Probing the fracture toughness of bond coats and graded NiAl single crystals by micro-cantilevers

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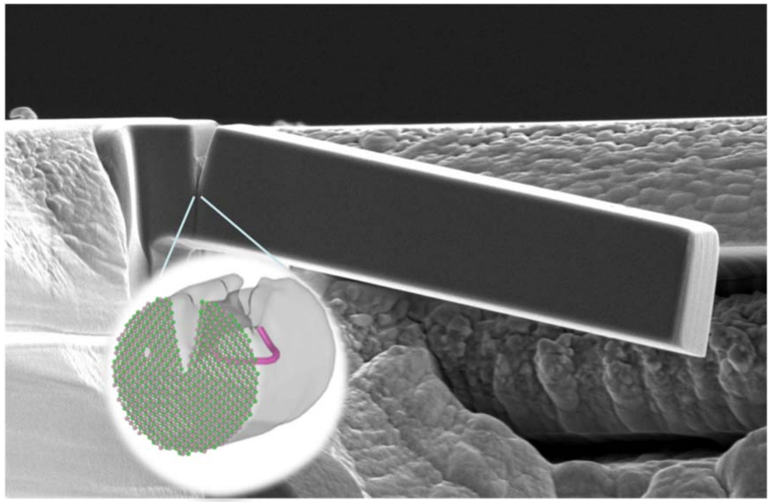
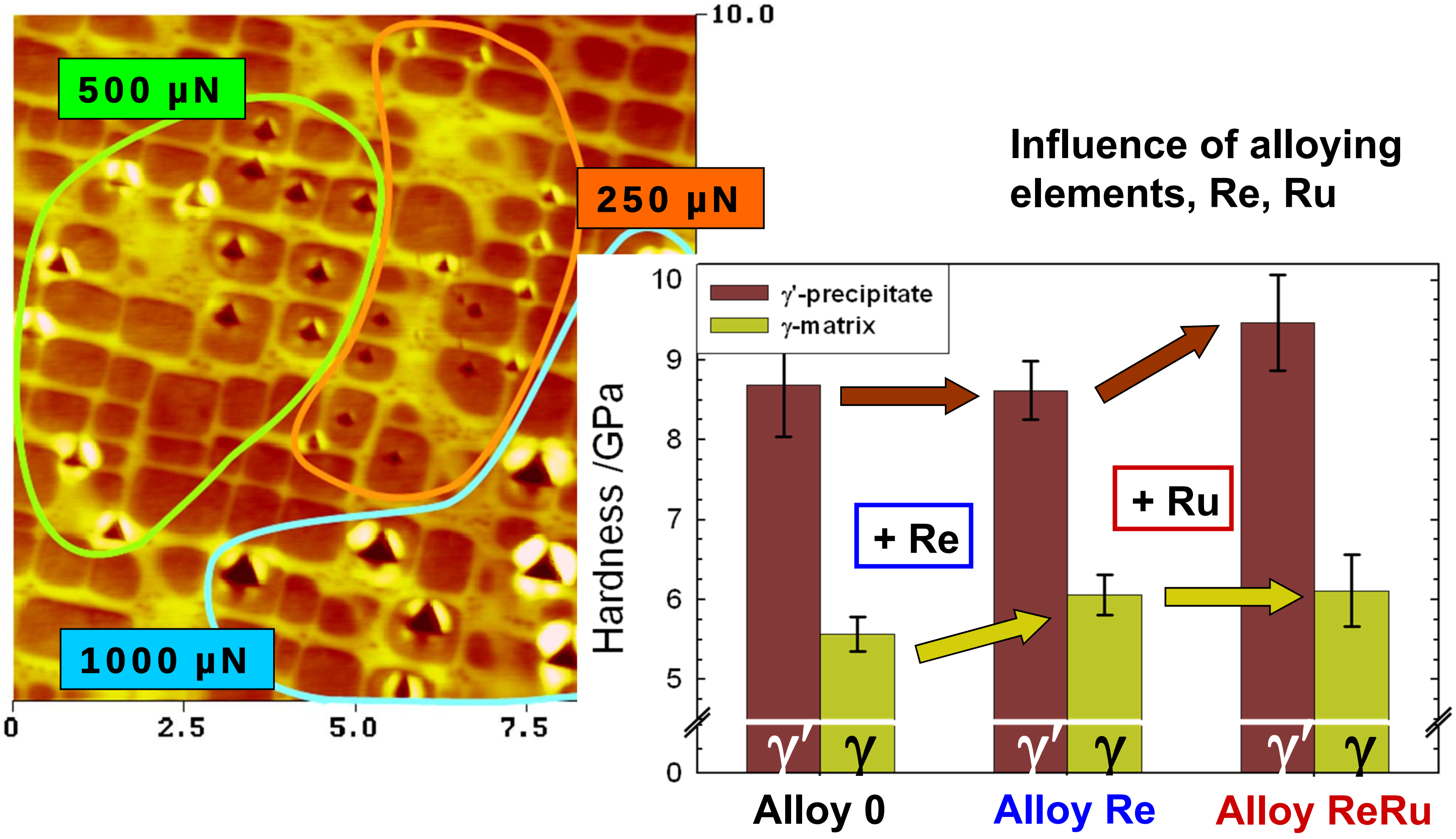
Outline

- Nanomechanical testing of high temperature materials

  (TiAl alloys, superalloys, bond coats)
- Fracture toughness testing with microcantilevers
  - FIB milling of microcantilevers
  - Fracture toughness evaluation
- Fracture toughness of graded NiAl crystals and bond coats



Nanomechanical Testing of High Temperature Materials

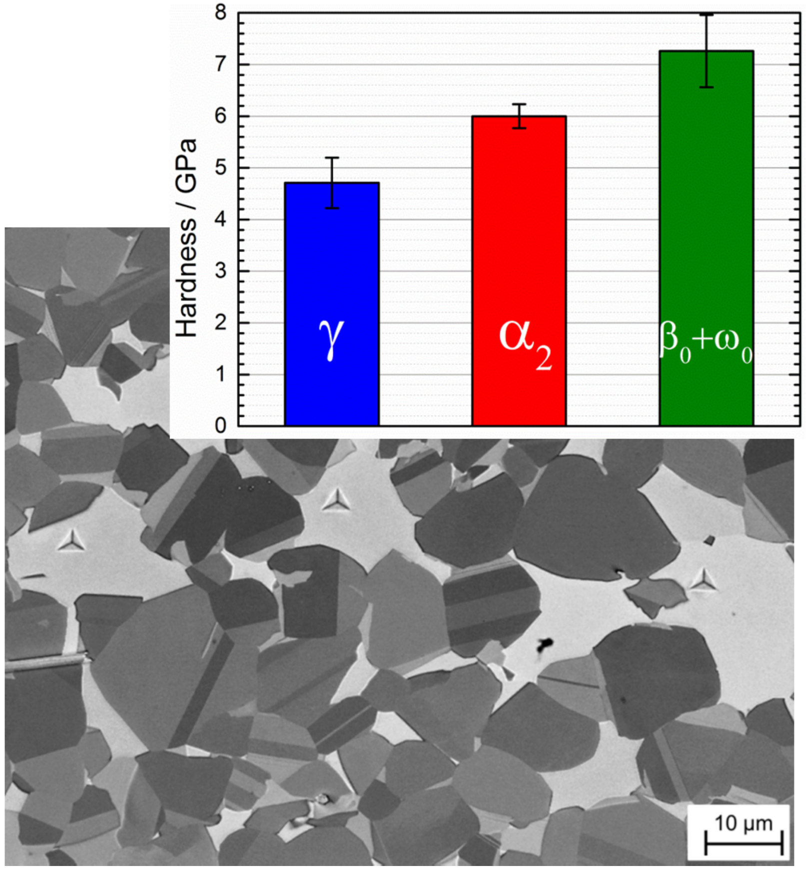


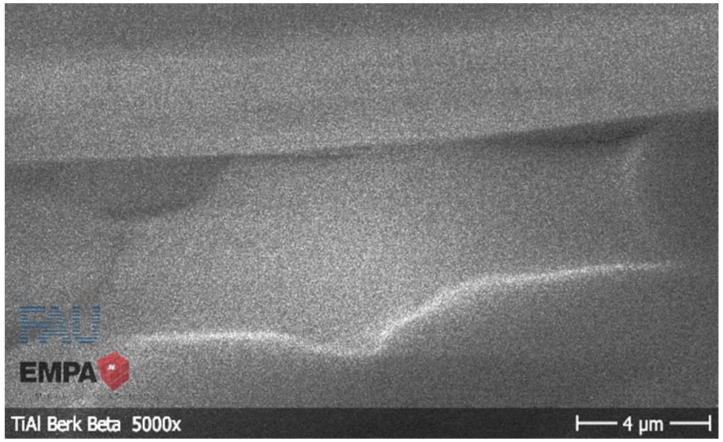
M. Göken; Acta mater 47, 1043 (1999)
K. Durst, Mat.Sci.Eng.A 387-389, 312 (2004)

