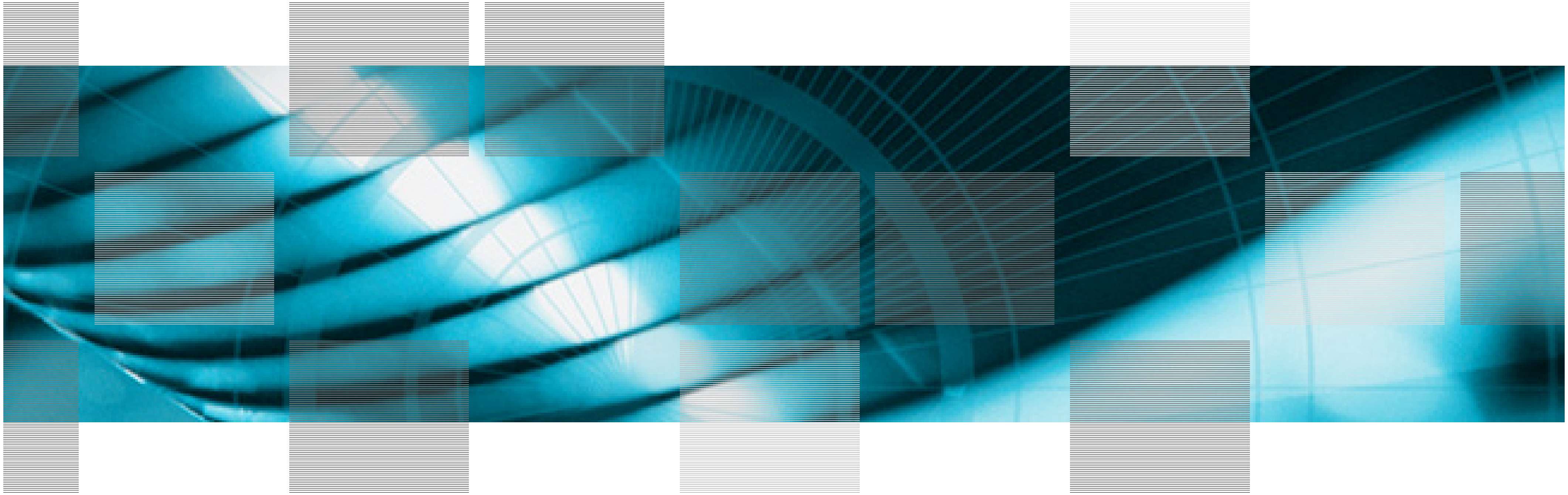

EUROMAT 2005

Topic: C3 Materials for Extreme Environments

C32 Materials for Fusion Applications

Material Technology Developments for Fusion Applications

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Overview

- The development of composite materials and bonding technologies is key to the realisation of the ITER Plasma Facing Components (PFC's).
- AMEC NNC (previously NNC) have been working, under the auspices of EFDA, on the development of ITER beryllium PFC's since 1996.
- Work started on the manufacture of prototype beryllium clad components for the blanket.
- Beryllium clad divertor baffle components were then produced; this required the development of a new bonding process.
- The most recent work has involved the application of this bonding process to produce prototype baffle components with a higher performance.
- Throughout this time AMEC NNC has performed several studies to consider the use of materials in ITER and future requirements for DEMO.

