Metal matrix composites

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M.M.S Metallic Materials Science

Outline

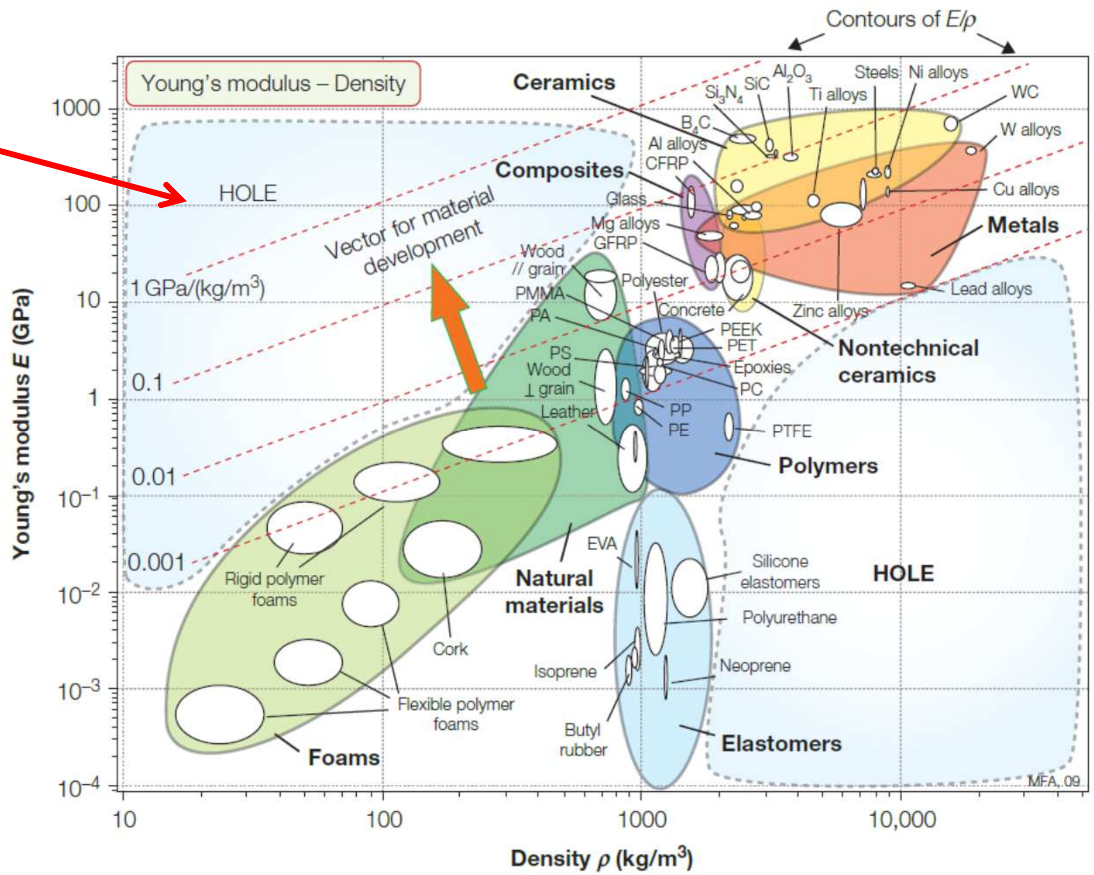
- Introduction: why composite materials?
- Case study I: Material for electronic packaging
- Case study II: Enhanced wear resistance
- Case study III: Functional materials
- Processing metal matrix composites:
  a problem of interface engineering!
- Summary

Introduction

Why composite materials

Why composite materials?

- To fill **gaps** in material-property space
- To obtain combination of properties not available with "simple" materials

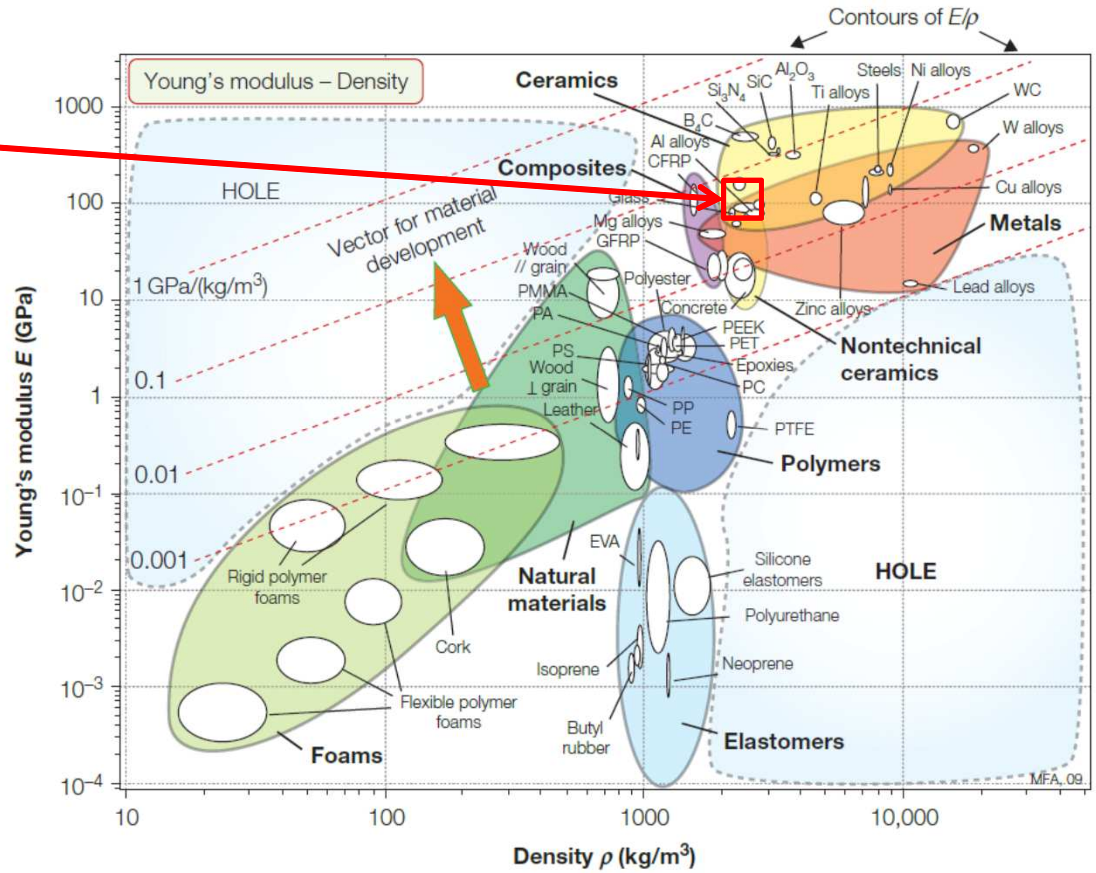


[M.F. Ashby, Materials selection in mechanical design]

Why composite materials?

- New combination of interesting mechanical properties

Improved stiffness compared to conventional Al alloys



[M.F. Ashby, Materials selection in mechanical design]

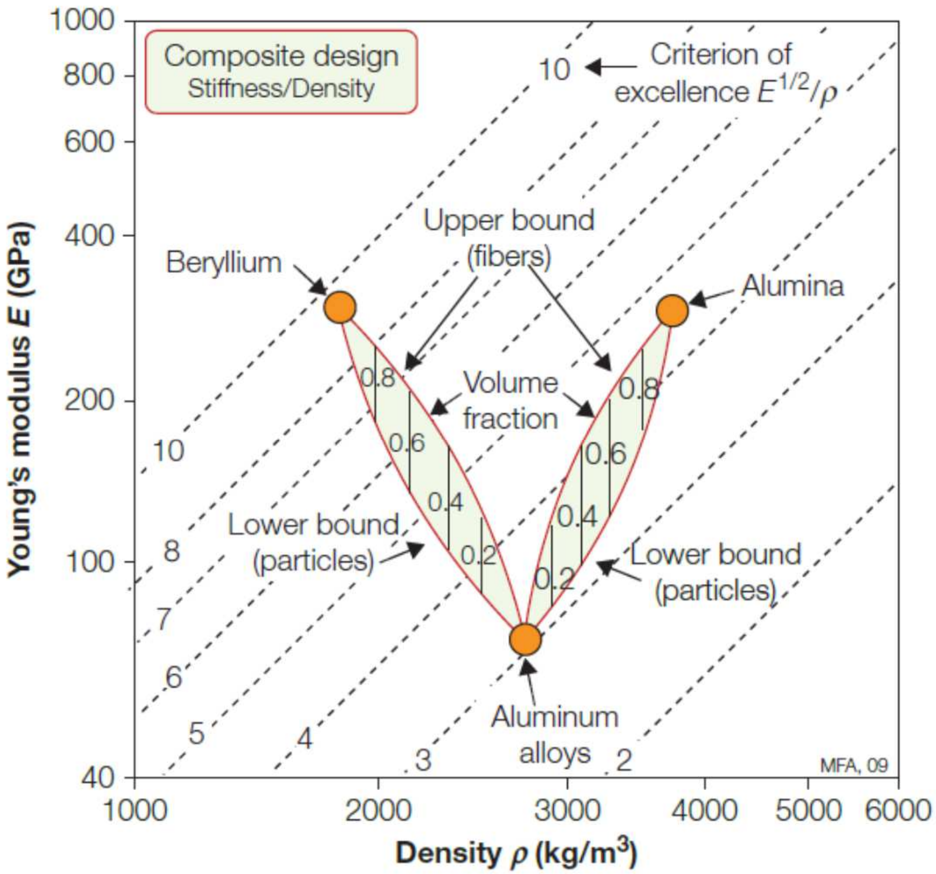
Why composite materials?

- New combination of interesting mechanical properties

Improved stiffness compared to conventional Al alloys

Choice of materials?

- Be is stiffer and lighter than Al
- Al_2O_3 is stiffer but heavier than Al



[M.F. Ashby, Materials selection in mechanical design]

Why composite materials?