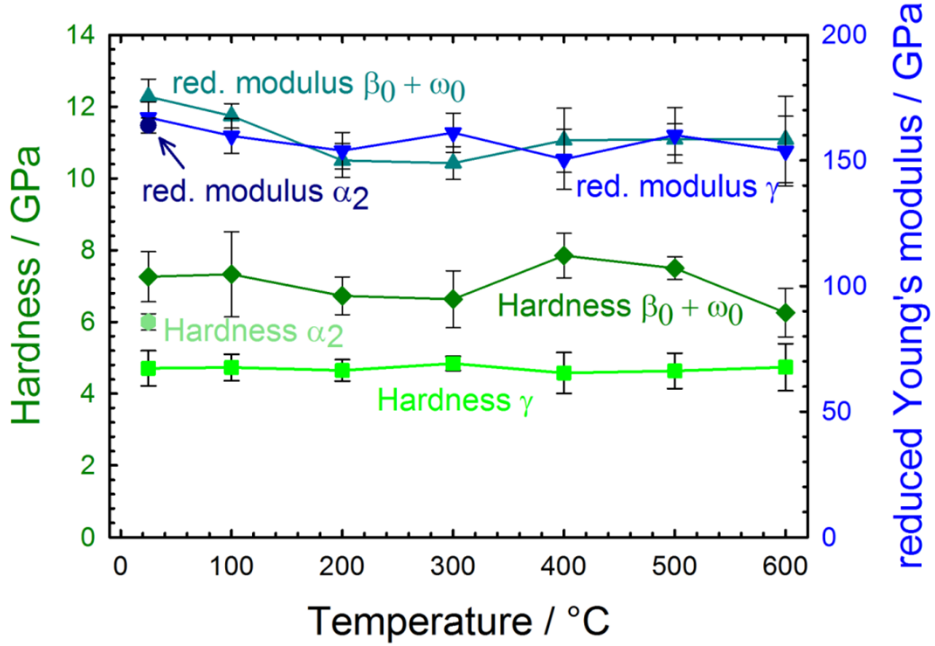
High Temperature (< 600°C) Nanoindentation of TiAl alloys

Advanced β-solidifying TiAl alloy

(Ti-44.5Al-6.25Nb-0.8Mo-0.1B alloy)





