Engineering, Test & Technology
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Advanced Materials and Manufacturing Methods for High Temperature Thermal Management Applications

ARPA-E High Efficiency High-Temperature Modular Power Workshop
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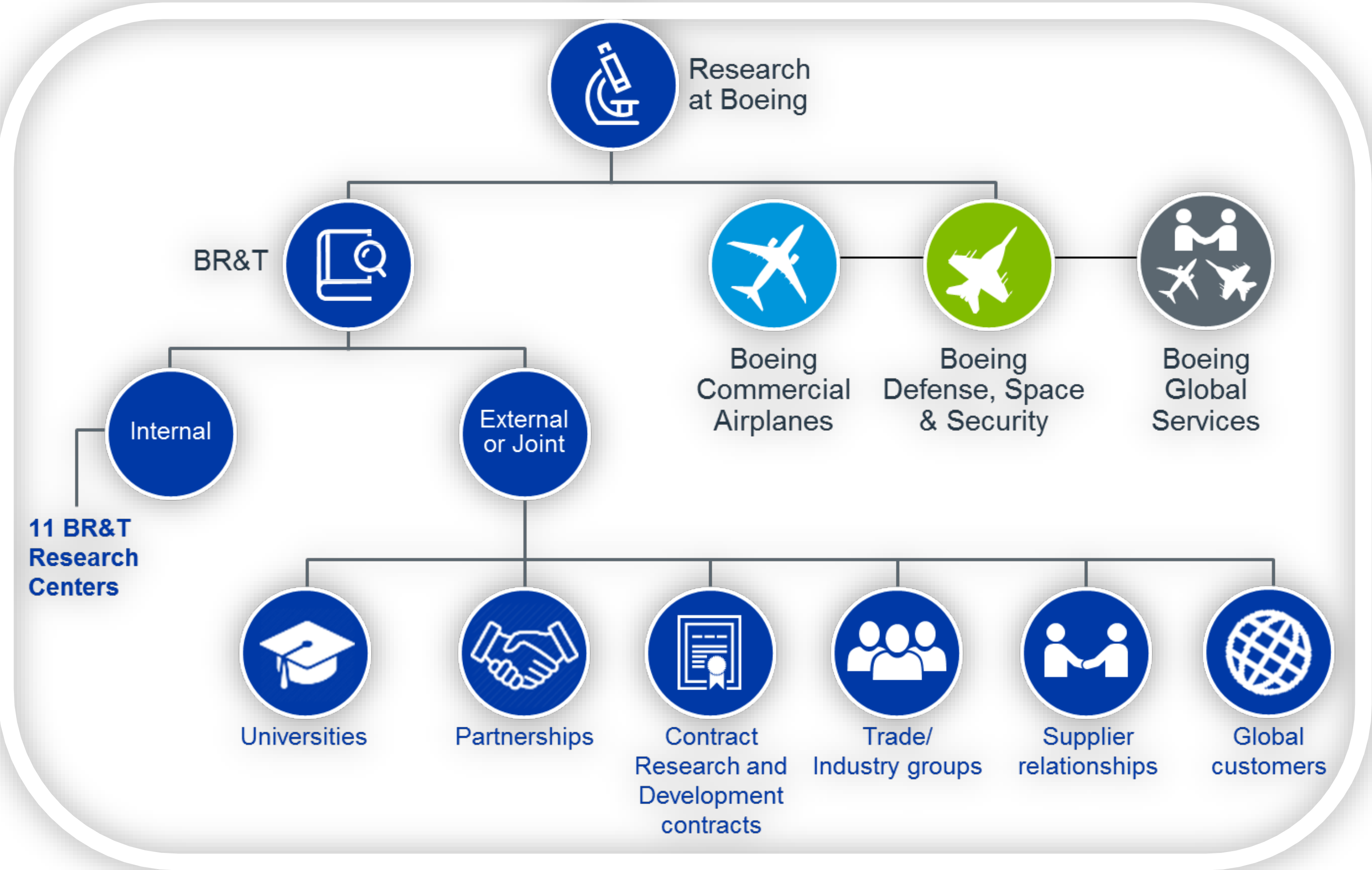
Boeing Commercial Airplanes

Product Development



Boeing Defense, Space & Security

Phantom Works

Independent R&D organization

Advanced central research and development organization that helps protect the second century through innovation and implementation

High Temperature Thermal Management (HT-TM)

- Technology development in early 1970's to address oil crisis (ceramic heat exchanger for gas turbine and oil pipeline applications)
- Limited use on traditional gas turbine cycle due to
  - Cost for developing high volume manufacturing methods
  - Durability limits due to operating temperature and pressure
- Distributed power generation (small gas turbines, fuel cell and hybrid power systems; 5-400 kW) renewed interests in 1990's and early 2000's
  - Need for improved thermodynamic efficiency
- Recent applications in high temperature power systems, waste heat recovery and emission control systems has resulted in need for heat exchangers in the range of 650-825C (1200-1500F)
- Key challenges:
  - Cost
  - Size/Weight
  - Material Durability
  - Life/ Reliability Requirements

