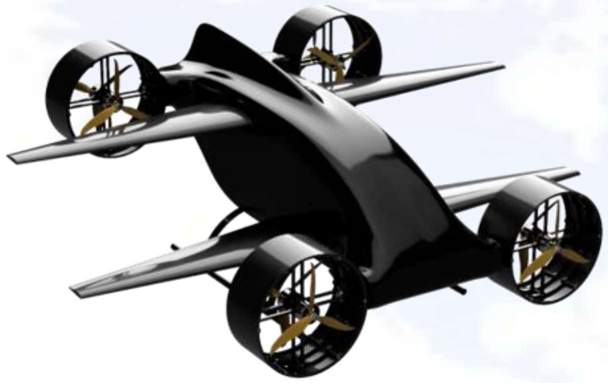
Aerolytics



Raw Materials and the Supply Chain in the Context of Advanced Air Mobility

Organizing body:

AGILITY PRIME

Bill Bihlman
President

Agility Prime Supply Chain WG Meeting

Virtual

9 June 2022

Contents

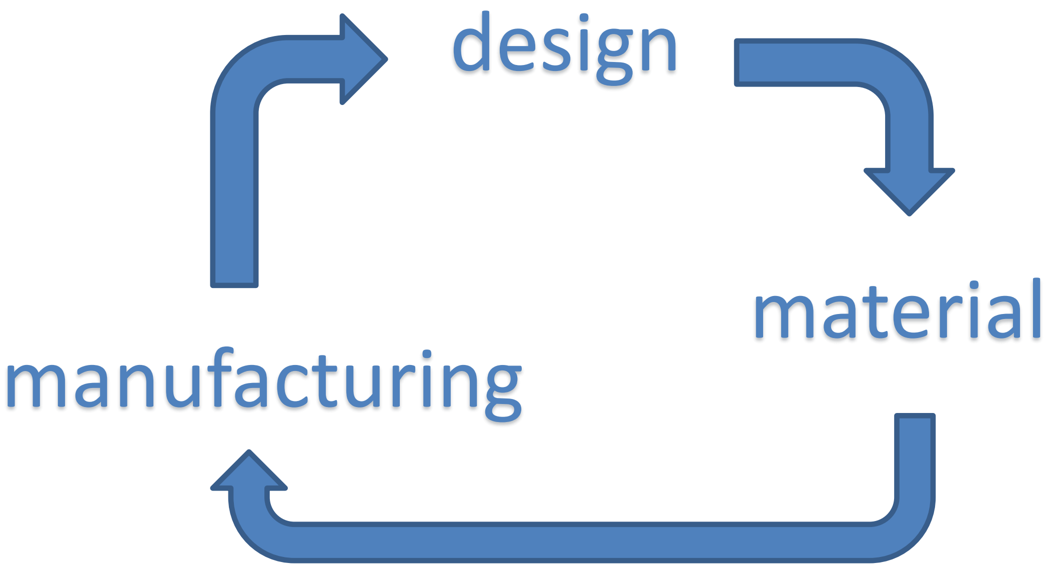
This presentation will answer four fundamental questions

1) What are the primary considerations for material selection for AAM aircraft?
2) What are barriers to implement these new material systems?
3) Are there any concerns regarding current and future composites supply chains?
4) What are the implications for rare earths for AAM production?

Contents

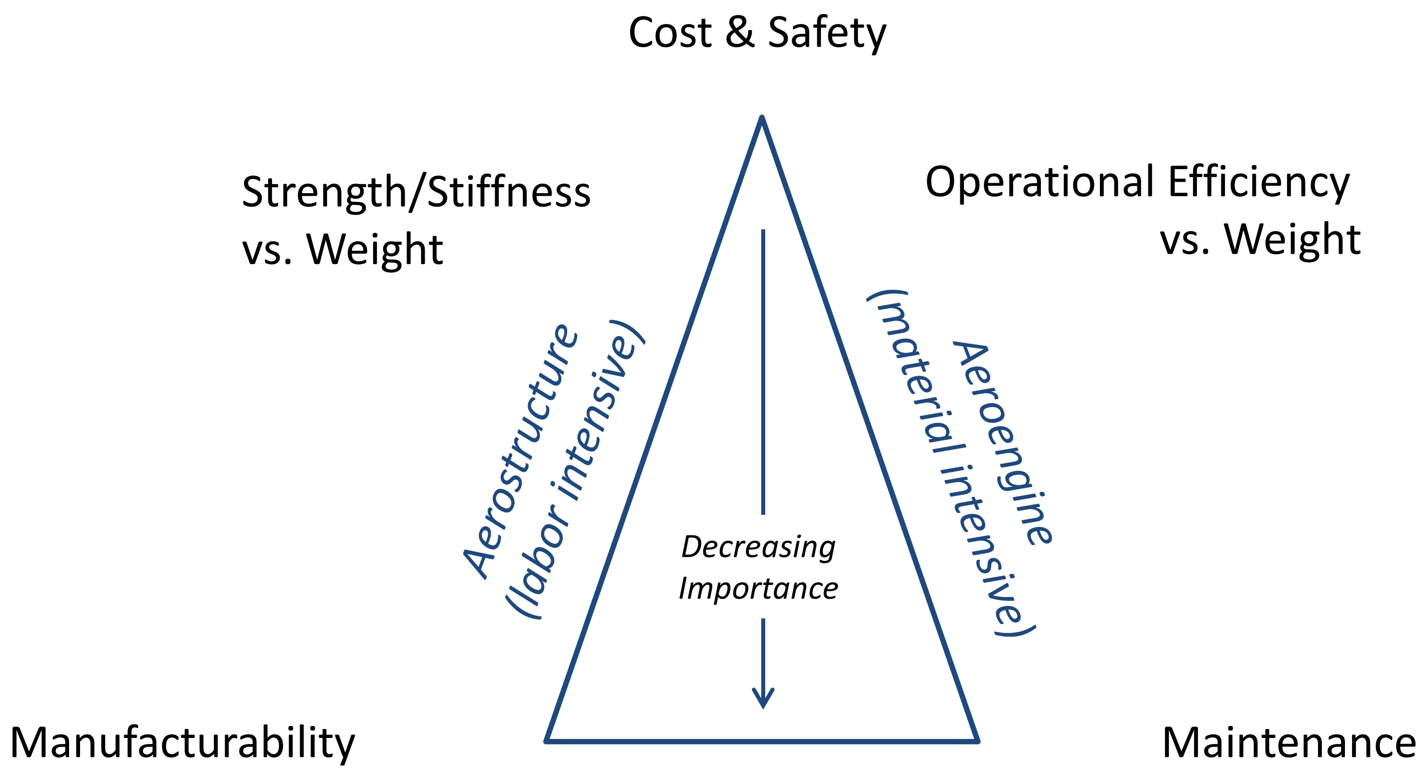
There is a symbiotic relationship between design, material, and manufacturing…

Product Design Iteration



…and the relationship is defined by the intend application of the artifact

Aerostructure vs Aeroengine Design Hierarchy



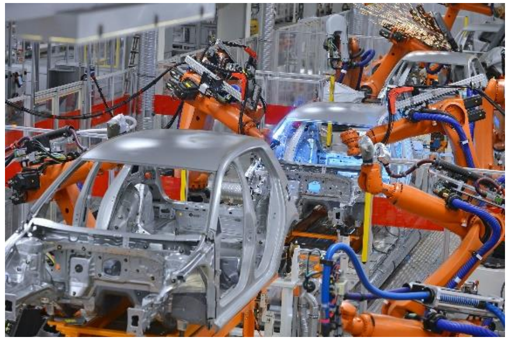
Material & Design

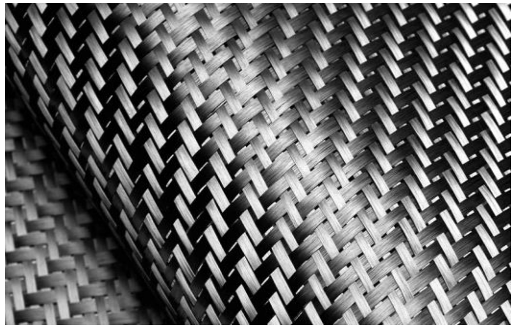
The Advanced Air Mobility (AAM) business model requires *both* manufacturing and materials excellence