Early blanket prototype components

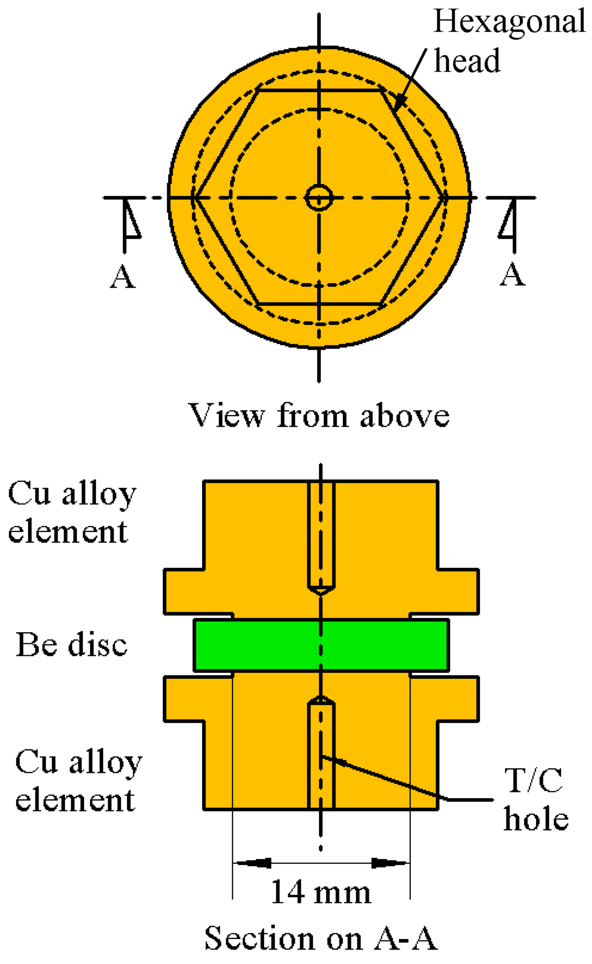
Blanket prototype prior to beryllium tile bonding

- DS-Cu heatsink bonded to SS316(L)N-IG backplate
  - HIP bonding conditions of 940ºC and 140MPa for 2hrs with no interlayer
- Large beryllium tiles (typically ~40 - 120mm x 10mm thick) bonded to DS-Cu
  - HIP bonding conditions of 850ºC and 140MPa for 2hrs with a 0.06mm titanium foil interlayer
- Heat flux tested at JCR ISPRA
  - 0.7MW.m^{-2} for 13,000 cycles

Divertor baffle / limiter components

- Early in the production of the prototype divertor baffle / limiter components, the existing beryllium to DS-Cu bonding process proved unsuitable.
- A molten ternary eutectic formed between the Cu, Ti and Be present in the HIP bonding process.
  - Eutectic melting temperature ~808ºC, HIP temperature 850ºC.
- The underlying cause was the new limiter geometry, a monoblock arrangement rather than large flat tiles.
- To solve this fundamental problem a new low temperature HIP bonding process was developed to bond the beryllium tiles.

Development of a low temperature DS-Cu / Be HIP bonding process



Geometry of the small torque test samples

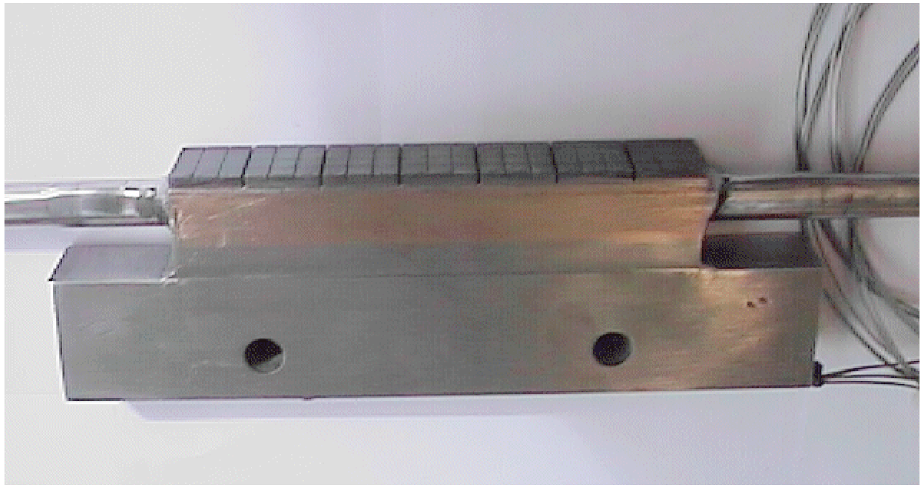
- Literature search to identify candidate HIP parameters
  - HIP bonding conditions needed for the diffusion bond (temperature, pressure and time)
  - Determine suitable interlayers
  - Identify potential problems (such as eutectic formation)
- Calculations
  - Diffusion calculations to determine the diffusion distances relative to the surface finish
  - Structural FEA to determine the evolution of residual stresses for small samples
- Experimental techniques
  - Reproduce the diffusion bonding conditions identified in the literature with small samples the laboratory (using mechanical press and an oven)
  - Mechanically test the bonds (torque test)
  - Pre and post failure examination of the bonds