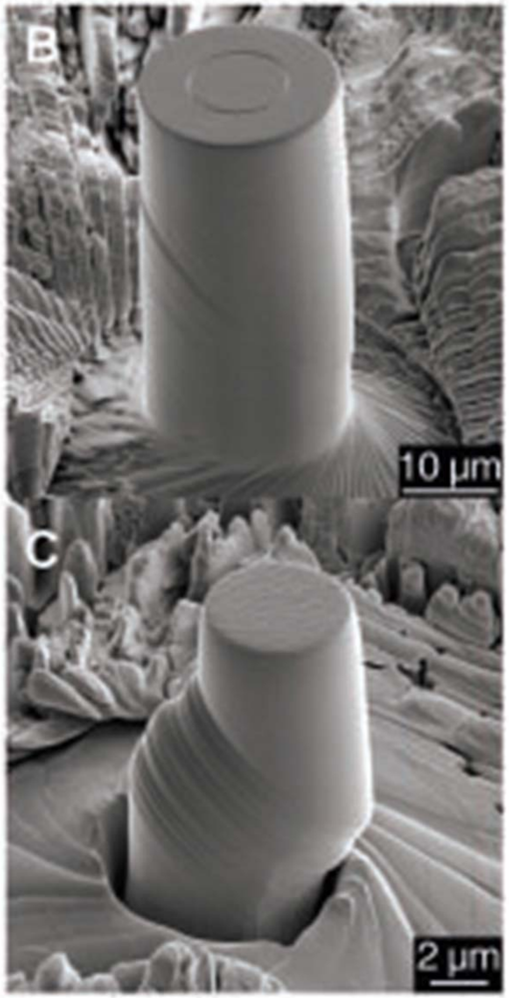


M. Kolb et al., Mat. Sci & Eng. A submitted (2016)

Nanomechanical Testing of FIB Prepared Microsamples

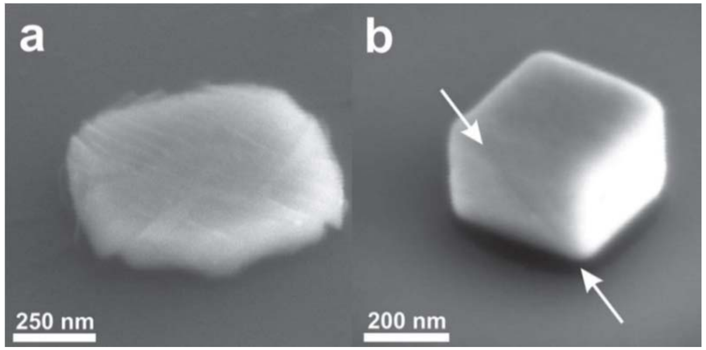
- *Pillar Testing*

M. Uchic Science 2004

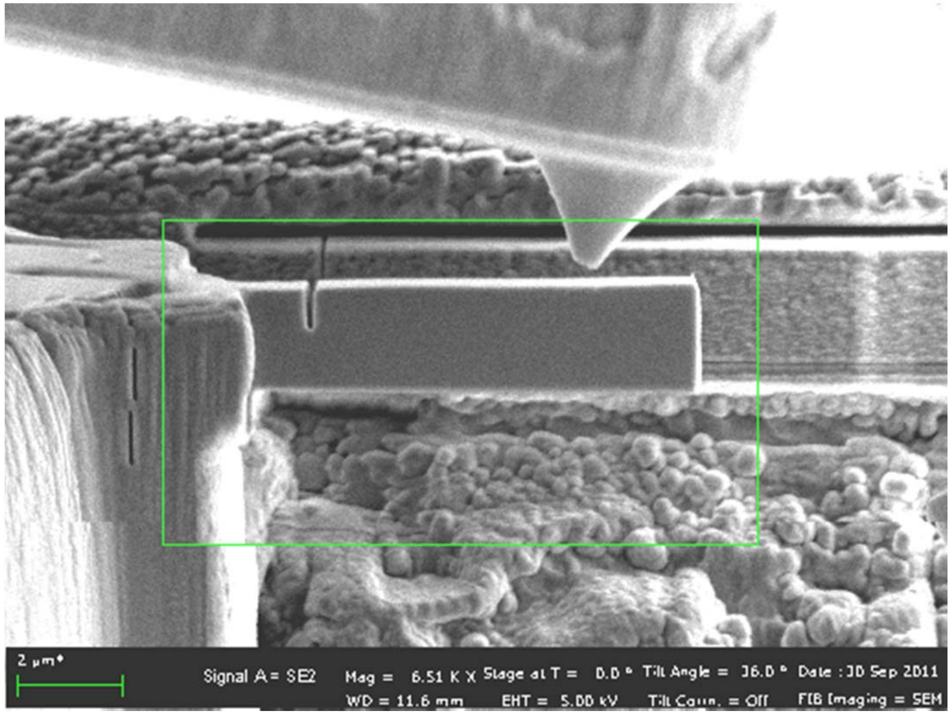


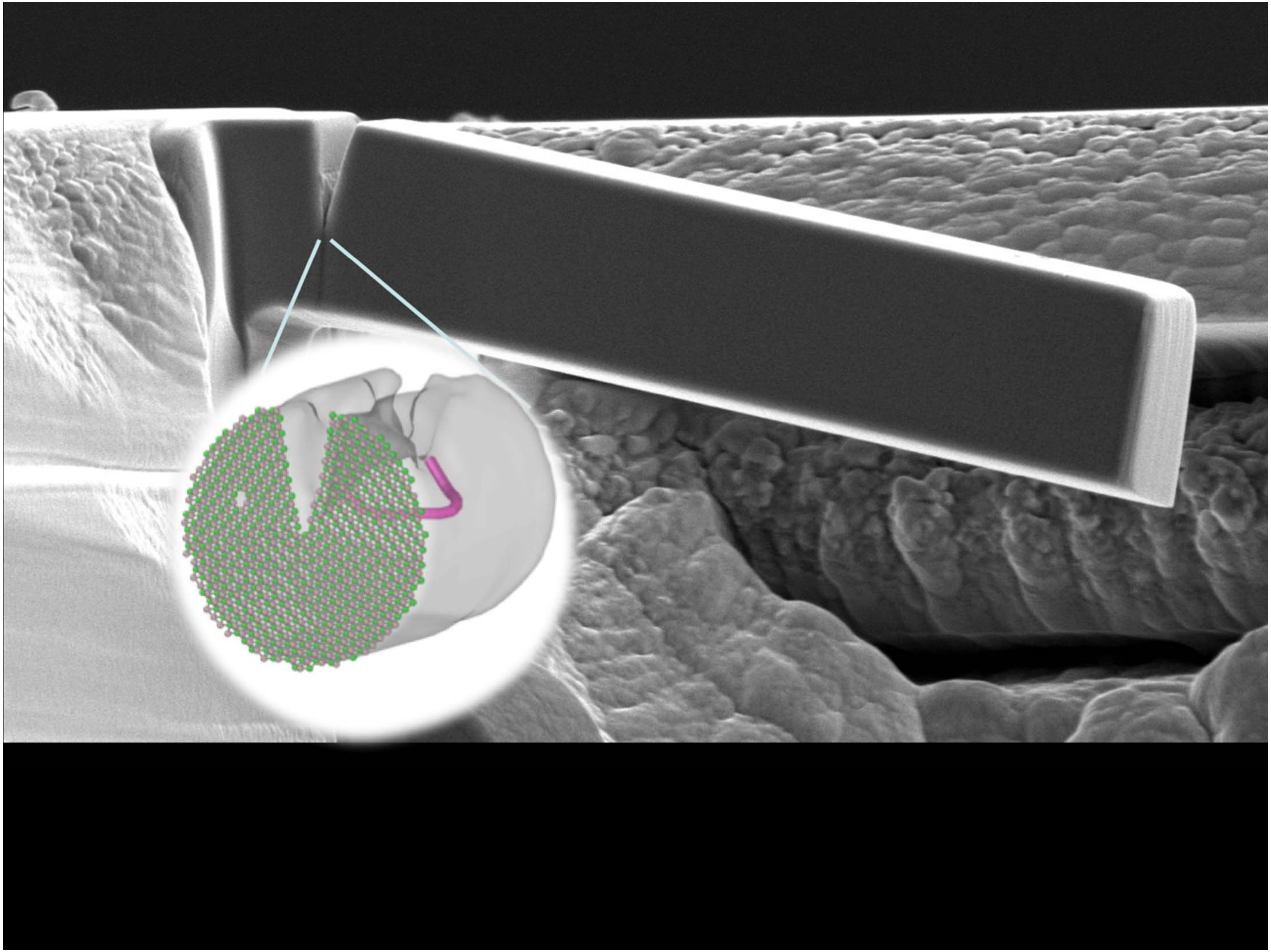
- Nanoparticle testing

R. Maaß et al,
Small 2012

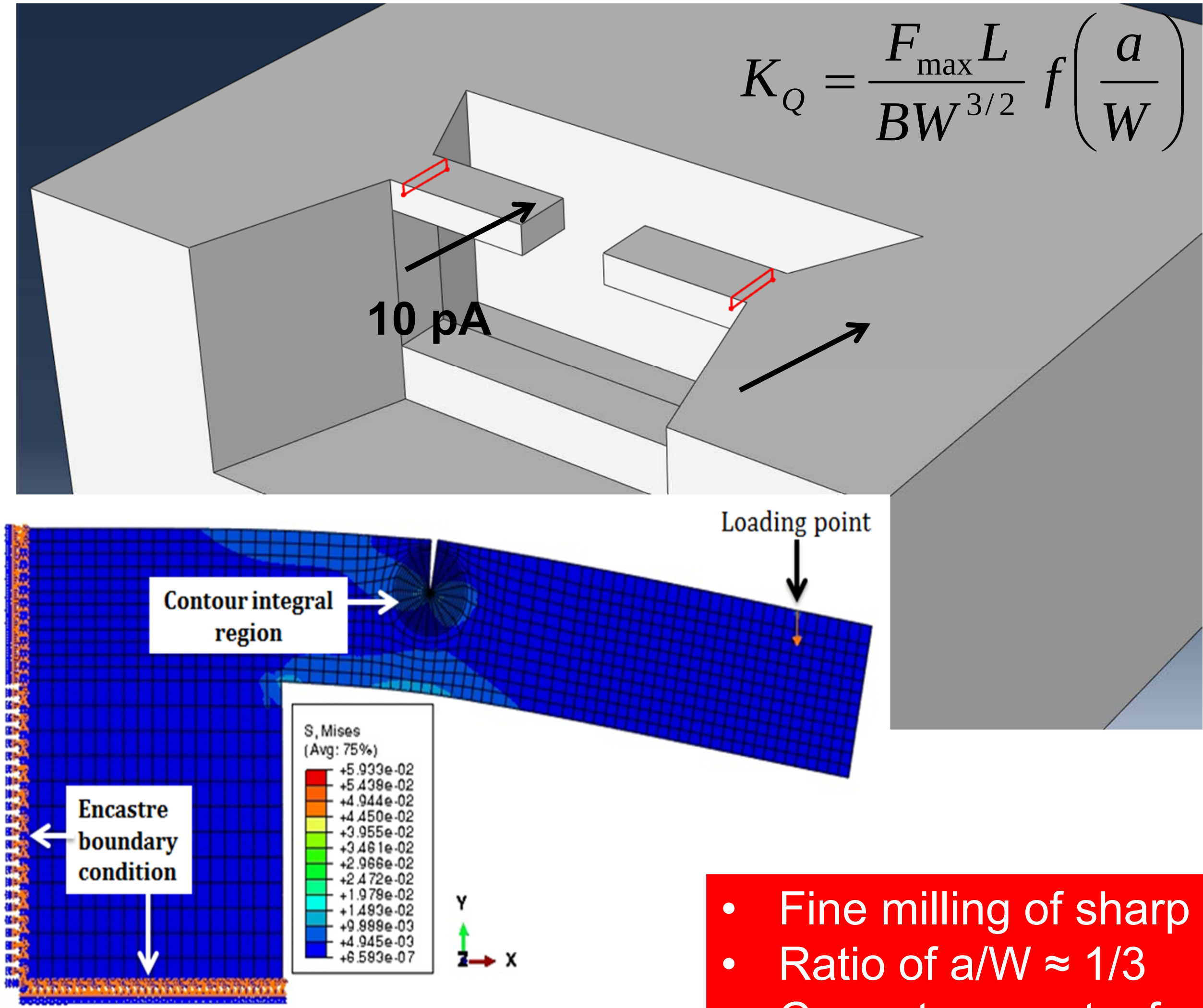


- Micro-cantilever experiments, F. Iqbal et al Acta 2012

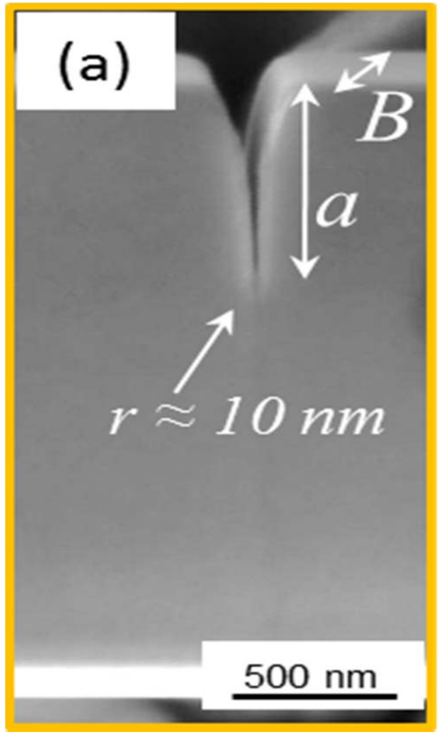




Experimental Procedure: FIB – Milling

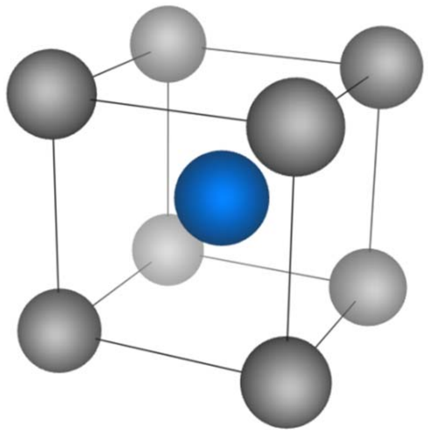


$$K_Q = \frac{F_{\max} L}{B W^{3/2}} f\left(\frac{a}{W}\right)$$



- Fine milling of sharp notches (top milling)
- Ratio of a/W ≈ 1/3
- Correct geometry function (FEM)

Properties of the B2 Intermetallic Compound NiAl



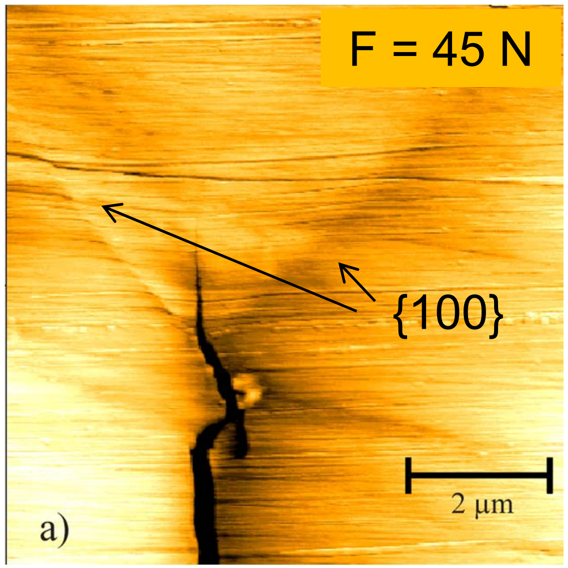
Mechanical properties

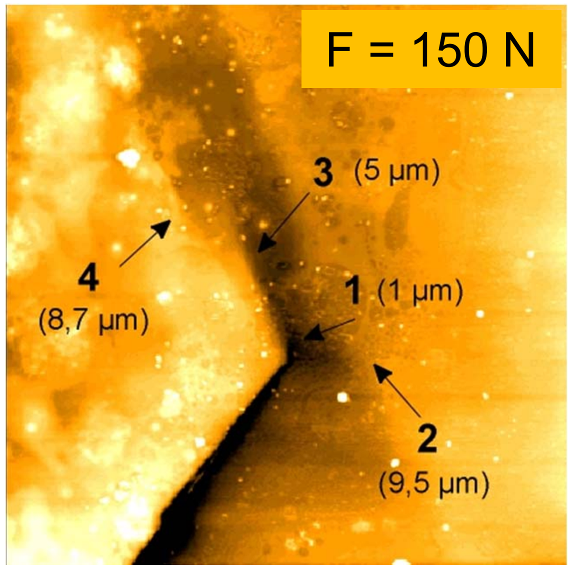
- Strong anisotropy
- „Hard orientation“ loading along <100> direction
- „Soft orientation“ loading along >110> direction
- Limited amount of plasticity

Crack propagation (Thome, Göken, Vehoff, *Intermetallics* 7, 1999)

