



## STRUCTURES AND PROPERTIES OF THE REFRACTORY SILICIDES $Ti_5Si_3$ AND $TiSi_2$ AND $Ti-Si-(Al)$ EUTECTIC ALLOYS

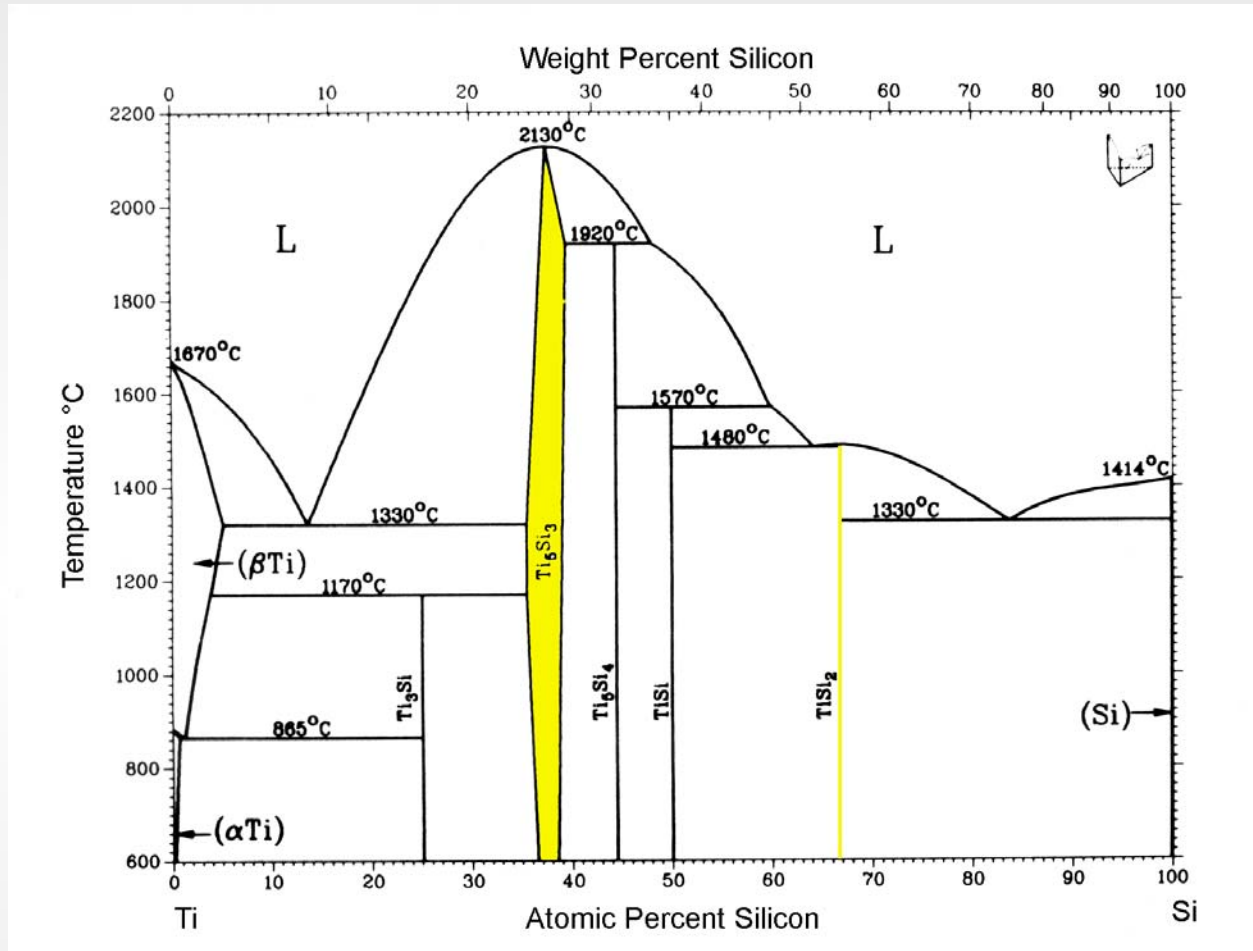
- ⊕ Introduction
  - ⊕ Constitution of the binary phase diagram  $TiSi$
  - ⊕ Intermetallic compounds  $Ti_5Si_3$  and  $TiSi_2$ 
    - ✧ Lattice structures, binding energies
    - ✧ Microstructures
      - optical and TEM images
    - ✧ Physical properties
      - thermal expansion coefficient  $\alpha(T)$
      - elastic moduli  $E, G, K$
    - ✧ Mechanical properties
      - flow stress
      - fracture toughness
      - creep properties
  - ✧ Applications
- } temperatur-dependent
- ⊕ Hypoeutectic and directionally solidified eutectic  $\alpha-Ti-Ti_5Si_3$  alloy
    - ✧ Microstructures
      - optical and SEM images
    - ✧ Physical properties
      - thermal expansion coefficient  $\alpha(T)$
      - Young's moduli  $E(T)$
    - ✧ Mechanical properties
      - yield stress
      - fracture toughness
  - ⊕ Conclusions

# Report Documentation Page

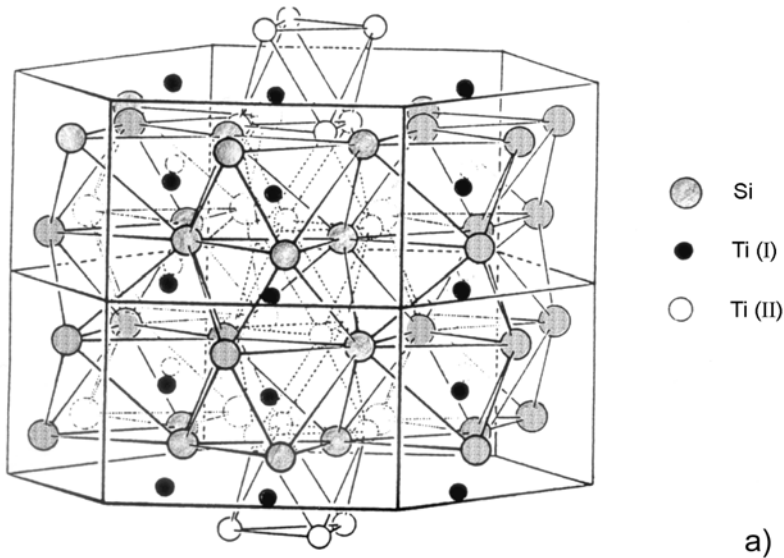
*Form Approved*  
*OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE <b>18 MAR 2004</b>	2. REPORT TYPE <b>N/A</b>	3. DATES COVERED <b>-</b>	
4. TITLE AND SUBTITLE <b>Structures and Properties of the Refractory Silicides Ti5Si3 and TiSi2 and Related Ti-Si-(Al) Eutectic Alloys</b>		5a. CONTRACT NUMBER	
		5b. GRANT NUMBER	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)		5d. PROJECT NUMBER	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Max-Planck Institute, Germany</b>		8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)	
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release, distribution unlimited</b>			
13. SUPPLEMENTARY NOTES <b>See also ADM001672., The original document contains color images.</b>			
14. ABSTRACT			
15. SUBJECT TERMS			
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT
a. REPORT <b>NATO/unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>	<b>UU</b>
			18. NUMBER OF PAGES <b>21</b>
			19a. NAME OF RESPONSIBLE PERSON



Equilibrium phase diagram of the binary Ti-Si system



Crystal structures of the intermetallic and compounds.