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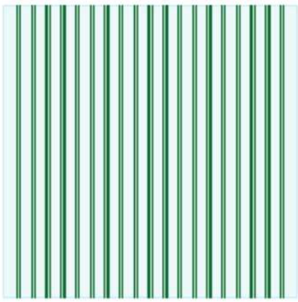
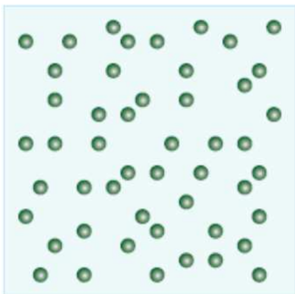
Improved stiffness compared to conventional Al alloys

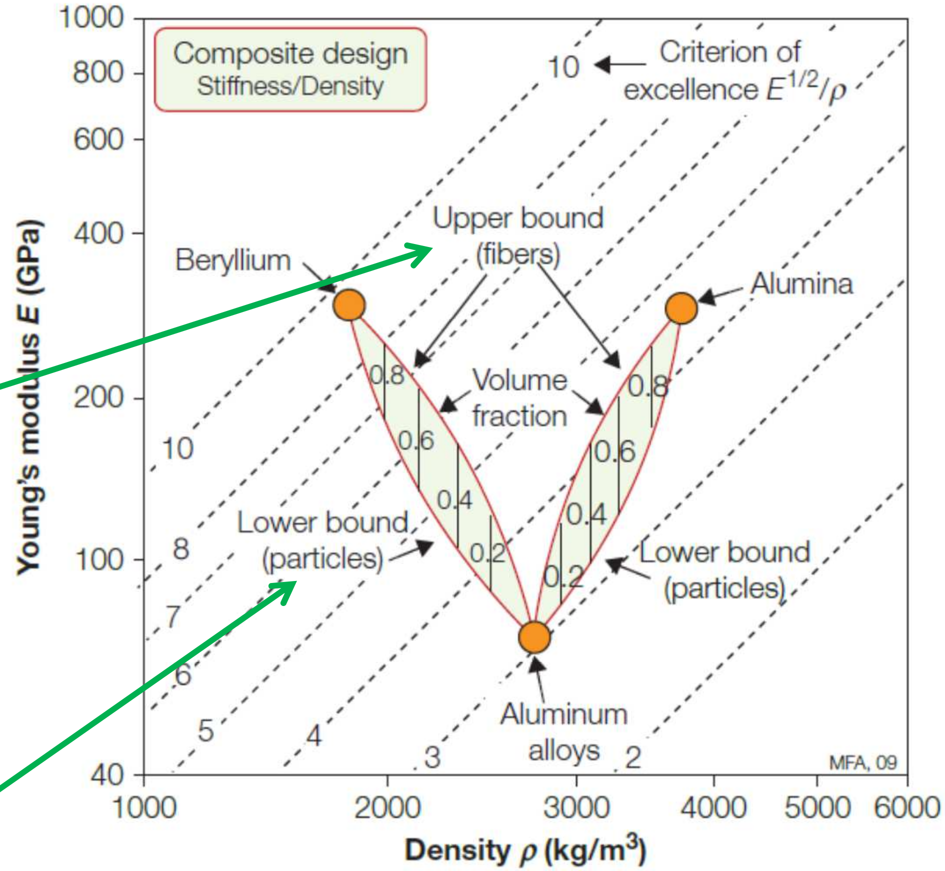


Unidirectional

Configuration?



Particulate



[M.F. Ashby, Materials selection in mechanical design]

Why composite materials?

One can be imaginative!

- Combine high thermal conductivity and low thermal expansion
- Enhance wear resistance
- Design functional materials
  - Self-lubricating
  - Self-cleaning
  - Self-healing

…

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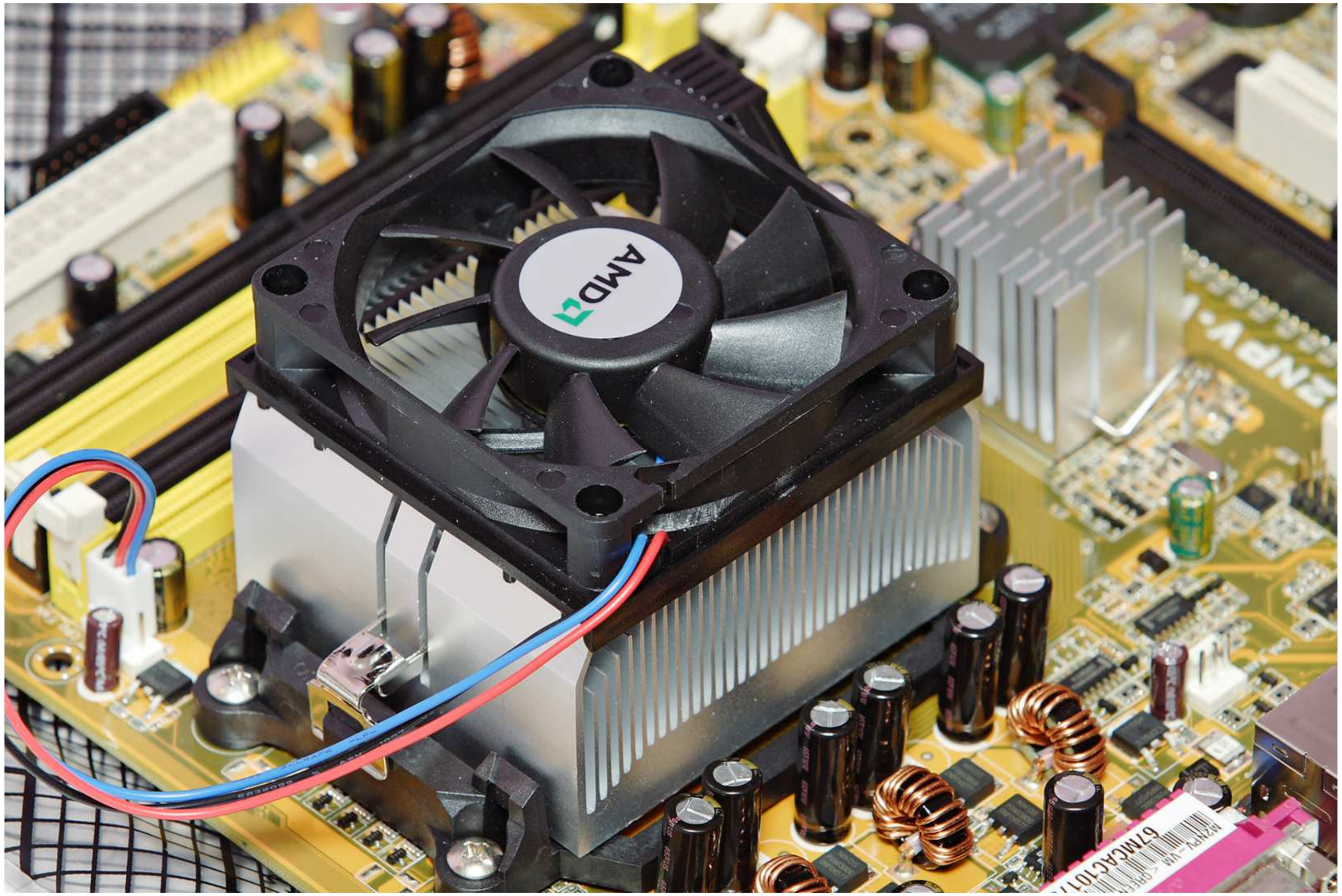
Case study I

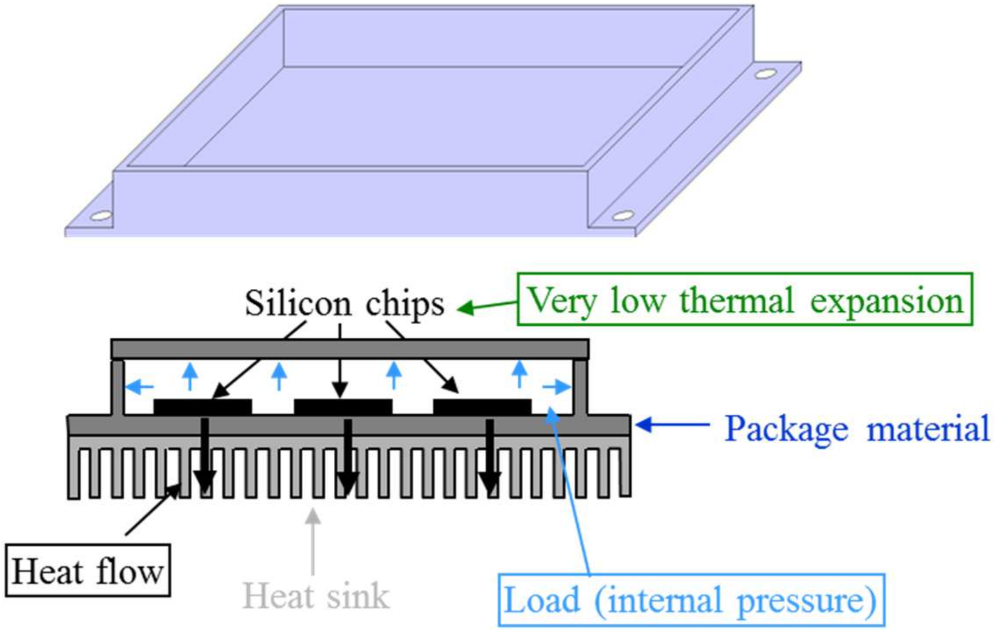
Material for electronic packaging

Electronic packaging and heat sink



[Wikipedia: Fir0002/Flagstaffotos]

