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SiC/SiC
Thermo-Physical Properties

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Issues

- Thermal conductivity:
  - Matrix, fiber, composite
  - Unirradiated, irradiated
- Elastic properties
- Plastic deformation
- (Thermal creep / static fatigue)
- (Cyclic fatigue)

Thermal Conductivity

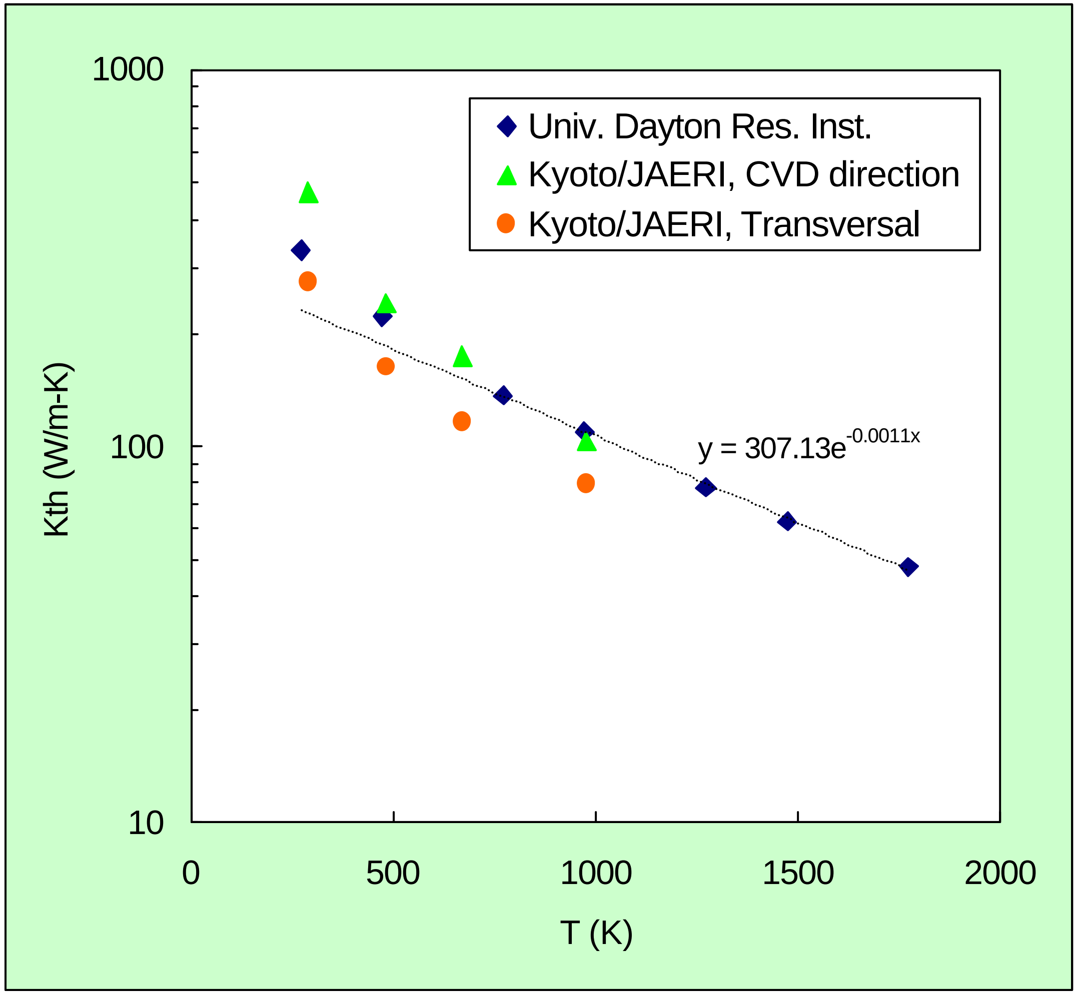
- Thermal conductivity of beta-SiC
    - Unirradiated thermal conductivity is generally well-understood.
    - Grain-boundary effects are being argued.