Experiment results

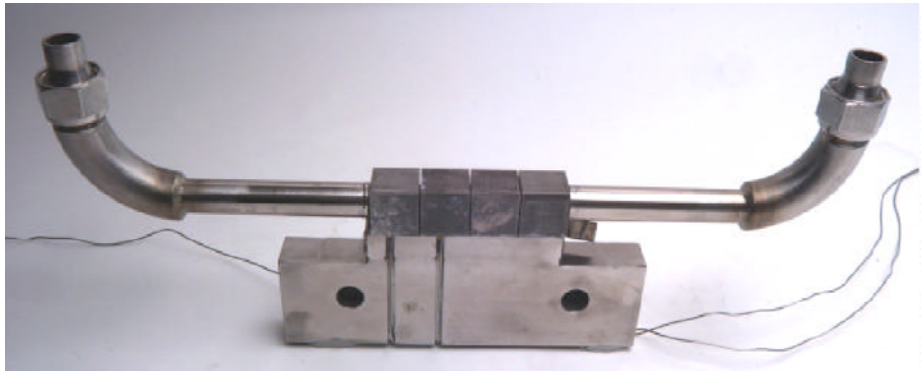
- DS-Cu was diffusion bonded to beryllium with copper and titanium interlayers at 580°C, 80MPa for 2hrs
- Bond strengths approaching the strength of the beryllium parent material were achieved

Trial number	Interlayer / µm	Torque / Nm	Shear Strength / MPa	Mechanical test failure location
1	5 Ti	0	0	Be / Ti interface
2	5 Ti + 100 Cu foil	85	139	Cu / DS Cu interface
3	5 Ti + 100 Cu foil	65	106	Cu / DS Cu interface
4	5 Ti + 45/65 plated Cu	119	186	Be / Ti interface (Be cracked)
5	5 Ti + 65/65 plated Cu	122	190	Be / Ti interface (Be cracked)

