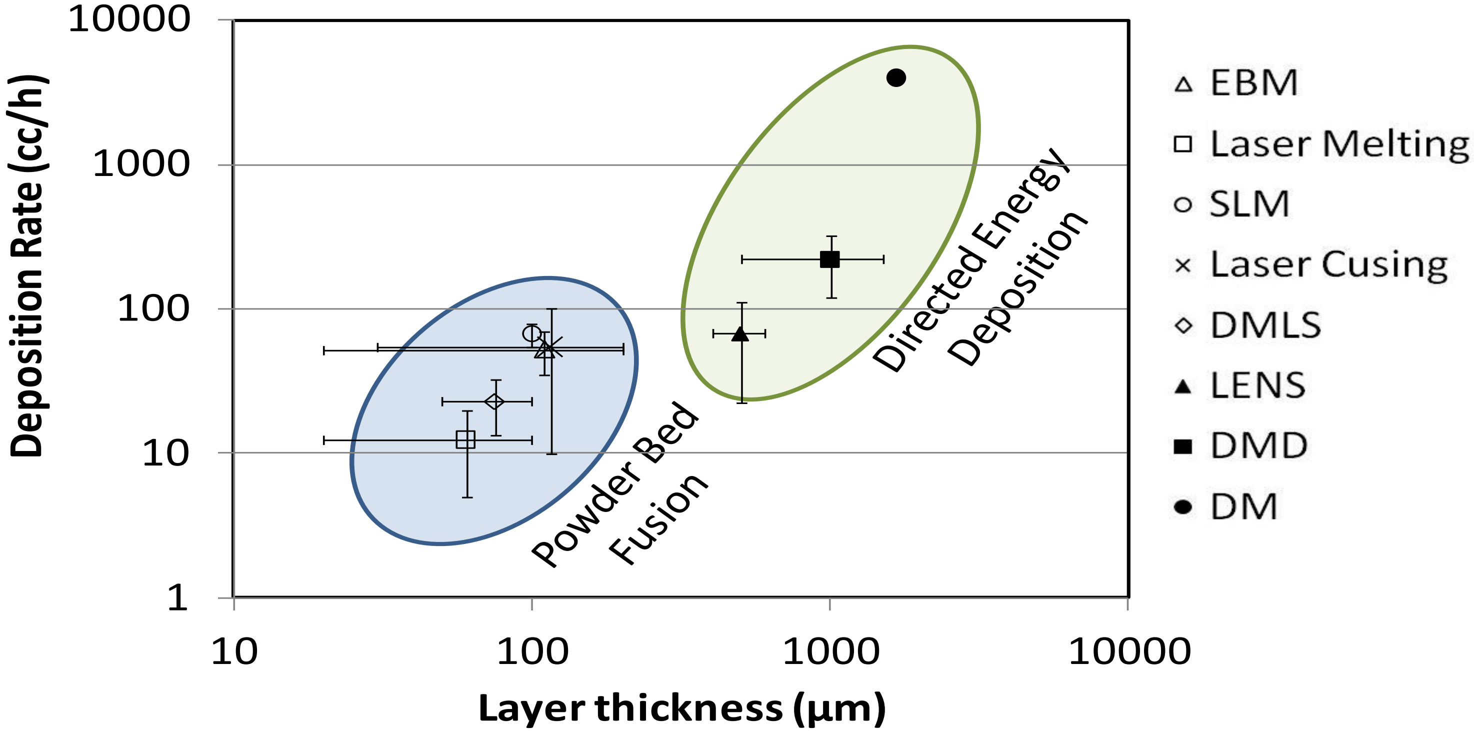
Comparison of Various Technologies Cont'd

Heat treatment	Stress relieve required, HIP'ing preferred	Stress relieve not required, HIP'ing may/ may not be performed	Stress relieve required, HIP'ing preferred
Chemistry	ELI grade possible, negligible loss of elements	ELI grade possible, loss of Al need to be compensated in powder chemistry	ELI grade possible, negligible loss of elements
Build capability	Complex geometry possible with very high resolution. Capable of building hollow channels.	Complex geometry possible with good resolution. Capable of building hollow channels.	Relatively simpler geometry with less resolution. Limited capability for hollow channels etc.
Repair/Remanufac ture	Possible only in limited applications (requires horizontal plane to begin remanufacturing)	Not possible	Possible (capable of adding metal on 3D surfaces under 5+1-axis configuration making repair solutions attractive)
Feature/metal addition on existing parts	Not possible	Not possible	Possible. Depending on dimensions ID cladding is also possible
Multi-material build or hard coating	Not possible	Not possible	Possible