Electronic packaging



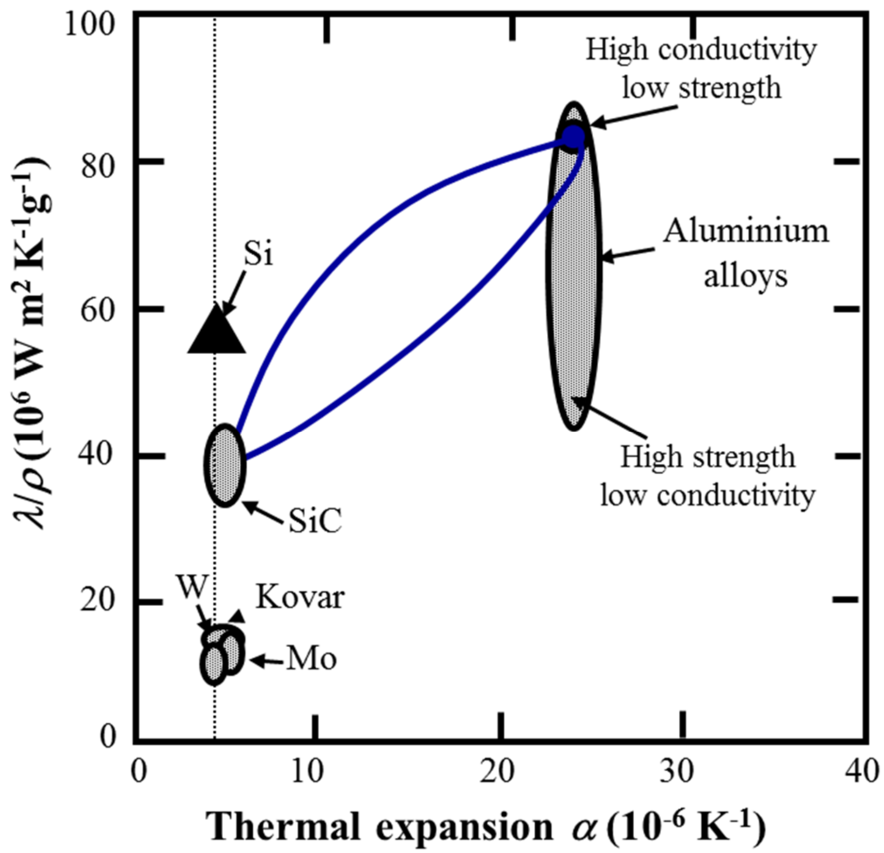
[S.Ryelandt et al., Euromat 2005]

- Thermal expansion α close to $\alpha_{silicon}$
- High thermal conductivity (λ)
- For portable applications: low density (ρ)

Materials for electronic packaging

- Thermal expansion α close to $\alpha_{silicon}$ ⇒ SiC
- High thermal conductivity (λ) ⇒ Al
- For portable applications: low density (ρ) ⇒ Al

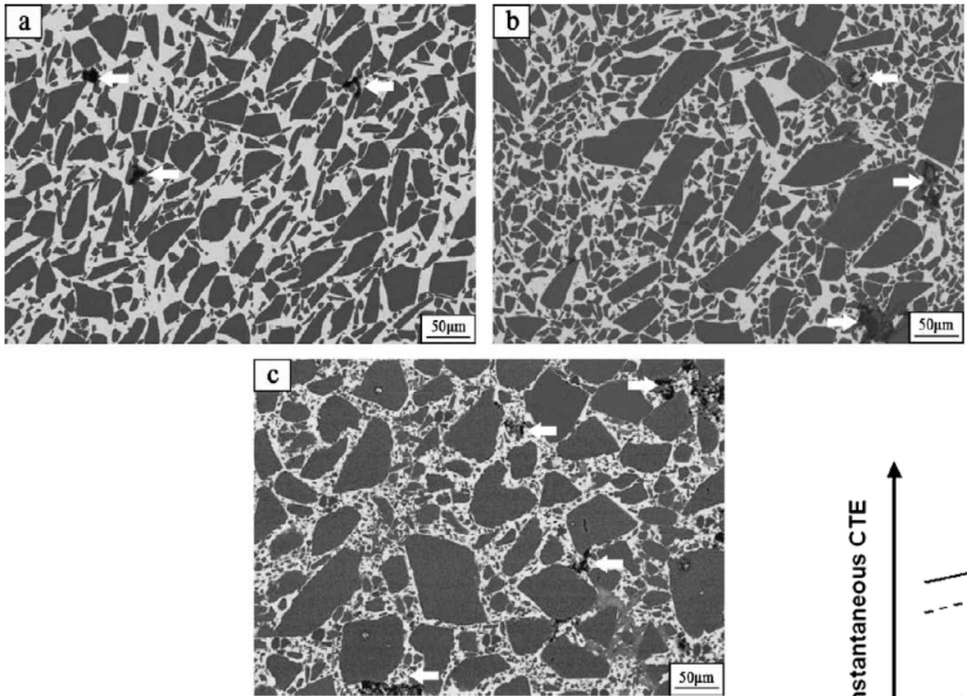
- Al-SiC composites?

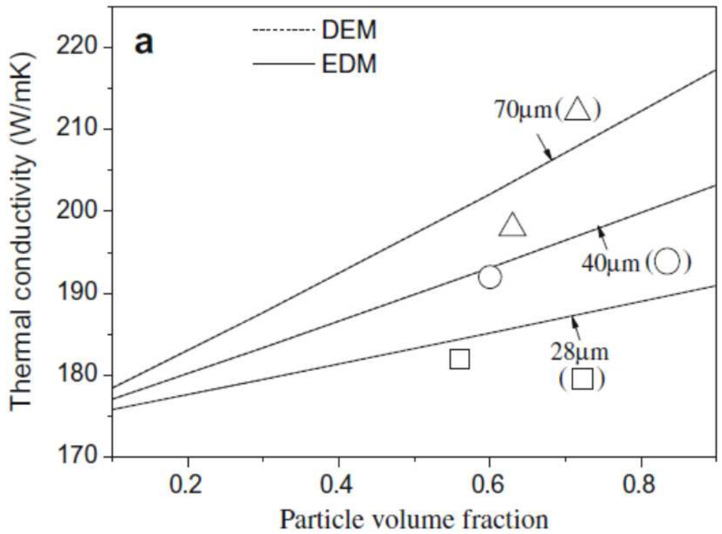


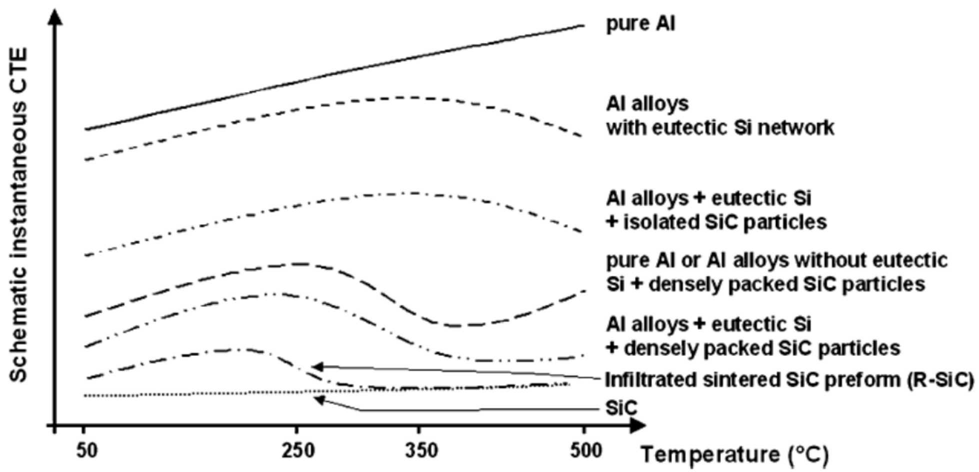
[S.Ryelandt et al., Euromat 2005]

Materials for electronic packaging

- Al + SiC particulates







... but SiC is very brittle!

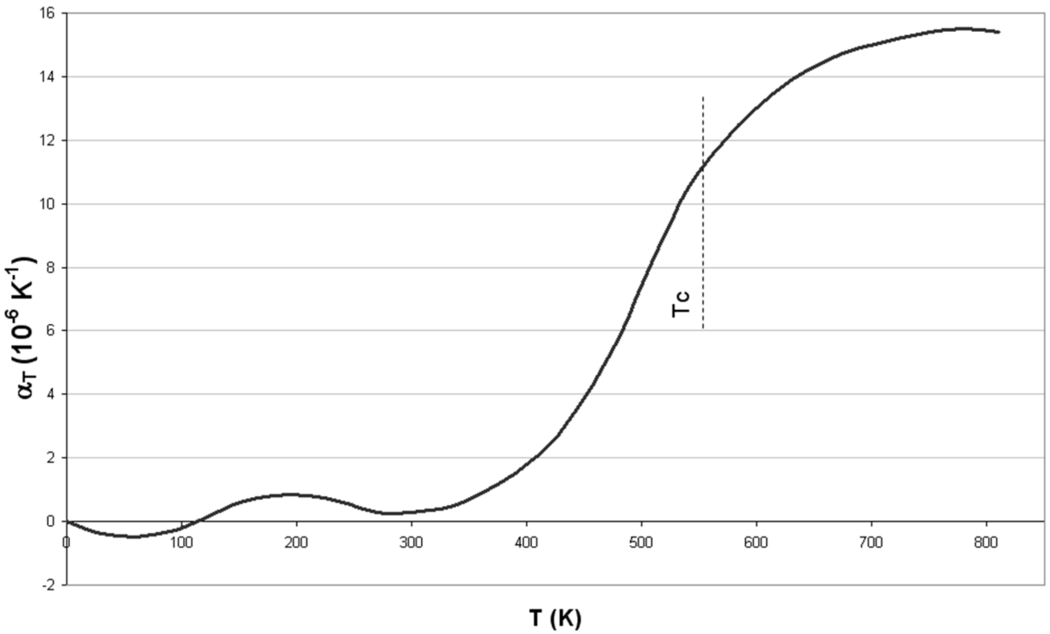
[Huber et al., Comp. Sci. Technol. 2006; Chu et al., Mater. Des. 2009]

Materials for electronic packaging

- Al + another metallic material with low α?

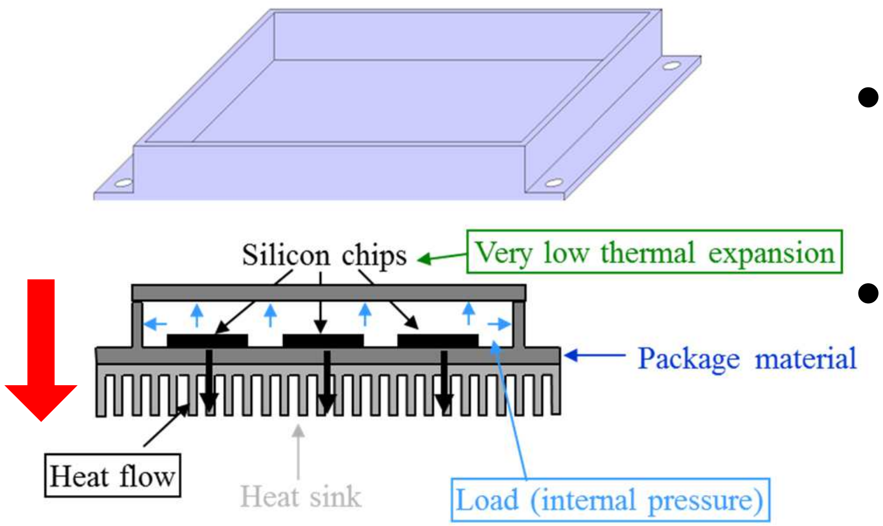
⇒ Invar (Fe-Ni or Fe-Co-Cr alloys)

[http://images-of-elements.com/other.php]



[Borvan53 (Own work) [Public domain], via Wikimedia Commons]

Anisotropy is desirable!