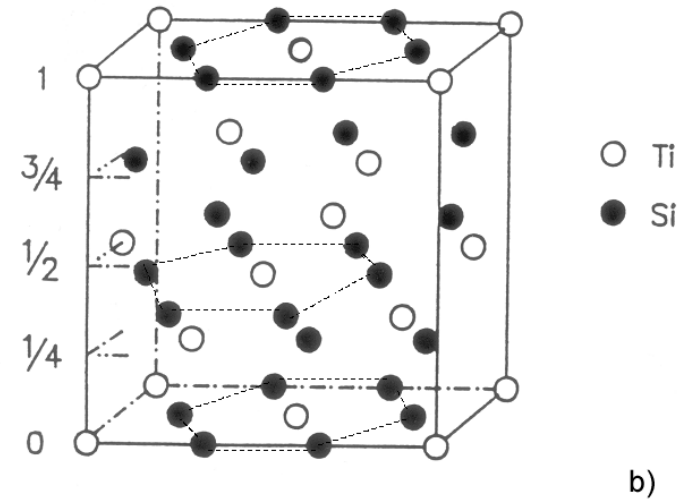
complex hexagonal  $D8_8$

lattice parameters

$a = 0.514 \text{ nm}$

$c = 0.744 \text{ nm}$

$N = 16$  per unit cell



orthorhombic  $C 54$

lattice parameters

$a = 0.8267 \text{ nm}$

$b = 0.4800 \text{ nm}$

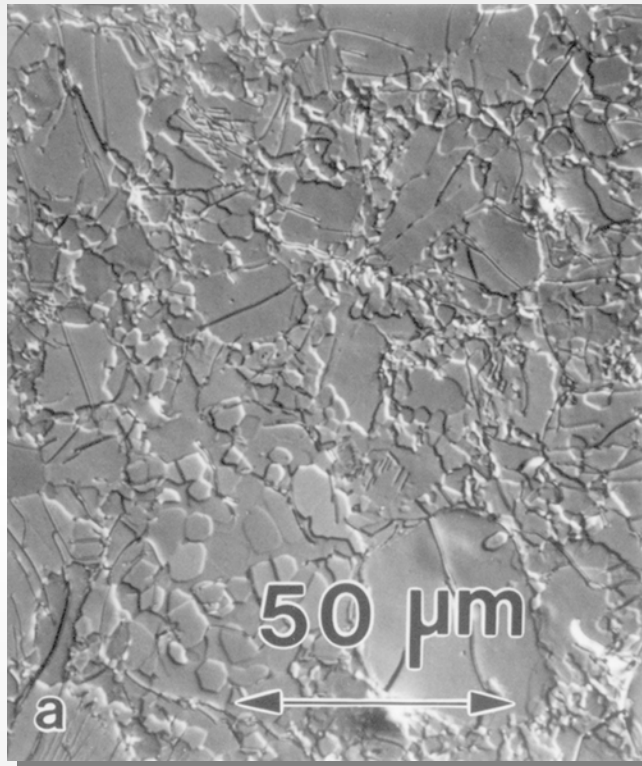
$c = 0.855 \text{ nm}$

$N = 24$  per unit cell

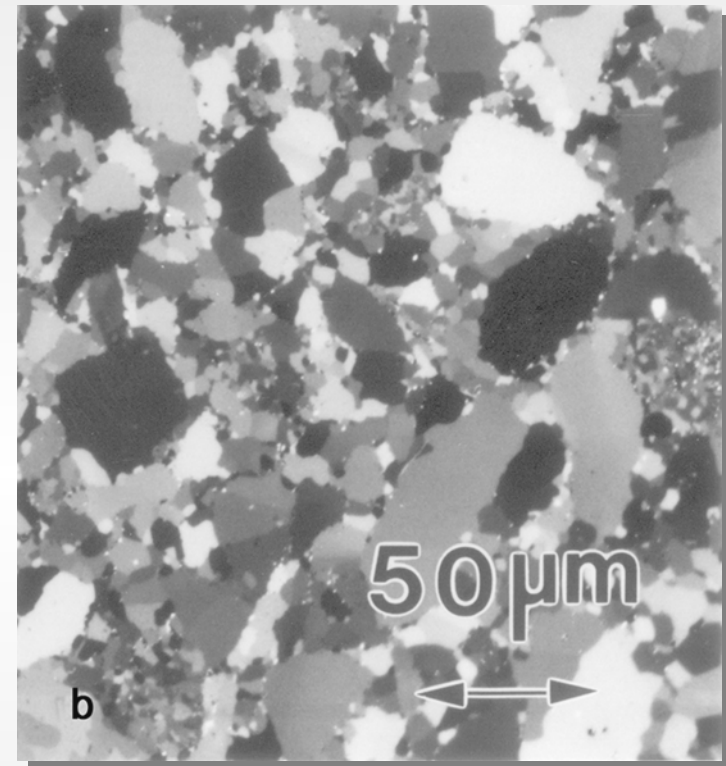


	<b>binding energy (kJ/mole)</b>	<b>melting temperature (K)</b>	<b>Vickers' hardness (load : 1kp) (HV1)</b>
<b>Ti<sub>5</sub>Si<sub>3</sub></b>	<b>- 1095 ± 40</b>	<b>2403</b>	<b>970 ± 20</b>
<b>TiSi<sub>2</sub></b>	<b>- 687,5 ± 25</b>	<b>1753</b>	<b>870 ± 15</b>