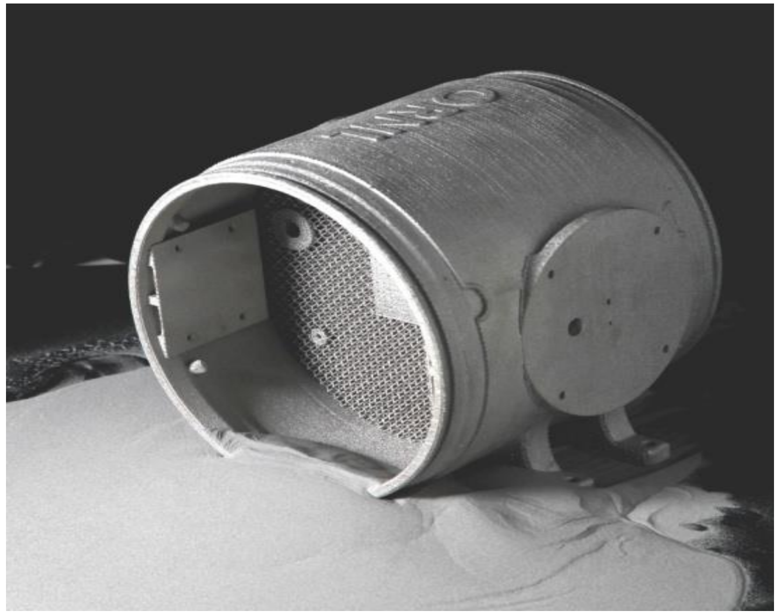
Comparison of Techniques

- PBF
  - Better Surface Finish
  - Slower Deposition
- DED
  - Rougher Surface
  - Higher Build Rate

Comparison of PBF and DED Technologies in terms of layer thickness and deposition rate



Hydraulic manifold built using EBM technology (Courtesy ONRL)



- PBF Allows
  - Complex Part
  - Good Surface Finish
  - Reduced Machining

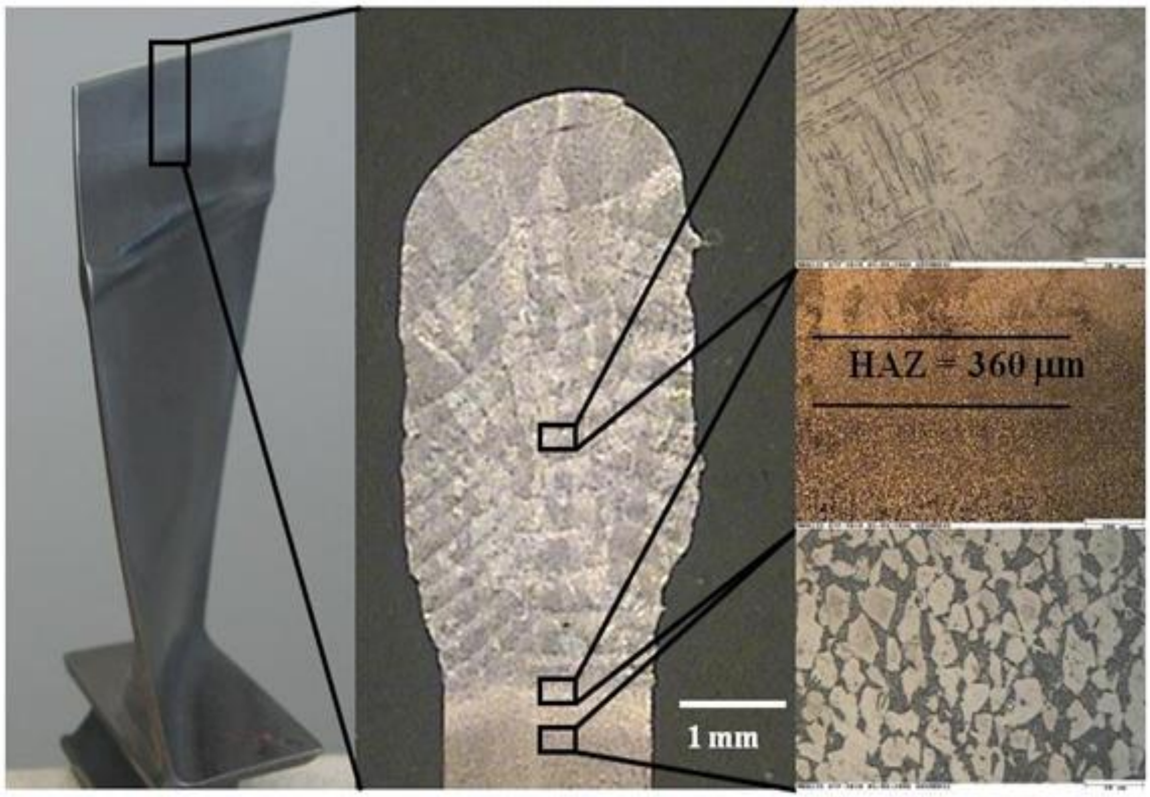
Medical implant application using DMLS technology (courtesy: Jim Sears)