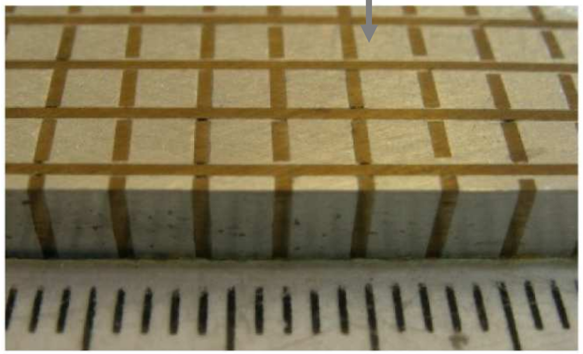
- Thermal expansion α close to $\alpha_{silicon}$ (in plane)
- High thermal conductivity (λ) (in transverse direction)
- For portable applications: low density (ρ)

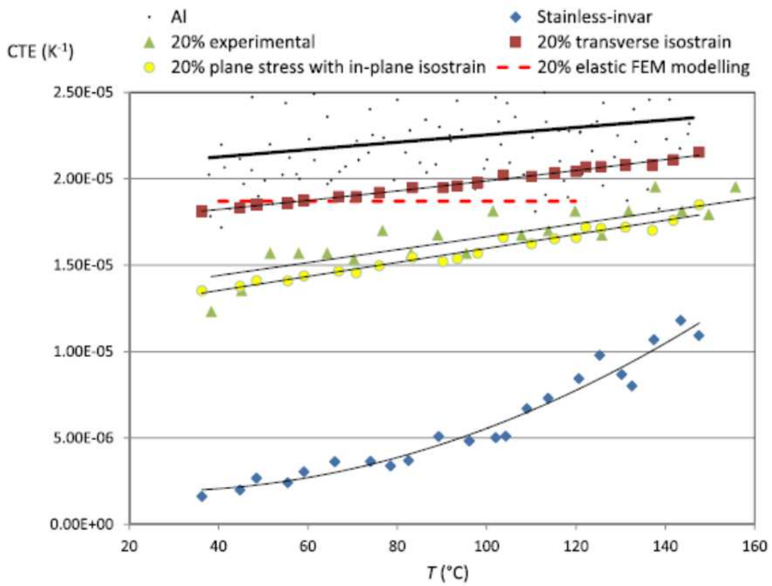
[S.Ryelandt et al., Euromat 2005]

Anisotropic Al-invar composite

Invar
(Fe-Co-Cr alloys)

Al



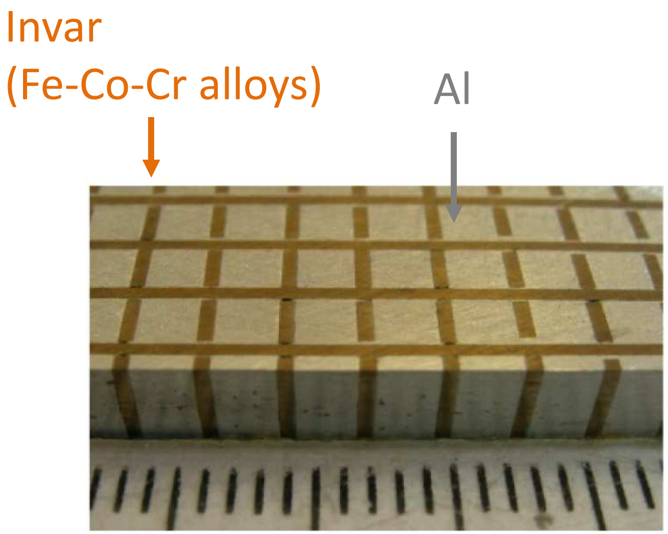


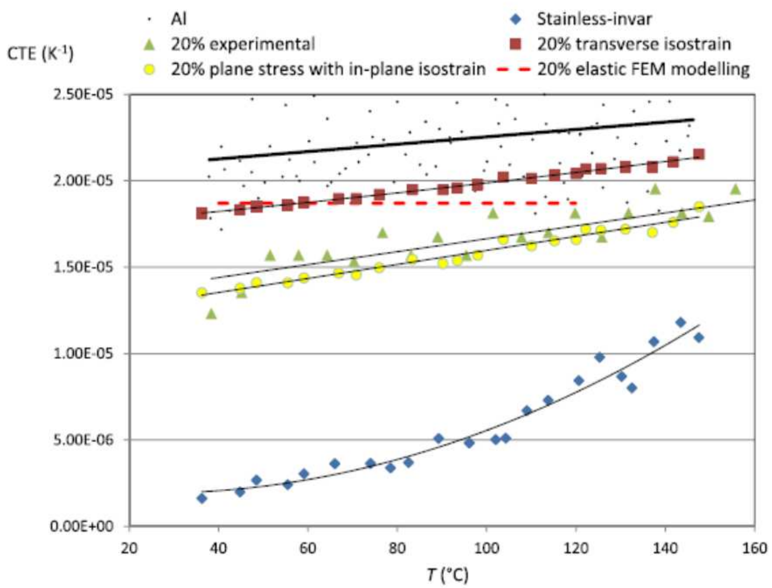
Al - 20 % stainless invar

- Thermal expansion α close to $\alpha_{silicon}$ (in plane)
- High thermal conductivity: $\lambda = 206\ \mathrm{Wm^{-1}K^{-1}}$ (in transverse direction)
- Low density (ρ)

[Ryelandt, Mertens & Delannay, Mater. Des. 2015]

Anisotropic Al-invar composite





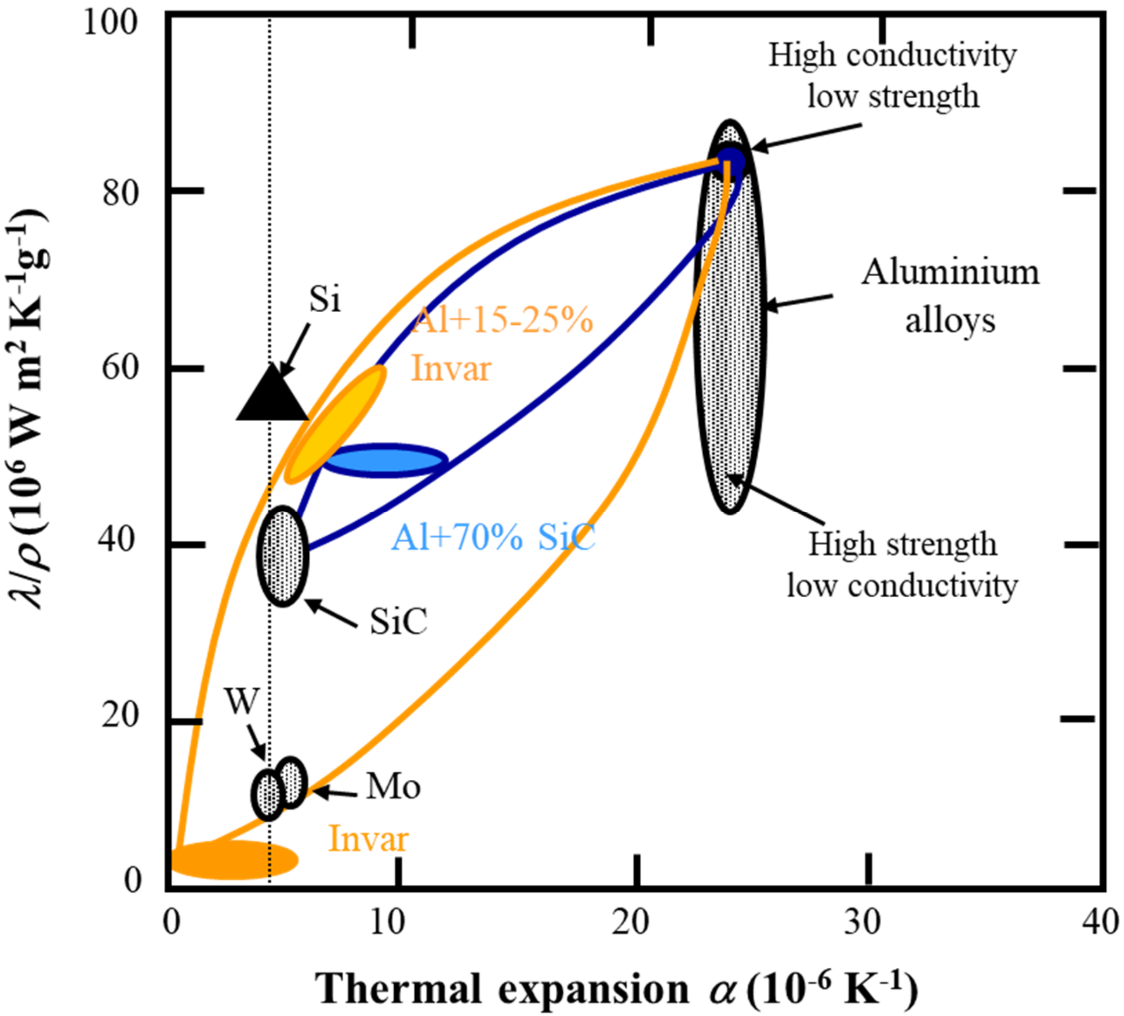
Al - 20 % stainless invar

- Thermal expansion α close to $\alpha_{silicon}$ (in plane)
- High thermal conductivity: λ = 206 $Wm^{-1}K^{-1}$ (in transverse direction)
- Low density (ρ)

Change α, λ and ρ by adjusting the volume fraction of invar

[Ryelandt, Mertens & Delannay, Mater. Des. 2015]

Al-invar composites



[Ryelandt, Mertens & Delannay, Mater. Des. 2015]

