Fracture Behaviour of Engineered Fiber/Matrix Interfaces in Fibrous Tungsten/Tungsten Composites

J. Du[1], T. Höschen[1], M. Rasinski[1,2], J-H. You[1]
A. Brendel[1], F. Koch[1], G. Matern[1]

[1] *Max-Planck-Institut für Plasmaphysik, EURATOM Association, Boltzmannstr. 2, 85748 Garching, Germany*

[2] *Warsaw University of Technology, Faculty of Materials Science and Engineering, ul. Woloska 141, 02-507 Warsaw, Poland*

Motivation

Backgrund

Tungsten— armour material for the plasma-facing component of fusion reactors

☺ Advantages

✓ high melting point

✓ high thermal shock resistance

✓ high erosion resistance

☹ Drawbacks

✗ inherent brittleness

✗ embrittlement { neutron radiation; recrystallization }

Severe brittleness limits its engineering application!

Metallurgical approaches

- Oxide Particle Dispersion (La_2O_3),
- Doping (K),
- Mechanical alloying (Re)
- Severe Plastic Deformation

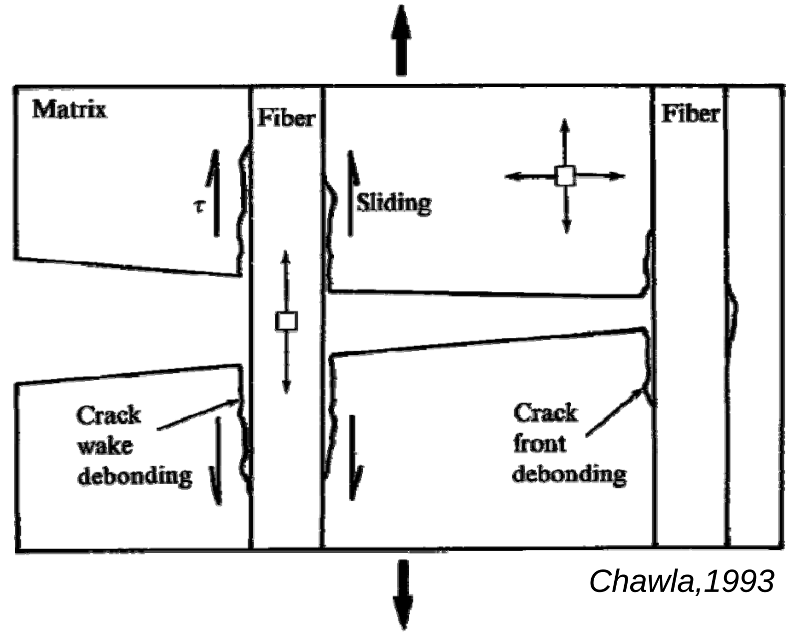
But can just get only limited improvement of tungsten toughness.

Therefore an effective toughening technique is required to increase the toughness to an acceptable level.

W_f/W composite concept

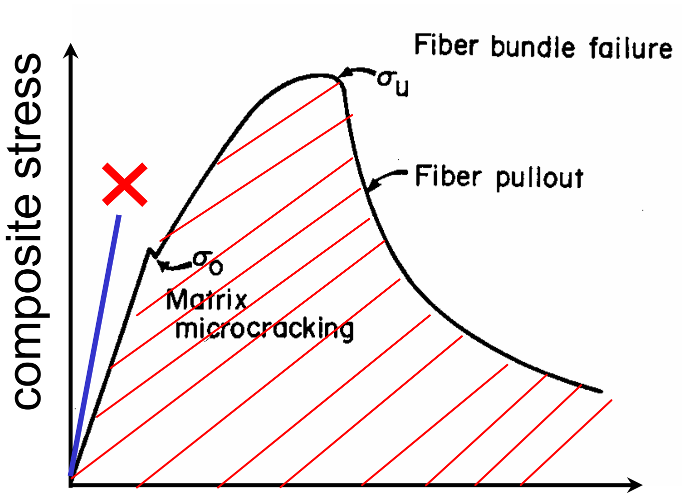
Ideas from Ceramic Matrix Composites (CMC)

- Engineered fibre/matrix interfaces allow controlled crack deflection.
- Interfacial debonding and friction lead to internal energy dissipation.
- Higher strength is endowed by strong fibres.



Chawla,1993

CMC toughening mechanism (pseudo ductile)



Chawla,1993

→ Why not with tungsten?

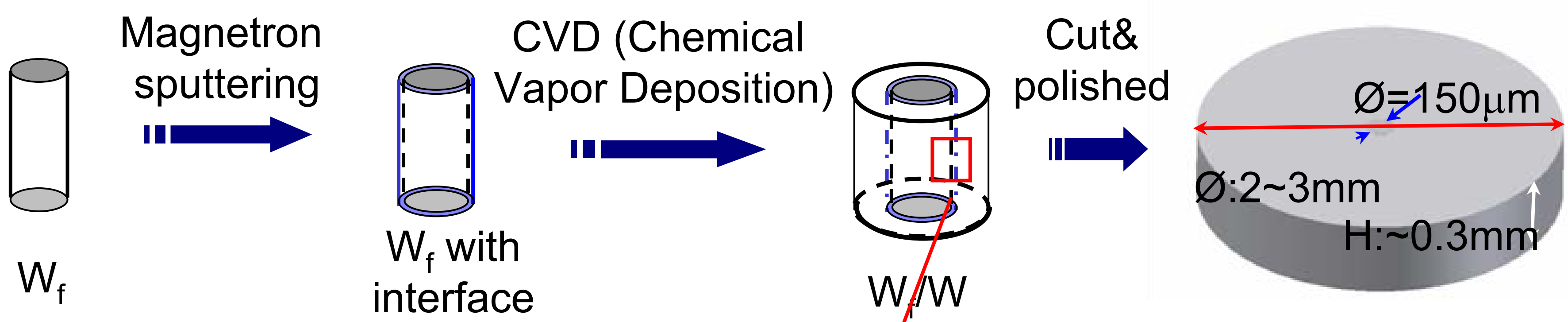
Tungsten fiber reinforced Tungsten (W_f/W):

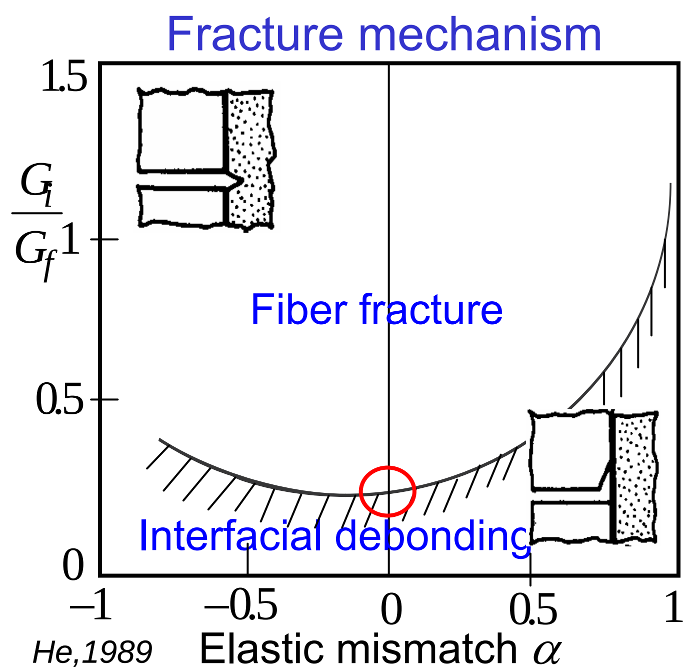
Chemical homogeneity.

Appropriate coating will be applied for interface

The aim of the present work is to explore the validity of the CMC toughening principle for the (W_f/W) composite case.