(Left- Biomedical implant/ Right- Tibial knee stem

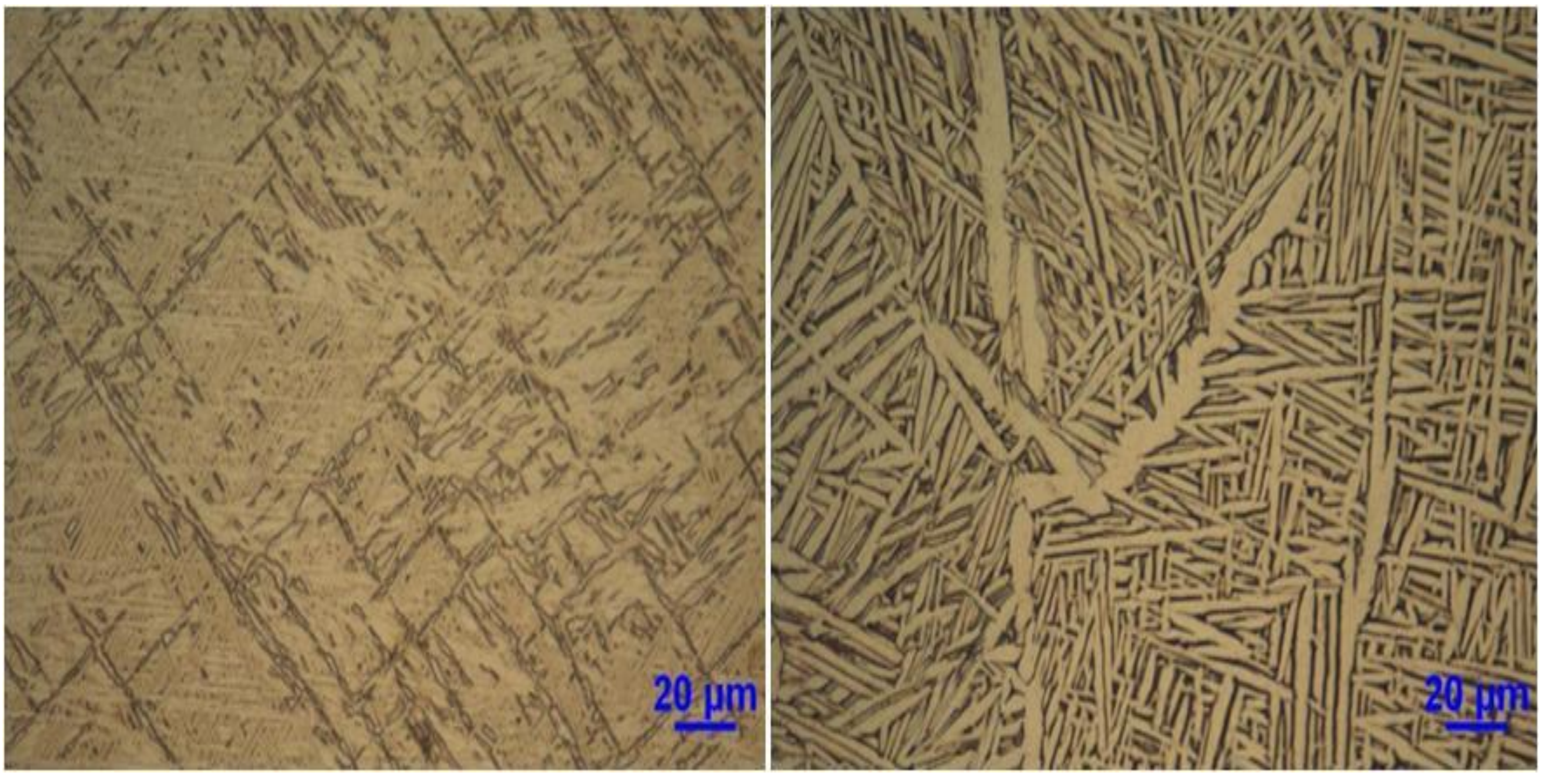
Fan case produced by adding features with AM (laser aided directed energy deposition) to a forged perform. (courtesy: Jim Sears)

