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Development of finely dispersed doped carbon-based materials for the strike point areas of the ITER divertor

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Content

- Introduction
- Why doped carbon for ITER?
- Manufacturing route
- Results
- Comparison with candidate materials
- Conclusions and outlook

Introduction

Carbon based materials (CFC) are present candidates for the strike point areas of the ITER divertor

Advantages of **CFC** materials:

- Very good thermo-mechanical properties (thermal conductivity at RT > 300 W/mK; high mechanical strength)
  - ⇒ Excellent **power handling capability**
- No melting under transient power loads and off-normal events (ELMs, disruptions, VDEs)
- **Low Z** → low radiative power losses in the plasma
- Broad tokamak operation experience with C-based materials → allows operational flexibility
- low neutron activation

Introduction

Main **disadvantages** of C-based materials for fusion application (graphite and/or CFC) :

- **CFC, graphite**: **chemical reactivity with H** → **erosion, tritium co-deposition** → the divertor is **not** a permanent component
- **Graphite**: **thermal conductivity** not high enough (>300 W/mK at RT needed)
- **CFC**: **anysotropy**
  - → unequal, partly severe erosion by **brittle destruction**
  - → joining process to heat sink more difficult
- **CFC**: high **cost**
- **CFC, graphite**: **neutron damage** > 0.5 dpa → loss of thermal conductivity, dimensional instability

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Introduction

Possible way for **improving carbon materials for fusion application**: addition of **metallic or ceramic dopants**.

Effects of **dopant addition** (several at.%):

- **Self-passivation** against **chemical erosion by hydrogen**. Passivation occurs due to
  - Influence of dopants on **thermal activated** hydrocarbon release
  - **Dopant enrichment** at the surface due to preferential erosion of C ▶

Introduction

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  Both effects are the more effective the smaller the dopants particle size
- Improvement of **thermal conductivity** → dopants showing **catalytic effect** on the graphitization
- Carbide addition → reinforcement effect ⇒ **improved strength**

In all cases improvement the more effective the smaller the particle size of the dopants ➡ **nanoscaled dopant distribution**

Introduction

Aim of this work: development and **optimization** of fine-grained isotropic **graphite** for **plasma facing application** by **doping** with finely dispersed **carbides**

→ **reduction of chemical erosion** by H while **improving thermo-mechanical properties** (high thermal conductivity, high thermal-shock resistance); **reduced costs** compared to CFC materials.

Keys for development:

- Selection of appropriate **dopants** and raw materials
- Use of starting powders with **very small particle size**
- Rigorous **control of all manufacturing steps**

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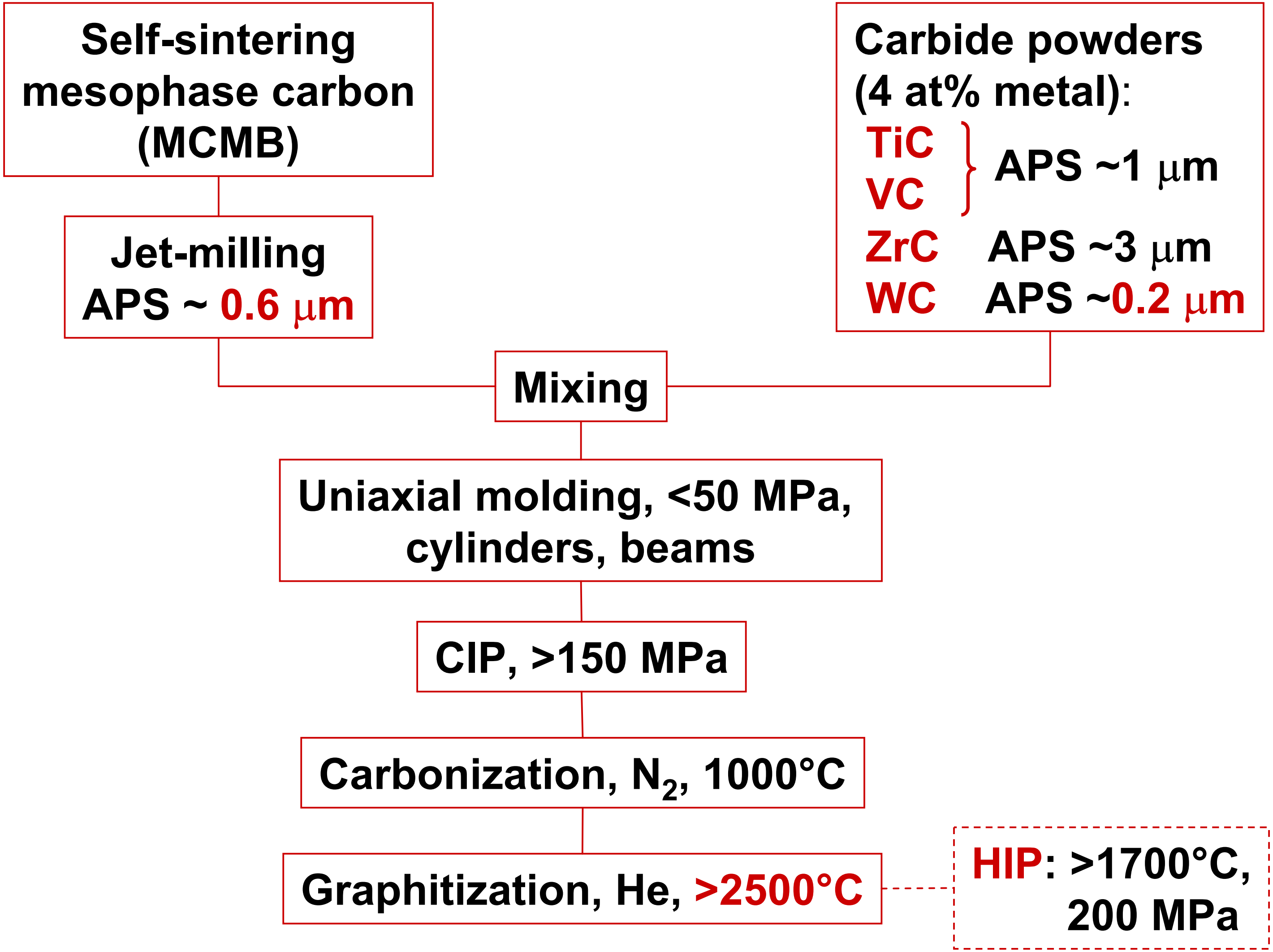
Manufacturing route



