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NASA

Assessing the Potential of Direct Metal Laser Sintering (DMLS) To Reduce The Cost Of Vehicle Components

2nd Global Lightweight Materials Manufacturing Summit

April 15, 2015

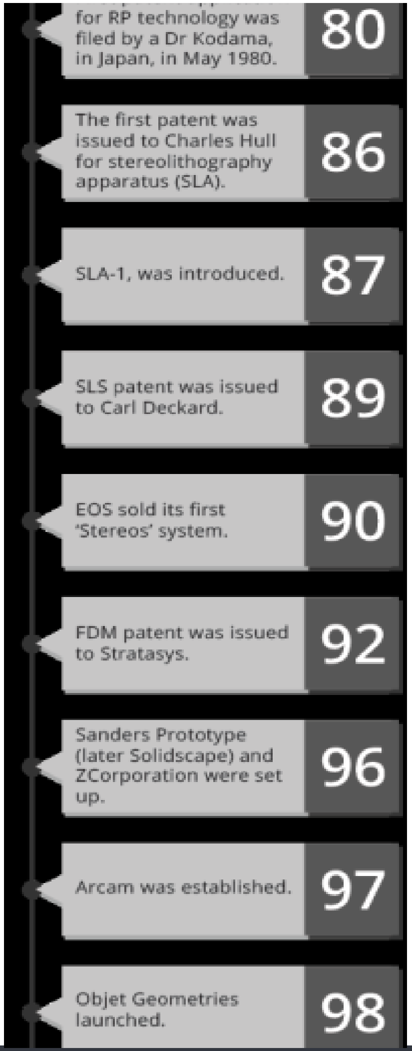
Agenda

1. What is DMLS?
2. Technology Overview: Assessing the Maturity Level Of DMLS
3. DMLS vs. Traditional Manufacturing Methods
4. Cost Assessment
5. Market Opportunities
6. Key Areas Requiring Technology Advances to Meet Automotive Needs
7. Acknowledgements

1. What is DMLS?

1. 3D Printing History

- First patent application: 1980
- First patent: 1986
- EOS sold first “Stereos” system: 1990
- 1st <$10,000 system (3D Systems): 2007
- 1st commercially available 3D printer: 2009
- Alternative 3D printing processes introduced at entry level: 2012
- DMLS parts go into production turbine engines: 2015



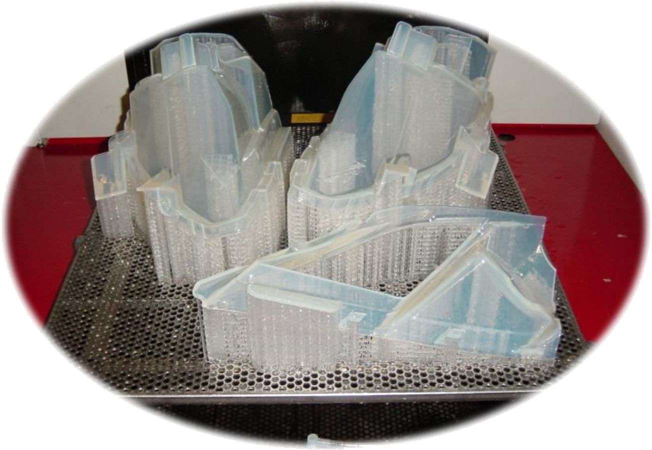
for RP technology was filed by a Dr Kodama, in Japan, in May 1980.	80
The first patent was issued to Charles Hull for stereolithography apparatus (SLA).	86
SLA-1, was introduced.	87
SLS patent was issued to Carl Deckard.	89
EOS sold its first 'Stereos' system.	90
FDM patent was issued to Stratasys.	92
Sanders Prototype (later Solidscape) and ZCorporation were set up.	96
Arcam was established.	97
Objet Geometries launched.	98

MCP Technologies introduced the SLM technology.	00
EnvisionTec was founded.	02
Dr Bowyer conceived the RepRap concept of an open source, self-replicating 3D printer.	04
ExOne was established as a spin-off from the Extrude Hone Corporation.	05
The first system under $10,000 from 3D Systems.	07
Desktop Factory was acquired by 3D Systems.	08
The first commercially available 3D printer – in kit form, based on the RepRap concept.	09
Alternative 3D printing processes were introduced at the entry level of the market.	12
Stratasys acquires Makerbot.	13

http://3dprintingindustry.com/3d-printing-basics-free-beginners-guide/history/

1.0 Additive Manufacturing Technologies

- Direct Metal Laser Sintering* (DMLS)
- Selective Laser Melting (SLM)
- Stereo Lithography (SLA)
- Selective Laser Sintering (SLS)



*Sintering is a process which heats a material to just below its boiling point

Source: Linear Mold & Engineering, Inc., EOS.

1.1 DMLS vs. SLS

- DMLS metal powder (20 micron diameter) is free of binder or fluxing agents used by SLS
- DMLS part retains properties of the original material
- DMLS produces a 95% dense steel part compared to roughly 70% density with Selective Laser Sintering (SLS)
- DMLS has higher detail resolution than SLS due to:
  - Thinner layers
  - Smaller powder diameter
  - This capability allows for more intricate part shapes.

ENGINEERING

Source: Linear Mold & Engineering, Inc., EOS.

http://www.custompartnet.com/wu/direct-metal-laser-sintering

1.2 3D Metal Printing – Typical Hardware & Materials

- **EOS M270s**
  - Materials Available:
    - 15-5/17-4/316 Stainless Steels
    - Cobalt Chrome (CoCr)
    - Inconel 625/718
    - Maraging Steel (MS1)
- **EOS M280**
  - Materials Available:
    - 15-5/17-4/316 Stainless Steels
    - Aluminum (AlSi10Mg)
    - Cobalt Chrome
    - Inconel 625/718
    - Maraging Steel (MS1)
    - Titanium (Ti64)
- **SLM 280**
  - Materials Currently Available:
    - Aluminum (AlSi10Mg)
    - Titanium (Ti 64)

Source: Linear Mold & Engineering, Inc.

1.3 3D Metal Printing Process

Any shape · Anytime · Anywhere

- Metal powders are fused together by a laser, creating 99.9% full melt
- Part built layer-by-layer
- Created quickly with no tooling, straight from CAD models
- Created with high accuracy, detailed resolution, and excellent mechanical properties

Source: Linear Mold & Engineering, Inc.

1.4 Industries and Markets

- Aerospace
- Automotive
- Aircraft Engine Development
- Housewares
- Injection Mold Tool Inserts
- Medical
- Military
- Sporting Goods

Source: Linear Mold & Engineering, Inc.

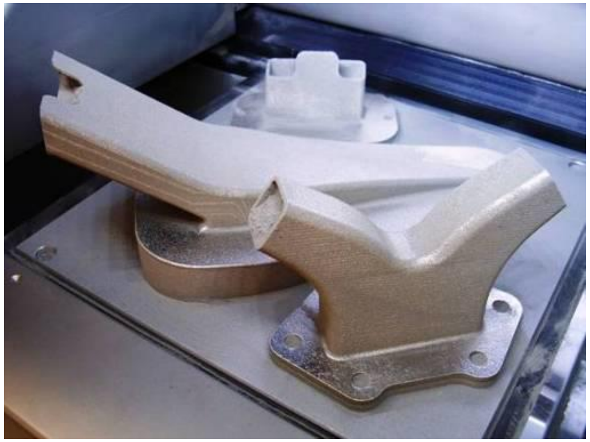
Source: Linear Mold & Engineering, Inc.

1.5 DMLS Benefits

- Rapid turn around time
- Accurate (+/- .002”)
- Excellent surface quality
- Wide array of materials
- Net-shape metal parts created directly in one step. No binder removal, and generally no post-machining
- Outstanding geometric flexibility: free-forms, deep slots and curved blades/channels.
- Compatible with other processes. Parts can be milled, drilled, welded, coated, etc.