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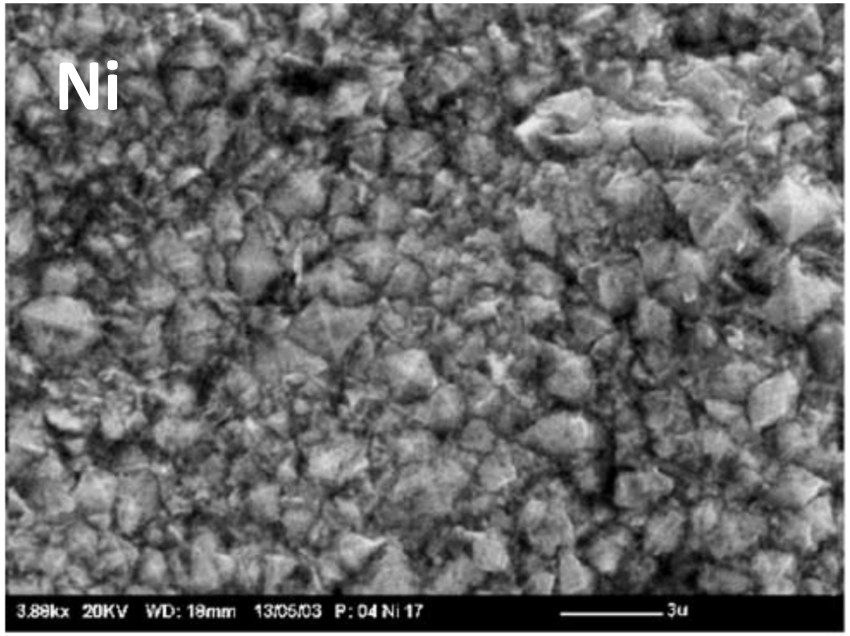
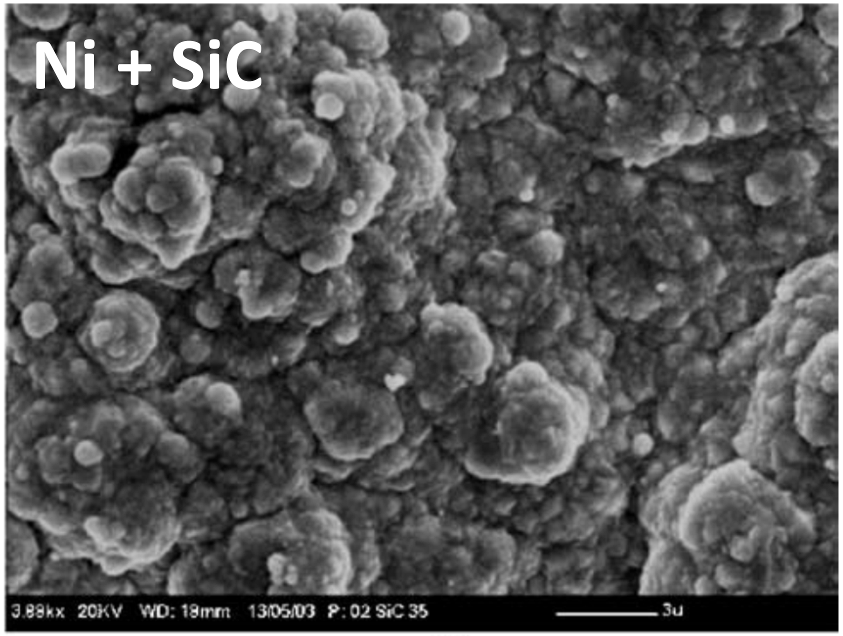
Case study II

Enhanced wear resistance

Ni+SiC composite coatings

Electro-deposition of Ni + (nano-particles) of SiC





Composite coating gives better coverage

[Lekka et al., Electrochim. Acta 2005]

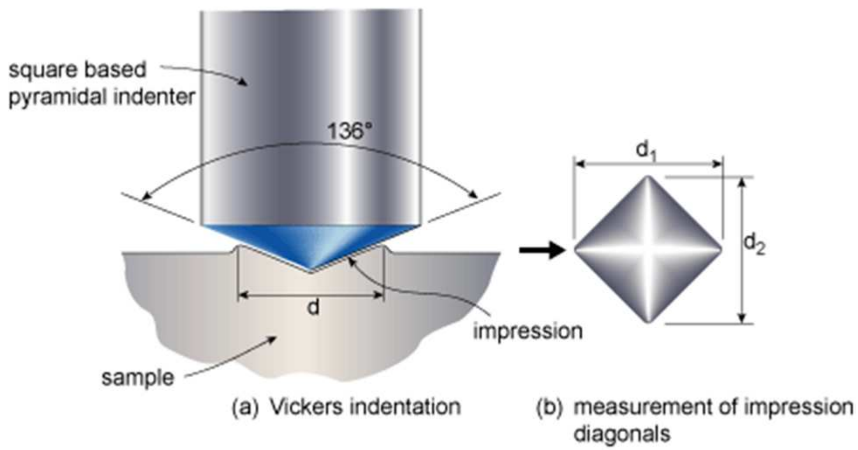
Ni+SiC composite coatings

Electro-deposition of Ni + (nano-particles) of SiC

Table 3
Surface roughness Ra and $HV_{0.3}$ mean values.

[Lekka et al., Surf. Coat. Technol. 2012]

Deposit	Ra (μm)	$HV_{0.3}$
Pure Ni	1.32 ± 0.2	162 ± 2
Ni/μSiC	1.97 ± 0.2	245 ± 5
Ni/nSiC	1.33 ± 0.3	270 ± 9



Hardness ↑

[http://www.twi-global.com/technical-knowledge/job-knowledge/hardness-testing-part-1-074/]

Ni+SiC composite coatings

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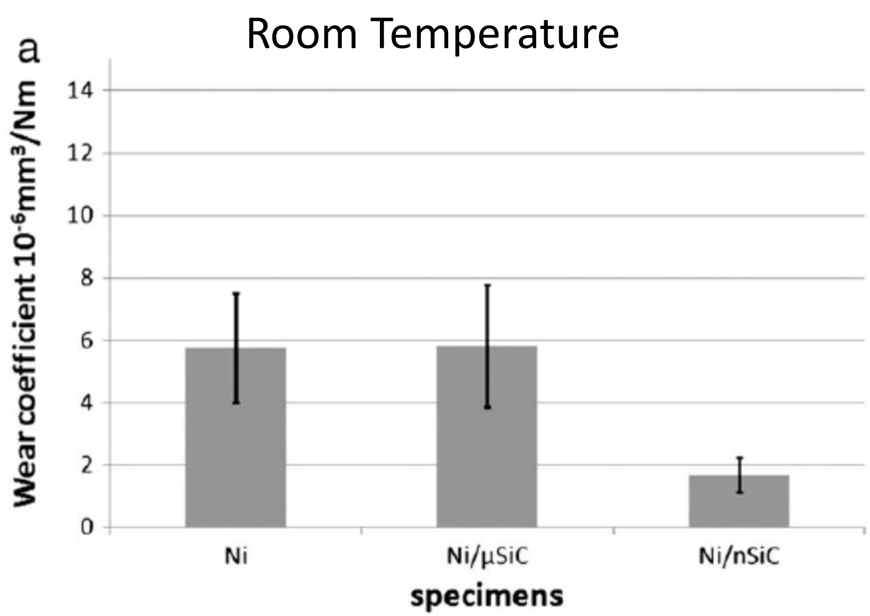
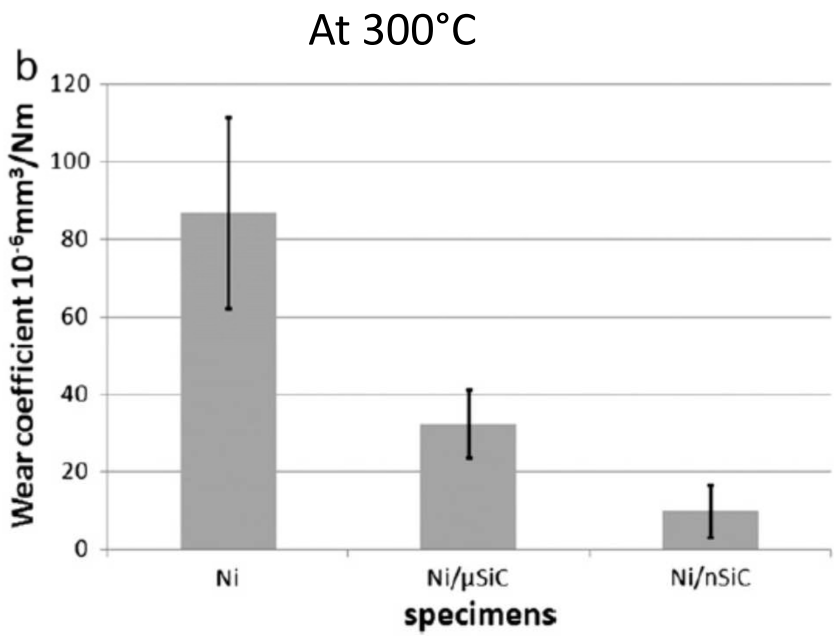
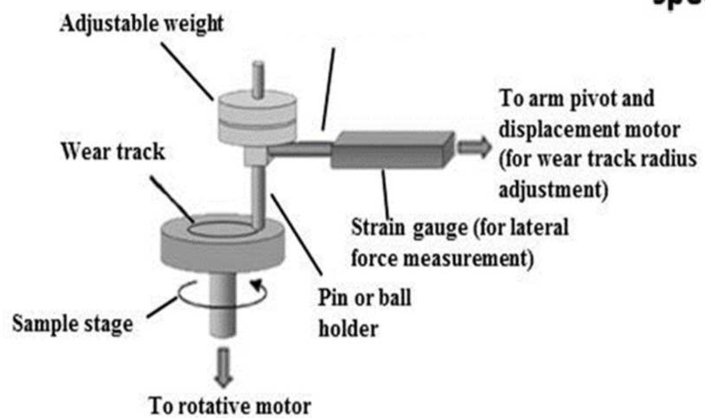