„soft“

<110>

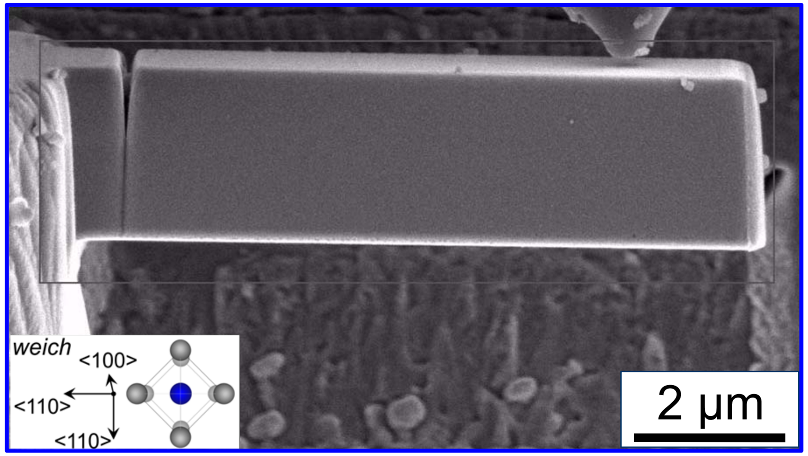


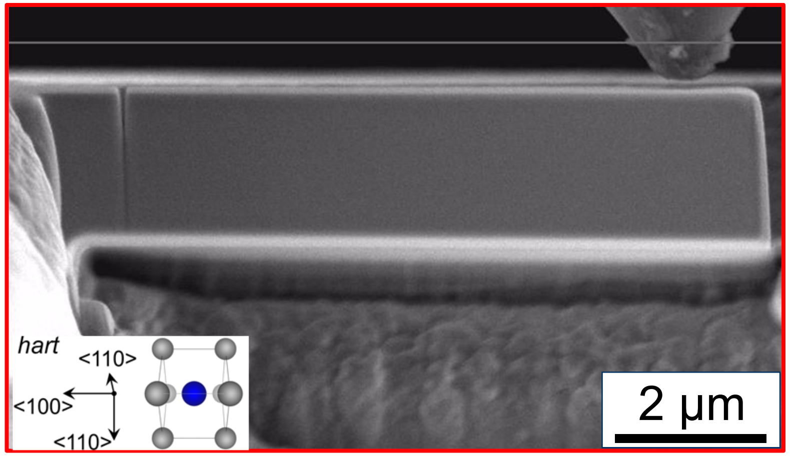


„hard“

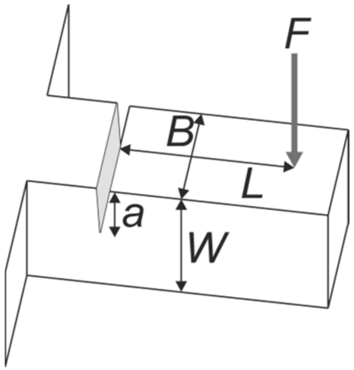
<100>

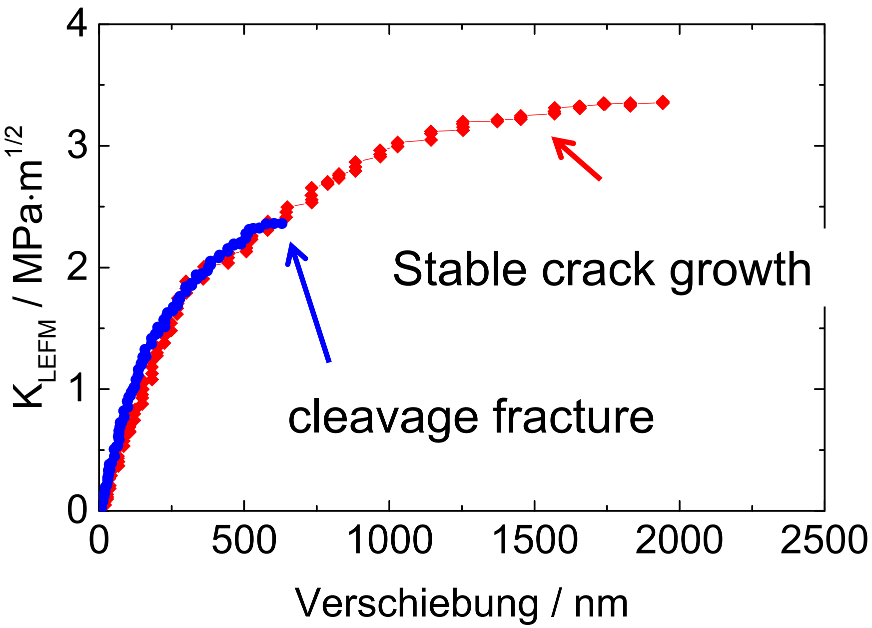
Fracture Behaviour of „Soft“ and „Hard“ NiAl Crystals



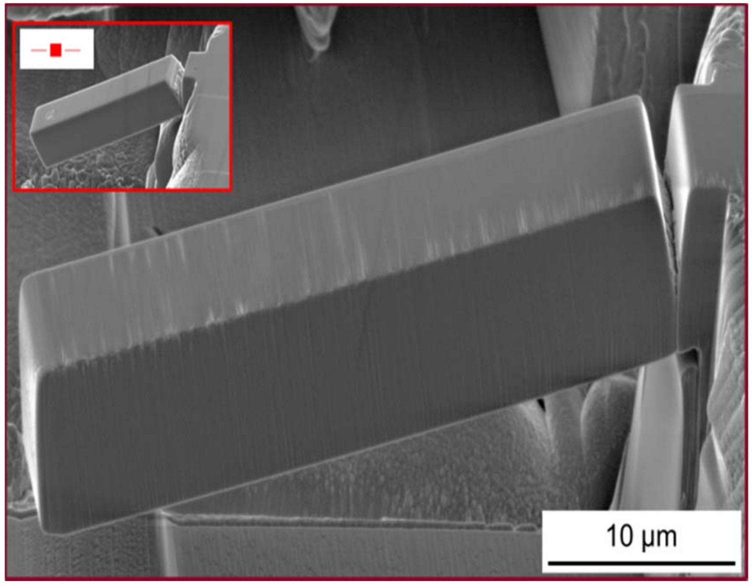


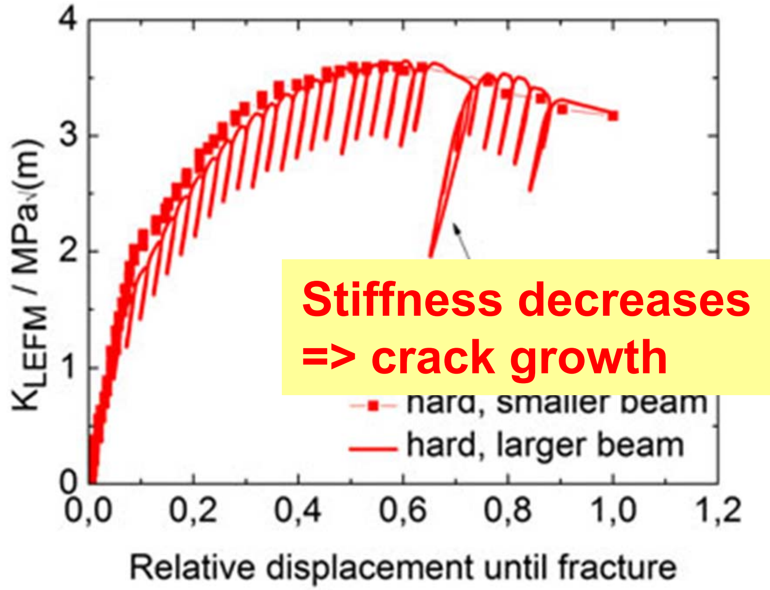
$$K_{LEFM} = \frac{F\,L}{B\,W^{3/2}}\, f\left(\frac{a}{W}\right)$$