Source: Linear Mold & Engineering, Inc.

1.6 DMLS Material Options & Storage Requirements



- Aluminum
  - light-weight, good thermal and dynamic properties
- Cobalt Chrome
  - excellent corrosion and temperature resistance
- Inconel 625 & 718
  - high tensile, fatigue and rupture strength
- Maraging Steel
  - superior toughness and strength
- Stainless Steels
  - excellent ductility and high corrosion resistance
- Titanium
  - low specific weight and biocompatibility
- Pre-conditioning:
  - powders stored in inert gas (Nitrogen or Argon)
  - powders stored in low humidity (typically <15% relative humidity)

Source: Linear Mold & Engineering, Inc.

1.7 DMLS – Current Technology Overview

- Lasers: single, dual, twin
  - Single: one laser per machine
  - Dual (sequential): low power for thin outer shell, high power for filling
  - Twin (simultaneous): make multiple parts simultaneously
    - Challenge: beam overlap co-ordination for creating a single large part

- Laser power: 400 watts to 1,000 watts;
  - EOS and SLM machines are both 220 volt AC, with 40 to 80 full load amperage

- Typical bed size: 8” x 8” x 8” EOS 270, 8” x 8” x 11” EOS 280, SLM 11” x 11” x 14”
  - EOS 400: 400 mm x 400 mm (15.8” x 15.8”)

Source: Linear Mold & Engineering, Inc., EOS.

1.8 DMLS – Typical Manufacturing Cost Considerations

- Machine cost/hr: typically $90/hr. to $140/hr.
- Additional related costs:
  - HIPping (hot isostatic pressing)
    - Eliminates porosity
    - Restores part to 100% theoretical density
    - Improves mechanical properties
  - Heat treating
  - 3D scanning
  - X-ray
  - CT scan
  - Other
- Note: substantial cost/part reductions are achieved by running large “batches” vs. individual part runs:
  - Heat treat process: $400;
    - cost for 1 part: $400/part;
    - cost for a batch of 40 parts: $10/part

Source: Linear Mold & Engineering, Inc., .

http://www.pressuretechnology.com/about-hip.php

1.9 DMLS – Material Costs

- Metal costs are substantially higher than non-powder form materials, primarily due to very precise sieve control (typically 20 micron to 40 micron particle size)

- Offsets for higher material cost/lb. include:
  - High level of parts consolidation
  - No tooling
  - No post process assembly time
  - No assembly fixtures required
  - No joining process required
  - Minimal post-processing finishing
  - Precise tolerance control minimizes finishing/rework

- Material cost is a low % of the piece price, typically 8% to 15%, vs. plastic molding where material costs are typically 50% of the piece price

Source: Linear Mold & Engineering, Inc., EOS.

1.10 DMLS – Part Build Speed

- Speed of build is a function of:
  - 1) layer thickness (typically 20 micron to 60 micron layer thickness)
  - 2) number of lasers (1 laser or 2 (twin) laser)
  - 3) vertical height of the build
  - 4) weld area of the individual layers

- Build Examples:

  - A 25 mm tall, 60 micron layer, small area part can be built in approximately 6 hours

  - A solid rectangular block that is 10” x 10” x 25mm tall would take over 100 hours

Source: Linear Mold & Engineering, Inc., .

1.11 Summary Assessment of DMLS Manufacturing

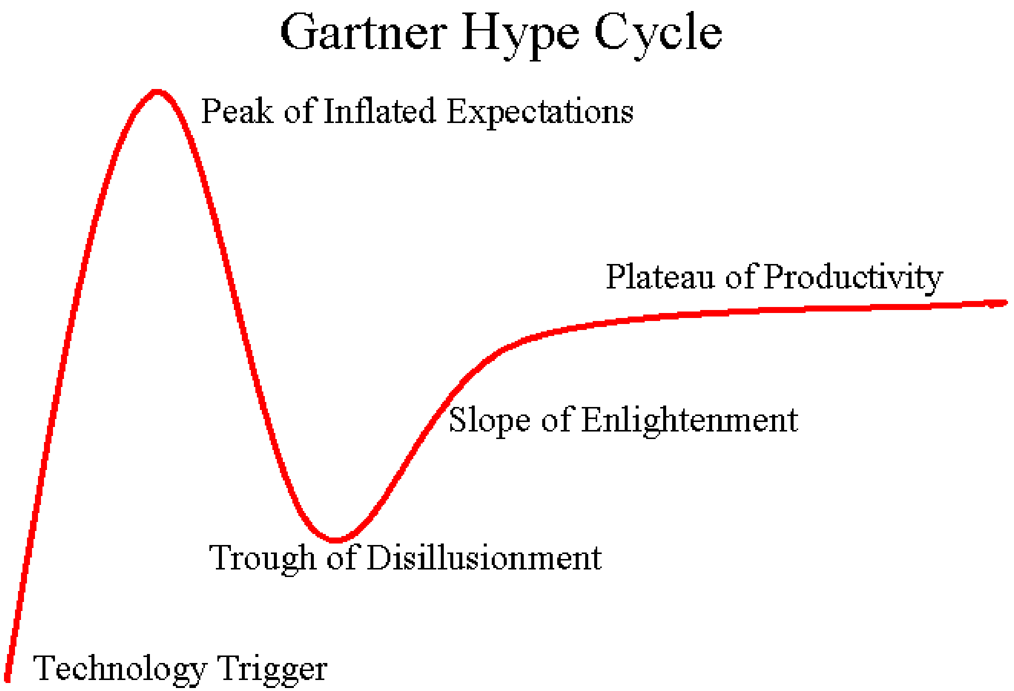
- Material cost/lb. is much higher than current casting/extrusion/molding/stamping material costs
- Offsetting factors:
    - Optimized design
        - No die lock constraints to compromise part design
        - Idealized part function
        - Reduced weight
        - High level of tolerance control
            - Minimizes or eliminates post process machining
    - No tooling costs
    - Fully functional parts built with short lead times
    - High level of parts integration
        - Component combining 18 parts into 1 is in production
    - No secondary fixturing
    - Eliminates the need for joining operations
        - No joining cost
        - No parent material degradation
        - No post-weld heat treatment

2. Technology Overview:

Assessing the Maturity Level Of DMLS

2. DMLS vs. Gartner Hype Cycle

- Where is DMLS on the Gartner Hype Cycle?



