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Thermo-mechanical behavior of C/C composites for fusion application

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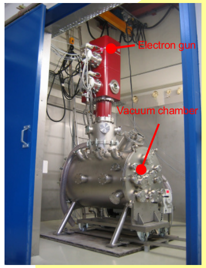
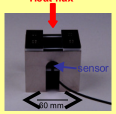
Thermal behavior

High heat flux facility

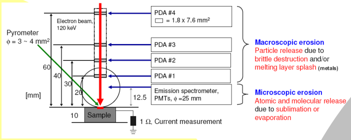


JUDITH II: electron beam facility

Diagnostics

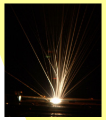


Acoustic emission holder for thermal shock tests

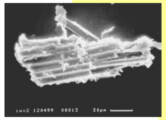


In-situ diagnostics of JUDITH II

Brittle destruction



Time integrated CCD picture of NB31 (2,4GW.m^{-2}, 5ms)



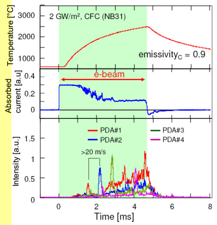
Collected ex-PAN fibers after thermal shock

Experimental results

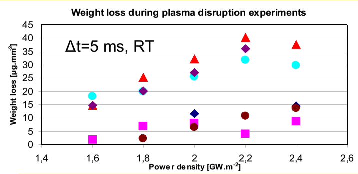
Acquired data:

In-situ
- Absorbed power
- Surface temperature
- Released species
- Time evolution of particle release
- Spatial distribution of released particles
- Acoustic frequencies of induced destructions

Post-mortem
- Characterization of collected particles and loaded volume
- Weight loss



Plotted dataset during a disruption simulation experiment in JUDITH I



Two groups can be distinguished.

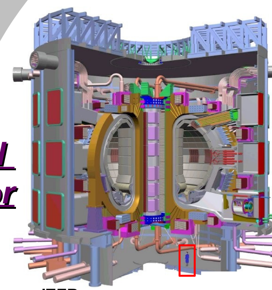
High heat flux loading allows one to qualify and quantify thermal erosion.

ITER

Advantages of CBMs in fusion devices:

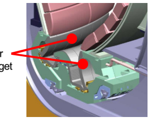
Fine grain graphite: low Z number, low coefficient of thermal expansion, absence of melting

CFCs: fine grain graphite properties + high thermal conductivity + superior mechanical properties



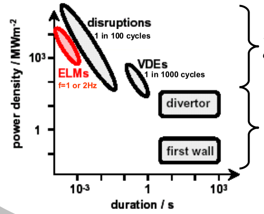
ITER

CFC surface in ITER: ~50 m²
CFC weight in ITER: ~6300 kg



CFC: lower vertical target

Drawbacks of CBMs in fusion devices:
- Tritium inventory
- irradiated induced decrease of thermal conductivity

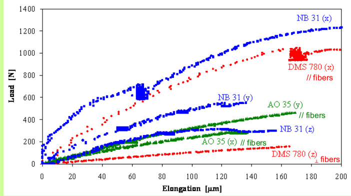


Mechanical properties

Tensile tests

Influencing parameters

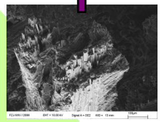
Size of the unit cell at the final crack location
+
Variation of density within the depth of a block
+
Needling process
+
ILSS



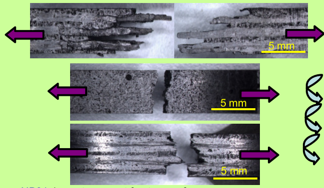
Tensile tests of CFCs in the SEM at room temperature
3 directional CFC: more macroscopically isotropic behavior

ITER requirements

Ultimate Tensile Strength
- x (pitch) :**110** MPa
- y (PAN): **20** MPa
- z (needling): **5** MPa



Top view of NB31 (x) fracture surface

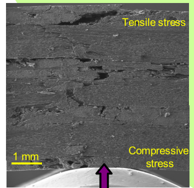


- Fiber bundles and fibers are pulled-out in NB31.
- The ILSS is low enough in NB31.
- Deflection of cracks is possible.
- Good mechanical properties are achieved.

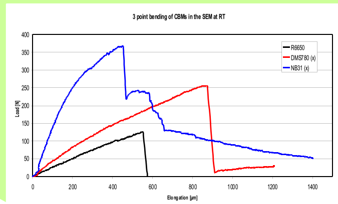
NB31: largest apparent fracture surface
Ex-Pitch fiber bundles are pulled-out at various length.

Mechanical tests (in the different directions) are essential to determine the crack resistance of CFCs.

