Image based modelling of silicon carbide composites (SiC_f/SiC) for use in a fusion power plant's breeding blanket

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1. DEMO – putting theory into practice

The first fusion power project to deliver electrical energy to the grid on a continual basis will be DEMO, a prototype fusion energy power plant planned for 2030. This scaled up magnetic confinement reactor plans to deliver 2GW of electrical output. Such output will create a harsh environment requiring materials at the forefront of mechanical engineering, able to withstand such situations and utilising previous experience from the fission community.

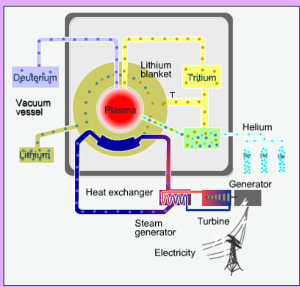

Figure 1 – Concept for DEMO

As well as the reaction chamber, the other key component in a fusion reactor is the tritium breeding blanket. Even though deuterium is plentiful (1 part in 6500 of hydrogen in seawater is deuterium), tritium is rare due to its short half life of ~12 years. Fortunately tritium can be bred by utilising the fast neutrons produced by the D-T reaction in a secondary reaction with lithium. Achieving this would ensure a self sufficient supply of tritium.

$$^{7}Li + n_{(fast)} \longrightarrow He + T + n_{(slow)}$$

$$^{6}Li + n \longrightarrow He + T$$

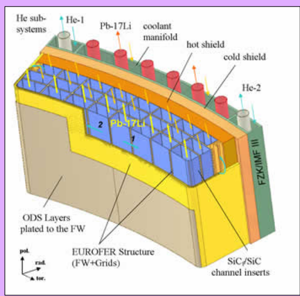

Figure 2 – Proposed tritium breeding blanket design

Compared to plasma facing components, this process requires materials with a different set of properties such as: high thermal conductivity, low reaction rate with liquid lithium, ability to retain properties at high neutron doses and tritium hermeticity. Due to its desirable behaviour, Silicon carbide (SiC) is currently being considered as a tube material for containing and transporting the liquid lithium.

2. Constructing a 3D map of the sample

Tomographic reconstruction was performed on a tube made of 3D woven Hi nicalon fibres with CVD SiC matrix to produce a 3D absorption map. This was done using a series of 2D x-ray radiographs taken whilst rotating the sample through 360°.

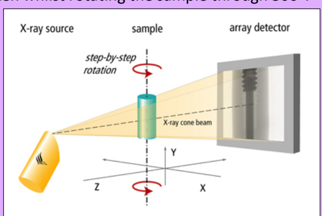

Figure 3 – Image acquisition method for tomography

Figure 4 – Metris X-tek at the Henry Moseley Imaging Facility

The 3D map was converted into a mesh for finite element purposes using Simpleware ScanIP.

Figures 5 & 6 – Photograph and 2D x-ray radiograph of silicon carbide composite tube

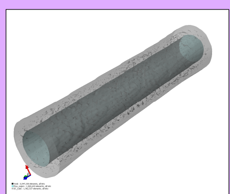

Figure 7 – Finite element mesh created from reconstructed 3D absorption map

3. Benefits of Image Based Modelling

The greatest benefit image based modelling has over traditional methods of creating geometries for modelling is the ability to model a real, rather than idealised, sample.

This has two main advantages:

1. Flaws in the manufacturing of the material, such as porosity, cracks or any other manufacturing defects are included in the model.
2. Direct comparison to experimental results can be made, as the modelled sample can also be subjected to laboratory tests.

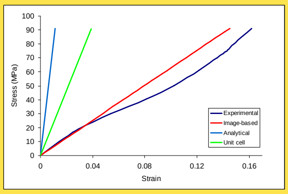

Figure 8 – Stress/Strain results from previous work at University of Manchester on graphitised composites in perpendicular direction

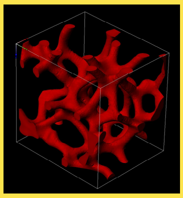

Figure 9 – Section of 3D image of Aluminium foam with around 500 million elements made with tomographical data

Another benefit of IBM is the ability to model very complex structures that would otherwise be too time-consuming to realistically reconstruct in a CAD program.

4. Simulating reactor conditions

Currently no material test facilities exist that can reproduce the conditions expected in a fusion reactor. Therefore, computational simulation is a valuable technique used to predict the behaviour of components in such environments.

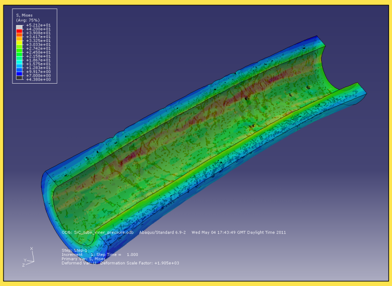

Figure 10 – Von Mises stress due to pressure caused by flow of coolant

In order to model the component behaviour, mechanical and thermal input data must first be collected. These were determined by: nanoindentation and appropriate interfacial tests, laser flash, differential scanning calorimetry and thermal gravimetric analysis, respectively.

Using the 2 million element mesh of the SiC tube created by Simpleware ScanIP from tomographical data, a model was constructed in ABAQUS to simulate the pressure applied by the flow of liquid lead-lithium coolant.

5. Future work

The model must next be validated using experimental data. Following this, the model may be further developed to include a thermal gradient along the length of the tube and pressure within the pores to simulate helium production associated with irradiated SiC.

The sample is currently treated as homogeneous material with thermal and mechanical problems being modelled separately. This is due to the computational limitations of a desktop workstation, which requires the data to be downsampled to 25% of its original resolution.

It is planned to develop a 100% resolution model using the finite element code ParaFEM running on HECToR, the UK's high performance research computer. The exponentially higher number of elements used will allow for a model that will distinguish between fibres and matrix of the composite and thus will account for the material's hugely anisotropic behaviour. It will also be possible to run thermo-mechanical coupled problems.

Arrangements are being made to irradiate SiC samples in Idaho National Labs' Advanced Test Reactor in order to collect properties of the irradiated material. These will be added to the model to simulate the change in behaviour with increased irradiation damage.

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