Relation between binding energy, melting temperature and Vickers' hardness

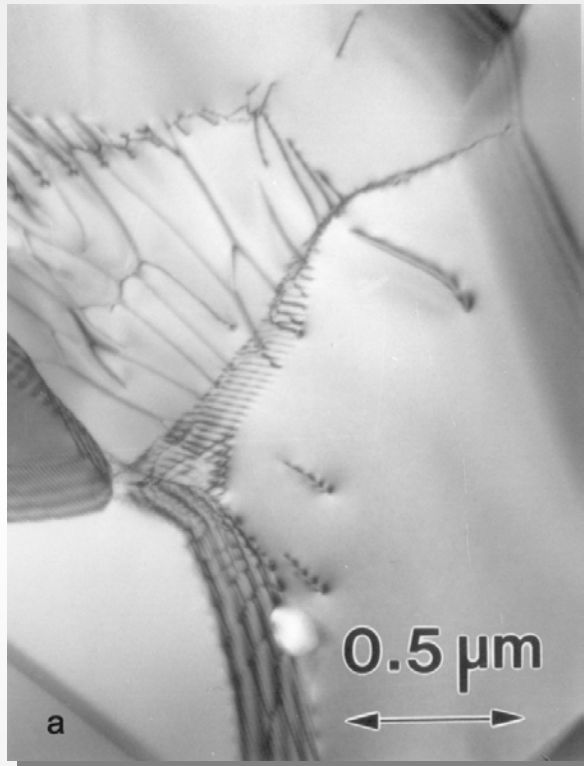


$Ti_5Si_3$

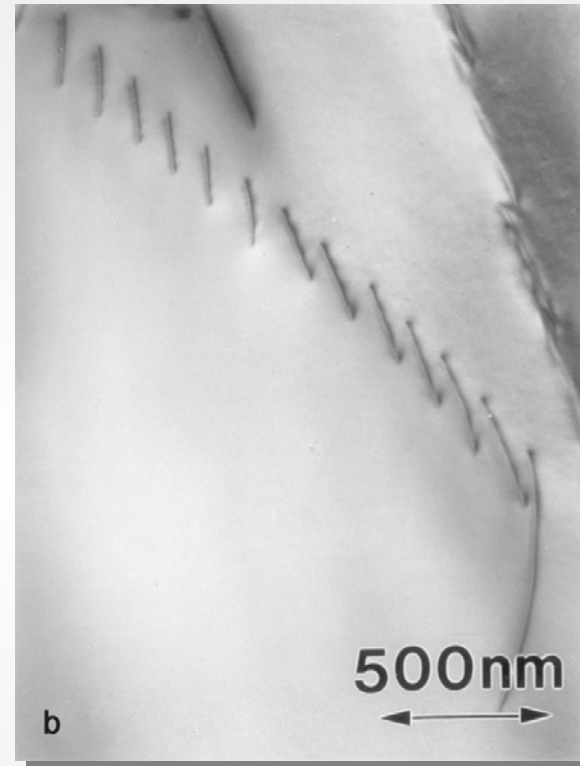


$TiSi_2$

Optical micrographs of as compacted compounds

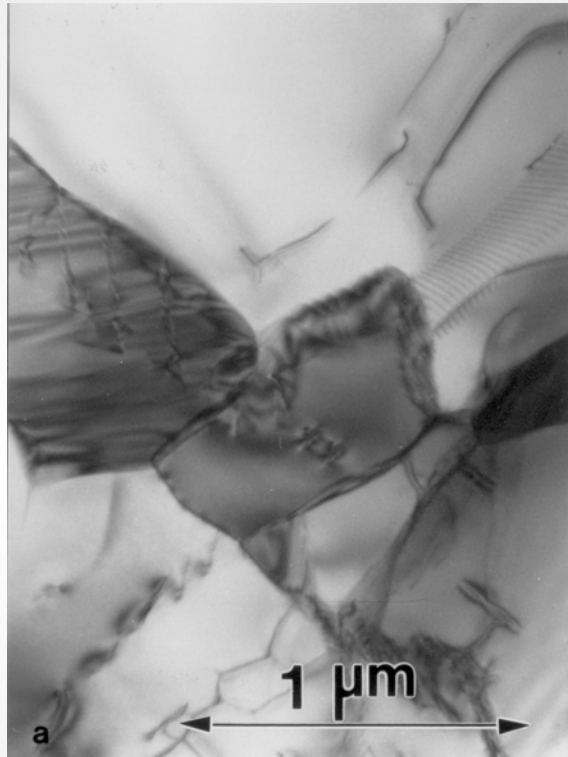


$\text{Ti}_5\text{Si}_3$

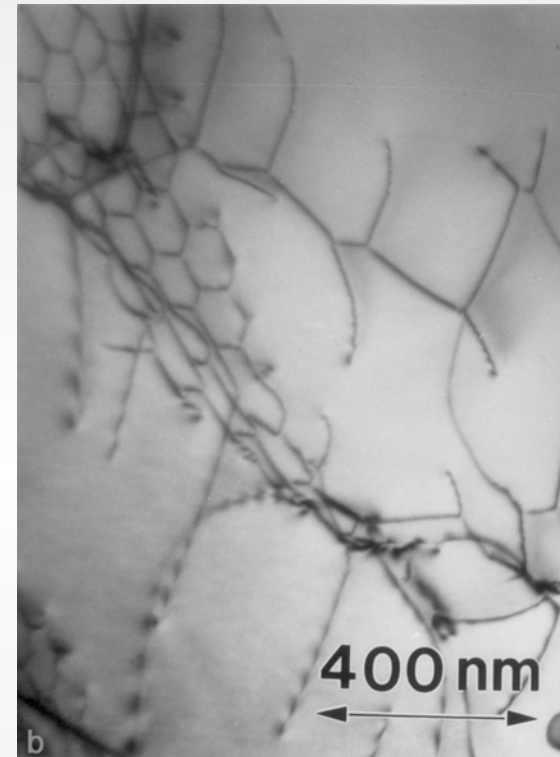


$\text{TiSi}_2$

TEM bright field images illustrating the dislocation structures in the as compacted samples



$\text{Ti}_5\text{Si}_3$



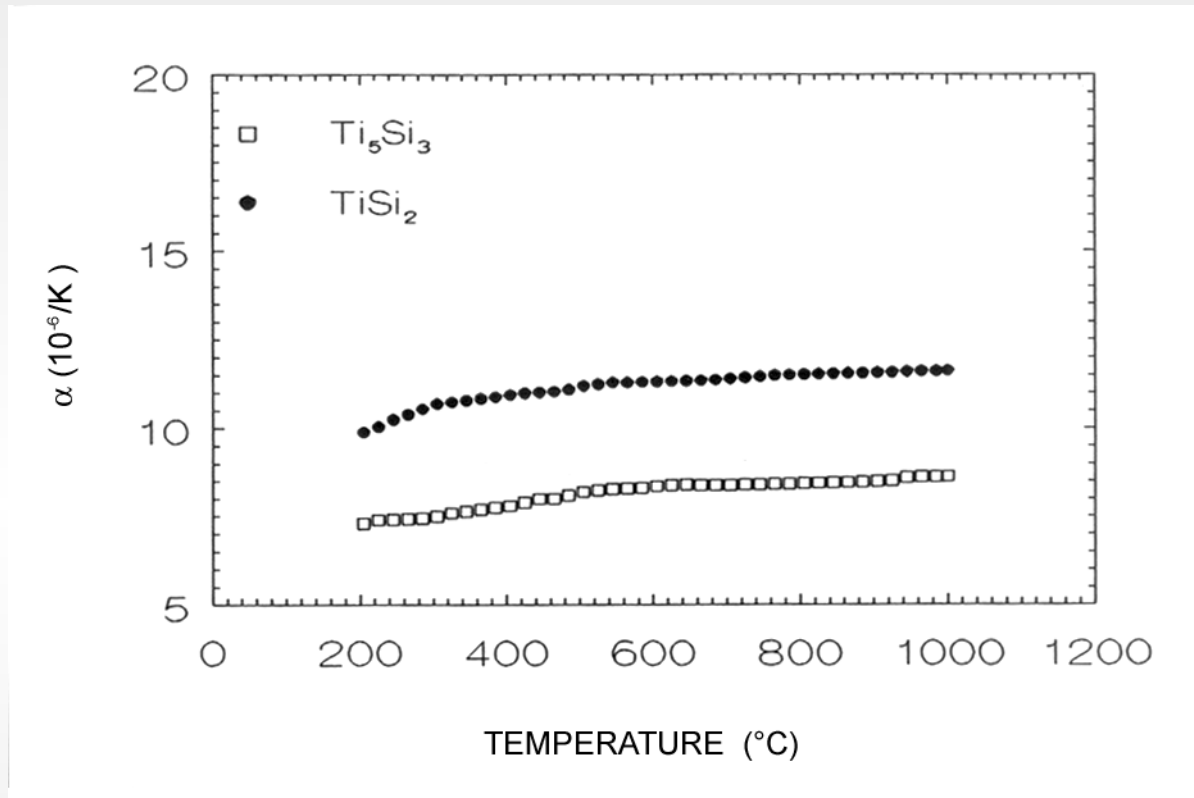
$\text{TiSi}_2$

TEM bright field images of creep deformed  
samples tested at 1000 °C, strain rate  $\dot{\epsilon} = 10^{-7} \text{s}^{-1}$

