3D Printing Technologies, Aeronautical Applications, and Next Steps

EAA Oshkosh AirVenture 2018

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UnderstandingAirplanes.com

Bernardo Malfitano

Academic

- B.S. Mechanical Engr., Stanford University
- M.S. Mechanical Engr., Columbia University
  Elective courses, lab work, and research topics included airplane design, aerodynamics, control systems, and propulsion

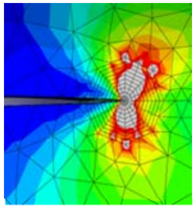
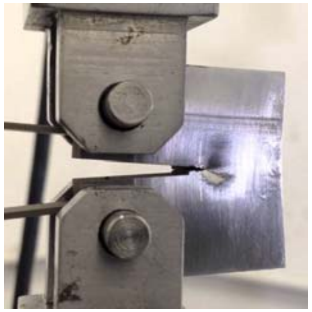
Hobbies

- Articles and photos on various aviation magazines, websites, & books, since 2003
- Pilot, RV-6 owner. 1st solo: 2009
  1st aerobatic solo: 2012
  1st flight to Oshkosh: 2014




Professional

- Boeing Commercial Aviation Services
  (Fleet support, structural analysis of repairs, maintenance planning); Long Beach: 2007-2008
- BCA Structural Damage Technology
  (Fatigue & Fracture Mechanics allowables testing and analysis methods development); Everett: 2009-2018
- BCA Airplane Configuration & Integration
  (Product Development); Harbour Pointe: 2018-Present


Agenda

- Overview of 3D-printing technologies
- Survey of aerospace applications including homebuilt airplanes
- Current Research, Next Steps

NOTE: A video of me giving this presentation can be found at ...youtube.com/channel/UCh7C3C5hKAVZR0SCPhECrMQ

NOTE: All opinions expressed in this presentation are my own and not my employer's.
I do not represent my employer, or the FAA or EAA.

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NOTE: Slides 5, 6, 7, 8, 10, 12, 29, 30, and 44 contain videos. These videos may not play properly if you view this file with non-Adobe software.

Additive Manufacturing Technologies

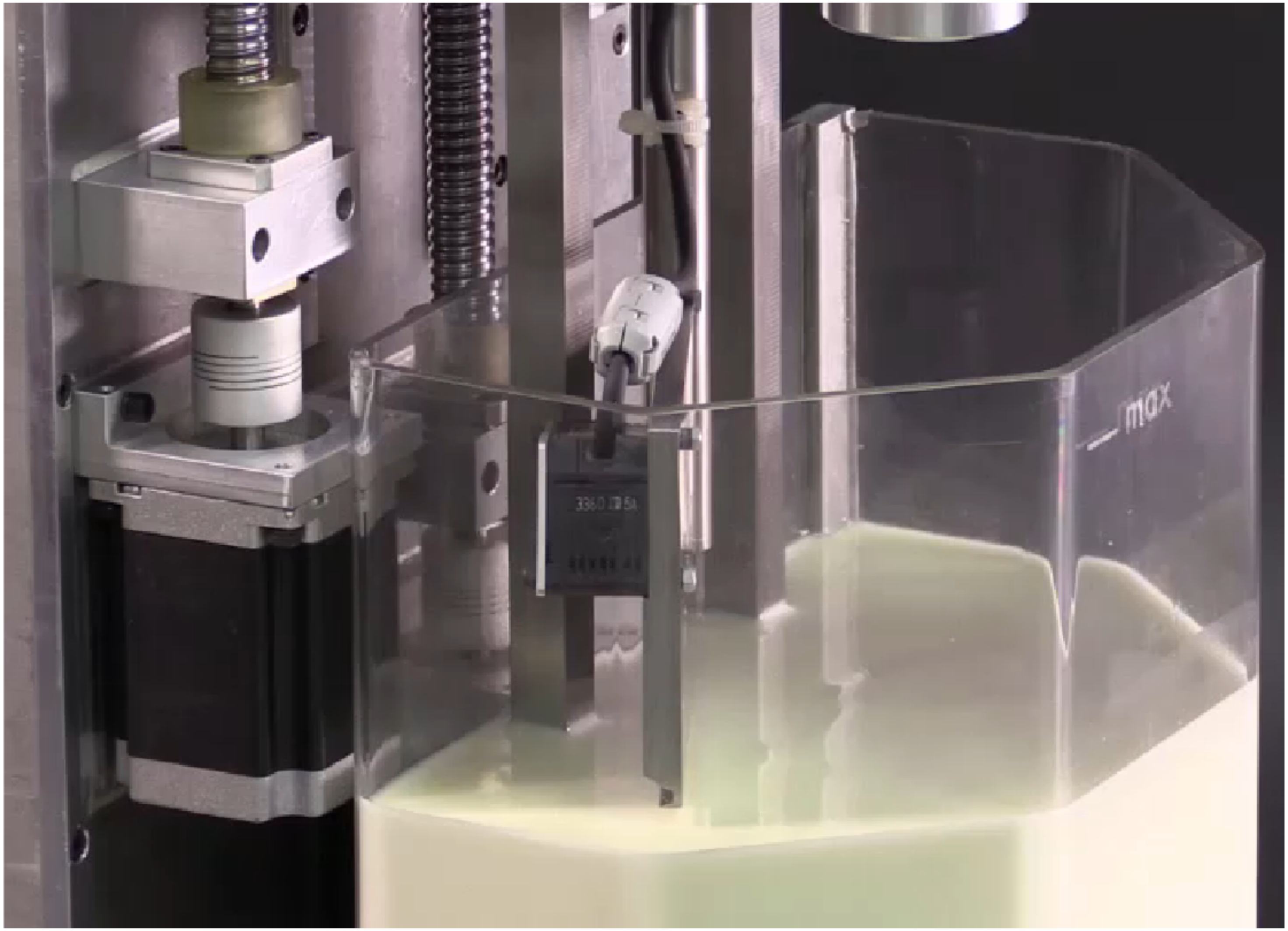
One layer at a time. Many ways to do that.
Most are a variation on these four:

- Plastic: Stereolithography
- Plastic: Fused Filament Deposition
- Metal/Plastic: Powder Bed & SLS
- Metal: Plasma Deposition / Spray

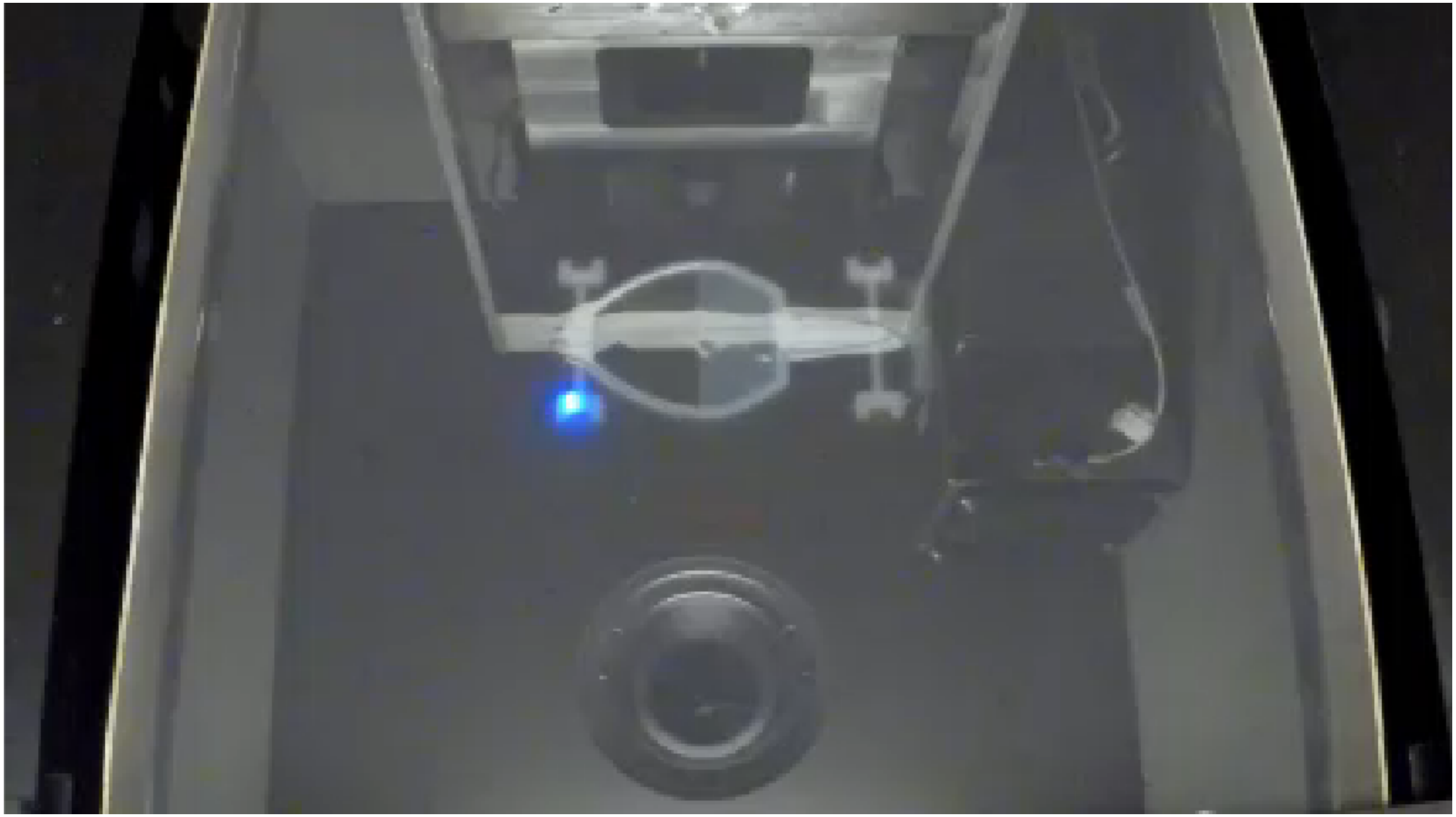
Stereolithography

- 1980s, original method
- Resin cured locally by laser or UV light
- Object is lowered (or raised) and another layer is cured.
- The only method that can be done at room temperature.

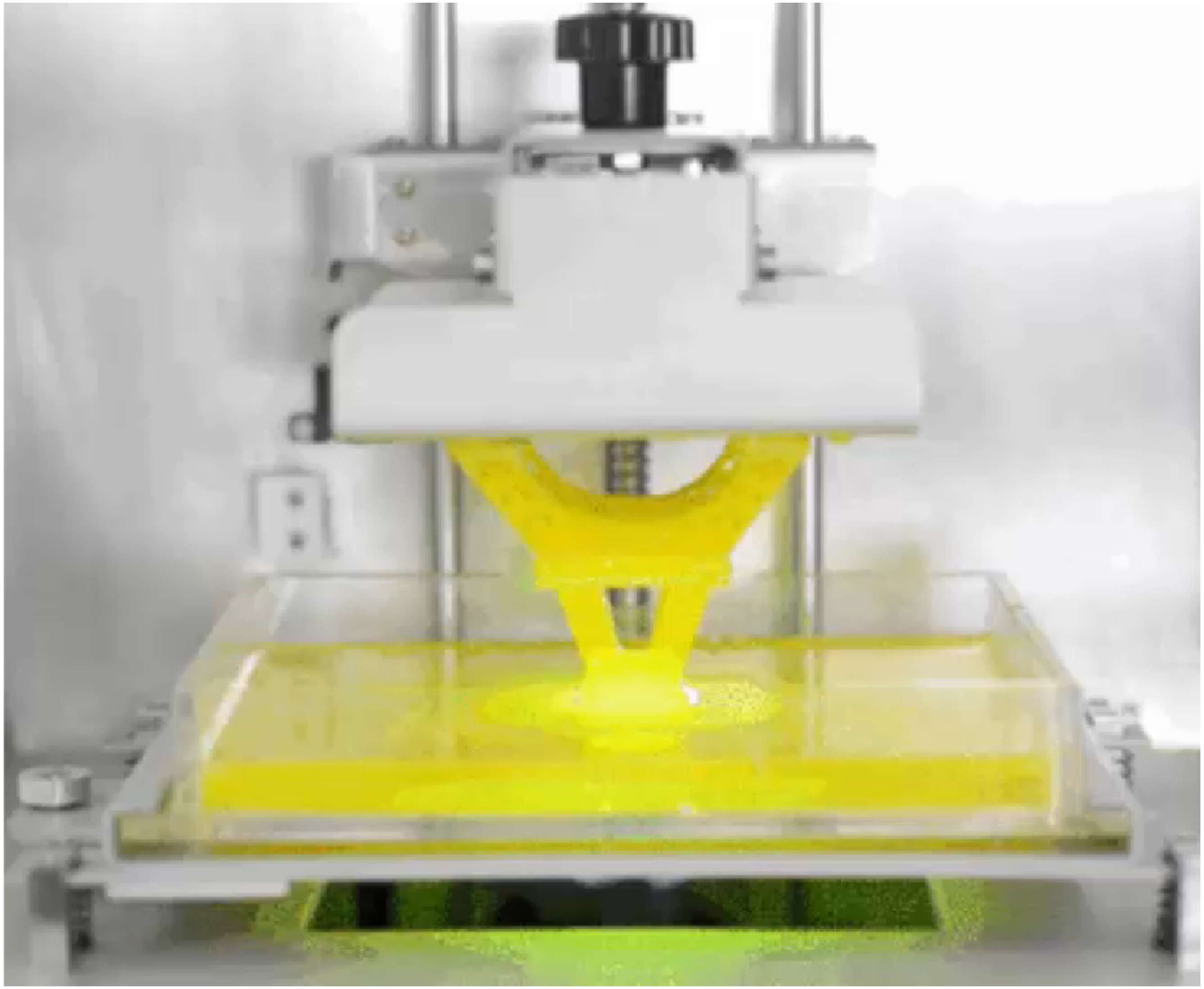
Stereolithography



Stereolithography

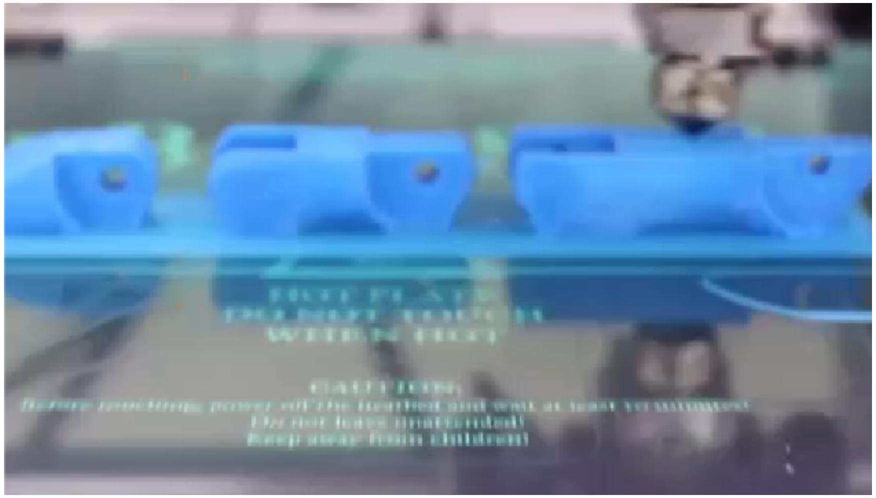


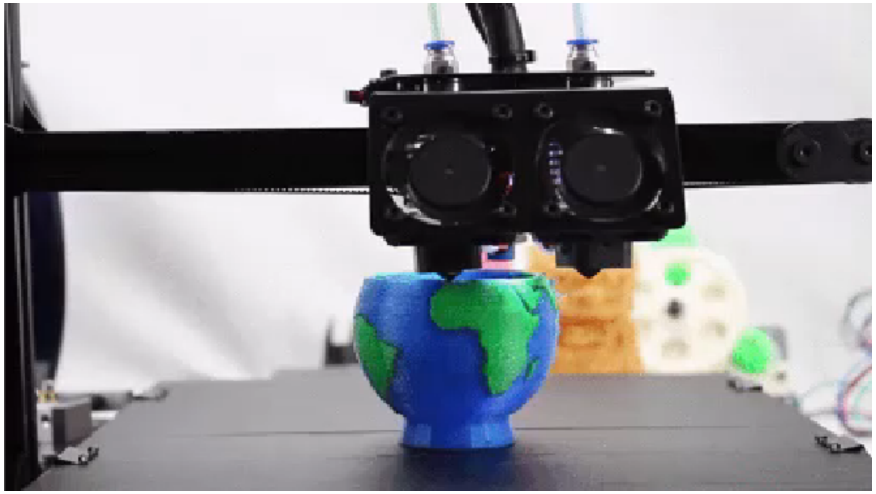
Stereolithography



Fused Filament Fabrication
a.k.a. Fused Deposition Modeling

- Wire-fed thermoplastic





Powder Bed

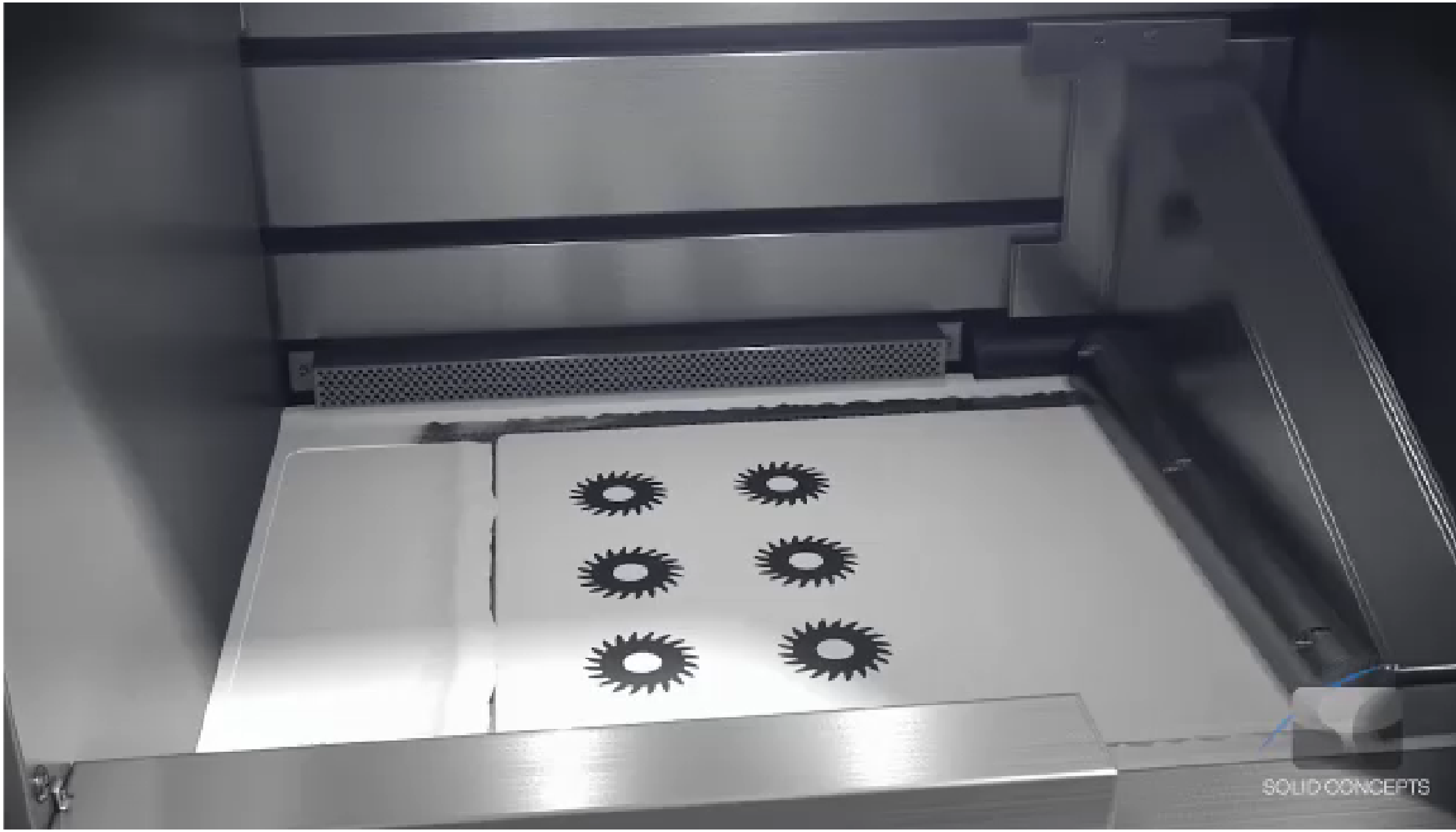
a.k.a. Selective Laser Sintering, Electron Beam Melting

- Container of metal or plastic powder.
  Beam melts layer on surface.
  Surface is re-coated.
  Repeat!

- Key advantage: Small details

- Key disadvantage: Limited size

Powder Bed



Direct Metal Deposition

a.k.a. Laser Freeform Manufacturing Technology, Rapid Plasma Deposition, Laser Metal Deposition

- Metal (wire or powder) fed into nozzle, heated, and ejected
- Key advantage: Size only limited by range of motion of nozzle robot
- Key disadvantage: Fine details are not possible, surface is very rough

Direct Metal Deposition

a.k.a. Laser Freeform Manufacturing Technology, Rapid Plasma Deposition

3D Printing: Pros?

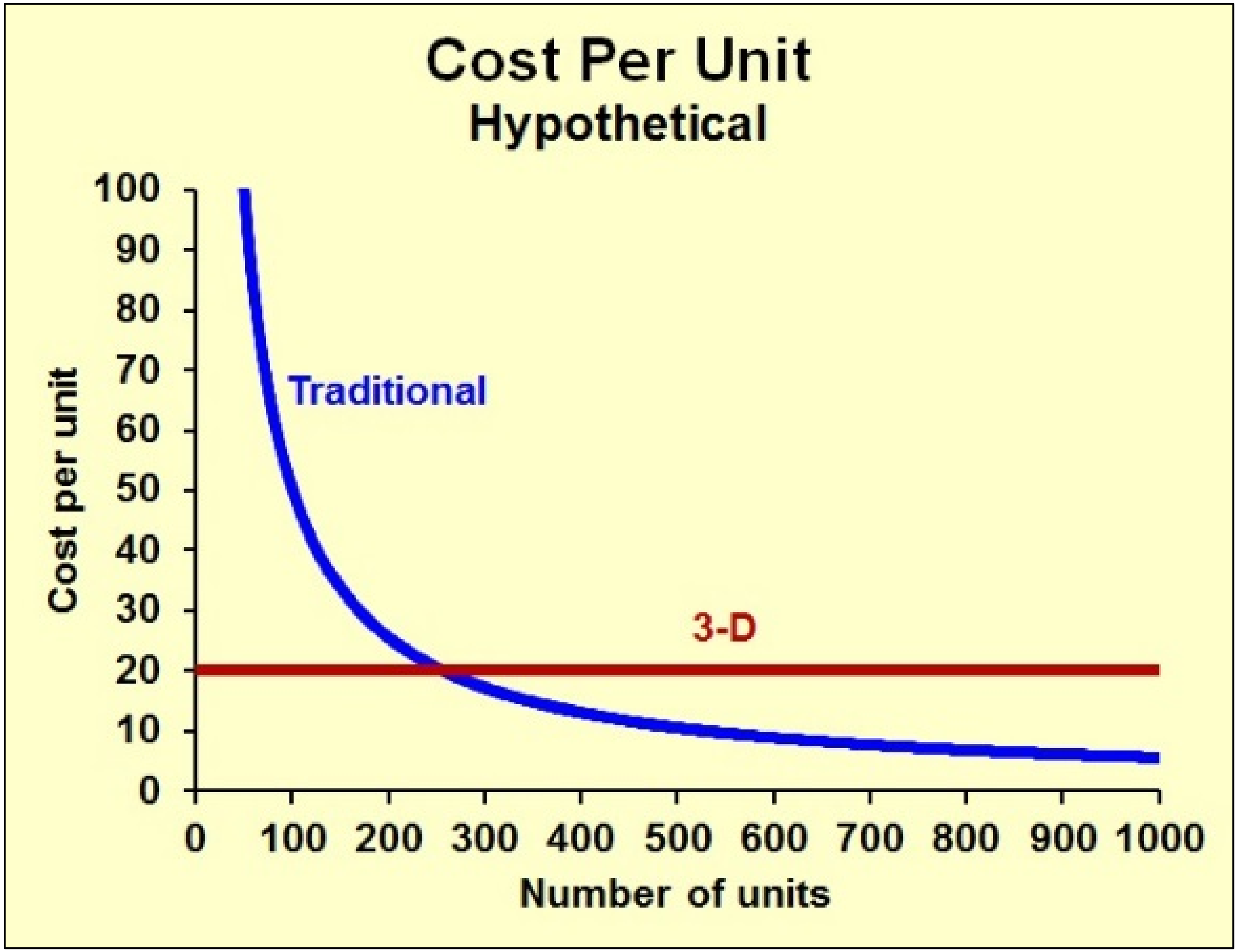
[∗: Not if surfaces need to be smooth]

- "Complexity is free"[∗]
- No tooling costs, allows for iterative design ("rapid prototyping")
- Short lead times
- Little or no material wasted (no "chips", low "buy to fly")

3D Printing: Cons?