- Thermal conductivity of SiC fibers
    - Chemistry
    - Microstructure
    - Grain size

- Thermal conductivity of as-fabricated SiC/SiC composites
    - CVI-SiC/SiC
    - PIP-SiC/SiC
    - RS-SiC/SiC

- Irradiated thermal conductivity

Unirradiated Thermal Conductivity of Poly-3C-SiC



- Thermal conductivity of Morton CVD-SiC as a function of temperature.
- The unirradiated thermal conductivity in high-purity CVD-SiC appeared very anisotropic, in spite that grain size (5-10mm) is much larger than estimated phonon mean free path (10-25nm).

Unirradiated Thermal Conductivity of SiC/SiC

Fiber	Fabric	Matrix	Thru-thickness K_{th} @RT(W/m-K)	Ref.
NL	P/W	CVI-SiC	5-10	
Hi-NL			10-15	
Hi-NL	Felt	CVI-SiC	14 (10@1273K)	Yamada
Type-S			16 (13@1273K)	Yamada
MER-CVR		CVR-SiC	40	Senor, et al.
NL/Hi-NL	P/W	PIP-SiC	2-5	
Hi-NL	3D (1:1:0.2)	PIP-SiC	3.6 (4.5@1273K)	Yamada
Type-S			6.0 (6.5@1273K)	Yamada
Hi-NL	Braid	RS-SiC	30	Toshiba

TyrannoHex(SA)	45-90	Morton CVD-SiC	270-450

- ◆ High unirradiated thermal conductivity in RS-SiC/SiC is promising.
- ◆ PIP-SiC/SiC will substantially improve thermal conductivity by high temperature processes, which is under development.
- ◆ 3D fiber architecture will improve the through-thickness thermal conductivity for all the processes. The 3D fabric configuration can currently be tailored within x:y:z = 1:1:0.1 to 1:1:4.

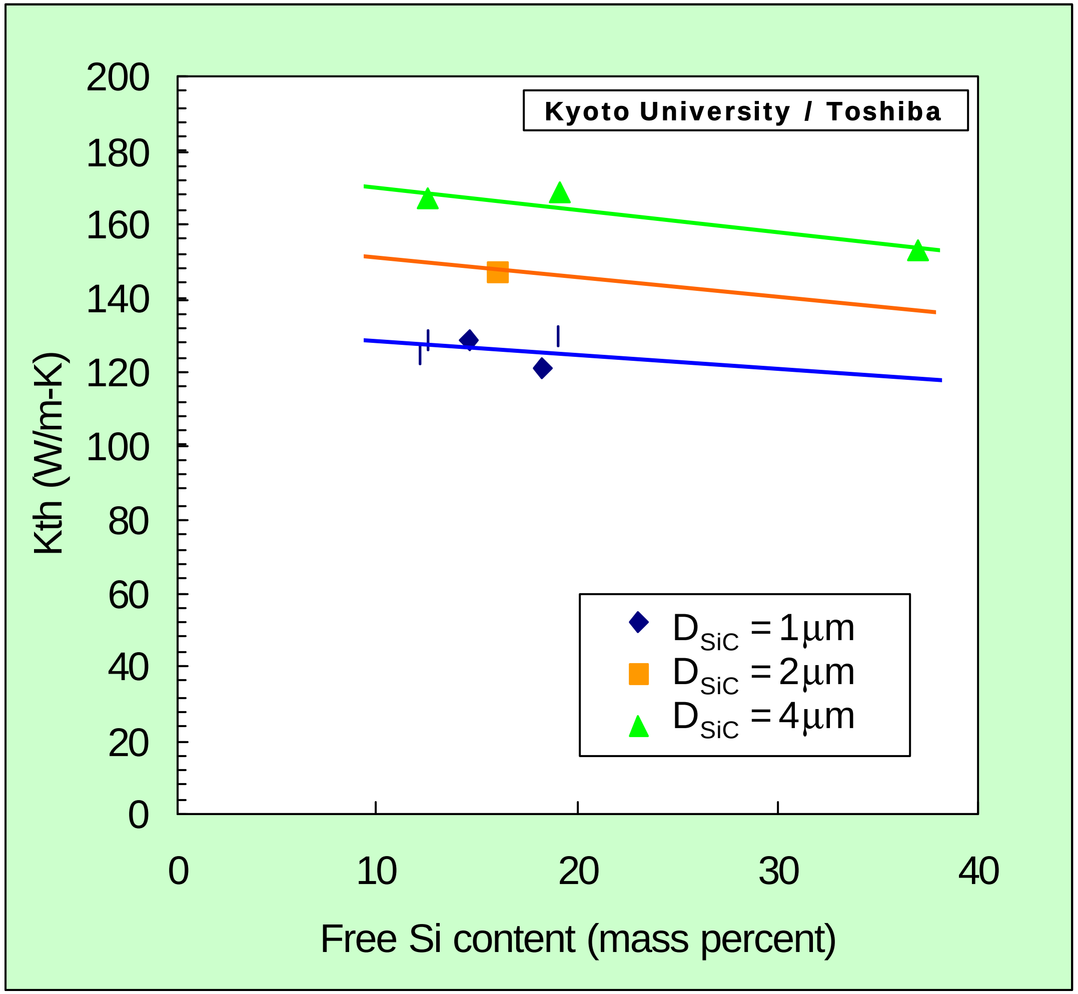
Thermal Conductivity of Polymer-derived SiC