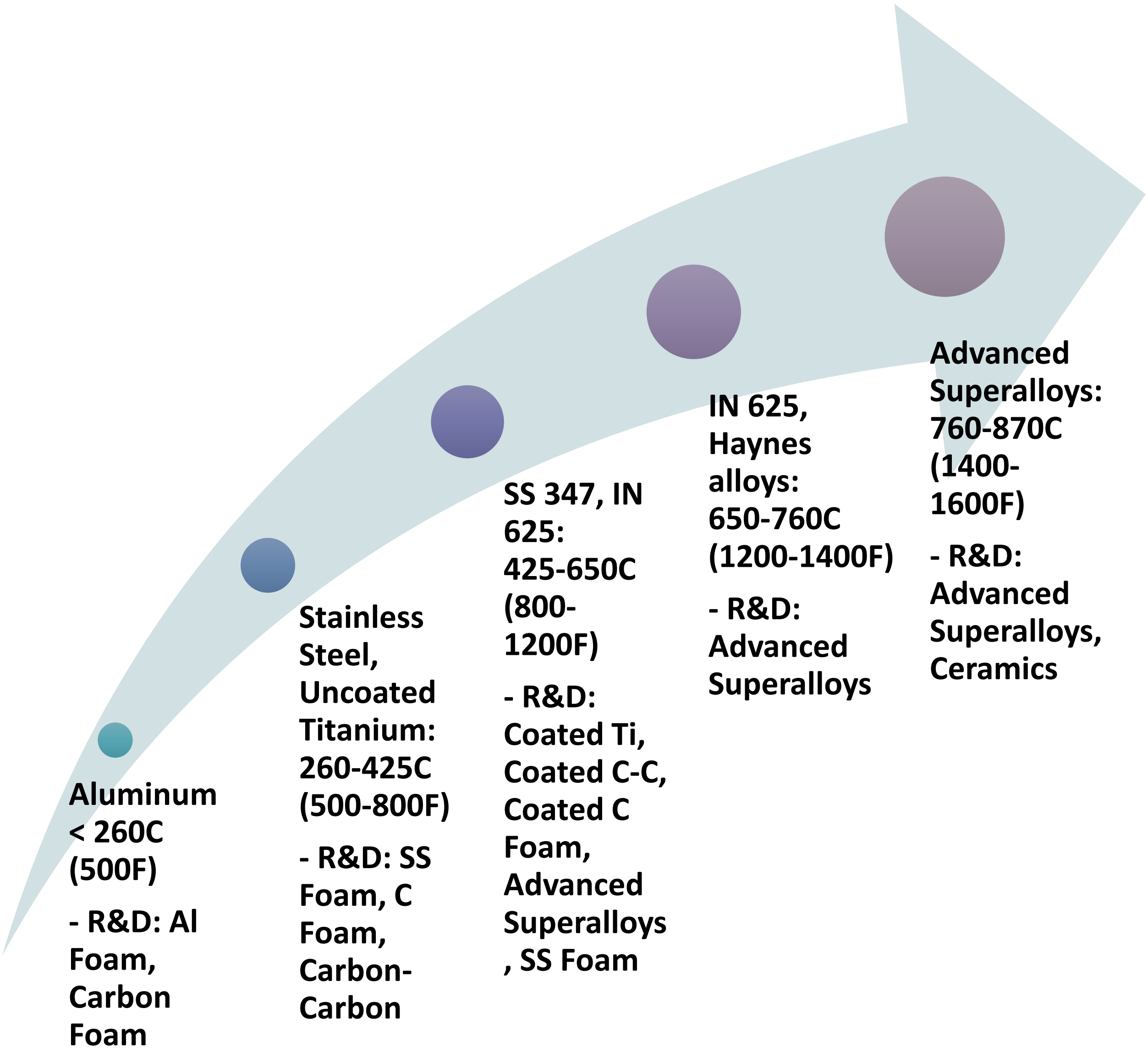
Aircraft System	Approximate Temperature
Power Electronics	150°F [66°C]
Hydraulic / Fuel	250°F [121°C]
Bleed Air	350°F [176°C]
APU	500°F [260°C]
Engine	800°F [426°C]
Landing Gear	1000°F [538°C]

Broad Temperature Range of Aircraft Systems demand diverse materials: COMPOSITE POLYMERS TO SUPERALLOYS

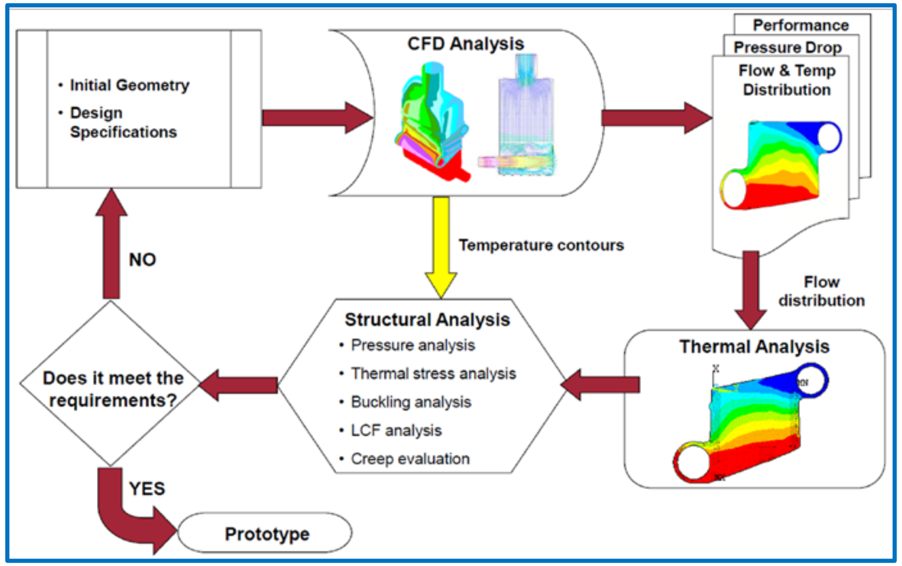
Low Temperature HX	High Temperature HX
Material selection and thickness typically driven by cost and weight	Material selection and thickness driven by thermal stresses and life
Differential coefficient of thermal expansion (CTE) does not drive HX design	Differential CTE may drive design to include expansions bellows, slip joints, tie-rods, etc.
Fins commonly used to enhance heat transfer	Prime surfaces may be preferred to fins due to erosion
Water as a common working fluid	Gases, liquid metals and molten salts preferred
Radiation effects are negligible	Radiation may be significant (e.g. insulation)

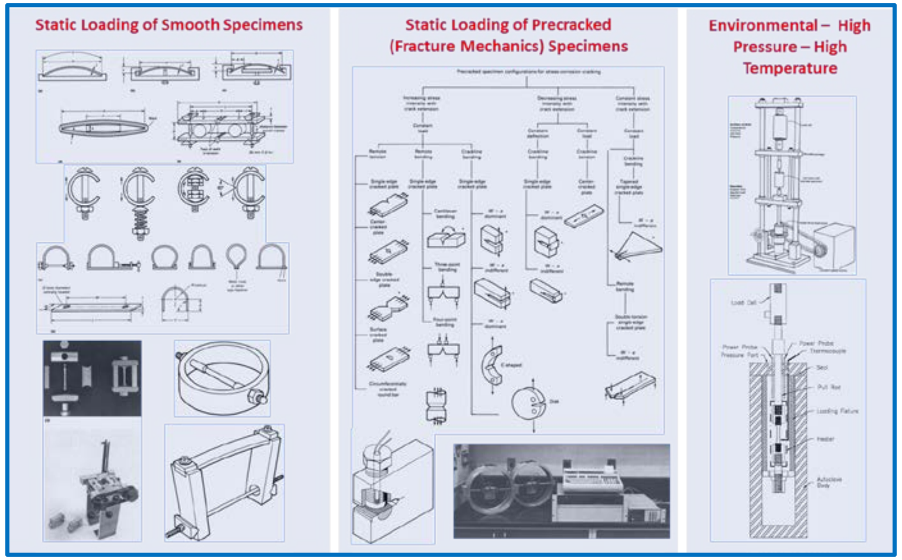
Novel/Affordable/Advanced TM Solutions Needed