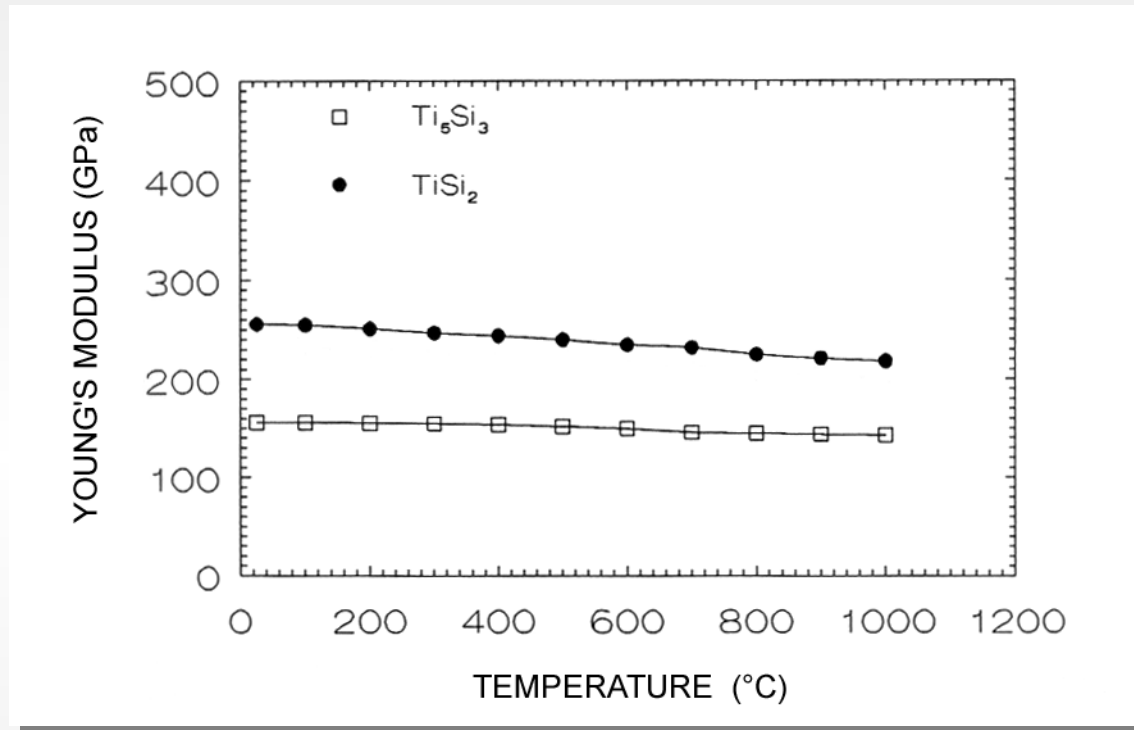


	<b>bulk modulus K(GPa)</b>	<b>Young's modulus E(GPa)</b>	<b>shear modulus G(GPa)</b>
<b>Ti<sub>5</sub>Si<sub>3</sub></b>	<b>110 ± 5</b>	<b>156 ± 8</b>	<b>61 ± 3</b>
<b>TiSi<sub>2</sub></b>	<b>125 ± 8</b>	<b>256 ± 10</b>	<b>103 ± 5</b>

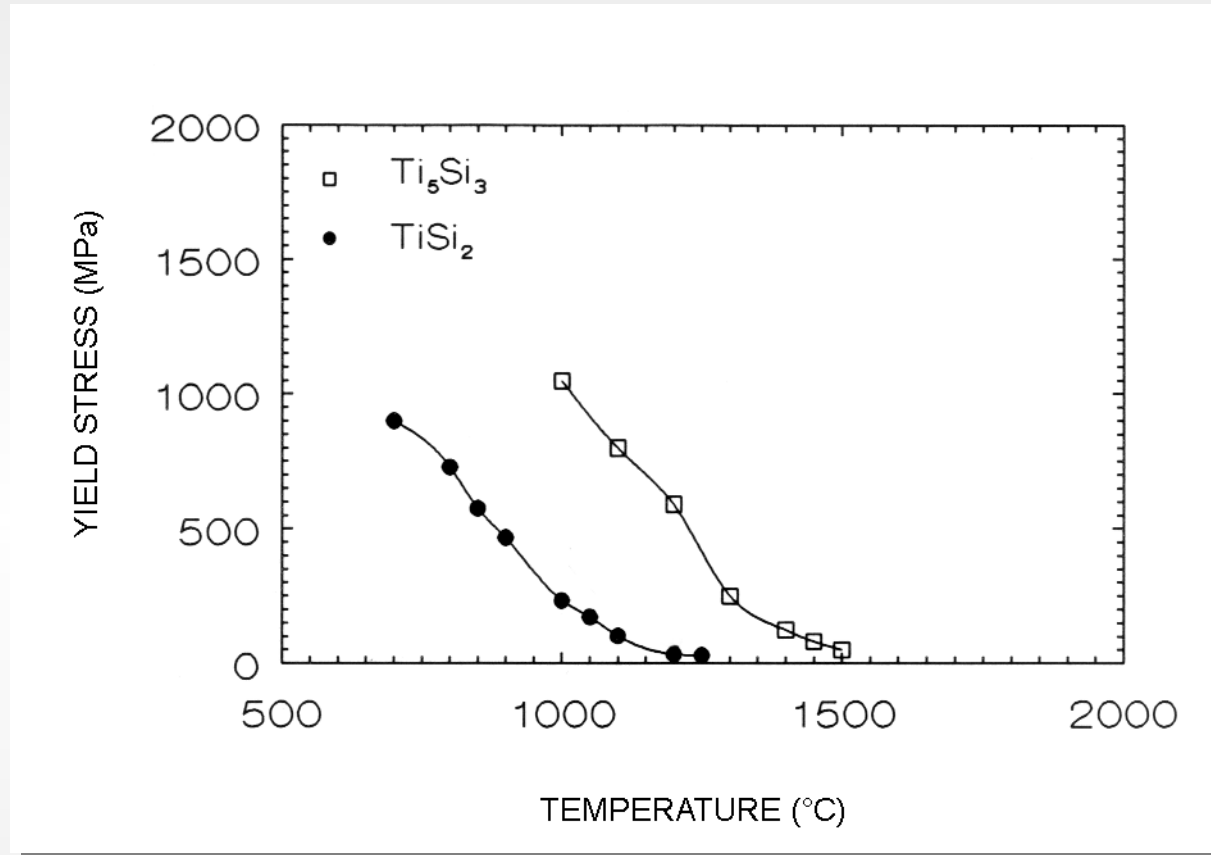
Elastic moduli K, E, G of Ti<sub>5</sub>Si<sub>3</sub> and TiSi<sub>2</sub> at room temperature