Self-sintering mesophase carbon (MCMB)

Jet-milling
APS ~ 0.6 μm

Carbide powders (4 at% metal):

TiC **VC**	**APS ~1 μm**
ZrC	**APS ~3 μm**
WC	**APS ~0.2 μm**

Mixing

Uniaxial molding, <50 MPa, cylinders, beams

CIP, >150 MPa

Carbonization, N_2, 1000°C

Graphitization, He, >2500°C

HIP: >1700°C, 200 MPa

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Results

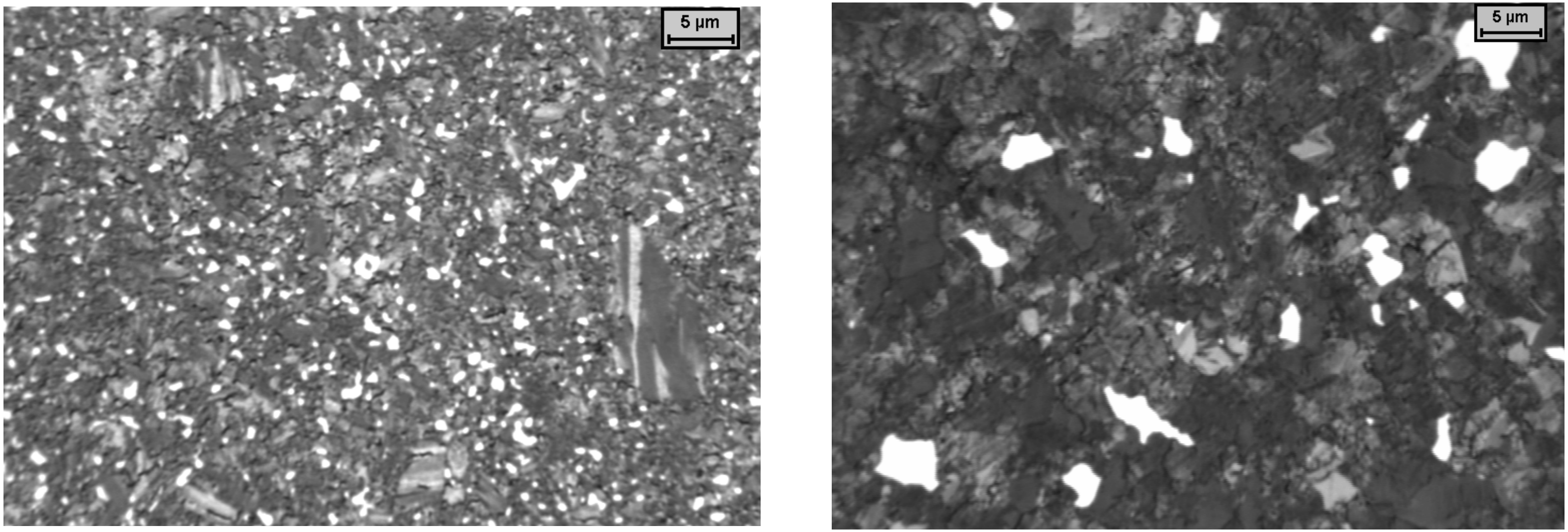
Parameters investigated after different graphitization cycles:

- **Carbide distribution**
- L_c, **thermal conductivity**
- **Porosity** (total, open)
- **Influence** of **dwell time** during graphitization, and of a **HIP** step subsequent to graphitization
- **Mechanical properties** (flexural strength, Young's modulus, strain-to-failure), **fracture surfaces** → responsible defect.
- Optimum **dopant concentration** (only for **TiC**)

Results

Carbide distribution:

- Homogeneous distribution after carbonization (1000°C)
- After **graphitization** → strong influence of cycle parameters (**T_{graph}, dwell time**): longer dwell time ⇒
  - Coarsening

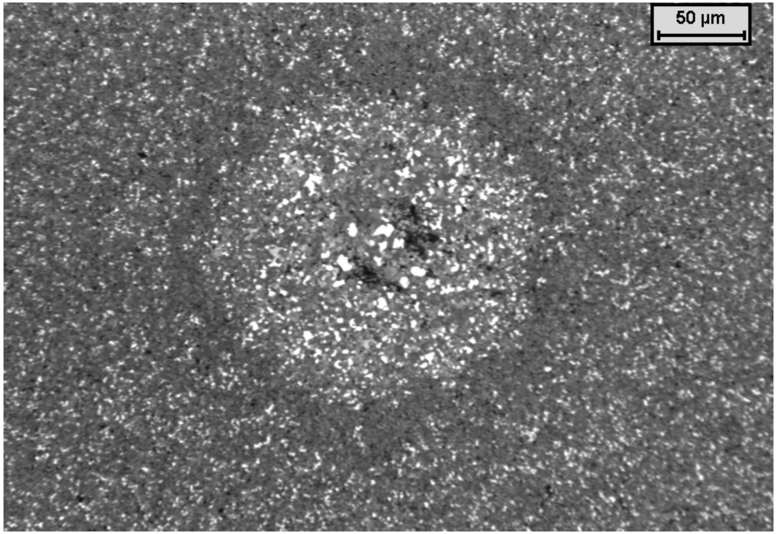


1 h dwell **2 h dwell**

TiC-doped sample after graphitization at 2650°C

Results

- Local agglomeration, carbide depleted zones → detrimental for **mechanical properties**