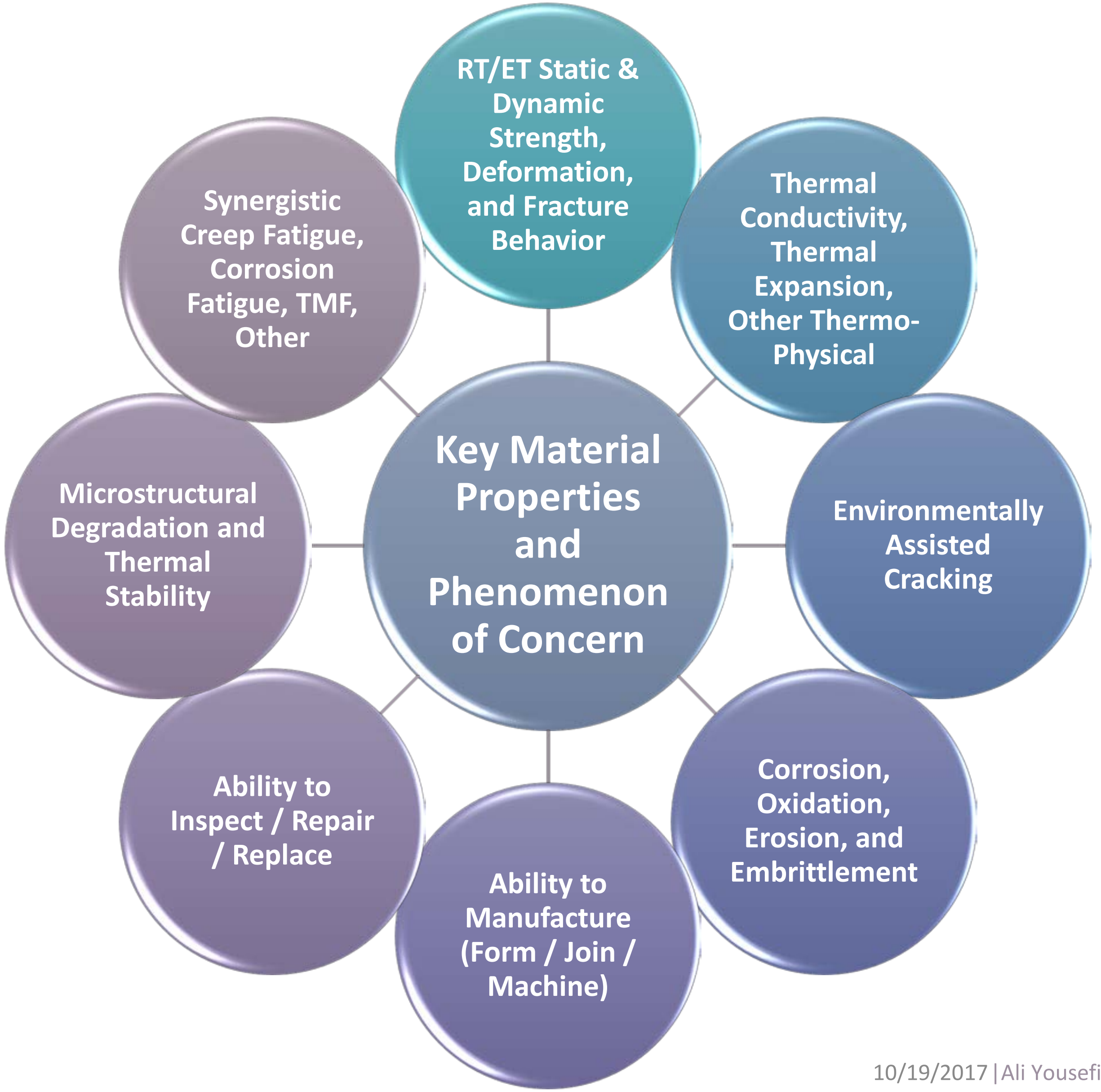
- High performance, compact, low cost heat exchanger technologies are needed for ever increasing heating and cooling requirements for range of applications
- Potential Applications
  - **Aerospace** (more electric, environmental control, avionics and propulsion systems)
  - **Automotive** (waste heat recovery and exhaust gas recirculation system)
  - **Power** (heat management in large-scale and distributed power plants)
  - **Processing** (process heat and cooling and waste heat recovery)
- Design and fabrication innovations need to
  - Accommodate demand for increased performance with minimum pressure loss
  - Reduce size (volume) and/or weight
  - Be affordable and scalable or modular



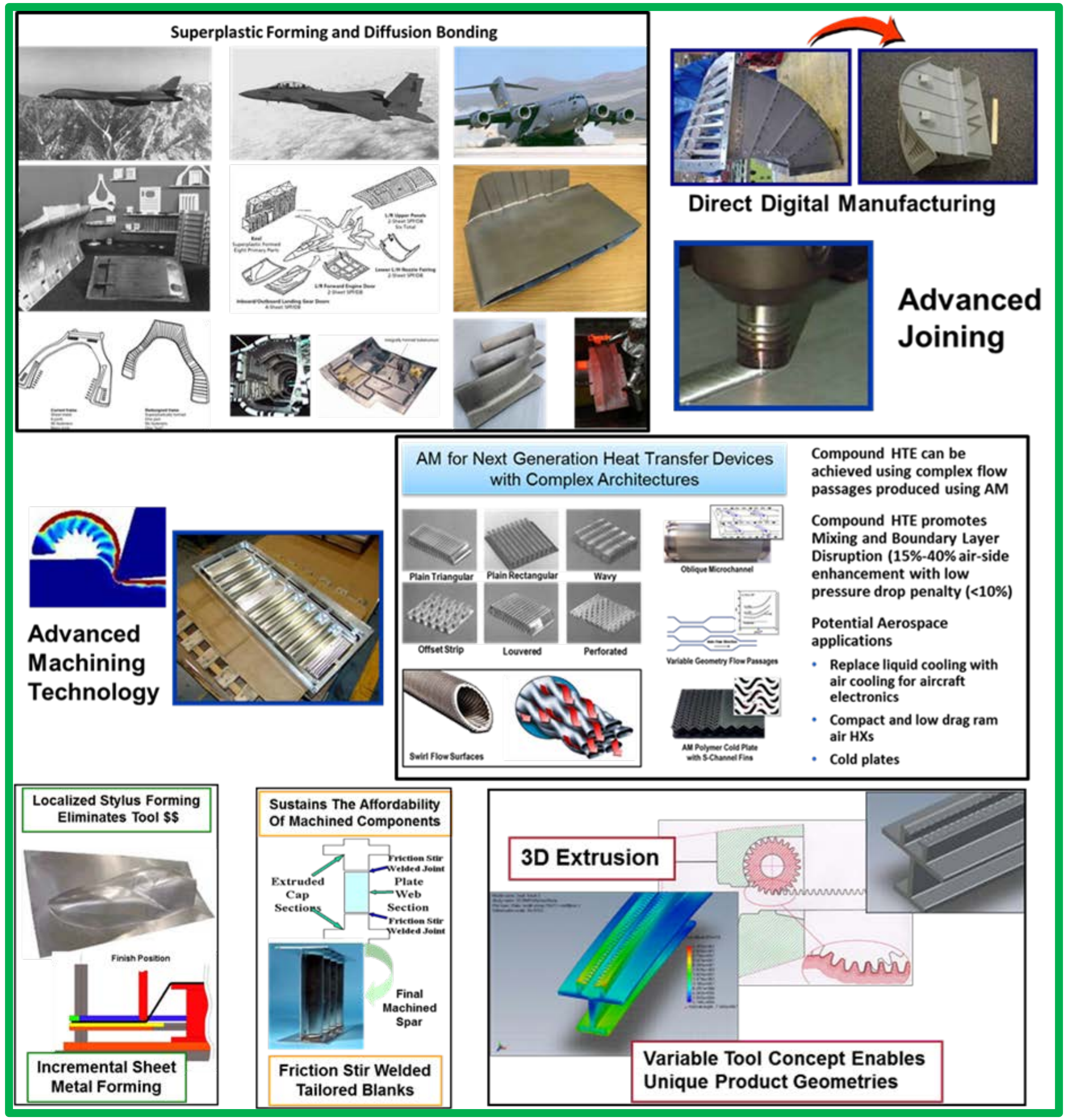
HT-TM Application Design/Test Considerations