Microcantilever Testing of NiAl with a Nanoindenter

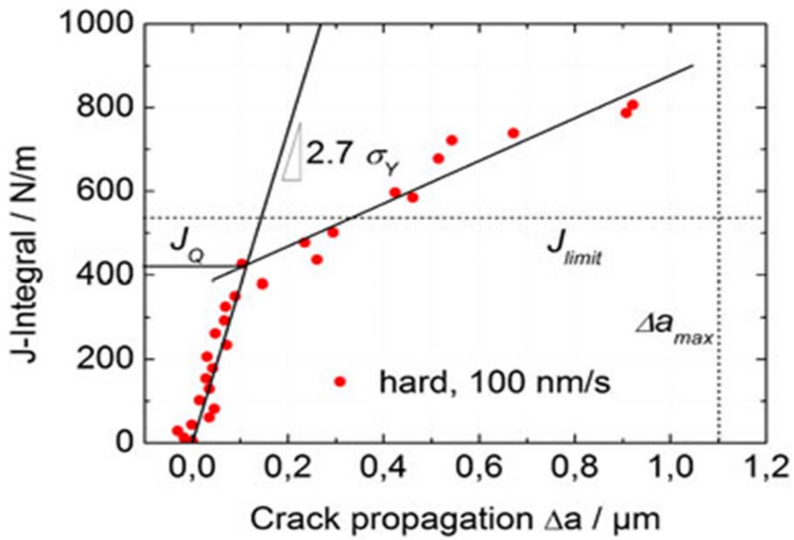




J-Integral approach

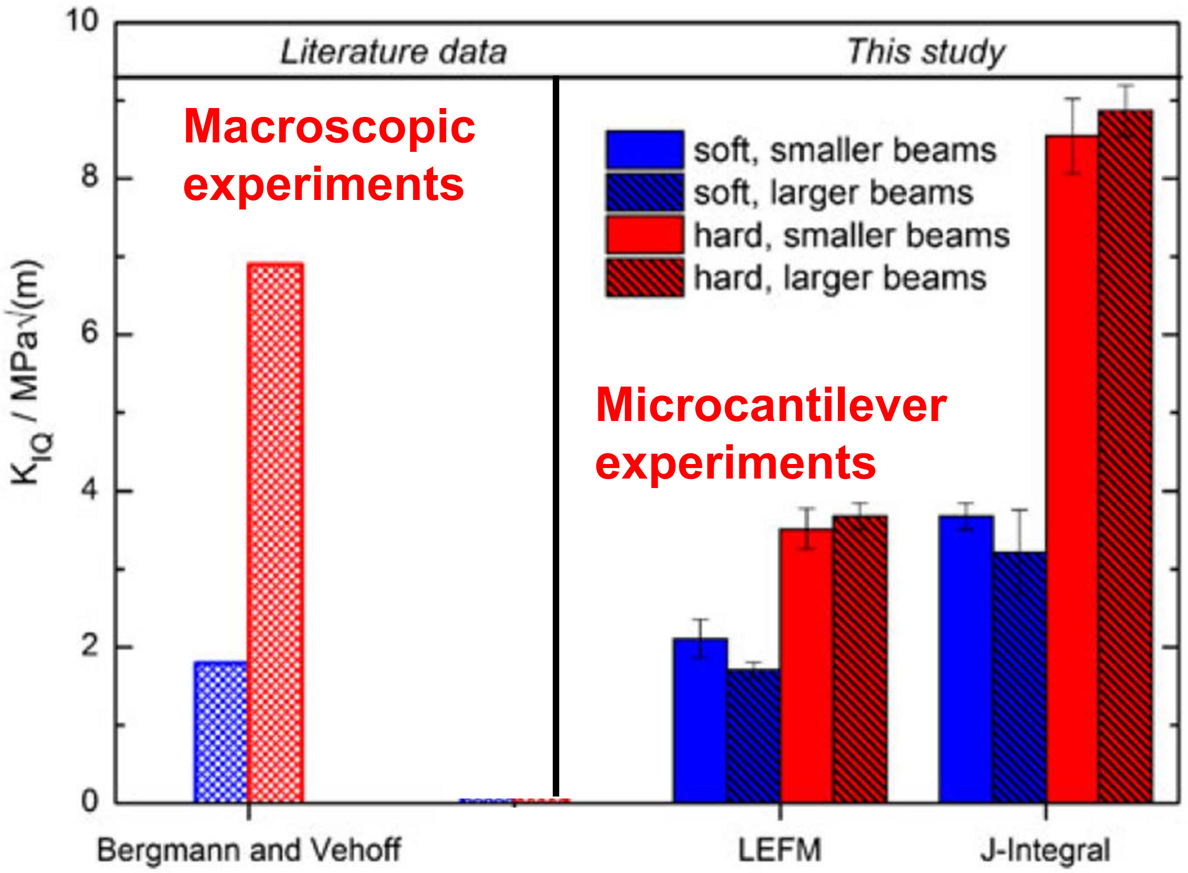
$$J = J_{elastic} + J_{plastic}$$

$$J = \frac{K^2(1-\upsilon^2)}{E} + \frac{2\,.\,A_{pl}}{B.(W-a_0)}$$

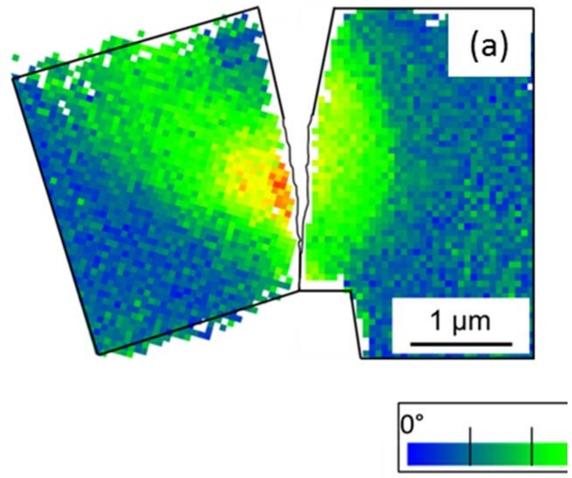


J. Ast et al., *J. Mater. Res*. 29 (18), 2014

NiAl – Fracture Toughness of Soft/Hard Single Crystals



EBSD picture shows crack tip plasticity

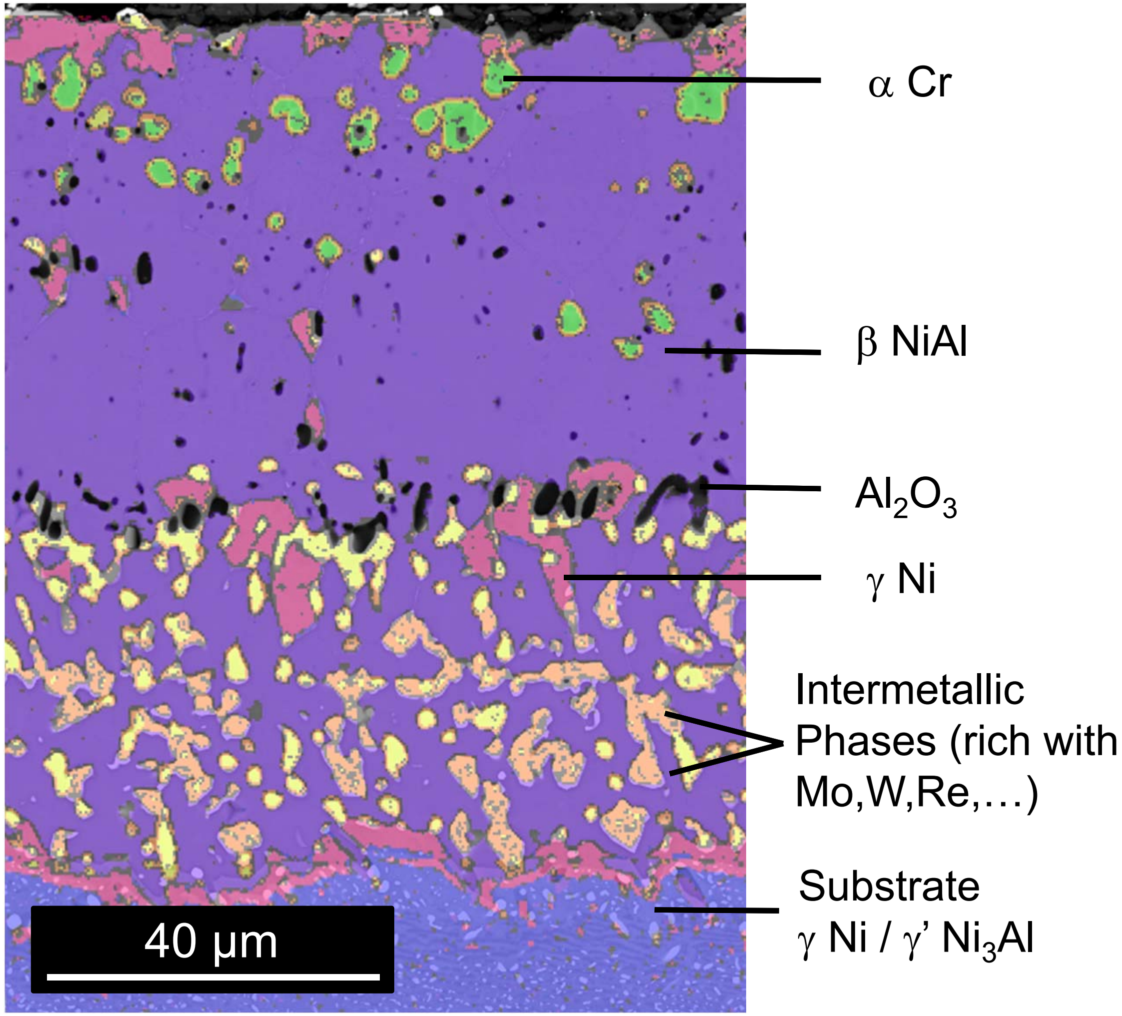


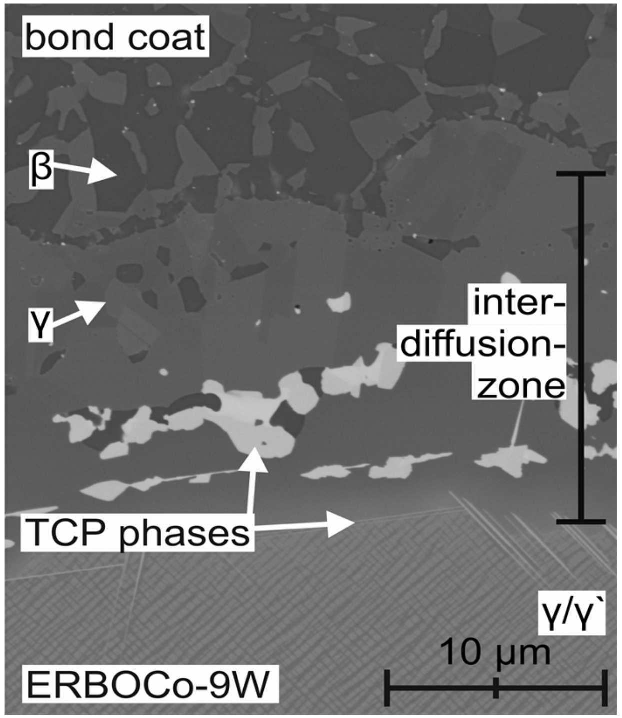
- Microcantilever experiments give reliable results
- No size effect in fracture toughness