Kyoto University / Ube Industries

Material System	Pyrolyzing Condition	C/Si (atomic ratio)	Density (Mg/m^3)	K_{th} (W/m-K)
Si-Ti-C-O	1573K in Ar	Data not available		
	2073K in Ar	1.65	2.68	11.2
Si-Zr-C-O	1573K in Ar	1.63	2.54	4.3
	2073K in Air	1.55	2.75	26.1
	1273K in H_2 2073K in Ar	1.10	2.93	37.2

- ◆ Enhanced crystallization by high temperature pyrolysis greatly improves thermal conductivity of polymer-derived SiC.
- ◆ Reduced glassy phase fraction through deoxidation further improves thermal conductivity.

Thermal Conductivity of Rection-sintered SiC

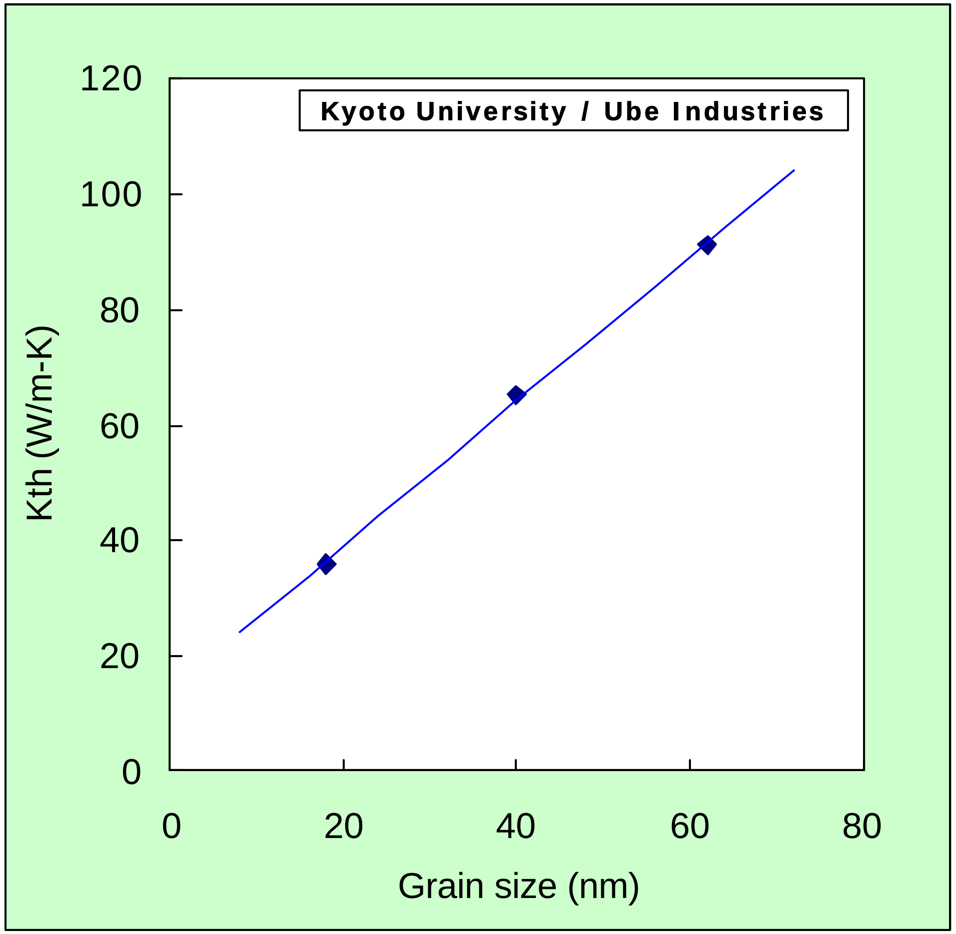


- Thermal conductivity of RS-SiC appears :
  - nearly independent of free Si amount.
  - determined by SiC powder filler size.
- Pore-free matrix in RS-SiC/SiC promises high thermal conductivity.

Properties of Commercial SiC Fibers

	Nicalon™			Tyranno™				
	NL-201	Hi-NL	Type-S	TE	ZE	AM	SA	SA-B
C/Si	1.34	1.39	1.05	1.37	1.48	1.48	1.08	1.08