- DED
    - Part Repair

DMD Repair of turbine components; left: repaired vane, middle: macro cross-section, and right: microstructures (top to bottom shows the clad, interface and base material). (courtesy: DM3D Technology).



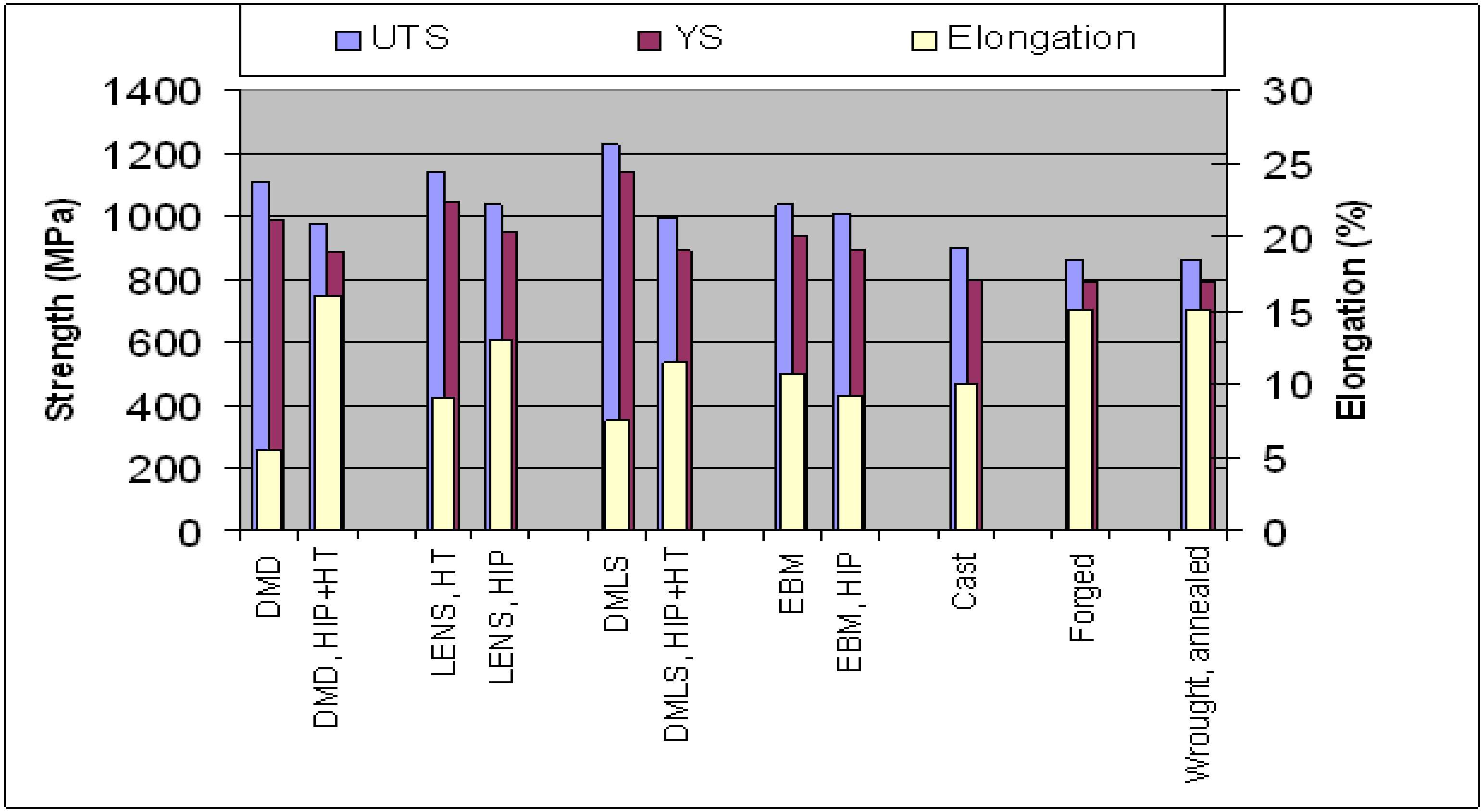
Microstructure of DMD built Ti6Al4V before and after HIP'ing (courtesy: DM3D Technology).