Materials & Manufacturing for HT-TM



Advanced Materials and Manufacturing Methods for High Temperature Thermal Management

Advanced Materials
- Derivative
- Next Generation
- NC/UFG PM Alloys
- Advanced MMC
- Intermetallics
- HEA/SMA/Hybrid

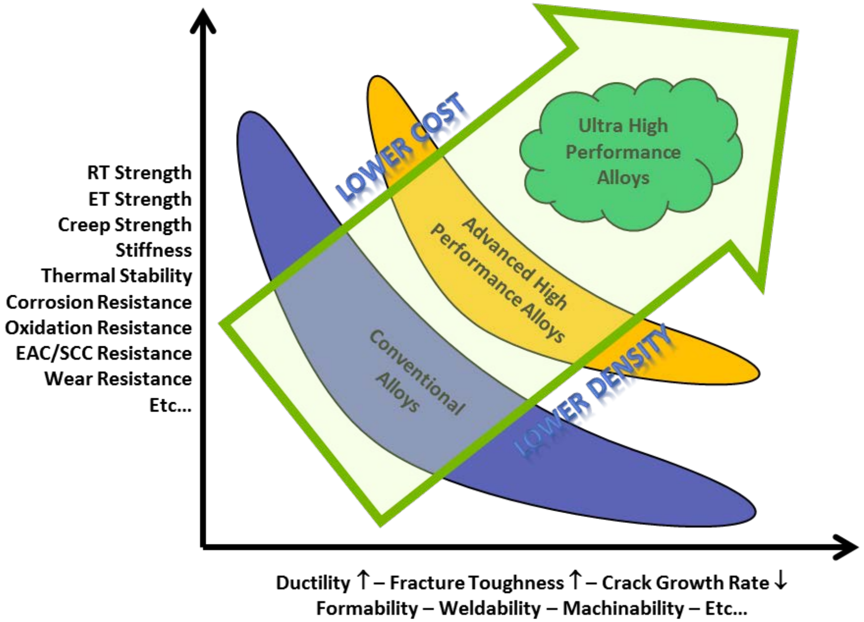
Additive Manufacturing
- Powder Feed
- Powder Bed Laser / Electron Beam
- Wire Feed
- Cold Spray

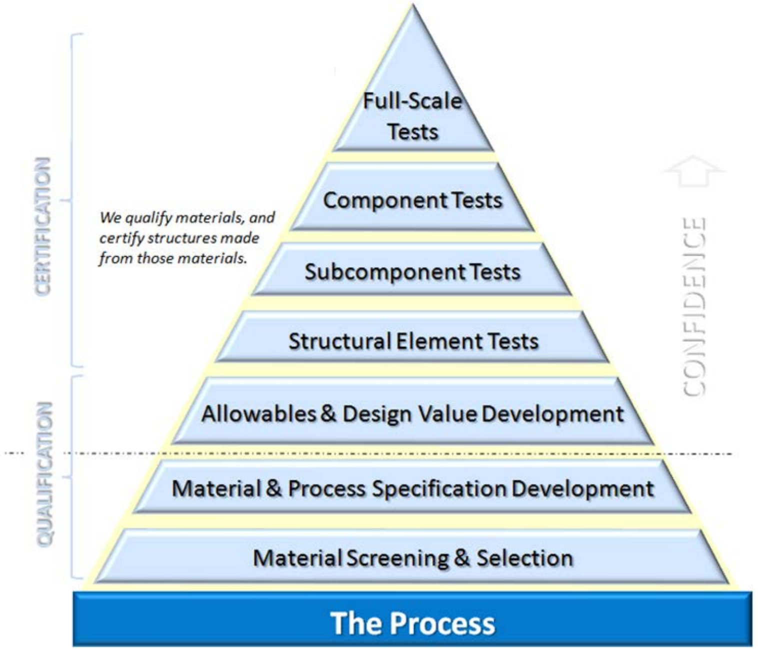
Forming and Joining Process Innovation
- Advanced Forming
- Solid State Joining
- Advanced PM Processing

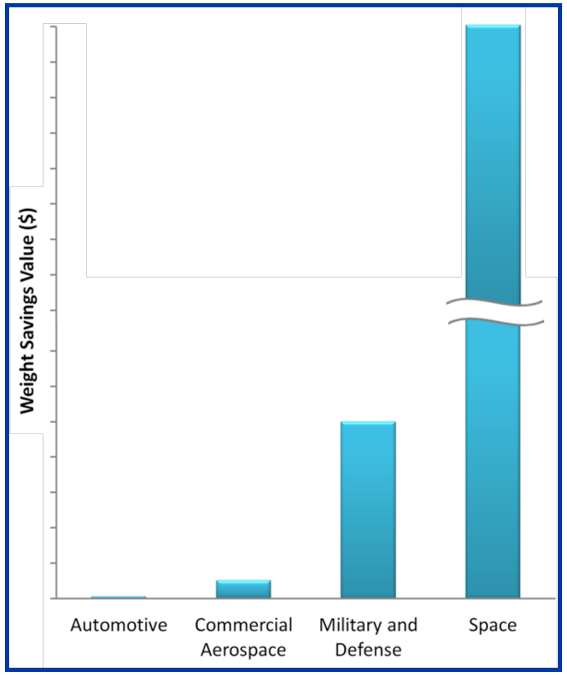
Revolutionary Products
- Advanced Near-Net Preforms
- Spatially Graded Structures
- Multifunctional & Tunable Structures