3-point bending



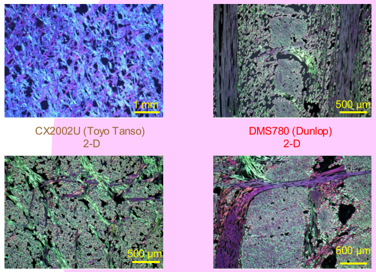
Crack path after 3-point bending of NB31 (x)



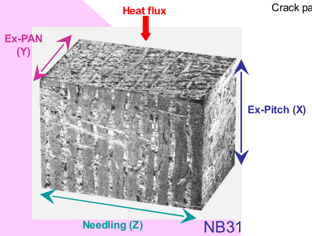
Fine grain graphite (R6650) illustrates a typical brittle fracture.
Fiber reinforcement allows stepwise fracture.

Microstructure

As-received materials



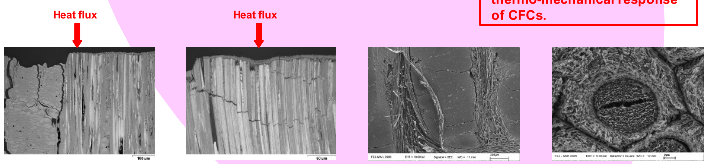
CX2002U (Toyo Tanso) 2-D; DMS780 (Dunlop) 2-D; AO35 (Carbone Lorraine) 2,5-D; NB31 (Snecma) 3-D



Tools:
- Ceramography
- SEM
- Micro-Raman
- Polarized light microscopy
- Laser profilometry
- Scanning thermal microscopy

NB31 after thermal shock

Microstructure influences the thermo-mechanical response of CFCs.



Preferential erosion of fibers parallel to the CFC surface; Dramatic cracks parallel to the surface; Top view of a loaded surface with preferential erosion after 2.4 GW.m^{-2} for 5 ms; Top view of an ex-Pitch fiber and the surrounding matrix after 2.4 GW.m^{-2} for 5 ms

General abstract:

ITER, the international thermonuclear experimental reactor, will be built in France and faces one of the biggest human challenges: to realize the energy production in the sun on Earth and turn it into electricity! It is a collaboration among 7 partners including the EU. Carbon fiber composites will be used as plasma facing material in ITER at the location where the deposited heat is the highest. They will have to sustain such heat fluxes. In order to better understand the behavior of these materials, mechanical tests to measure the resistance to fracture and thermal shock experiments simulating the transient events which are expected in ITER were done. Comprehensive diagnostics were used for the data acquisition during these tests.

Scientific abstract:

ITER is the next step Tokamak-type fusion device. Carbon fiber composites are the primary candidate for the lower vertical targets of the divertor. Due to instabilities of the plasma confinement, transient heat loads will be deposited on the plasma facing materials. These will create severe stresses within the CFCs which have to sustain them without major crack formation and significant physical erosion. Tensile tests on different batches of the European reference CFC material (NB31, SNECMA) have been performed. Additional mechanical tests were done for graphites and CFCs with simultaneous acoustic emission acquisition. Thermal shocks events which are predicted in ITER are simulated in electron-beam facilities (JUDITHs) in order to gain knowledge on the thermal shock resistance of CBMs. Various in-situ diagnostics are available as well as post-mortem analysis tools. Special attention is paid to microstructural differences between grades and batches of materials, before and after loading. Understanding of the thermo-mechanical behavior of these advanced composites is of primary importance to assess their performance under ITER-relevant loads.

Glossary:

Tokamak: a experimental device which confines a hot fusion plasma inside a toroidal chamber by magnetic fields. It is one of several types of magnetic confinement devices and the leading candidate for producing fusion energy.
Plasma: a plasma is an ionized gas, and is usually considered to be the fourth state of matter. The free electric species make the plasma electrically conductive so that it responds strongly to electromagnetic fields. Plasma constitutes 99% of the universe.
Divertor: the ITER divertor exhausts the flow of energy from charged particles produced in the fusion reactions, removes helium and other impurities resulting from the reactions, and allows a controlled interaction of the plasma particles with the material walls.
Thermal shock: transient heat pulse, typically between 0,5 and 10 ms, producing tremendous stresses within the materials due to thermal gradients during heating up and cooling down phases. Thermal shocks occur in tokamaks during instabilities of the magnetic confinement (Disruptions, VDEs, ELMs).
Brittle destruction: formation of micro-cracks which is associated with the emission of carbon particles occurring during and after thermal shock.
CFC: Carbon Fiber Composite, a carbon fiber-reinforced carbon matrix material. Typically constituted of a fibrous preform filled with a matrix via CVD, CVI or liquid impregnation.
Pitch: a residue from pyrolysis of organic material or tar distillation which is solid at room temperature, consisting of a complex mixture of numerous, essentially aromatic hydrocarbons and heterocyclic compounds. Precursor for carbon fiber production.
PAN: Poly Acrylo Nitrile, a precursor for carbon fiber production.
ILSS: Interlaminar Shear Strength, the maximum load required to shear the specimen in such a manner that the moving portion has completely cleared the stationary portion.
Needling process: process used in the CFC industry to create a 3 directional material by the attachment of fabrics layers to each other with fibers carried by hook-fitted needles.

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