OPPORTUNITIES AND APPROACHES FOR DOUBLING THE STRUCTURAL EFFICIENCY OF METALLIC MATERIALS

NATO Advanced Research Workshop

Metallic Materials with High Structural Efficiency

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### Opportunities And Approaches For Doubling The Structural Efficiency Of Metallic Materials

**Abstract:**

See also ADM001672., The original document contains color images.

**Subject Terms:**

- unclassified
- unclassified
- unclassified
HIGH STRUCTURAL EFFICIENCY
—What is it, and why is it important?

STRUCTURAL EFFICIENCY OF METALLIC MATERIALS

CANDIDATE TECHNOLOGIES

SUMMARY
Stiffness and strength are primary design factors in every aerospace structure
  - controls size (mass) and spacing (number) of structural members
  - reduces deflections, controls instabilities
  - fatigue response often scales with stiffness
  - stiffness defines vibrational frequencies

**Higher specific properties provide equivalent structural response at reduced mass**—**higher structural efficiency**
  - doubling specific properties decreases weight by 50% without redesign
  - improved performance for dynamic parts and systems
  - enabling requirement for many advanced aerospace systems
  - enables more efficient design, such as unitized construction
  - fewer parts provides significantly improved affordability

**Isotropy is required to provide pervasive technology impact**
Skin/stringer construction is inefficient
- low $E/\rho$ requires close spacing of support structure
- joints do not transfer loads efficiently
- many simple detail parts require expensive assembly operations
Composites Affordability Initiative

OUR VISION

Today

- 11,000 Metal Components
- 600 Composite Components
- 135,000 Fasteners

Design For Affordability

- 450 Metal Components
- 200 Composite Components
- 6,000 Fasteners

- Reduce Part Count
- Improve Producibility
- Dramatically Reduce Assembly Costs

BOEING
LOCKHEED MARTIN
NORTHROP GRUMMAN
Advanced LH$_2$ Turbopump
Advanced Metals Enable Simplified Design

Sophisticated manufacturing and design and improved material properties enable reduced part count and cost

Integrated Powerhead Design
Part Count = 524 pieces
(SSME = 1433 pieces)

RL-10b Rocket Engine
A Full Spectrum of Dreams... and Demands for Better Materials

- Global Reach Aircraft
- Multi-role Unmanned Air Vehicle (UAV)
- SensorCraft UAV
- Hypersonic (Mach 8-10) Aircraft
- Reusable Space Lift
- Single Stage to Orbit
- Advanced Liquid Rocket Engines
- Hybrid Propulsion
OUTLINE

HIGH STRUCTURAL EFFICIENCY

STRUCTURAL EFFICIENCY OF METALLIC MATERIALS

CANDIDATE TECHNOLOGIES

SUMMARY
Metals will not compete with OMC’s when ambient temperature structural efficiency in one direction is the only consideration

- primary advantages of metallic materials include elevated temperature capabilities and isotropic properties

Aerospace applications often require secondary characteristics which enable the material to achieve the primary function

- compatibility with aggressive environments (hot oxidizing and corrosive gases, wet corrosion, hydraulic fluid, jet fuel, cryogens, AO, UV, ionizing radiation . . . )
- fatigue resistance
- high bearing loads for fasteners, assembly
- affordability, supportability . . .

Metals typically excel in secondary characteristics required for structural applications
**HIGH STRUCTURAL EFFICIENCY**

**DRA** offers very good specific stiffness, with modest improvement in specific strength
- ability to implement highest specific stiffness limited by inadequate fracture properties
- higher specific strength can be obtained by improved matrices or by selective fiber reinforcement

**Amorphous metals** offer exceptional specific strength, but marginal specific stiffness and fracture properties

Boron-modified Ti (**Ti-B**) offers significant improvements in both specific strength and stiffness

Continuously reinforced **MMCs** offer very good specific strength and stiffness along the fiber direction, but poor transverse properties and poor ability to produce complex shapes

**Nanocrystalline metals** offer approach for achieving high strength and good fracture properties
OUTLINE

HIGH STRUCTURAL EFFICIENCY

STRUCTURAL EFFICIENCY OF METALLIC MATERIALS

CANDIDATE TECHNOLOGIES

— MMCs
— Advanced Al
— Ti-B Alloys
— Metallic Glasses

SUMMARY
MMC’s represented a business volume of >2500 metric tons in 1999, valued at >$100M

