Composite Materials as a Threat to Ti

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Modern Engineering Materials: Composites

A composite material can be broadly defined as an assembly two or more chemically distinct materials, having distinct interface between them and acting to produce a desired set of properties.

Composites – MMC, PMC & CMC.

The composite constituents can be divided into two:

Matrix

Structural constituent/reinforcement

Properties/behavior depends on the size & distribution, volume fraction & shape of the constituents, & the nature and strength of bond between constituents. Mostly developed to improve mechanical properties; i.e. strength ($\sigma$), stiffness (E), creep resistance & toughness.

Composite materials usually are more expensive than monolithic materials.
The relative importance of different material classes has changed over time.
Bronze Age
Iron Age
The use of both Ti and composites in significant quantities for structural and other applications is considered to have blossomed in the 20th century, partly due to war/defense efforts.

Composites have become a serious threat to Ti for some applications and they are growing in importance.
History of Aircraft Materials

- 1843 vulcanization (Charles Goodyear): tires, seals, and gaskets
- 1903 First Flight: Wright Brothers: Al engine block, Spruce and Steel wire structure
- 1907 Leo Hendrik Baekeland – refines plastic production to create bakelite
- 1915 All Metal Airplane
- 1930s Increased Al use: Duralumin and Alclad
- 1931 Stainless Steel construction: Budd BB-1 Pioneer
- 1936 Plastic use expands: plexiglass for cockpit, etc.
- **1942 Composites-Fiberglass:** Cockpit components for war effort
- 1940s-1950s Before World War II, Iron based alloys were developed for high temperature work. The war increased demand of performance materials for turbochargers and jet.
- 1950-1963; The A-12 precursor to the SR-71
- **1969 Carbon Fiber Composites:** Rolls-Royce RB211 jet turbofan engine
- 1970 Boron Fiber Composites: F-14 Tomcat
- 1981: Space Shuttle Thermal Protection Tiles
- **2005 GLARE:** “GLAss-REinforced” Fiber Metal Laminate (FML)
- 2009 Boeing 787 Dreamliner: Large Scale Composite Use
Materials weight distribution of advanced technology airplane. Courtesy, Boeing Commercial Airplane Co.
## WEIGHT PERCENTAGE OF AEROENGINES THROUGHOUT 80 YEARS OF POWERED AVIATION

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>Wright FLYER (II AND III)</th>
<th>BOEING 747</th>
</tr>
</thead>
<tbody>
<tr>
<td>YEARS OF PRODUCTION</td>
<td>1903</td>
<td>1983-1991</td>
</tr>
<tr>
<td>TOTAL AIRCRAFT WEIGHT (EMPTY)</td>
<td>605 LBS.</td>
<td>391,000 LBS.</td>
</tr>
<tr>
<td>ENGINES WEIGHT</td>
<td>180 LBS.</td>
<td>40,000 LBS.</td>
</tr>
<tr>
<td>NUMBER OF PASSENGERS</td>
<td>1</td>
<td>550</td>
</tr>
<tr>
<td>RANGE</td>
<td>24 MILES</td>
<td>7,500 MILES</td>
</tr>
<tr>
<td>FLIGHT DURATION</td>
<td>38 MINUTES</td>
<td>16 HOURS</td>
</tr>
<tr>
<td>WEIGHT OF ENGINES</td>
<td>30%</td>
<td>10%</td>
</tr>
</tbody>
</table>
Major trends in materials used in jet aircraft engines. Performance improvements are increasingly difficult to achieve by modifying the design of metal engines. Alternative materials such as reinforced glass and glass/ceramic composites are said to offer the greatest potential to attain significant gains in engine performance. Courtesy, Rolls Royce.
Development of Aerospace Composites

• The development of aerospace composites has been both costly and risky, therefore initial development was performed by military (i.e. Air Force Research labs like WPAFB through the 1980s and 1990s) who had relatively large R&D budgets and were not so risk adverse as the civil or commercial side

• Drivers to produce lightweight structures:
  – Cost of oil, environmental consciousness, increase in airline traffic

• The cost of development and introduction of these new composite structures is now offset by their performance and environmental gains, hence the increase in their usage.

Two stages of a SCS-6/Ti-6Al-4V (wt.%) MMC compressor ring rotor, with an MMC spacer in between. The continuous SiC fibers are wound in the hoop orientation.
Boeing 787 Material Makeup

- 50% advanced composites (i.e. contain strong and stiff fibers)
- Boeing engineers were able to specify the material for specific applications throughout the airframe.
- 20% Al
- 15% Ti
- 10% Steel
- 5% other

Boeing Goals

- Reduce cost without sacrificing properties, workability
- ~20% improvement in mechanical properties
- ~20% improvement in modulus
- Maintain reasonable ductility
- Maintain reasonable fatigue performance, toughness, and crack growth properties
Airbus A380 series

Primary structures:

- Empennage – Carbon fiber reinforced plastic (CFRP)
- Fin leading edge – Glass fiber reinforced plastic (GFRP)
- Radome – Quartz fiber reinforced plastic (QRFP)
- Upper sections of fuselage – Glass reinforced Aluminium Laminate (GLARE)
Damage Tolerance and Assessment

- Advanced composites have significant wt, E and $\sigma$ advantages over Ti
- Advanced composites are more resistant to damage than Ti
- Advanced composites are susceptible to sunlight (infrared) exposure, however pre-spun prepreg C-fiber is less affected due to the tight weave reducing surface area of resins/catalysts
- Airbus research & assessment (validated by (ASTM)) has shown that the damage tolerance of GLARE is significantly better than Ti, however not as resistant as C-fiber prepregs
Applications of MMC’s

• **Space:** The space shuttle uses B/Al tubes to support its fuselage frame. In addition to decreasing the mass of the space shuttle by more than 145 kg, B/Al also reduced the thermal insulation requirements because of its low thermal conductivity. The mast of the Hubble Telescope uses C-reinforced Al.