AAM – The Intersection of Automotive & Aerospace

Automotive-like Production Rates

Successful AAM OEMs will need to employ factory automation to meet the expected high rate required to satisfy market projections





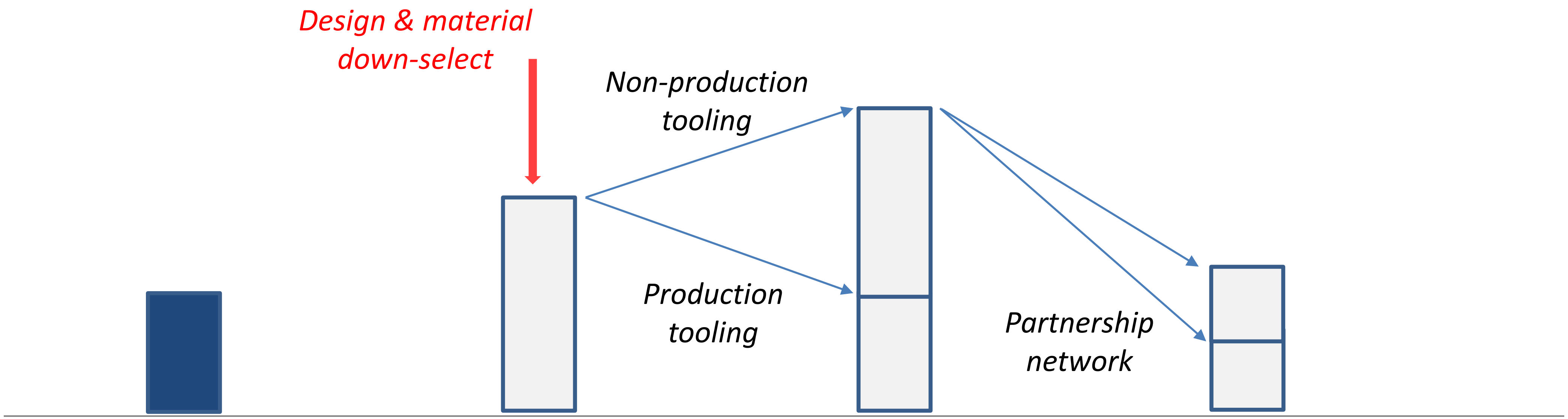
Aerospace Material Excellence

Carbon-fiber reinforced polymers (CFRP) has become the material paradigm for conventional aerospace, and has become standard for AAM

Note: typical general aviation OEM produces hundreds of units annually – however, to achieve high rate, AAM requires new material systems

As discussed, material system affects both design and manufacturing, although Type Certificate requires all engineering to be frozen

<u>Notional Effort Required for AAM Product Lifecycle</u>



Stage:	*(1) Prototype*	*(2) Type Certificate*	*(3) Production Cert*	*(4) Sustainment (MRO)*
Goal:	Aerodynamic stability	Reliability, crashwrthy	Mfgr repeatability	Spares & repairs strategy
Basis:	Fundamental physics	Empirical substntation	Article conformity	Continued airworthiness

Contents

Over the last century, aerospace has pivoted from simple alloys to include engineered materials, such as composites and additive manufacturing

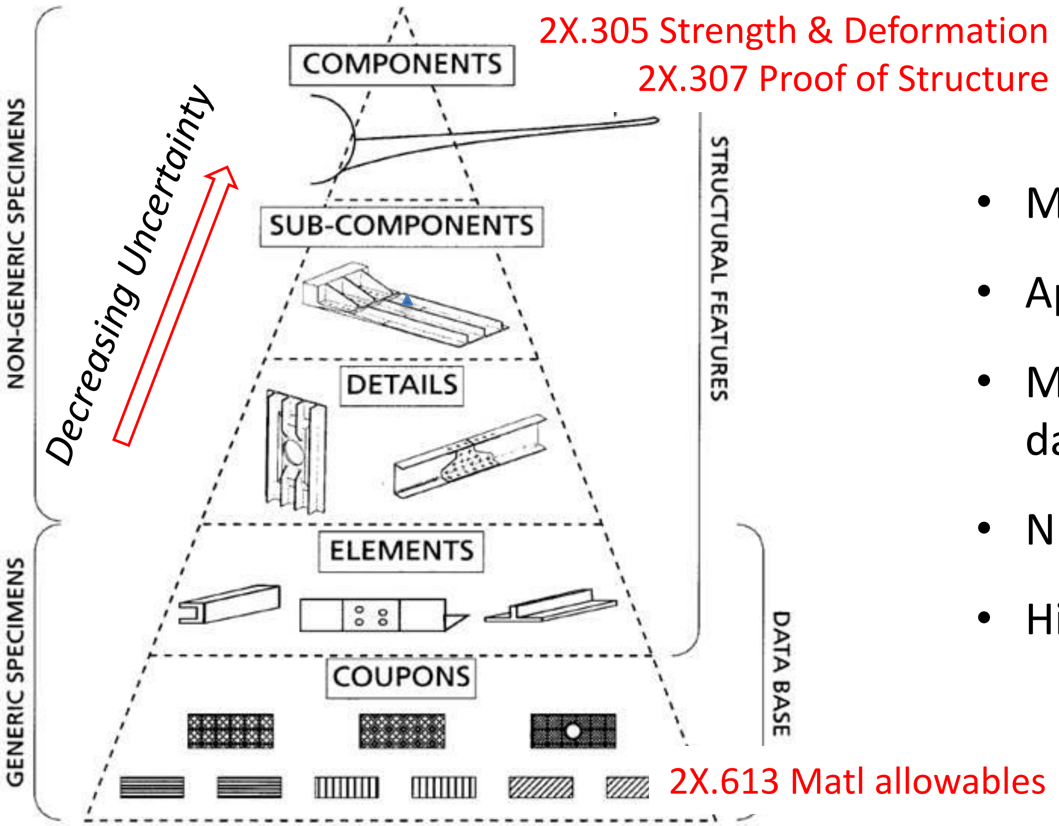
Evolution of Aerospace Structural Materials

1 *Commodity Alloys*	2 *Tailored Properties*	3 *Process Intensive*
• Most wrought product • Simple castings	• Directional solidified (DS) and single crystal (SX) castings • Stir-friction welding	• Carbon fiber composites • Metal additive manufacturing (AM) • Chopped-fiber polymer additive
• Homogeneous constitution • Largely isotropic	• Some inhomogeneity • Some anisotropy	• Potentially inhomogeneous • Potentially highly anisotropic
• Chemistry/process available	• Chemistry/process semi-available	• Chemistry/process often proprietary
1920s (steel)	1950s (superalloy)	1980s (composites)

Increasing complexity

FAA offers a framework for new materials – to be cost effective, AAM requires new material allowables database for quick-processing composites

FAA Building-block Approach



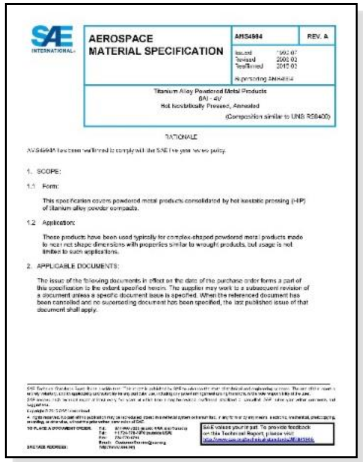
- Material allowables provide the foundation for design values
- Applicants may certify via "building block" or testing "point design"
- Materials properties may be company proprietary or in public database (e.g. MMPDS, CMH-17 handbooks)
- NIAR NCMAP is in the process of qualifying new composites
- Historically, material companies sponsored develop of databases

Full characterization is costly – estimated 2-3 years and $3-5 million

Material Qual & Stnds 2

Consensus standards help with this materials development process – SAE International is the global leader in material standards for aerospace

Overview of SAE International Consensus Documents



AEROSPACE MATERIAL SPECIFICATION

AMS4994 REV. A

Titanium Alloy Powdered Metal Products
6Al - 4V
Hot Isostatically Pressed, Annealed
(Composition similar to UNS R56400)

RATIONALE

1. SCOPE:

1.1 Form:

This specification covers powdered metal products consolidated by hot isostatic pressing (HIP) of titanium alloy powder compacts.