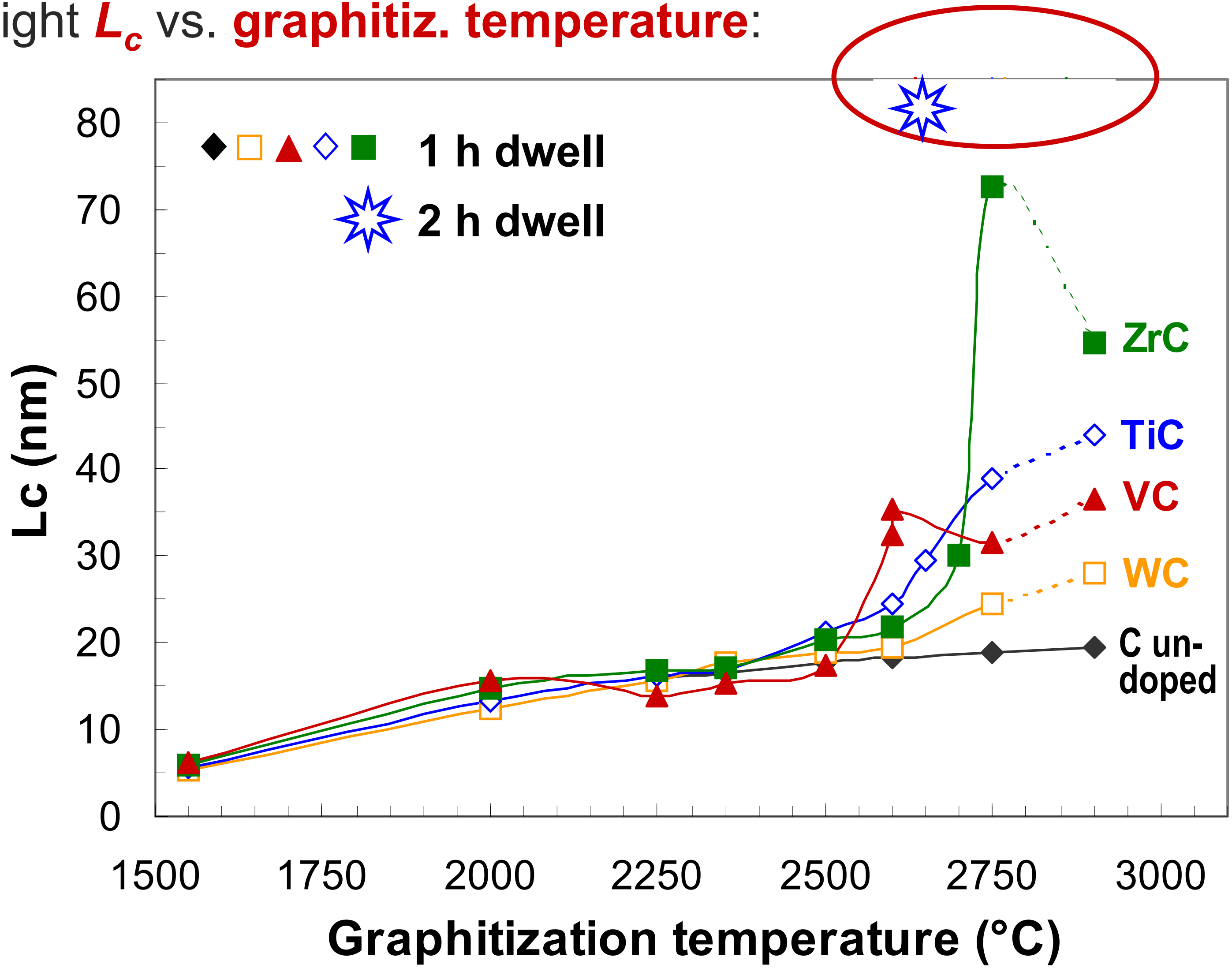
VC-doped sample after graphitization at 2600°C

⇒ Necessary to find **compromise** between **high T_{graph}** and **long dwell time**

