CMC with a Graded Lay-up Manufactured via LSI-Process

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Ceramic Matrix Composites (CMC)

- Damage tolerant failure behaviour
  - Pseudo plasticity (crack deflection, fibre pull out)
  - Micro cracks, weak fibre matrix bonding

- High temperature application
  - T > 1200 °C: C/ SiC, C/C-SiC
  - T < 1200 °C: Ox/Ox, SiC/SiC

- Materials for lightweight structures
  - Low density (1.9 – 2.5 g/cm³)
  - High specific material properties

- New manufacturing methods
  - Large sized, thin walled parts
  - Joining technologies

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New manufacturing methods

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Liquid Silicon Infiltration Process (LSI)

Precursor Additives Fibres

CFRP (SHAPING)
- RTM-, Autoclave-, Filament-Winding-, Press-Technique
- T < 250 °C

PYROLYSIS
- Matrix Shrinkage
  - T > 900 °C
  - Inert Gas

SILICONIZATION
- Si + C → SiC (Matrix)
  - T > 1420 °C
  - Vacuum

Intermediate Machining
- Joining
- Fixing C/C-Parts with Paste

In-process coating (SiCralee)

Silicon-Granulate

Joining
Fixing C/C-Parts with Paste

Finishing Machining with Diamond Tools
General Properties of C/C-SiC Materials

- High thermal shock stability
- Internal oxidation protection
- Variable mass fractions of SiC and C
- Low porosity
- Short manufacturing times
- Low density (ca. 2 g/cm³)
- Good wear and corrosion resistance
- Damage tolerance
C/C-SiC Thermal Protection Systems (TPS) for Reusable Spacecraft

- Full scale nose cap for CRV of ISS
  - Ø 700 mm, h=190 mm, d=6 mm
- Segmented structure
  - Ø 300 mm, d =3 mm
  - Re-entry flight 2005
- Facetted structure
  - Ø 370 x 800 mm, d =3 mm
  - $T_{\text{max}}=2200 \, ^\circ\text{C}$ (Mach 7)
- High aerodynamic performance
- Low cost approach
- Flight test in 2005

Material development

EXPRESS-CETEX

- Curved structure
  - Ø 300 mm, d=5 mm

1988

2002

2005

Shefax

Foton

X-38

Folin
Tailor-design of C/C-SiC Microstructure and Properties

XB - Quality
- Fibre bundle segmentation
- High fibre content
- High strength
- Quasi-ductility

XD - Quality
- Single fibre impregnation
- High ceramic content
- High stiffness
- High abrasive resistance

Control via raw materials and process parameters
Graded C/C-SiC Materials for Brake Pads

- Symmetrical lay-up of fabrics
  - Outer layers (XD) with
    - high SiC content (≈ 60 vol.-%)
    - high density ($\rho = 2.3 \text{ g/cm}^3$)
    - low strength
    - fibres treated @ $1100 \, ^\circ\text{C} (\text{N}_2)$
      ⇒ high wear resistance
  - Centre layers (XB) with
    - low SiC content (≈ 40 vol.-%)
    - low density ($\rho = 1.9 \text{ g/cm}^3$)
    - low wear resistance
    - fibres treated @ $600 \, ^\circ\text{C} (\text{N}_2)$
      ⇒ high strength / thermal shock resistance.
- Manufacture of CFRP preform via resin transfer moulding (RTM)
Brake System and Brake Pads

Emergency brake for elevators (Schindler Elevator)

C/C-SiC brake pad (142 x 34 x 6 mm³; DLR)
- 2D-fabric reinforcement
- Machined out of plate (300 x 300 x 8 mm³)

Brake calliper with U-shaped spring elements (steel plates)
Bracket
Brake pad
Friction partner: Steel (St 44) guiding rail (not shown)

Grooves to collect wear particles
Countersink for screw joining in metallic bracket

Contact pressure very sensitive to brake pad thickness
⇒ No wear of brake pads and guiding rail required to ensure constant deceleration
Microstructure of Graded Brake Pads Based on Different Methods for CFRP Manufacture

RTM

Warm pressing

Autoclave technique

1 mm

8 layers (1100 °C)

1 mm

1 mm

8 layers

8 layers (no thermal treatment)

1 mm

1 mm

1 mm
Material Properties of Brake Pads Based on Different CFRP Manufacture Methods

<table>
<thead>
<tr>
<th>Manufacture method</th>
<th>RTM</th>
<th>Autoclave</th>
<th>Warm Pressing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{b, \text{max.}}$ [MPa]$^*$</td>
<td>64.7</td>
<td>100.8</td>
<td>100.4</td>
</tr>
<tr>
<td>$\rho$ [g/cm$^3$]</td>
<td>2.21</td>
<td>2.03</td>
<td>2.08</td>
</tr>
<tr>
<td>$e'$ [%]</td>
<td>&lt; 5</td>
<td>2.06</td>
<td>1.28</td>
</tr>
</tbody>
</table>

* 3 point bending tests; sample geometry 25 x 10 x 6 mm$^3$

- Reduced XD layers in autoclave and warm pressed materials lead to 50 % increase in bending strength.
- First tribological investigations in elevator test facility showed comparable of wear behaviour and coefficient of friction.
Preform Manufacture - Wet Filament Winding

Raw materials and equipment:
- C-fibre T800 12K
- Precursor JK 60 (phenolic resin)
- Filament winding machine controlling winding speed and angle
- Aluminium mandrel equipped with Teflon tape
- IR-lamp and ventilation for support of evaporation of solvent

Warm Pressing for manufacture of plate material
Pressure less curing on mandrel in oven for manufacture of tubes
SEM micrographs of filament wound C/C-SiC tubes (I): view in axial (top) and tangential direction (bottom)

- Winding angle 15°
- Winding angle 30°
- Winding angle 45°
SEM micrographs of filament wound C/C-SiC tubes (II): view in axial (top) and tangential direction (bottom)
SEM micrographs of filament wound C/C-SiC tubes (III): view in axial (le.) and tangential direction (ri.)

+/-15° delamination

+/-45° delamination

90°
SEM micrographs of filament wound C/C-SiC tubes (IV): view in axial (le.) and tangential direction (ri.)
SEM micrographs of filament wound C/C-SiC tubes (V): view in axial (le.) and tangential direction (ri.)

cross ply

\[+/-15^\circ\]

\[+/-30^\circ\]

\[+/-45^\circ\]

\[+/-60^\circ\]

\[+/-75^\circ\]

\[90^\circ\]
SEM micrographs of filament wound C/C-SiC tubes (VI): view in axial (le.) and tangential direction (ri.)

cross wound

+/−15°

+/−30°

+/−45°

+/−60°

+/−75°

90°
SEM micrographs of filament wound C/C-SiC tubes (VII): view in axial (le.) and tangential direction (ri.)

cross ply

+/−15°

+/−30°

+/−45°

+/−60°

+/−75°
Summary

• The cost efficient LSI-process opened up new application areas besides aerospace

• C/C-SiC materials can be tailor-designed w.r.t. micro structure and SiC content, and therefore provide excellent properties

• C/C-SiC materials based on graded microstructures have been successfully developed for brake pads in emergency brakes of high speed elevators

• CFRP manufacture based on autoclave technique and warm pressing provides high potential for cost reduction

• Filament winding of C-fibres was successfully applied to improve mechanical properties similar to CFRP

• Winding angles strongly influence process parameters such as shrinkage during curing and pyrolysis

• Combining suitable winding angles open up new possibilities to tailor-design properties of C/C-SiC such as mechanical strength