1.2 Application:

These products have been used typically for complex-shaped powdered metal products made to near net shape dimensions with properties similar to wrought products, but usage is not limited to such applications.

2. APPLICABLE DOCUMENTS:

The issue of the following documents in effect on the date of the purchase order forms a part of this specification to the extent specified herein. The supplier may work to a subsequent revision of a document unless a specific document issue is specified. When the referenced document has been cancelled and no superseding document has been specified, the last published issue of that document shall apply.

- SAE International has worked in aerospace standards for over a century
- 7,700+ aerospace consensus documents are maintained by 180 SAE technical committees and subcommittees
- Documents span Aerospace Recommended Practices (ARP) to Aerospace Material Specifications (AMS) standards, first published in 1939
- Committees are industry led and involve a diverse collection of organizations

SAE actively participates in three areas germane to AAM – composites, additive manufacturing, and advanced materials and manufacturing

Relevant SAE AMS (Aerospace Material Specifications) Group for AAM

	P-17 Composites*	Additive Manufacturing	AAM Advance Material & Mfgr
Founded	2003	2015	2021
Published	211	31	n/a
Documents WIP	34	22	n/a
Members	270+	650+	34
Countries	17	27	7

* Works closely with CMH-17 hdbk

Contents

AAM will eventually leverage additive manufacturing – though in limited instances – in order to lightweight structural parts

Principal Design Approaches for AM Parts

Organic Shape Optimization

Internal Lattice Structure

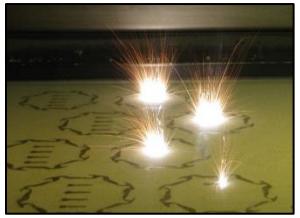
Part Consolidation

AM is used most effectively to produce parts that cannot be machined

There are seven common metal "modalities," however aerospace is dominated by two – powder bed fusion and directed energy deposition

Principle AM Modalities for Aerospace and Automotive

Powder Bed Fusion (PBF)

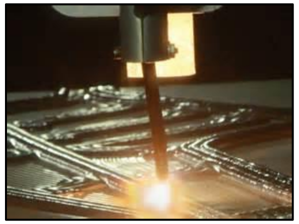


Sequentially melting extremely thin layers of metal powder usually via a laser

PROs: complex geometry, near net shapes

CONs: limited size, small batches, feedstock control

Directed Energy Deposition (DED) – Wire



Sequentially melting metal wire (welding) using plasma arc, laser, or electron-beam

PROs: high deposition rate, economical

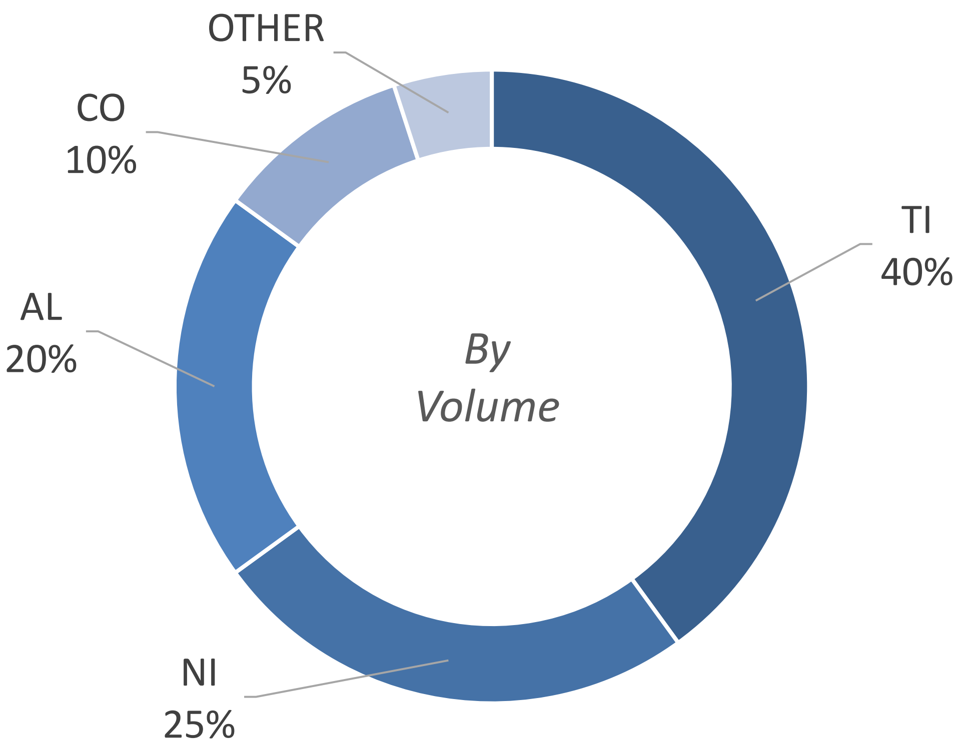
CONs: machining required, high residual stresses, voids

PBF favors aeroengine components and wire DED aerostructures

Emerging Material 3

Metal printing for aviation is predominately powder bed fusion using TI 6-4

Metal Powder Demand for Aviation (2021)



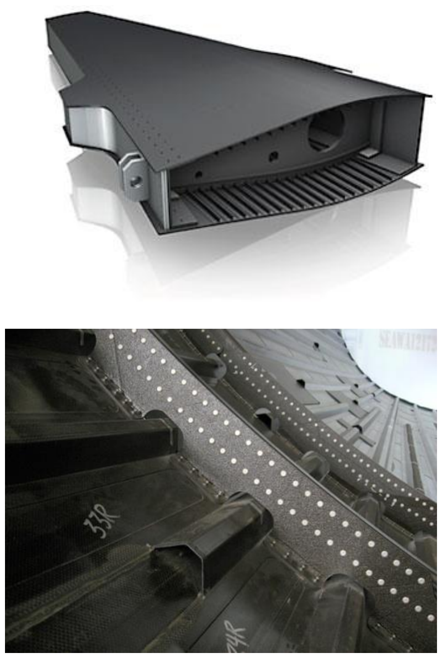
- Powder bed fusion (PBF) represents 70 to 80% of the total AM market for aviation
- Most parts printed using titanium (especially TI 6-4), followed by nickel alloys (e.g. IN 718), and aluminum (e.g. AlSi10Mg)
- In general, materials that are being qualified are those already common to aerospace

Composites are the *de facto* material for AAM – nevertheless, they need to be evaluated in the context of mission profile

Pros and Cons of Thermoset Composites vs Aluminum Structures

ADVANTAGES

- Lower part count and labor content
- Fatigue resistant
- Corrosion resistant
- Smooth surfaces/finishes
- More complex geometries



DISADVANTAGES

- Structural properties dependent upon manufacturing, with variation of fiber and resin
- Damage detection and repair more complicated
- Higher cost structure
- Contamination threat during lay-up and bonding
- Raw materials are perishable
- Limited materials database

In particular, thermoplastics have been heralded as the solution to meet AAM rate projections…but there are challenges

Pros and Cons of Thermoplastics vs Thermosets

TP ADVANTAGES:

- Low cycle time
- Inherent toughness
- High temperature performance
- Mechanically strong
- Ease of storage
- Low moisture/solvent absorption
- Recyclable