Results

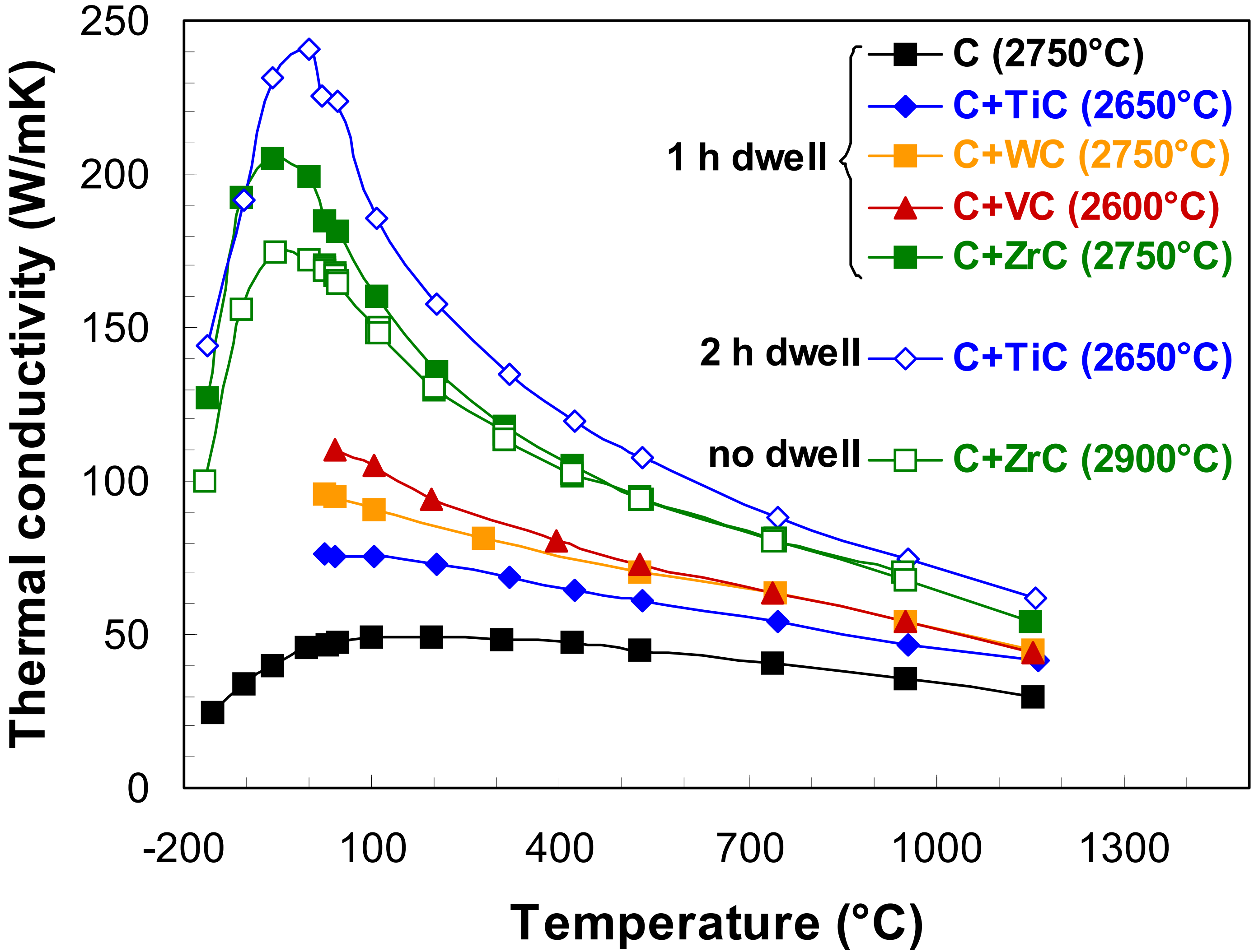
Crystallite height L_c vs. **graphitiz. temperature**:

L_c: X-ray diffraction (Scherrer)



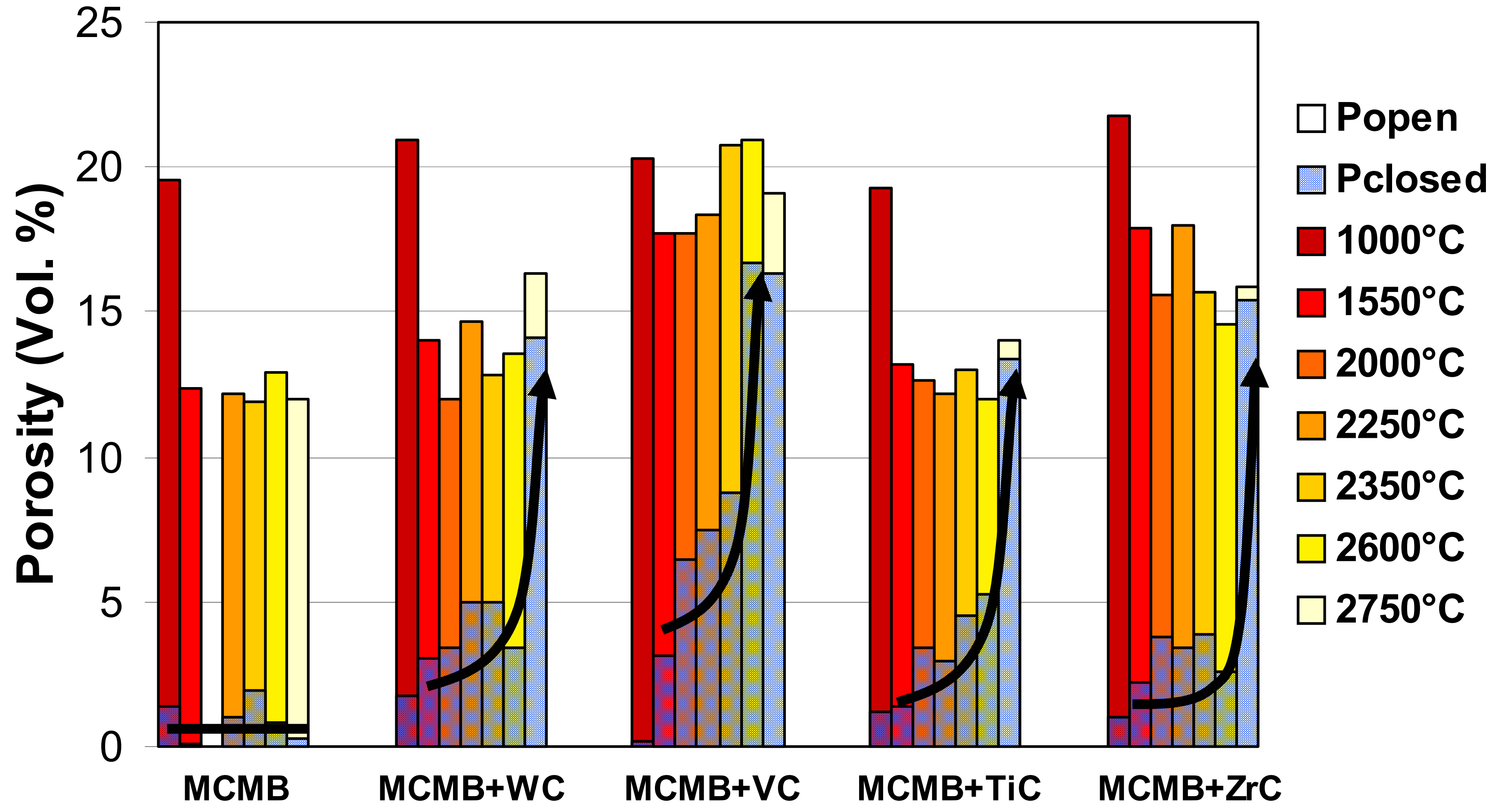
Results

Thermal conductivity:



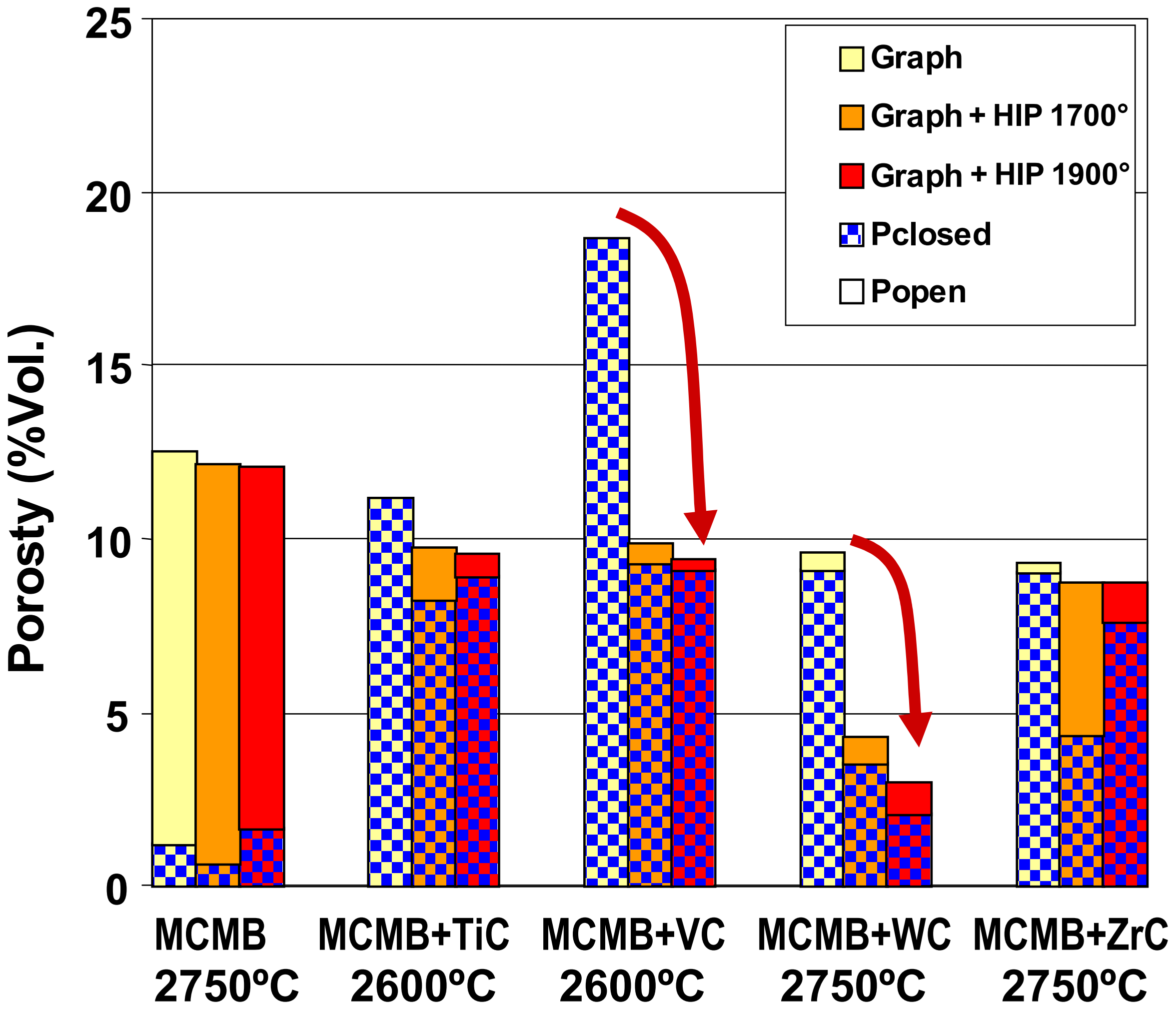
Results

Total and open porosity after graphitization at different temp.:



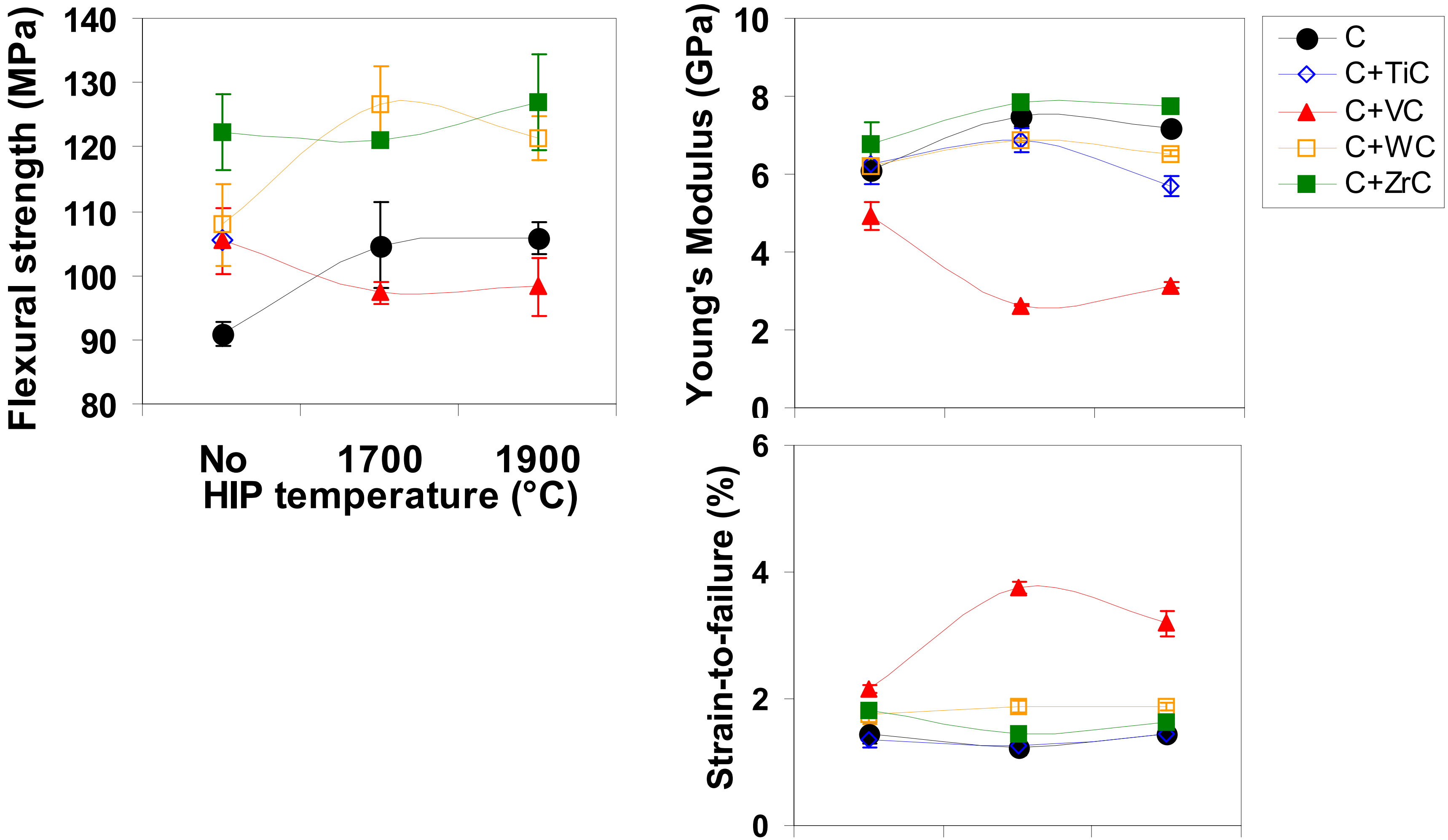
Results

Decrease of porosity by **HIP** subsequent to graphitization:



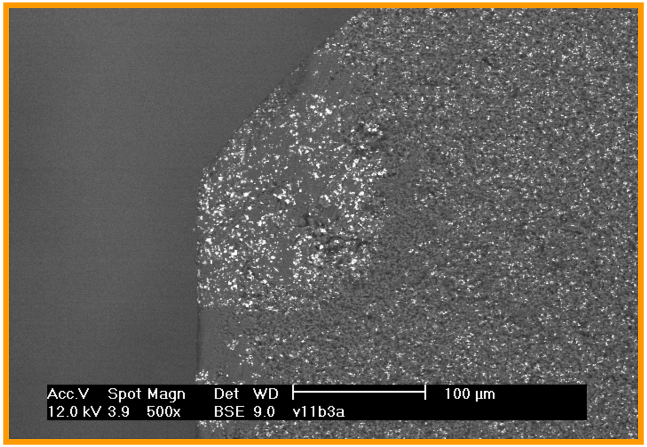
Results

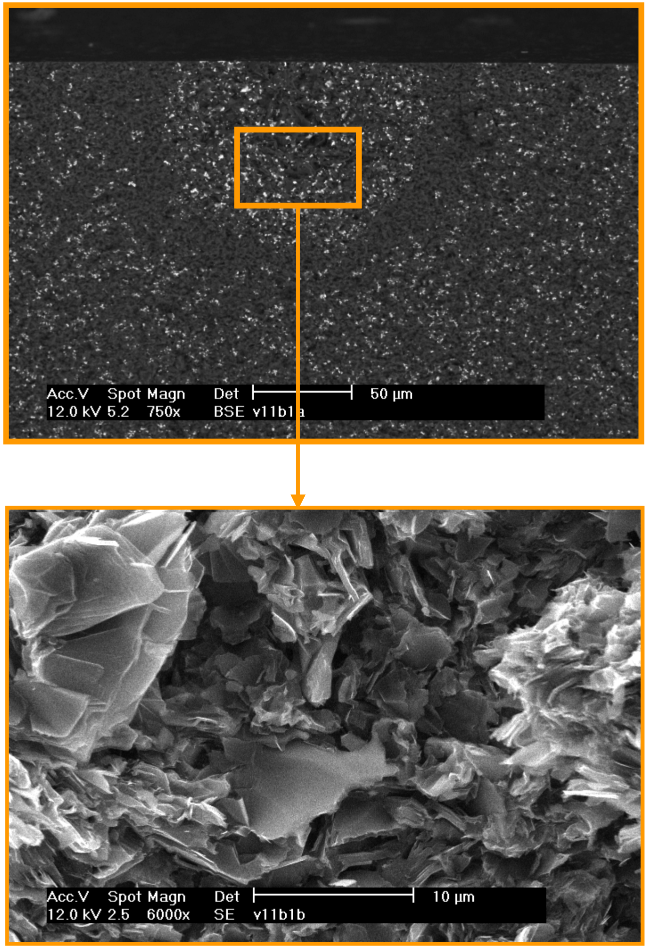
Mechanical properties; influence of **HIP**