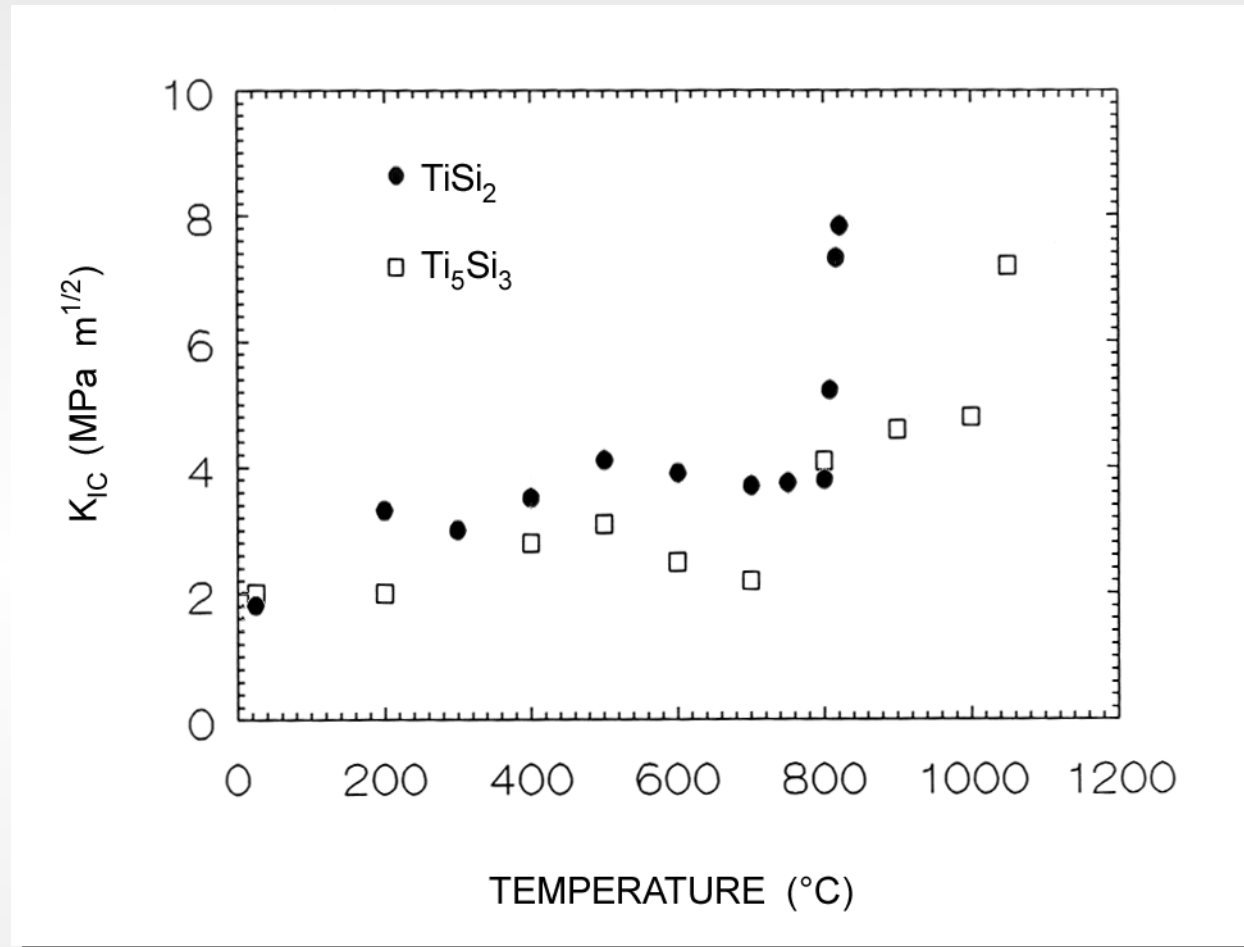
Temperature dependence of the thermal expansion coefficients of the monolithic  $Ti_5Si_3$  and  $TiSi_2$  compounds



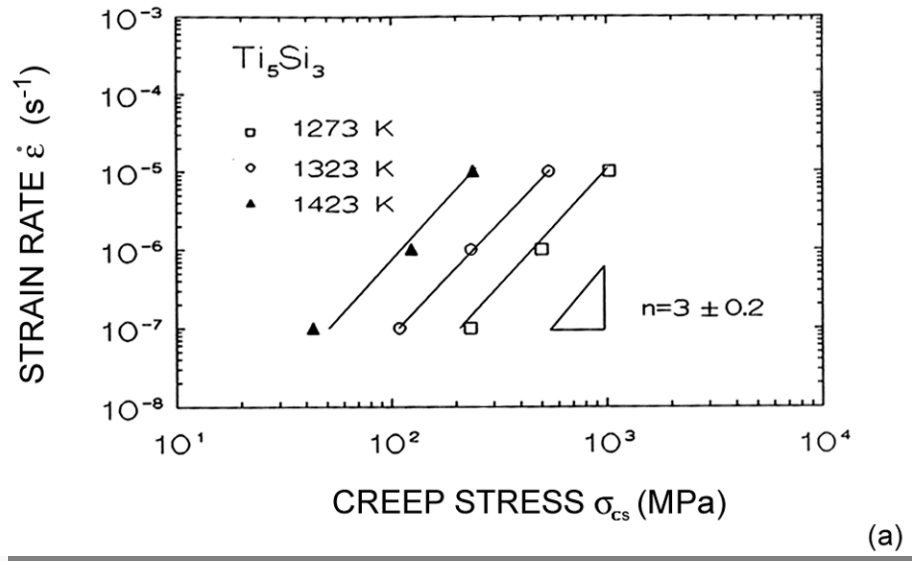
Young's moduli of the monolithic  $Ti_5Si_3$  and  $TiSi_2$  compounds as function of temperature



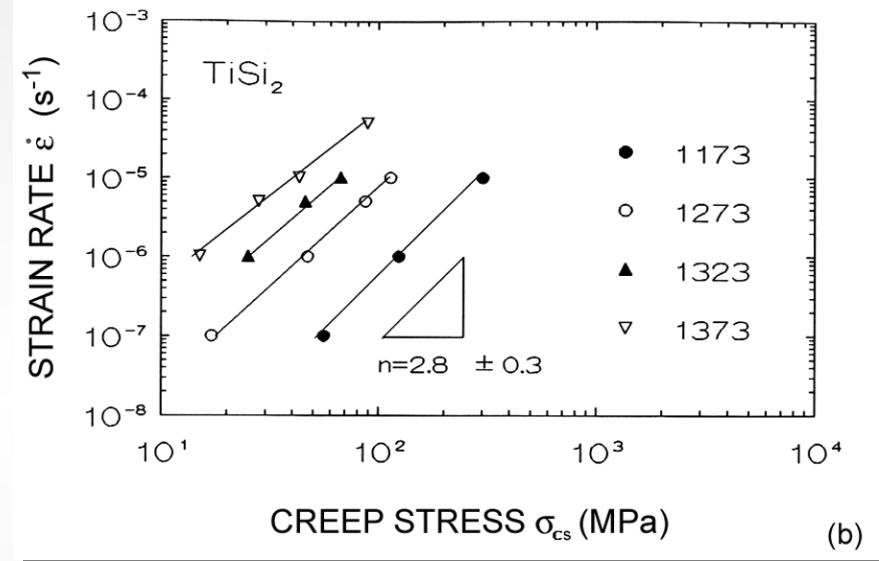
**Yield stress vs. test temperature of the monolithic intermetallic  $Ti_5Si_3$  and  $TiSi_2$  compounds**



Stress intensity factors of the intermetallic  $Ti_5Si_3$  and  $TiSi_2$  compounds as function of test temperature