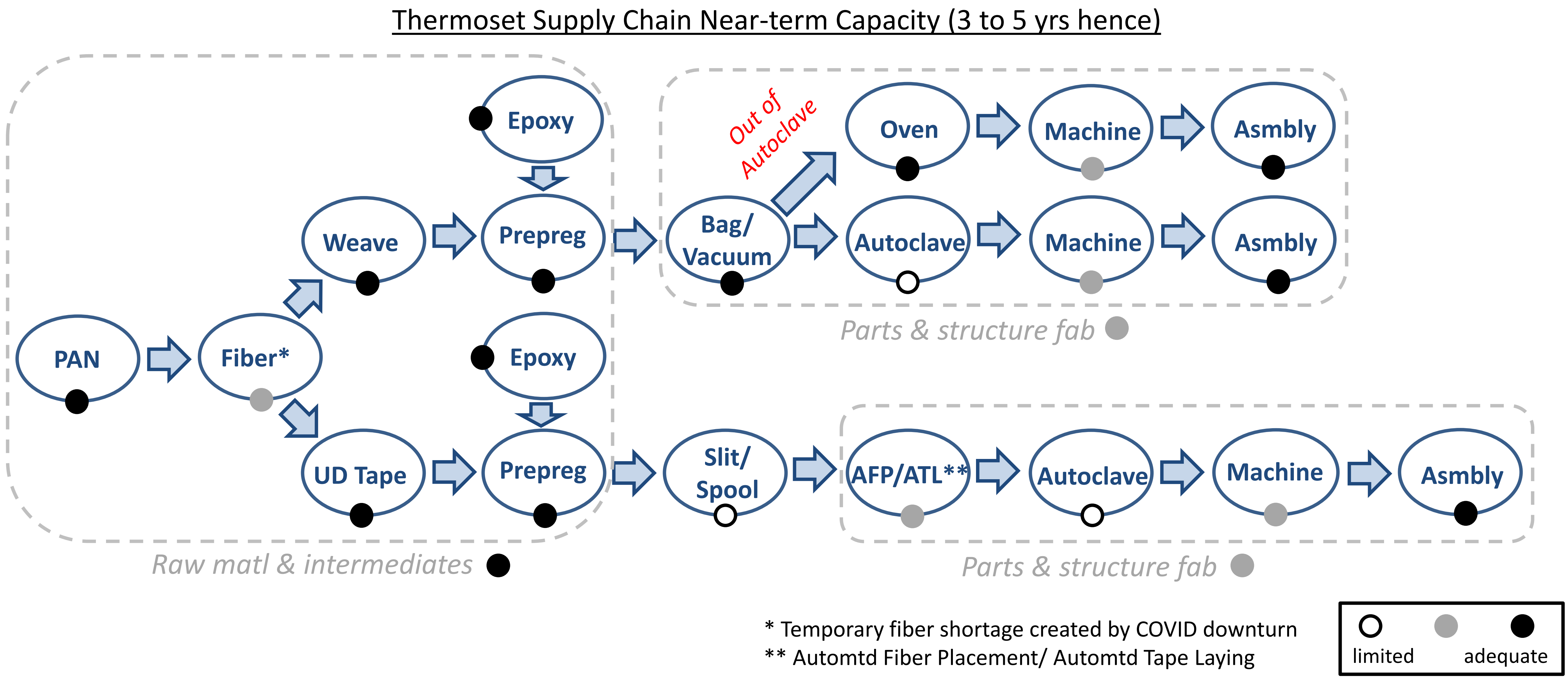
TP DISADVANTAGES:

- More challenging processing conditions (higher temp and pressure)
- Non-recurring expenses (engineering and tooling)
- More expensive raw materials

Source: Sourkes - Vetrix (2020)

3 Emerging Material

Autoclaves appear to be a pain-point near term for thermoset, but fabrication overall may be the true limiter



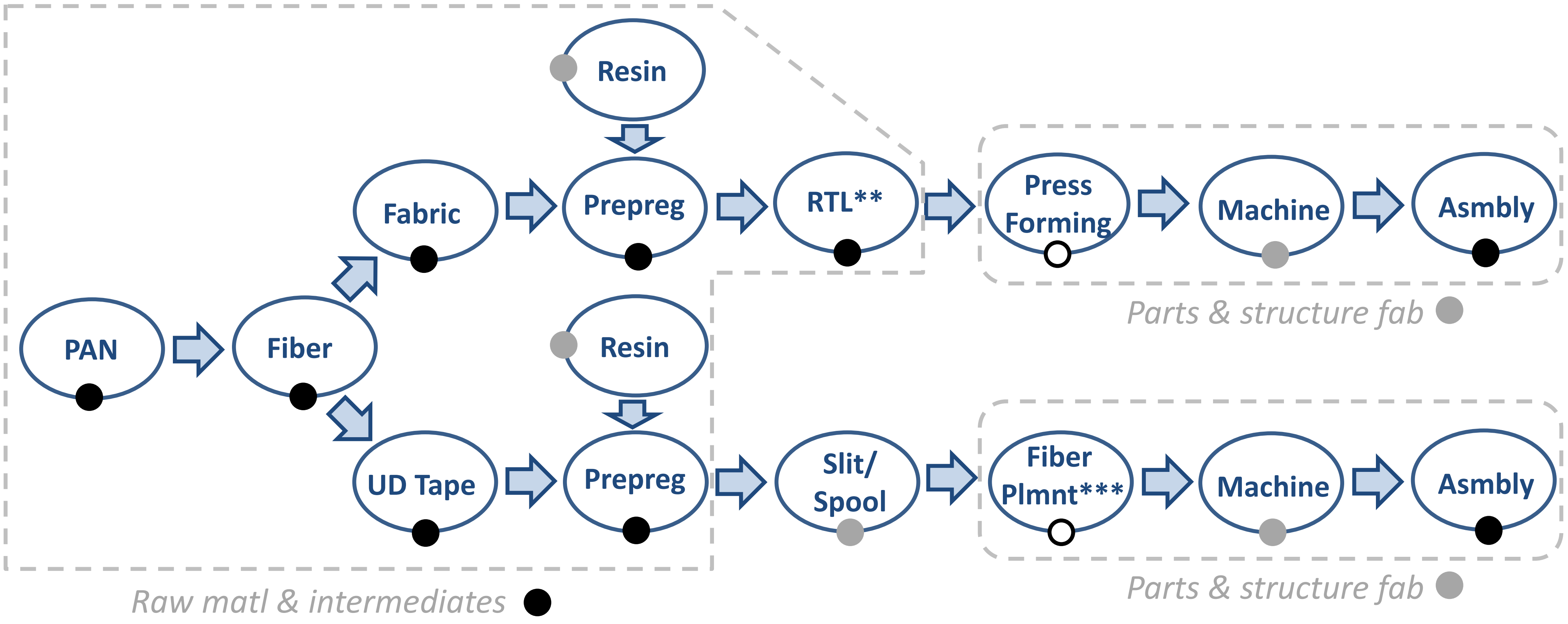
* Temporary fiber shortage created by COVID downturn

** Automtd Fiber Placement/ Automtd Tape Laying

Emerging Material

Longer term, press forming and fiber placement show potential to limit thermoplastic throughput – again, fabrication may be the main constraint

Thermoplastic Supply Chain Mid-term Capacity (5 to 10 yrs hence)*



* assume qualified TP available
** reinforced TP laminate
*** in-situ consolidation

limited — adequate

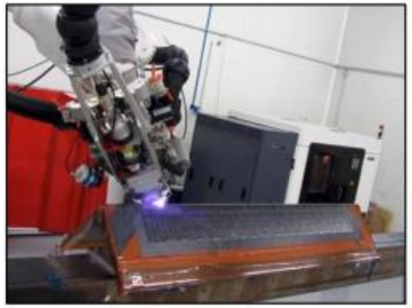
Emerging Material

Press forming and fiber placement are only two of the manufacturing technologies available for thermoplastics

Modalities for High-rate Thermoplastic Manufacturing


Automated Tape Layup (ATL)

Pick & Place Layup


Automated Fiber Placement (AFP)


Braiding


Automated Material Conversion (Off-axis rolls)


Press Consolidation / Compression Molding


Stamp Forming (Thermoforming)


Continuous Compression Molding (CCM)