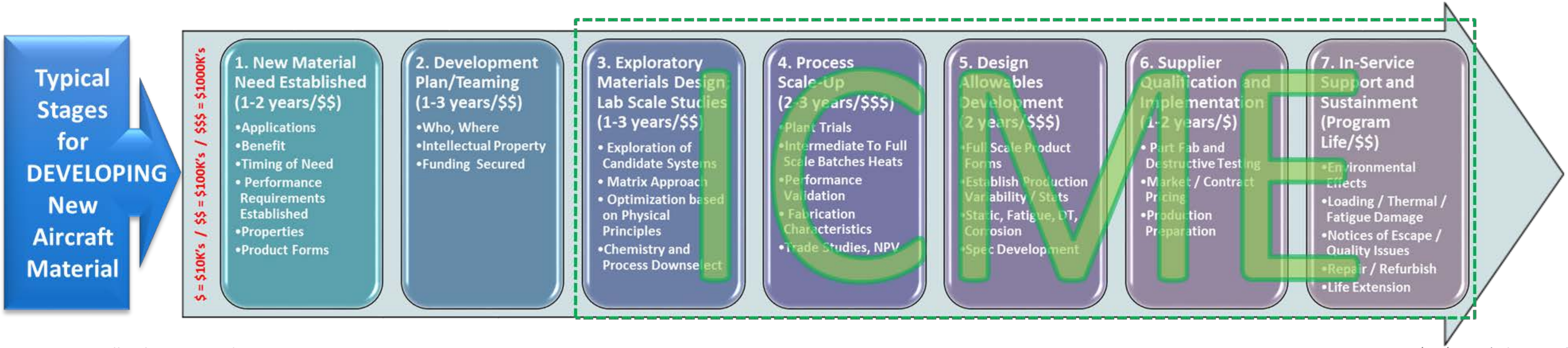
Dynamically Optimized Machining
- Unitizing Structure
- Complex Preforms

Material Performance Goals



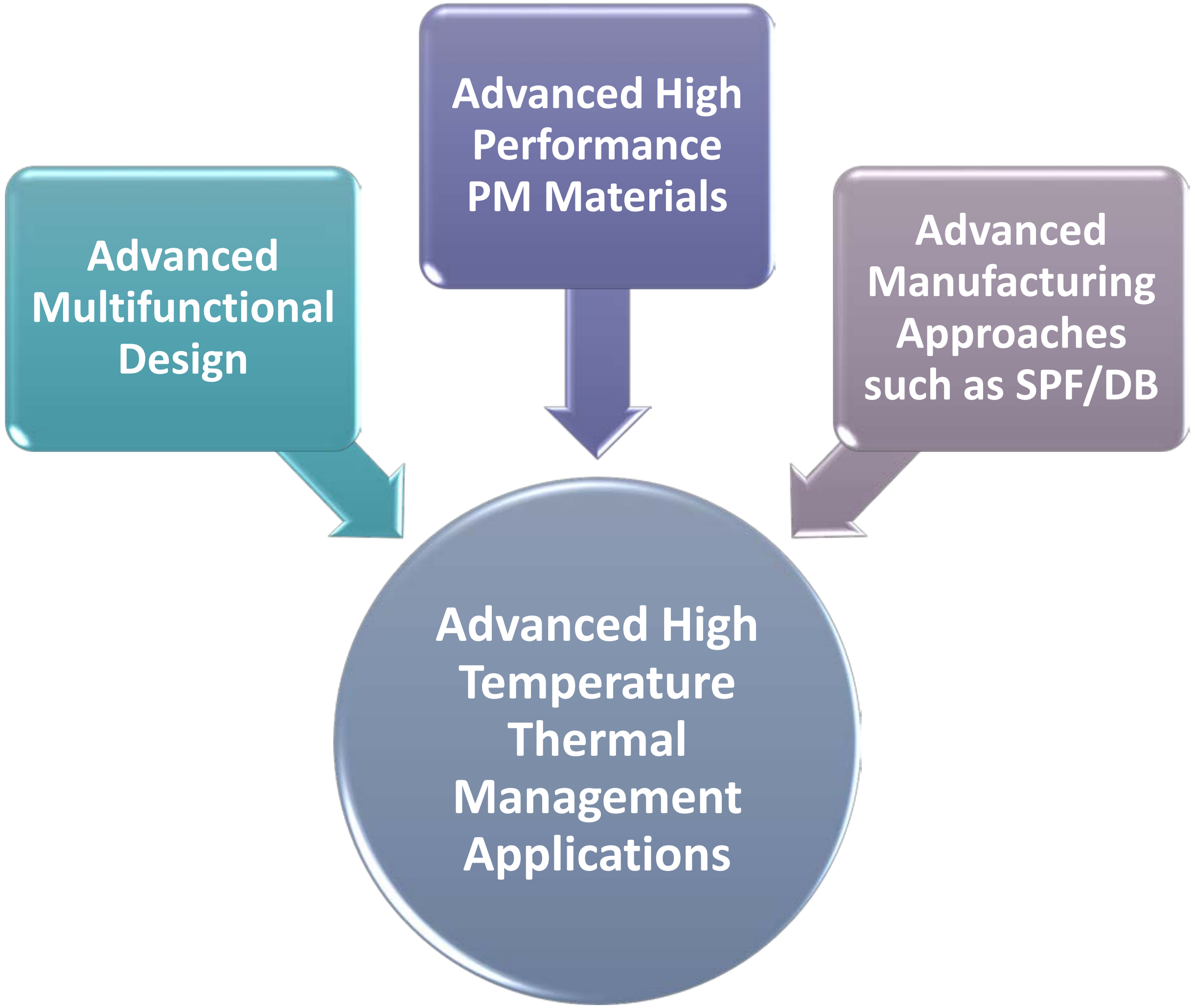






Challenges and Opportunities

- Materials are vital part of aircraft / spacecraft performance improvements
- A new material system must earn its way onto the aircraft:
  - Targeted Application
  - Breakthrough performance improvements
  - Value and affordability across the life cycle
- Significant improvements must be realized to offset development/certification costs
- We need to:
  - Get smarter/leaner with R&D activity + team up + leverage resources whenever possible
  - Implement Integrated Computational Materials Engineering as early as possible
  - Chose the appropriate application with the best business case
  - Integrate various technologies and incorporate multiple functionality



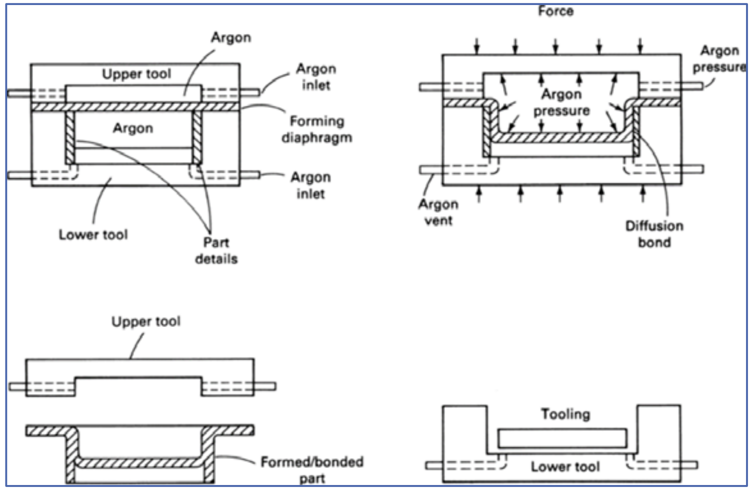
Superplastically Formed and Diffusion Bonded Structures