Results

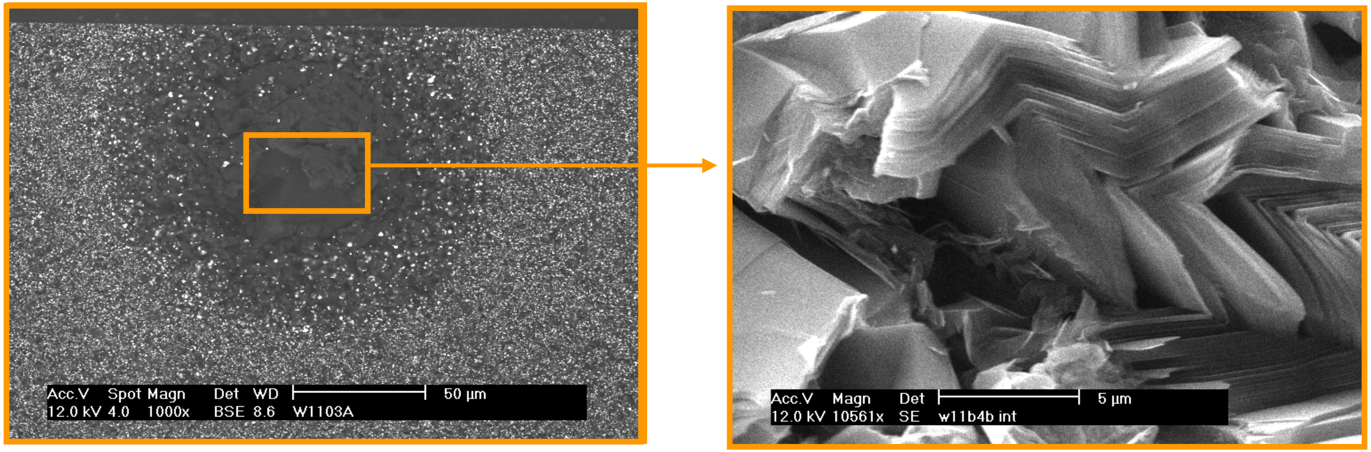
Fracture surfaces: VC-doped material





Results

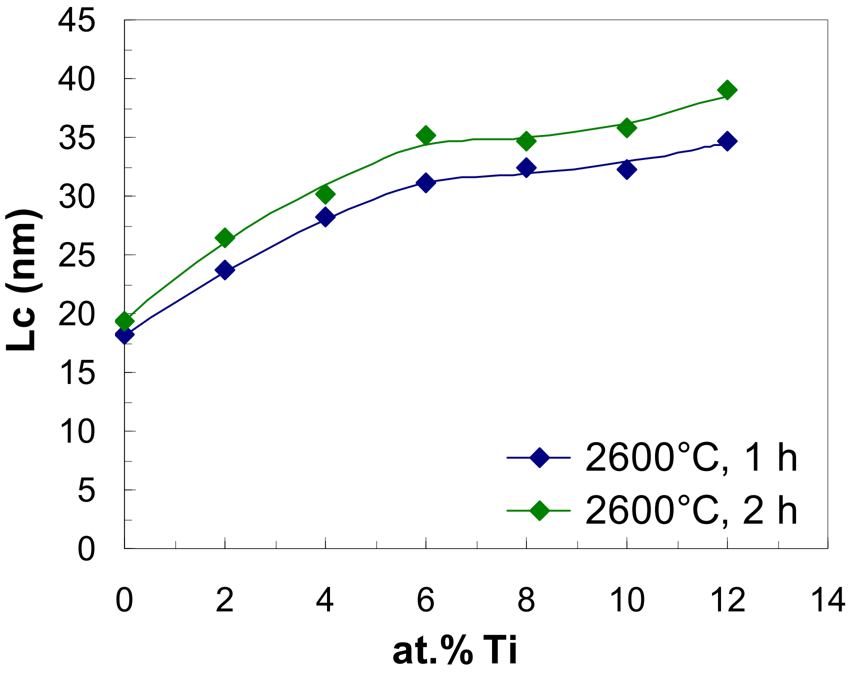
Fracture surfaces: WC-doped material

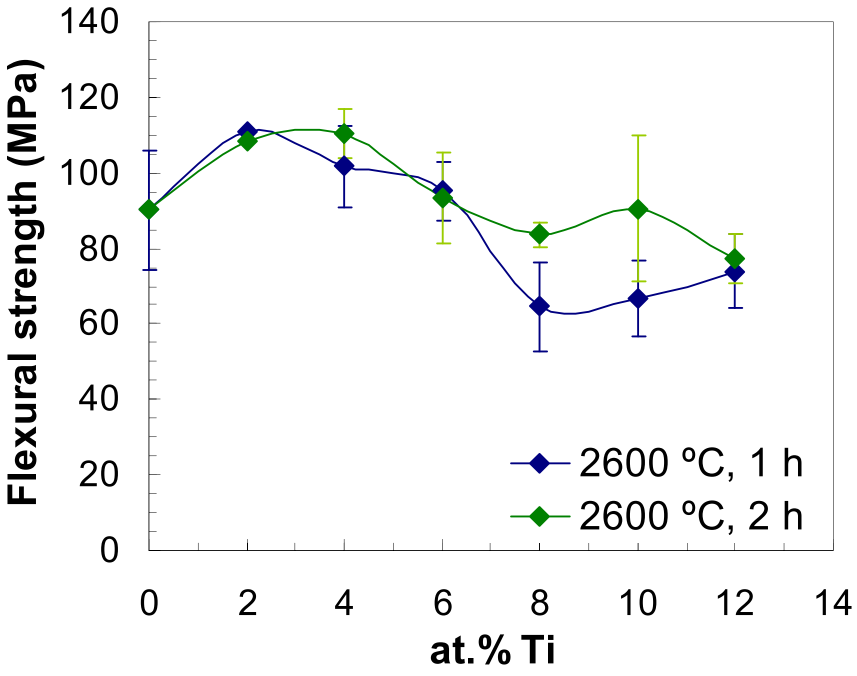


Results

Determination of **optimum dopant concentration**

→ variation of **Ti** content between 2 and 12 at% Ti





➡ **Optimum Ti concentration** (for TiC APS ~1 μm): **~4 at.% Ti**

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Comparison

Comparison with present candidate materials:

- European reference CFCs: **NB31** and **Concept 2**

		Density (g/cm^3)	**Thermal conduct. (W/mK)**	**Strength (MPa)**	**Young's modulus (GPa)**
NB31	Pitch	1.90	323	σ_t 130	107
	PAN		117	30	15
	Needling		115	19	12
Concept 2	Pitch	1.86	360	σ_t 106	
	PAN			57	
	Needling			13	
Doped graphites		1.92 (undoped)	50 - **230**	σ_f 100 –125	3 – 8

Advantages: low chemical erosion + good thermo-mechanical properties + isotropy + low cost; further improvement possible

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Conclusions and outlook