Divertor baffle / limiter prototypes



Flat tile divertor baffle prototype



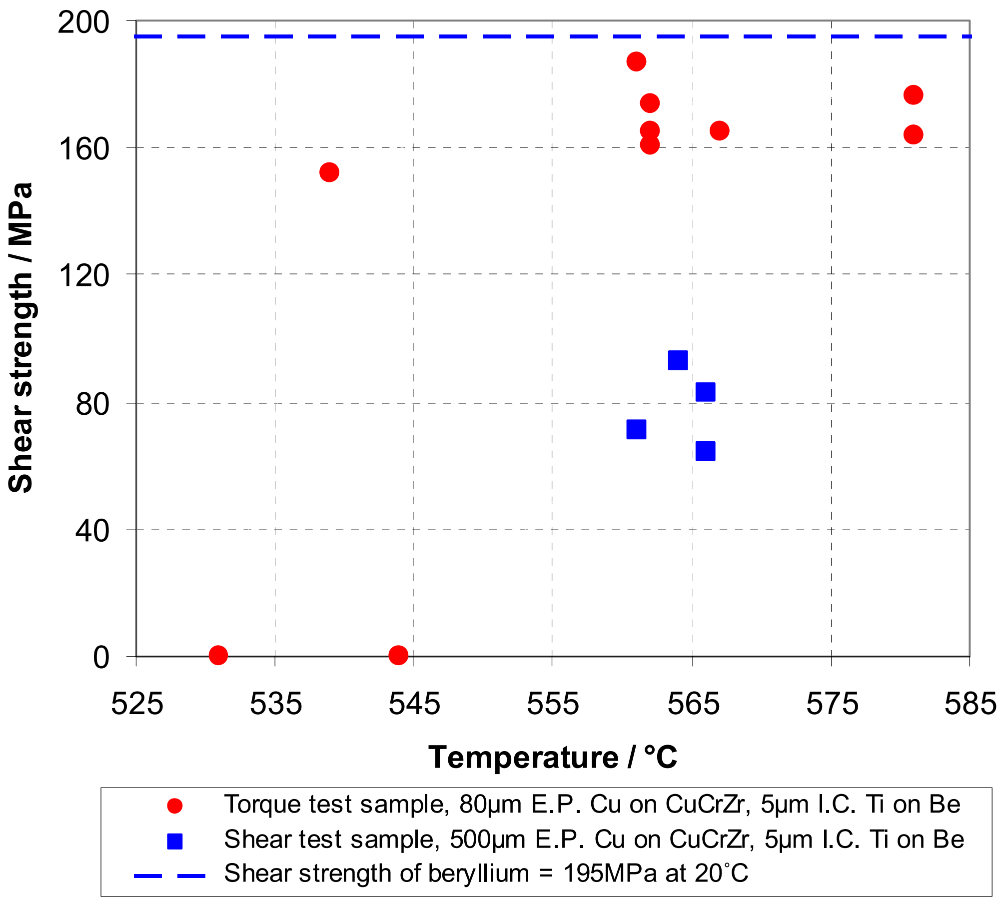
Monoblock limiter prototype

- Components manufactured
  - Flat tile prototype
    - Composite DS-Cu / SS 316 heatsink base
    - 7 castellated beryllium tiles, 24 x 20 x 4mm thick
    - Manufacture using 3 stage HIP (2 for heatsink base, 1 for tiles)
  - Straight monoblock
    - 4 beryllium blocks, 20 x 20 x 31mm bonded to a DS-Cu tube
    - Manufacture using a single stage HIP
- HIP processes
  - DS-Cu / SS
    - Direct bond
    - 940˚C, 140MPa for 2hrs
  - Be / DS-Cu
    - 5µm ion coated Ti interlayer on Be
    - 200 - 400µm electroplated Cu interlayer on DS-Cu
    - 580°C, 55 - 100MPa for 2hrs
- Heat flux tested at JUDITH facility at FZJ
  - Flat tile mock-up withstood 1000 cycles at 5MW.m^{-2}
  - Monoblock mock-up withstood 1000 cycles at 7MW.m^{-2}, plus 740 cycles at 10MW.m^{-2}

Possibility introduced by the low temperature Cu / Be HIP bonding process

- The introduction of the low temperature HIP process for DS-Cu / Be bonding allowed the possibility of using CuCrZr rather than DS-Cu, attractive due to:
  - superior mechanical properties, i.e. CuCrZr has better fracture toughness, elongation and strength
  - lower cost
- CuCrZr is a precipitation hardened alloy, which requires that the bonding process be integrated with the heat treatment requirements for the material.
  - Stage 1: HIP Bond CuCrZr to 316L(N) SS at 1040°C and 140MPa
  - Stage 1a: Quench as part of stage 1 or complete a separate cycle with a quench to solution anneal
  - Stage 2: HIP Bond beryllium tiles to CuCrZr at temperatures that match as closely as possible the optimum heat treatment parameters of 475°C for 3hrs to age harden