Other elements (mass %)	10.1% O	0.5% O	0.2% O	10.2% O 2% Ti	1.7% O 1% Zr	12.0% O <2% Al	< 0.3% O < 2% Al	< 0.3% O < 2% Al
Tensile strength (GPa)	2.9	2.8	2.6	3.3	3.5	2.8	2.8	3.5
Tensile modulus (GPa)	205	270	420	190	230	180	420	280(?)
Elongation (%)	1.4	1.0	0.6	1.8	1.5	1.6	0.7	1.0
Mass density (Mg/m^3)	2.55	2.74	3.10	2.48	2.55	2.42	3.02	3.02
Diameter	14	14	12	11	13	11	10	7.5
Filament/yarn	500	500	500	800	400	800	800	1600
Crystallite size (nm)	< 2	5-10	50	2	2	< 2	> 200	50-100
Thermal cond. (W/m-K)	**1.45**	**7.9**	**18.4**	**1.35**	**3.78**	**N/A**	**65**	**65**

Thermal Conductivity of Stoichiometric SiC Fibers



- Grain sizes determined by XRD.
- Thermal conductivity of Tyranno-SA fiber can be tailored within a range of 30 – 100 W/m-K.
- Improved thermal conductivity requires larger grain sizes. This leads to :
  - Improved creep resistance.
  - Enhanced surface roughness.
  - Reduced tensile strength.
  - Reduced weavability.

Thermal Conductivity – C/C Composites

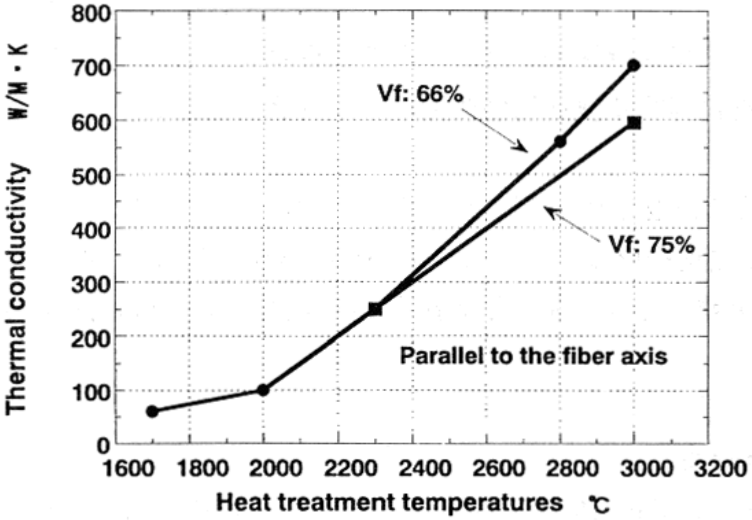
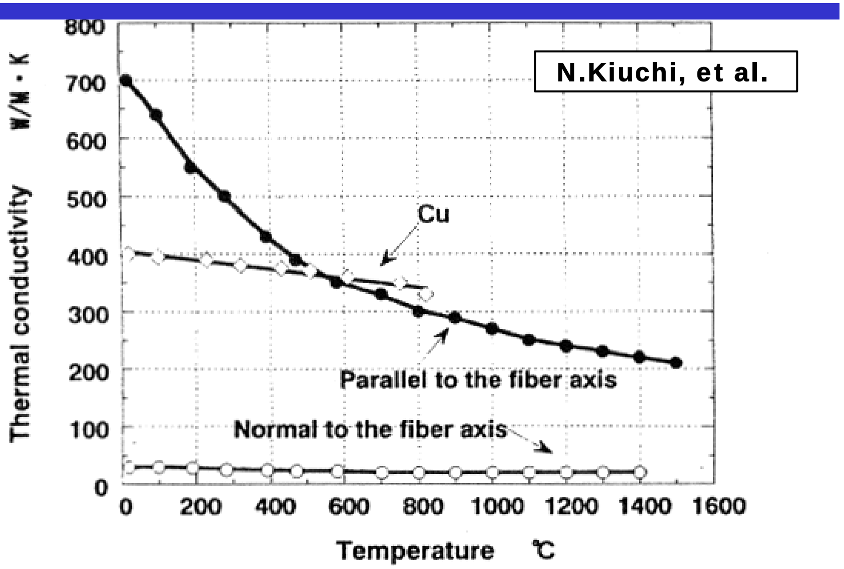