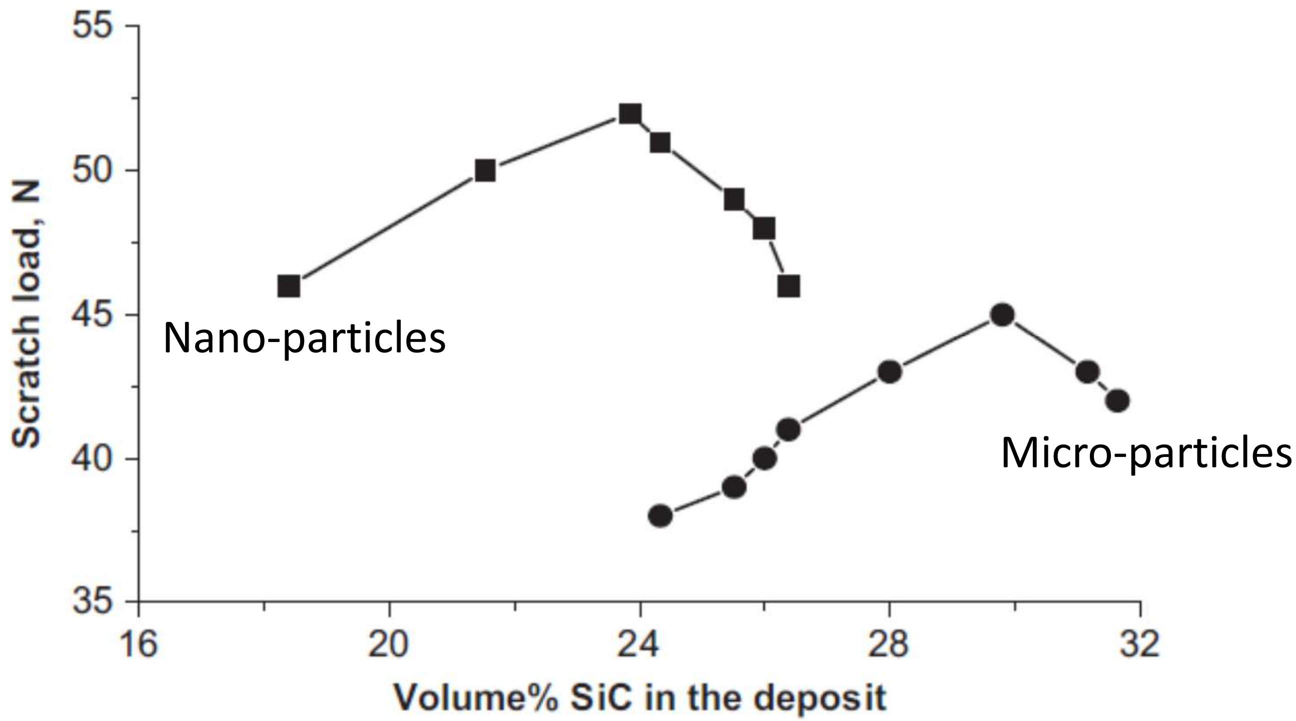


Resistance to wear ↑

[Lekka et al., Surf. Coat. Technol. 2012]

Ni+SiC composite coatings

Electro-deposition of Ni + (nano-particles) of SiC



Resistance to scratch ↑

[Narasimman et al., Wear 2012]

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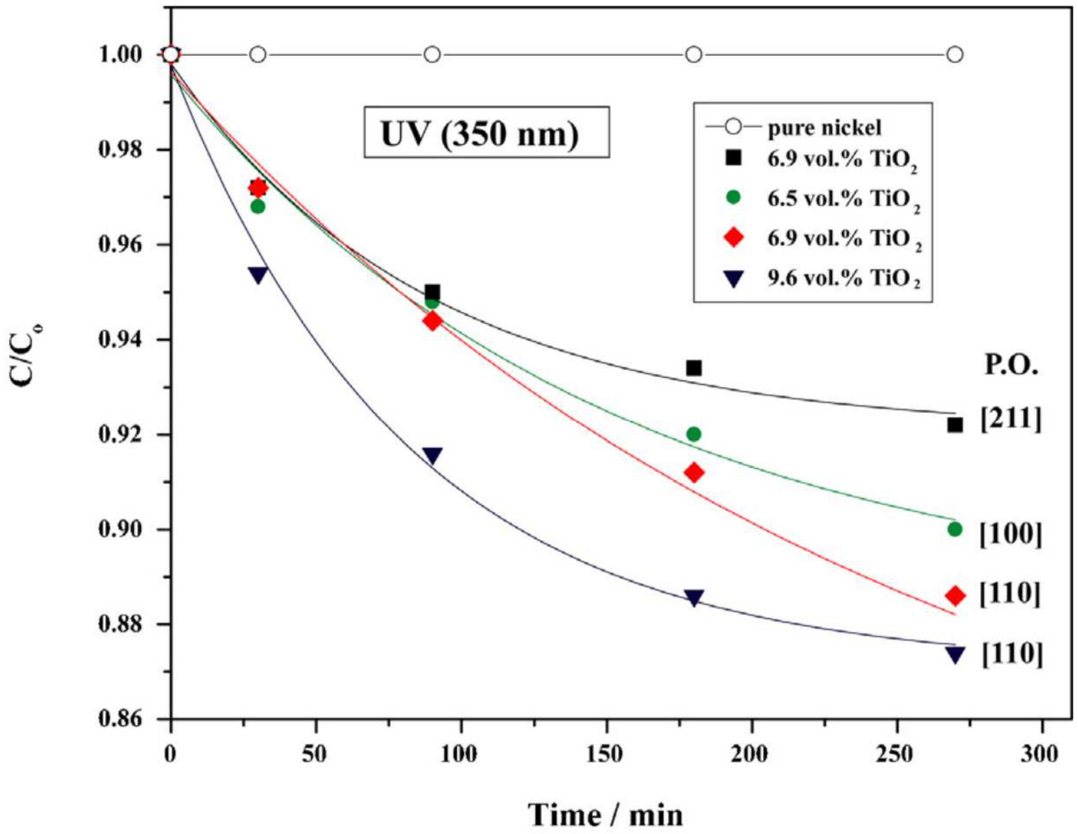
Case study III

Functional materials

Self-cleaning materials

Electro-deposition of Ni + nano-particles of TiO_2



Under UV light, TiO_2 causes photocatalytic degradation of pollutants

Efficiency of "self- cleaning" depends on

- volume fraction of TiO_2
- structure of Ni matrix

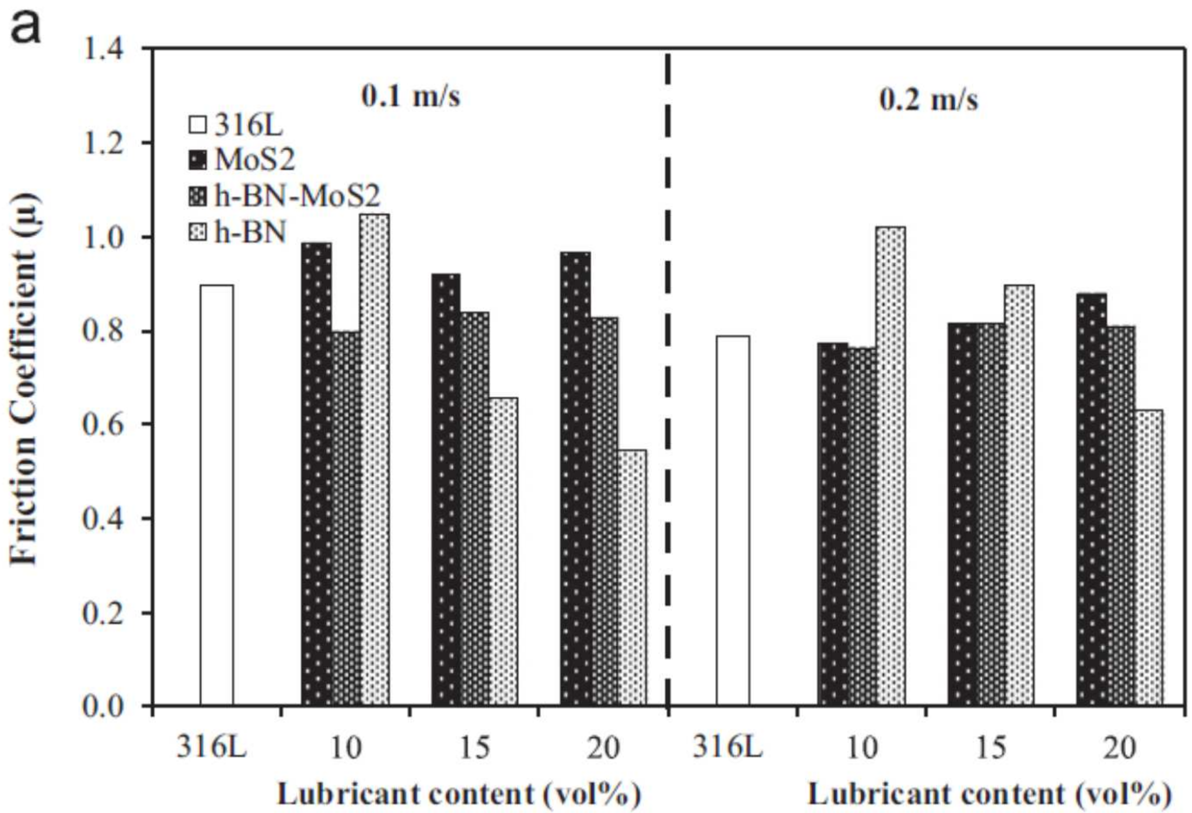
[Spanou et al., Electrochim. Acta 2013]

Self-lubricating materials

- Lubrication is important in decreasing friction and wear e.g. during machining or sliding contact
- At high temperature, conventional liquid lubricants (oil, ...) do not work
- Dry lubricants that are stable at high temperatures offer alternatives
  - graphite
  - boron nitride (BN)
  - molybdenum di-sulfide (MoS_2)

Self-lubricating materials

Dry lubricants are included in the bearing material (stainless steel 316L) and then released progressively



Friction may ↓

[Mahathanabodee et al., Wear 2014]