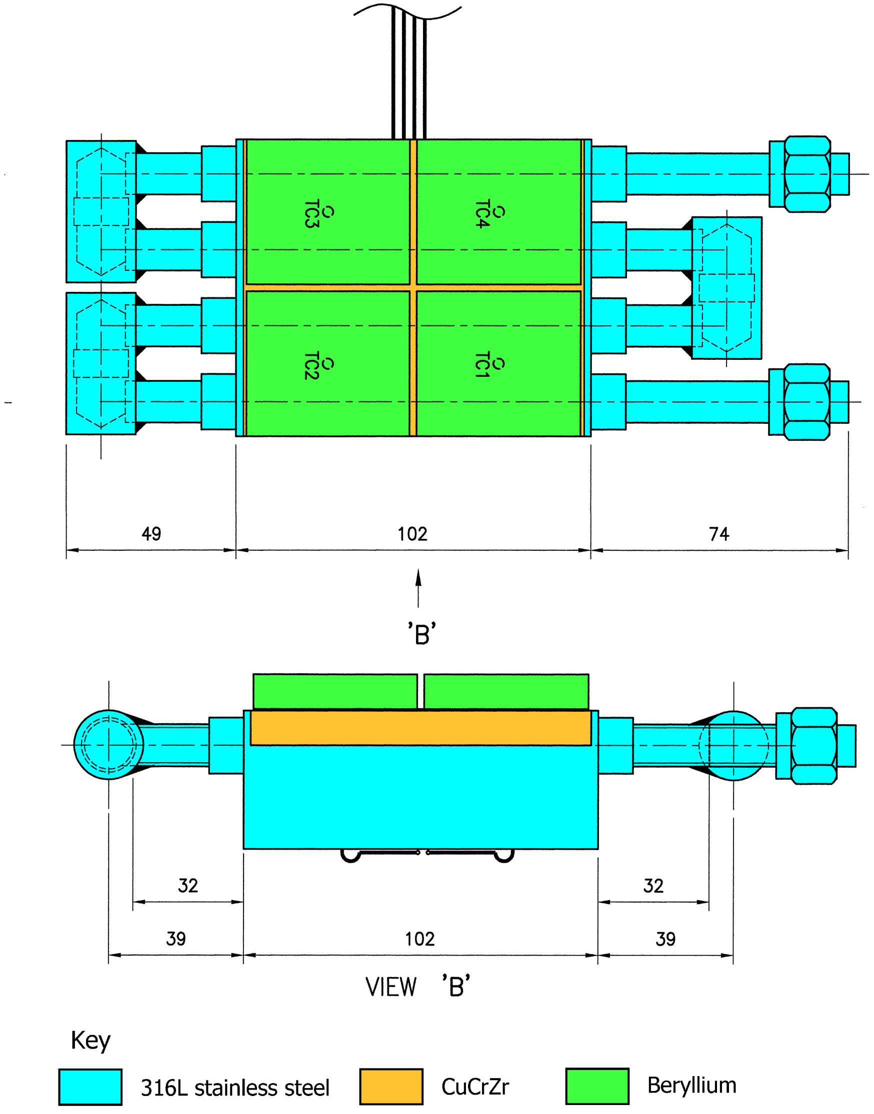
Development of a CuCrZr / Be bond (Further laboratory experiments)



Equivalent shear strength against bonding temperature

- Further small samples of the type already described
  - 14mm bond diameter
  - press bonded at 80MPa for 2hrs
  - tested by torque
- Production of larger shear test samples
  - Initially 43mm bond diameter
  - press bonded at 60MPa for 2hrs
  - cut to 30mm sq. x 20mm thick
  - tested by direct shear
- Objective
  - Reduce the temperature with Ti and Cu interlayers to the lowest possible

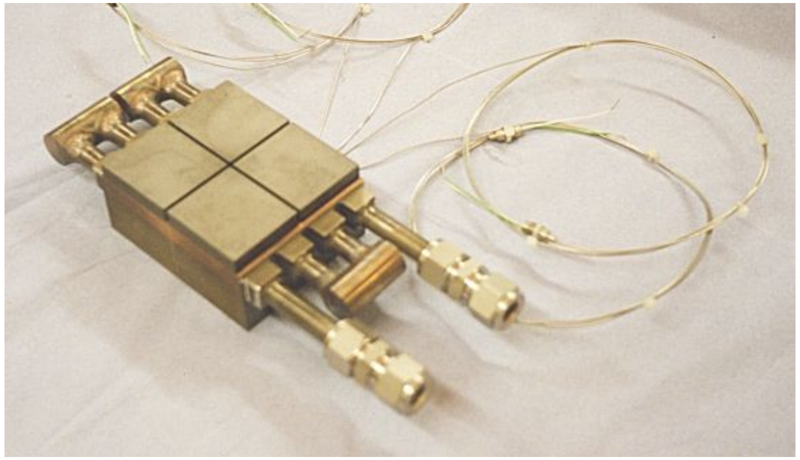
Manufacture of CuCrZr blanket prototypes (Overview)