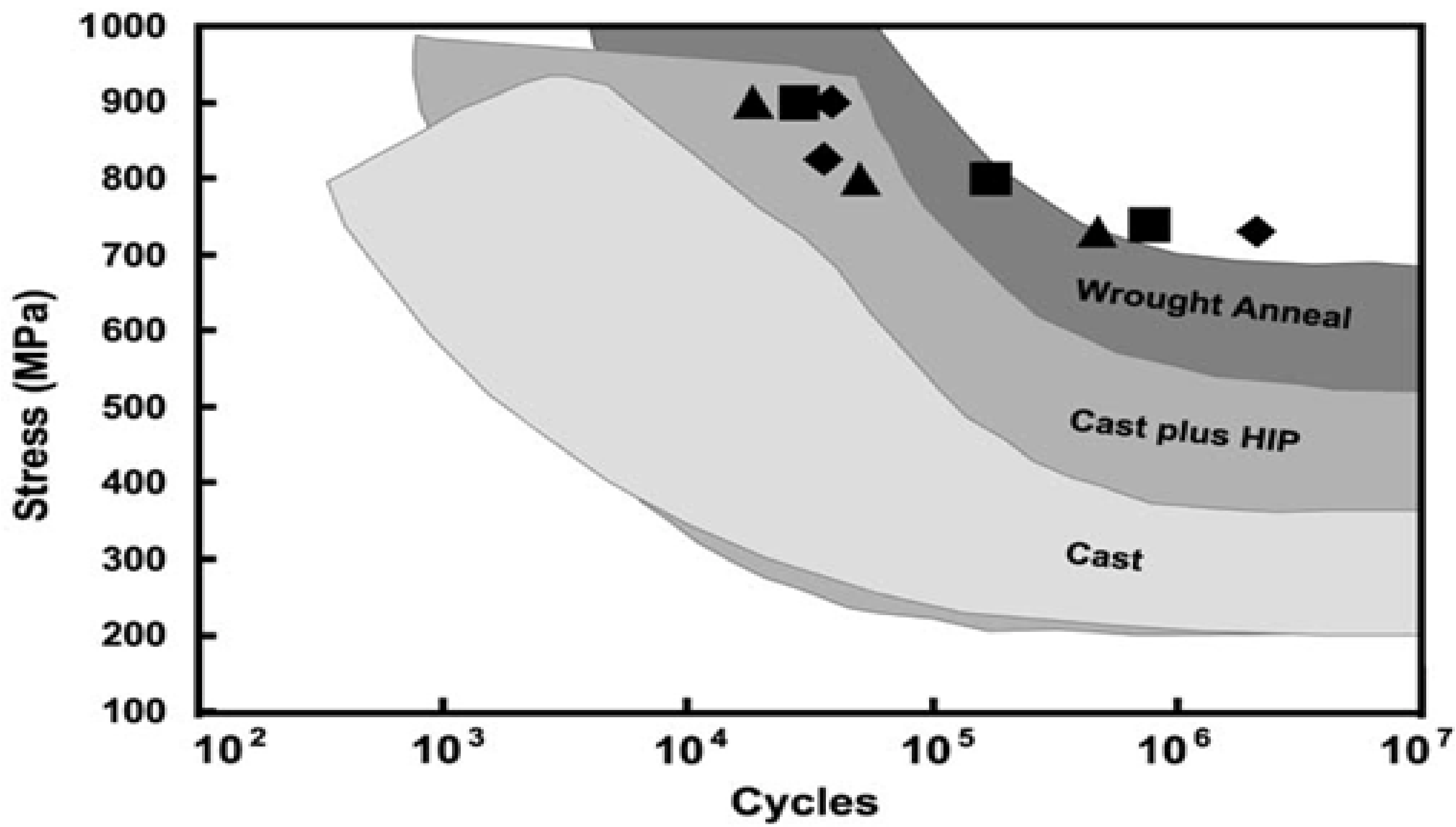
Mechanical Properties

- Similar or Better Than Cast and Wrought
    - Tensile
    - S-N Fatigue

Tensile strength, yield strength and elongation of Ti-6Al-4V alloy built using various AM processes. DMD-Direct Metal Deposition, LENS-Laser Engineered Net Shaping, DMLS-Direct Metal Laser sintering, EB-Electron Beam Melting, HIP-Hot Isostatic pressing, HT-Heat treatment.