Specimen preparation





Debonding prerequisite

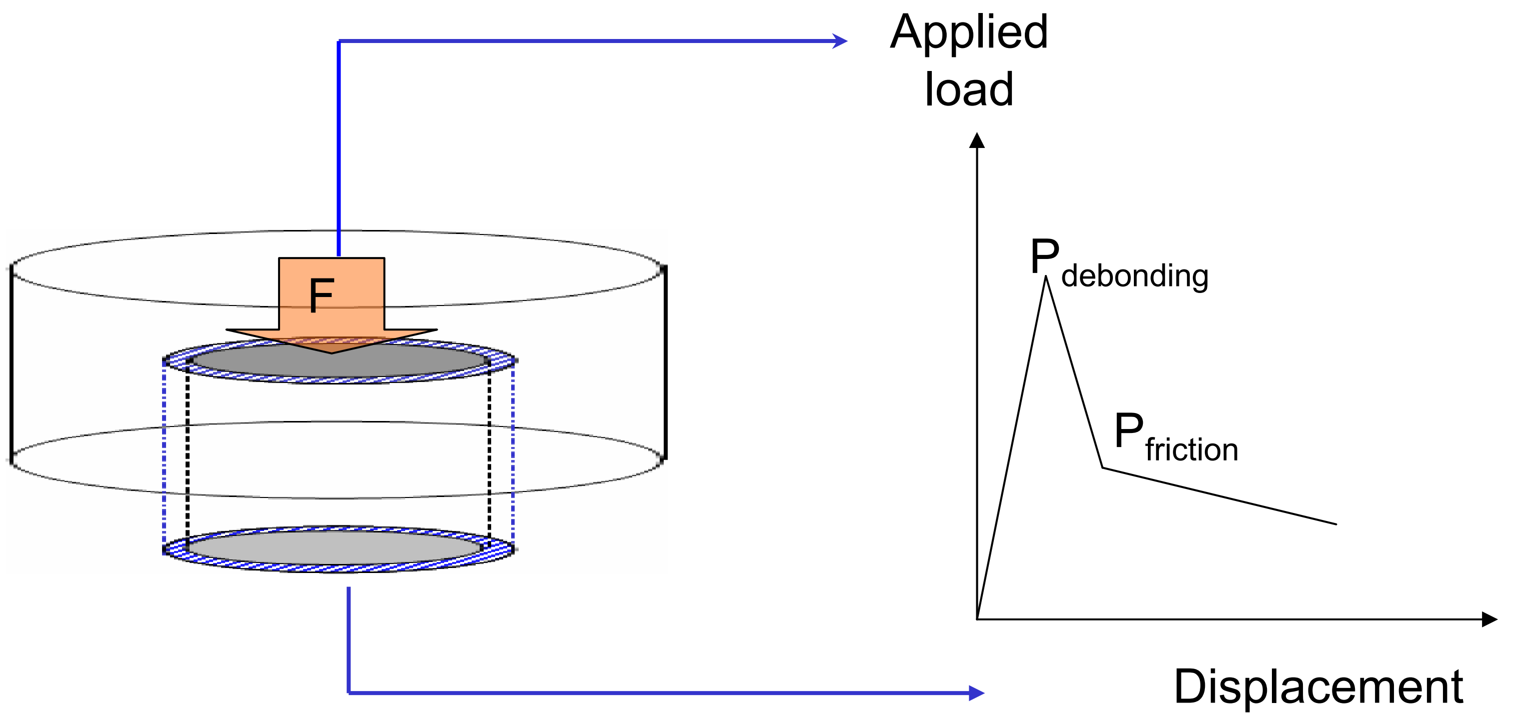
$$\frac{\text{Interface fracture energy } G_i}{\text{Fiber fracture energy } G_f} \leqslant \mathbf{0.25}$$

Interface	ZrOx single-layer	ZrOx/Zr multi-layer	Cu/W multi-layer	Cu single-layer
Thickness	266nm	640 nm	900 nm	480 nm

How to identify the interfacial properties?

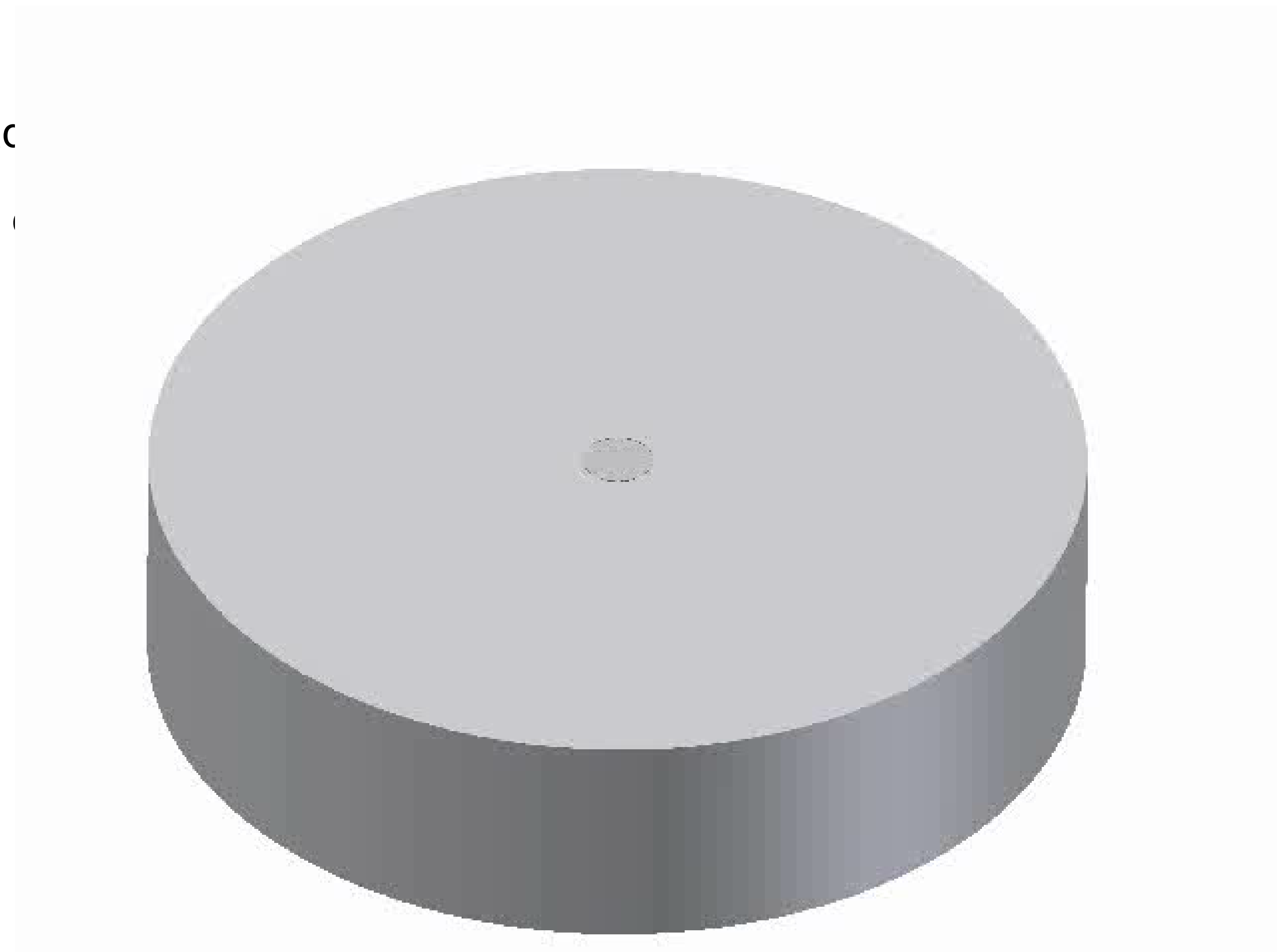
Single fiber debonding — Push-out test

- Load is applied on the end of fiber, force and fiber movement are recorded.
- L-D curve reveals the debonding strength and frictional resistance.