Fig. 6 The effect of heat treatment temperature on thermal conductivity of UD-C/C composites



N.Kiuchi, et al.

Fig. 7 The thermal conductivity of UD-C/C composites

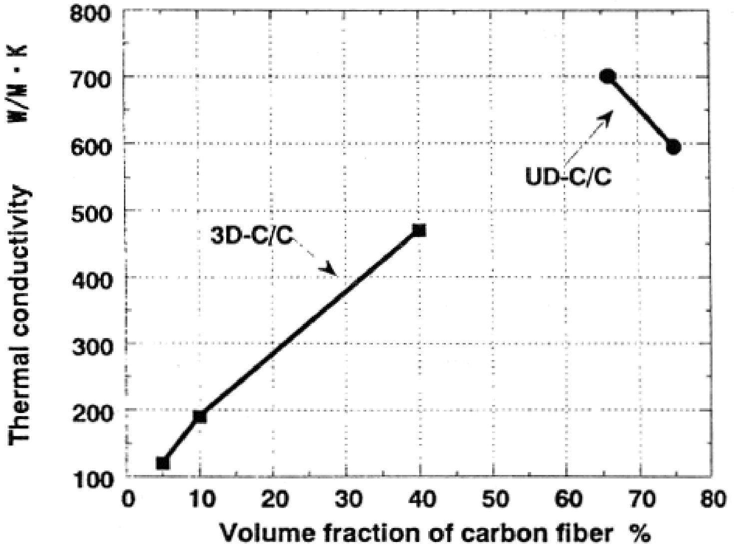


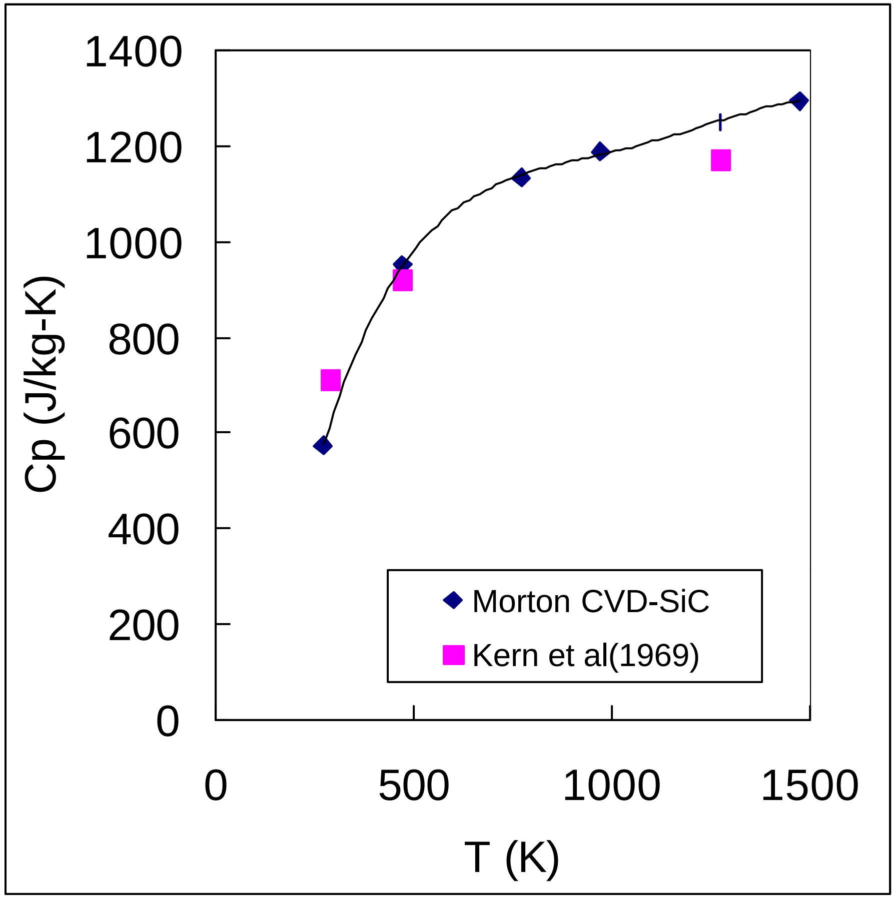
Fig. 8 The effect of Vf on thermal conductivity of C/C composites at room temperature