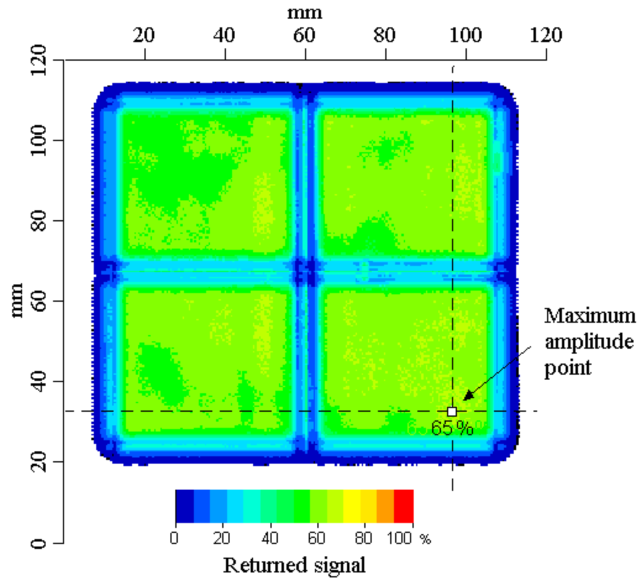
Layout CuCrZr blanket prototypes

- 3 prototypes manufactured
  - Composite CuCrZr / SS water-cooled heatsink base
  - 4, 47 x 42mm beryllium tiles
- Two HIP stage process
  - HIP Stage 1
    - Bond CuCrZr to 316L(N) SS
    - Solution anneal CuCrZr
  - HIP Stage 2
    - Bond Be tiles to CuCrZr
    - Age harden CuCrZr
- Subject to vigorous quality controls
  - Traceability of materials
  - NDE

Manufacture of CuCrZr blanket prototypes (HIP stage 2, Be / CuCrZr)