Self-Heated Tooling

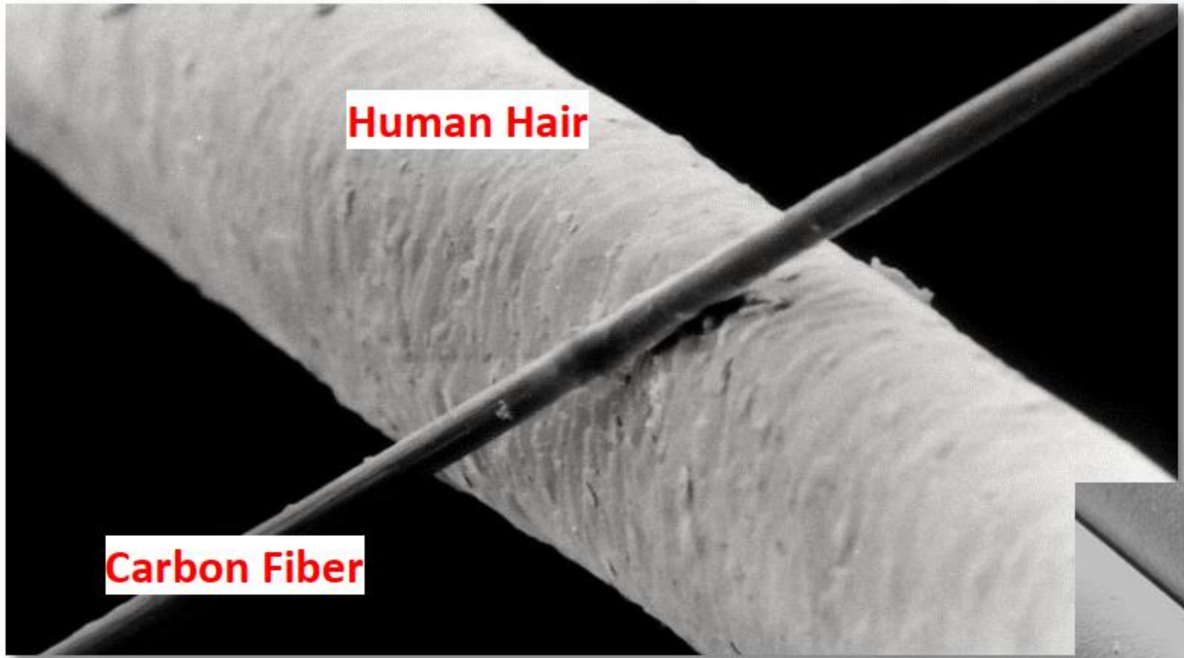

Thermoplastic Welding


Advanced Assembly

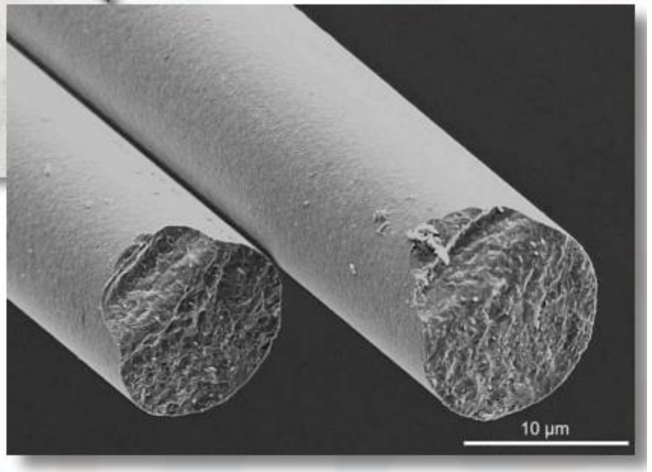
Emerging Material

Composites intellectual property is associated with the fiber, which is ultimately a function of the PAN precursor to achieve near-perfect properties

Carbon Fiber Strand vs Human Hair



- Carbon fiber filaments magnified 200 times.
- Diameter of the filament is 10 µm



Emerging Material

There are over a dozen composites manufacturers globally – aerospace is dominated by four major companies

Major Producers of Aerospace Composites

HEXCEL

TORAY

SOLVAY

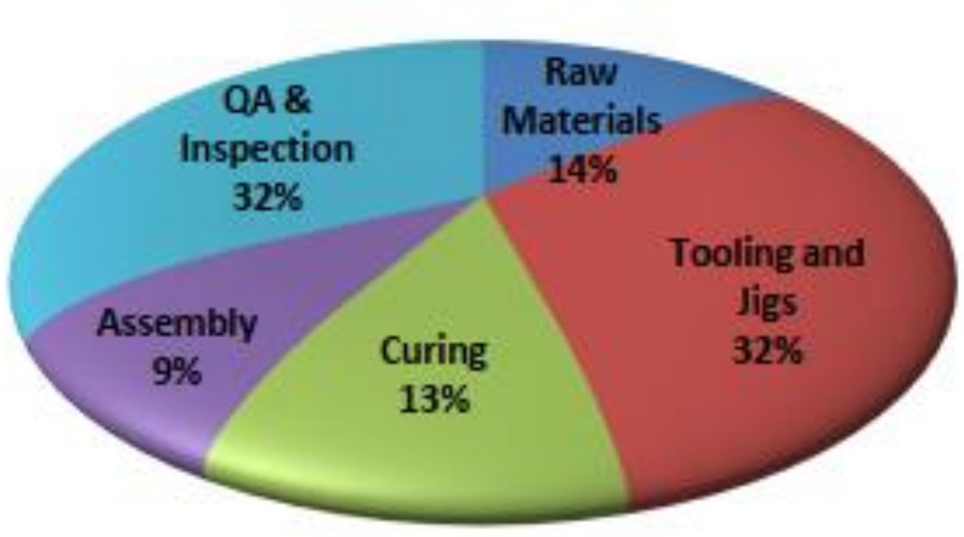
TEIJIN

- All four producers offer aerospace quality (intermediate modulus, toughened epoxy) prepreg
- Each producer has production capability in the US
- Hexcel and Toray provide most of the fiber consumed in aerospace
- Toray is sole-sourced for Boeing (777* & 787), Hexcel for Airbus (A350), and Solvay/Cytec aligned with Lockheed Martin and Boeing military
- Each company has signed purchasing agreements with AAM OEMs
- Thermoplastics prepreg is led by Toray/TenCate and Solvay/Cytec, but also includes Victrex, Suprem, Barrday, Porcher, etc.

*777 empennage was the first large-scale adoption in 1995 (via Toray)

Composite structural parts are expensive – technology advances should help reduce costs