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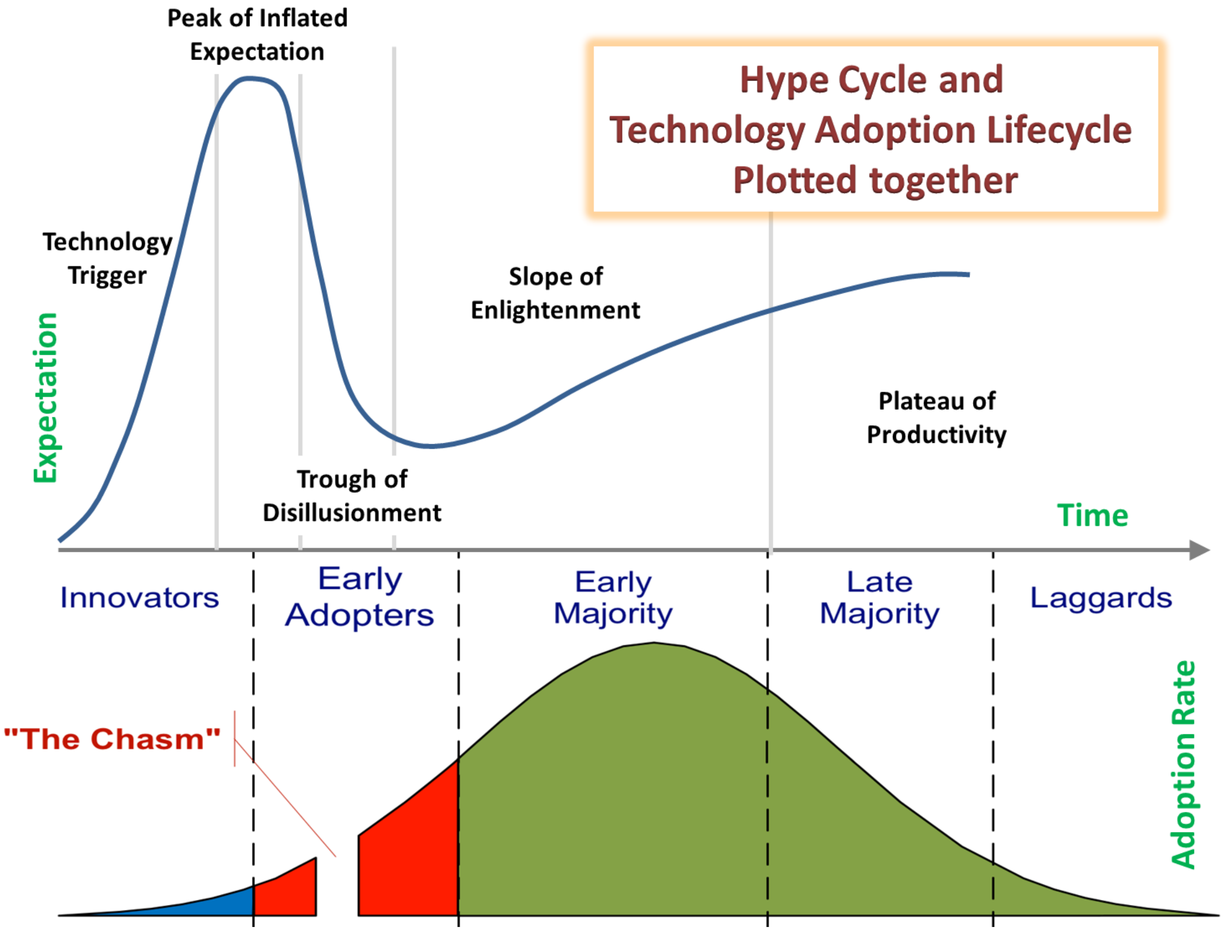
2.1 Gartner Hype Cycle vs. Technology Adoption Timing

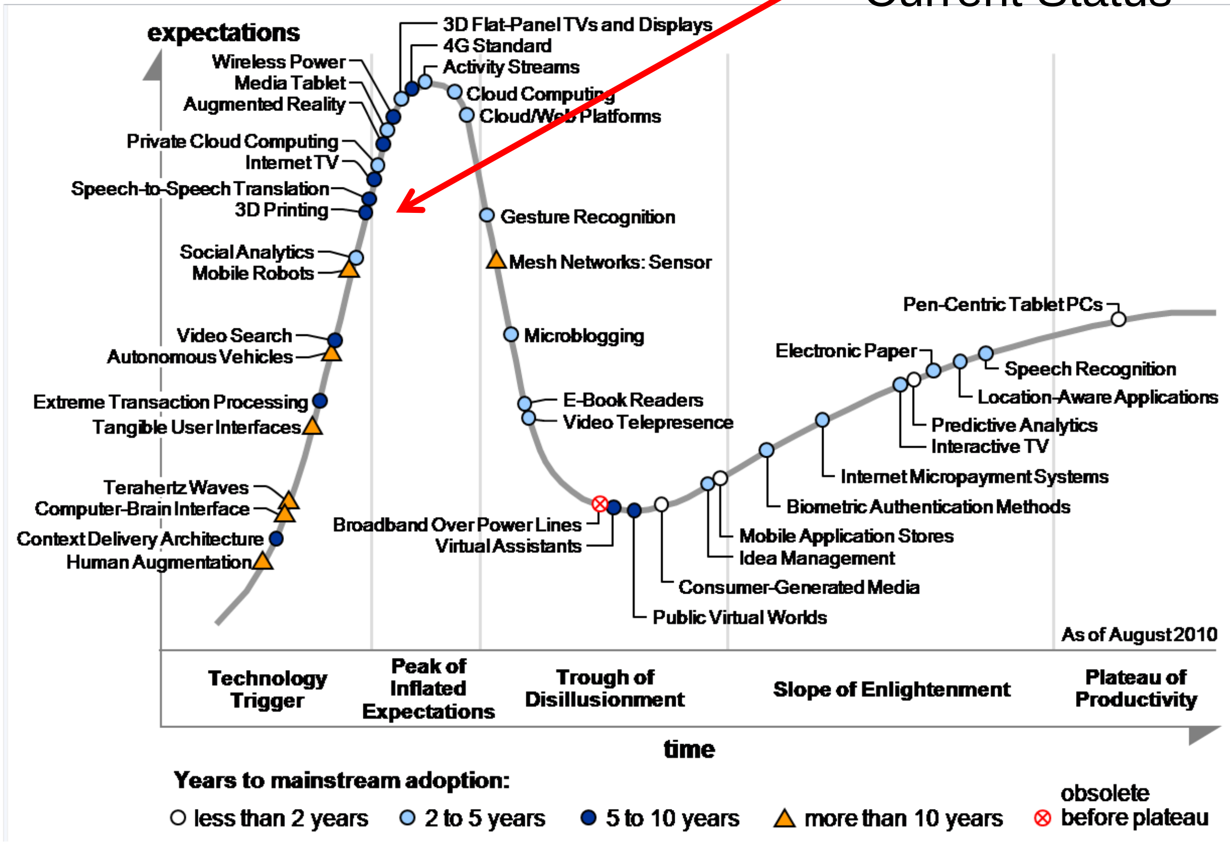


Hype Cycle and Technology Adoption Lifecycle Plotted together

http://search.tb.ask.com/search/AJimage.jhtml?searchfor=technology+implementation+curve&p2=%5EY6%5Exdm003%5EYYA%5Eus&n=780cbf3d&ss=sub&st=bar&ptb=37C591F3-A913-43AB-A9A5-92A61AD8A5A2&si=CM-s14ramMECFcRAMgodZ2wABw&tpr=sbt#./&imgsize=all&safeSearch=on&imgDetail=true

2.2 Technology Adaptation Summary – Circa 2010

Current Status = ??



http://search.tb.ask.com/search/AJimage.jhtml?searchfor=technology+implementation+curve&p2=%5EY6%5Exdm003%5EYYA%5Eus&n=780cbf3d&ss=sub&st=bar&ptb=37C591F3-A913-43AB-A9A5-92A61AD8A5A2&si=CM-s14ramMECFcRAMgodZ2wABw&tpr=sbt#./&imgsize=all&safeSearch=on&imgDetail=true?&_suid=142730574641706907364264136515

2.3 Current Applications – Dental Industry

DMLS Output

The DMLS system runs automatically, quickly and economically, providing a typical accuracy of ± 20 microns. Whereas a **traditional casting process** can produce about **20 dental frames per day**, **DMLS** manufacturing is capable of up to **450** units of crowns and **bridges in the same time period**.