Very complicated geometry panels can be fabricated with multi-sheet SPF/DB processes. Compound curvature easily formed “net shape” with single hot forming operation

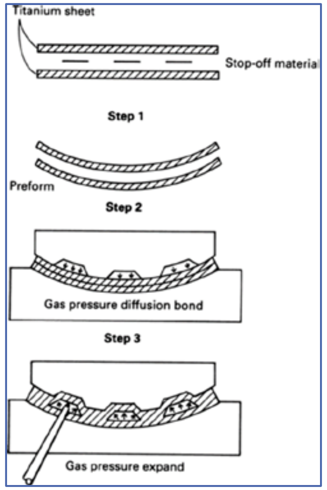
SPF/DB panels can be formed with integral complex ribs / stiffeners with sharp angles and complex surface geometry including pan downs and doublers

Tonnage for SPF/DB is much less than that required for conventional press forming; reducing press equipment and tooling costs

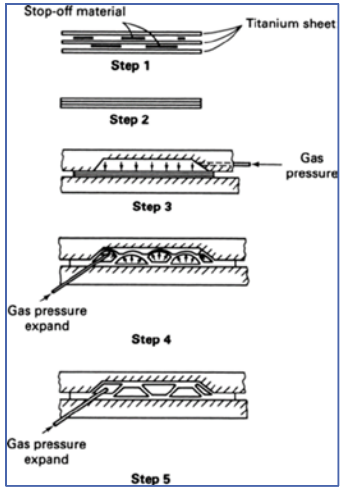
Secondary fabrication steps including welding or riveting may not be required, but are possible if desired.



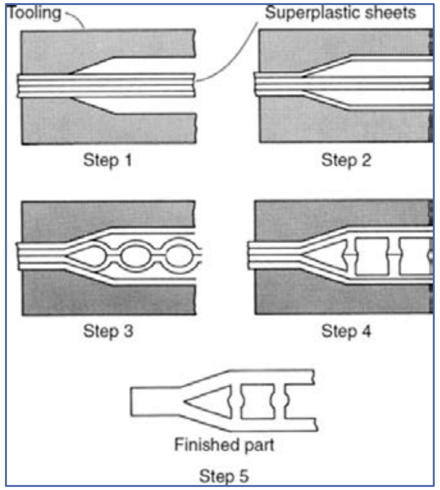
Single Sheet SPF/DB (with preplaced details)



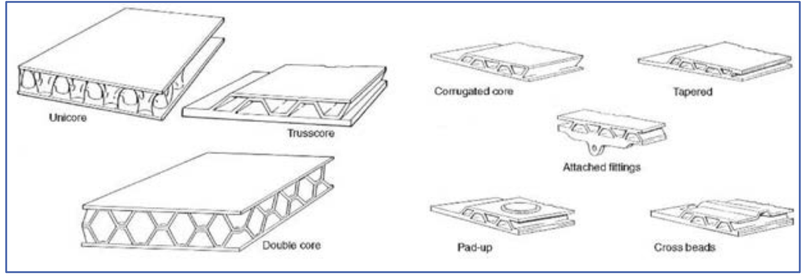
2-Sheet SPF/DB

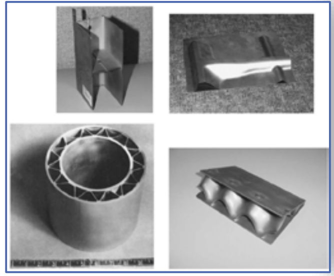


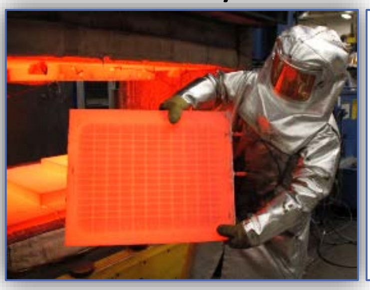
3-Sheet SPF/DB

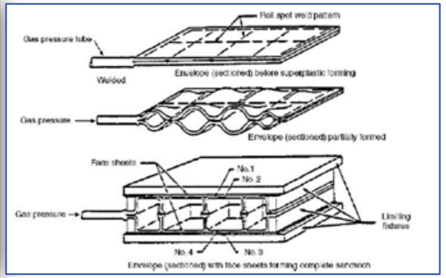


4-Sheet SPF/DB









Thickness pad up areas are easily diffusion bonded into face sheets

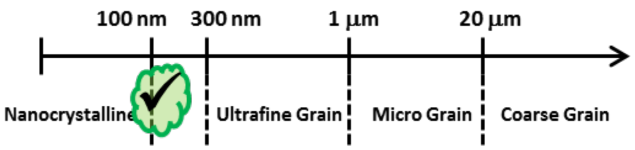
SPF/DB requires a single die set as opposed to multiple dies required conventionally, leading to tooling cost saving and faster time to market

Weight savings is realized compared with other methods, due to evenly distributed monolithic stress fields which can allow the use of thinner sheet

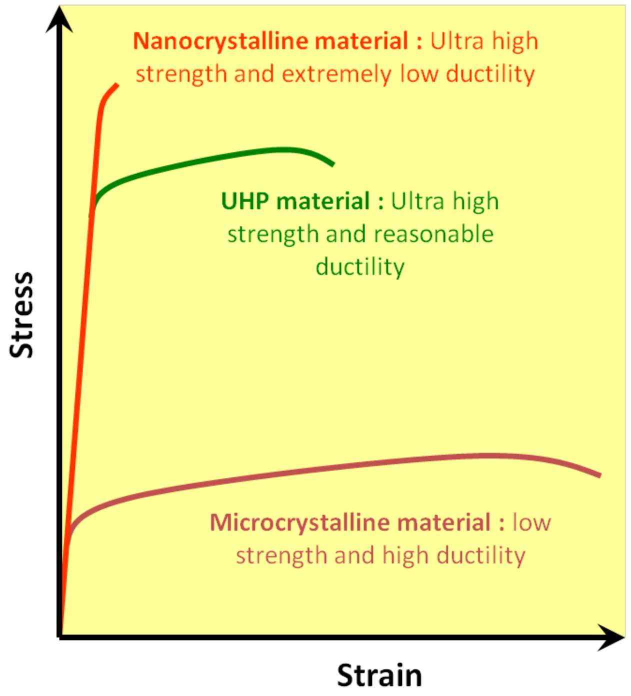
Excellent repeatability of the net shape forming process is achieved compared with other forming methods. Stress relieving operation occurs during SPF/DB (no spring back)