Single fiber debonding — Push-out test

- Loac



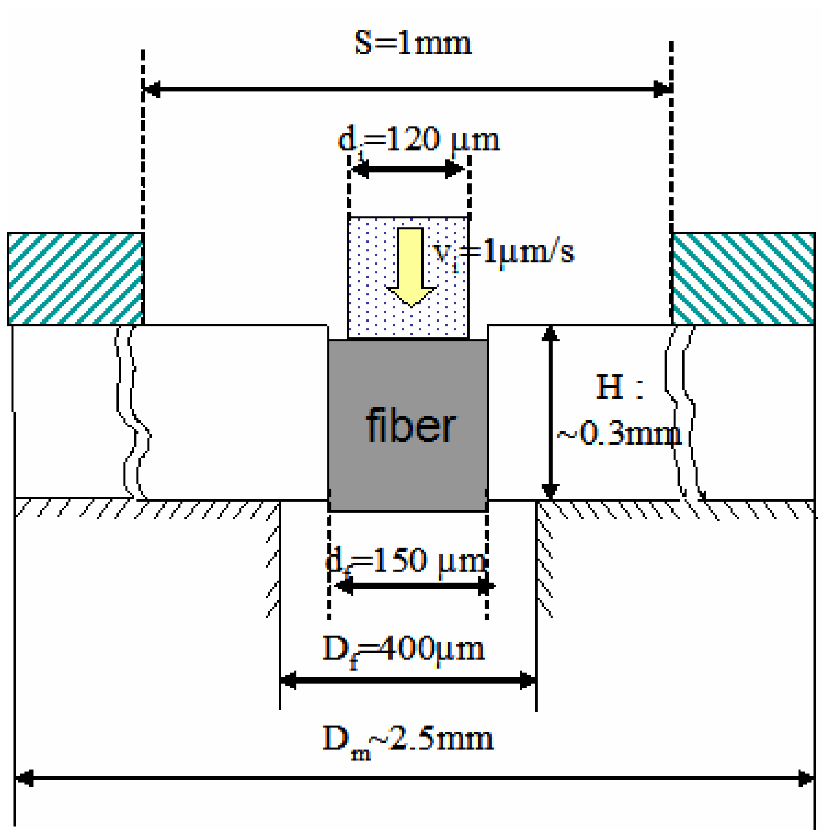
rded.

- L-D (

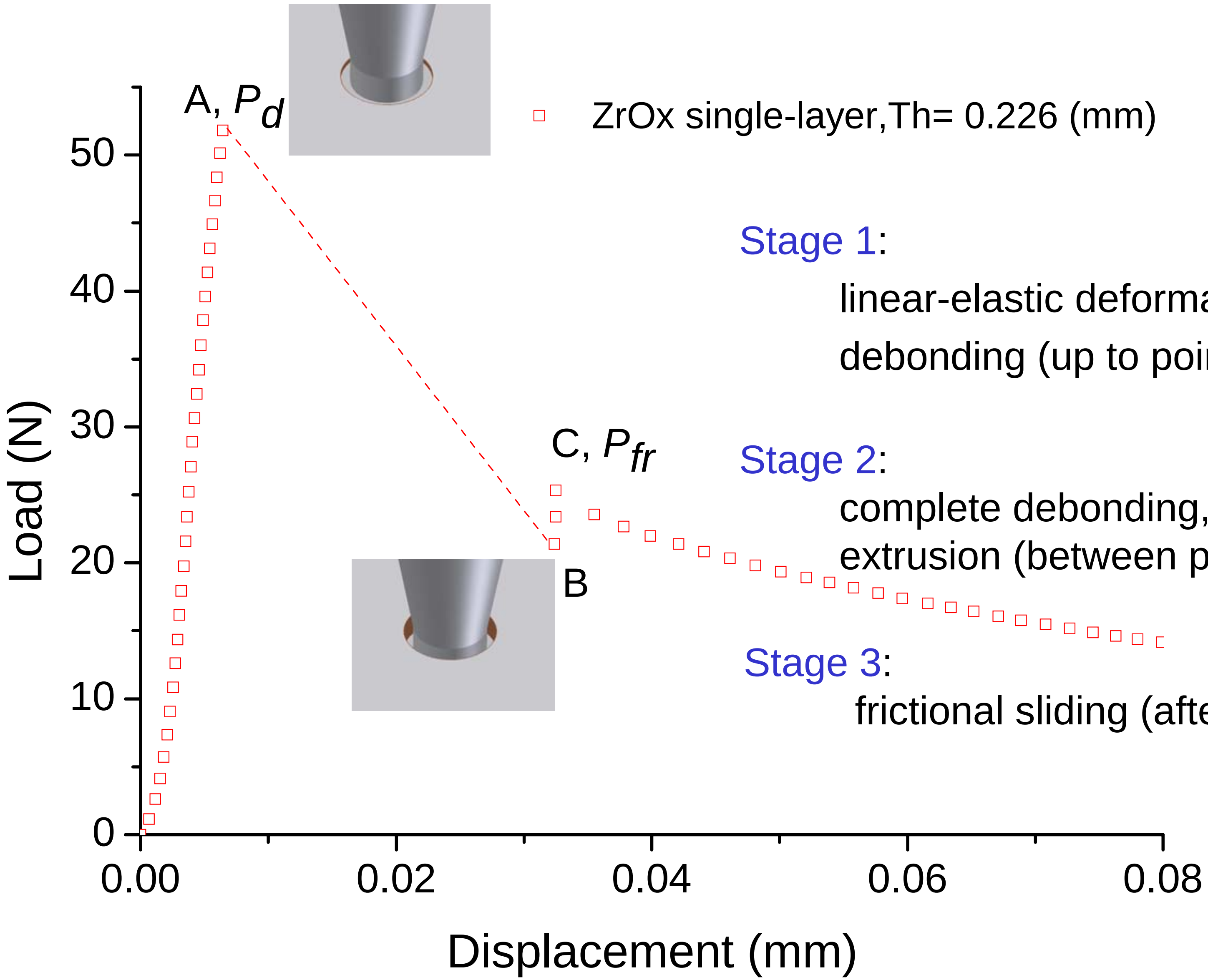
Displacement

Single fiber debonding — Push-out test

- Load is applied on the end of fiber, force and fiber movement are recorded.
- L-D curve reveals the debonding strength and frictional resistance.



Push-out curves

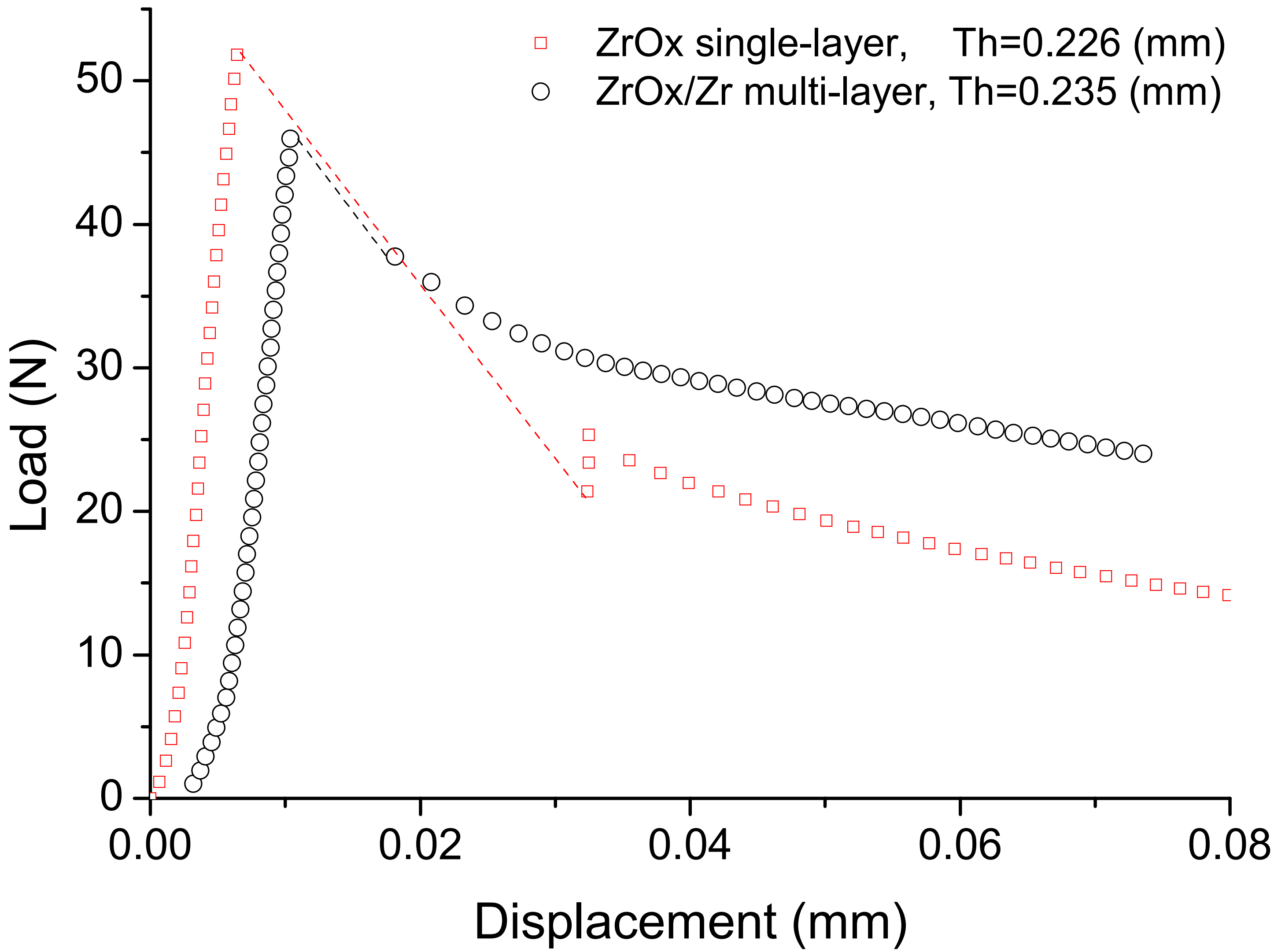


Stage 1:
linear-elastic deformation, initial debonding (up to point A)