Completed prototype

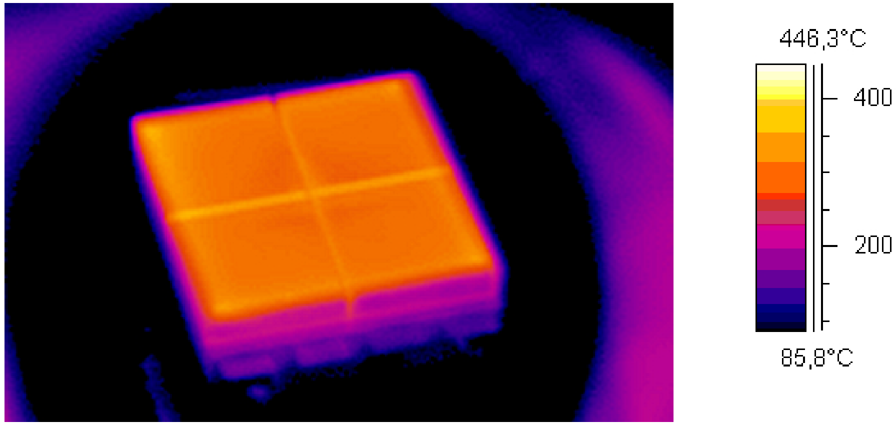


Ultrasonic examination of the tile bonding

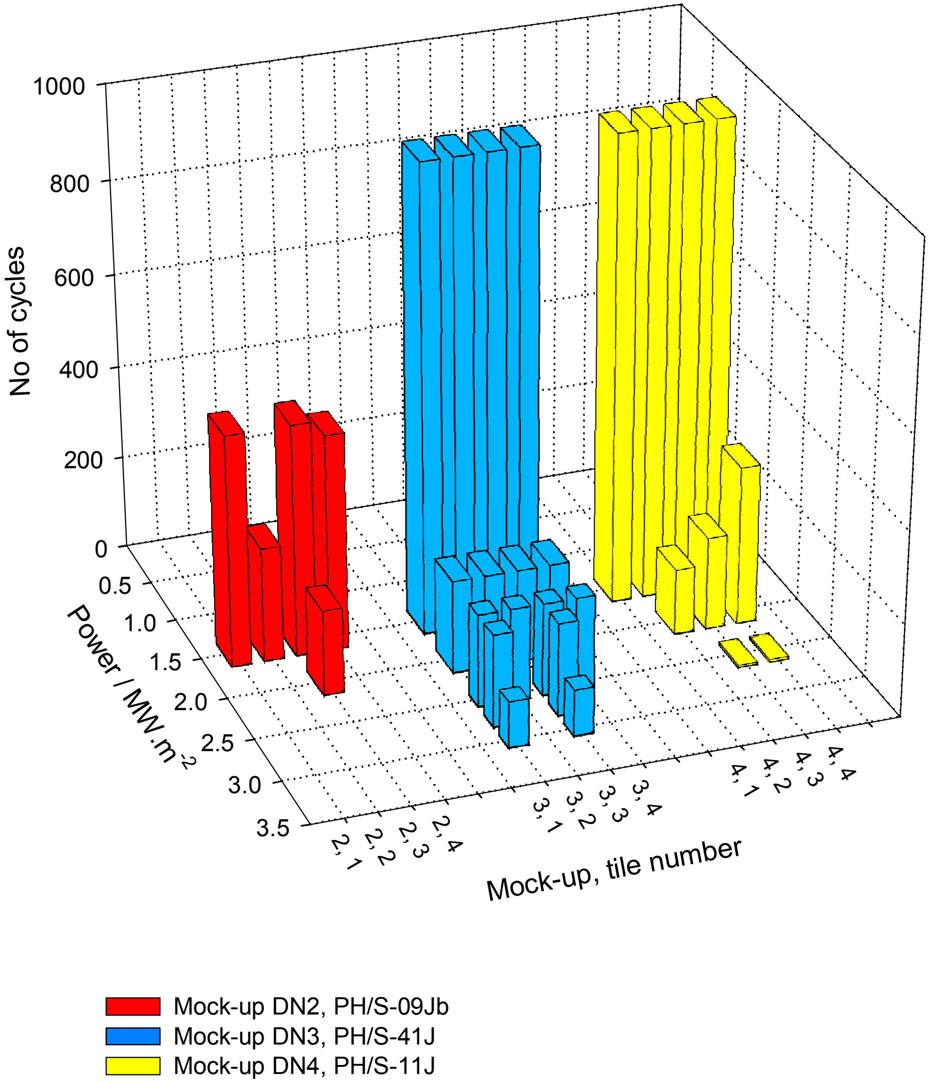
- Preparation for HIP
  - Clean components
  - Assemble into HIP can
  - Seal weld HIP can
  - Helium leak test
- Be / CuCrZr HIP bonding process
  - Evacuation of HIP can
  - HIP under conditions of 580ºC, 140MPa for 2hrs
  - ~500um E.P. Cu on CuCrZr, 5um Ti I.C. on Be
- NDE
  - Machine tile away HIP can
  - Ultrasonic examination
  - Hardness test on CuCrZr
- Finish
  - Weld pipe fittings
  - Leak and pressure test

Heat flux testing

- Prototypes tested in JUDITH by FZJ
- Highest performance for selected tiles
  - 1000 cycles at 1.5MW.m^{-2}
  - 200 cycles at 2.0MW.m^{-2}
  - 200 cycles at 2.5MW.m^{-2}
  - 200 cycles at 2.75MW.m^{-2}
  - 100 cycles at 3.0MW.m^{-2}



Typical thermograph of a prototype at 1.5MW.m^{-2}



Performance of the three prototypes

Summary of manufacture and development

- Early blanket (DS-Cu) components
  - Large 80mm sq. approx. x 10mm thick Be tiles
  - Heat flux tested to 0.7MW.m^{-2}
- Divertor baffle / limiter (DS-Cu) components
  - Flat tile and monoblock Be components manufactured
  - Required development of a new low temperature Be / DS-Cu HIP bond
  - Small 20mm sq. approx. x 4mm thick Be tiles
  - Heat flux tested to 5MW.m^{-2}
- CuCrZr blanket components
  - Development of a low temperature Be / CuCrZr HIP bond, based on divertor baffle work
  - Intermediate size 45mm sq. approx x 10mm thick Be tiles
  - Heat flux tested up to 3MW.m^{-2}

Long term material development

- **ITER**
  - **First sustained fusion power facility**
  - **Testing of critical power reactor features**
  - **Conventional materials based on the fission programmes**
  - **Possibility of testing some DEMO modules**
- **IFMIF**
  - **Materials test facility**
  - **High neutron fluence and energies**
  - **Limitations in terms of scale and geometry**
- **DEMO**
  - **Pre-power plant demonstration**
    - **'fast track' precursor to first power plant**
    - **needed for licensing of power generating reactors to follow**
  - **Test bed for new fusion specific materials**
    - **Low activation**
    - **High neutron energies**

Concluding remarks

- Over the last ~10 years the materials technology needed for the beryllium blanket has been developed
- Development will continue with the production of further part scale prototypes for fatigue testing and full scale components
- ITER and IFMIF will be used to further develop fusion materials, towards DEMO which will be used to validate fusion power plant design.