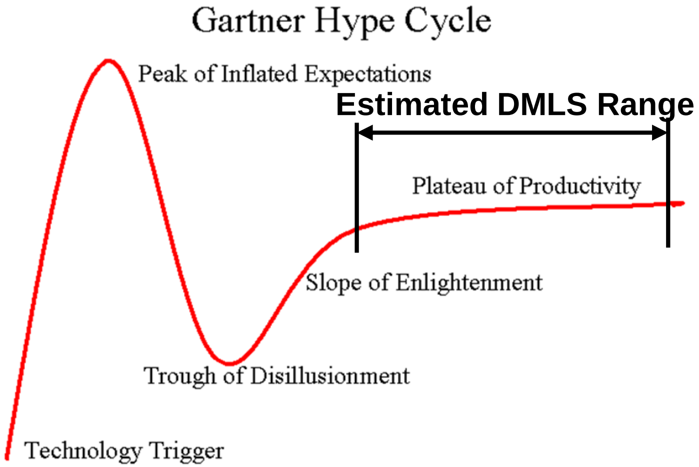
DMLS Quality

"The **quality** of the restorations **is truly excellent**, the surface structure of the copings is much better, and the marginal integrity is phenomenal. Moreover, we **save cost and time.**

“**Lost wax accuracy: 50% – 60%; DMLS accuracy: 90 -95%**”

DMLS Ten to Fifteen Year Prognosis

Bill Oremus, President of Rhode-Island based dental prosthetics manufacturer, BEGO USA, predicts, "Our current product line based on lost wax is probably going to be **obsolete in ten to fifteen years**. The end of casting is approaching as the introduction of layer-by-layer manufacturing to dentistry begins to alter the landscape.”



http://www.scientistlive.com/content/25980

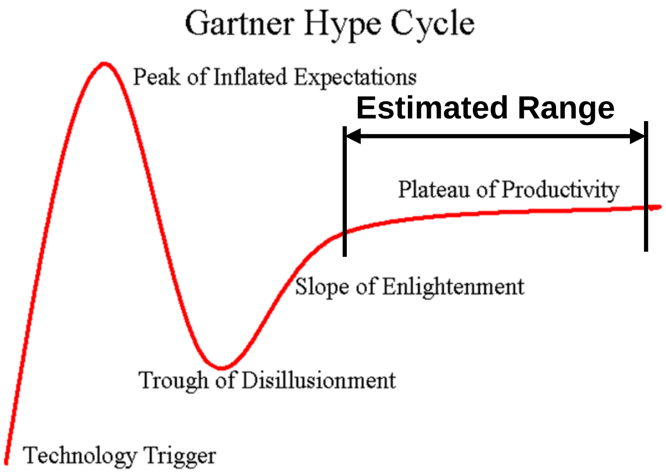
2.4 Current Applications – Aerospace Industry

Pratt & Whitney prepares to deliver the first PurePower PW1500G engines to Bombardier. This latest engine will feature what are called "**entry-into-service jet engine parts**," and they're **produced using additive manufacturing techniques** and space-age metals.

Lynn Gambill, the chief engineer for Manufacturing Engineering and Global Services at Pratt & Whitney, says that during production tests, the company has realized up to a **15 month lead-time savings** and **up to 50 percent weight reduction** in a single part when **compared to parts made with conventional manufacturing processes.**

The project means **dozens of parts produced using 3D manufacturing** processes made from titanium and nickel have been flight-tested for use in Airbus and Bombardier aircraft entering passenger service in the second half of 2015.

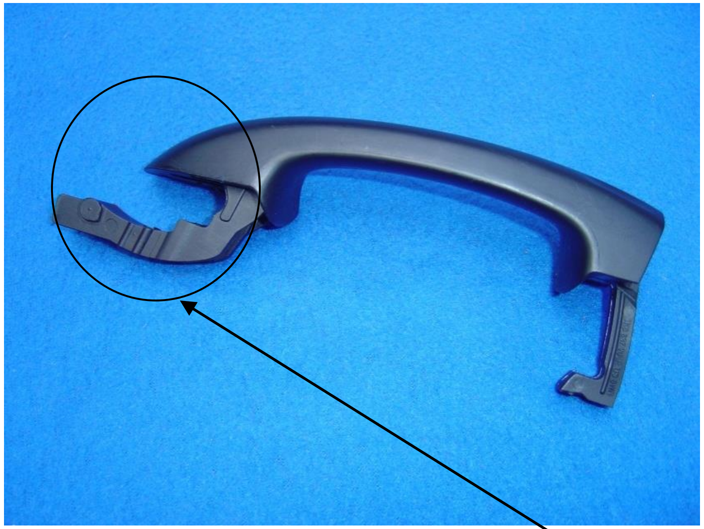
The **list of parts includes brackets, oil nozzles, fuel-bypass manifolds, mounts, fittings, and airfoils**, and it's the ability of additive manufacturing techniques to make parts of nearly any shape or geometry that makes it possible.



http://3dprint.com/55492/pratt-whitney-jet-engine-parts/

2.5 Current Applications – Automotive Industry

Conformal Cooling Study



Material : 30% GF Nylon
(435 ° F operating temp)

Mold : 2 cavity injection mold,
P-20 material

Banana cores: P-20 material,
no cooling

Production : 350,000 parts/year

- Only 12 shots before severe deformation in this area
- Banana core reaches temperature of 300° F
- 100% scrap

Source: Linear Mold & Engineering, Inc.

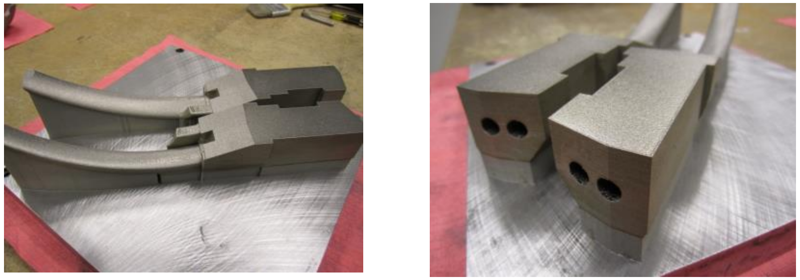
2.6 Current Applications – Automotive Industry

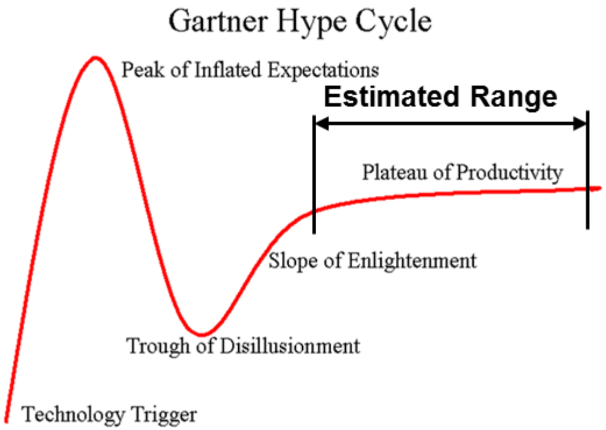
- Banana cores redesigned and grown using DMLS with conformal cooling lines extending to the problem area, and cooling entire length
- Banana core maintains temperature of 72 ° F during 11 hours of production.
- No scrap
- Cycle time reduced from 35 to 16 seconds (54% reduction)

Total savings: 19 seconds X 350,000 parts = 1,847 hours (76 days production)

> “The quoted cycle was 35 seconds, and we are making the handle in 16. Before we added the redesigned core, it was not possible to run the tool after 12 shots. So, I would say we have achieved nirvana.” - Customer Feedback