- **Doping** → efficient way for improving isotropic graphite such as to achieve specifications of candidate C-based materials for ITER
- **Longer dwell time** during graphitization → ↑ L_c → ↑ **thermal conductivity**. But **carbide coarsening and agglomeration**, depending on temperature → ↓ **flexural strength** ⇒ balance between dwell time and graphitization temperature to obtain optimum properties.
- **HIP** subsequent to graphitization → ↓ **porosity** → improved mechanical properties: ↑ **flexural strength**, ↓ **Young's modulus**, ↑ **strain-to-failure** ⇒ ↑ **thermal shock resistance**.
- Further improvement expected with **nanoscaled dopant distribution** ➡ **ExtreMat IP** → extension to other applications

END

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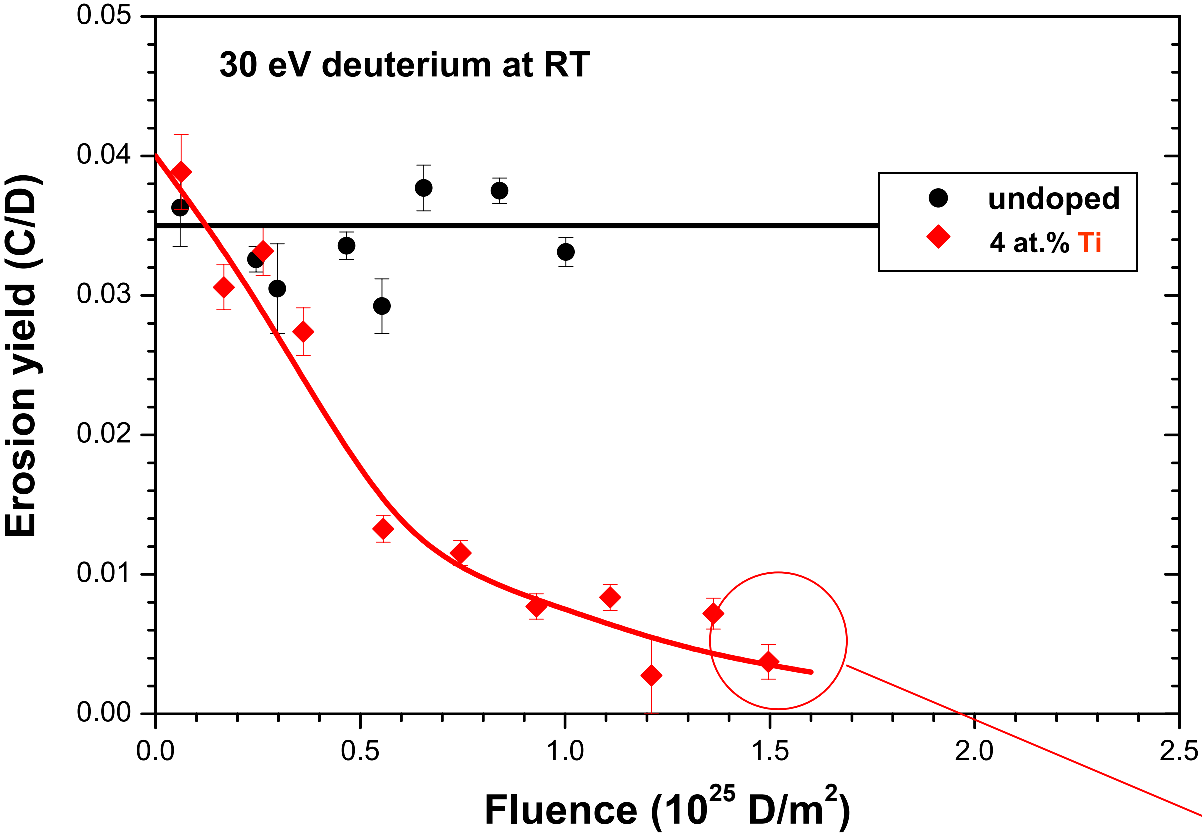
Introduction

Fluence dependence of chemical erosion yield
(E. de Juan Pardo et al., Physica Scripta T111, 2004)



columnar surface topography, where carbide grains protect underlying graphite from further erosion