[∗: Depends how many.
See next slide.]

- High cost per item [∗]
- Materials typically with lower strength, more inclusions and porosity, worse durability
- Surfaces rough until polished
- Cantilever features & overhangs may require temporary supports
- Highly process-sensitive, challenge for certification. [Details soon]


Cost Per Unit
Hypothetical
Traditional
3-D
Cost per unit
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
800
900
1000
Number of units

Aerospace Applications

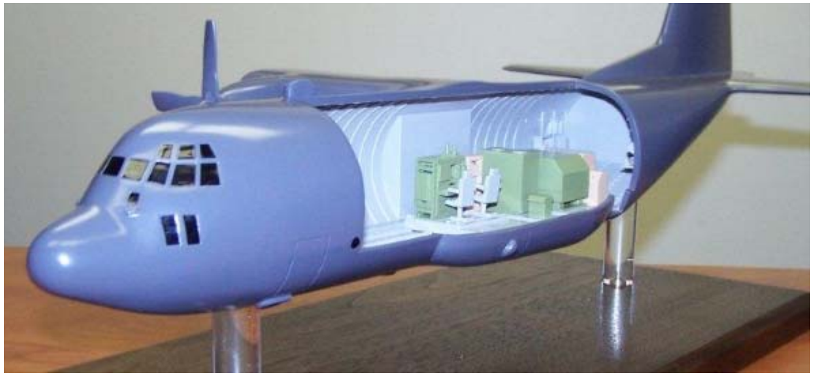
- Models: display, wind tunnel
- Flight-test parts
- Factory tooling

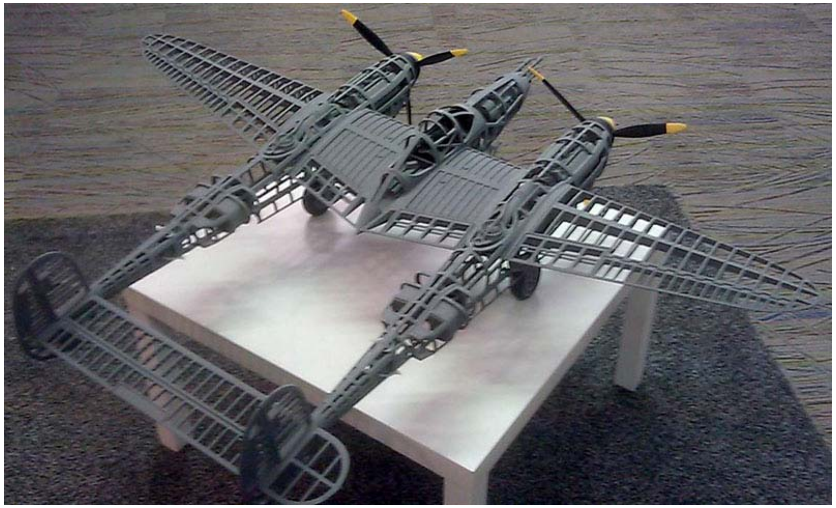
- Air Ducts
- Propulsion
- Spare Parts
- UAVs

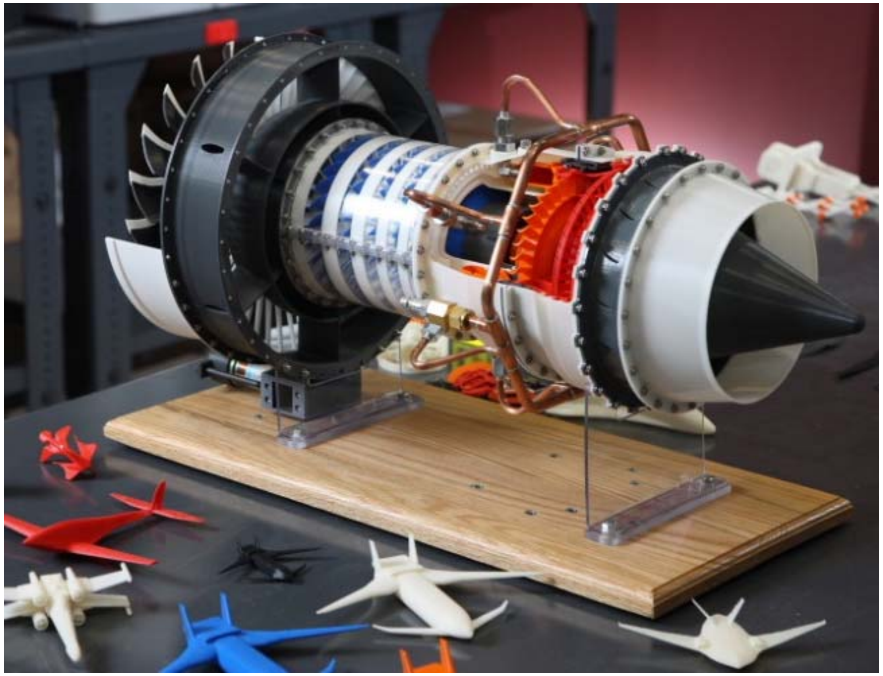
- Spacecraft
- Structures?

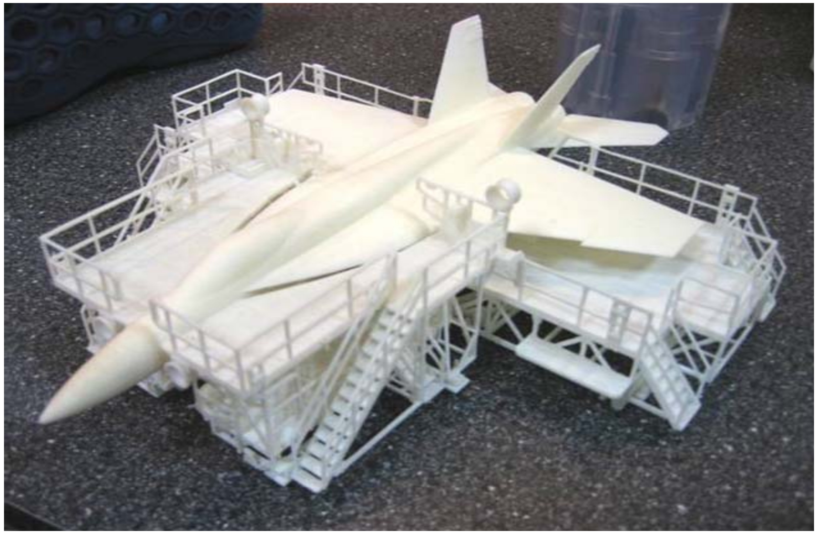
Actual Airplane Parts!

Display Models









Wind Tunnel Models

Lockheed's
Robert Belie

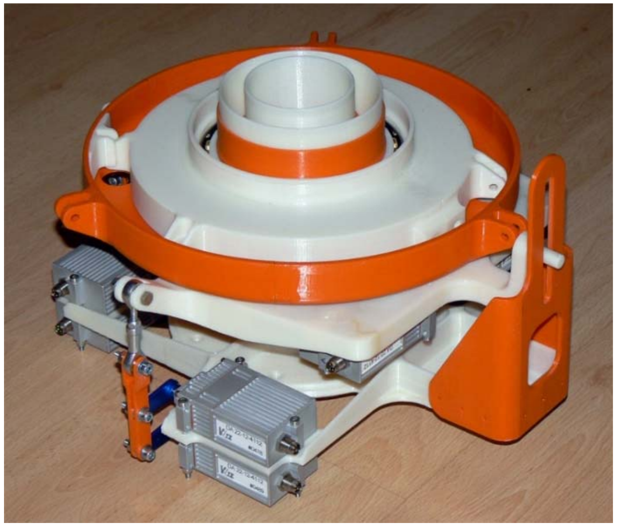
Wind Tunnel Models

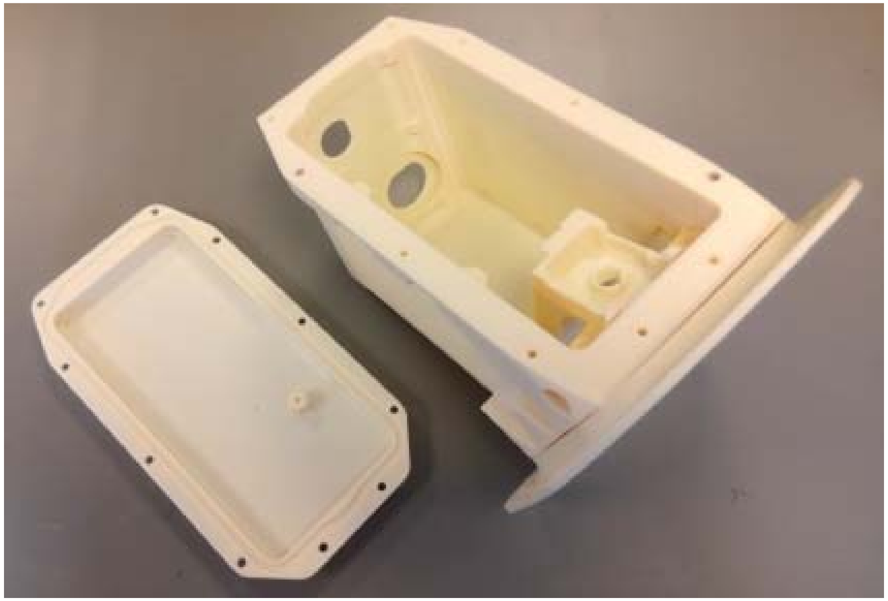
D8

Typhoon w/ conformal tanks

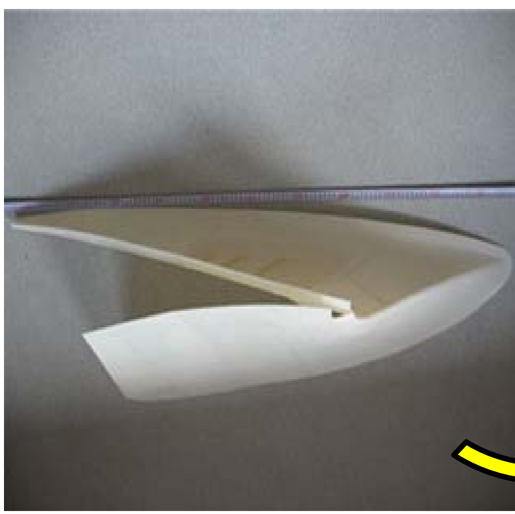
icing test

Fit Validation Models





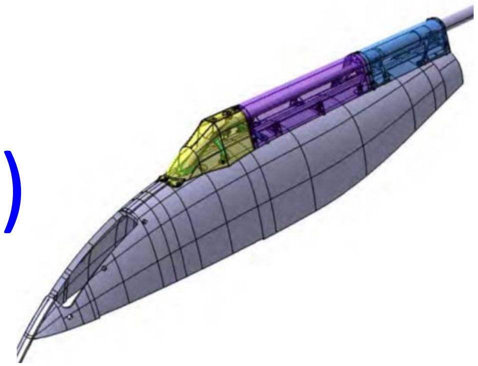
Flight-Test Parts (e.g. Evektor)

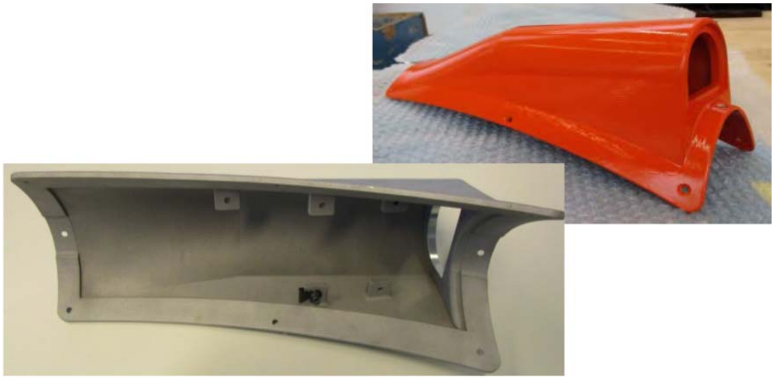


Flight-Test parts (e.g. C-17 Drag Reduction)

Flight-Test parts (e.g. Ice Shapes)

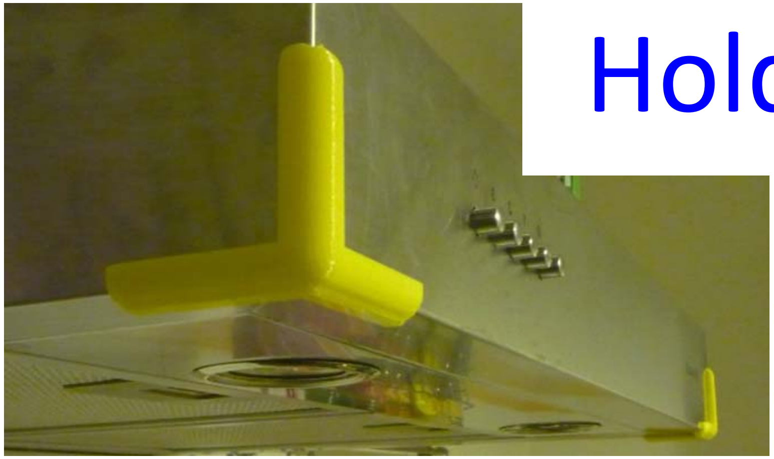
Flight-Test parts
(e.g. A330NEO Static Cone Fin Tip)



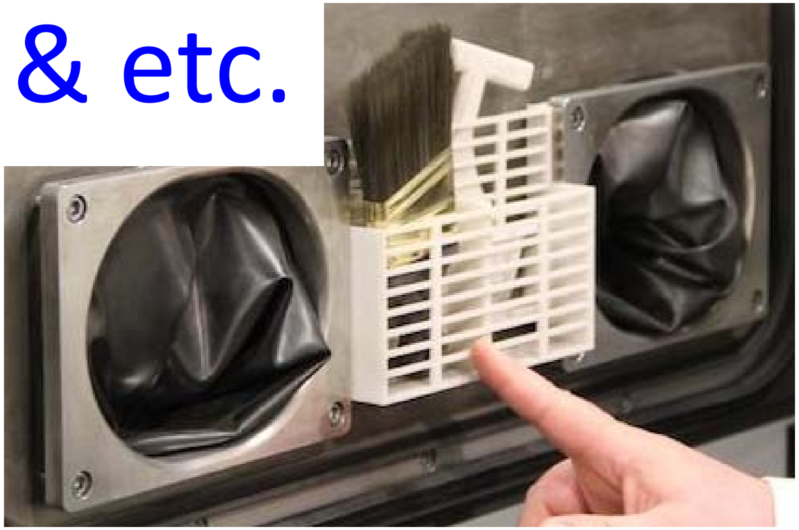


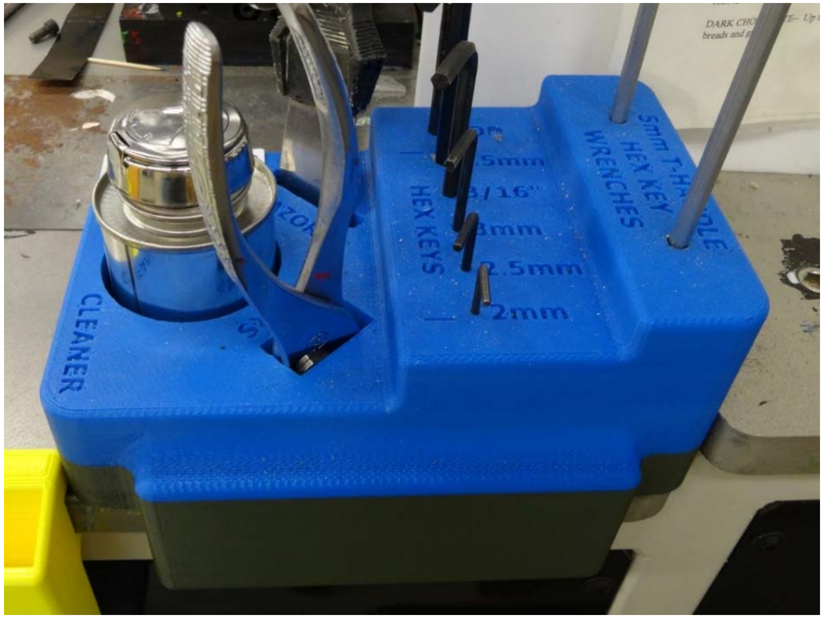
Flight-Test parts
(e.g. Helicopter Windshield Wiper Mechanisms)

Holders & etc.

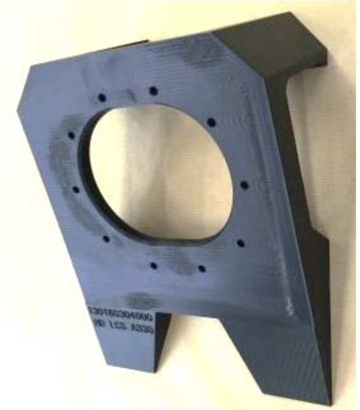


corner protector



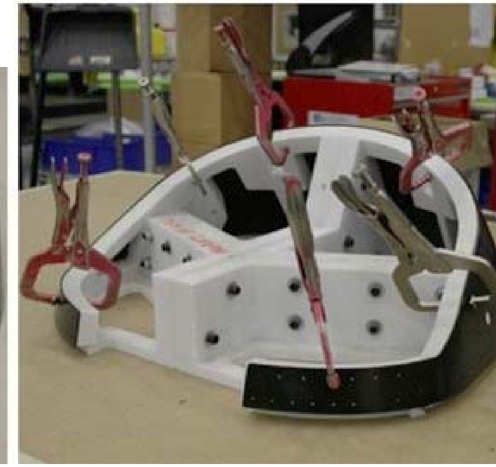


Jigs, Guides, Checks



A380 wiring guide

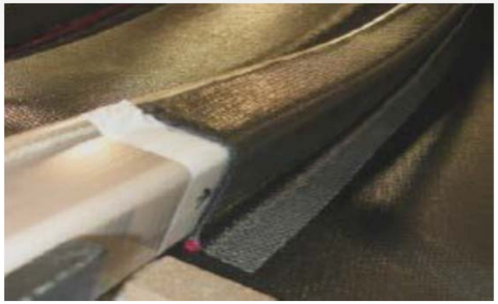
drill guide



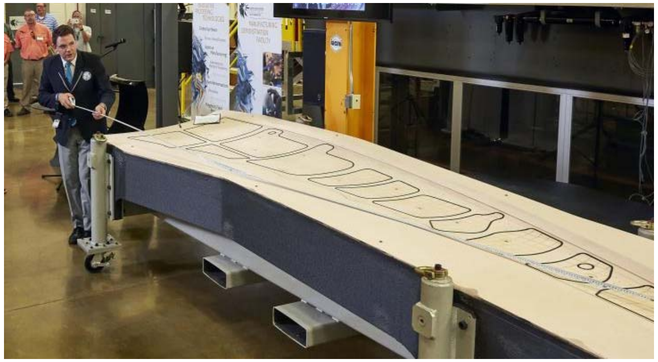
A-10 bonnet fit-check tool

T-38 floor panel jig

Tooling (e.g. plugs, Dassault Falcon molds)

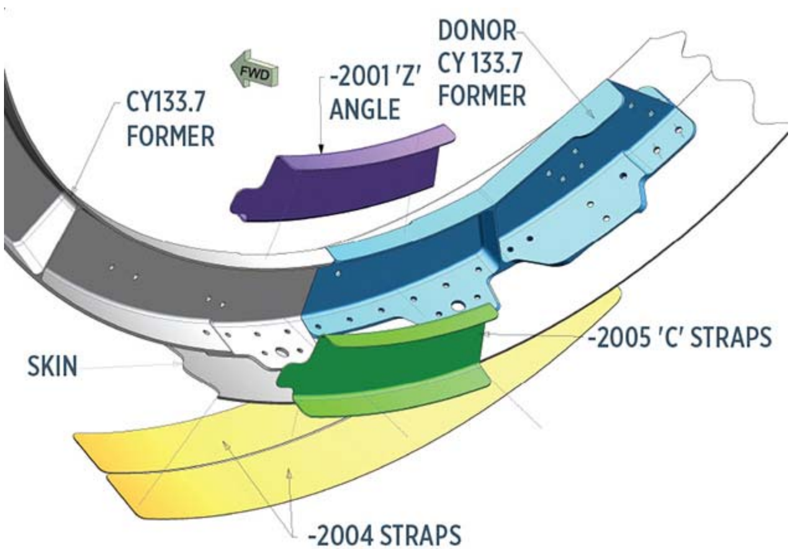


Tooling

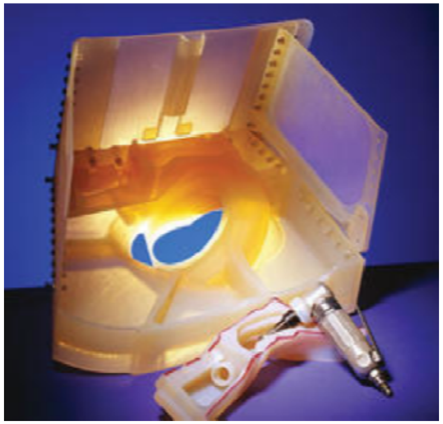


Largest 3D-printed object in the world: 777X wing tool

Shapes for Repairs



Harrier



Northrop

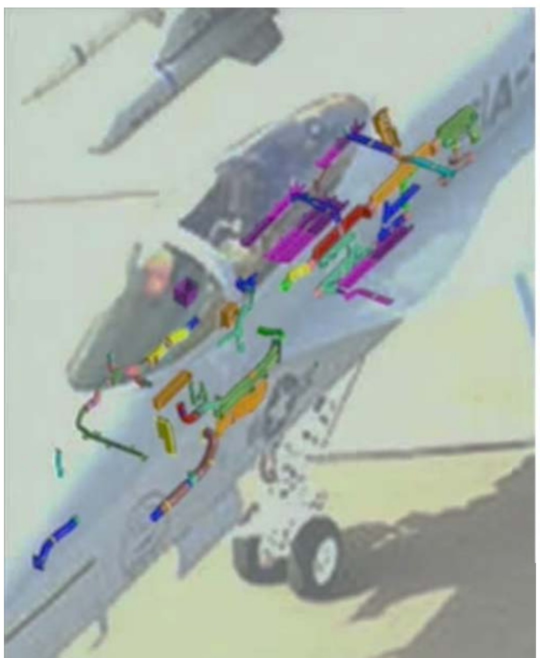
Actual Airplane Parts!