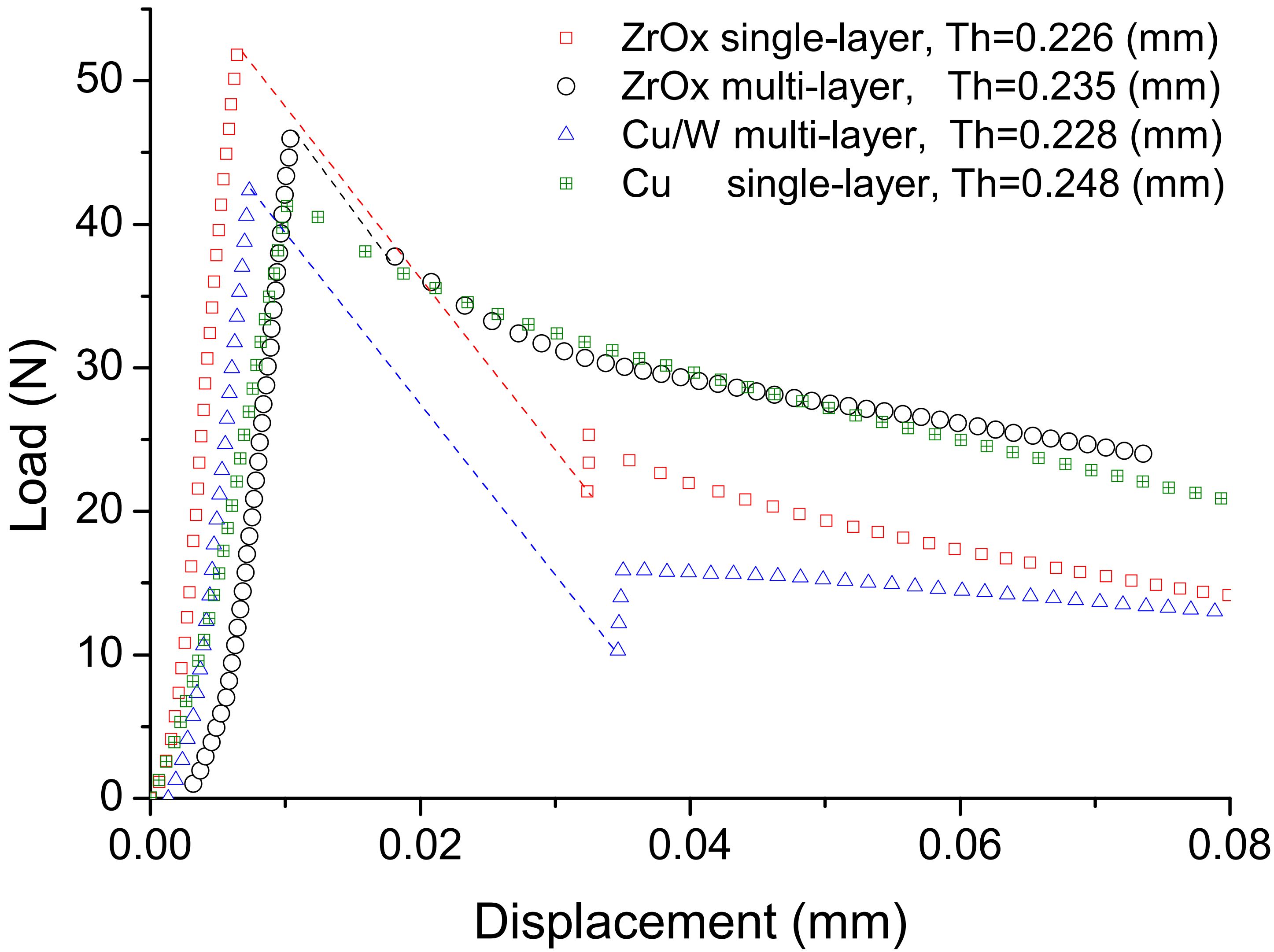
Stage 2:
complete debonding, dynamic extrusion (between point A and B)

Stage 3:
frictional sliding (after point C)

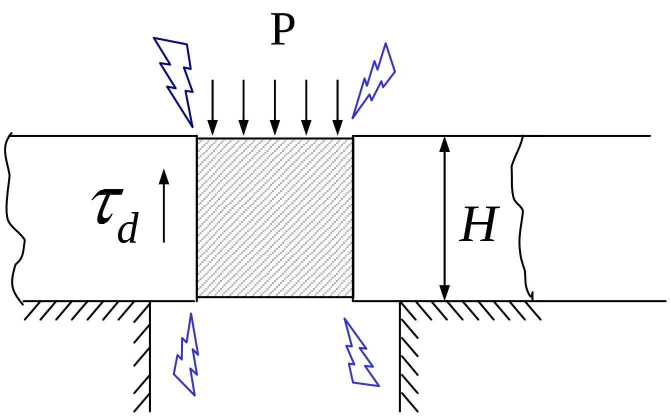
Push-out curves



Push-out curves



Interfacial parameters calculation



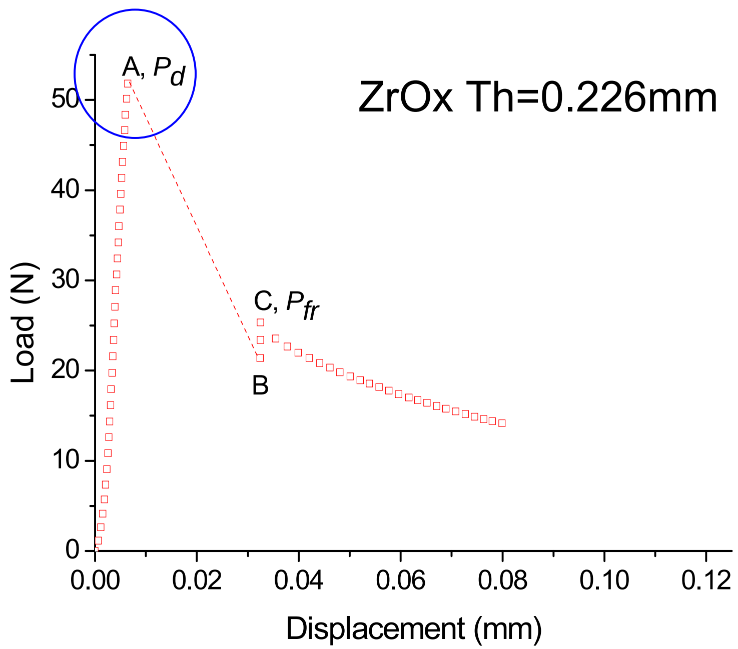
Interfacial shear strength, τ_d:

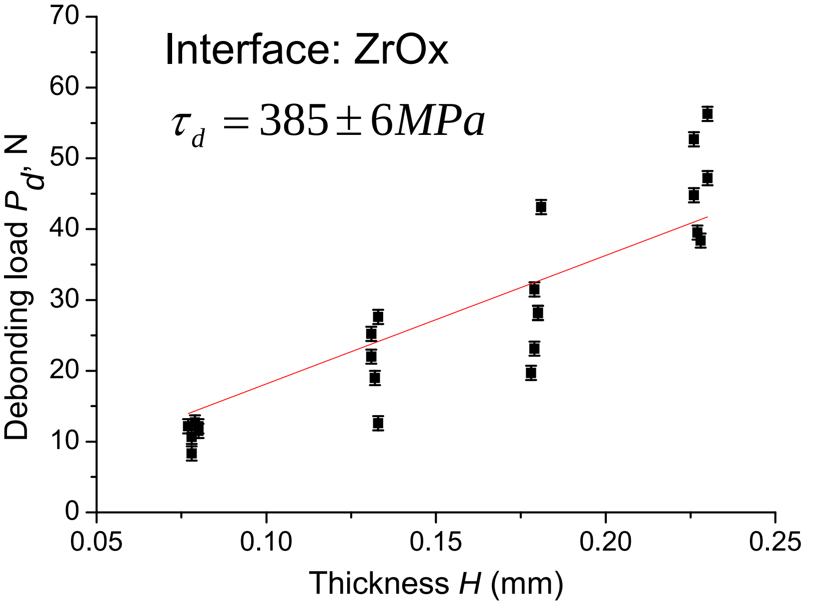
maximum average shear stress the bonded interface can afford.

$$P_d = \frac{\pi d_f \tau_d}{\alpha} \tanh(\alpha H) \quad \text{(Lawrence 1970)}$$

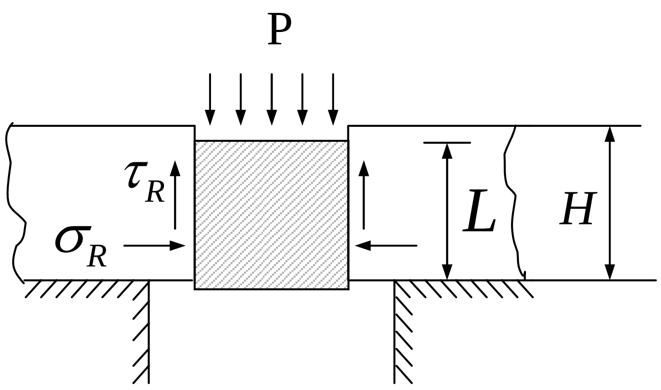
P_d : debonding load; d_f : fiber diameter

α : shear-lag parameter; H : embedded length.





Interfacial parameters calculation

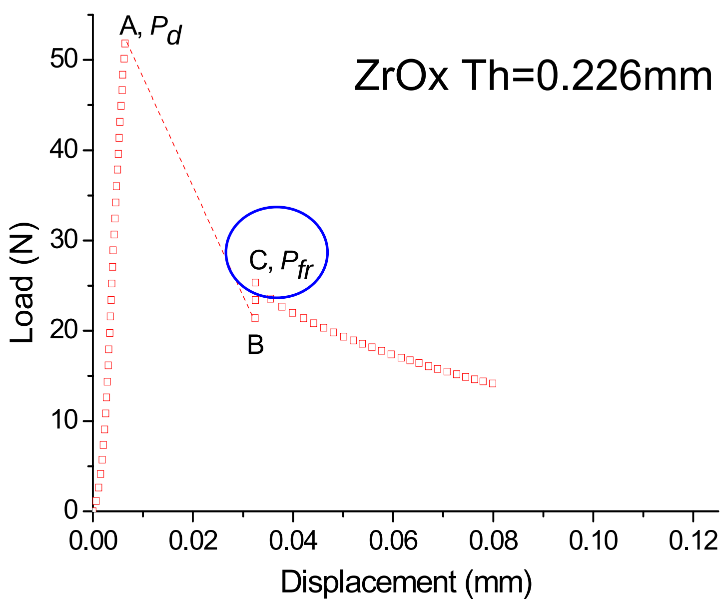


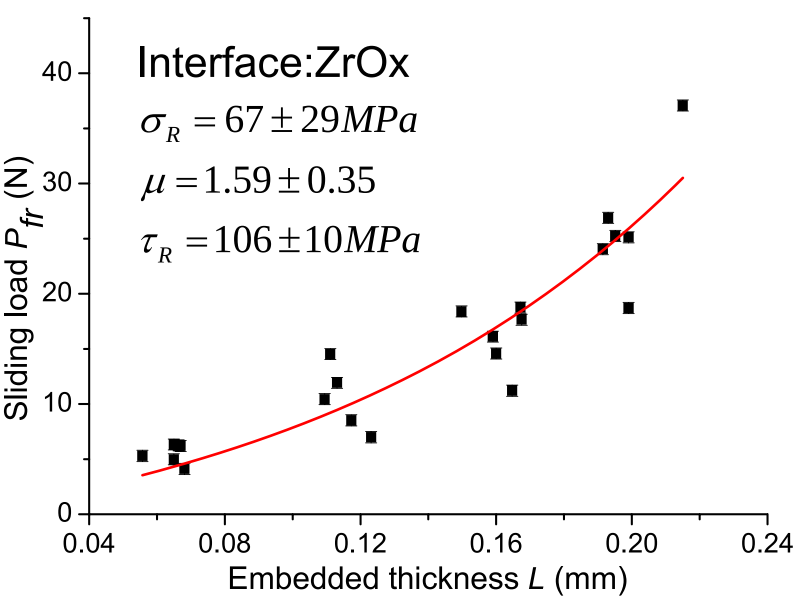
Roughness stress σ_R : radial stress due to mismatch of the surface asperity of a debonded interface; Friction coefficent μ :

$$P_{fr} = \frac{\pi r_f^2 \sigma_R}{k}[\exp(\frac{2\mu k L}{r_f})-1]$$ (Shetty, 1988)

P_{fr} : sliding load r_f : fiber diameter

k : elastic parameter L : embedded length





Interfacial parameters calculation

Interfacial fracture toughness G_i

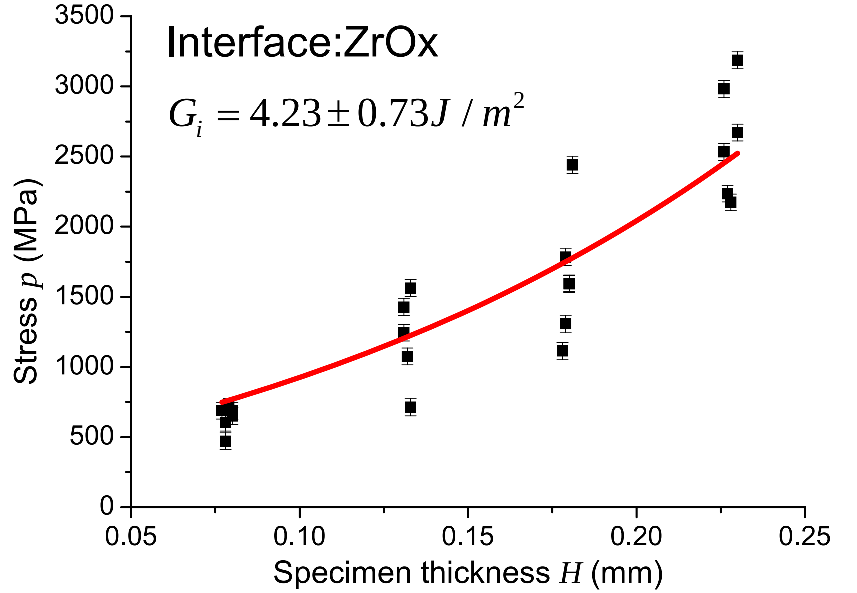
$$\frac{\text{Interface fracture energy } G_i}{\text{Fiber fracture energy } G_f} \le 0.25$$

$$p = 2\sqrt{\frac{G_i E_f}{B_2 R_f}}e^{\frac{2\mu B_1 H}{R_f}} + \frac{\tau_0}{\mu B_1}(e^{\frac{2\mu B_1 H}{R_f}} - 1)$$

(Liang,1993)