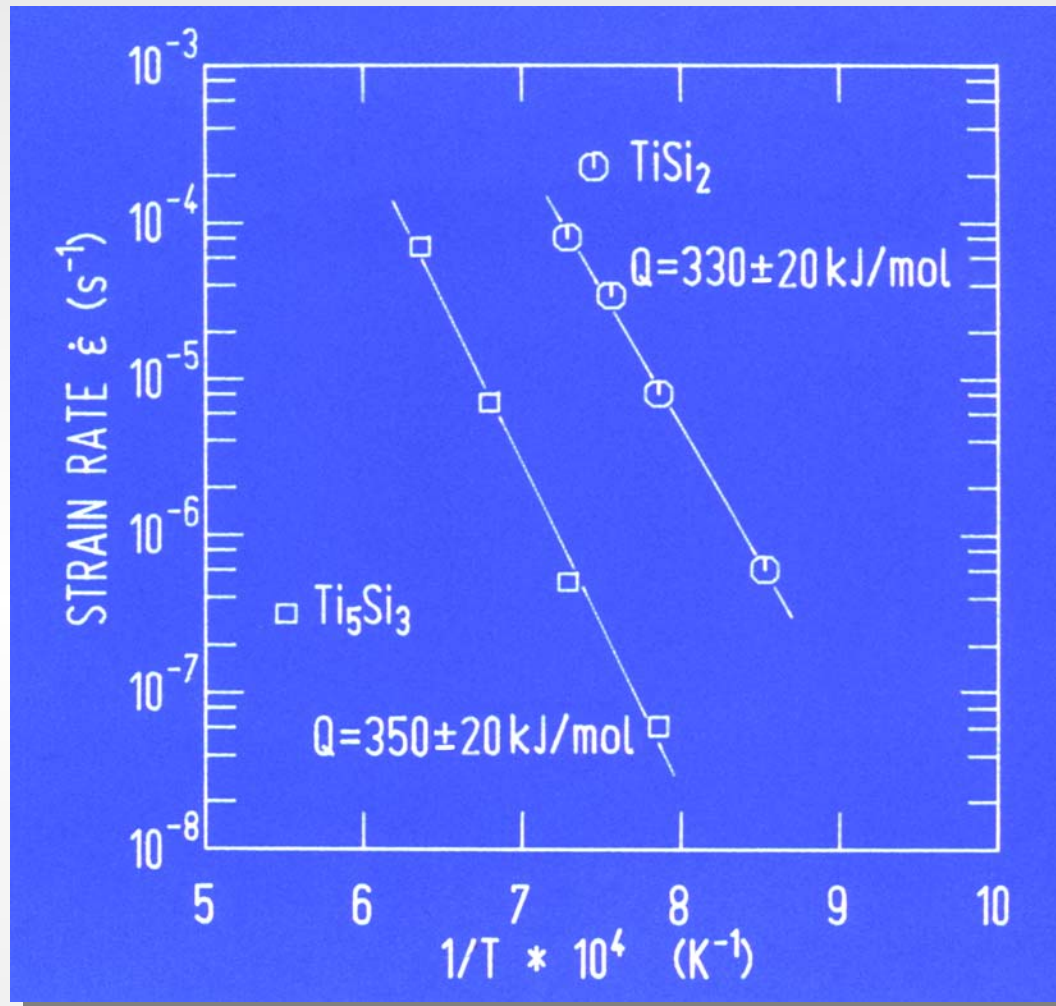


Ti<sub>5</sub>Si<sub>3</sub>

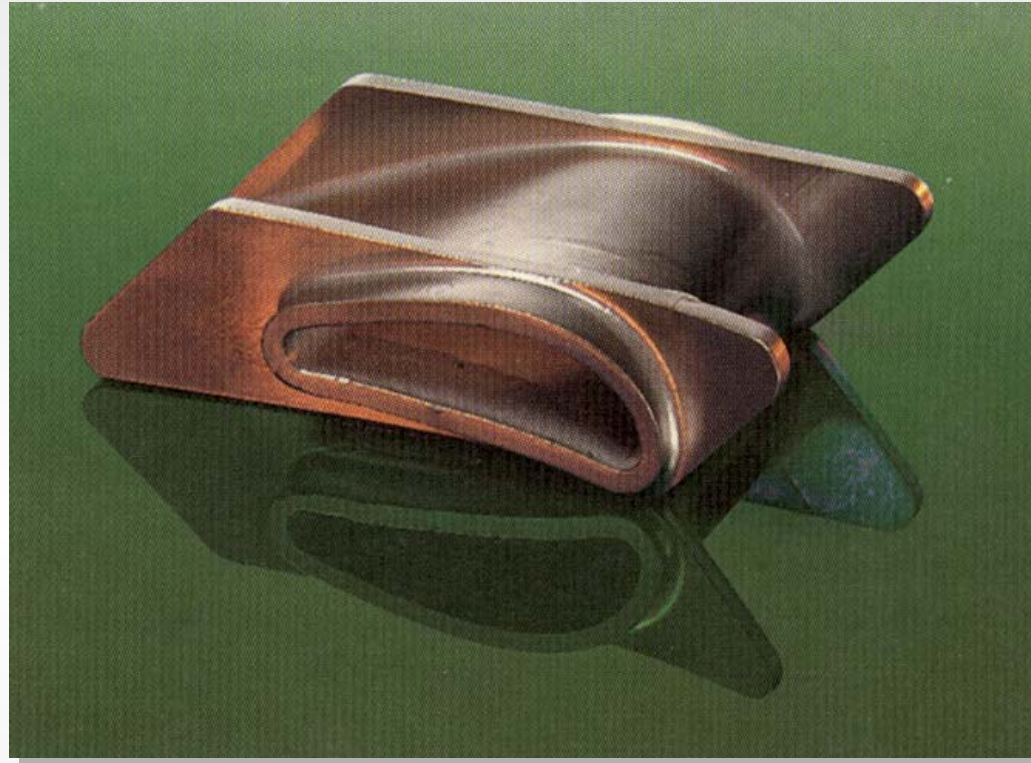


TiSi<sub>2</sub>

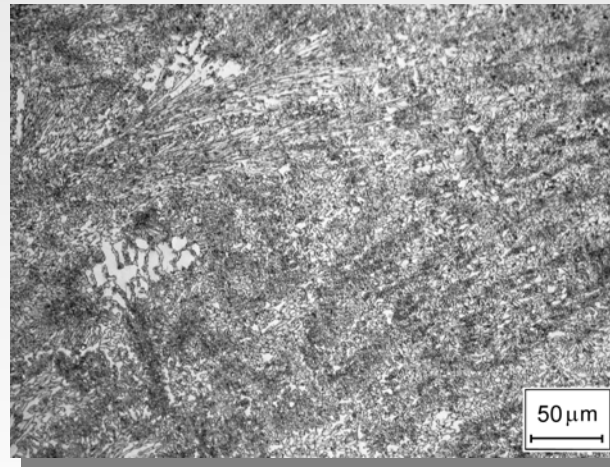
Stress exponent  $n$  derived from the slope of the  $\log \dot{\epsilon}$  vs.  $\log \sigma$  plot



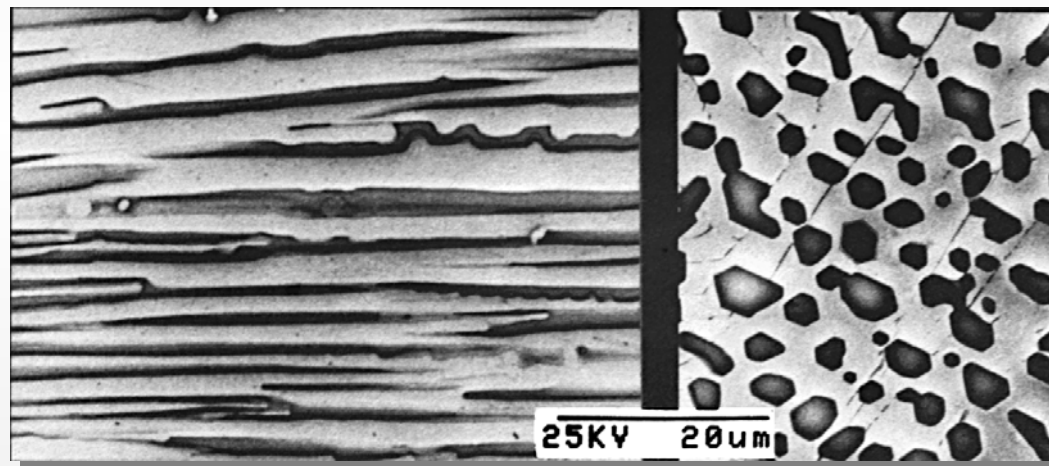
activation energies of  $\text{Ti}_5\text{Si}_3$  and  $\text{TiSi}_2$



**Powder metallurgically processed air foil of  $\text{TiSi}_2$   
tested in a combustion chamber at 1400 °C for 100 h**



(a)