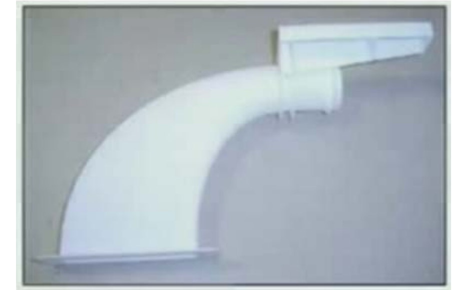
"Boeing Commercial Airplanes are currently flying 25,000 additively-manufactured parts, and the F-15 and F/A-18 fleets have about 40,000. Each 787 contains about 30 additively-manufactured parts.

Most of them are components like air ducts".

Air Ducts


F/A-18



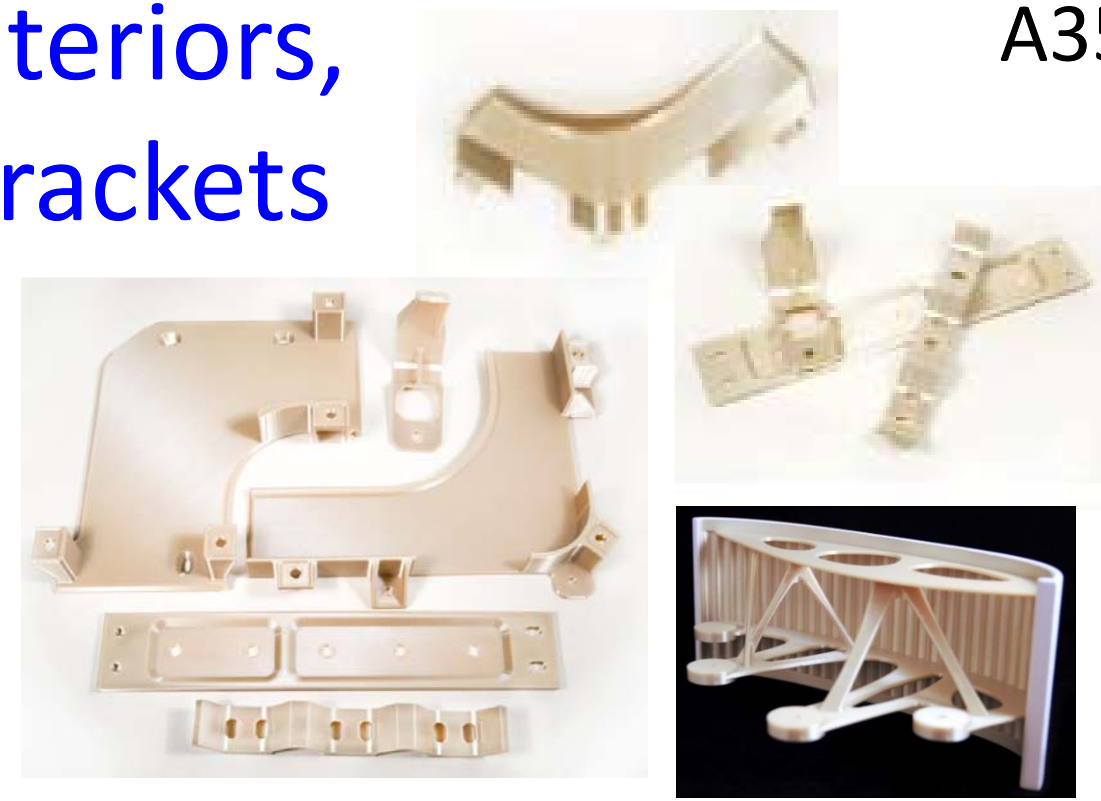



787


F-35

Bell 429

Interiors, Brackets



A350: >500 parts

Etihad

Air New Zealand

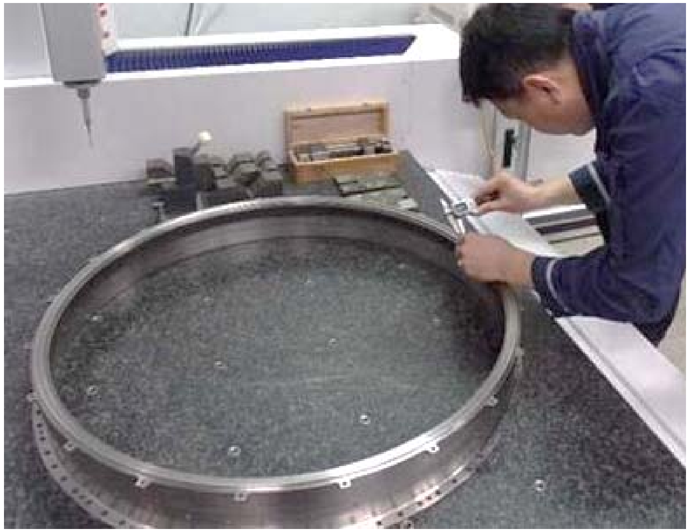
787

Propulsion

(777) GE 90 compressor inlet temperature sensor housing

(737MAX) GE Leap fuel injection nozzle (19 per!)

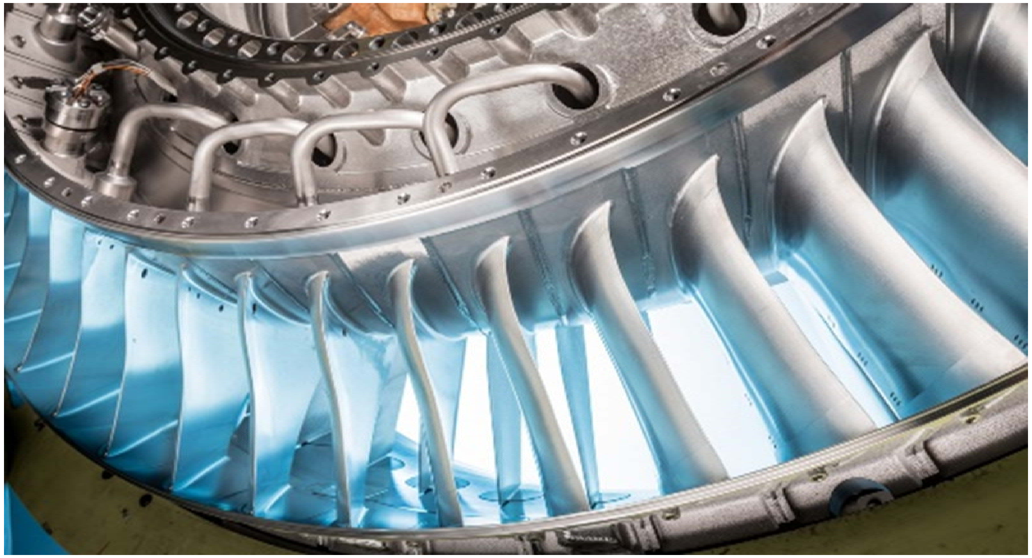
Propulsion



(F-15K)
F110-GE-129
turbine casings

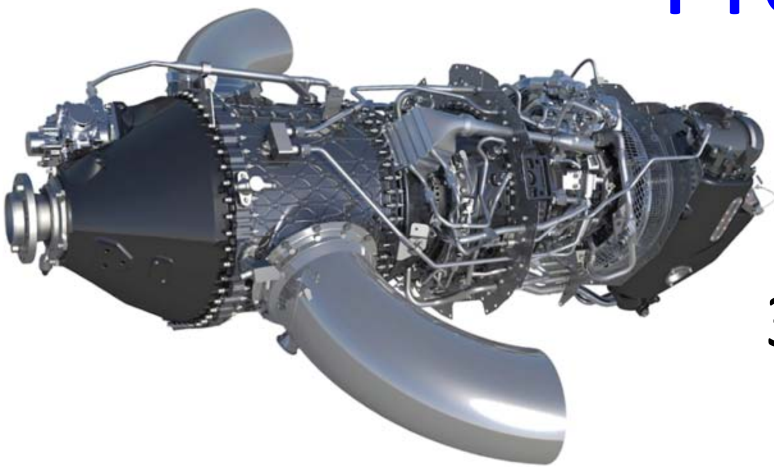
Unit cost:
$34,000 → $2,550

Lead time:
40-60 days → 20 days



Trent XWB-97 bearing housing
(A350-1000)

Propulsion

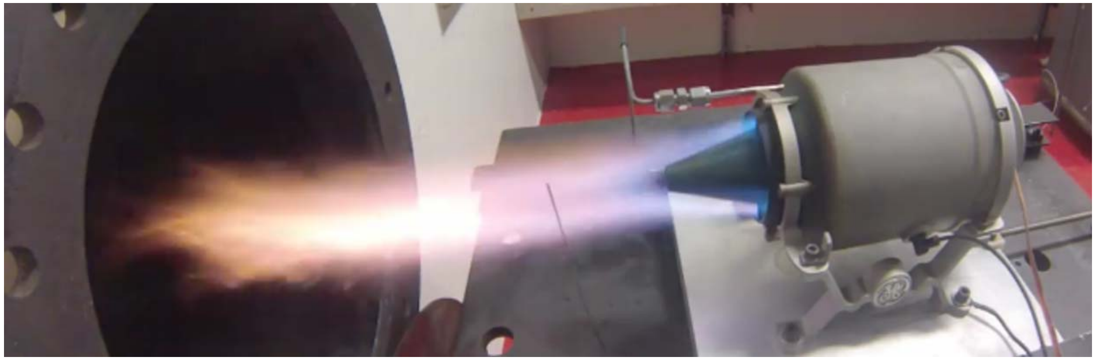


GE CT7-based "Catalyst" ATP:
900 parts became 16
3D-printed parts (Cessna Denali)

GE T700-based T901:
50 parts became a single
3D-printed part (Blackhawk)

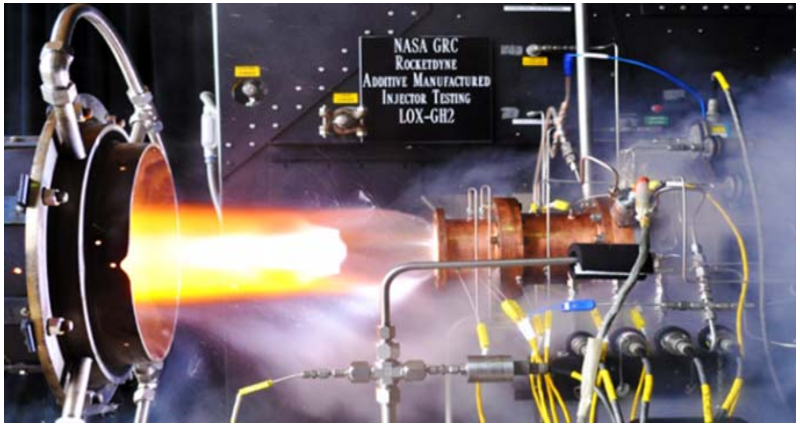
Turbomeca Arrano & Ardiden 3:
fuel injector nozzles,
combustor swirlers (Ka-62)

Propulsion; Demonstrators



GE (Jet)

Monash University & Amaero (Aerospike)



NASA & Rocketdyne (Rocket)

Small Spare Parts

A300/A310:
crew seat bracket
& seatbelt mold

DC-10
air duct

Small Spare Parts

RAF Tornado: radio covers and throttle guards

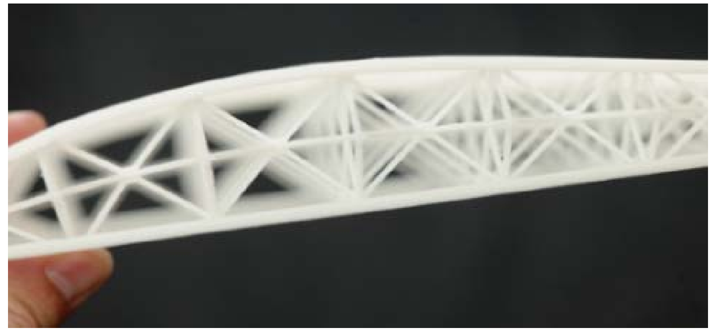
Small Spare Parts

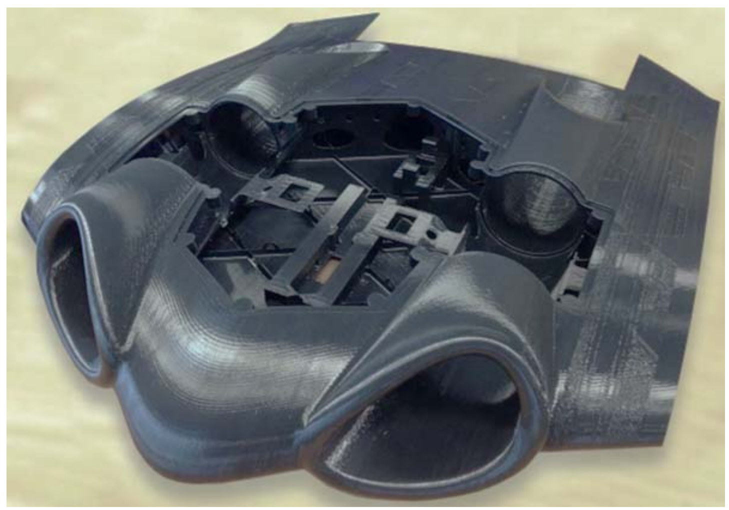
AWACS
arm-rest
end-caps

UAVs: Airbus Thor

UAVs: Aurora/Stratasys Jet

Misc. UAVs





NASA
FrankenEye

U. of Sheffield
AMRC

UVA Razor UAV

Spacecraft

SpaceX Falcon 9 Main Oxidizer Valve

AerojetRocketdyne MPS-120 cubesat propulsion system

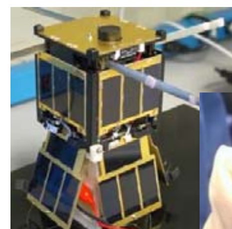
Koreasat-5A and Koreasat-7 antenna supports

Blue Origin engine pumps & nozzles

Lockheed Juno (Jupiter probe) waveguide brackets

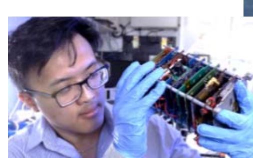
Boeing 702MP satellite Receiver Antenna Deployment Actuator cage

Boeing SES-15 satellite components



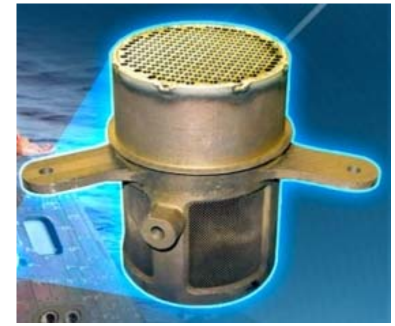
KySat-2 cubseat camera annulus, lens cover, deployable extensions, antenna clips, and battery holders

UNSW-Ec0 cubesat chassis



Lockheed A2100 backing connectors

Spacecraft (Crewed)

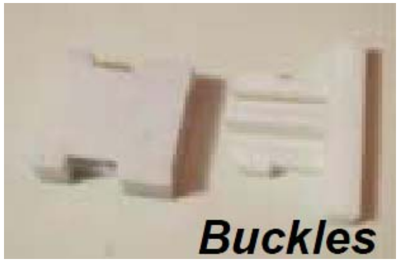


Shenzhou 10 seats

CST-100 structure
(~600 3D-printed parts!)

Orion pressure vents

Tools & etc. on the ISS



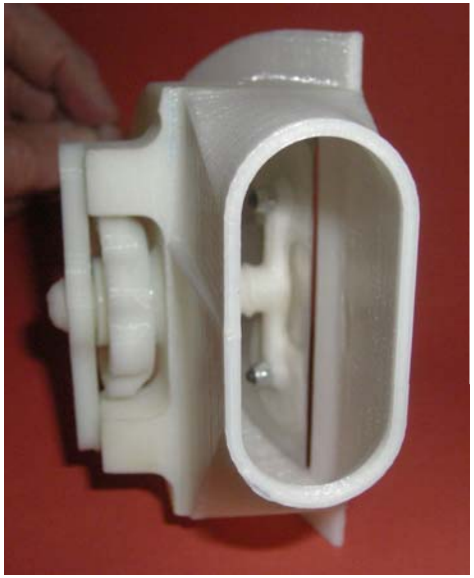
100% 3D-Printed Rocket?

Relativity Space: Terran rocket, Stargate printer, Aeon-1 engine

In a homebuilt airplane near you: EMG-6 clips & fairings

In a homebuilt airplane near you:

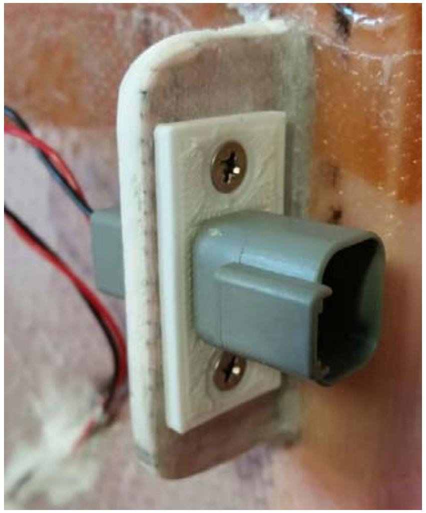
Sonex air intake

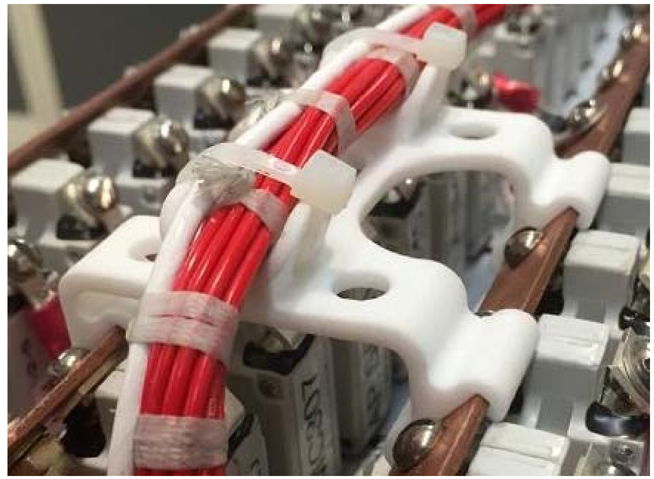


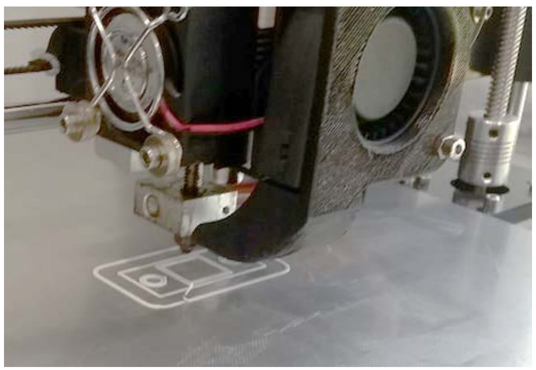




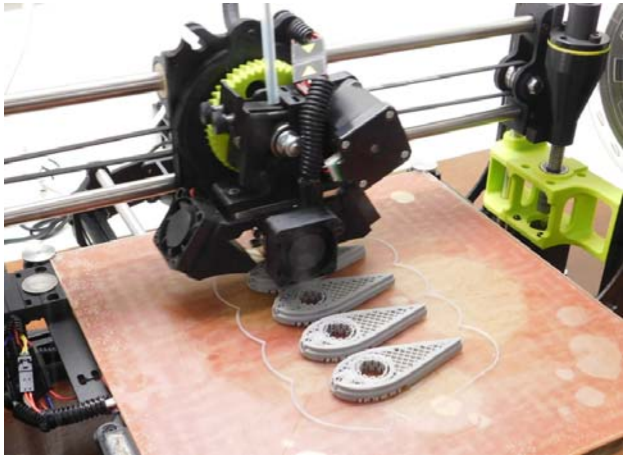
In a homebuilt airplane near you: RV wire brackets / clips / holders





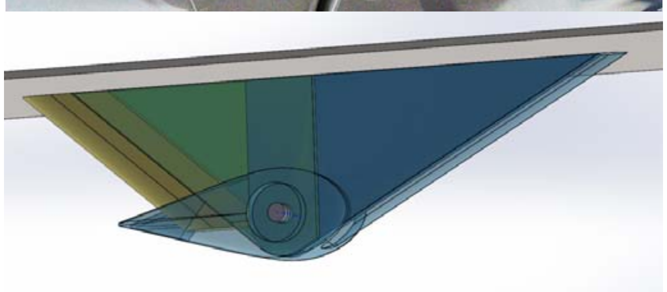


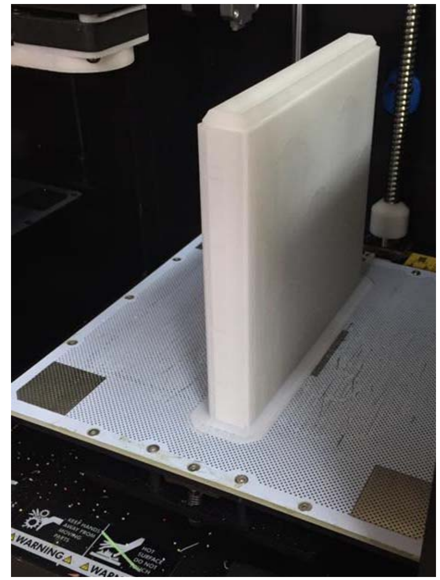
In a homebuilt airplane near you:
RV fuel drain fairings



In a homebuilt airplane near you:

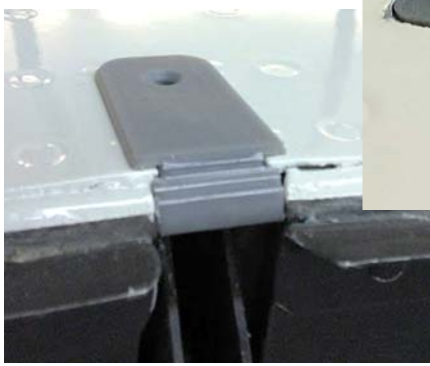
RV flap bracket fairings, EZ map pocket

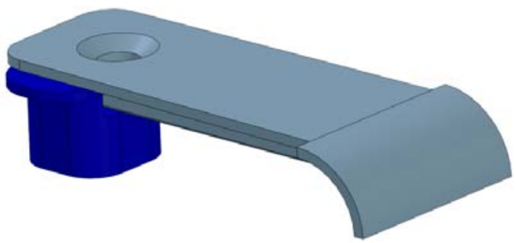


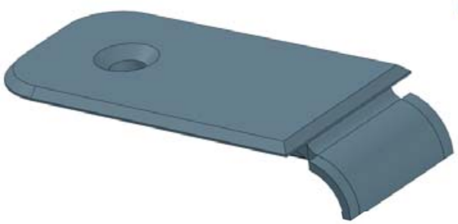


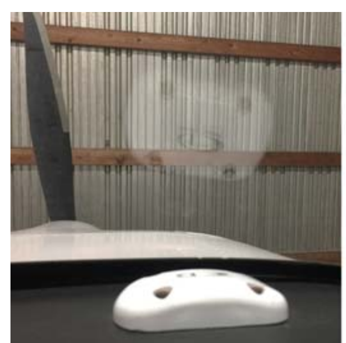
In a homebuilt airplane near you:

RV Hinge Cover, GPS antenna anti-glare cover, seatbelt holder





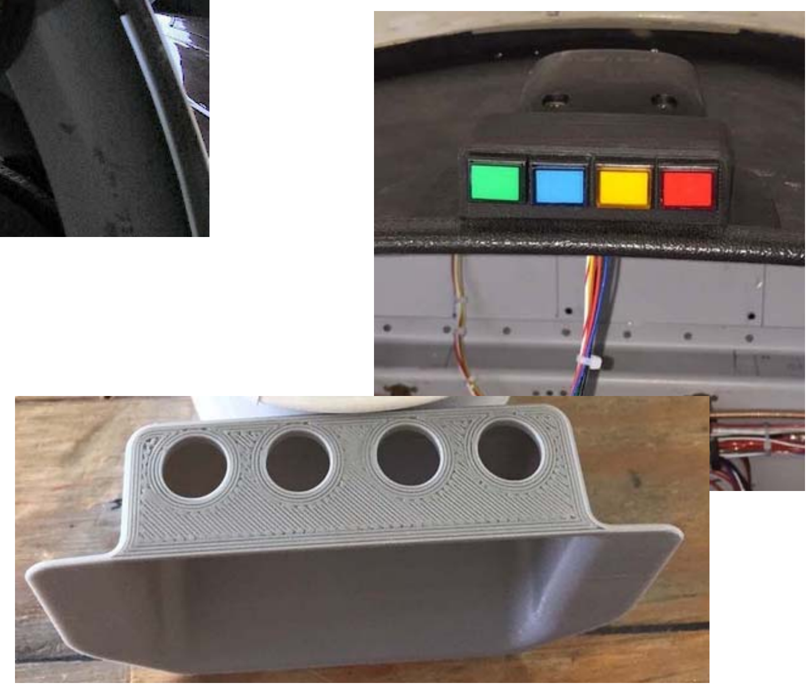




In a homebuilt airplane near you:
RV landing light bezel, step cap,

In a homebuilt airplane near you:

RV mirror holders, EFIS glare shield, lighting mount

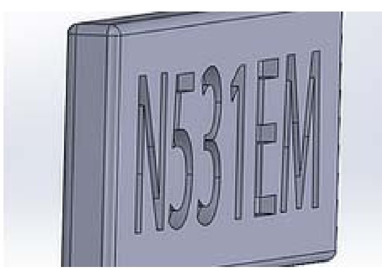


In a homebuilt airplane near you: 3D-printed RV parts for sale!