Cost Structure for Thermoset Aerostructures

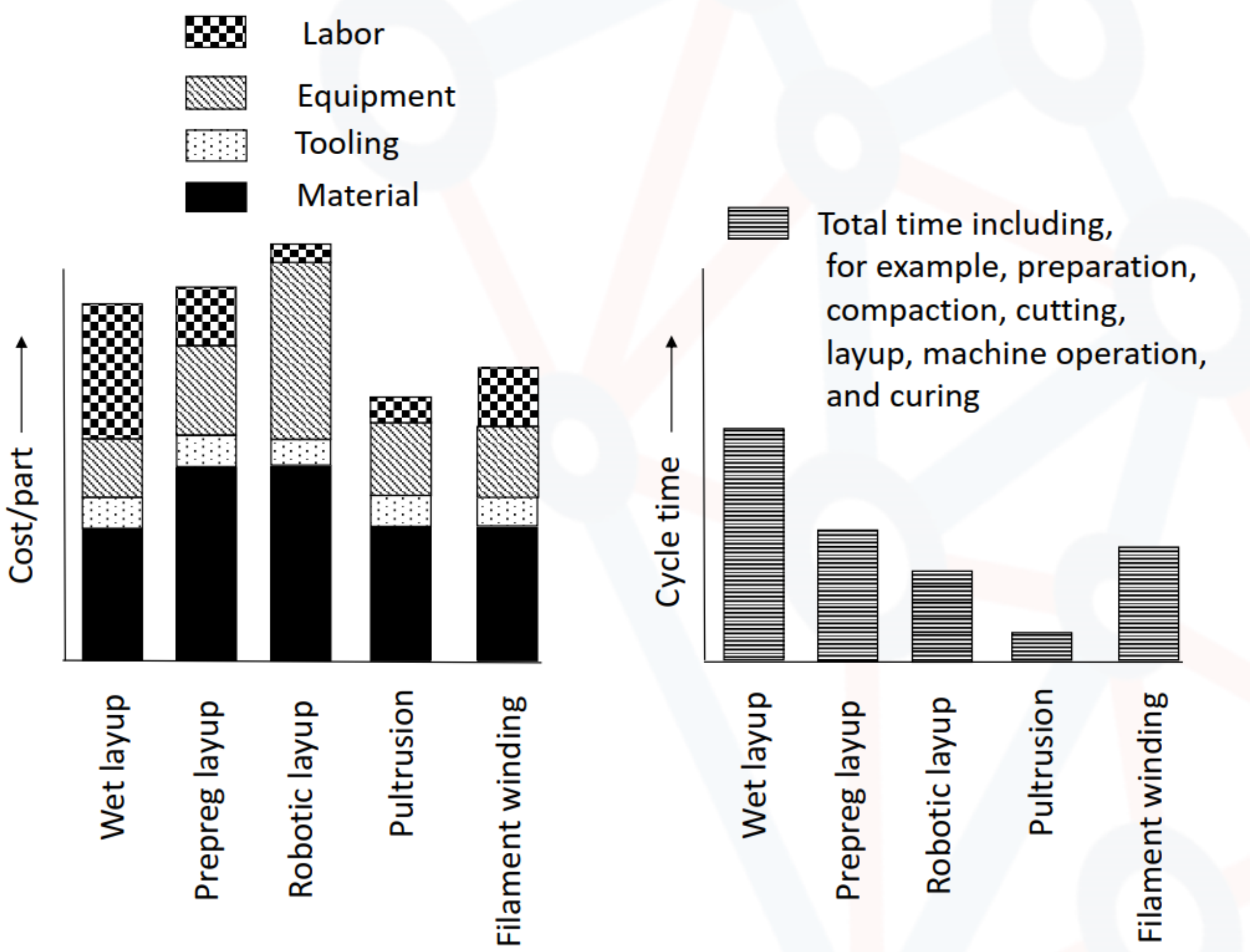


- Finished aerospace composite structural parts typically cost more than $350/lb
- This is estimated as 5 to 7 times the cost of an aluminum part/structure*
- Tooling/jig is the largest contributor but is heavily dependent upon method
- QA costs are also substantial, yet automation will help significantly reduce cost and throughput

*Aerolytics estimate

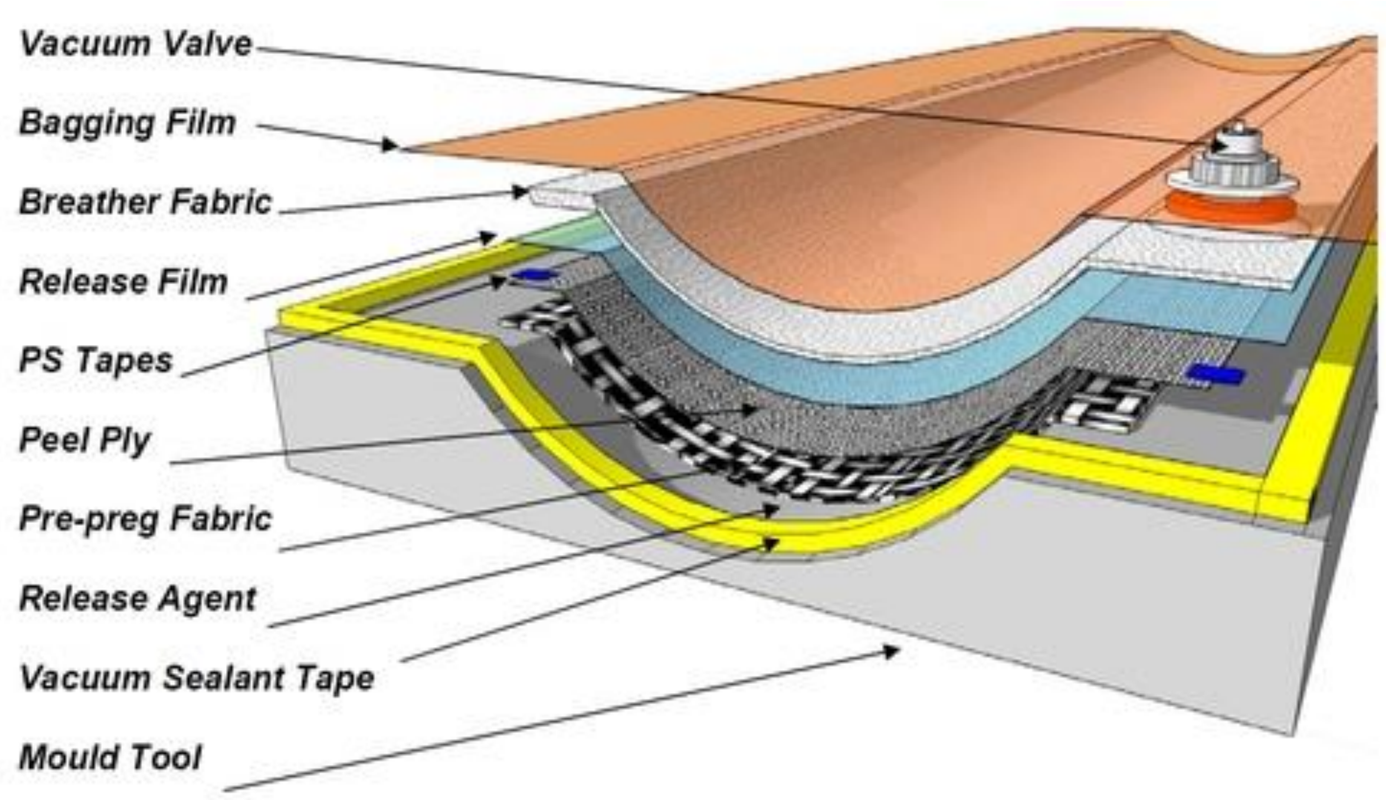
Composites manufacturing ranges from labor-intensive hand layup to capital intensive robotic layup, such as ATP and ATL

Manufacturing Cost Breakdown and Cycle Time



Hand-layup is labor intensive due to an involved bagging process – its widely used, yet it is not practical for high volumes