• **Military:** Precision components of missile guidance systems demand dimensional stability — that is, the geometries of the components cannot change during use. MMCs such as SiC/Al composites satisfy this requirement because they have high yield strength. In addition, the volume fraction of SiC can be varied to have a CTE compatible with other parts of the system assembly.

• **Transportation:** MMCs are now finding use in automotive engines that are lighter than their metal counterparts. Also, because of their high $\sigma$ and low wt, MMCs are the materials of choice for gas turbine engines.
MMCs

- Typical fibers are based on C & SiC. Metals are mainly reinforced to increase or decrease their properties to suit the needs of design. For example, the E & UTS of metals can be increased, and the large CTEs and the thermal & electric conductivities of metals can be reduced, by the addition of fibers.

- MMC advantages over PMCs include higher elastic properties; higher service T; insensitivity to moisture; higher electric and thermal conductivities; better wear, fatigue, and flaw resistances. The drawbacks of MMCs over PMCs include higher processing temperatures & higher ρ
### Strengths/Weaknesses/Opportunities/Threats (SWOT) Composites

#### Positives

**Strengths**
1. Properties, high strength-to-weight ratio
2. Fatigue and corrosion resistance
3. Complex shapes, reduced # fasteners needed
4. Tailorability of properties for a given part
5. Recyclable and increased processing yield
6. Easy incorporation of other materials into composites during processing to provide integrated functionality; self-healing & energy storage

**Weaknesses**
1. High cost
2. NDT requirements
3. Need specialized repair techniques
4. Anisotropic: need design tools and failure analysis

**Opportunities**
1. Carbon fiber availability (accelerating)
2. Recycling technologies to suit composites (i.e. C-fibers)
3. Materials development: Boeing 787 opened opportunities for more composites usage; now tougher composites may be used for aerospace, etc, (threat to Ti)
4. Innovative repair and manufacturing
5. Legislation

**Threats**
1. Ti
2. Innovation in metals; superplastic forming, PM
3. Recycling issues
4. High profile failures
5. Cost of Oil
6. Material shortages/resources
Summary

- Environmental regulations have lead to technologies for introducing lightweight and environmentally-friendly composites structures, where previously cost did not offset gains in performance. Now composites are commonly used in aerospace and other transportation sectors where Ti was more competitive than the more expensive composites.

- Current challenges of composites include: development of rapid manufacturing processes

- Current opportunities include the ability of composite structures to include functionality like self-healing, energy storage, etc.

- Future challenges of composites include: supply of carbon fiber to reach the demand for it, recycling (including recycling a lot of carbon fibers), and development of new composite materials and technologies

- Current challenges of Ti include: further development of (rapid) manufacturing processes and powder processing

- Future challenges of Ti include: R&D for affordable Ti alloys with enhanced properties
**Strengths/Weaknesses/Opportunities/Threats (SWOT) Titanium**

**Positives**

*Strengths*
1. Properties, good strength-to-weight ratio
2. Fatigue and corrosion resistance
3. Complex shapes possible
4. Good Elevated Temperature Capability
5. Common Matrix for MMCs

*Weaknesses*
1. Medium/High cost
2. Anisotropic: hexagonal phase

*Opportunities*
1. Biocompatible Applications
2. Growing demand and processing technologies to result in lower costs
3. Materials R&D development resulting in alloys with enhanced properties
4. Legislation for lightweight materials use

*Threats*
1. Composites (MMCs and PMCs especially)
2. Innovation in lightweight metals; Magnesium technologies
3. Recycling issues
4. Material shortages/resources
Typical Mechanical Properties of MMCs


<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>SiC/aluminum</th>
<th>Graphite/aluminum</th>
<th>Steel</th>
<th>Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>—</td>
<td>2.6</td>
<td>2.2</td>
<td>7.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>Msi</td>
<td>17</td>
<td>18</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>ksi</td>
<td>175</td>
<td>65</td>
<td>94</td>
<td>34</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>µin./in./°F</td>
<td>6.9</td>
<td>10</td>
<td>6.5</td>
<td>12.8</td>
</tr>
</tbody>
</table>

System of units: USCS

System of units: SI

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<td>7.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>GPa</td>
<td>117.2</td>
<td>124.1</td>
<td>206.8</td>
<td>68.95</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>MPa</td>
<td>1206</td>
<td>448.2</td>
<td>648.1</td>
<td>234.40</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>µm/m/°C</td>
<td>12.4</td>
<td>18</td>
<td>11.7</td>
<td>23</td>
</tr>
</tbody>
</table>
The CTEs for candidate matrices and reinforcements, averaged from RT to 1000°C.

SCS-6/Ti-24Al-11Nb MMC. The cracks in the β-depleted zone formed after thermomechanical fatigue testing.
BSE SEM photomicrograph identifying cracking in the interface for a fiber near the fracture surface for a RT tensile-tested cruciform sample for the Ultra SCS-6/Ti-24Al-17Nb-0.66Mo IMC (a) above the fiber and (b)