- The materials are XN-70A / pitch-derived matrix composites.
- Enhanced crystallization in pitch-based carbon fiber improves thermal conductivity.
- When fibers are the primary heat-transfer media, 3D fiber architecture is the quickest way to control the anisotropic thermal conductivity of the composite.

Thermal Conductivity - Summary

- ‘Bulk’(=pore-free) thermal conductivity of CVI-, RS- and improved (near stoichiometry and high temperature-pyrolized) PIP-produced matrix will not be very different. Irradiation effect should further shadow the differences in bulk thermal conductivity.
- Thermal conductivity of stoichiometric crystalline SiC fiber may fall on somewhere around 50W/m-K. Further improvement is feasible but will sacrifices the mechanical properties.
- Given the fibers and the matrix with reasonable bulk thermal conductivity, irradiated thermal conductivity of the composite will be determined by the reinforcement architecture, matrix pores and F-M interface integrity.
- Thermal conductivity of the 3D-composites can easily be tailored, compromising the mechanical properties.

Specific Heat of 3C-SiC



- Specific heat of SiC/SiC composites for fusion should be very close to that of bulk 3C-SiC.

Elastic Properties

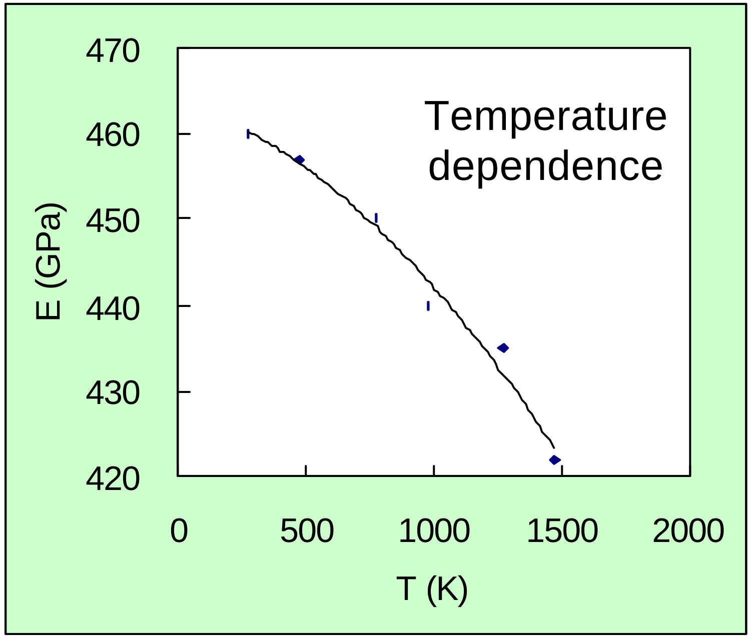
- Comparison of elastic properties of SiC/SiC composites produced by various processes
- Effective elastic modulus in cyclic loading conditions
- Proportional limit
- Irradiation effects