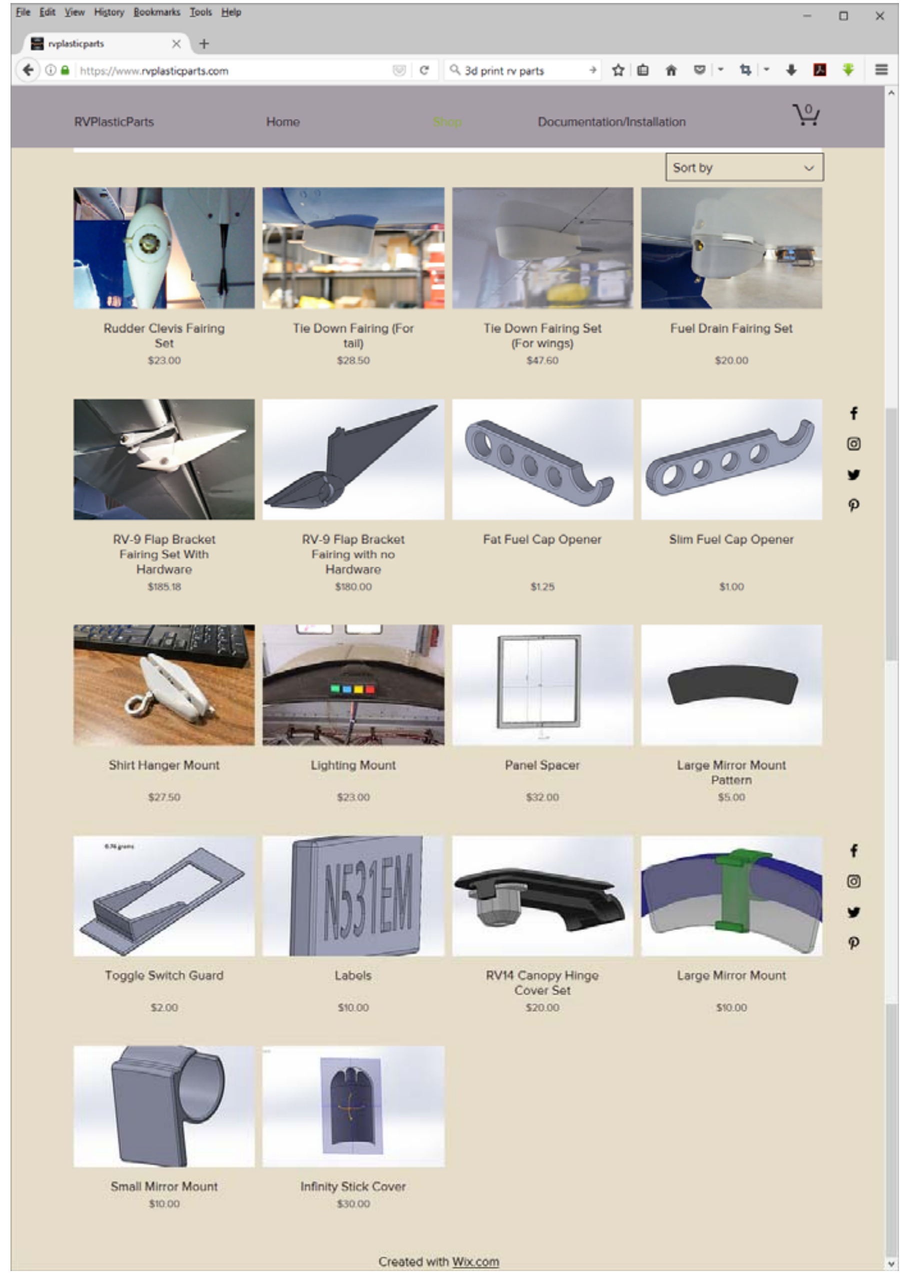

Rudder Clevis Fairing Set


Tie Down Fairing Set (For wings)


Panel Spacer

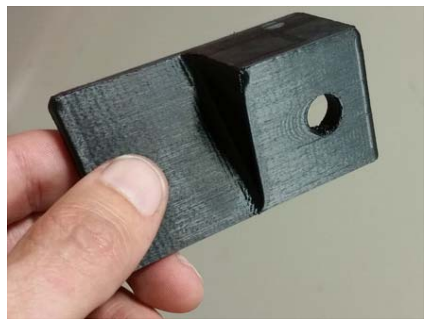

Labels

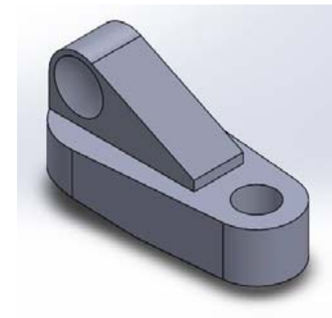
including custom parts!

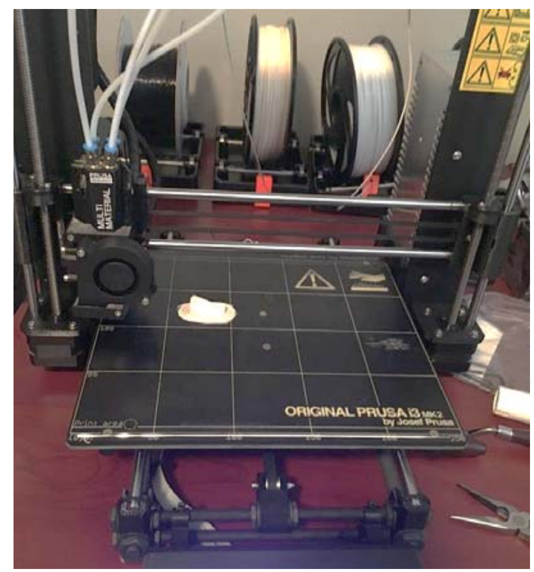


In a Piper near you:

Cub heating duct and carb heat bracket, Cherokee storm window latch



To recap so far…

When does 3D-printing deliver the lowest-cost solution?

Low production rate & unique articles:

- Spacecraft
- Interiors spare parts
- Test-related equipment, mock-ups, prototypes
- Tooling
- Homebuilts

Complex geometry; Lowering buy-to-fly ratio, reducing weight, combining many small components:

- Air ducts
- Engine components

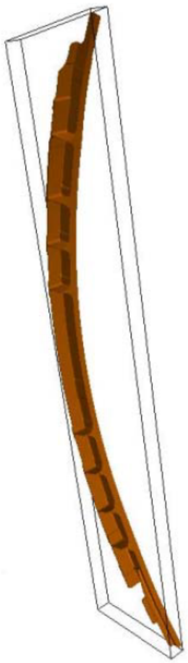
Airplane Structures?

Why try?

- Low “buy to fly” ratio
- Highly optimized, lower-weight, “organic” shapes
- Less inventory, “print on demand” parts, simpler supply chain
- *…maybe.*

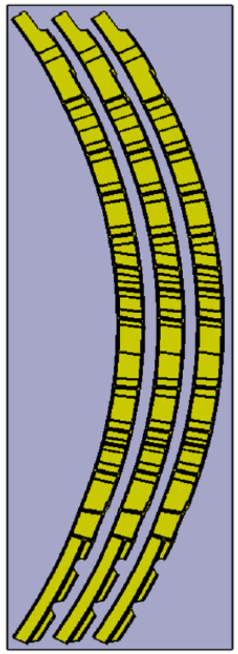
"Buy-to-Fly Ratio"

Cut from Plate



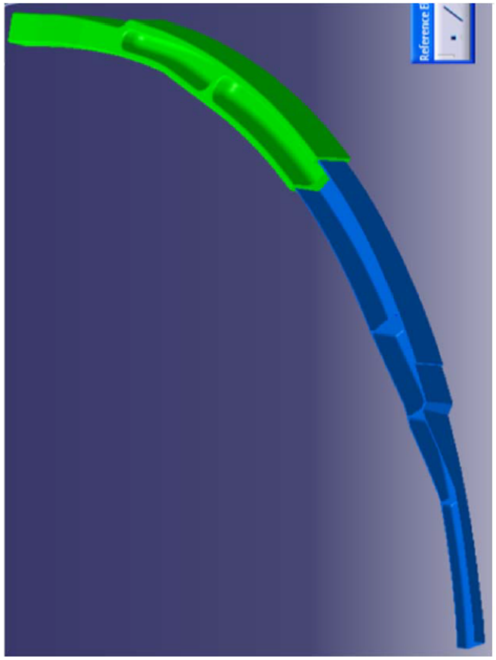
1347 lbs/frame
27:1

Nested Plate



575 lbs/frame
11.5:1

Die Forging

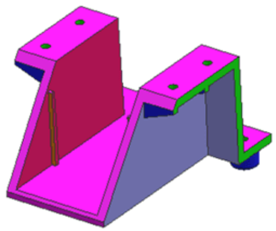


425 lbs/frame
8.5:1

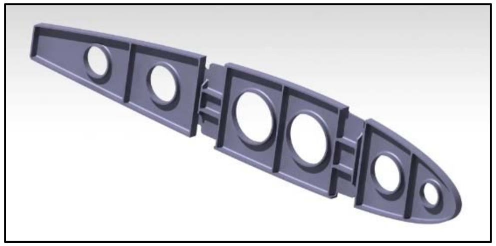
Weldment

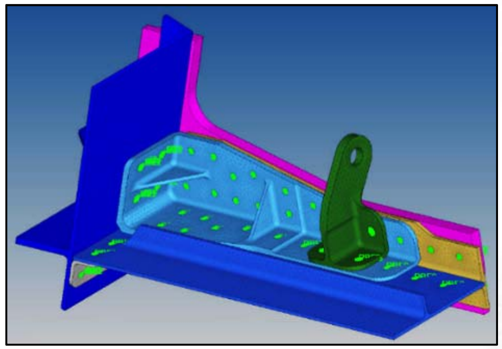
100 lbs/frame
2:1

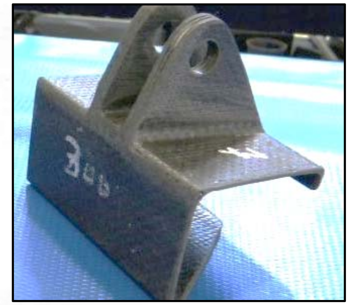
3D printing "cuts the buy-to-fly ratio of titanium parts from as much as **40-to-1** to as little as **3-to-1**".

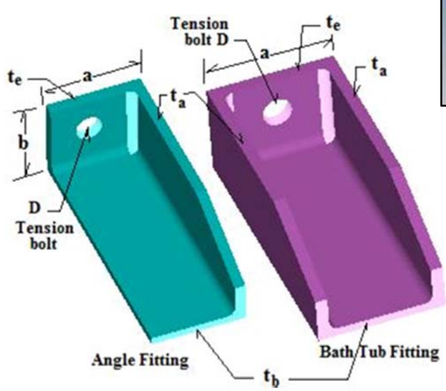


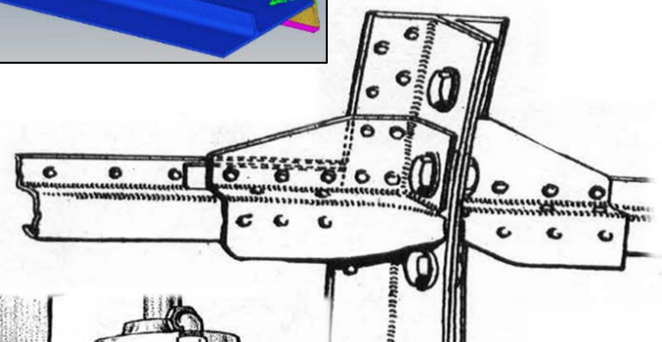
Traditional Airplane Part Design & Analysis

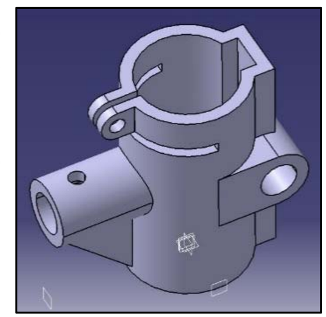


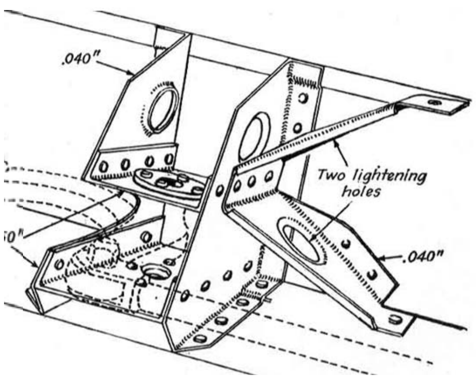


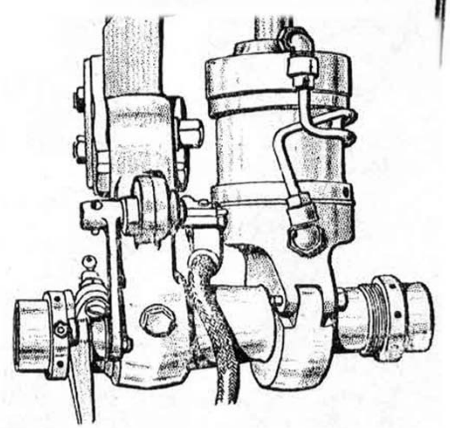








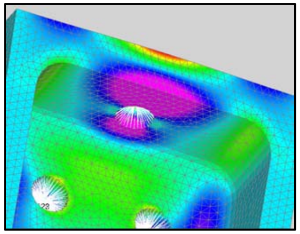
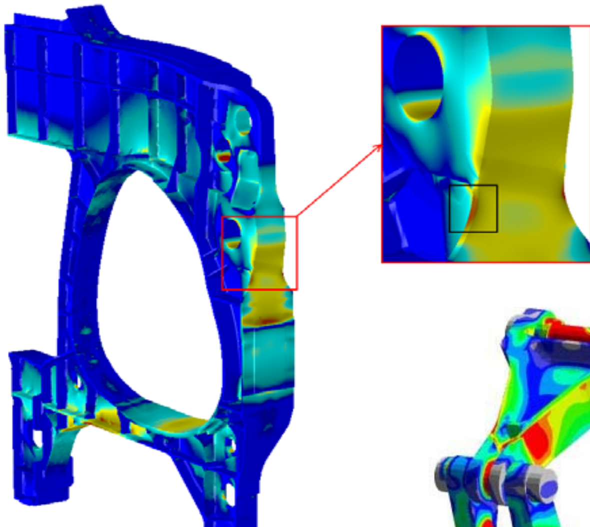
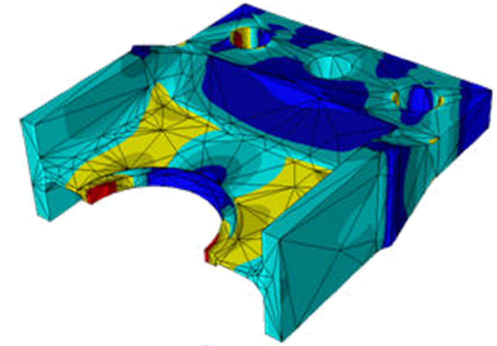
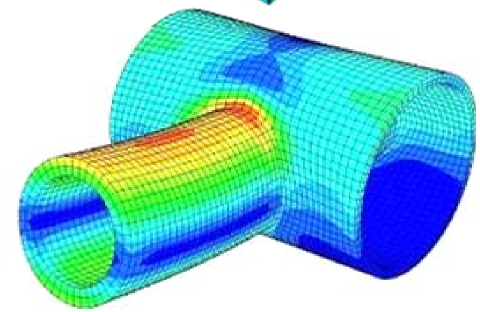
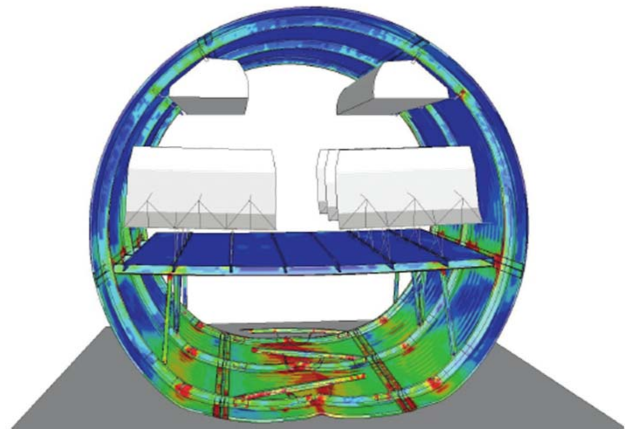
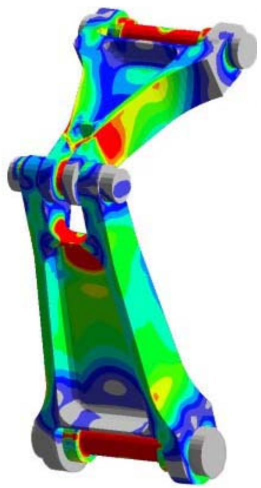
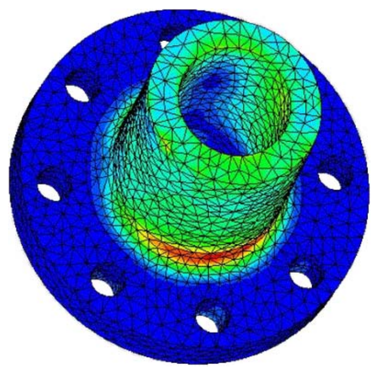
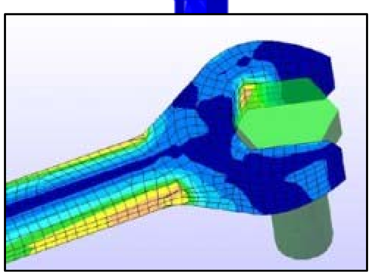
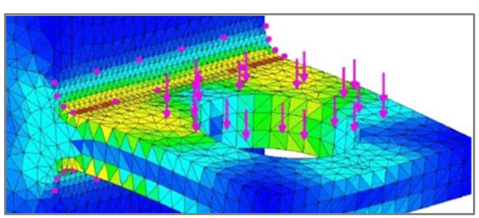
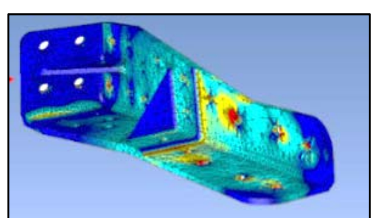




Design for manufacturability:

- Surfaces at 90 degrees
- Constant widths and thicknesses
- Parallel and flat edges and surfaces
- Straight lines and circles

Traditional Airplane Part Design & Analysis

Finite Element Analysis and weight reduction:

Ideally, if we could, we would…

- Shave away some material / use curvier or sharper angle where stress is low (blue)
- Make the part a little thicker / use flatter / blended shapes where stress is high (red)

Highly Optimized Structure

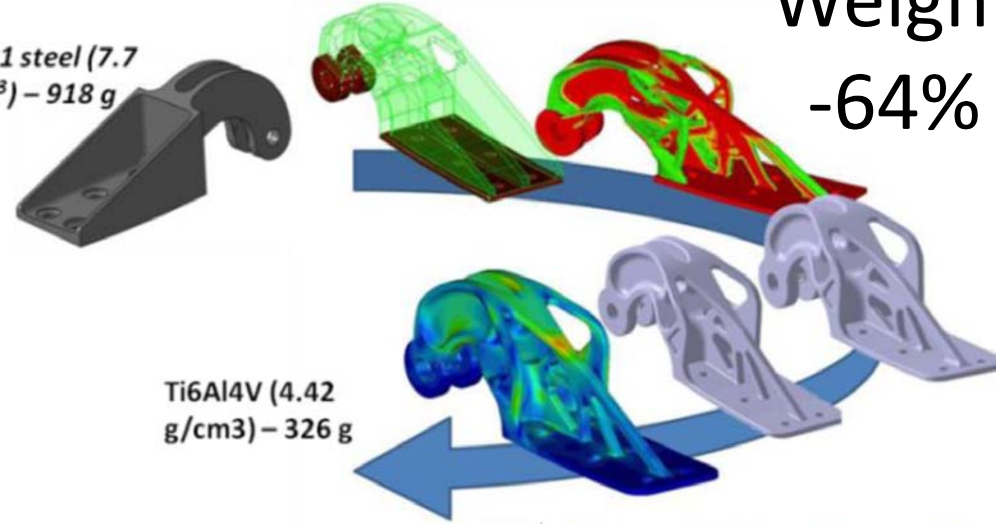
Weight
-42%

conventional bracket

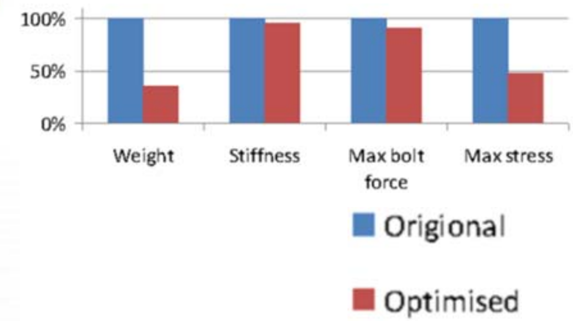
- $12 \cdot 10^4$ mm^3
- Aluminium 7075
- 330 g

final design

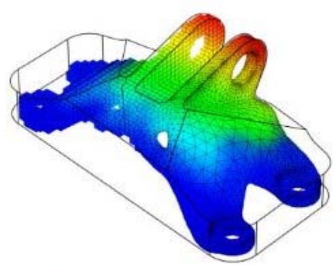
- $4{,}3 \cdot 10^4$ mm^3
- Titanium TiAl6V4
- 191 g



Weight
-64%



GE's original design
The original design of the bracket used in the GE Aircraft challenge. The re-designed bracket was required to fit within this volume and meet load requirements while reducing the overall weight of the part.