Self-lubricating materials

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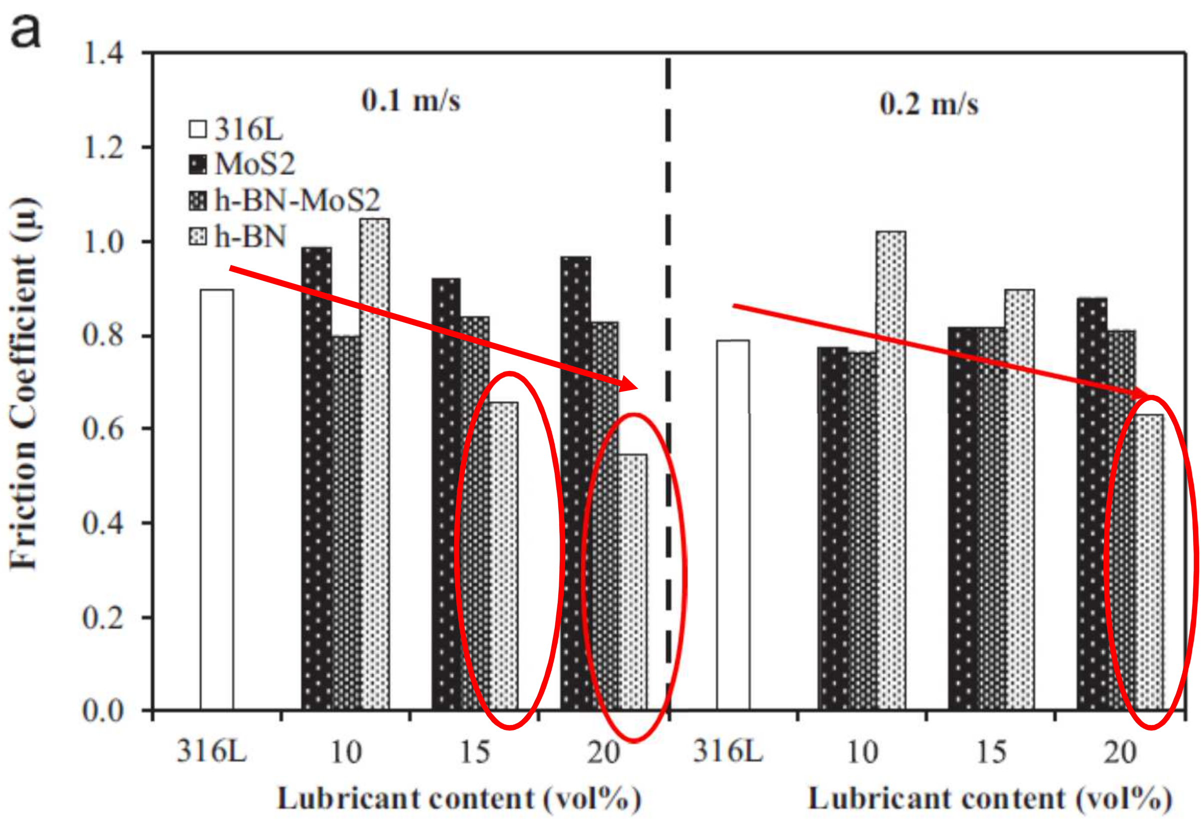
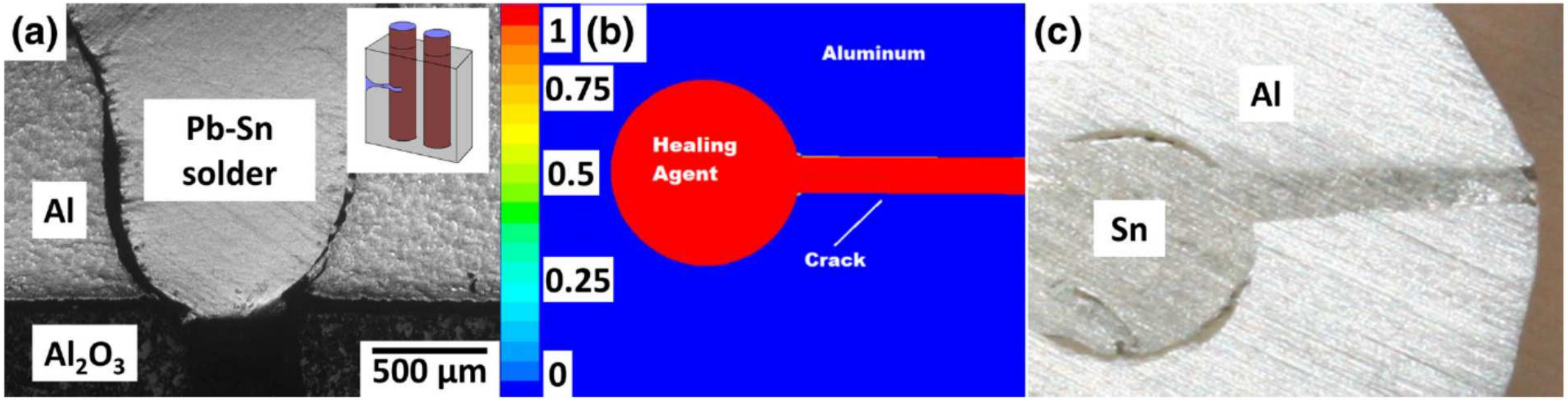


Friction may ↓ (here with BN additions)

[Mahathanabodee et al., Wear 2014]

Self-healing materials

- Healing agents/capsules (e.g. with low melting temperature) are dispersed in the material
- After service, the material is heat treated to release the healing agent where it is needed



[Ferguson et al., JOM 2014]

- Self healing developed 1st for polymers
- Very early stage for metals!

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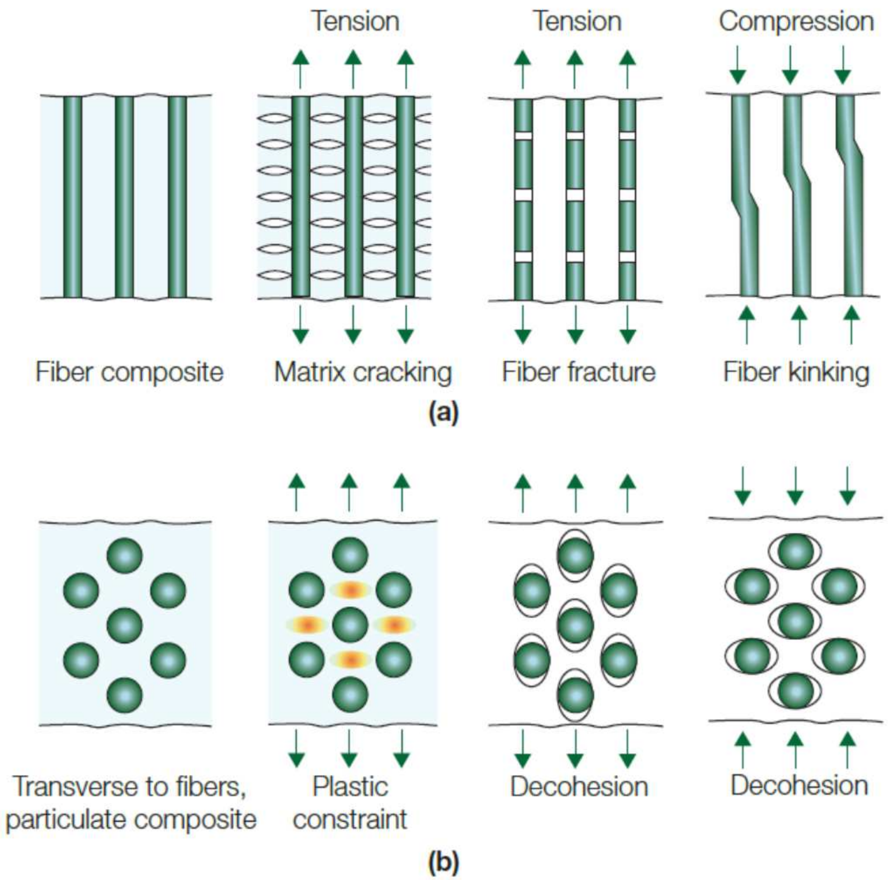
Processing of MMCs

A problem of interface engineering!

Role of interface!



When using composites, designers generally make the assumption of **fully dense, strongly bonded** composites

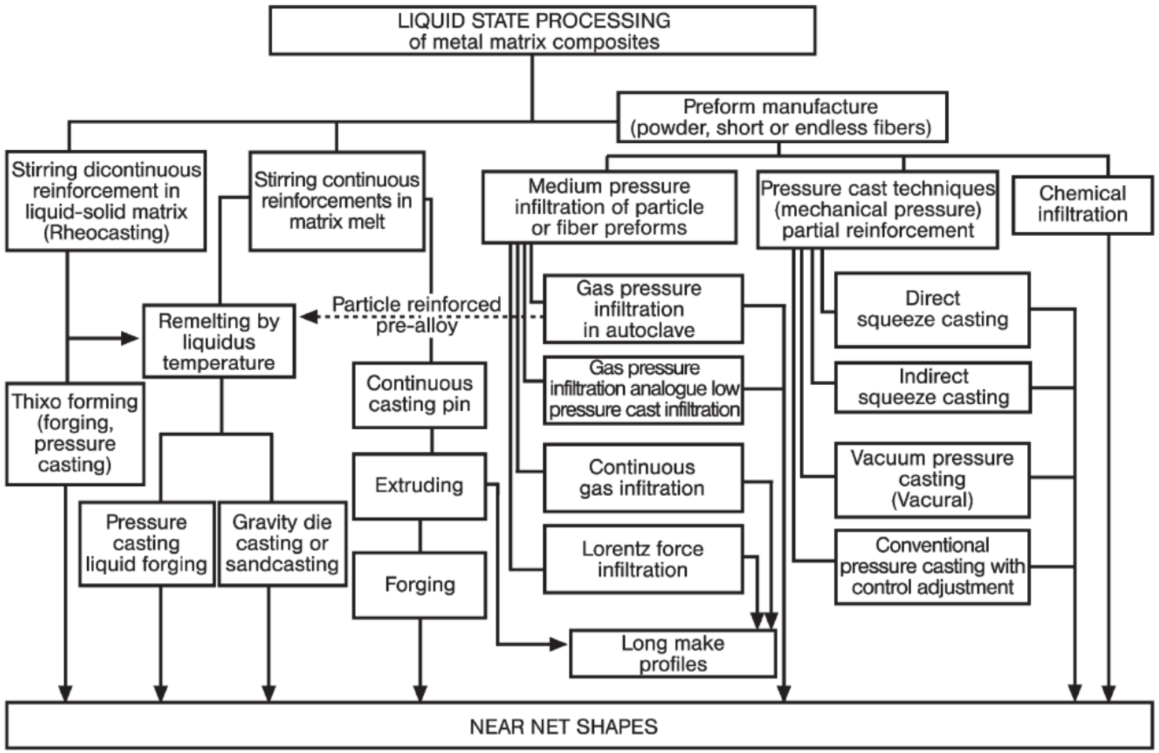
$\Rightarrow$ Optimal load-transfer between matrix and reinforcement

[M.F. Ashby, Materials selection in mechanical design]

Processing?