Advanced High Performance Powder Metallurgy (PM) Alloys

- Nanocrystalline (NC) and ultrafine grained (UFG) alloys can be synthesized either by consolidating small clusters (bottom-up) or breaking down bulk (top-down)
- NC/UFG alloys show promise for ultra high performance, but have shown disappointingly low ductility/toughness, limiting their structural applications
- Commercial application depends strongly on successful thermomechnical processing into bulk components, while preserving microstructure
- Poor damage tolerance and poor thermal stability needs to be addressed

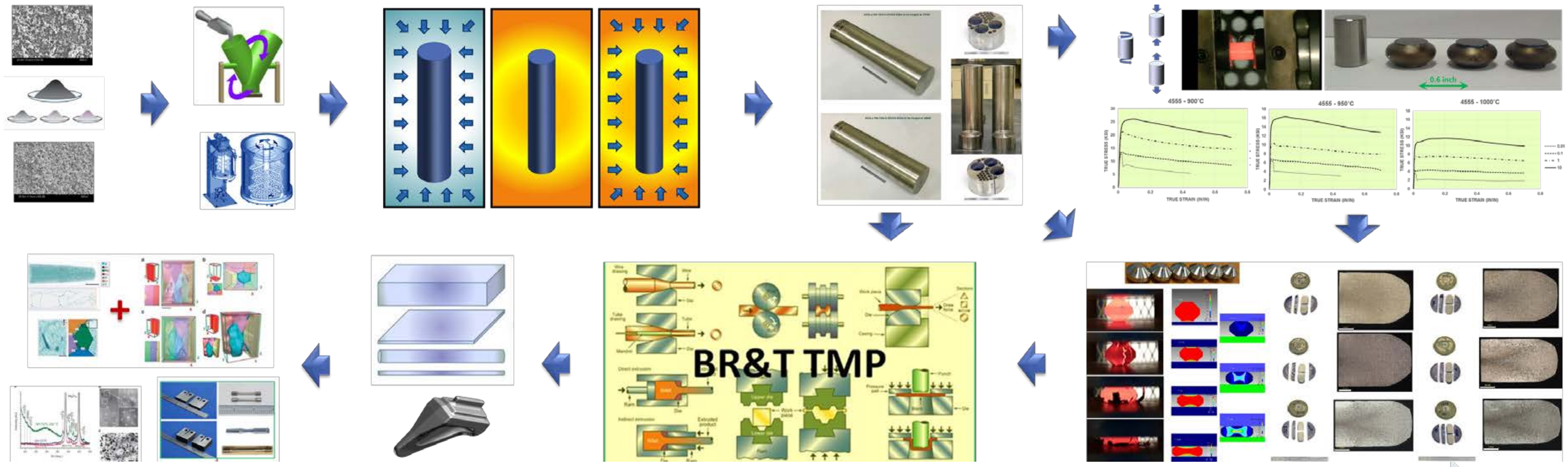


Principal (practical) bulk material synthesis methods
(1) Mechanical alloying and compaction/consolidation
(2) Bulk severe plastic deformation



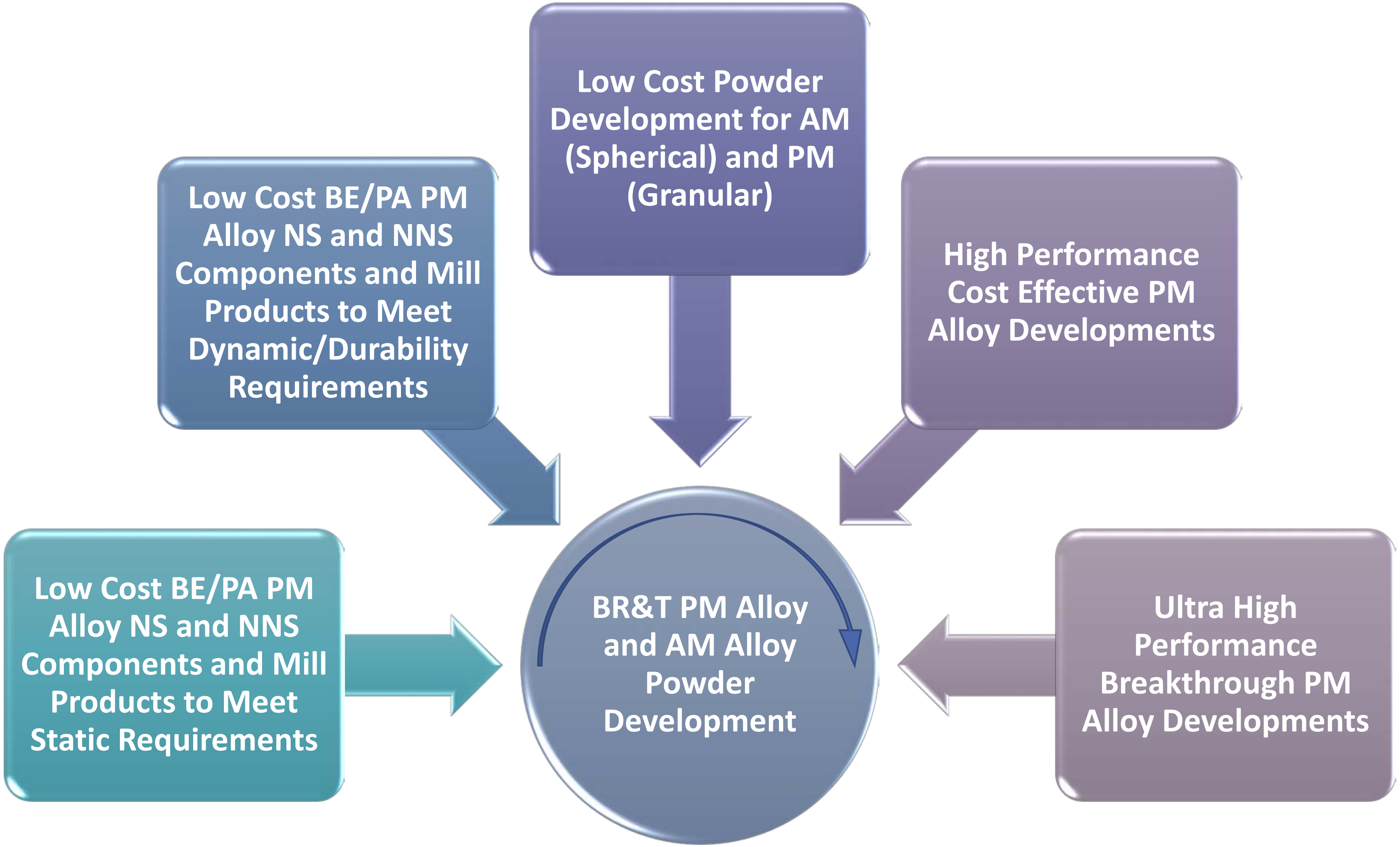
Why Advanced Powder Metallurgy Processing?