- Ground Transportation represents largest market by volume (62%), but Thermal Management represents largest market by value (66%)
- Aerospace represents 5% by volume (~140 metric tons), 14% by value (~$15M)
- Other major markets include industrial and recreational

Al MMC’s represent the largest market volume at 69%, while refractory MMC’s (Cu/W, Cu/Mo) represent 25%
- Other MMC systems include Ni, Ti, Be, Fe

Liquid metal processing represents about 2/3 of the market by volume, and about 1/4 the market by value
- existing aerospace applications use only MMC produced by solid state processes

Discontinuously-Reinforced AI
High Specific Properties Offer Performance and Affordability

F-16 DRA Ventral Fin has provided $26M savings

DRA has replaced gr/epoxy fan exit guide vanes in PW 4XXX engines

DRA has replaced Ti in flight-critical application on N4, EC-120 Helicopters

DRA fuel access doors have reduced fuselage cracking in F-16
Discontinuously-Reinforced Al
High Specific Properties Offer Performance and Affordability

Honda Prelude
DRA Cylinder Liners

Toyota Altezza
Ti/TiB Exhaust Valves

Chevy Corvette
DRA Driveshaft

Plymouth Prowler
DRA Brake Rotors
**Discontinuously-Reinforced Al**

High Specific Properties Offer Performance and Affordability

DRA active cooling systems, chassis, and enclosures provide dramatic improvements in weight, performance, and cost

DRA has replaced Fe/Ni, Cu/Mo and Cu/W for chip carriers and microwave devices

DRA is used for power semiconductor bases in GEO comsats, cell phone base stations
**Composition**
- Al, Fe, Cu, Ti . . . matrix with 10-70% SiC, Al₂O₃, B₄C, TiC . . . reinforcements

**Microstructure**
- extensive range of control for matrix microstructure and particulate distribution

**Processing**
- wrought, cast, P/M techniques
- established and affordable for most primary and secondary processes
- utilizes existing infrastructure

**Properties**
- high specific stiffness, strength
- excellent fatigue—270 MPa @ 10⁷ cycles
  - v. 155-180 MPa for 2024-T4 and 7075-T6
- isotropic properties
- metallic behavior
- tailorable stiffness, CTE

**Applications**
- structural
- thermal
- wear
- electrical
Improved structural efficiency of DRX can be achieved with a higher volume fraction of reinforcements

– for DRA, reinforcement volume fraction $f > 0.20$ produces inadequate ductility and toughness for fracture-critical structural applications

Influence of morphology, volume fraction and distribution of reinforcements must be established

– scientific basis for quantifying distribution now being established

– positive influence of particle morphology has been established
TMCs Have Achieved Production Status

FMW Composite Systems, Inc.

Composite Design & Manufacturing

FMW Compression Links

FMW Actuator Piston Rod
Progress toward affordable TMC products has been achieved in unidirectional selectively reinforced components.

A dramatic reduction in TMC component cost has lead to the achievement of production status.

Success has initiated a developing market for this type of component.
Titanium Matrix Composites Ti-6Al-4V/SiC

- **Ultimate Tensile Strength (Longitudinal)**: 1690 MPa (245 ksi)
- **Young’s Modulus (Longitudinal)**: 200 GPa (29 Msi)
- **Ultimate Tensile Strength (Transverse)**: 400 MPa (58 ksi)
- **Young’s Modulus (Transverse)**: 145 GPa (21 Msi)
- **Low Cycle Fatigue, Longitudinal**: [120 ksi (830 MPa), R=0.1, 3Hz] >500,000 cycles
- **Low Cycle Fatigue, Transverse**: [27.5 ksi (190 MPa), R=0.1, 3Hz] >500,000 cycles
- **High Cycle Fatigue, Longitudinal**: [77 ksi (530 MPa), R=0.1, 30Hz] > 10^7 cycles
- **High Cycle Fatigue, Transverse**: [13 ksi (89.6 MPa), R=0.1, 30 Hz] > 10^7 cycles
- **Compression Strength**: >4480 MPa (>650 ksi)
- **Density**: 3.93 gm/cm^3 (0.142 lb/in^3)
- **CTE**: 5.9 x 10^{-6}/°C (3.3x10^{-6}/°F)
Development efforts are underway to address transverse property improvement.