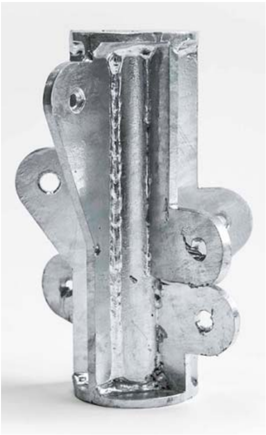


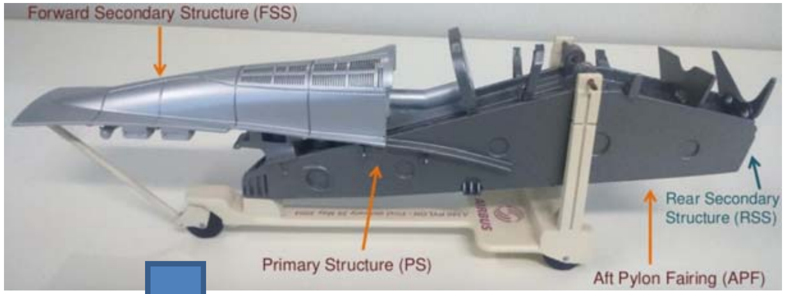
Cloudmesh optimization
The topology optimized part design generated by Frustum's software.

Final DMP part
The GE Aircraft engine bracket redesigned by Frustum and manufactured by Quickparts on a 3D Systems ProX DMP 320 printer. The new part passed all the load condition requirements specified by the GE challenge and stayed within the same footprint while reducing weight by a staggering 70 percent.

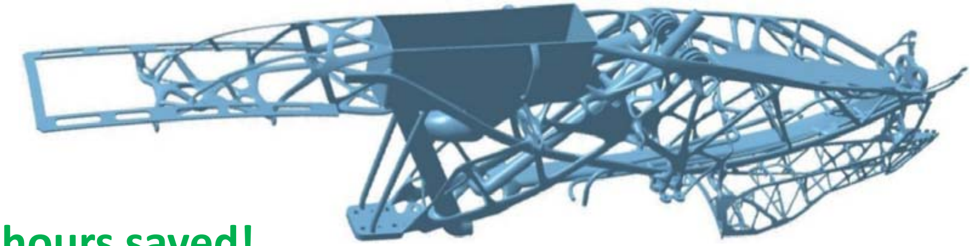
Weight
-70%

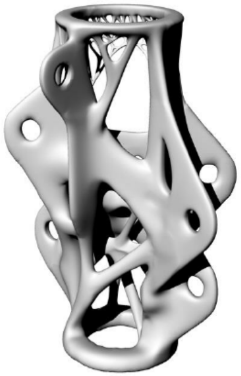
Highly Optimized Structure



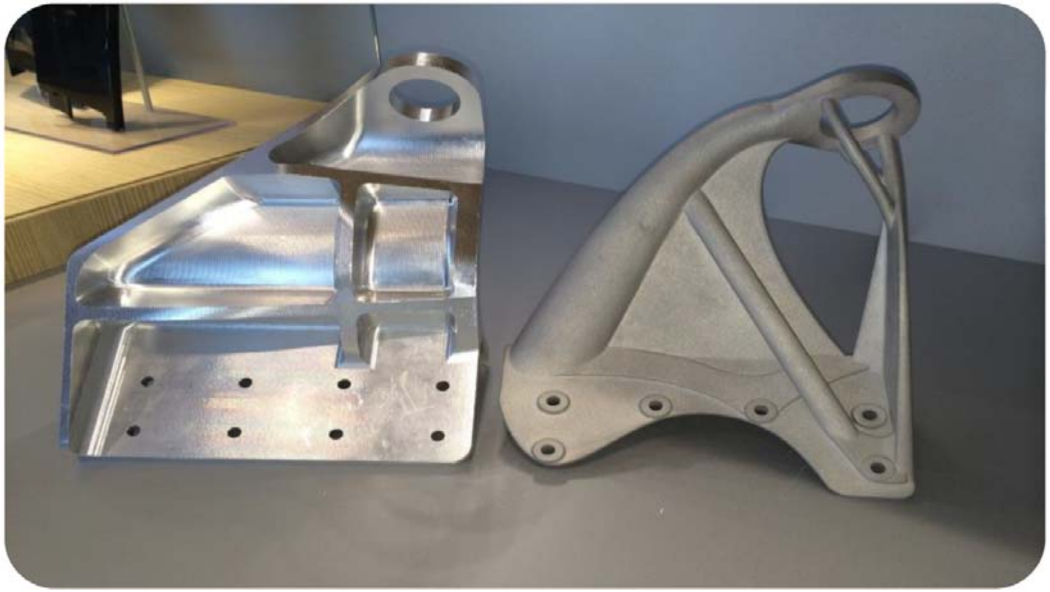


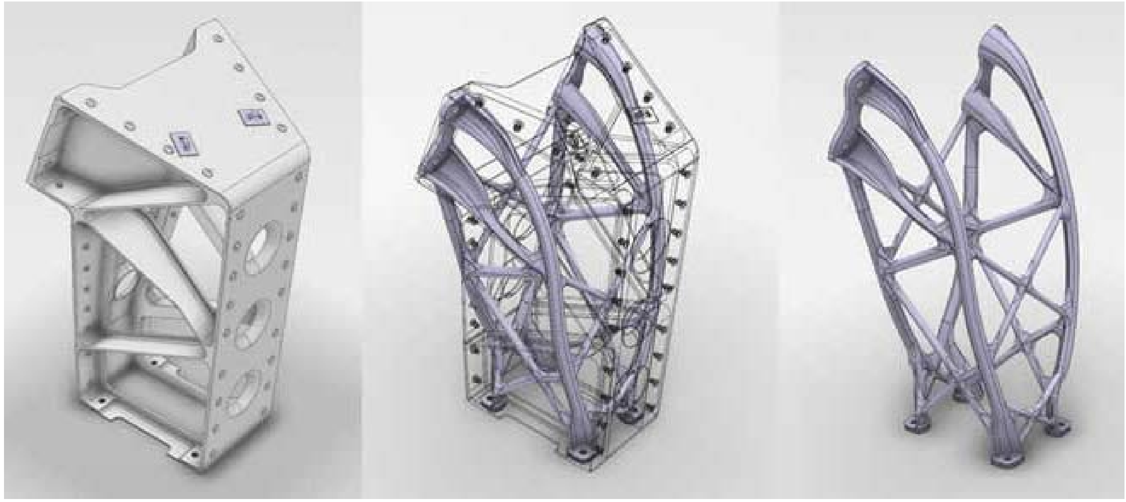
1000 lbs → 770 lbs!
654 parts → 14 parts!
2600 attachments
→ 350 attachments!
Hundreds of assembly hours saved!



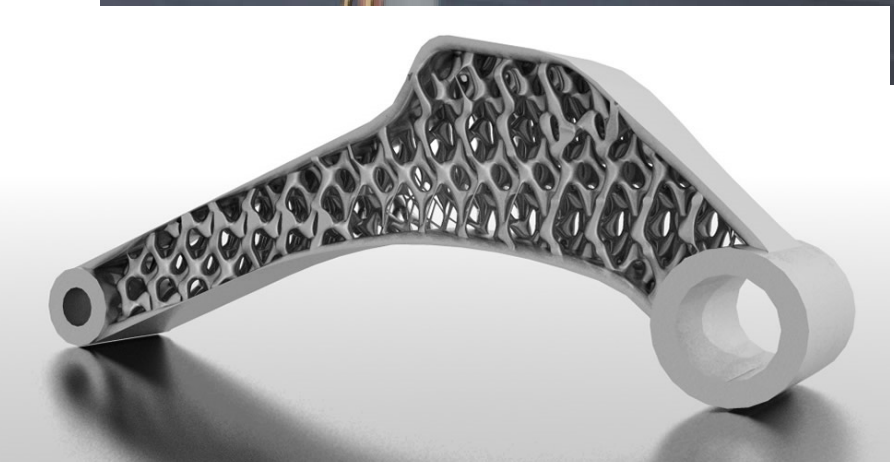


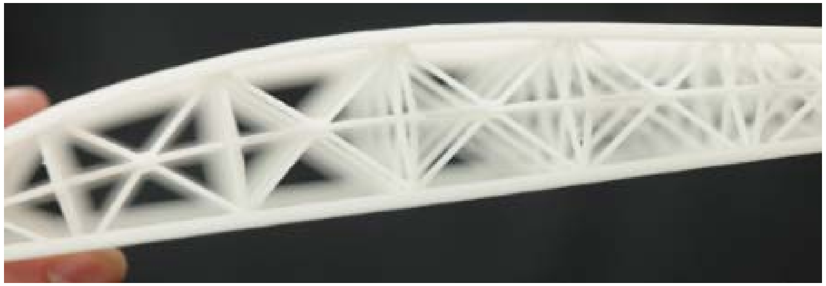
Highly Optimized Structure





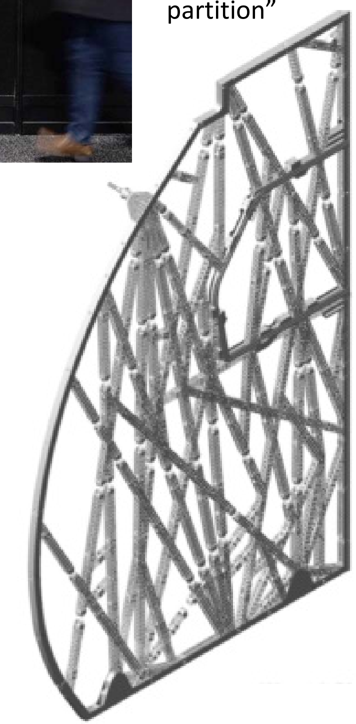
Lattice / "Micro-Truss" Structure





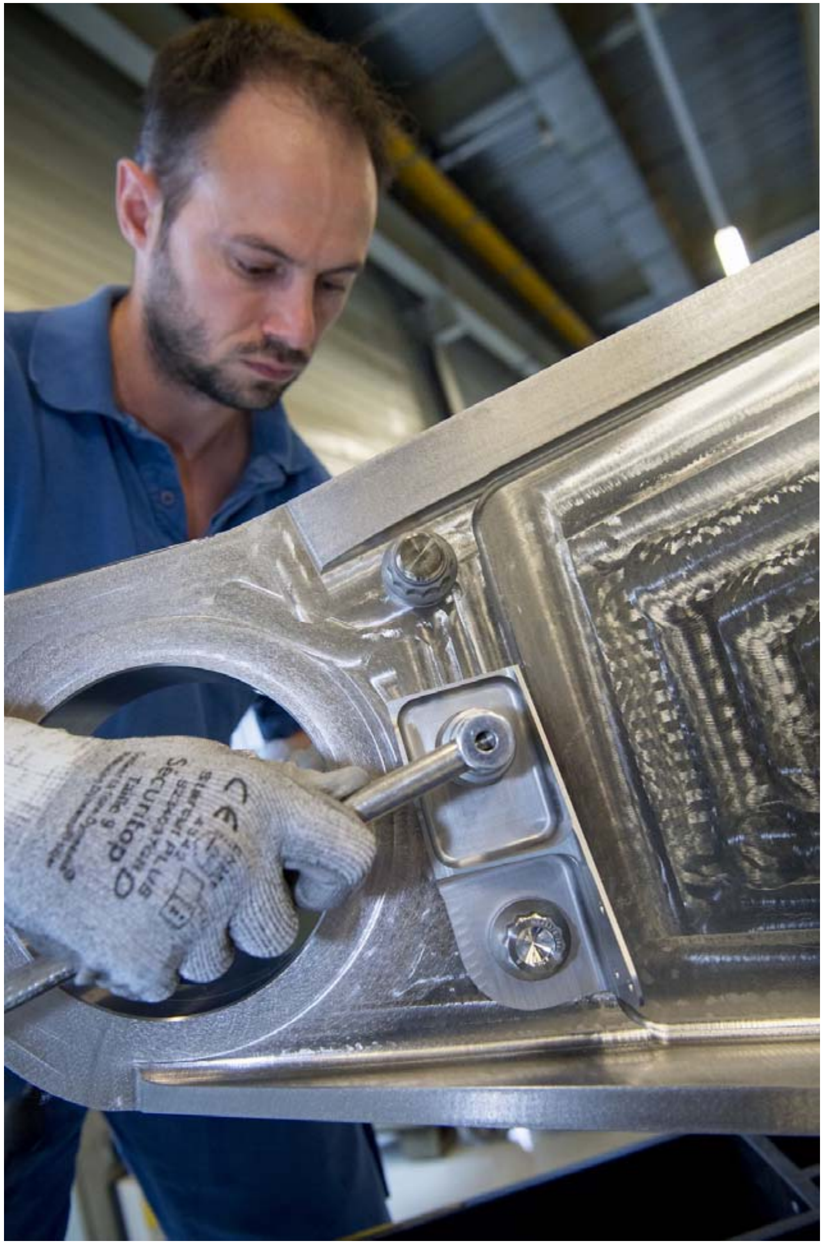
Airbus Brackets & “Bionic Partition”

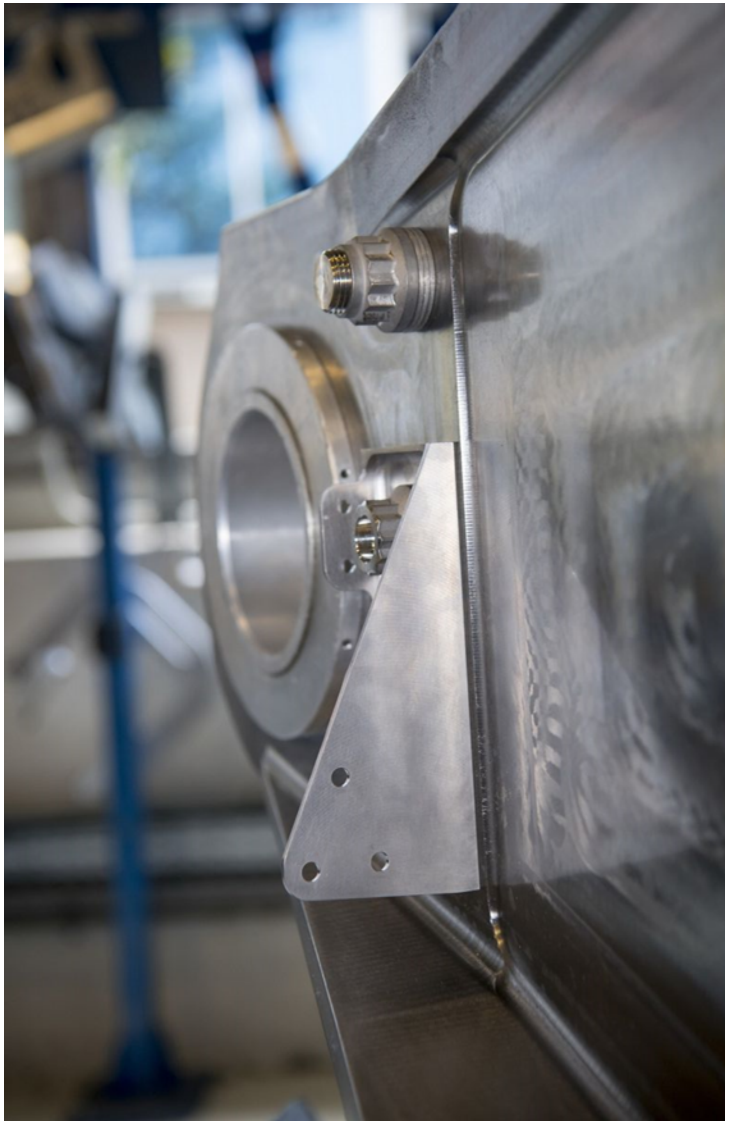
Interior “bionic partition”



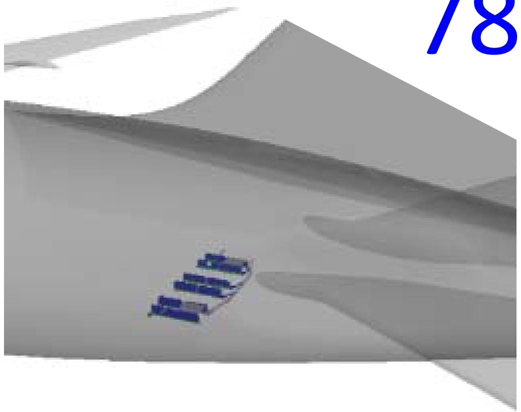
-122 parts in 7 builds in Scalmalloy
-40 parts in Titanium

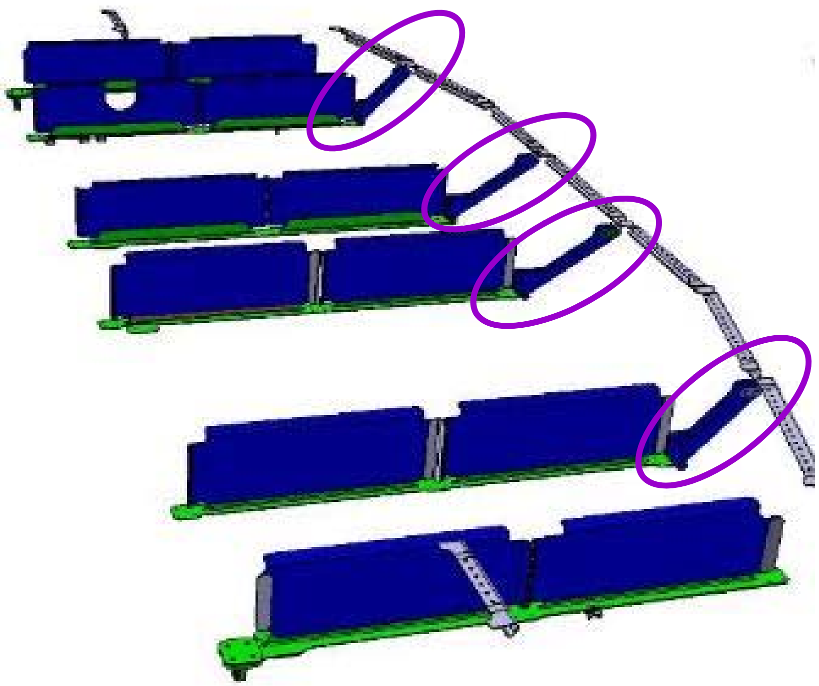
A350 pylon bracket



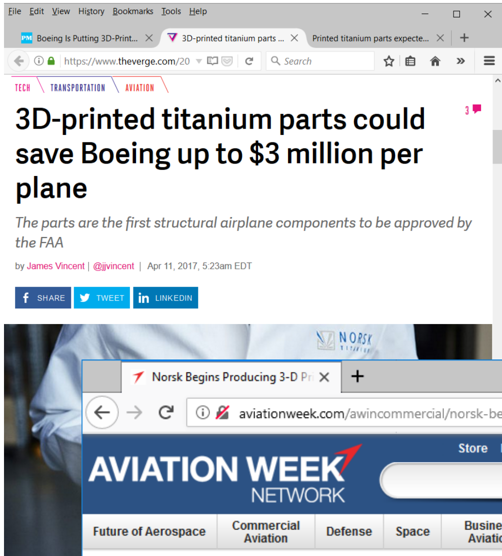


787 Aft Galley Diagonal Fitting





787 Aft Galley Diagonal Fitting



TECH \ TRANSPORTATION \ AVIATION

3D-printed titanium parts could save Boeing up to $3 million per plane

The parts are the first structural airplane components to be approved by the FAA

by James Vincent | @jjvincent | Apr 11, 2017, 5:23am EDT

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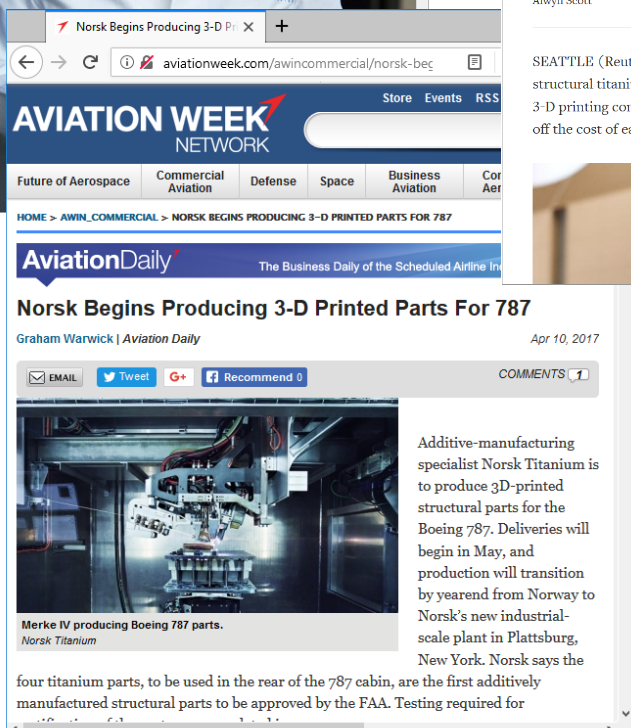

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AviationDaily The Business Daily of the Scheduled Airline Industry

Norsk Begins Producing 3-D Printed Parts For 787

Graham Warwick | Aviation Daily Apr 10, 2017

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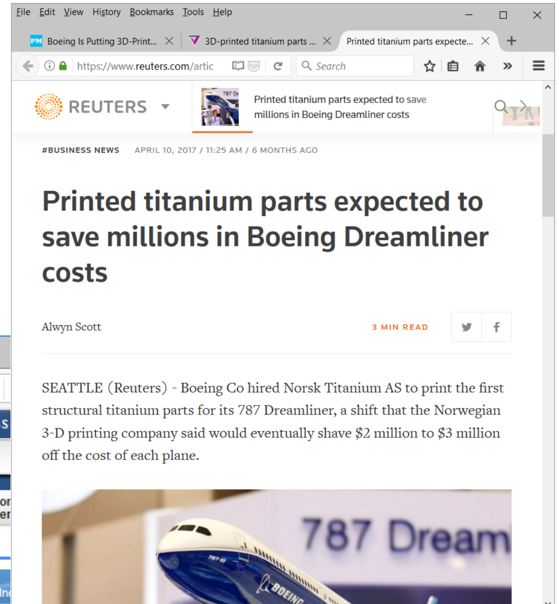
Merke IV producing Boeing 787 parts.
Norsk Titanium

Additive-manufacturing specialist Norsk Titanium is to produce 3D-printed structural parts for the Boeing 787. Deliveries will begin in May, and production will transition by yearend from Norway to Norsk's new industrial-scale plant in Plattsburg, New York. Norsk says the four titanium parts, to be used in the rear of the 787 cabin, are the first additively manufactured structural parts to be approved by the FAA. Testing required for



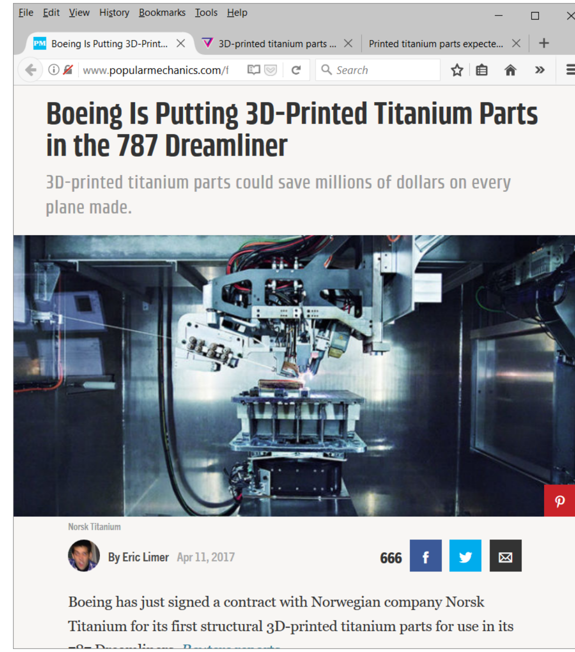
REUTERS

#BUSINESS NEWS APRIL 10, 2017 / 11:25 AM / 6 MONTHS AGO

Printed titanium parts expected to save millions in Boeing Dreamliner costs

Alwyn Scott 3 MIN READ

SEATTLE (Reuters) - Boeing Co hired Norsk Titanium AS to print the first structural titanium parts for its 787 Dreamliner, a shift that the Norwegian 3-D printing company said would eventually shave $2 million to $3 million off the cost of each plane.