Initial Elastic Properties of SiC/SiC

Material			Elastic modulus
Fiber	Architecture	Matrix	
CG-NL/Hi-NL	2D-P/W	CVI-SiC	E ~ 200GPa
Tyranno-TE Hi-NL	2D-P/W	PCS-PIP-SiC (T_{py}=1473K)	E=30 ~ 100GPa
Hi-NL	U/D	PVS-PIP-SiC (T_{py}=1473K)	E ~ 200GPa
Tyranno-SA	U/D	PVS-PIP-SiC (T_{py}=2073K)	E ~ 300GPa
Hi-NL	Braid	RS-SiC	E=250 ~ 300GPa

Bulk and fiber data

Morton CVD-SiC	E=460GPa
PCS-derived SiC (T_{py}=1473K)	E=100 ~ 200GPa
RS-SiC	E ~ 400GPa
CG-NL / Hi-NL	E=205/270/420GPa
Tyranno-SA / Type-S	E=420GPa



Effective Elastic Modulus

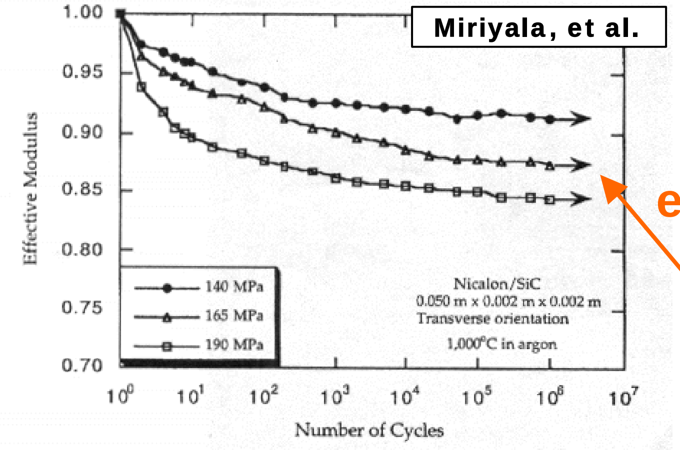


Fig. 7. The reduction in effective modulus due to fatigue in the transverse orientation of the Nicalon/SiC composite at 1000°C in argon.

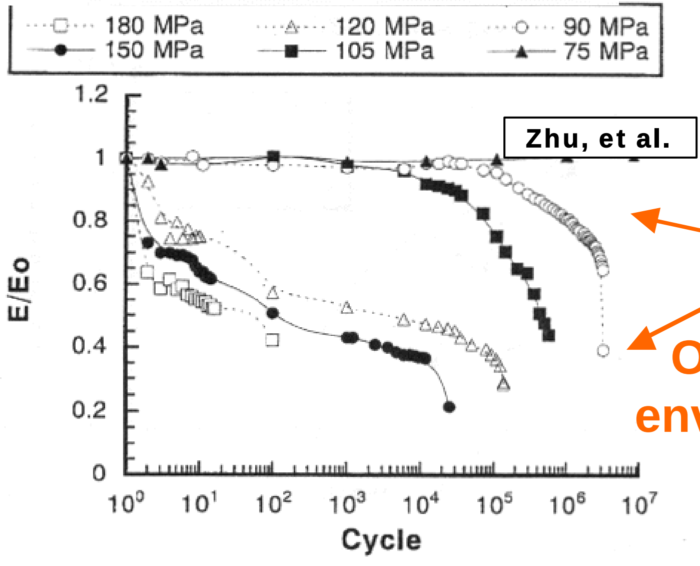


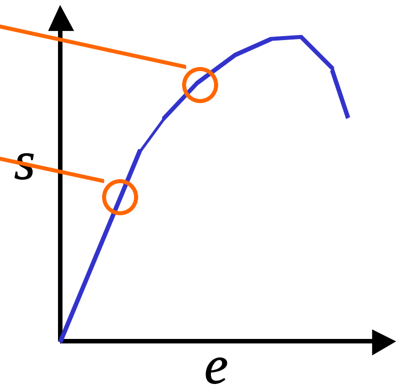
Fig. 11. Elastic modulus normalized by the value of the modulus under the first loading (*E*/*Eo*) versus fatigue cycles of Hi-Nicalon^{TM}/SiC in air at 1300°C under different maximum stresses.