Conformal Cooling Results





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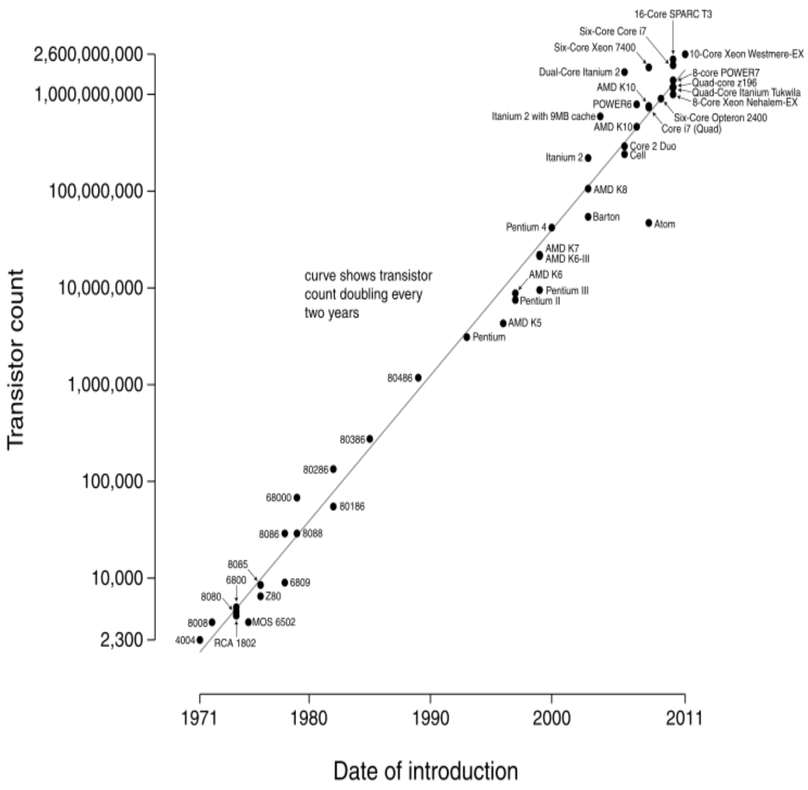
Source: Linear Mold & Engineering, Inc.

2.7 DMLS vs. Moore’s Law

Will DMLS follow Moore’s Law?

1. Electronic density doubles about every two years
2. Processing speed doubles every 18* – 24 months
3. 40 year history of compliance
4. Moore’s Law not expected to be sustainable much longer

Microprocessor Transistor Counts 1971-2011 & Moore’s Law



* David House, Intel

http://en.wikipedia.org/wiki/Moore's_law#mediaviewer/File:Evolution_(34_365).jpg

2.8 Size, Cost and Performance Implications of Moore’s Law

25 year time delta – 1982 Portable Computer vs.2007 Smartphone

Smartphone advantages:

- 1/500 packaging volume
- 10% of cost (inflation adjusted)
- 100x faster processing speed

An Osborne Executive portable computer, from 1982 with a Zilog Z80 4MHz CPU, and a 2007 Apple iPhone with a 412MHz ARM11 CPU; the Executive weighs 100 times as much, has nearly 500 times as much volume, cost approximately 10 times as much (adjusted for inflation), and has about 1/100th the clock frequency of the smartphone.

"Evolution (34 365)" by Casey Fleser - Flickr: Evolution (34 / 365). Licensed under CC BY 2.0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Evolution_(34_365).jpg#mediaviewer/File:Evolution_(34_365).jpg
http://en.wikipedia.org/wiki/Moore's_law#mediaviewer/File:Evolution_(34_365).jpg

2.a Technology Overview:

Assessing the Maturity Level Of DMLS from A NASA Perspective

2.a.1 NASA: Diverse AM Research from Diverse Centers

Goddard
Evaluating a variety of instrument-development efforts and satellite components .

Langley
Developing/evaluating Electron Beam Freeform (EBF3) process.
    Consists of: electron-beam gun, a dual-wire feed, and computer controls.
    Near net shape metallic parts in hours, rather than days or weeks.

Kennedy
Investigating simulated regolith as feedstock for building 3-D habitats & other structures.

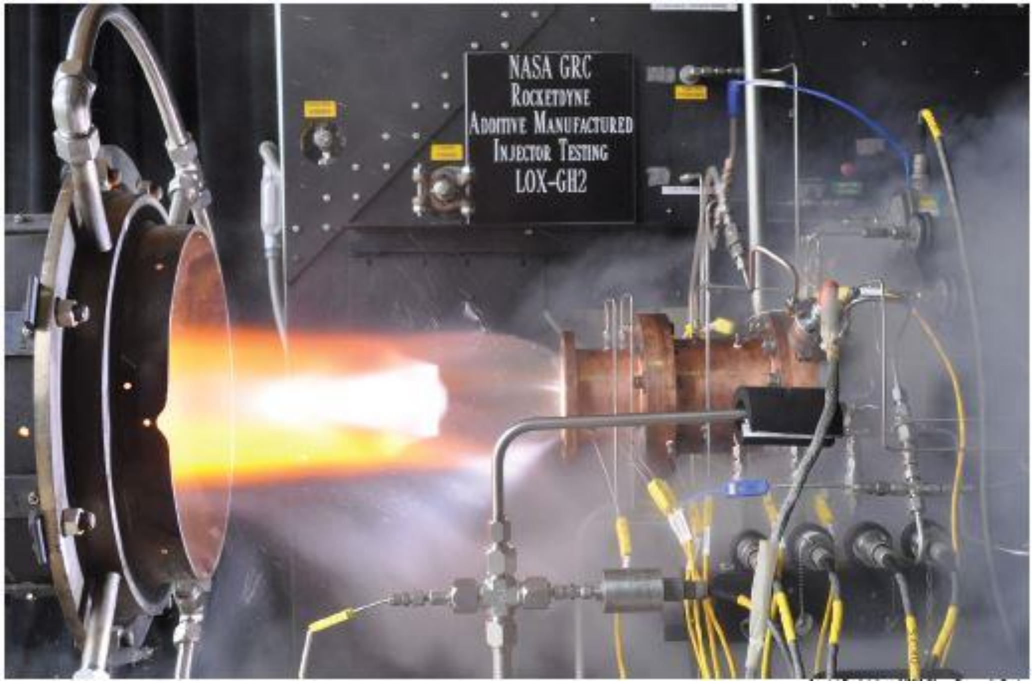
Ames
Exploring synthetic biology for the manufacturing of biological materials

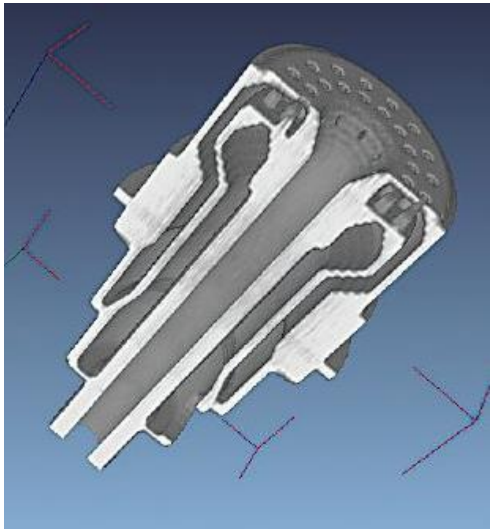
Glenn
Evaluation of AM materials and AM subsystems.
Recently collaborated with Aerojet Rocketdyne to fabricate/evaluate an RL-10 rocket .

Marshall
Fabricate replacement components for the J-2X and RS-25 rocket engines.
Working with Made In Space to develop a 3-D printer to be use on the ISS (October 2014).

Source: NASA Glenn.

2.a.2 Evaluating Propulsion Components and Developing New AM Materials and AM Materials Test Databases



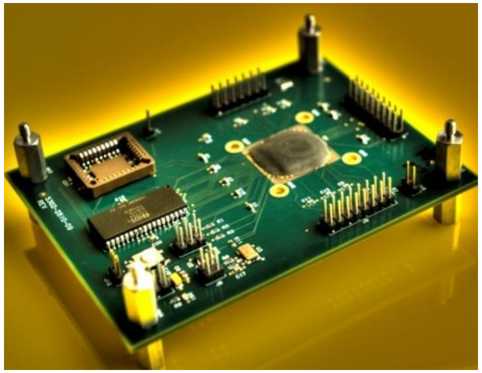


First test of an AM rocket injector With As Fabricated Surface Finish:

- Reduced Part count from ~18 to 2
- Injector Performance better than previous design

Source: NASA Glenn.