- SiC fiber coating strength
- Boron modified titanium matrix alloys (Ti-B) for continuously reinforced Ti-MMCs provides unique opportunities for hybrid composites
FIBER-REINFORCED MMC’S

Prospective matrices include Ti, Al, Cu, Ni . . .
- applications include structural, thermal, electrical . . .
  - aero structures, cryo tankage, orbital spacecraft, liquid rocket propulsion, gun barrels, directed heat transfer . . .
- multifunctionality for structural/thermal or structural/electrical
- shape memory alloys (SMA) provide sensor/actuator functions

Scientific foundation and practical techniques to tailor interface properties not yet known
- control composition and structure of C coatings for SiC fibers
- predictive capability for interface bond required
- common methods to quantify interface properties are inadequate

Advanced processing is essential
- selective reinforcement
- hybrid composites

Design concepts require investment
- selective reinforcement concept well-known, but not yet mastered
- cross-ply architectures not yet established for MMC’s
- must be able to understand and control CTE mismatch and residual strains
OUTLINE

HIGH STRUCTURAL EFFICIENCY

STRUCTURAL EFFICIENCY OF METALLIC MATERIALS

CANDIDATE TECHNOLOGIES

— MMCs
— Advanced Al
— Ti-B Alloys
— Metallic Glasses

SUMMARY
Collaborative effort is developing a new class of age-hardenable Al with dramatic increase in structural properties

— both metastable precipitates and thermodynamically stable dispersoids are uniformly dispersed in the microstructure
— dispersoids are 5-10nm in diameter and provide strength and microstructural control
— strength increases of over 40% are achieved with excellent ductility
— material is cast and wrought with good affordability
— in-house effort funded through a Phase II SBIR

![Graph showing mechanical properties of Al alloys with nano-dispersoids](image)
Transition opportunities for super-high strength Al alloy technology are being established

- funded collaboration is underway with Boeing/Rocketdyne for advanced LH$_2$ turbopump impeller, rotor and housing
  - funded by AFRL/PR (Edwards AFB) through UES, Inc. (Dr. O. Senkov, PI)
- selected as only structural metal technology for recent Missile Defense Agency (MDA) call for topics
- discussions have been initiated with Metals Affordability Initiative (MAI) based on dramatic potential for cost reduction of high performance Al alloys
  - wrought strength can be achieved in a cast product
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SUMMARY
HISTORY OF Ti-B TECHNOLOGY

Early work in aeropropulsion industry
  – Rolls-Royce

Independent effort at Dynamet, Inc.
  – sinter and HIP powder metallurgy process
  – produced commercially for small parts

NASA/Boeing effort on High Speed Civil Transport
  – material iteration, process development, mechanical properties
  – feasibility of large extruded parts established

Focused effort at Toyota has developed and transitioned
Ti-B alloys for automotive intake and exhaust valves
  – lighter valves enable reduced spring mass, lower cycle losses
  – over 500,000 parts manufactured by 2000

Ti-B is an established technology in automotive and commercial sectors, but requires development for aerospace applications
**Alloy**

- B is essentially insoluble and does not embrittle Ti alloys
- Typically conventional $\alpha+\beta$, but may be near-$\alpha$, $\beta$ or orthorhombic
- Fine grained microstructure produced and stabilized by TiB

**Intermetallic**

- Volume fraction typically ~10%, but may be as high as 40%
- TiB is formed *in situ*
- TiB is chemically and thermally compatible with Ti alloys
- TiB intermetallic is very strong and stiff (~480 GPa)
- Typically whisker-shaped with aspect ratio of 5-20
- Size depends upon processing
**Ti-B PROCESSING**

**Cast**
- Eutectic reaction provides castability, affordable near net shape possibilities
  - TiB intermetallic refines cast grain size
  - Limits TiB volume fractions to ~10%

**P/M**
- Prealloyed powder processing provides fine TiB at cost comparable to conventional Ti P/M
  - Limits TiB volume fractions to ~10%
- Blended elemental powder approach provides higher $V_f$ at higher cost
- Compatible with advanced materials and processes
  - Continuously reinforced Ti-MMCs
  - Laser additive manufacturing