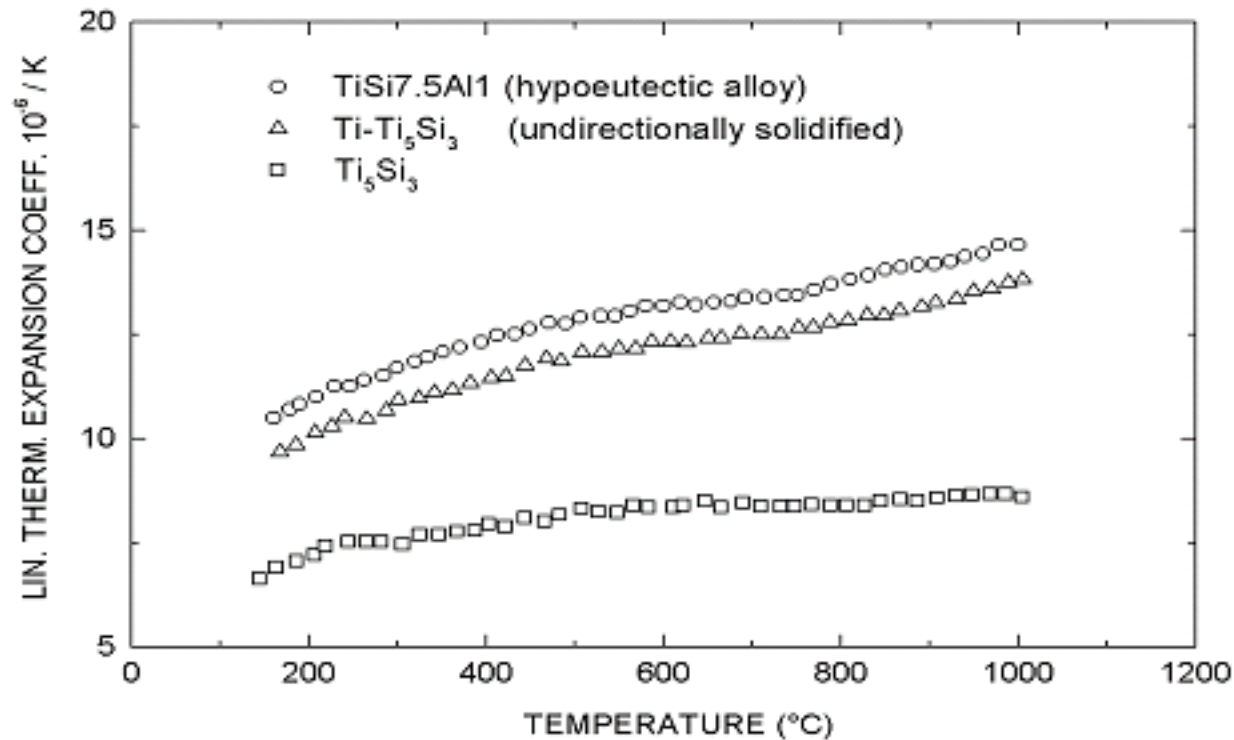


longitudinal section (b)

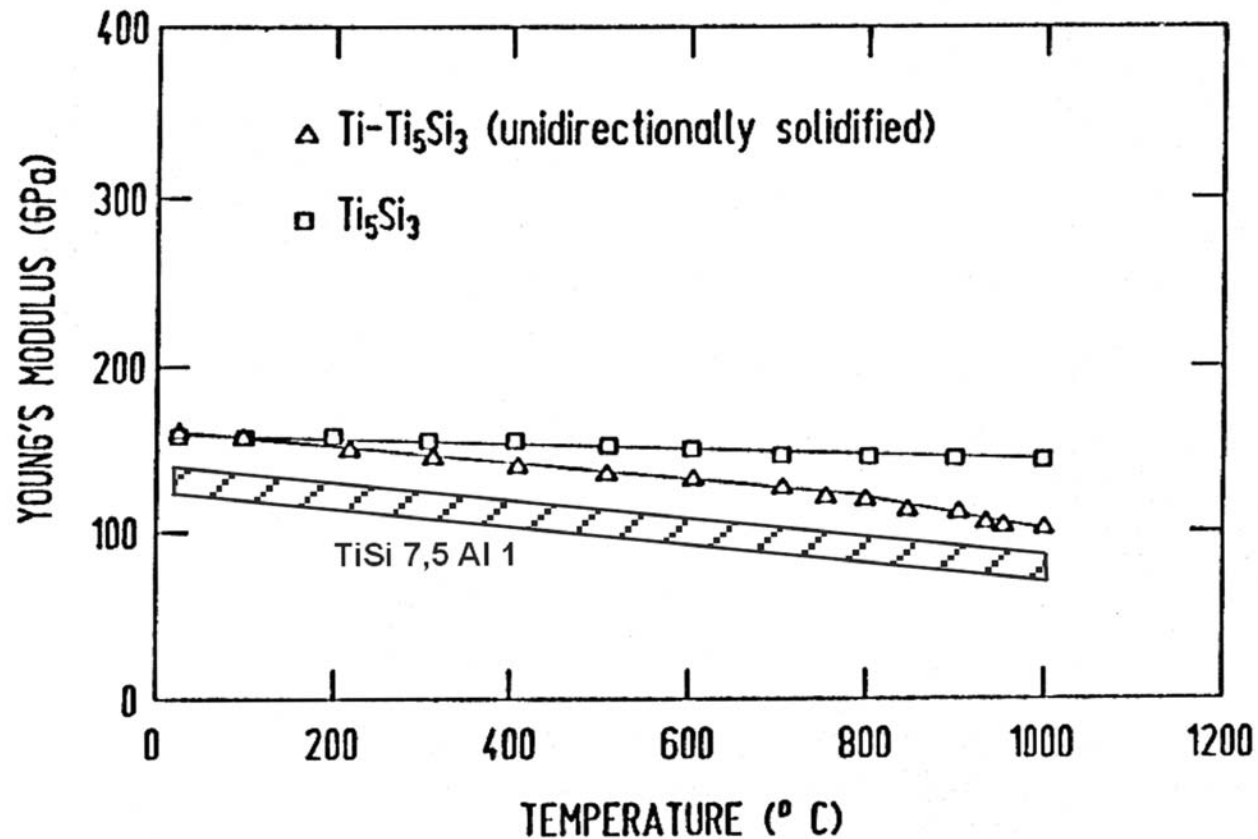
cross section (c)

**Optical micrograph of the hypoeutectic Ti-7,5Si-Al1 illustrating primary solidified  $\alpha$ -Ti solid solution grains (white areas) and fine grained eutectic (a).**