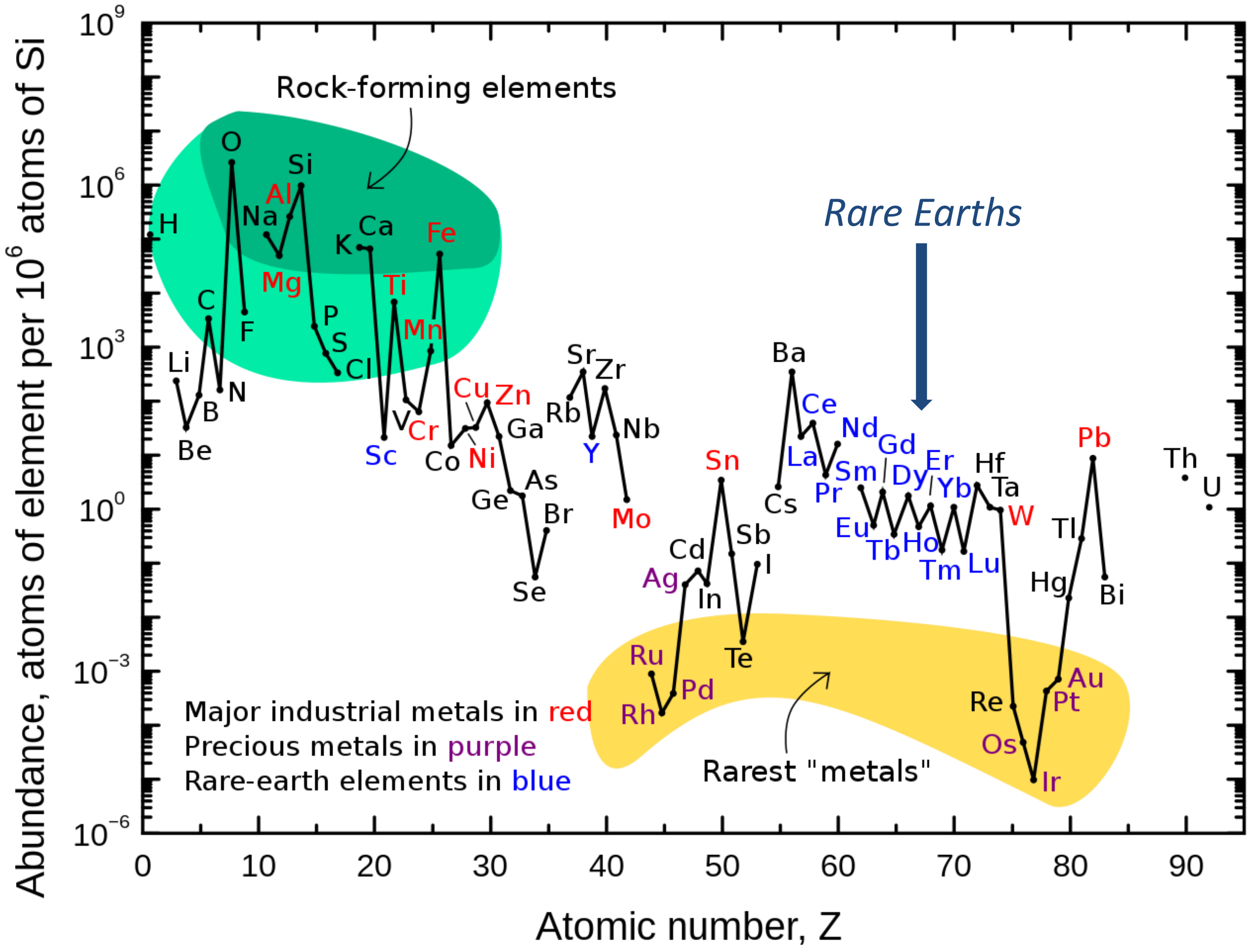
Schematic of Vacuum Bag Build-up



Source: B Strong – UAMMI (2022)

Rare earths are extremely stable elements with special magnetic properties, but they are not rare *per se*

Abundance vs Atomic Number of Natural Elements

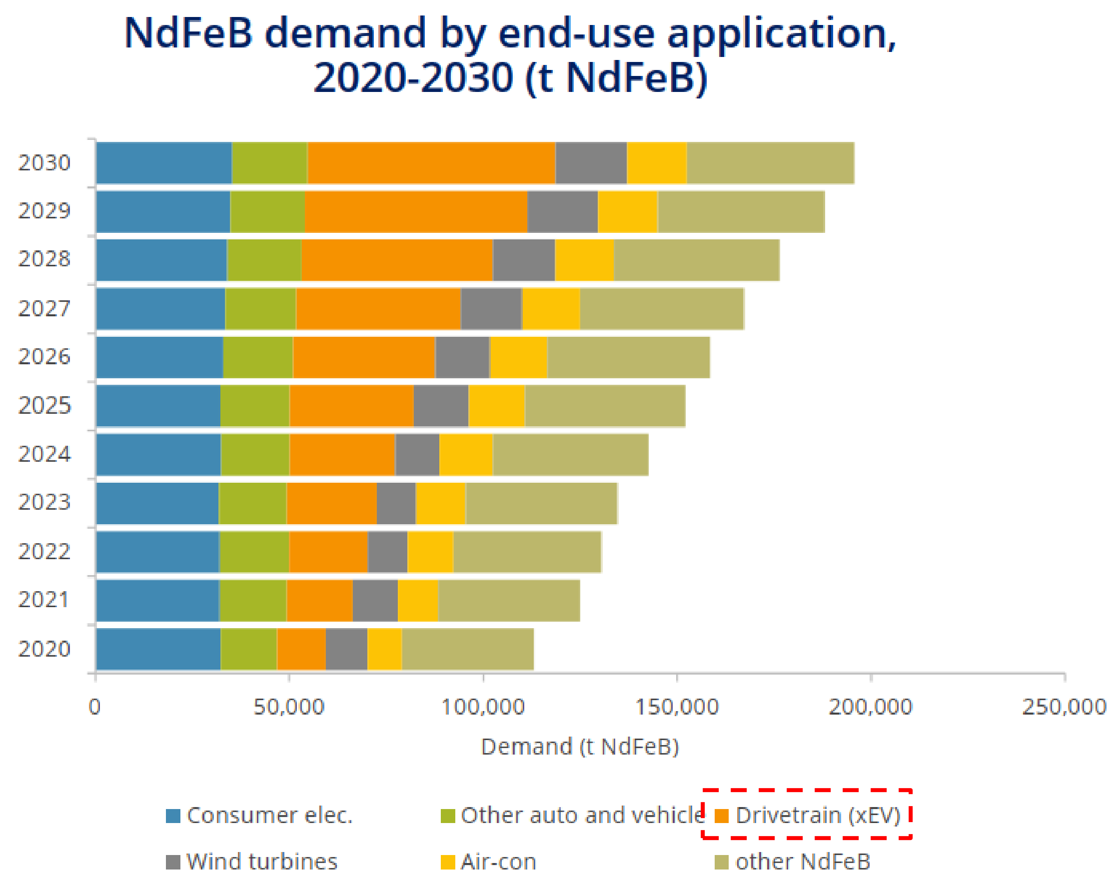


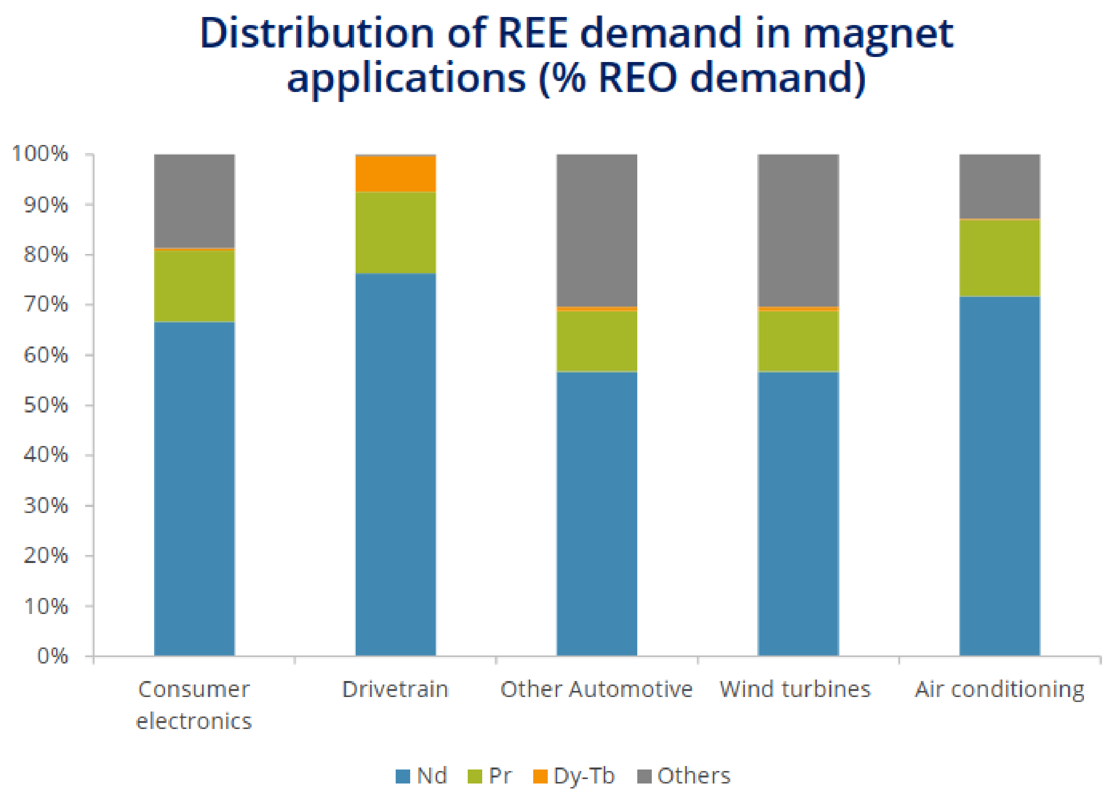
- Paradoxically, rare earths are not exceptionally rare, but rather costly to mine and refine
- They are typically more stable than metals and have higher melting points
- These oxides are highly paramagnetic when combined with iron and cobalt
- Most common are Cerium, Lanthanum, and Neodymium, which constitute 90% of demand