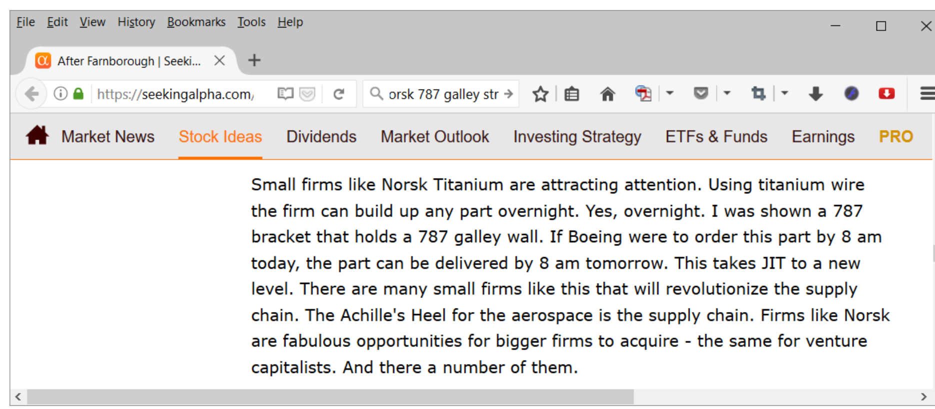
Boeing Is Putting 3D-Printed Titanium Parts in the 787 Dreamliner

3D-printed titanium parts could save millions of dollars on every plane made.

Norsk Titanium

By Eric Limer Apr 11, 2017 666

Boeing has just signed a contract with Norwegian company Norsk Titanium for its first structural 3D-printed titanium parts for use in its



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Small firms like Norsk Titanium are attracting attention. Using titanium wire the firm can build up any part overnight. Yes, overnight. I was shown a 787 bracket that holds a 787 galley wall. If Boeing were to order this part by 8 am today, the part can be delivered by 8 am tomorrow. This takes JIT to a new level. There are many small firms like this that will revolutionize the supply chain. The Achille's Heel for the aerospace is the supply chain. Firms like Norsk are fabulous opportunities for bigger firms to acquire - the same for venture capitalists. And there a number of them.

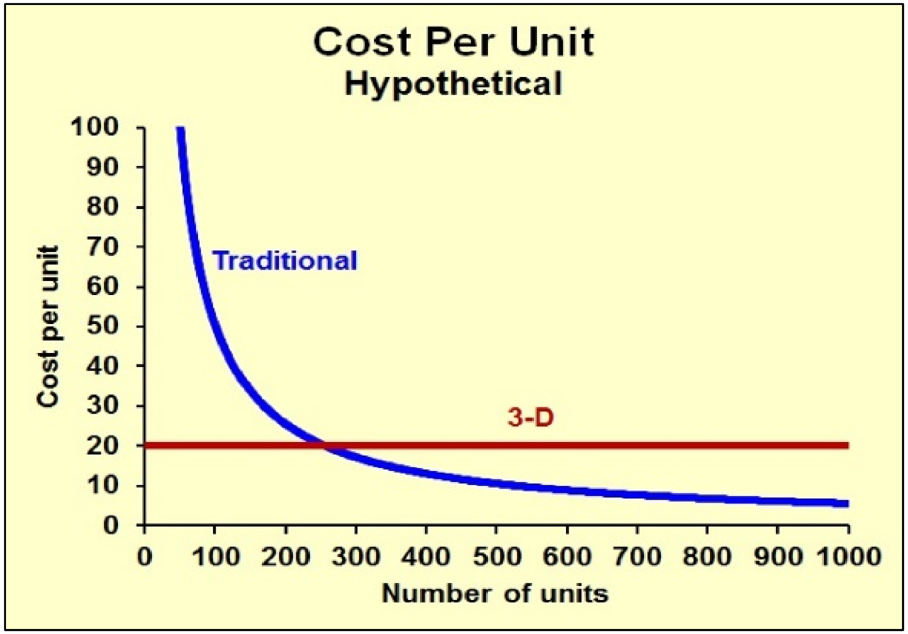
3D Printed Metal Structure, More Examples

F-15

Next Steps?

Why don't we print a whole airplane?
Two reasons.

1) Cost:



2) Safety! [See next slide]

How do we “ensure” safety?

FAR 25 does a good job establishing requirements that preserve safety:

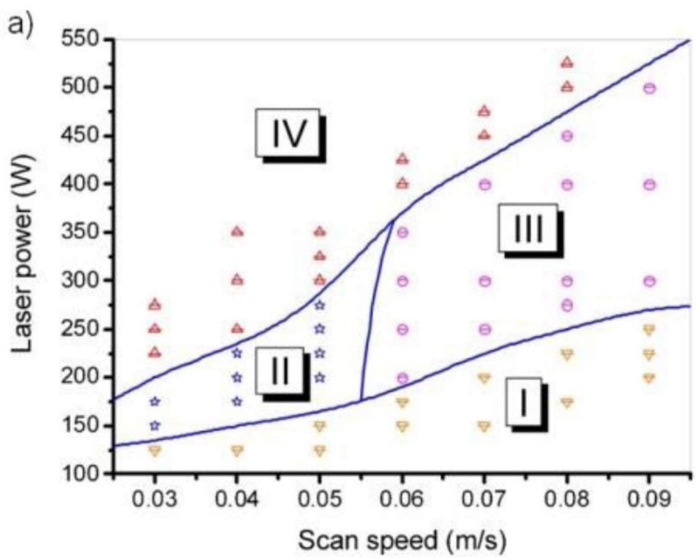
CFR 25.603 & 25.605: Materials must be tested. Fabrication must be consistent, new methods must be tested. Materials should have specs, many processes should have controls/specs too.

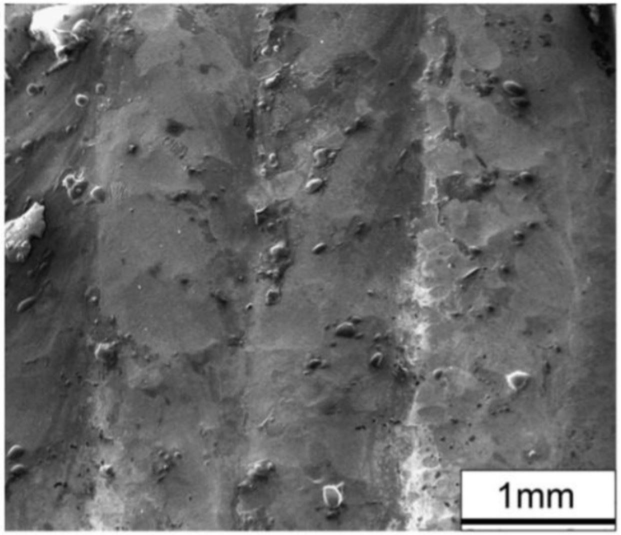
CFR 25.305, 25.307 & 25.601: Structure must be strong. Analysis or tests must show this. Details must be reliable, tests must show this.

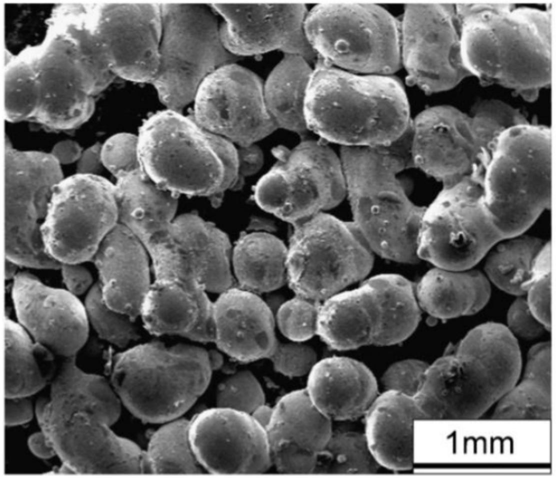
Challenges

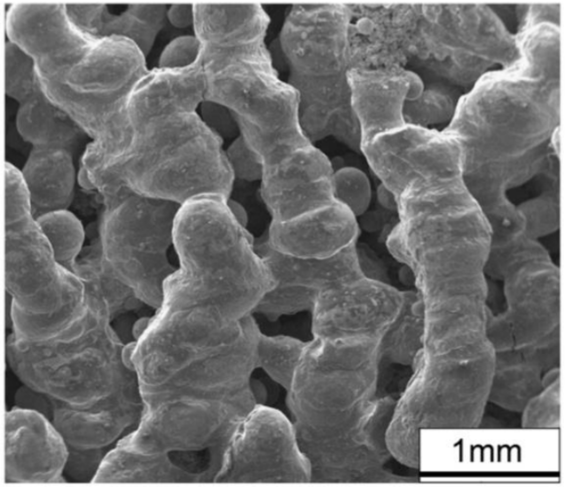
"The **critical standards** are still being written, but the industry needs to keep moving… You have very little **design data**… There's a huge amount of work around **consistency**… Everybody wants to **be second**…"

Consistency, Process-Dependence



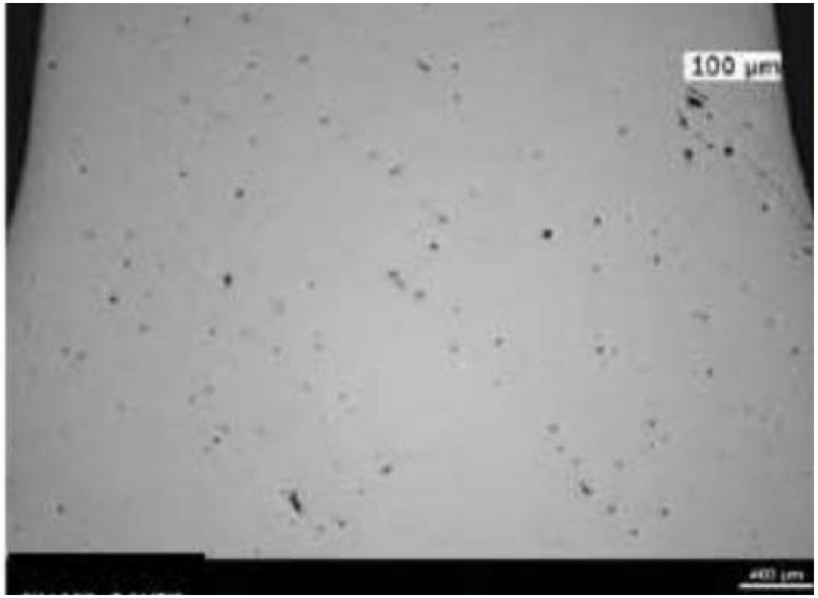




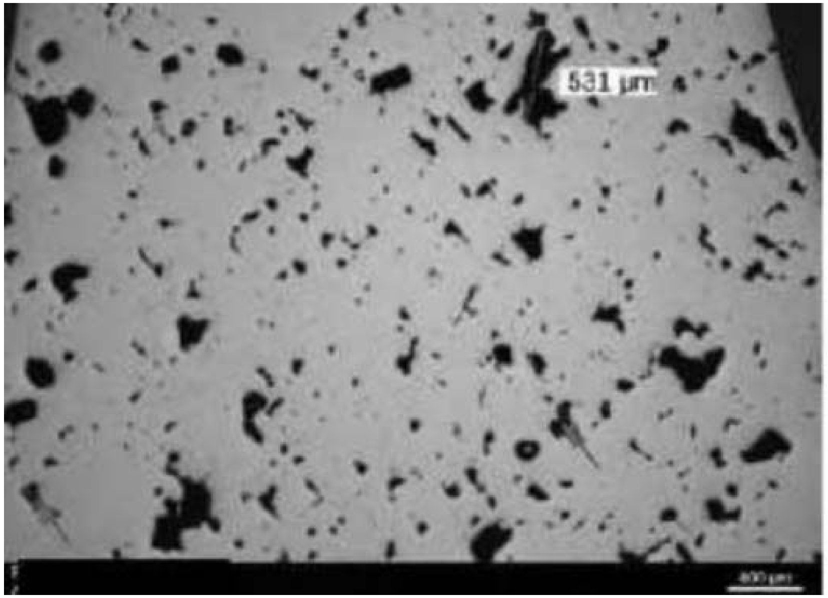


Consistency, Process-Dependence

17-4 Steel

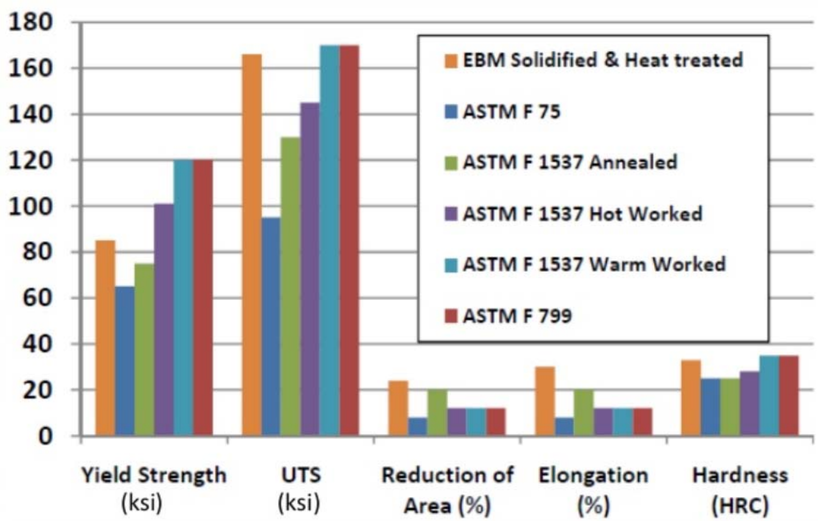


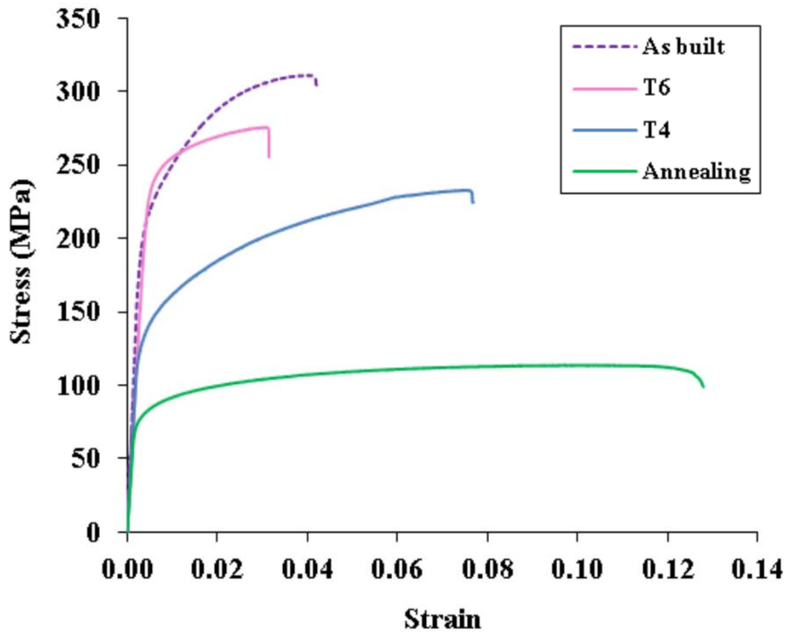
Power = 190 W
V_{scan} = 0.80 m/s
T_{layer} = 30 μm



Power = 190 W
V_{scan} = 1.30 m/s
T_{layer} = 50 μm

Process-Dependence: Heat-Treats



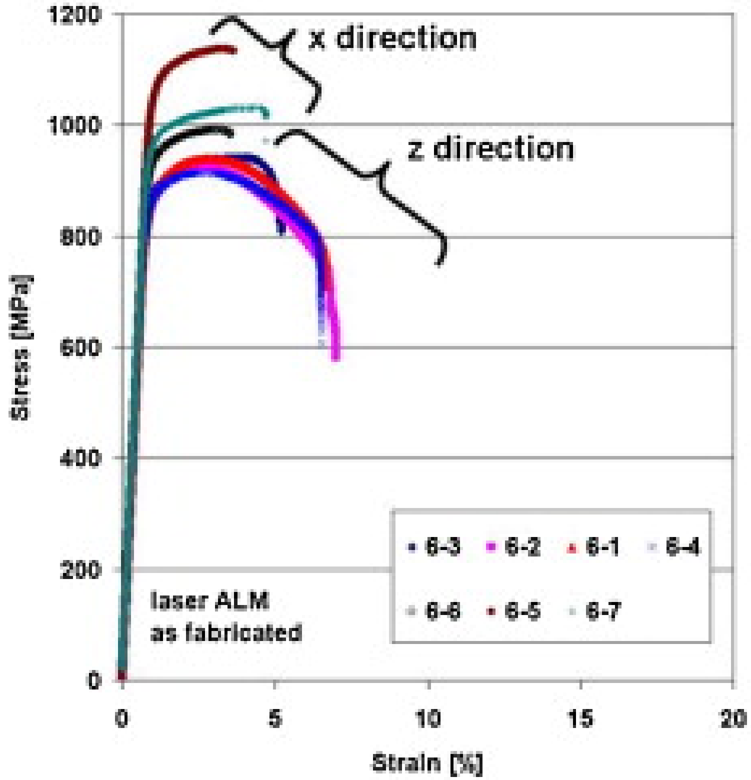


66 Co – 28 Cr – 6 Mo

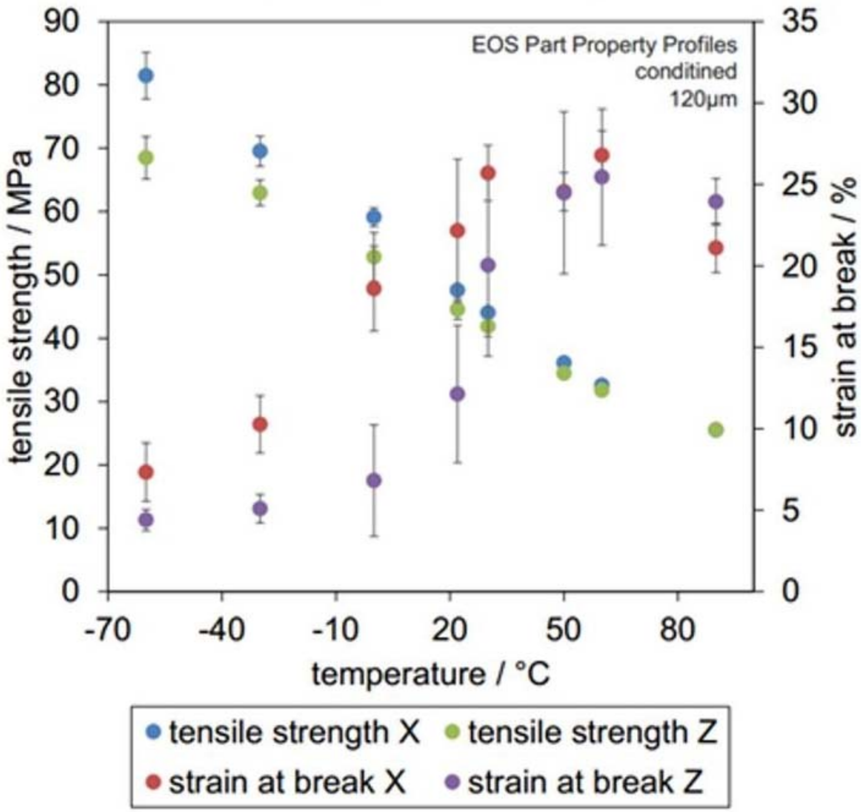
Al – Si – 10Mg

Also: Thickness, curvature…

Directionality



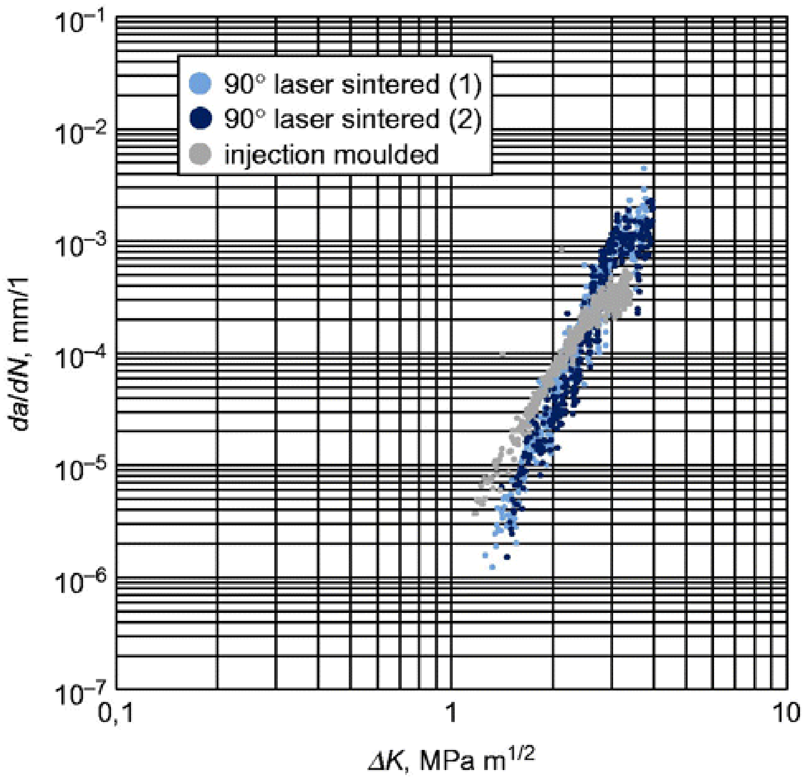
Ti–6Al–4V

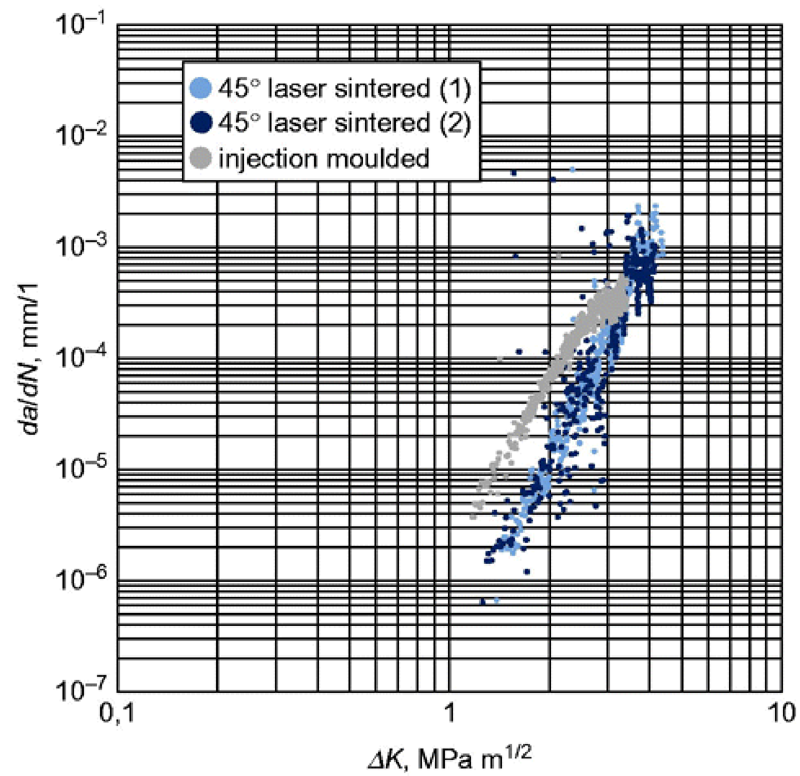


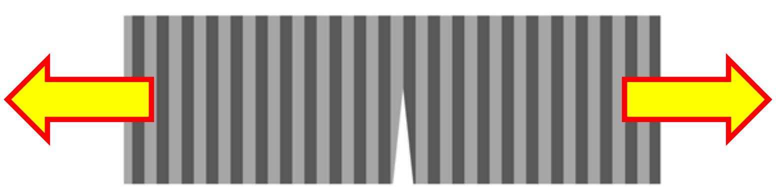
PA12

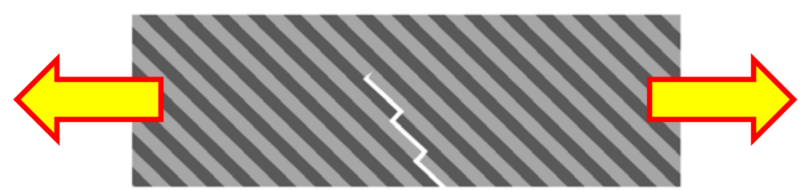
Directionality

(PA12)