**Wrought**
- Full range of primary and secondary techniques are feasible
  - Extrusion, forging established for automotive applications with low B additions
- Alignment of whiskers provides opportunity to tailor properties, but must be controlled
Alloy
✓ equiaxed fine grained alpha microstructure stabilized by TiB intermetallics

Intermetallic
✓ typical TiB morphology is whisker with \( l/d \sim 10:1 \)
  \[ \rightarrow \text{Width: } \sim 1-5 \, \mu m \text{ and } \sim 100 \, \text{nm} \]
✓ control of orientation and TiB volume fraction possible
  \[ \rightarrow \text{aligned or random orientations possible} \]
  \[ \rightarrow \text{volume fractions up to 40\% are practical} \]
**Ti-B MECHANICAL PROPERTIES**

**Structural and Functional**
- Exceptional specific stiffness, strength
- Widely tailorable properties
- Isotropic or anisotropic properties
  - Alignment of TiB whiskers (1D) provides fiber-like properties
  - Randomly oriented whiskers (3D) provides isotropic properties
- Cost comparable to conventional Ti alloys
- Metallic behavior (supportable)

### Ti-B MECHANICAL PROPERTIES

<table>
<thead>
<tr>
<th>Ti-6Al-4V</th>
<th>Ti-6Al-4V-0.5B (3% TiB)</th>
<th>Ti-6Al-4Sn-4Zr-1Nb-1Mo-0.2Si-0.8B (5% TiB)</th>
<th>Ti-6Al-4V-1.6B (3D) (10% TiB)</th>
<th>Ti-6Al-4V-3.0B (1D) (20% TiB)</th>
<th>GOAL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modulus (GPa)</strong></td>
<td>110-115</td>
<td>125</td>
<td>132</td>
<td>136</td>
<td>200</td>
</tr>
<tr>
<td><strong>YS (MPa)</strong></td>
<td>840-1070</td>
<td>1007</td>
<td>1175</td>
<td>1400</td>
<td>1250</td>
</tr>
<tr>
<td><strong>UTS (MPa)</strong></td>
<td>940-1180</td>
<td></td>
<td>1500</td>
<td>1350</td>
<td></td>
</tr>
<tr>
<td><strong>Strain (%)</strong></td>
<td>7-20%</td>
<td>9.5</td>
<td>5.0</td>
<td>2.4</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>Kic (MPa√m)</strong></td>
<td>44-110</td>
<td>47</td>
<td>40-55</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fat Str (MPa) (&gt;10⁶ cyc)</strong></td>
<td>494-744</td>
<td>675</td>
<td></td>
<td></td>
<td>&gt;1000</td>
</tr>
<tr>
<td><strong>Tmax</strong></td>
<td>427°C/800°F</td>
<td></td>
<td></td>
<td></td>
<td>600°C/1100°F</td>
</tr>
</tbody>
</table>

Diagram: 
- Ti-6Al-4V-1.6 B (Aligned)
- Ti-6Al-4V-2Sn-4Mo-2Zr (Isotropic)
- Ti-6Al-4V (Isotropic)
A new class of Ti alloys provides dramatic increases in structural properties

- TiB whiskers are thermodynamically stable
  - micron-sized whiskers are ~1µm diameter with l/d ~ 10:1
  - submicron whiskers are ~100nm diameter with l/d ~ 10:1
- TiB provides strength and stiffness
  - uniform dispersion of TiB achieved *in situ*
  - alignment of TiB easily achieved via extrusion, rolling
- P/M is currently being studied; casting offers large payoff in performance and affordability

<table>
<thead>
<tr>
<th>Ti alloy</th>
<th>E (GPa)</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>ε (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6-4</td>
<td>110</td>
<td>924</td>
<td>993</td>
<td>14</td>
</tr>
<tr>
<td>Ti-6-4-1.6B</td>
<td>152</td>
<td>1284</td>
<td>1420</td>
<td>3.5</td>
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<tr>
<td>Ti-6-4-1.4B-0.5C/-35#</td>
<td>164</td>
<td>1443</td>
<td>1575</td>
<td>2.2</td>
</tr>
<tr>
<td>Ti-6-4-1.4B-0.5C/-250#</td>
<td></td>
<td></td>
<td>1602</td>
<td>2.2</td>
</tr>
</tbody>
</table>