J. Ast et al. J. Mater. Res. 29, 2129 (2014)

Oxidation Protection Bond Coats

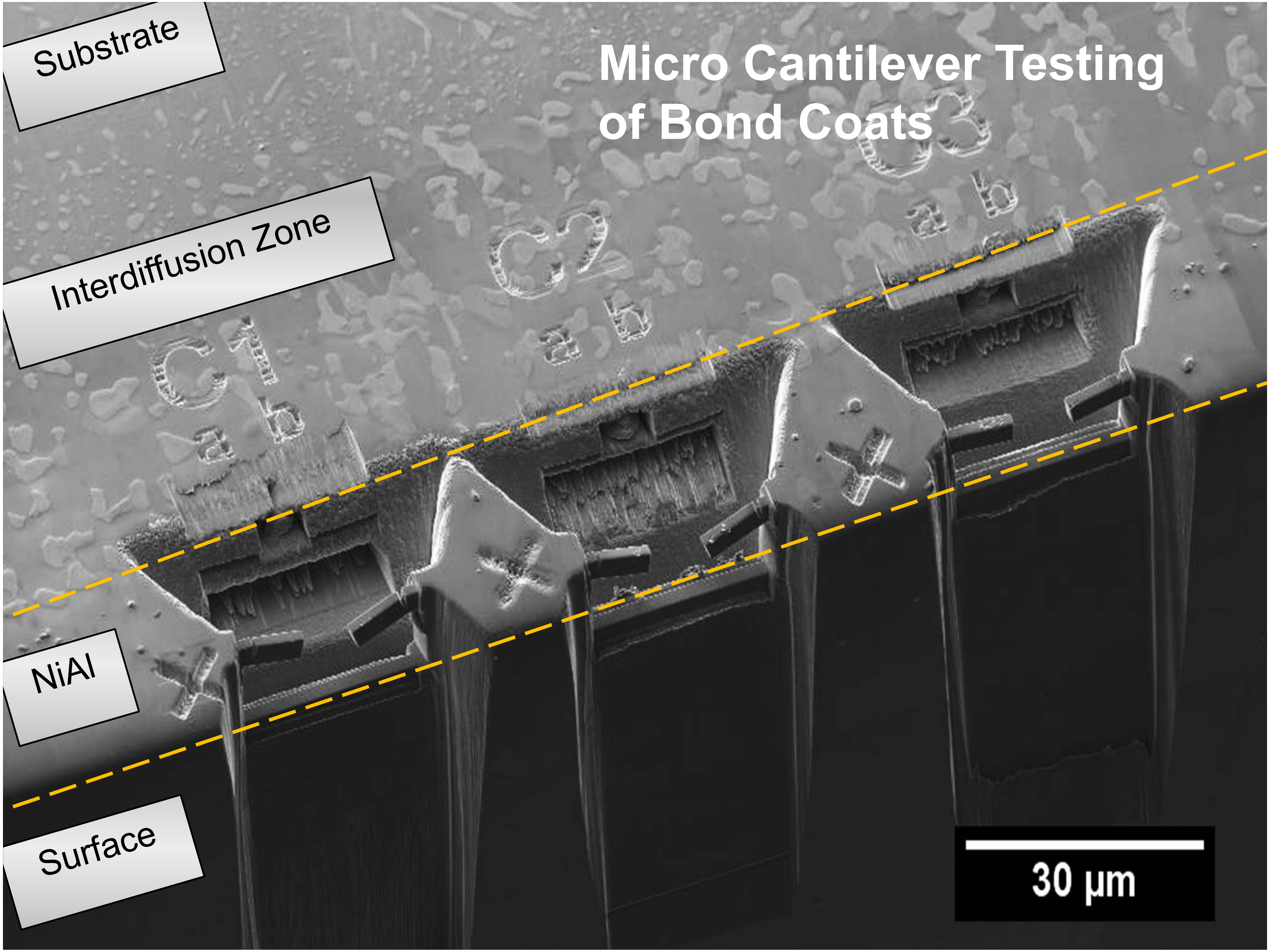
EDX Phase Mapping





Bond coats on
Co-Base superalloys

R. Webler et al. Pract. Metallogr. 51, 568 (2014)

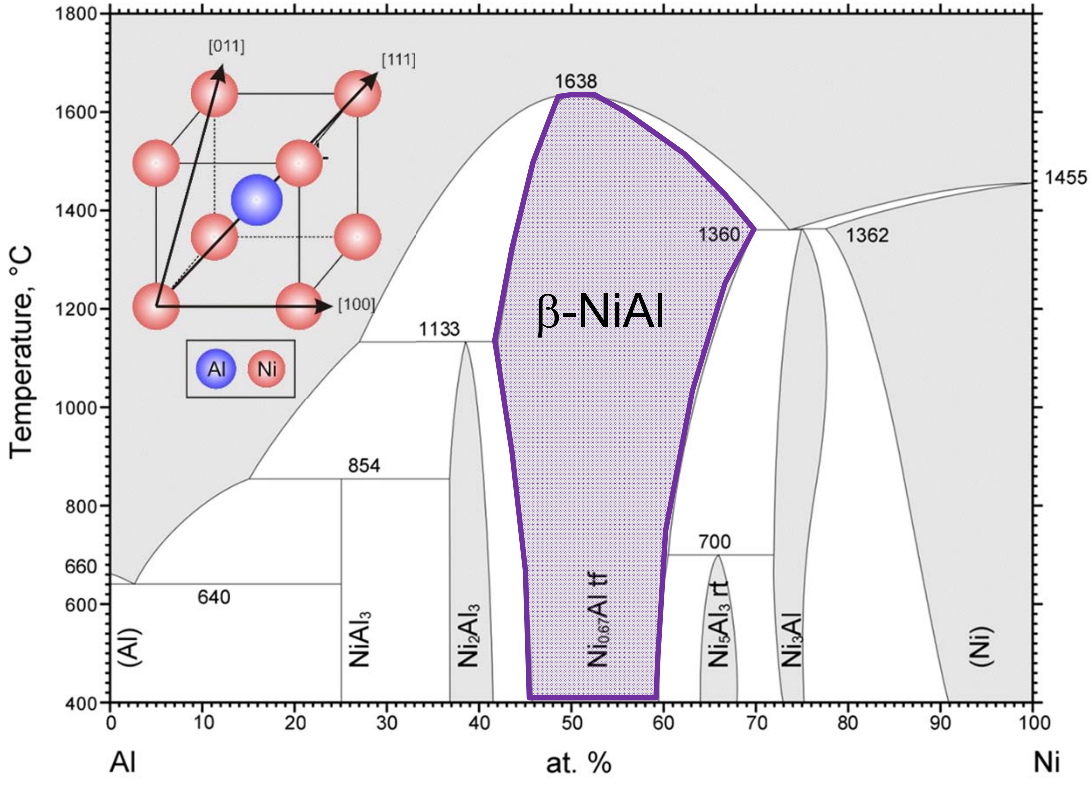


Micro Cantilever Testing
of Bond Coats
Substrate
Interdiffusion Zone
NiAl
Surface
C1
C2
C3
a b
a b
a b
30 µm

The intermetallic β-NiAl phase

B2 (CsCl-type) crystallographic structure

ASM International, Diagram No. 100023



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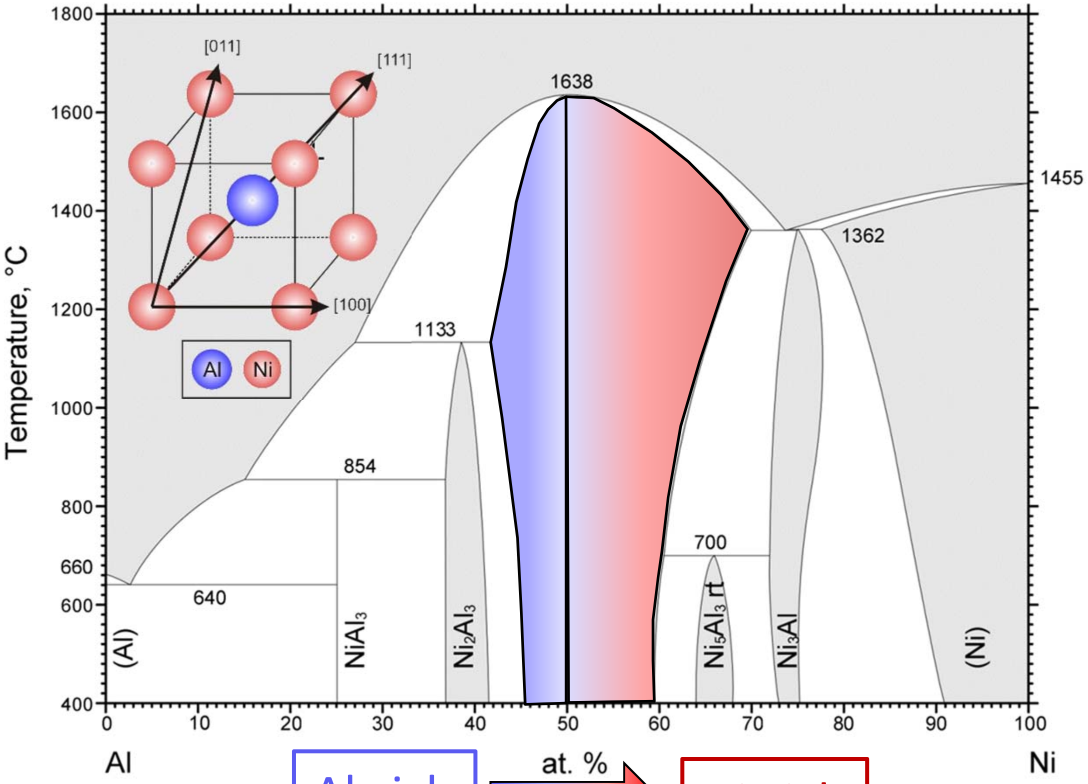
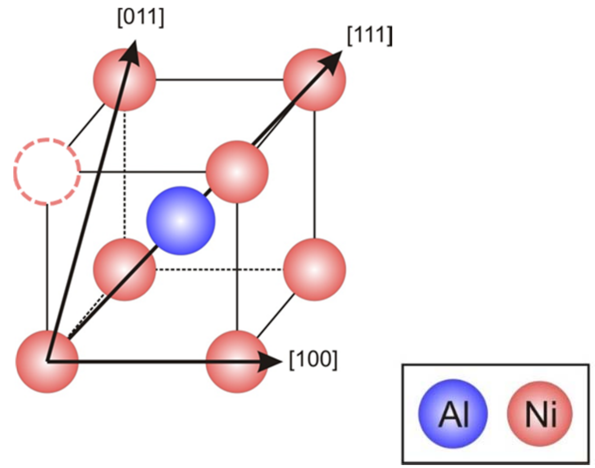
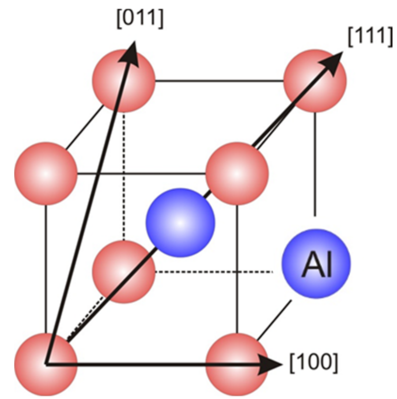