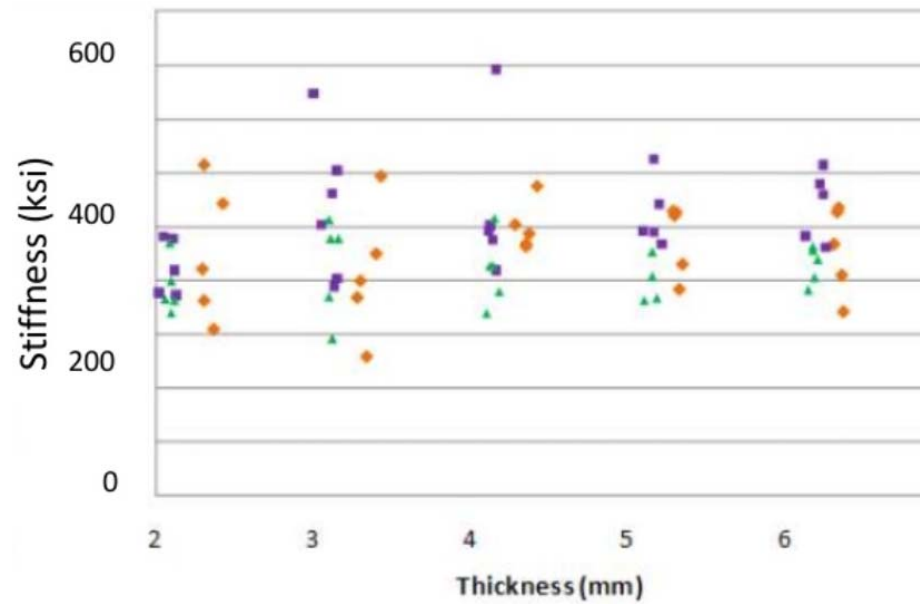


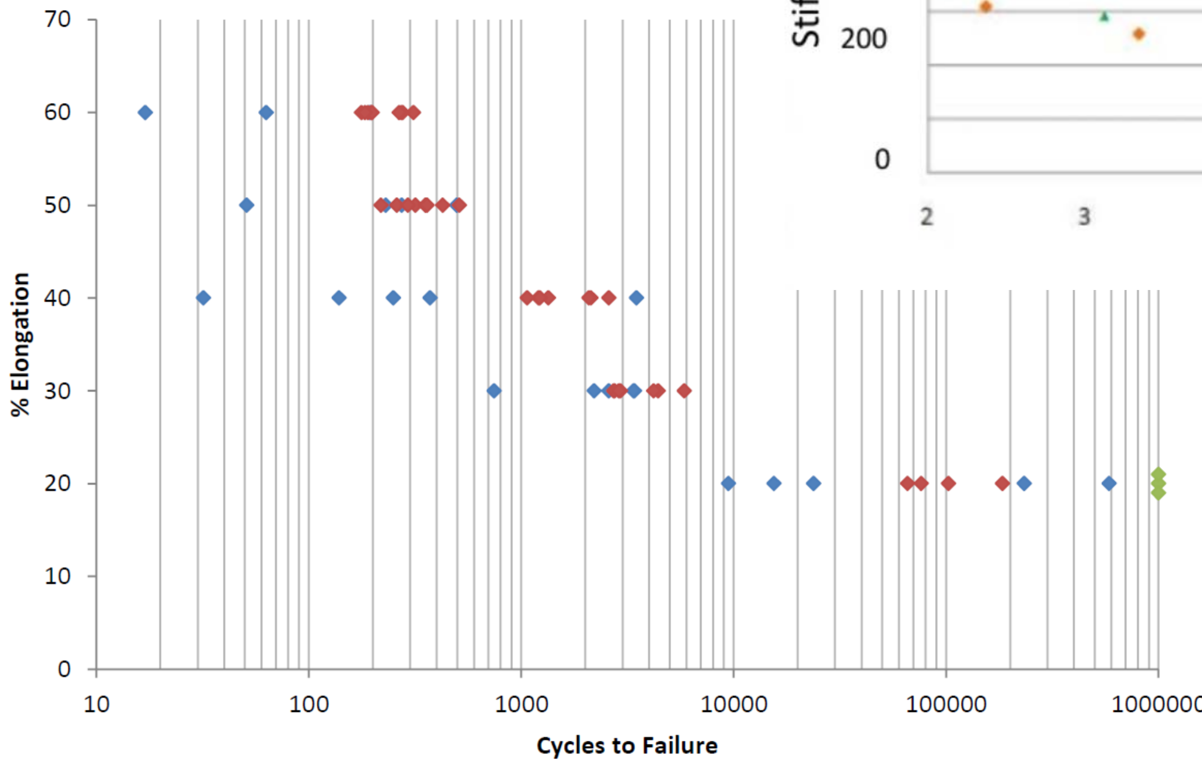


Scatter

(Nylon 12)

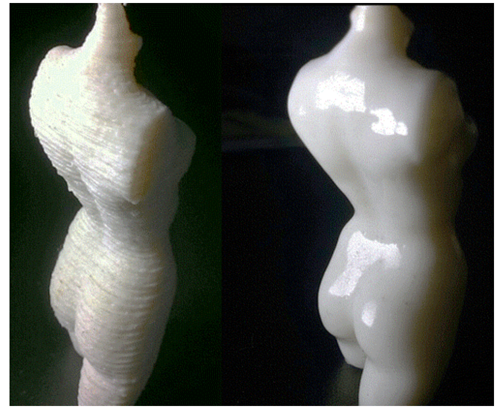
Even with process control… ☹

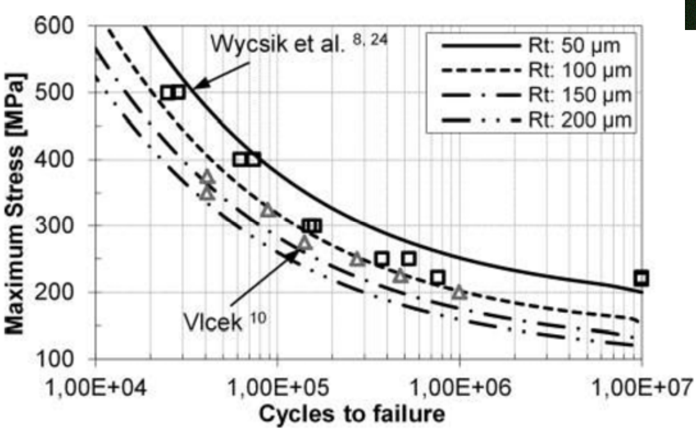




(TangoBlackPlus & VeroWhitePlus Polymers)

Rough Surfaces Fatigue!

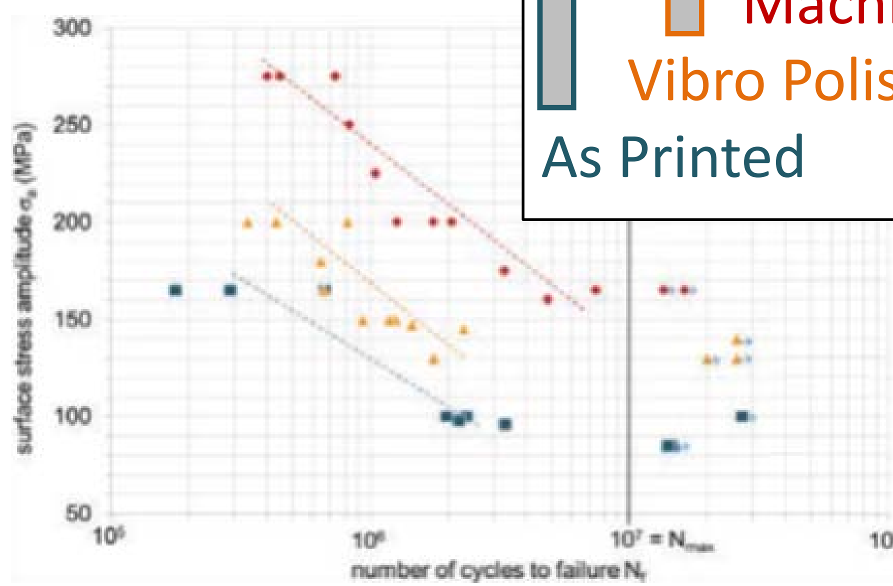


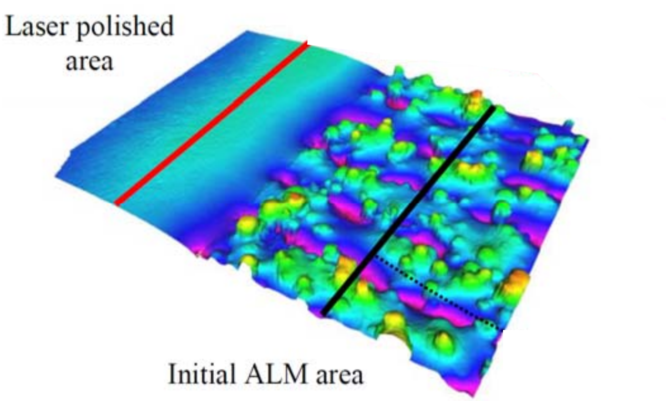


Machined

Vibro Polished

As Printed

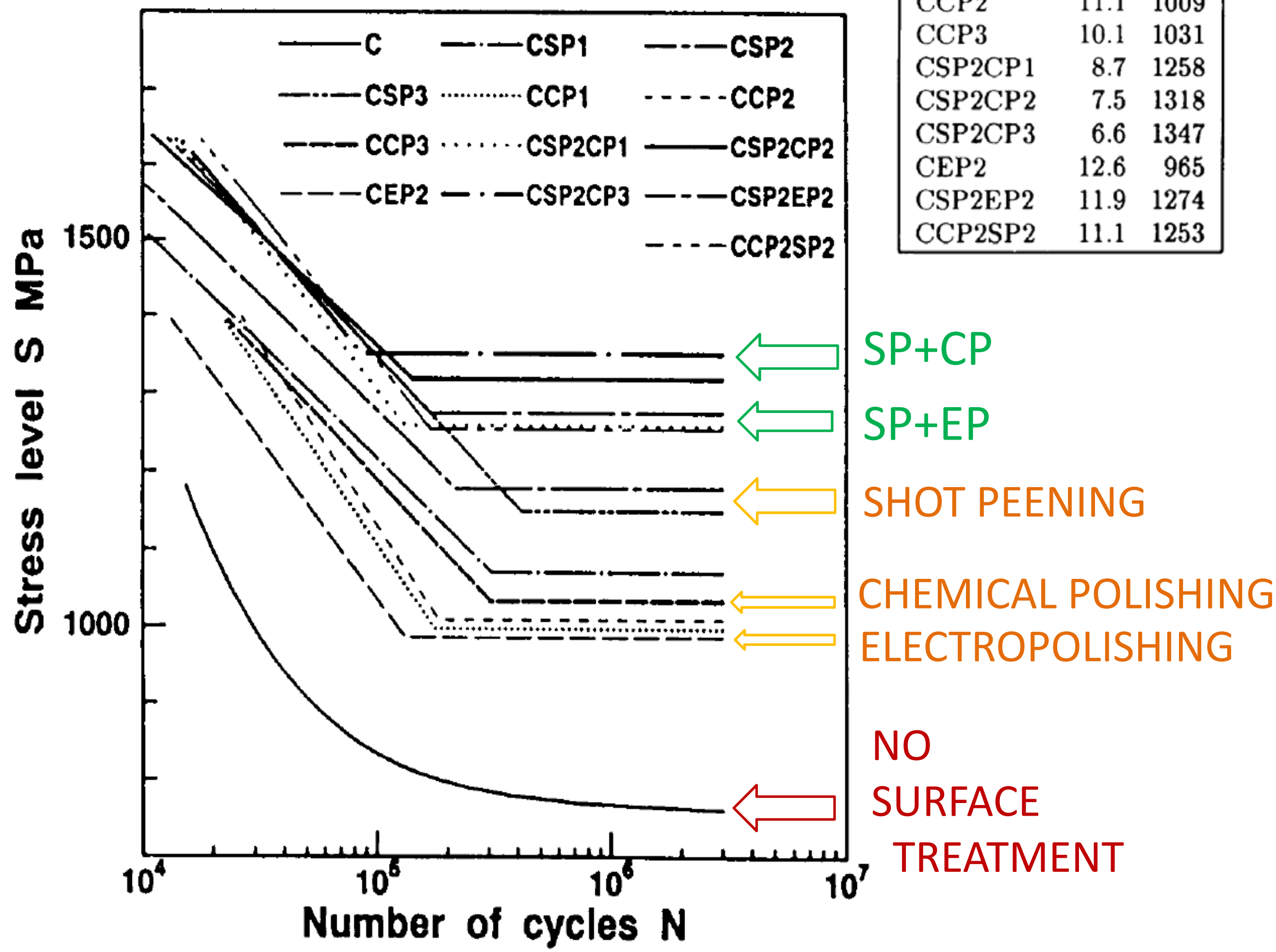




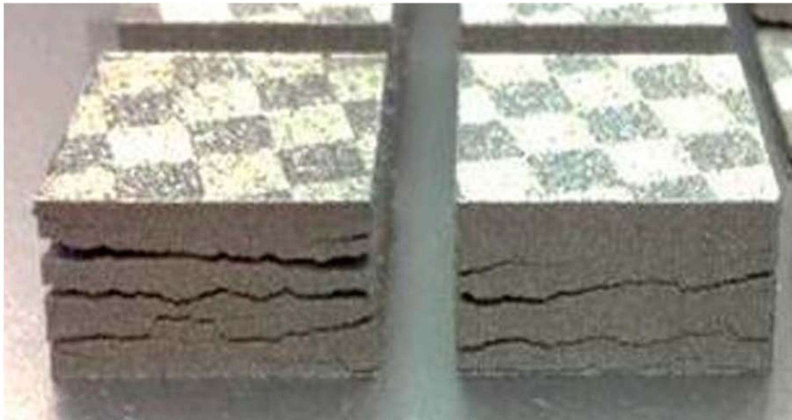
Surface Smoothing Works!

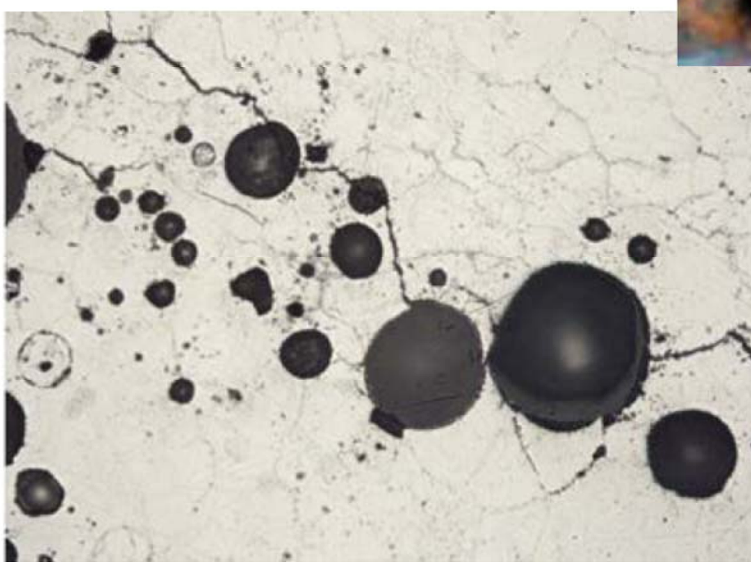
Code of gears	R_z µm	σ_u MPa
C	20.3	761
CSP1	14.0	1070
CSP2	13.6	1176
CSP3	12.9	1148
CCP1	13.8	985
CCP2	11.1	1009
CCP3	10.1	1031
CSP2CP1	8.7	1258
CSP2CP2	7.5	1318
CSP2CP3	6.6	1347
CEP2	12.6	965
CSP2EP2	11.9	1274
CCP2SP2	11.1	1253

"The [fatigue] strengths of chemically polished gears are 30-35% increased as compared with [non-treated] gears. The strengths of shot-peened gears are enhanced by 40-54%. The combination of shot peening and polishing is more effective than a single treatement: [Fatigue] strength is improved by 65-77%..."

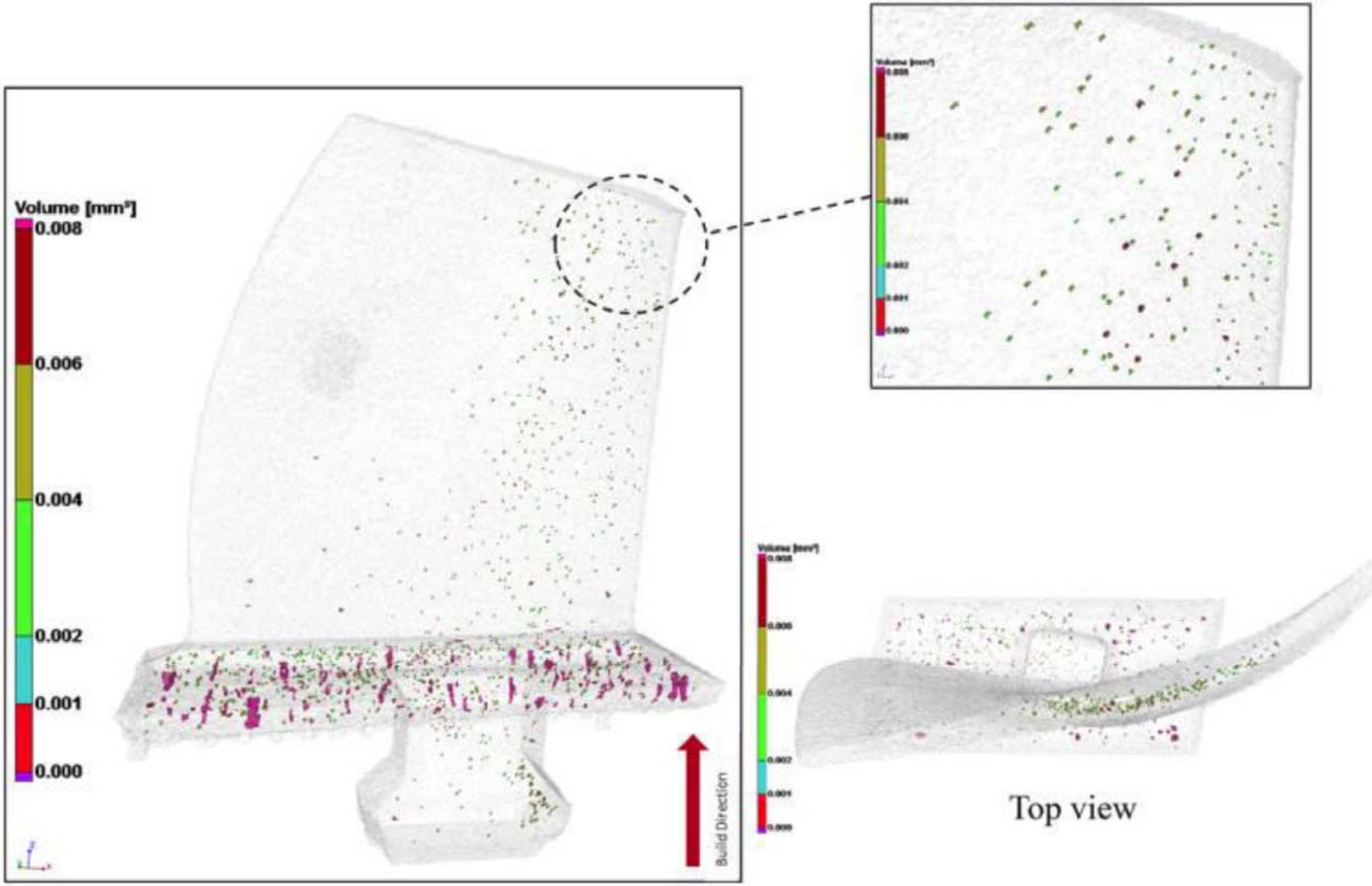


Defects

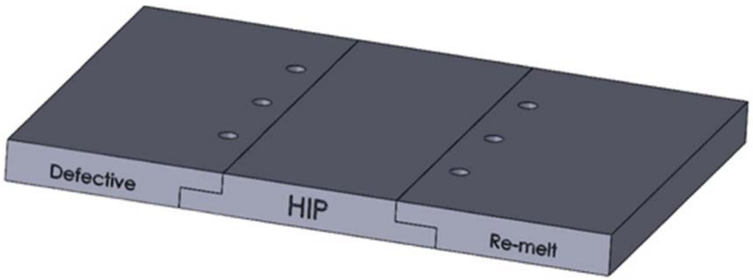


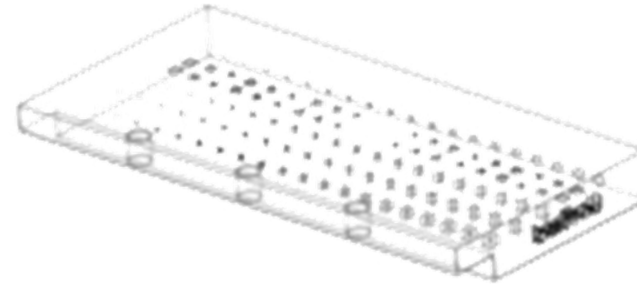


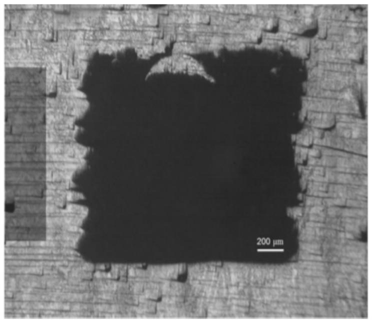
Defects

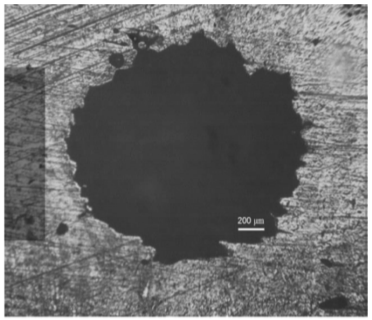

Volume [mm³]
0.008
0.006
0.004
0.002
0.001
0.000
Build Direction
Top view

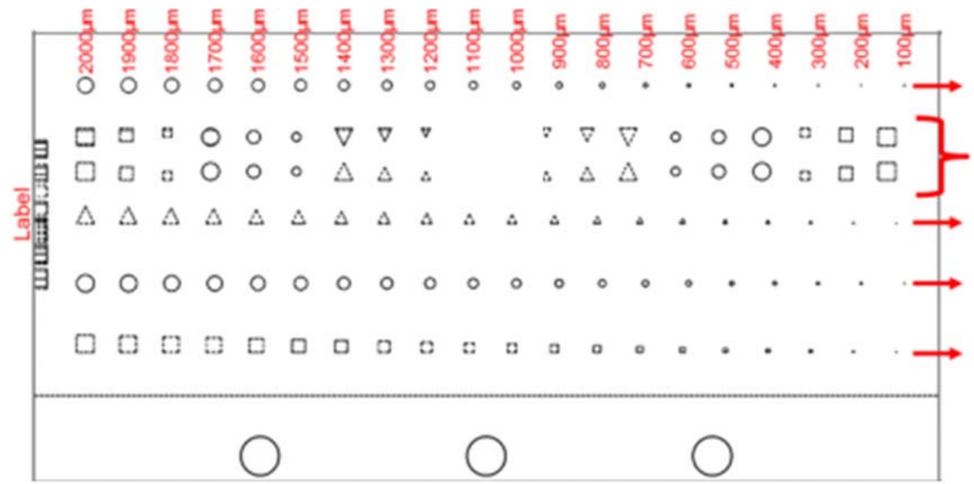
Detectable?