Inert environment

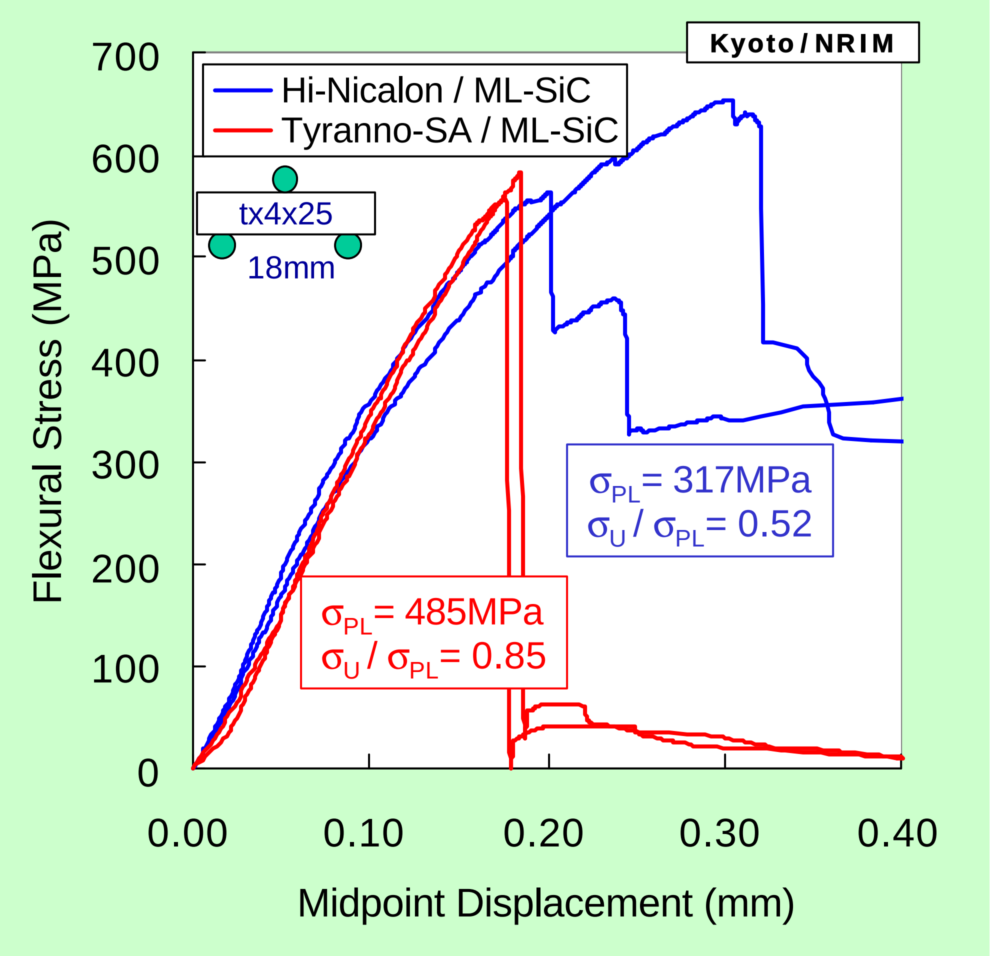
Oxidizing environment

◆ Effective elastic modulus depends on :

- Composite design
- Load to be cycled
- Environment



Proportional Limit



- The ratio of proportional limit to the ultimate strength in SiC/C/SiC composites can be tailored by controlling the fiber surface roughness, chemistry and F-M interphase thickness.
- The higher proportional limit may lead to reduced elongation.
- The influences of swelling and creep need to be accounted in irradiation environment.

Stress-Strain Behavior Beyond Proportional Limit

- The stress-strain behavior of SiC/SiC composites beyond the proportional limit depends on various material parameters (controllable), loading condition and environment.
- The present SiC/C/SiC system should be used below the proportional limit, mainly because the fatigue property beyond the proportional limit in ‘nominally inert’ environment is not predictable.
- Effects of neutron irradiation to high fluences needs to be addressed.