2.a.3 NASA Goddard ➔ Satellite Improvements



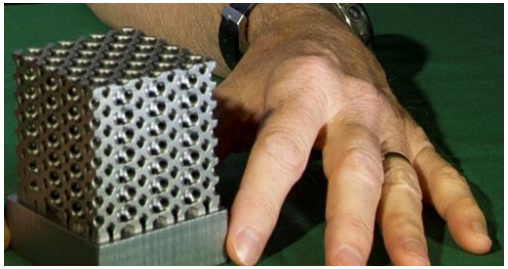
Electronics Packaging

AM printed conductors from chip to substrate

Multi functional 3D chip or stack of chips:
(housekeeping, data processing, power, digitization, control and data handling, and amplification)

Electronics Shielding

Selectively print radiation shield to minimize mass/volume and maximizing protection.



Satellite structures

Invar➔ (64FeNi) extremely low coefficient of thermal expansion used where high dimensional stability is required, such as precision instruments & optics for satellites.

Fact: ~1000 lbs of Invar used in the James Webb Space Telescope's Integrated Science Instrument Module

Source: NASA Glenn.

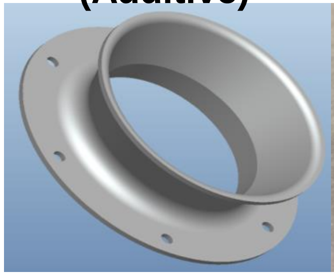
2.a.4 Additive Manufacturing Material Savings

Additive Manufacturing substantially decreases machining waste compared to traditional methods resulting in meaningful decrease in cost and raw material weight.

- Manufacturing Processes:
  - Traditional (Subtractive) Manufacturing –final shape achieved by controlled material-removal.
  - Additive Manufacturing (AM) – process of joining materials to make objects from 3D CAD data

AM Comparison using ECLSS Urine Processor Assembly (UPA) Demister

Start with CAD (Additive)

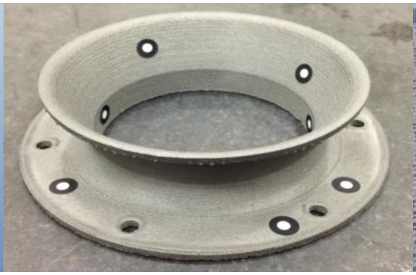


Net Part

Volume: 1.47in^3

Weight: 0.23 lbs

EBM Part



Material savings: 99.25%

Volume: 1.81in^3

Weight: 0.29lbs

Difference from CAD: 0.06 lbs

Difference from Cylinder: 7.35 lbs

EBF^3 Part

Material Savings: 87.24%

Volume w/out base plate: 7.37in^3

Weight: 1.18lbs

Difference from CAD: 0.95 lbs

Difference from Cylinder: 6.46 lbs

Start with Block (Subtractive)

Cylinder

Volume: 47.71in^3

Weight: 7.64lbs

Difference from CAD: 7.41 lbs

Machining Waste Weighs 32X more than the Net Produced Part

Note: Calculation assumes Ti-6-4 composition, density 4.43g/cm^3 (ASM standard)

EBM: Electron Beam Melting
EBF^3: Electron Beam Free Form Fabrication

2.a.5 NASA: AM Challenges for Metals

- **Databases, databases, databases**
  - Need at least a b-basis database on each material system
  - At least 30 repeats for each test condition/type

- **Understanding of the anisotropy**
  - Aspect ratios of final part to grain size/layer
  - Design methods to take advantage of anisotropy
  - Increased testing for database generation

- **Design processes on when to use AM and when to go conventional**
  - Relatively small complex parts
  - Low production rates
  - Potential anisotropy and internal surface finish will influence component life
  - How thin can you go? What geometries are problems (i.e., >45° ramps will slump)?

- **Understanding of residual stresses from the AM**
  - Manufacturing models/tools to take advantage of residual stresses
    - To maintain tolerances
    - To build in compressive stresses that are beneficial to component application

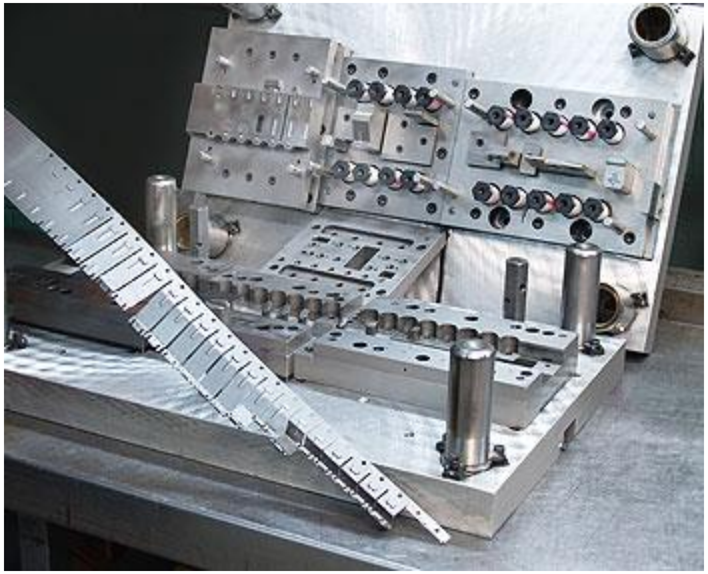
- **Feedstock**
  - Handling: Contamination prevention and shelf life (especially for powders)
  - Recyclability
  - Learning curve for new materials systems

Source: NASA Glenn.

3. DMLS vs. Traditional Manufacturing Methods

3. DMLS vs. Traditional Forming Technologies

- DMLS eliminates tooling
- DMLS minimizes/eliminates design compromises required by manufacturing process
- Replaces forming options including:
  - Stamping
  - Casting
    - Low pressure
      - Die cast
      - Investment cast
      - Ablation cast
    - High pressure
      - Thixomolding
  - Extrusion
    - Impact
      - Cold forming
  - High pressure forming
  - Molding
  - Ultra high speed forming
  - Other



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3.1 DMLS vs. Traditional Joining Processes

- DMLS component integration eliminates the need for a separate joining process
- DMLS eliminates the need to select a compromised method of joining materials
- DMLS eliminates the need for post-process fixturing & assembly

.

Joining Technologies								
	Speed	100% Flange Length Joining	Durability	Dissimilar Metal Joining	Relative Flange Width	Metal Types	Parent Material Degardation	Peel Strength
IDEAL JOINING PROCESS	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
RSW	🟩	🟨	🟩	🟨	🟨	🟩	🟥	🟩
RPW	🟩	🟨	🟩	🟨	🟨	🟩	🟥	🟩
Mechanical Fastening	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩
Laser Welding	🟩	🟩	🟩	🟨	🟨	🟩	🟥	🟩
Continuous Resistance Welding	🟩	🟩	🟩	🟥	🟨	🟩	🟥	🟩
Friction Stir Welding	🟩	🟩	🟩	🟩	🟨	🟩	🟥	🟩
Friction Spot Joining	🟨	🟨	🟩	🟥	🟩	🟥	🟩	🟩
Bonding (structural adhesives)	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟥
Riveting	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩

4. Cost Assessment

4. Key Cost Factors

Primary costs are a function of:

- Number of parts
- Design complexity
- Individual part weight
- Scrap material
- Material cost/lb.
- Tooling costs
- Joining costs
  - Preparation
  - Energy consumption
- Secondary machining/processing
- Fixturing costs
- Assembly costs
- Shipping costs

Secondary costs include:

- Time required to make tools/parts after design is complete
- Increased test time due to lack of prototype part fidelity to production parts
- Increased “time to market” for new vehicles

http://search.tb.ask.com/search/AJimage.jhtml?searchfor=DMLS+parts&p2=%5EY6%5Exdm003%5EYYA%5Eus&n=780cbf3d&ss=sub&st=bar&ptb=37C591F3-A913-43AB-A9A5-92A61AD8A5A2&si=CM-s14ramMECFcRAMgodZ2wABw&tpr=sbt#./&imgsize=all&safeSearch=on&imgDetail=true?&_suid=142898442505700654286821047175 3

4.1 Cost Assessment

DMLS primary cost advantages include:

- Reduced number of parts through component integration
- Increased design complexity
- Optimized part weight
- Minimal scrap material.
- No tooling costs
- No joining costs
- No joining equipment required
- Low energy consumption for build process
- Minimal oversight of process
- Minimal or no secondary machining/processing
- No fixturing costs
- No assembly costs
- Reduced shipping costs
- Reduced handling costs

P&W turbine engine fuel nozzle
(18 parts into 1 part)

DMLS secondary cost advantages include:

- Immediate part turnaround following design completion
- Increased part fidelity to production for test parts
- Decreased “time to market” for new vehicles

4.2 A Methodology for Developing Generic Cost Targets - Weight

- Development of Generic System Weights
  - System weight percentages based on peer reviewed Lotus study[1]
  - System weight % multiplied by vehicle weight yields estimated system weight
  - The BIW, powertrain, suspension/chassis and interior systems represent the majority of the vehicle weight

	Weight	BIW Wt.	P/T Wt.	Susp/Chassis Wt.	Interior Wt.
	(lbs.)	23%	24%	22%	15%
Vehicle Class/Type					
A	2,269	511	547	506	335
B	2,727	614	658	608	403
C	3,084	695	744	688	455
D	3,393	764	818	756	501
E	3,730	840	900	832	551
Hybrid	3,786	853	913	844	559
E Luxury	4,006	903	966	893	591

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[1] Lotus ARB Phase 1 Study

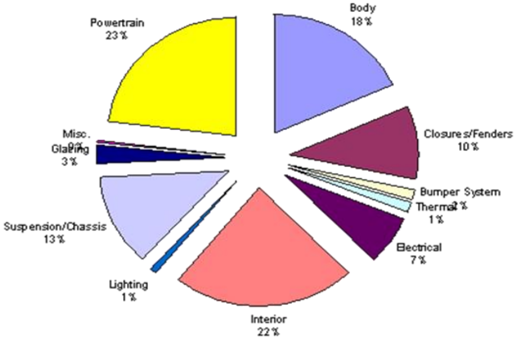
Vehicle Data Sources: Chevrolet.com., Cadillac.com

4.3 A Methodology for Developing Generic Cost Targets - Cost

- Development of Generic System Costs
  - System cost % breakout based on Lotus peer reviewed study[1]
  - System % multiplied by vehicle RPE[2] cost (A, B, C, etc. class)

	Invoice	RPE	BIW Cost	P/T Cost	Susp/Chassis Cost	Interior Cost
			18%	23%	13%	22%
Vehicle Class/Type						
A	$11,900	$8,151	$1,467	$1,875	$1,595	$1,793
B	$13,880	$9,507	$1,711	$2,187	$1,852	$2,092
C	$17,120	$11,726	$2,111	$2,697	$2,307	$2,580
D	$21,670	$14,842	$2,672	$3,414	$2,920	$3,265
E	$27,990	$19,171	$3,451	$4,409	$3,810	$4,218
Hybrid	$33,345	$22,839	$4,111	$5,253	$4,465	$5,025
E Luxury	$42,200	$28,904	$5,203	$6,648	$5,806	$6,359
*Estimated invoice						

Generic System Cost Chart[1]



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[1] Lotus ARB Phase 1 Study

[2] RPE: Retail Price Equivalent = Invoice/1.46 - http://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryID=205147

Vehicle Data Sources: Chevrolet.com., Cadillac.com, http://www.car-buying-strategies.com/dealer-invoice/

4.4 A Methodology for Developing Generic Cost Targets – Cost/Lb.

- This approach allows prioritizing vehicle classes and systems based on highest $/lb.
  - Larger vehicles, e.g., E class, have greater $/lb. costs than smaller vehicles, e.g., B class
  - The interior system cost/lb. is 55% to 85% higher than the BIW, powertrain and suspension/chassis systems
  - The luxury class vehicle $/lb. is approximately 40% higher than a non-luxury equivalent size vehicle

	MSRP	Invoice	RPE	Weight	BIW $/lb.	P/T $/lb.	Susp/Chassis $/lb.	Interior $/lb.
				(lbs.)				
Vehicle Class/Type								
A	$12,270	$11,900	$7,933	2,269	$2.79	$3.33	$3.15	$5.21
B	$14,245	$13,880	$9,253	2,727	$2.71	$3.24	$3.05	$5.06
C	$17,745	$17,120	$11,413	3,084	$2.96	$3.53	$3.36	$5.51
D	$22,465	$21,670	$14,447	3,393	$3.40	$4.06	$3.86	$6.34
E	$29,310	$27,990	$18,660	3,730	$4.00	$4.77	$4.58	$7.45
Hybrid*	$34,345	$33,345	$22,230	3,786	$4.69	$5.60	$5.29	$8.75
E Luxury	$44,660	$42,200	$28,133	4,006	$5.61	$6.70	$6.50	$10.46
*Estimated invoice								

[1] RPE: Retail Price Equivalent = Invoice/1.46 - http://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryID=205147

Vehicle Data Sources: Chevrolet.com., Cadillac.com, http://www.car-buying-strategies.com/dealer-invoice/

5. Market Opportunities

5. Market Opportunities - Overview

- DMLS components must meet stringent performance, cost, mass, quality and reliability standards

- DMLS parts have already demonstrated the ability to meet the above requirements in the medical, automotive tooling and aerospace industries

- High volume automotive applications require substantial increases in output for DMLS to be competitive

- DMLS parts need to be designed to maximize DMLS benefits for automotive applications to reduce costs

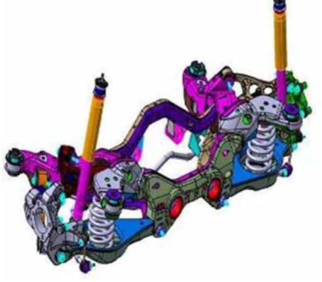
5. Assessing High Potential Areas For Implementing DMLS

- Vehicle Interiors
    - Target areas with opportunities for high level of component integration, e.g., seat structure
    - Target complex structural parts, e.g., integrated air bag/IP mounting structure
    - Curved mini-heat exchangers for localized heating/cooling
    - Knee bolster structure with variable strength tuning

- Crash Energy Management
    - Highly optimized lightweight local “crush cans”

- Powertrain
    - Fuel & oil delivery system components

- Chassis/suspension
    - Target complex lightweight components, e.g., steering knuckles, brake rotors



Source: Linear Mold & Engineering, Inc.