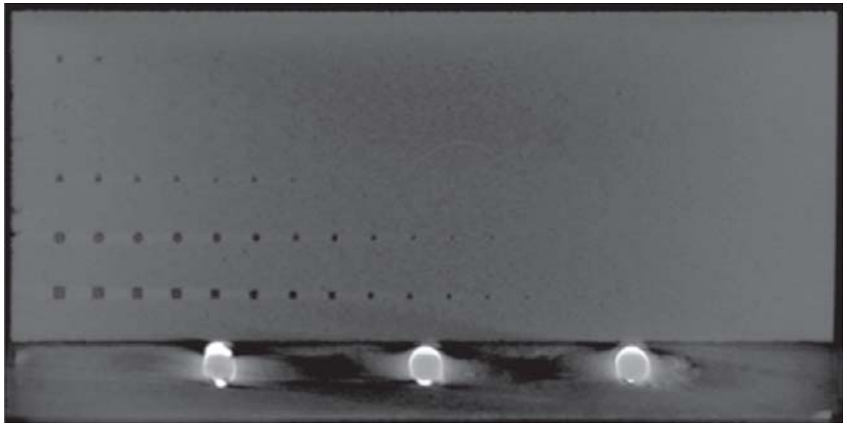

Defective
HIP
Re-melt

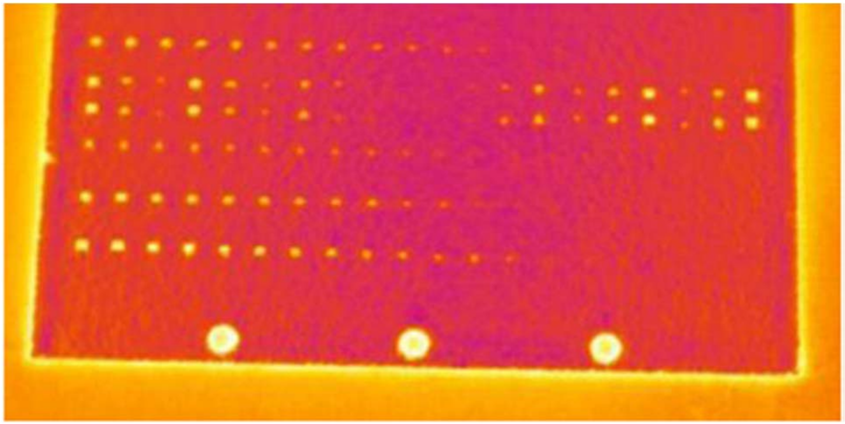



200 µm

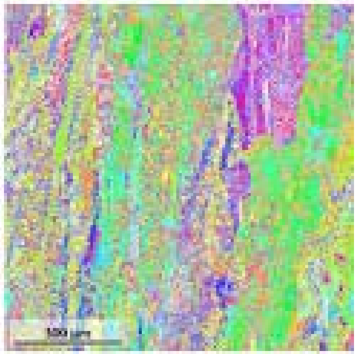

200 µm

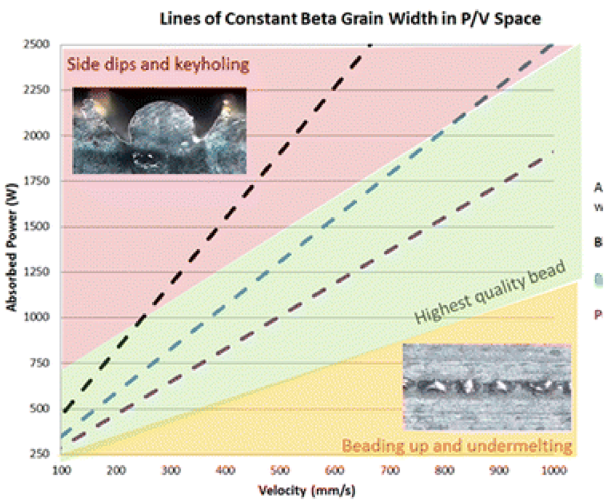

2000µm
1900µm
1800µm
1700µm
1600µm
1500µm
1400µm
1300µm
1200µm
1100µm
1000µm
900µm
800µm
700µm
600µm
500µm
400µm
300µm
200µm
100µm
Label

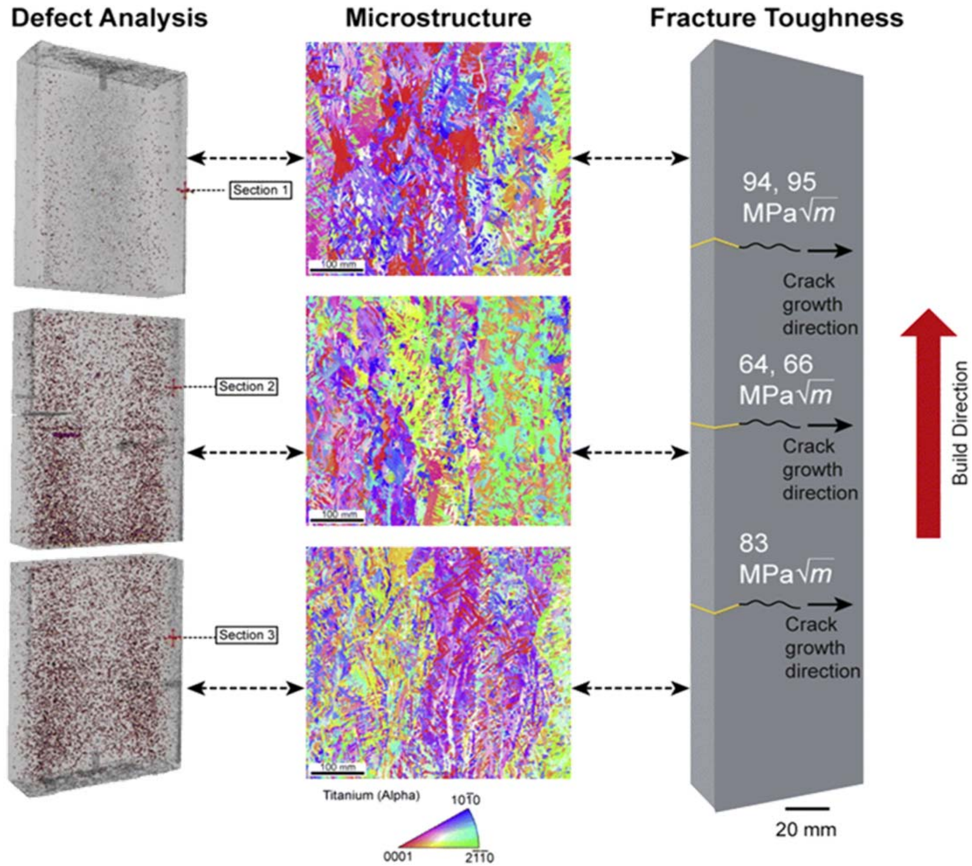




Detectable? Predictable Properties?

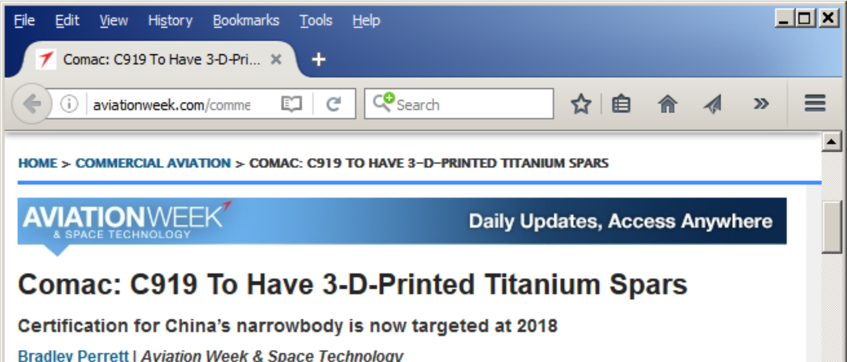




This is COMPLICATED and not 100% understood!

So don't believe everything you read!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Certification for China's narrowbody is now targeted at 2018

Bradley Perrett | *Aviation Week & Space Technology*

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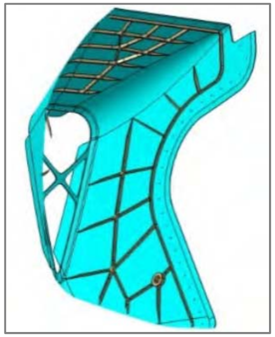
A version of this article appears in the July 14 edit
Technology. Before the end of this year, if the lates
will begin coming together in Shanghai. The progr
a sense, it is behind schedule on schedule—that is,
industry executives widely expected the aircraft to




October 2016

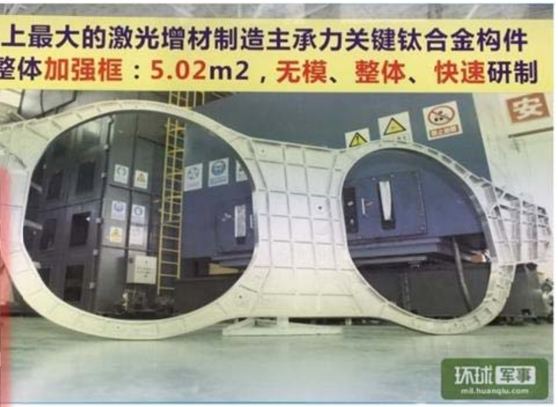
Airbus Emerging Technologies & Concepts

Perhaps more than any other major OEM, Airbus is planning a future that integrates AM into production processes. An astounding variety of exploratory projects have been conducted using AM for metal and polymer parts, repair, and tooling. The company has worked closely with Laser Zentrum Nord to develop advanced methods of topology optimization that reduce material and weight in designs, sometimes by more than 50%.

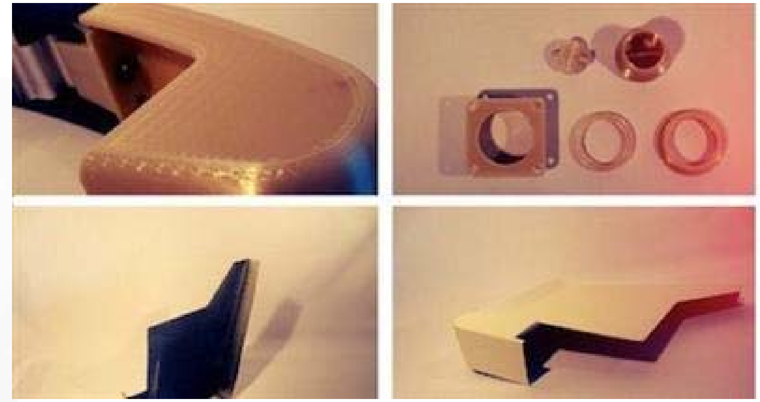
AM-produced hydraulic reservoir rack consolidates 126 parts into one, courtesy of Airbus

Airbus has done considerable work with the design and production of polymer and metal AM parts for its aircraft. It has manufactured and is flying thousands of different types of plastic brackets, clips, and other devices for holding cables, wires, and hoses in place. Many are produced in ULTEM 9085 on FDM equipment.

AIRBUS



So don't believe everything you read!



Sogeclair uses voxeljet 3D printer to realize new lightweight aircraft door design

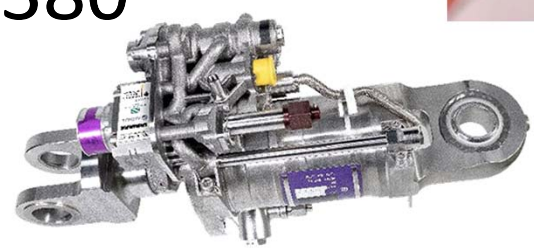
Sep 14, 2017 | By David

The aerospace sector has been one of 3D printing technology's main new adopters over the last few years or so, and all kinds of manufacturers and suppliers at every level of the industry have been using additive manufacturing to rethink or even revolutionize the way aircraft are put together. The latest development comes from French aviation supplier Sogeclair, which has used 3D printing to come up with an innovative new way to produce doors for aircraft, saving materials and money as well as drastically reducing weight. Prototypes were presented for the first time at this year's Paris Air Show.

The Latest

777F
Eco-D

A380



Functional Integration?

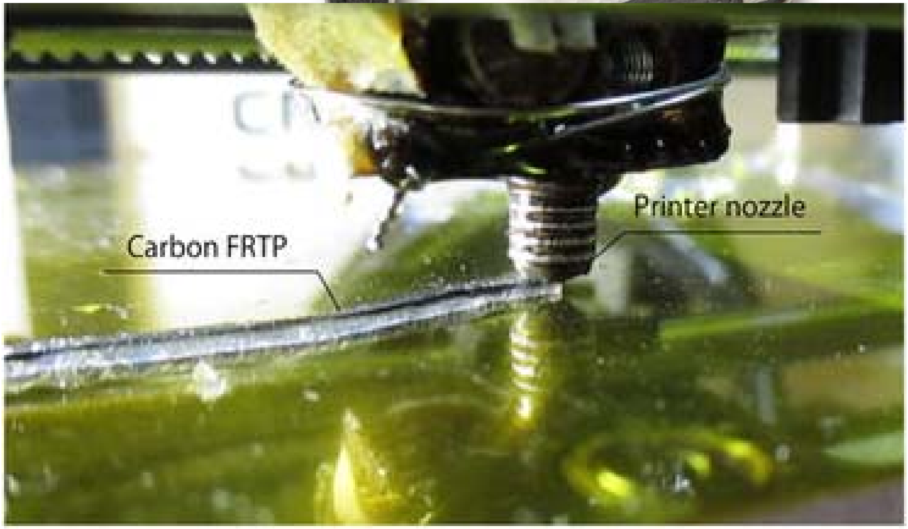
- Passive Cooling
- Active Cooling
- Liquid storage
- Load-bearing & crashworthiness
- [VW & APWORKS, an Airbus subsidiary]

What's next for us? Affordable 3D-printed metals?

"Studio System" by Desktop Metal

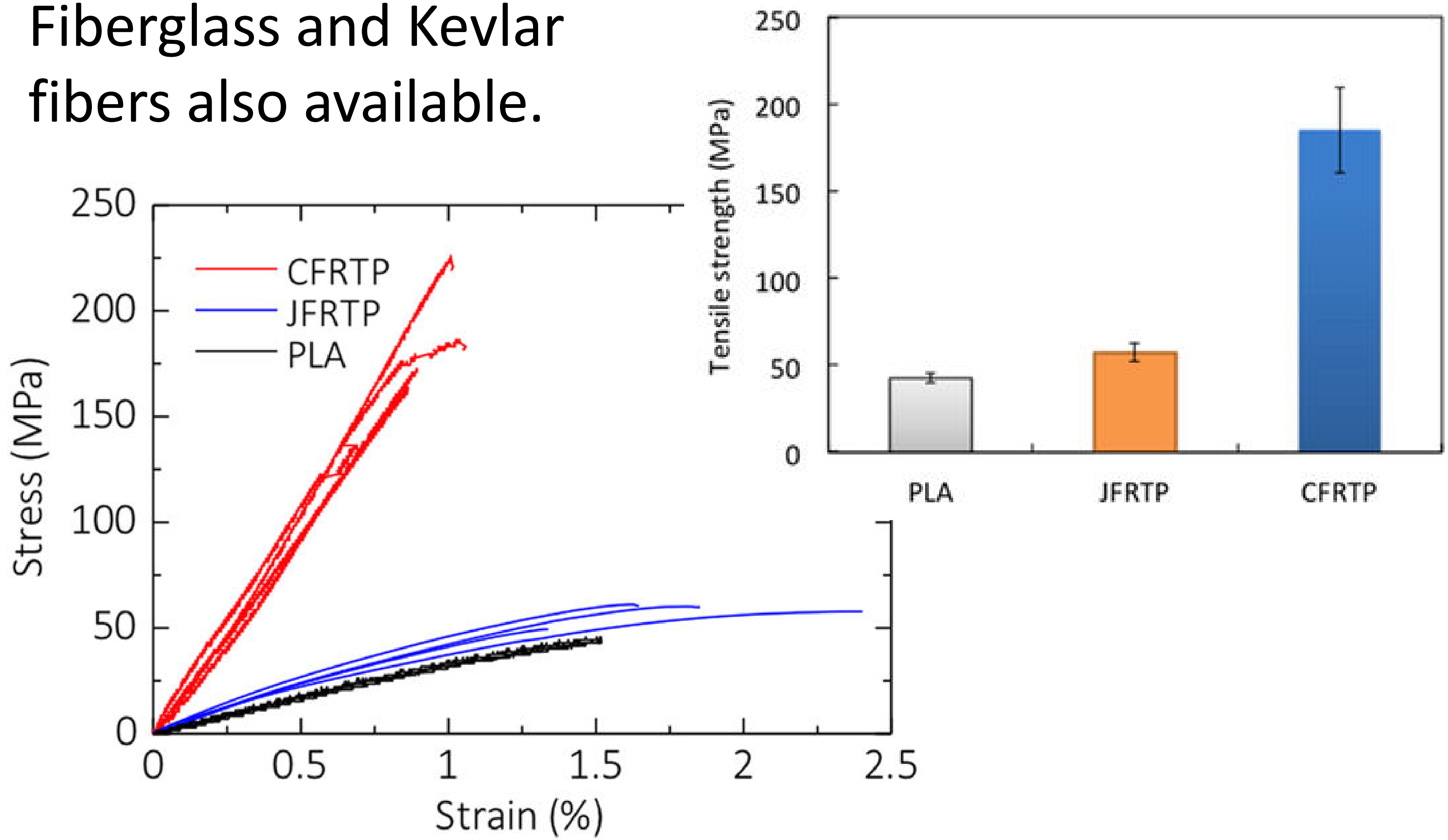
See also: "Virtual Foundry" filament:
88.5% metal, 11.5% plastic (removed later)

What's next for us? 3D-Printed Carbon Fiber?

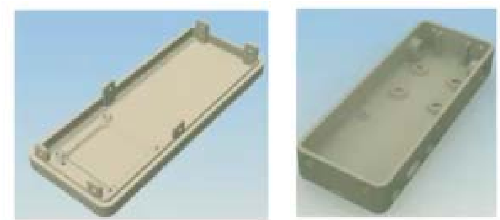


Stronger and Stiffer! (No surprise)

Fiberglass and Kevlar fibers also available.



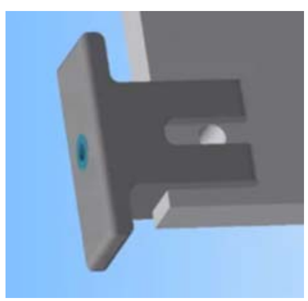
3D Printing and YOU:



ADS-B “Stratux” TuffCase

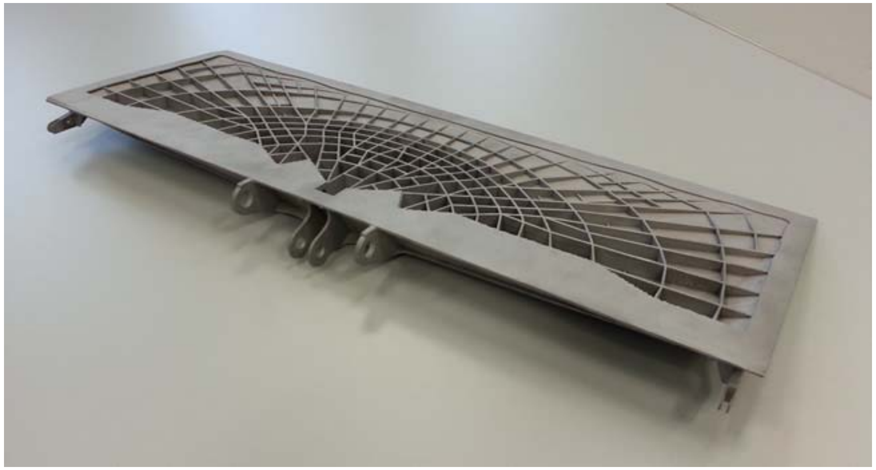
Fairings

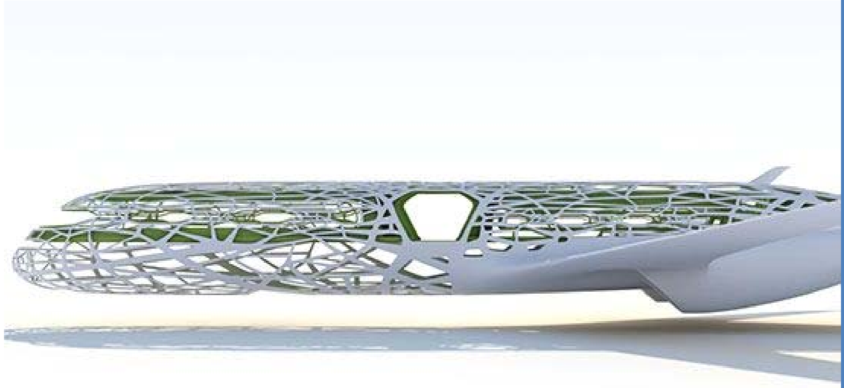
Tooling & Jigs



Misc

Questions?





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