Emerging Material

Neodymium is used extensively in electric vehicles for magnets – it is forecasted to grow significantly over the next decade

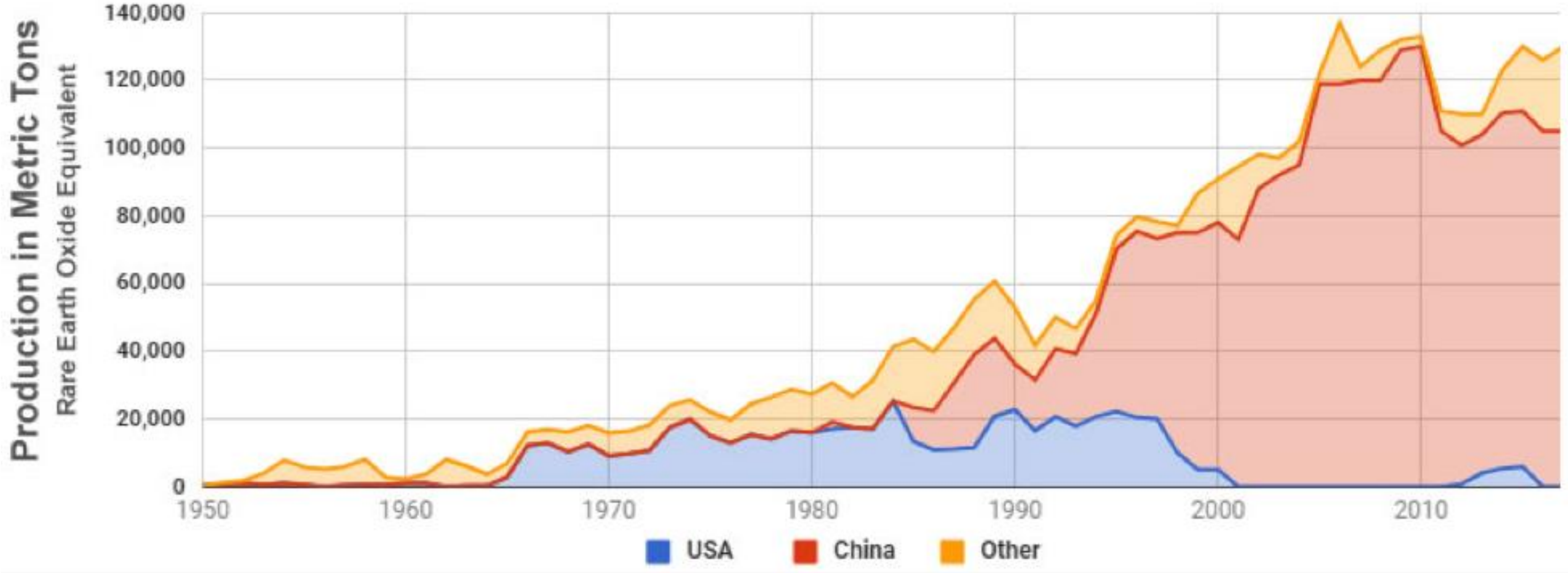
Neodymium Magnet Demand Forecast





Notwithstanding, China has moved to dominate global production of rare earths over the last 3 decades – today they control over 85%

Historical Production of Rare Earths



Conclusion

The main limitation is the lack of qualified composite materials – this should be resolved within the decade

Key Takeaways

- Material, design, and manufacturing are inextricably linked
- Quick processing composites are key enablers for this market, although they currently are not qualified – standards will facilitate
- Both near and mid-term, composite production is limited by the available of fabrication ability and not upstream feedstock
- Non-structurally, rare earths for electric motors (i.e. Neodymium) could be a constraint since production is controlled by China
- Finally, the real bottleneck may be completely unrelated to aforementioned materials – specifically lithium used for batteries

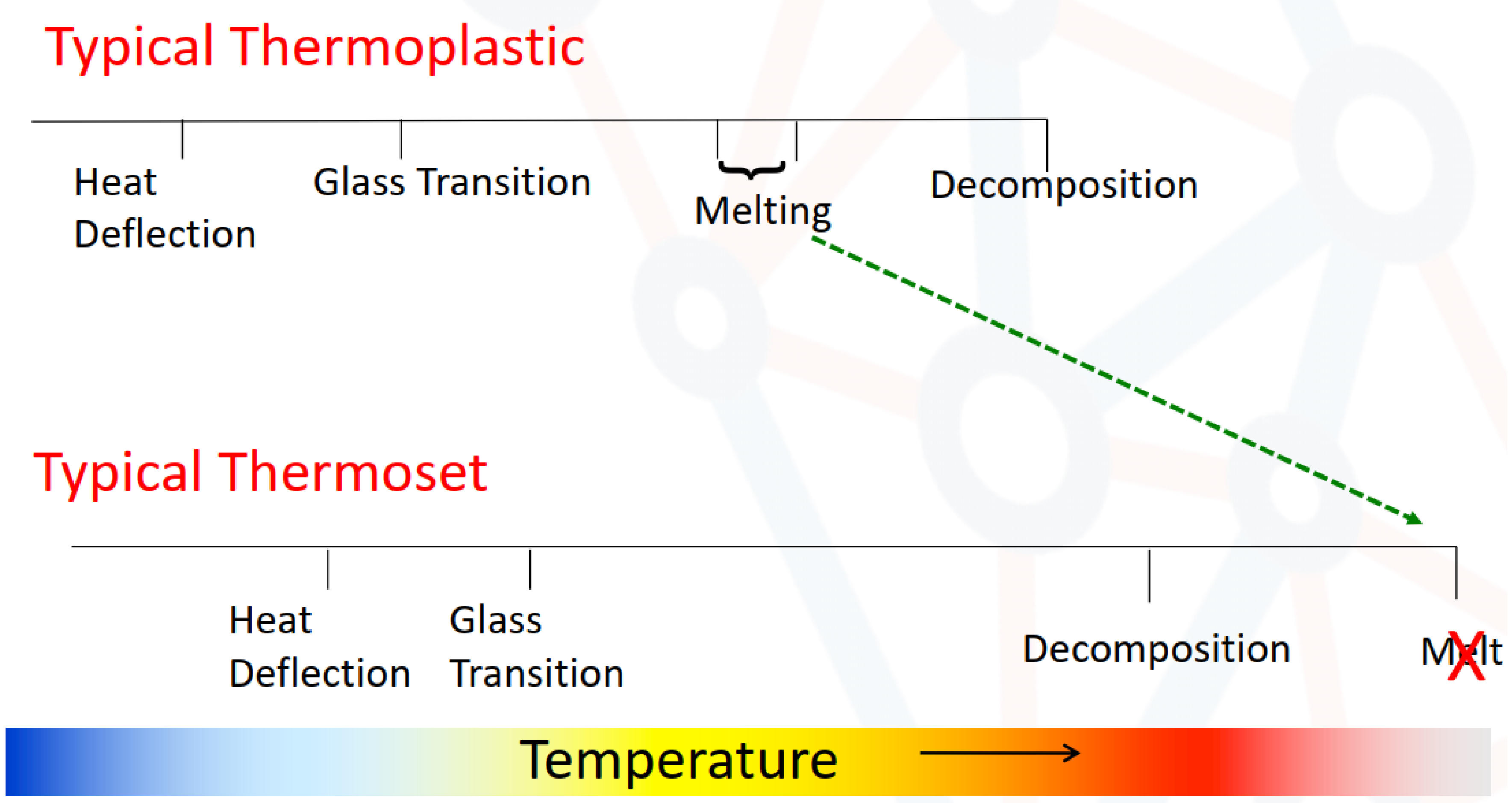
Thank you

- Aerolytics LLC -

Aerospace Analytical Market Research & Consulting

www.aerolyticsllc.com

Affects of temperature on thermoplastics vs thermosets



Throughput vs complexity for composites manufacturing