BR&T Advanced PM Alloy Development Approach



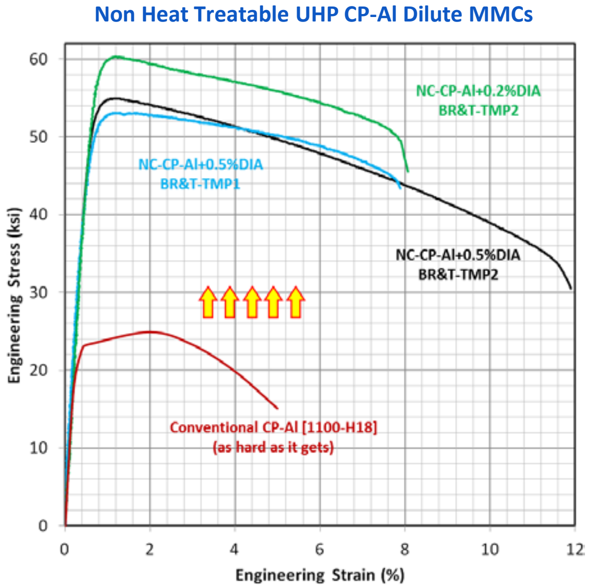
- LOW COST FEEDSTOCK
- Laboratory Scale Consolidation and TMP
- Coupon Level Testing, Characterization, and Optimization
- Scale Up ↑↑↑ DISCOVERY GATE
- Subcomponent + Coupon Level Production and Evaluation
- Scale Up ↑↑↑ FEASIBILITY GATE
- Component Level Production and Evaluation
- PRACTICALITY GATE
- Allowables and Specifications Development

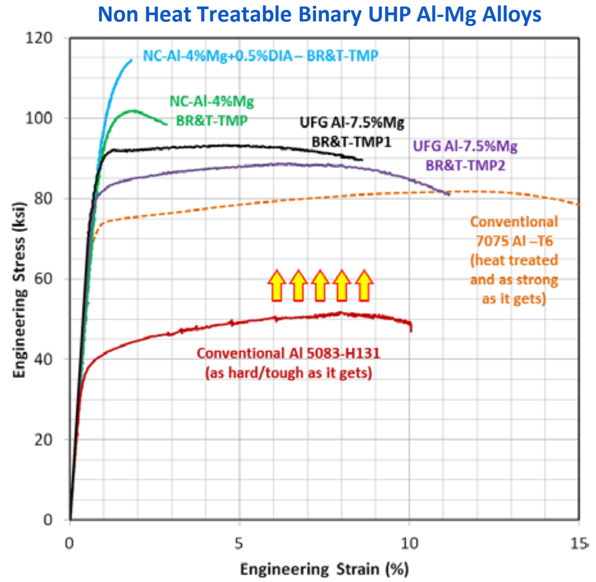
BR&T PM Alloy Component Development Roadmap

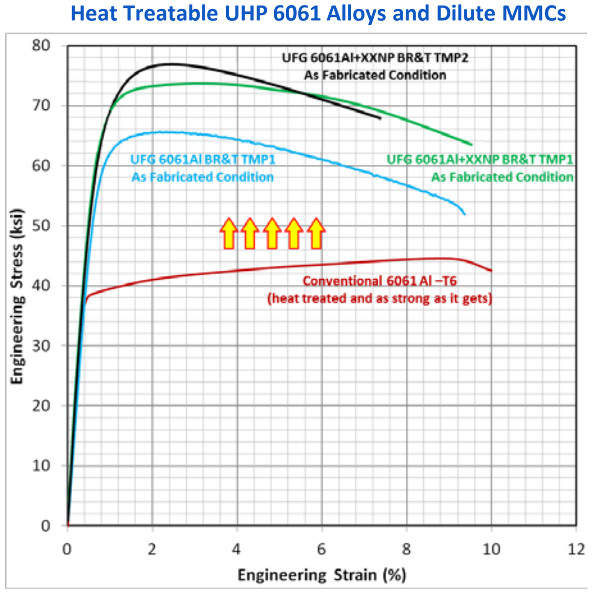


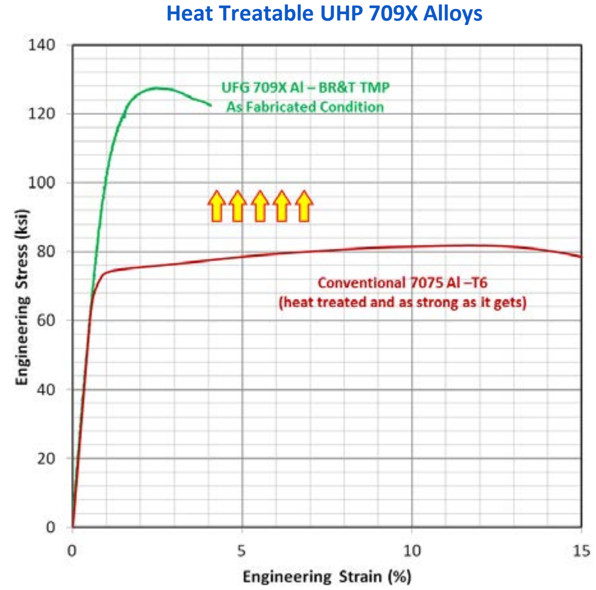
UHP PM Al Alloy Development

- High performance (strong and ductile) nanocrystalline bulk diamondoid reinforced CP Al alloy extrusions with substantial thermal and nanostructural stability.
- Tailorable extra light (ρ ≈ 0.094 lb/in3) non heat treatable UFG binary Al-Mg alloy extrusions with very high strength and ductility.
- Bulk UFG 709X Al alloy extrusions with exceptionally high strength and reasonable ductility as fabricated, through the implementation of novel BR&T TMP.
- Thermally stable and corrosion resistant bulk UFG 6061 Al alloys and dilute MMC extrusions with high strength and ductility as fabricated.









Low Cost PM Ti Alloy Products

Rolled Products

Forgings

Extrusions

Summary

- BR&T is actively involved in R&D of novel and advanced alloys for a wide array of applications, aiming at significantly enhancing performance to ultimately reduce cost and cycle time
- Developing cost effective energy-efficient strategies for manufacturing high temperature metallic components by taking advantage of low cost feedstock and application of advanced PM processing techniques
- Demonstrated much achievement in addressing the two main issues (poor thermal stability and poor damage tolerance) which have historically impeded development of bulk structural advanced high performance NC/UFG PM alloys.
- While most evident performance enhancement is strength, other parallel improvements have been made depending on the alloy system, such as corrosion resistance, machinability, and advanced SPF/DB capability.
- Initial efforts on HP Al alloys paved the way for development of more economically viable high performance alloy and dilute MMC systems.
- Current efforts are focused towards development and maturation of high performance high temperature Ti based, Ni-based, and Nb-based NC/UFG PM alloys that demonstrate advanced SPF/DB capability optimized to meet requirements of various extreme environment applications.
- Such matured high performance materials systems can have broad application in a variety of multifunctional cellular metallic structures being developed for high temperature thermal management components.


Thank You!