5.1 Lightweight Brake Rotor

Integrated cooling channels help to reduce weight and increase performance

Lattice structure brake rotor

Application

- Conceptual break disk for formula SAE student race car
- Integrated cooling channels to reduce weight and optimize cooling effect

Product details

Weight:	390 g
Material:	Cobalt Chrome

Advantages

- Reduced weight by 25%
- Significant increase in performance due to controlled cooling flow

Source: ka.race.ing Karlsruhe

6. Key Areas Requiring Advances in DMLS Technology

6. Technical Limitations – Current Technology

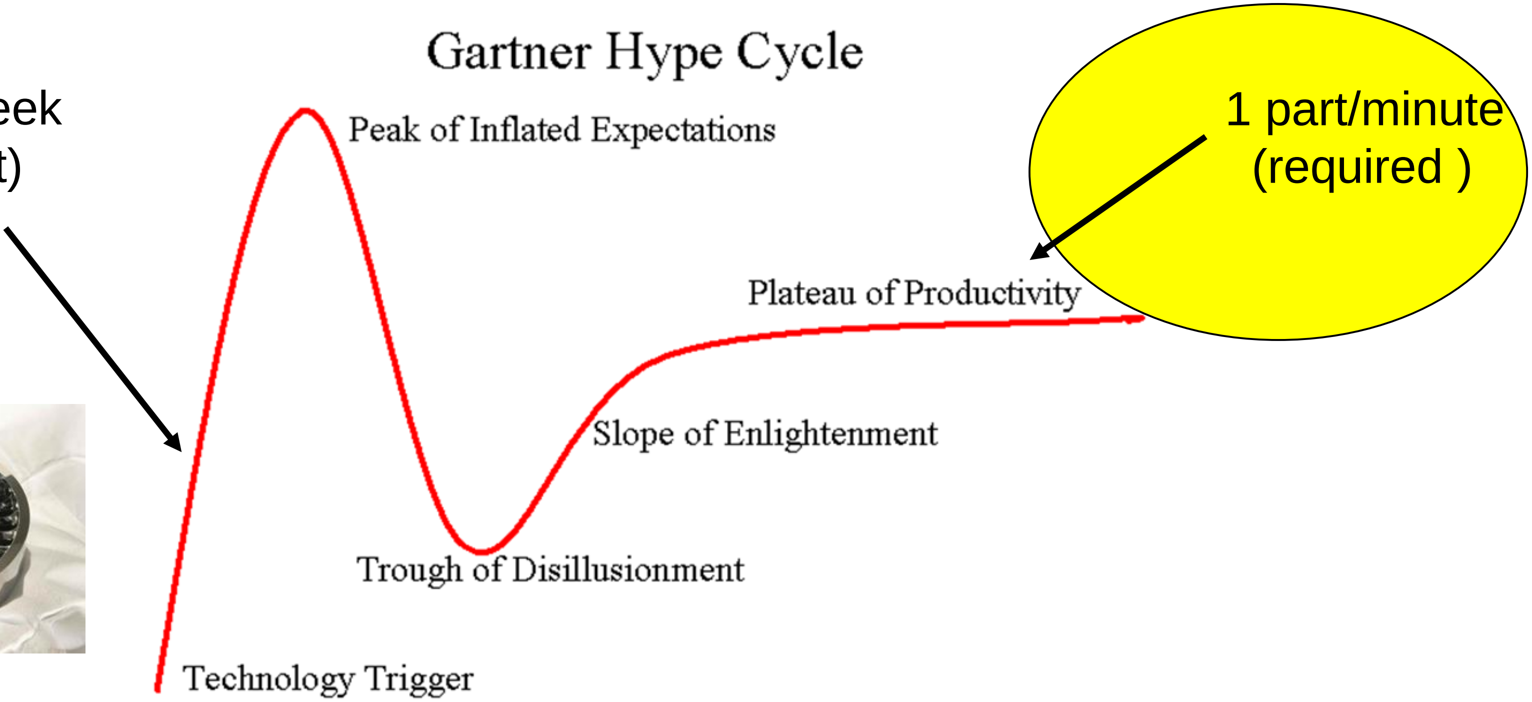
- In laser melting type machines, the speed of an individual laser is limited by the mechanical movement of the mirrors that direct the laser
  - Build speed increases come from the addition of multiple lasers.
- Relatively small plate sizes
  - Larger plate sizes require additional lasers

- Plate sweep speed
  - Larger plates could increase build time at current speeds
- Support structure
  - Time consuming process for both build and post-build finishing
- High material costs ($/lb.)
  - Typically small batches
  - High level of filtration required

Picture Source: Linear Mold & Engineering, Inc., .

6. Meeting Automotive Volume Requirements: Assessing DMLS Readiness on The Gartner Hype Cycle

1 part/week
(current)



1 part/minute
(required)

Picture Source: Linear Mold & Engineering, Inc., .

6.1 Future DMLS Enhancements – Beam Function

- Replace mirror guided lasers with electron beams
  - The Arcam EBM Q10 electron beam maintains several melt pools simultaneously
    - Advantage: Much faster response than a mirror guided laser
    - Disadvantage: Cannot make intricate shapes.
    - Used primarily to make titanium medical implants

- Increase power level
  - Arcam EBM Q10 electron beam energy is 3,000 watts
    - 3x to 7x more energy than typical laser

- Increase number of lasers/electron beams

Source: Linear Mold & Engineering, Inc., .

6.2 Langley ➔Electron Beam FreeForm Fabrication (EBF3)

Basics:

- Layer-additive process to build parts using CNC techniques
- Electron beam melts pool on substrate, metal wire added to build up part
- Successfully demonstrated in 0-g during parabolic flight tests
- Demonstrating design and build of candidate replacement part for finishing and testing in ground-system test bed
- Developing S-basis allowables and modeling to predict properties for certification

Benefits:

- High energy efficiency and feedstock usage efficiency compatible with space-based operations
- Electron beam can be modulated to perform multiple operations (welding, deposition, heating, surface modification, machining, etc.)
- Wire feedstock safely handled in reduced gravity
- Can process wide variety of metallic materials

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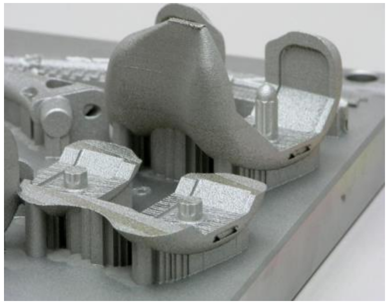
6.3 Future DMLS Enhancements – Non-Beam Functions

- Automated support structure removal
  - The DMLM process builds a part that is constructed inside of a large honeycombed metal support structure
  - New technology for support structure removal is required to replace the labor intensive process of removing the support structure



- Material processing
  - Improve throughput for large batches

- Increase plate size

- Increase plate sweep speed

- Combine post-build processes into initial build
  - HIPping
  - Heat treat

Picture Source: GPI Prototype & Manufacturing Services, Inc., .

Source: Linear Mold & Engineering, Inc., .

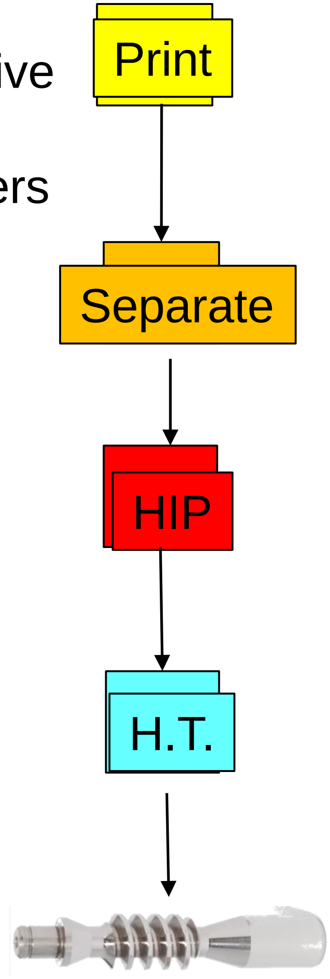
6.4 Future DMLS Enhancements – Ideal Process

- One part/minute (10,000 parts/week) output for high volume automotive
  - Precision electron beams or large array lasers
  - Robotic removal of support structure using electron beam or lasers
    - Performed on same platen or
    - Transferred to a second machine as part of the process
  - Very large bed sizes
    - Discrete bed areas

- In-line HIPping process

- In-line large batch heat treating

- Large batch material pre-treatment
  - Quick & efficient filtration



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HIP

H.T.

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