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Development of Design Rules for Fusion Structural Materials

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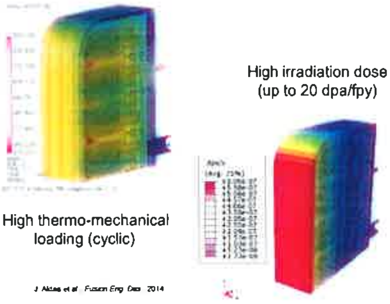
Introduction

In DEMO and future fusion power plants structural materials of the highly loaded in-vessel components, blanket and divertor will be subjected to complex thermo-mechanical loadings and high irradiation doses. Therefore new structural materials, e.g. the reduced activation ferritic martensitic (RAFM) steels and tungsten / tungsten alloys have been selected and developed which can withstand the harsh fusion specific loading conditions. For the assessment and qualification of in-vessel components built from these materials structural design criteria are required which allow reliable consideration of the failure modes to be expected due to loading conditions and material limits.

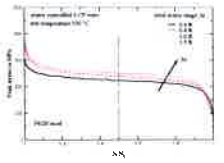
Design rules for RAFM steels

Structural materials for DEMO breeding blanket

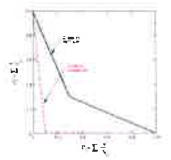


J. Aktaa et al., Fusion Eng. Des. 2014

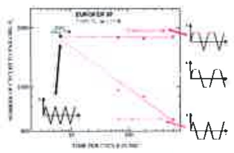
Cyclic softening



Creep-fatigue design rules (FM steels)

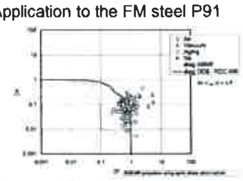


Hold-time influence



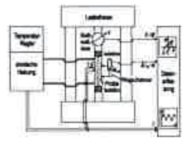
J. Aktaa & R. Schmitt, Fusion Eng. Des. 2006

Application to the FM steel P91



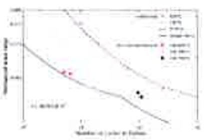
T. Asayama and Y. Tachibana, JAEA, Technical Report, 2007

Thermo-mechanical LCF-tests



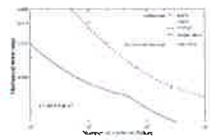
→ Out-of-phase TMF

C. Petersen, J. Nucl. Mater. 1998

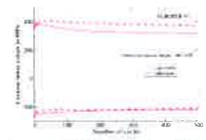


→ Thermo-mechanical loading seems to be critical(?)

FEM-Simulation



J. Aktaa et al., J. Nucl. Mater. 2007



Damage relevant tensile stresses are underestimated

→ Predicted lifetime higher than experimentally observed

Isothermal multiaxial fatigue tests: two types

Cyclic pull-push in axial and circumferential directions

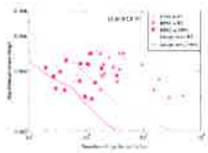
→ fixed directions of principal stresses and strains (FPSS)

room temperature tests only!

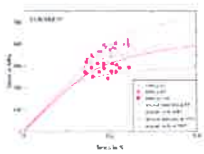
Cyclic pull-push and alternating torsion

→ rotating directions of principal stresses and strains (RPSS)

M. Weick & J. Aktaa, J. Nucl. Mater. 2007



→ Multiaxial loading is critical und needs to be further investigated



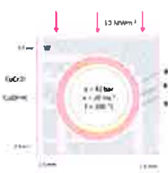
→ Reduced cyclic softening in comparison to uniaxial loading

Aktaa et al., FZKA-Report 7309, 2007

- Creep-fatigue rules of conventional design codes are either not sufficiently conservative or too conservative.
- Rules for progressive deformation (ratcheting) are also of concern due to cyclic softening.
- Development of new design rules for creep-fatigue and conceivably for ratcheting is crucial and requires a comprehensive test program:
  - LCF tests with long hold-times
  - Cyclic tests for investigating material and structural ratcheting
  - Thermo-mechanical LCF tests
  - Multi-axial LCF tests
  - Mock-up tests
- Reduced cyclic softening under thermo-mechanical and multiaxial fatigue loadings yields much shorter lifetimes in comparison to equivalent uniaxial loadings.
- Conventional fatigue design rules fail in providing sufficient safety margin in case of thermo-mechanical loading and might be even non-conservative in case of multiaxial loading.
- Modification of the rules requires proper constitutive modeling for the correct interpretation and assessment of observed phenomena and bridging the gaps between the different test types.

Design rules for W / W alloys

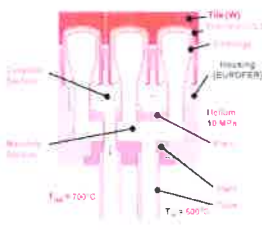
Armour and structural materials for DEMO divertor



A. Li-Puma, Fusion Eng. Des. 2012

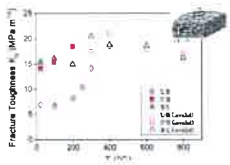
Water cooled divertor:
Failure of armour W shall not yield failure of structural part

Helium cooled divertor:
Failure of structural WL10 must be prevented



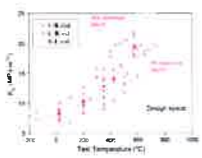
P. Norajitra, FZKA Report 7100, 2005

Brittleness of tungsten



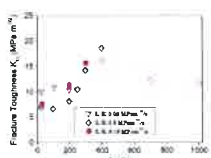
→ Strong anisotropy

Rules for design against brittle fracture



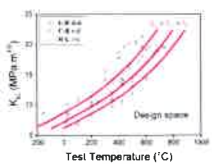
→ Narrow design space

Influence of loading rate



→ Increase of toughness in the brittle regime with decreasing loading rate

Probabilistic design rules



→ Enlargement of design space by utilizing probabilistic concepts

E. Gaganidze et al., J. Nucl. Mater. 2014

- Brittleness of W / W alloys is a bottle neck for their use as armour and structural materials in DEMO divertor.
- Design against brittle fracture is mandatory for structural tungsten components and requires reliable not excessively conservative rules.
- Consideration of anisotropy, loading rate dependence and probabilistic nature of the brittle fracture behavior of tungsten in the design rules would allow to enlarge the design space particularly in the lower temperature range.
- Influence of irradiation on the allowable design space is expected and needs to be quantitatively explored performing and evaluating proper irradiation experiments.

EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.