... but obtaining **fully dense, strongly bonded** composites is not trivial!

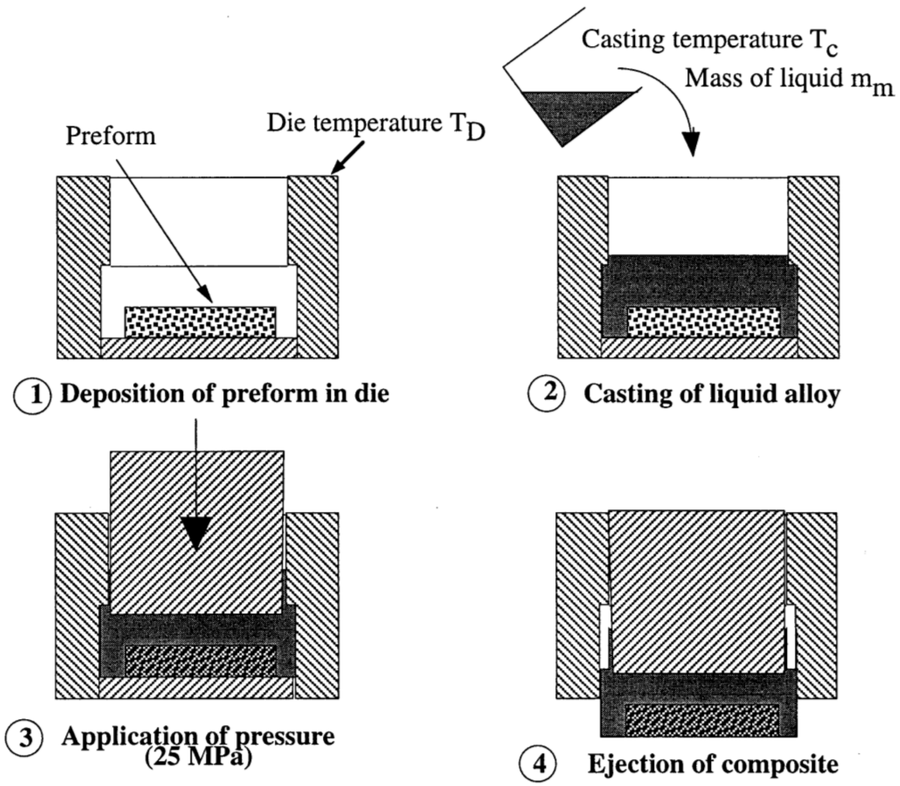
Especially by liquid (molten) state processing



[K.U. Kainer, Basics of metal matrix composites, 2006]

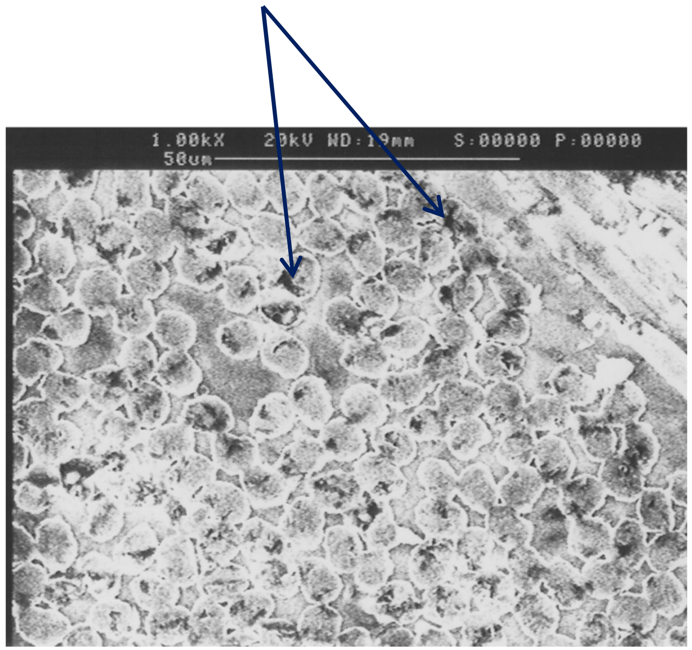
Processing must be optimized!

Example of liquid (molten) state processing: squeeze casting



[F. Boland et al., MMTA, 1998]

Fast solidification may result in poor infiltration and porosities



Mg alloy + C fibres composites

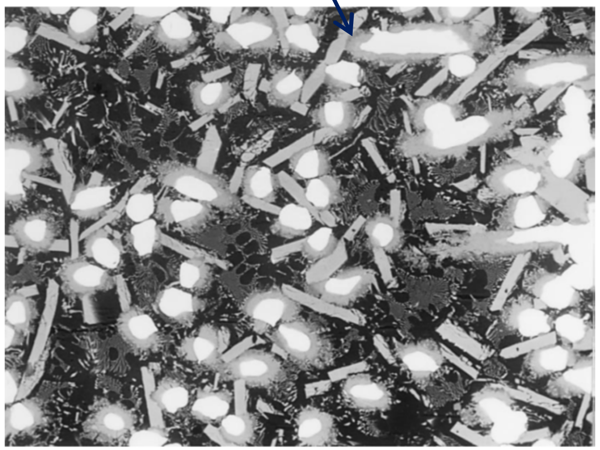
[A. Mertens, 2007]

Processing must be optimized!

Interfacial reactions between matrix and reinforcement may

- degrade the reinforcement
- result in undesirable (brittle) reaction products

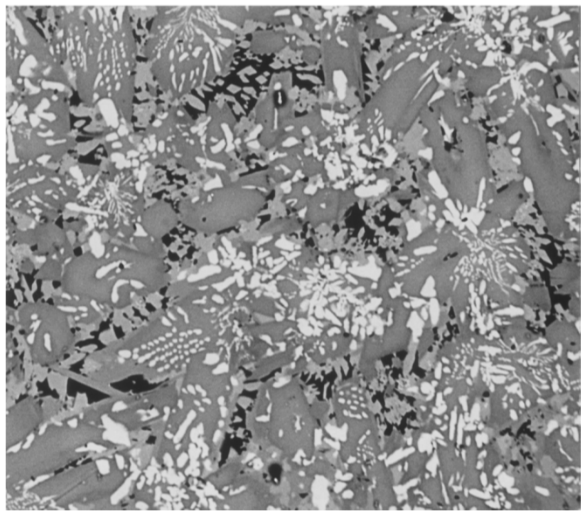
Brittle intermetallics formed by reaction between Al matrix and inconel fibres



(c) Al-20In/thin/850°C/400°C/400g 50 µm

In extreme cases, fibres may be completely consumed!

(a) Al-20In/750°C/250°C/400g 100 µm

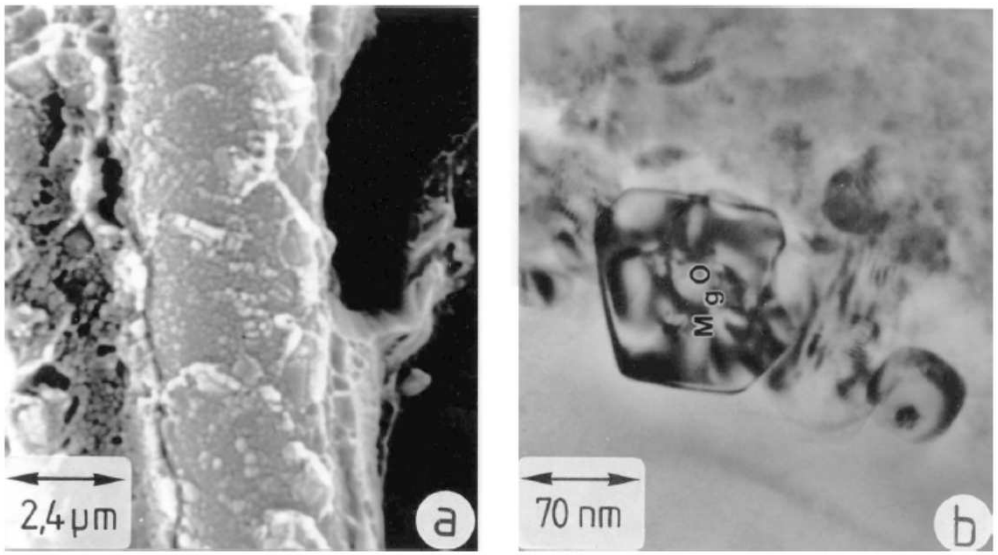


[F. Boland et al., MMTA, 1998]

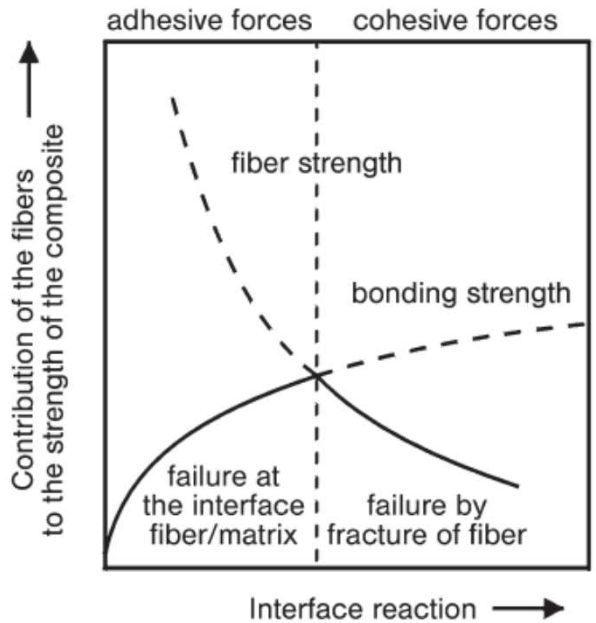
Processing must be optimized!

Interfacial reactions between matrix and reinforcement may

– A small amount of reaction may sometimes be beneficial



Mg + Al_2O_3 fibres



[K.U. Kainer, Basics of metal matrix composites, 2006]

Summary

- Composites allow to fill gaps in the material-property space and obtain new combination of properties
  - enhance mechanical properties (stiffness, wear resistance...)
  - obtain specific combination of thermophysic properties e.g.: material for electronic packaging
  - Functional materials (self-cleaning, self-lubricating, self-healing...)
- Warning: processing must be optimized to guarantee the desired properties
  - in metal matrix composites, quality of interface may be affected by reactions between the matrix and reinforcement