5 µm

500 nm
**SUMMARY**

**Ti-B alloys offer exceptional promise for development and transition into aerospace systems**

- exceptional structural properties for enabling defense applications
  - increases in strength and stiffness of ~50% already achieved
- microstructure and properties tailorable over a very wide range
- cast, wrought, P/M and advanced processes are feasible
- affordability comparable to conventional Ti products

**Different primary process paths provide three materials with distinct characteristics**

- as-cast product for lowest cost, especially in complex shapes
- pre-alloyed P/M for best balance of structural efficiency and affordability
- blended elemental P/M product for highest structural efficiency

**Approaches underway to address technology challenges**

- elimination of primary TiB
- optimization of primary and secondary process parameters
- characterization of 1\textsuperscript{st} and 2\textsuperscript{nd} tier properties
- technology issues of joining and machinability
OUTLINE

HIGH STRUCTURAL EFFICIENCY

STRUCTURAL EFFICIENCY OF METALLIC MATERIALS

CANDIDATE TECHNOLOGIES
  — MMCs
  — Advanced Al
  — Ti-B Alloys
  — Metallic Glasses

SUMMARY
What are amorphous metals?
- no long range atomic symmetry or periodicity

How are they produced?
- usually by rapid quenching
- in a few alloys, rapid quenching is not needed

What makes them ‘special’?
- exceptional structural, magnetic, corrosion properties
  - strengths up to 2% of the elastic modulus are achieved (up to 3 GPa)
- plastic-like manufacturing (injection molding)
- may possess exceptional damping properties

What are the technical challenges?
- lack of symmetry eliminates experimental techniques for characterization of structure
- fundamental mechanisms of strengthening, deformation, mass transport, etc. are not known
- what controls stability?
AMORPHOUS METALS
Current Applications

Low loss magnetic material
- power transformers
- magnetic resonance imaging (MRI) for medical field
- video recording heads

Corrosion resistance
- coatings for safety razors
- coatings for nuclear containment currently being validated

Structural applications
- golf club heads, tennis racquets, baseball bats
- electronics cases for cell phones, laptops, PDAs
- micro-mirror array hinges for digital projection systems
Marginal glasses require rapid quench to form glass structure
  - only very thin sections (<300 μm) can be formed

Thicker sections (>1cm) can be formed in bulk glasses
  - process time increases dramatically after cooling below the ‘nose’
  - provides opportunity for metal injection molding

Metal injection molding is now being used for a wide range of consumer goods
  - metals compete successfully with plastics for both cost and performance
  - electronics, sports, jewelry applications
  - provides approach for unitized construction of complex shapes where volume is an important consideration
Stability, strength, deformation and properties are all tied to the atomic structure

IH research is developing a structural model to guide exploration of new BMGs and exploitation of a-metals

Atomic clusters about 3 atom diameters (<1nm) are the fundamental building blocks of the atomic structure
Our research has established:

- a phenomenologically-based characteristic topology for BMGs that shows a clear relationship between atom size and concentration
  - previous topological models could not reproduce the observed trends

- a physically-based model that reproduces the observed topological trends
  - based on substitutional or interstitial solute occupancy in the competing crystalline lattice depending on solute radius ratio, $R$

- a model based on the structure-forming principle of efficient atomic packing that predicts that solutes with specific sizes relative to the solvent atoms ($R^*$) are preferred in BMGs

Together, these models provide specific guidance for the exploration of new BMGs.
Two new BMG systems have resulted from this research

- Fe-based BMG developed at INEEL as part of DARPA SAM Initiative
- Several Ca-based glasses discovered in-house at ML
  - 12 of 15 alloys are fully amorphous in 1 mm cast plate

Discovery of new BMGs is necessary to take full advantage of plastic-like processibility

\[ \text{Ca}_A(Y,\text{Ln})_B(\text{Mg,Sn})_C(\text{Zn,Al,Ag})_D(\text{Cu,Ni,Si})_E \]
Nanocrystal dispersions can be formed \textit{in situ} in amorphous Al

- Al nanocrystals are 5-10 nm in diameter
- Al nanocrystals occur at an exceptionally high number density \((10^{21} \text{ to } 10^{23} /\text{m}^3)\)

Improves both strength and ductility

- mechanisms of improvements unknown

Mechanism of nucleation unknown

- conventional mechanisms (homogeneous and heterogeneous nucleation) do not fit experimental observations

\textbf{Control of nanocrystalline precipitation represents the next challenge to control properties of amorphous Al}