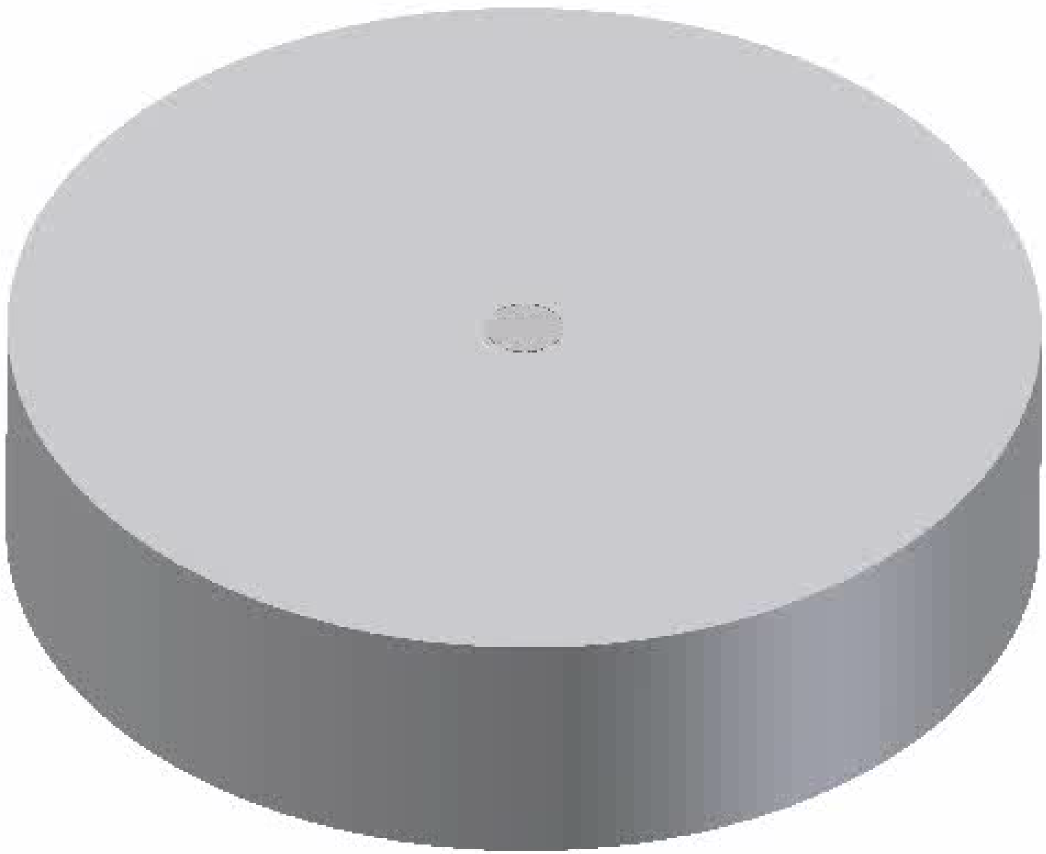
$$p = \frac{P_d}{\pi R_f^2}$$

H : Specimen thickness

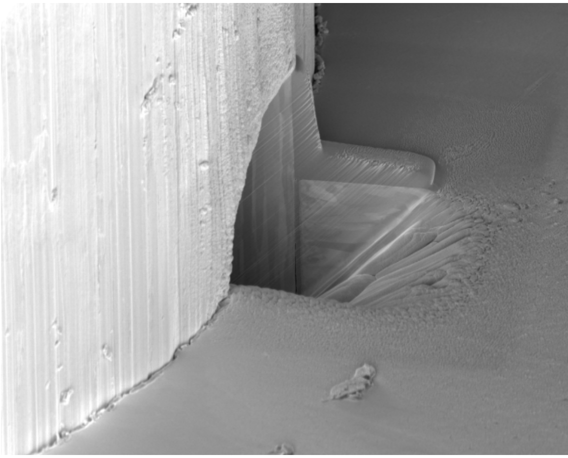


Interfaces	Debonding strength (MPa)	Asperity radial stress (MPa)	Friction coefficient,μ	Fracture toughness, Γ_i ($J*m^{-2}$)	G_i/G_f (G_f=320$J*m^{-2}$)
ZrO_x Single-layer	385±6	67±29	1.59±0.35	4.2±0.7	0.013
Zr/ZrO_x Multi-layer	362±2	117±57	1.22±0.34	3.5±1.0	0.011
W/Cu Multi-layer	429±6	123±21	0.81±0.09	22.2±3.1	0.068
Cu Single-layer	393±4	-	-	-	-

Microstructure analysis



Microstructure analysis



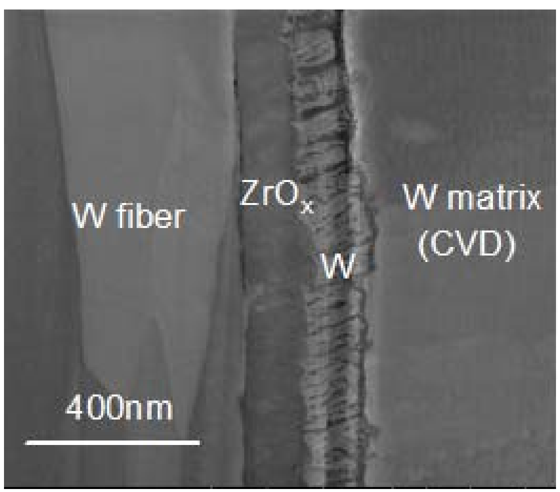
FIB cutting location

ZrOx mono-layer specimen:

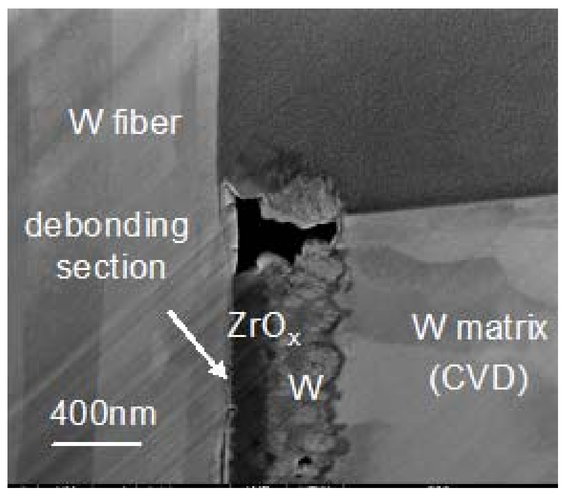
Debonding locations:

W fiber & ZrOx coating(MS)

W coating(MS) & W matrix(CVD)



Before push-out



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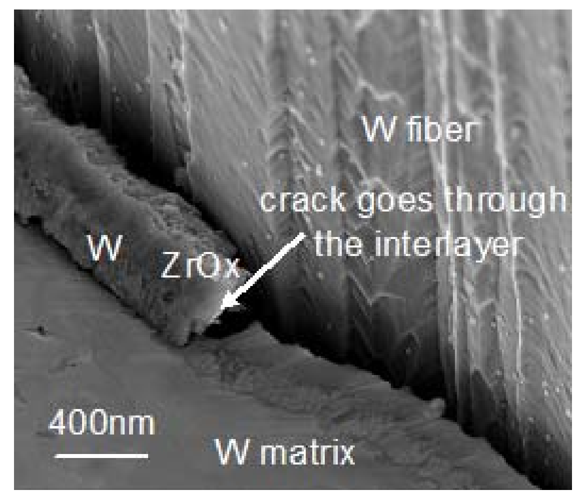

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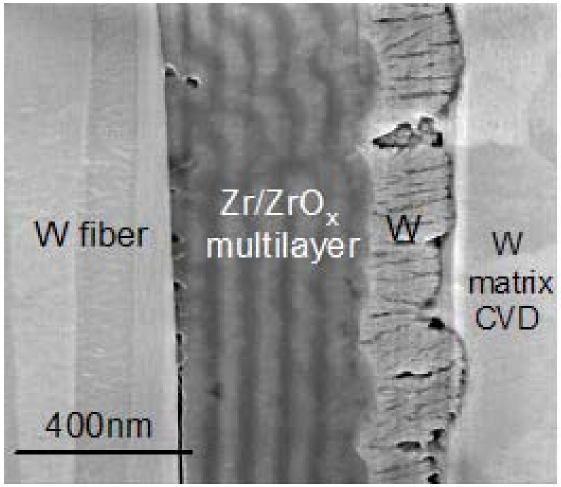


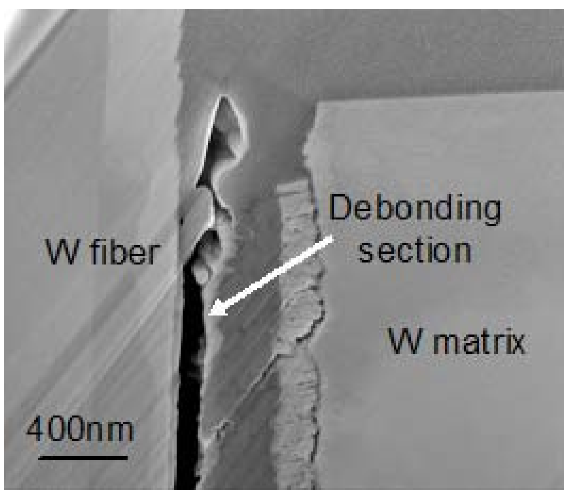
Before push-out

ZrOx/Zr multi-layer specimen:

Debonding locations:

W fiber & ZrOx/Zr coating(MS)

W coating(MS) & W matrix(CVD)



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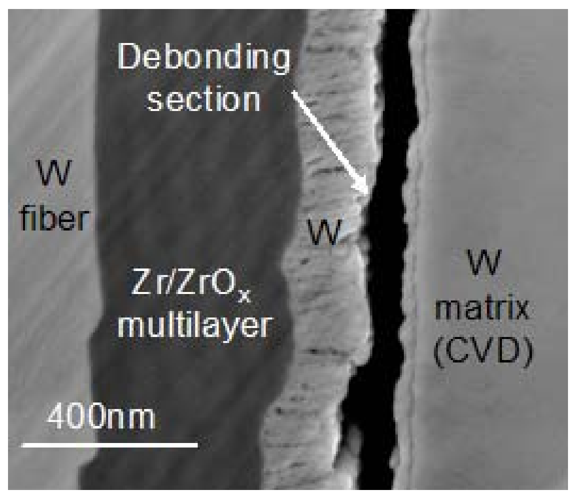

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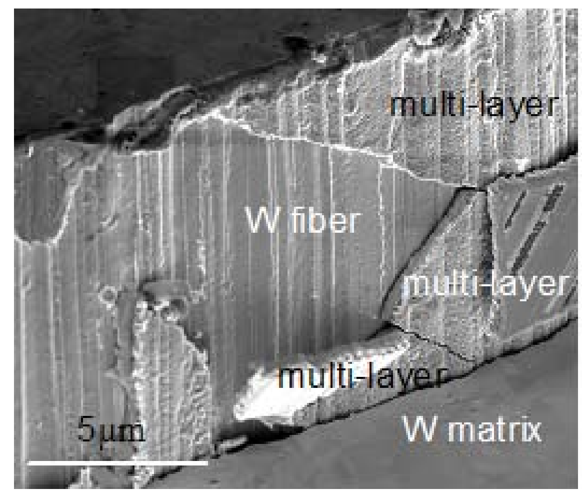

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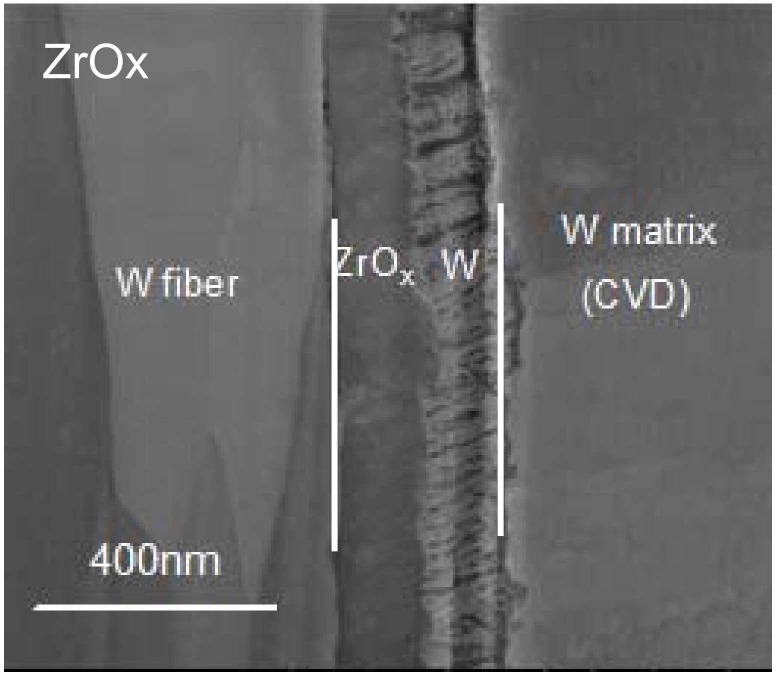

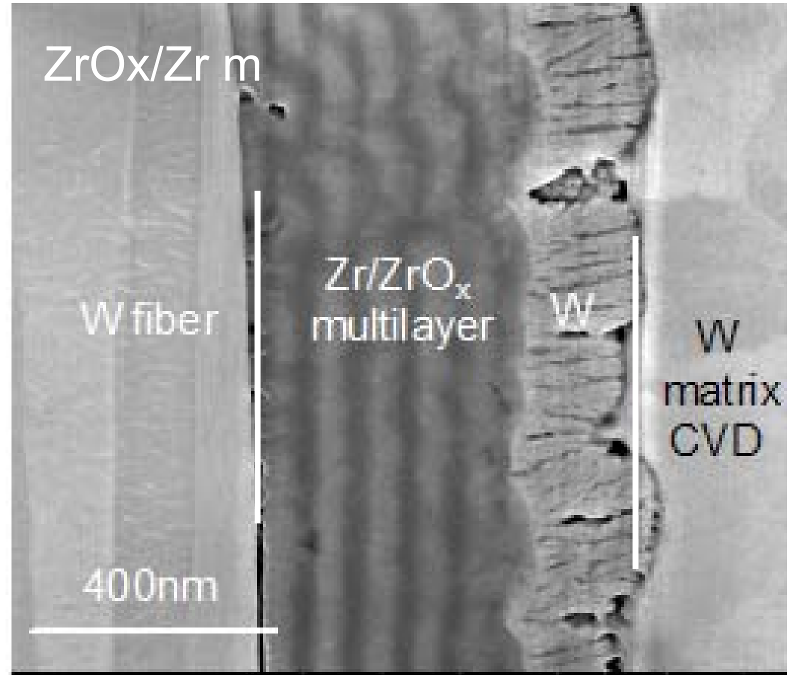

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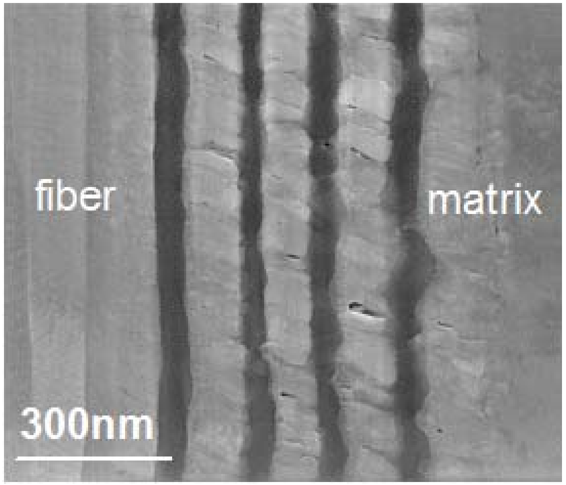
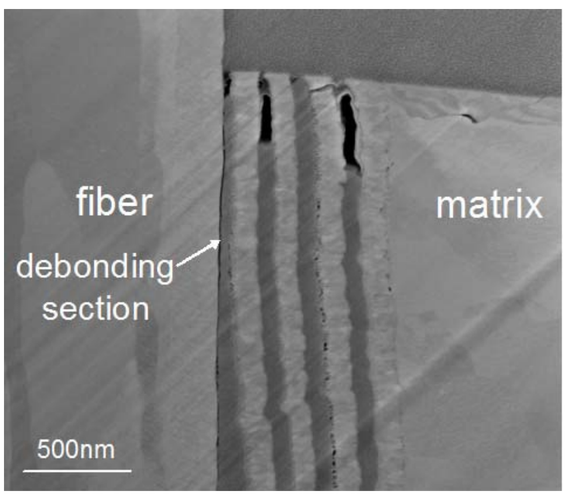


Before push-out

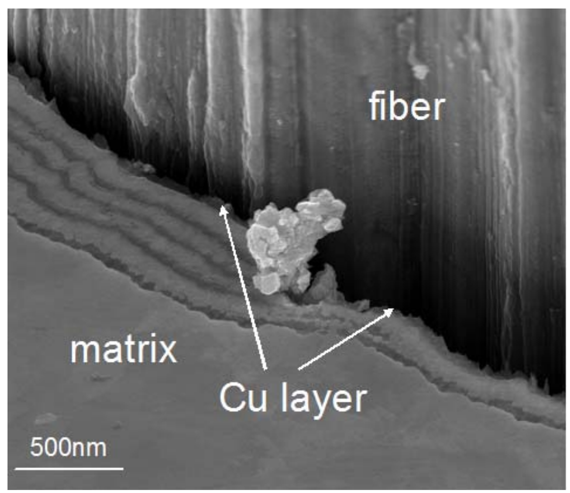
Cu/W multi-layer interface specimen:

Debonding locations:

One of the Cu layer



After push-out



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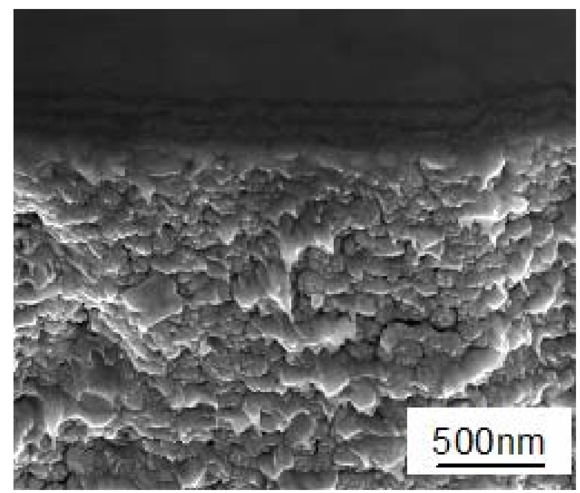
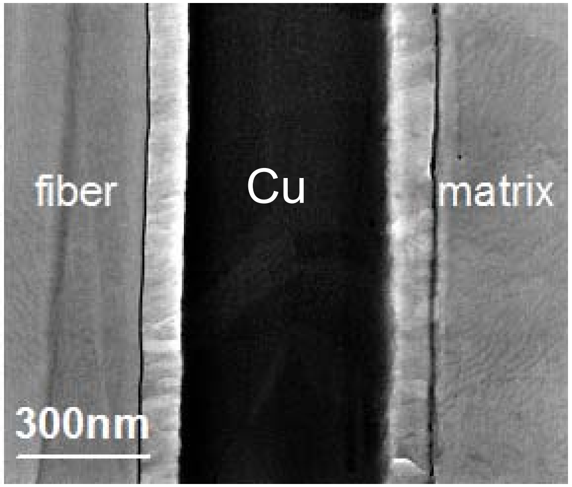


After push-out

Microstructure analysis



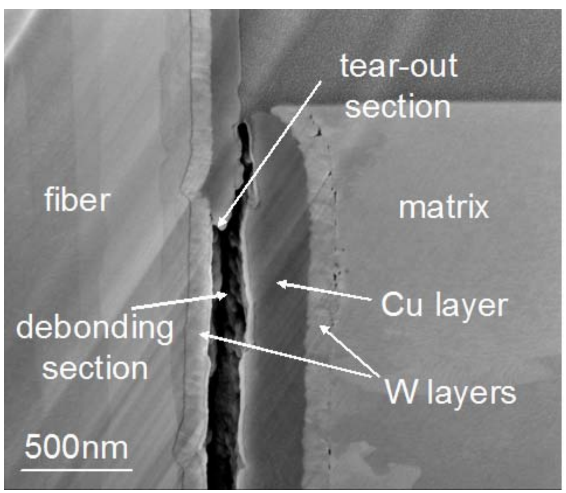
Before push-out

Cu single-layer interface specimen

Debonding locations:

In interlayer

For Cu based specimens, debonding happened mainly in Cu layer



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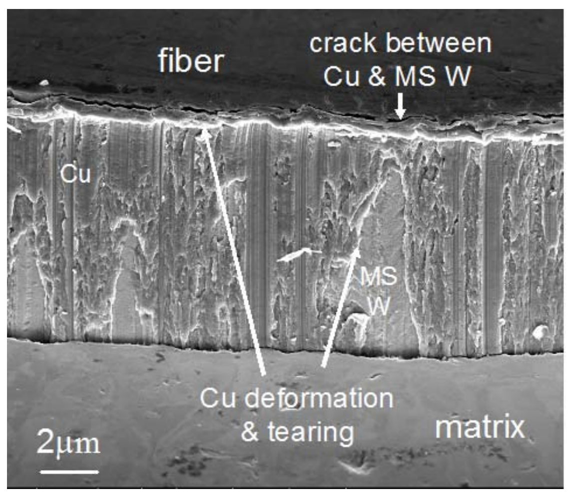

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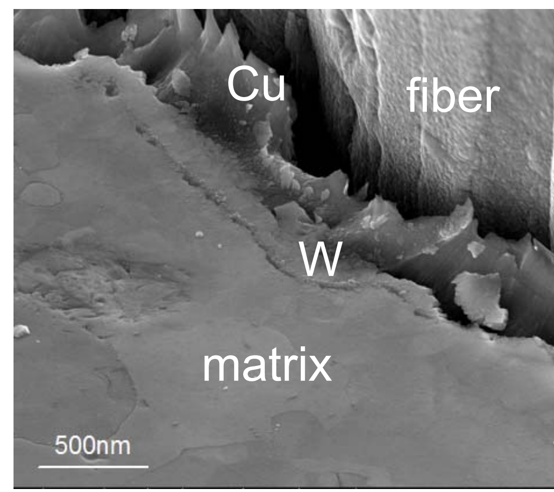
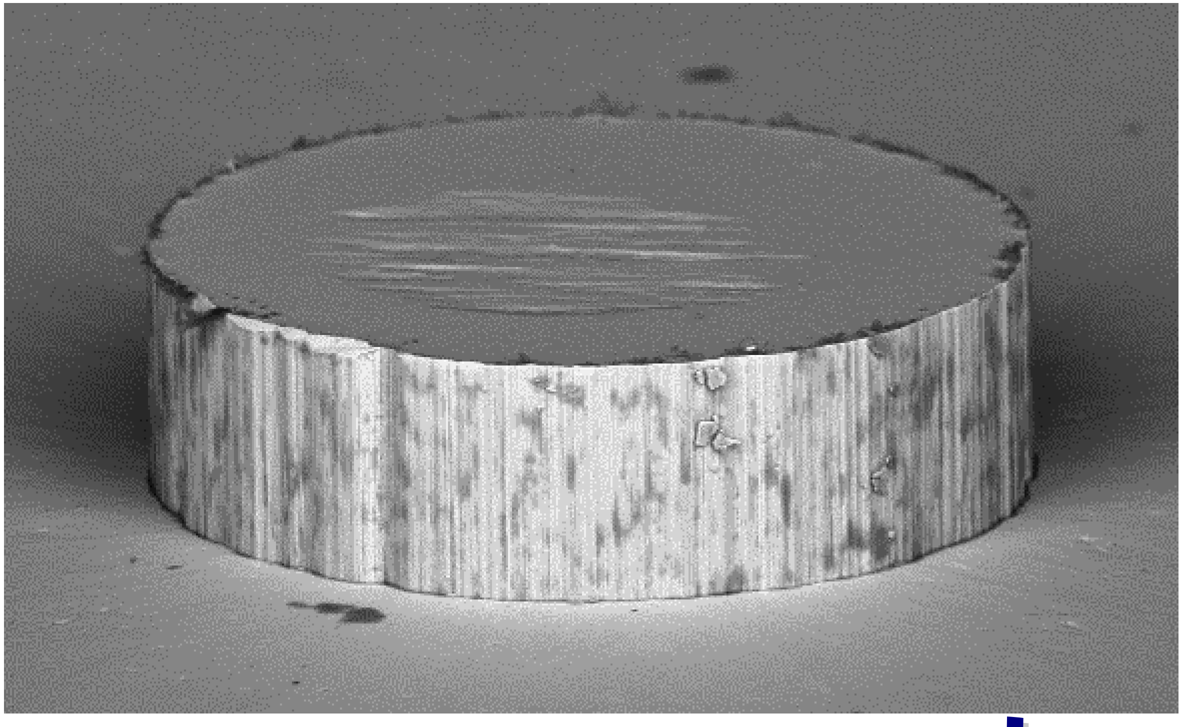


After push-out

Conclusion

- A novel concept of W_f/W composite was developed according to CMC mechanism.
- Different fiber/matrix interfaces were investigated by means of fiber push-out test.
- The estimated fracture energy values satisfied the crack deflection criterion so that interface debonding is preferred than fiber fracture.
- Microstructure investigation results also support the calculated values.



Thanks for your attention !