Al-rich → Ni-rich

Al-rich: Ni-vacancies



Ni-rich: Ni-anti site atoms



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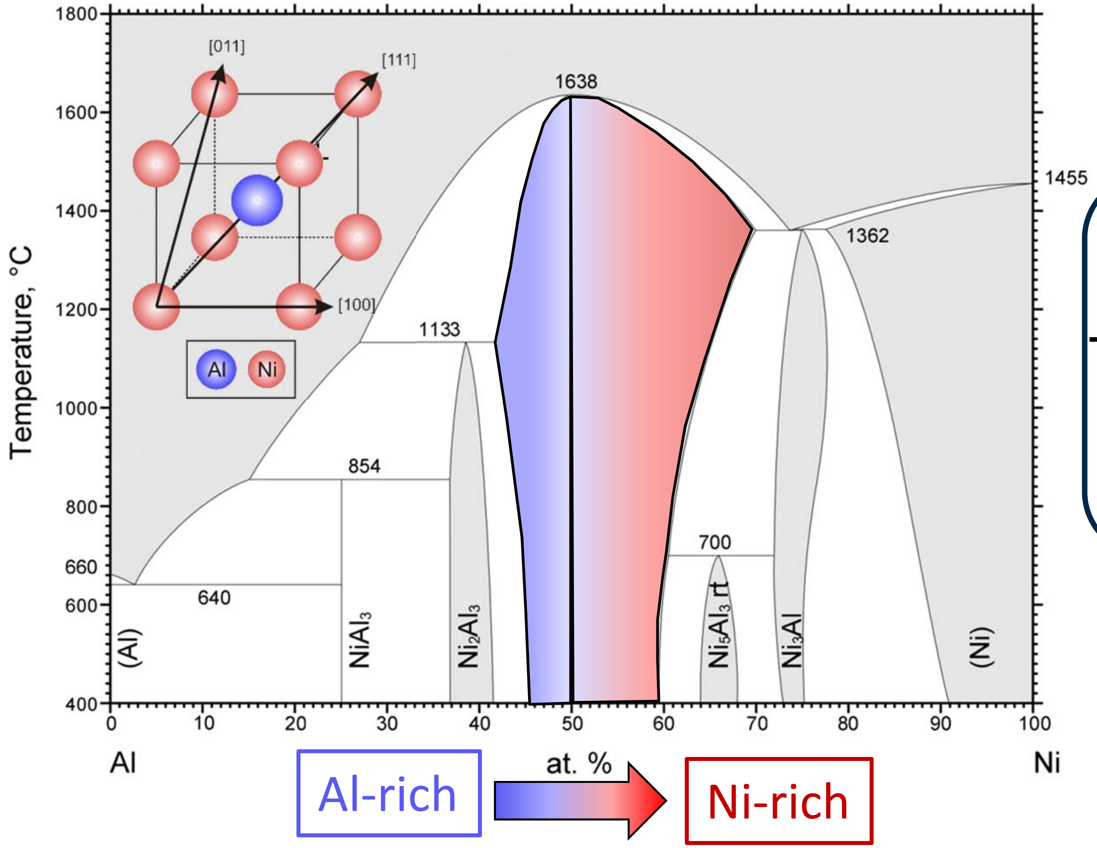
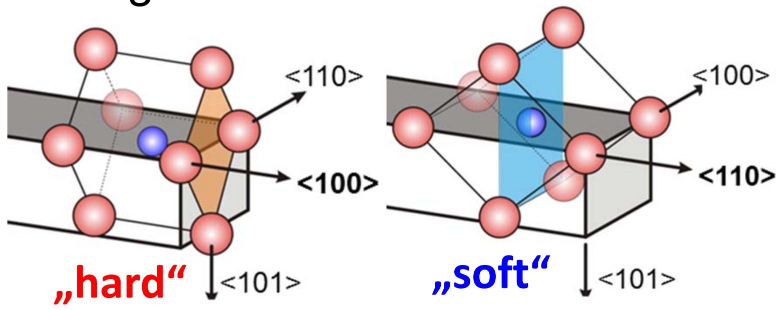
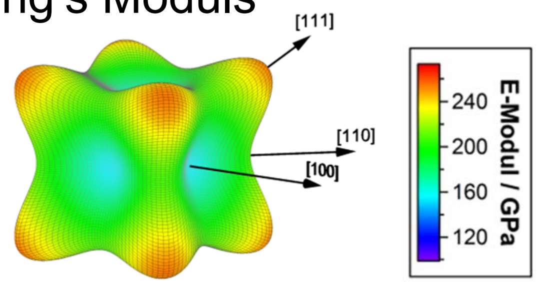


Strength:



	hard	soft
orientation	<100>	<110>
σ_y (MPa)	1400 a)	150 b)
K_{IC} (MPa $m^{1/2}$)	8 c)	4 c)

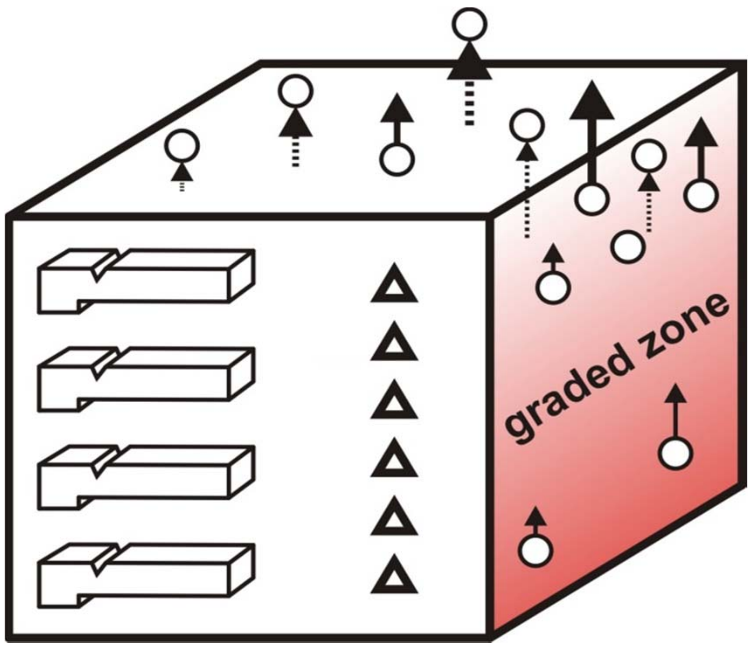
Young's Moduls

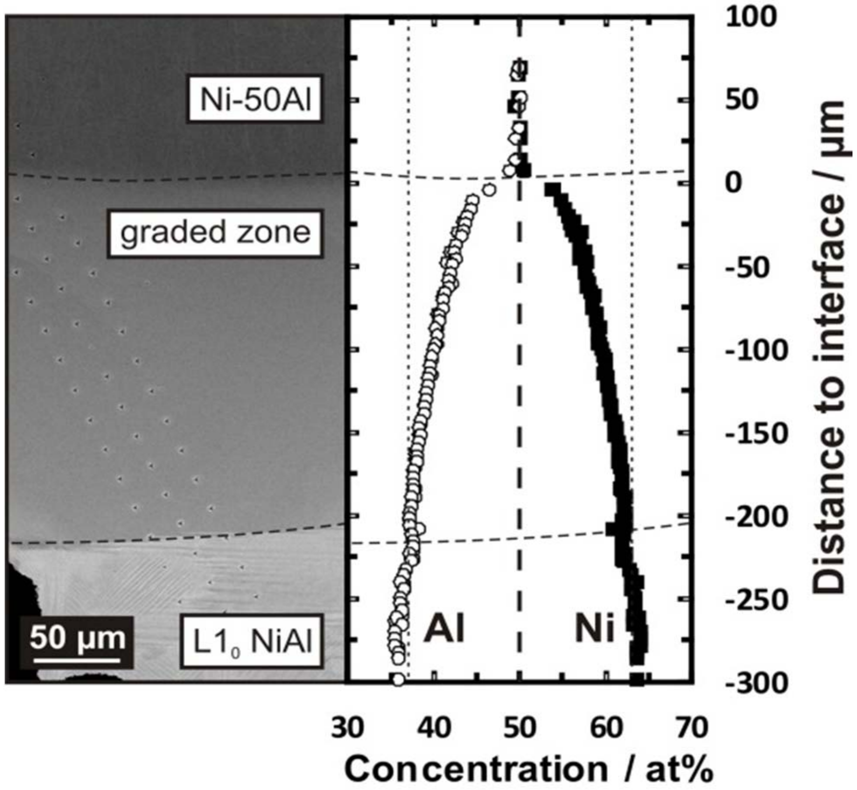


a) R.D. Noebe et al, Int. Mater. Rev., 38, 4 (1993) 193-232
b) F. Ebrahimi et al, Acta materialia, 46, 5 (1998) 1493-1502
c) F. Thome et al., Intermetallics, 7 (1999) 491-499