A. Inoue, H. Kimura; \textit{Mat. Sci. Eng.}, 2000
TECHNOLOGY ISSUES

How to make bulk glasses?
— required to produce bulk components
  • restricted thermal stability makes consolidation and forming of marginal glasses a significant technical challenge
  • enables ‘plastic-like processing’ below the nose of the TTT curve

A scientific basis is being established and applied to produce new bulk metallic glass systems for wider commercial applications

How to provide fracture properties (ductility, toughness)?
— two-phase co-continuous crystalline/amorphous microstructures
— nanocrystalline dispersion via controlled precipitation

Approaches have been conceived and validated for amorphous/crystalline composites, but much more work is required to understand and control devitrification process to produce nanocrystalline dispersions
DoD emphasis on high temperature materials now being joined by requirements for high specific strength, stiffness
  — enables structural minimization for highly efficient structural designs
  — configuration of future systems will be controlled by these properties
  — strong impact on systems affordability

A broad range of AF systems require materials with exceptional specific strength and stiffness
  — space systems
  — current and future aeronautical systems
  — sustainability of existing fleet

Affordable metallic materials approaches for achieving exceptional specific properties are being pursued
  — metal matrix composites (discontinuous and continuous reinforcements and ‘hybrid’ composites)
  — advanced Al alloys
  — boron-modified Ti alloys (Ti-B)
  — amorphous and nanocrystalline metals
QUESTIONS?
**CAST Ti-B ALLOYS**

**“Composition and Processing”**

**Limited casting experience**
- ingots have been cast using induction skull melting (Duriron) and consumable electrode (Timet)
  - skull melt billets up to 4” diameter, consumable electrode billets to 14” diameter
- boron addition is fully dissolved in molten alloy
- compositions limited to eutectic and hypoeutectic alloys

**Cost comparable to conventional cast product is expected**

**Casting studies required**
- elimination of primary borides
- O increases ΔT, C slightly reduces ΔT, Sn and Zr significantly reduce ΔT
**CAST Ti-B ALLOYS**

“Microstructures and Properties”

**Boron additions exert important influence on microstructures**

- primary borides and micron-sized borides are produced, but no submicron TiB
- uniform boride distribution and random orientation produced
- borides stabilize fine grain size

**Properties of as-cast Ti-B alloys not available**

*Cast material courtesy PCC Structurals, Albany OR*
**PREALLOYED POWDER**

“Composition and Processing”

*Use conventional powder production*
- compositions limited to eutectic and hypoeutectic alloys
- boron addition is fully dissolved in molten alloy
- molten alloy is converted to powder via inert gas atomization at Crucible Research

*Use conventional powder consolidation*
- vacuum degas at RT/24h + 300C/24h with argon backfill between steps
- blind die compaction at 1400MPa/1200C/180s
- extrusion at 1100C / 16:1 / 6mm/s

*Cost comparable to conventional P/M product is expected*
Uniform distribution, random orientation of TiB formed in as-produced powder

Eutectic composition (~1.6 wt% B) limits TiB volume fraction to ~10%

Powder consolidation produces microstructural changes

- fine grained α/β microstructure with coarsening of TiB

Nanometer-sized TiB is unique feature of P/M Ti-B alloys

- retained after consolidation
TiB is produced in a range of sizes

Primary TiB

Micron-sized TiB

Submicron TiB

Ti-6Al-4V-1.6B billet from -100# (<150μm) Powder
Blind Die Compacted @1200°C/1400 MPa AC
PREALLOYED POWDER
“Properties”

- Stiffness $\uparrow 80\%$ and strength $\uparrow 40\%$ compared to Ti-6Al-4V
- Strength increases maintained at elevated temperatures
- Improved properties by thermo-mechanical processing (*)
- Fracture toughness values in the range 40-55 MPa$\sqrt{\text{m}}$
Compositions expanded to include hypereutectic
- solid state processing eliminates primary borides
- desired compositions achieved by blending elemental metal powders or master alloy powder with B or TiB₂ powder

Blend + outgas + consolidate + react
- powder blending (wet / 24 hr + dry / 0.5 hr)
- degas and seal (RT / 24 hr + 300°C / 24 hr)
- blind die compact (1200°C / 1400 MPa / 180 sec)
- heat treat to transform B or TiB₂ to TiB (1300°C / 6 hr)

