Max-Planck-Institut für Plasmaphysik, EURATOM Association

Sigma SiC-fibre reinforced copper for heat sink application

IPP

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Motivation

In future fusion reactors like DEMO the plasma leads to a heat flux of up to 15 MW/m² in the divertor region. The heat has to be removed efficiently from the plasma facing material (PFM) through the CuCrZr heat sink to the cooling channel.

Goal: high thermal efficiency requires high operating temperature for the coolant, therefore the heat sink material needs a thermal conductivity of > 200 W/mK

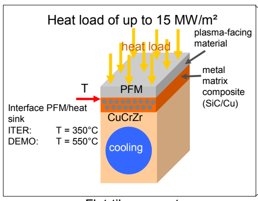
This increases also the temperature at the interface between plasma facing material and heat sink up to 550°C.

Problem: **stresses induced by different coefficients of thermal expansion & temperature gradient at the PFM/CuCrZr interface**

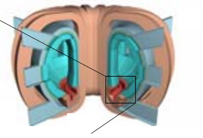
possible solution: Copper matrix composites (Cu-MMC) reinforced with silicon carbide fibres as an interlayer between the PFM and CuCrZr. Strength of 300 MPa at 300°C

- High thermal conductivity (copper)
- High mechanical strength (SiC fibres)

DEMO - Divertor



Flat-tile concept



DEMO: Demonstration reactor

- Deuterium-Tritium Plasma
- fusion power 2000 MW

Experimental

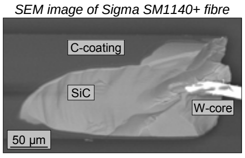
Fibre characterisation / Microindentation:

Measurement of micro-hardness and Young's modulus along the fibre cross section with maximum loads of 20 mN.

Fibre characterisation / Single fibre tensile test:

- tests performed according to DIN ENV1007-4 for brittle ceramic fibre
- traverse speed: 0,6 mm/min; clamping length: 25 mm
- determined results: tensile strength R_m; Young's modulus; ultimate elongation
- investigation of coatings and heat treatment on fibre strength

SEM image of Sigma SM1140+ fibre



chemical composition:

Tungsten	10 % w/w
Silicon carbide	84 % w/w
Carbon	6 % w/w

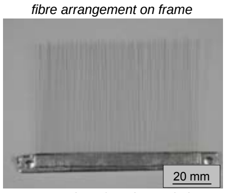
structural composition:

tungsten wire	14 µm thick
carbon coating	3 µm thick
overall diameter	101-108 µm

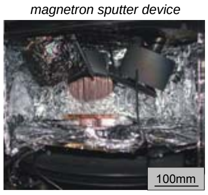
Cu-MMC synthesis steps:

1. Magnetron sputtering of Titanium interlayer (~ 200 nm) and copper (~ 500 nm) on silicon carbide fibres with a carbon-rich layer at the surface (Sigma SM1140+, TISICS)
2. Electroplating of Copper as matrix material in a $CuSO_4$ bath for: - various fibre volume fraction
   - homogenous fibre distribution
3. Heat treatment for hydrogen degassing and interlayer reactions to form TiC as coupling agent
4. Etching of electroplated fibres to remove oxide layer
   Etching agent: - phosporic acid (55%)
   - nitric acid (20%)
   - acetic acid (25%)
5. Unidirectional fibre arrangement in capsule
6. Electron-beam welding of capsule
7. consolidation via hot-isostatic-pressing of capsule
   - 650°C; 100 MPa; 60 min

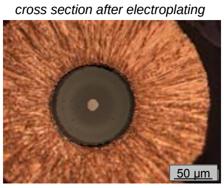
fibre arrangement on frame



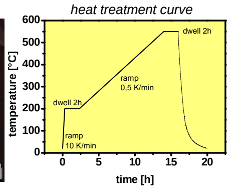
magnetron sputter device



cross section after electroplating

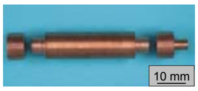


heat treatment curve

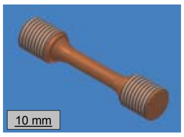


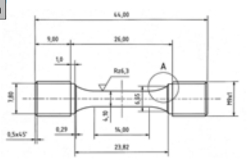
Cu-MMC tensile tests:

The number of fibres in one capsule defines the fibre volume fraction of the MMC after consolidation. According to the rule of mixture (ROM) a fibre volume fraction of ~10 % is necessary for reaching the required composite strength of 300 MPa at 300°C, for the given Sigma fibre strength. The reachable composite strength will be validated by tensile tests with fibre volume fractions between 10-20 % and at temperatures up to 550°C.