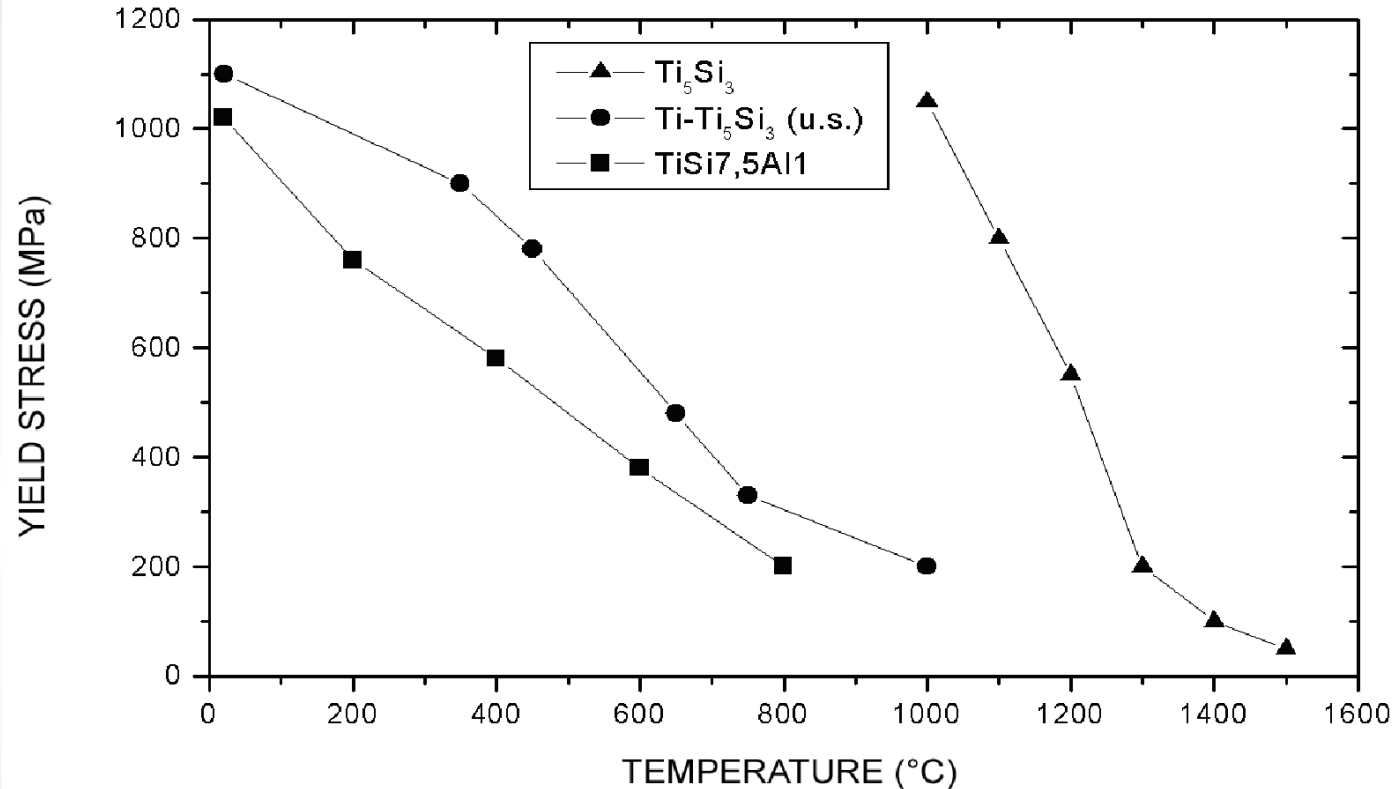
**SEM micrographs showing the fibre structure of an unidirectionally solidified eutectic Ti-Ti<sub>5</sub>Si<sub>3</sub> composite in longitudinal (b) and cross section (c)**



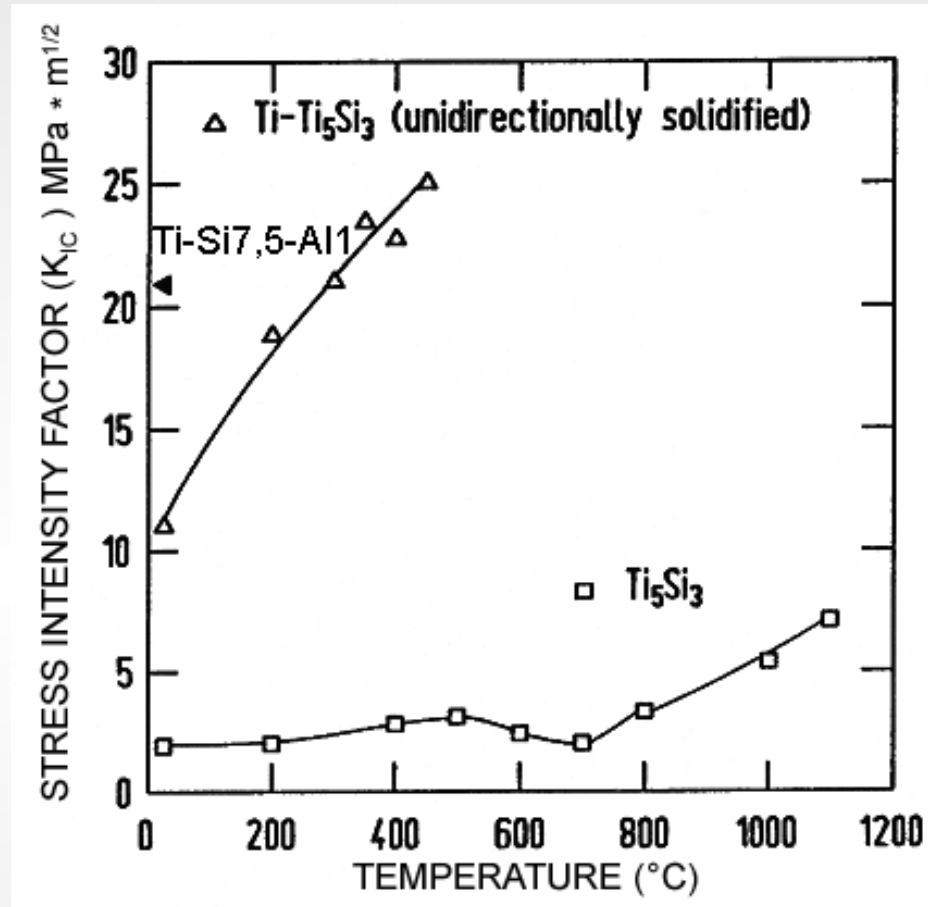
Temperature dependence of thermal expansion coefficients of  $\text{Ti}_5\text{Si}_3$ , the hypoeutectic  $\text{Ti-Si}_{7.5}\text{-Al}_1$  alloy and the unidirectionally solidified eutectic  $\text{Ti-Ti}_5\text{Si}_3$  composite



Young's moduli of the monolithic  $\text{Ti}_5\text{Si}_3$  compound and of the hypoeutectic  $\text{Ti-Si7.5-Al1}$  and the unidirectionally solidified eutectic  $\text{Ti-Ti}_5\text{Si}_3$  alloy as function of the test temperature



**Yield stress as function of temperature of the hypoeutectic Ti-Si<sub>7.5</sub>-Al<sub>1</sub> alloy and the unidirectionally solidified eutectic Ti-Ti<sub>5</sub>Si<sub>3</sub> composite. In comparison the yield stress curve of the Ti<sub>5</sub>Si<sub>3</sub> compound is plotted in the diagram.**



Stress intensity factors as function of temperature of the hypoeutectic  $\text{Ti-Si}_{7.5}\text{-Al1}$  alloys and of the directionally solidified  $\text{Ti-Ti}_5\text{Si}_3$  composite in comparison to the  $\text{Ti}_5\text{Si}_3$  compound



## ⊕ Summary and Outlook

- ❖ Innovative refractory titanium silicides  $Ti_5Si_3$  and  $TiSi_2$  exhibit extraordinary physical and mechanical properties and show great potential applications as high-temperature light-weight materials for turbine air foils, heat shield tiles for combustion chambers and missile nozzles.
- ❖ The superior oxidation resistance is due to the formation of very stable  $SiO_2$  surface layers
- ❖ The high elastic stiffness and hardness of these silicide compounds are caused by the strong covalent bonding of s-p and d-p electron interactions of the Si-Si and S-Ti atoms.
- ❖ The prominent high temperature strength, creep resistant and the restricted room temperature ductility are of intrinsic nature. The complex superlattice possess sessile superdislocations of large Burgers' vector of high energy.
- ❖ For improving the ductility and toughness of silicides micro- and macro alloying have been performed. Alpha titanium –  $Ti_5Si_3$  composites exhibit improved room temperature ductility and combine the advantages of high flow stresses and elevated temperature strength.
- ❖ Hypoeutectic and directionally solidified eutectic  $\alpha$ -Ti /  $Ti_5Si_3$  composites show considerable potential applications for axial compressor blades and outlet valves in internal combustion engines.