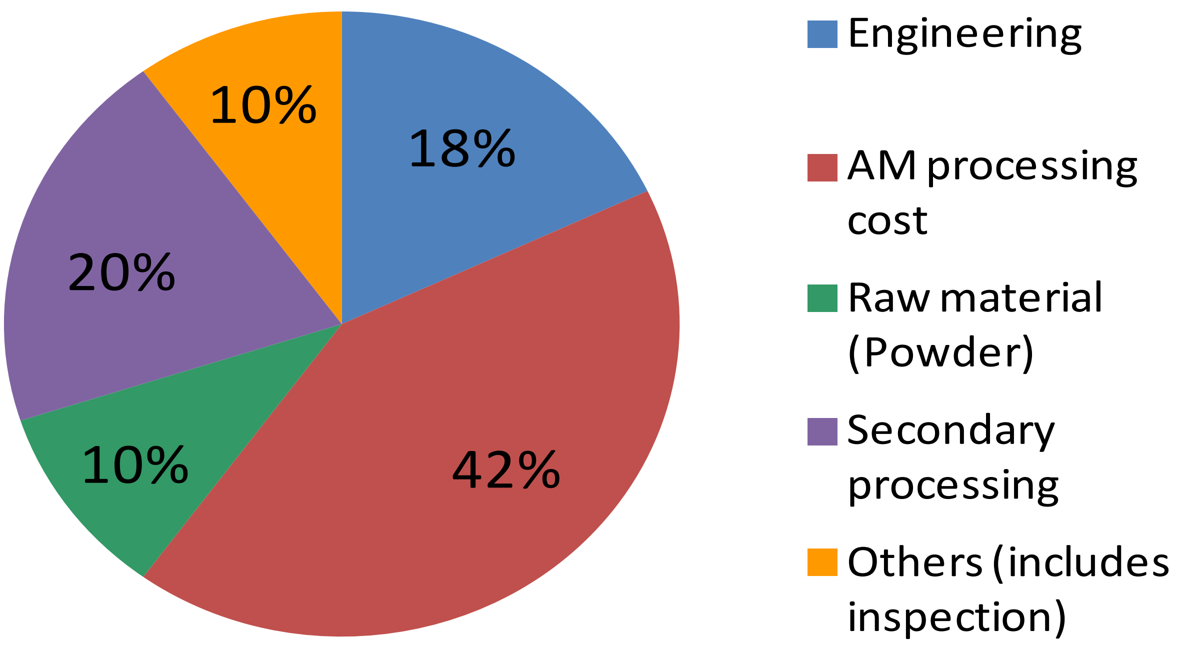
Comparison of Room Temperature fatigue properties of AM fabricated Ti-6Al-4V and conventionally fabricated Ti-6Al-4V. ■,♦ and ▲ represent properties in the 3 orthogonal directions, x, y and z respectively. (courtesy: EADS/Jim Sears).



Economics

- AM is good for small throughput
- AM is not as attractive for high volume manufacturing

Typical cost breakdown of various steps involved in AM of Titanium



Seat buckle produced using DMLS technology.

- PBF Used
  - Lower weight by 55%
  - Lower cost manufacturing and cost of ownership (Fuel)

Titanium Powder Metallurgy

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BALD bracket for Joint Strike Fighter (JSF) built using EBM technology (courtesy: ORNL, TN)

- Reduce buy-To-Fly Ratio (1:1, compared to 33:1)
- Savings of 50%

Advances

- Addition of Different Material Surfaces (E.G. Rene 88 on Ti-6Al-4V)

Conclusions

- Additive Manufacturing is Here
    - Monolithic complex parts and Bi-material components
    - Creative design
    - Adding features
    - Damage repair
    - Cost saving possible

- Mechanical Properties as Good as Ingot Metallurgy Parts