Process path is similar to that for conventional discontinuously reinforced metals
- additional step to fully react TiB₂ to form TiB
Uniform distribution of randomly oriented TiB produced

- primary and submicron TiB eliminated
- fine alloy grain size is retained
- effective blending required to eliminate TiB clustering

BE offers possibility of higher specific properties via hypereutectic concentrations

- BE product will not compete with PA at equivalent B content
- isotropy/anisotropy can be tailored by subsequent thermo-mechanical processing
Higher stiffness relative to alloys with lower B content
Slightly lower strength- currently limited by inadequate processing
Additional characterization required
Double the structural efficiency of conventional Ti alloys at comparable cost

― enabling specific stiffness *and* specific strength (2X compared to existing aerospace structural metals) and useful fracture properties

― full-life elevated temperature capabilities extended by 150°C compared to conventional Ti matrix alloys

― establish primary and secondary processing techniques (including casting) capable of producing useful product forms

― produce and validate selected components for defense applications
Implementation Strategy

Identify cross-industry opportunities and teams
- multiple markets provide larger motivation for materials suppliers
- provides pervasive market impact
- spreads risk and cost of development, certification, insertion
- lack of direct competition encourages open cooperation

Form technology teams
- an internal advocate at each partner organization is essential
- interaction between design and material is a required activity

Include all stakeholders
- early enough to impact system requirements
- strong contribution from materials suppliers
- academia, industry and national / government labs

Demo programs are essential
- provides direct and immediate path for material validation
- provides imperative for material / design interactions
Fighter Aircraft Materials

Utilization of high cost airframe materials has been increasing to improve aircraft performance. Affordability is now being emphasized when selecting airframe materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>F-15E</th>
<th>F/A-18E/F</th>
<th>F-22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>49%</td>
<td>31%</td>
<td>16%</td>
</tr>
<tr>
<td>Titanium</td>
<td>32%</td>
<td>21%</td>
<td>39%</td>
</tr>
<tr>
<td>Composite</td>
<td>17%</td>
<td>19%</td>
<td>24%</td>
</tr>
<tr>
<td>Other</td>
<td>2%</td>
<td>29%</td>
<td>21%</td>
</tr>
</tbody>
</table>

Affordability is now being emphasized when selecting airframe materials.
Ti-B APPLICATIONS

Potential applications for Ti-B technology include any where higher structural efficiency will produce significant improvement in performance, capability or affordability

**Cast Ti-B** for improved properties at lowest cost and/or complex shapes

**Prealloyed Ti-B** for significant improvement in structural efficiency at cost of typical Ti P/M product

**Hybrid materials** provide an opportunity to expand capabilities of continuously reinforced Ti MMCs

- incorporate Ti-B alloys as matrices in TMCs

**Blended elemental Ti-B** may produce highest structural efficiency at a premium in cost

- cost increment comparable to that of conventional discontinuously reinforced MMC
Solute distribution plays a critical role in nanocrystal nucleation

- solute-free regions allow nanocrystals to form

Atomic simulation of solute distribution shows good agreement with experiment

Solute distribution is manipulated through solute-solvent chemical bonding

- controls chemical short range ordering
AEROSTRUCTURES

- elevated temperature DRA, amorphous Al to replace Ti at 150–200°C
- metallic materials with high specific strength/stiffness to replace gr/epoxy sheet
- affordable unitized construction for conventional and revolutionary (UAV) aircraft

AEROPROPULSION

- replace Ti in compressor for existing and future (JSF) systems
  - LPC blades and stators, HPC stators and shrouds, fan blades (long term)
  - flow path sheet structures, bleed valves, shrouds and bearing supports
- reduced mass and cost for rings, cases

SPACE

- isotropic material with high specific strength is principle requirement for cryo turbopumps and propellant management devices
  - housings, inducers, impellers, lines, ducts, flanges, structural jacket
- many applications for orbital systems
  - bus structures, truss nodes, brackets, hinges, radiator panels, PCB heat sinks...

SUSTAINMENT

- direct substitution for overspecified materials to maintain form/fit/function
  - higher specific properties can support loads unanticipated in original design
  - examples include F-16 ventral fin, B-1 bungee wedge link, F-15 door skin...
- amorphous Al offers possibility of dramatically reduced corrosion