Cu capsule structure and specimen geometry for tensile test





Summary / Outlook

Processing of MMC

- **synthesis of Cu-MMC specimens with Sigma SM1140+ fibres successful**
- **large grains (up to ~50µm), no pores along grain boundaries promise good thermal conductivity**

Single fibre tensile tests

- **slight strength decrease for Sigma fibre coated with Ti-interlayer after heat treatment due to chemical reactions between fibre and interlayer**
- **results for single fibre MMCs follow the rule of mixture and are in good agreement to ROM calculation**
- **The crack behaviour of single fibre MMCs exhibit that the Ti-interface leads to a good bonding between copper matrix and carbon coating. The weak point of the composite is the interface C/SiC within the fibre.**

Outlook: tensile test Cu-MMC

- **tests for various fibre volume fractions between 10-20% for 20°C, 300°C, 550°C**

Outlook: thermal conductivity (λ) of Sigma fibre reinforced Cu-MMC

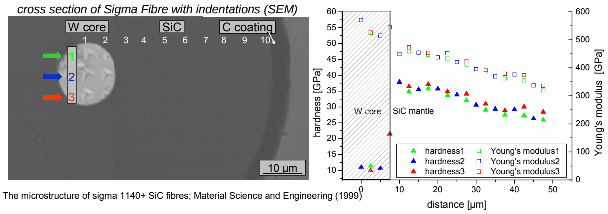
- **thermal conductivity measurement via laser-flash method of Cu-MMC with fibre volume fractions between V_f = 10-20%**

Results

Microindentation:

Microindentation tests were performed on the cross-section of a fibre embedded in the copper matrix. The plotted points in the diagram show the 3x10 indentation-matrix from tungsten core to carbon coating of the fibre and the results for hardness (± 2 %) and Young's modulus (± 10 % experimental error) obtained from the load-displacement curves. The hardness across the SiC mantle decreased due to different grain structures, which is explained by Cheng et al. *. The results for the Young's modulus are in good agreement to the results of the single fibre tensile test.

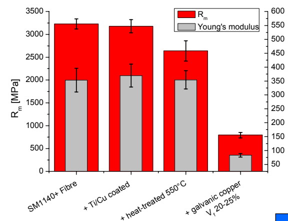
cross section of Sigma Fibre with indentations (SEM)

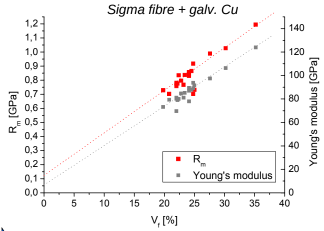


* The microstructure of sigma 1140+ SiC fibres; Material Science and Engineering (1999)

Single fibre tensile tests:

At least 20 valid tests were performed for each fibre condition. A test was successful when the fibre brokes between the grips.





slight strength decrease after heat treatment (~18 %), due to chemical reactions in interlayer (TiC,Cu_4Ti; Brendel et al *)

* Titanium as coupling agent in SiC fibre reinforced copper matrix composites; Materials Chemistry and Physics (2005)

strength and Young's modulus follow ROM

estimation of fibre reinforcement by calculation with ROM (ultimate fibre elongation: ~0,9%)

$$\sigma_c = \sigma_f \cdot V_f + \sigma_m \cdot V_m = \sigma_f \cdot V_f + \sigma_m \cdot (1 - V_f)$$

R_m ... ultimate tensile strength

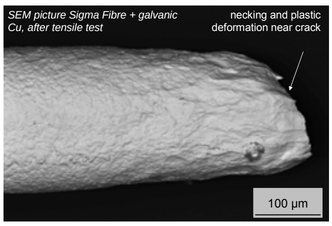
V_f ... fibre volume fraction

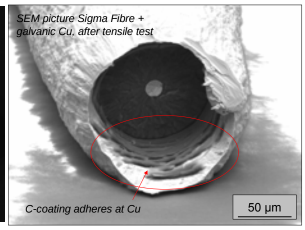
$\sigma_{f,c,m}$ ... stress (fibre, matrix, composite)

$\sigma_{copper} \approx$ 50 MPa; $\sigma_{fibre} \approx$ 3200 MPa; V_f= 23 %

ROM: $\sigma_{composite} \approx$ 774,5 MPa

tensile test: $\sigma_{composite}$ = 794 ± 61 MPa

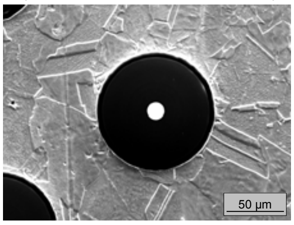


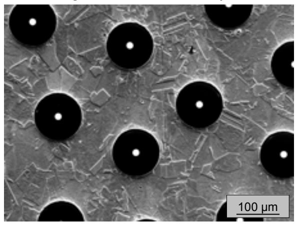


- results show good agreement to rule of mixture
- fibre/matrix bonding works well; C-coating on fibre is the weak point

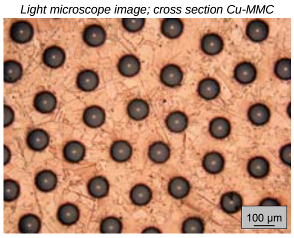
Cu-MMC:

Cross section SEM images of a consolidated capsule exhibit no pores. The typical laminar grain structure after electroplating changes completely to large grains up to 50 µm in size after heat treatment. This promises a high thermal conductivity.

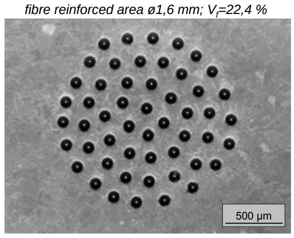




Light microscope image; cross section Cu-MMC



fibre reinforced area ø1,6 mm; V_f=22,4 %



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