Preparation of Graded NiAl Single Crystals

By annealing stoichiometric single crystals at 1100 °C/100h

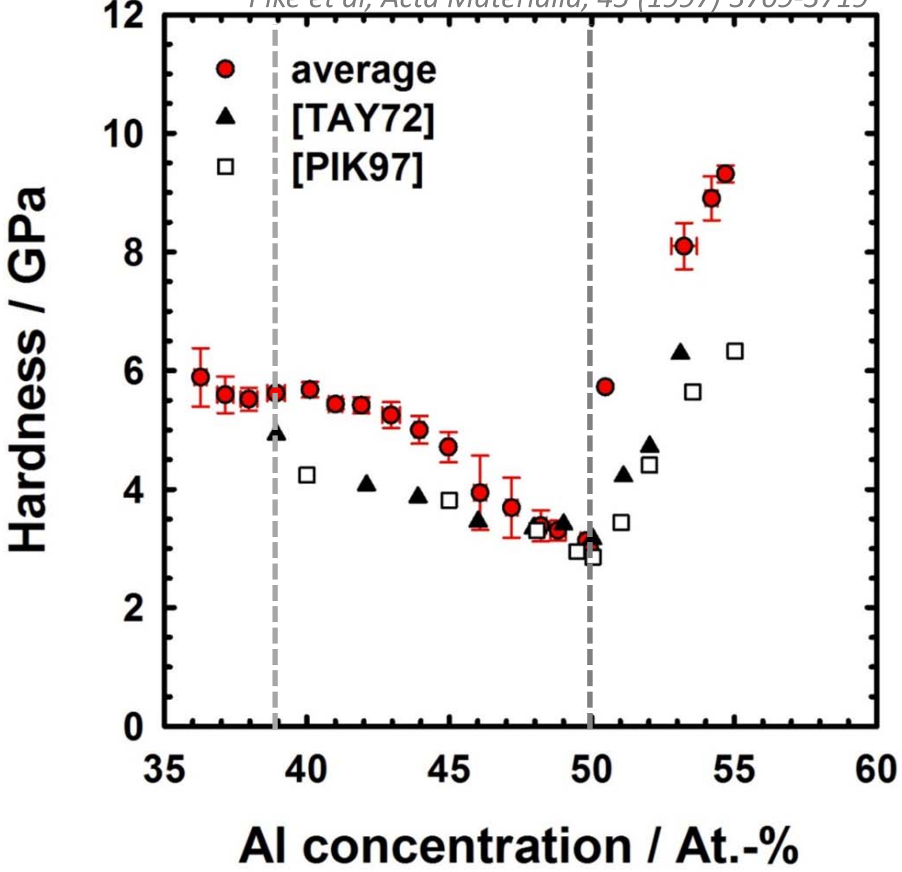




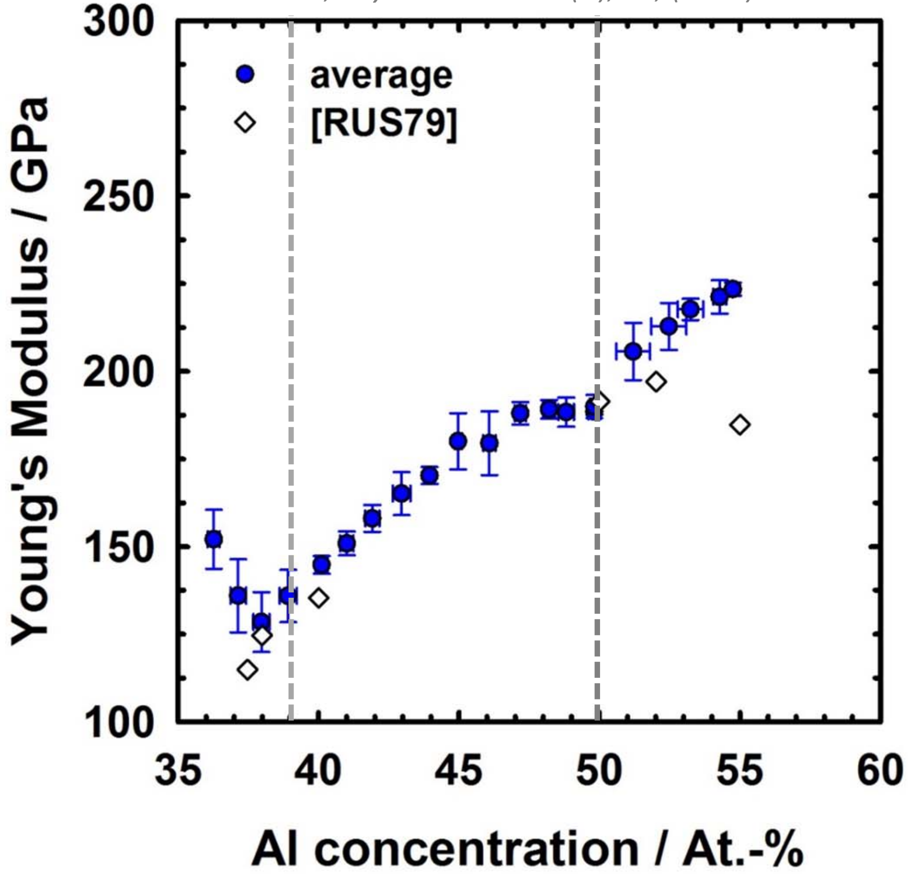
=> Single crystalline graded samples !

Nanoindentation – Hardness & Young's Modulus

Taylor, J. Appl. Cryst., 5, (1972) 201-209
Pike et al, Acta Materialia, 45 (1997) 3709-3719



Rusovic, Phys Status Solidi (A), 53, (1979) 283-288

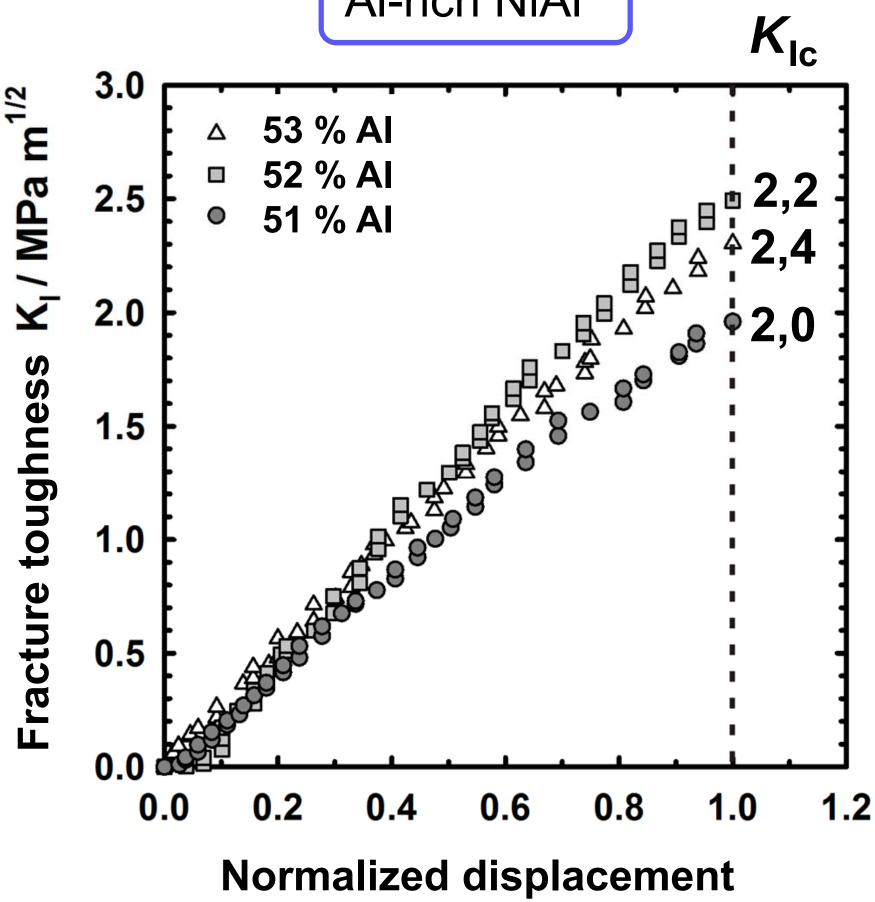


→ Defects impede dislocation motion
→ Increasing hardness

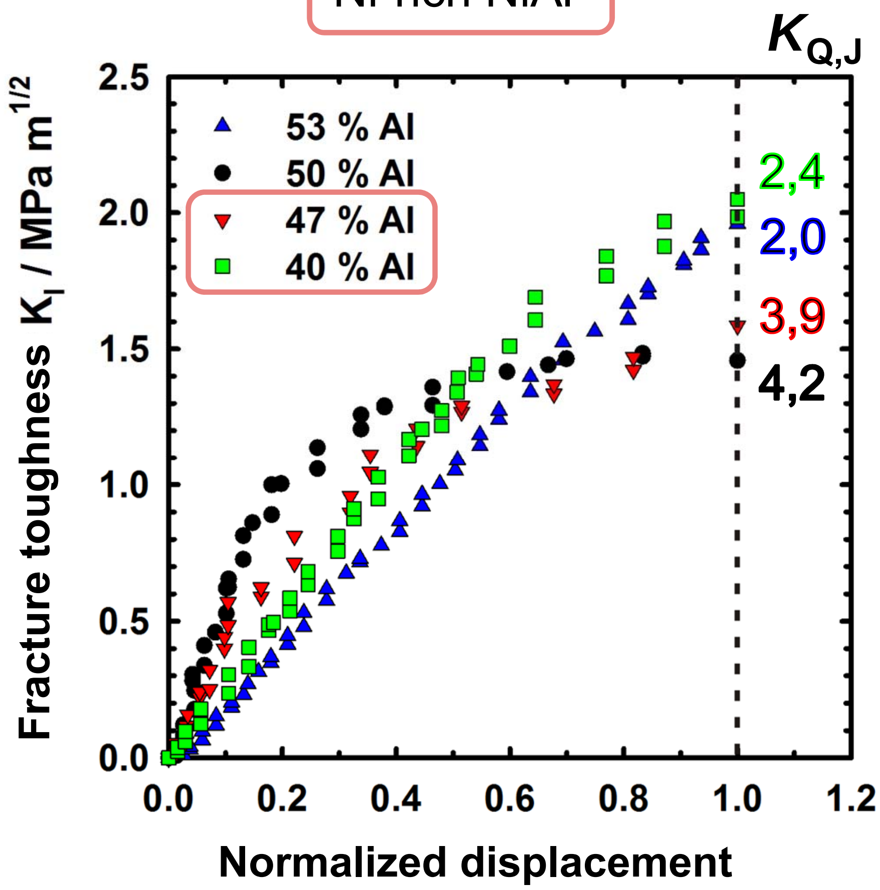
→ Young's modulus decreases with Al ↓

Microcantilever Tests on Off-Stoichiometric SX-NiAl

Al-rich NiAl



Ni-rich NiAl

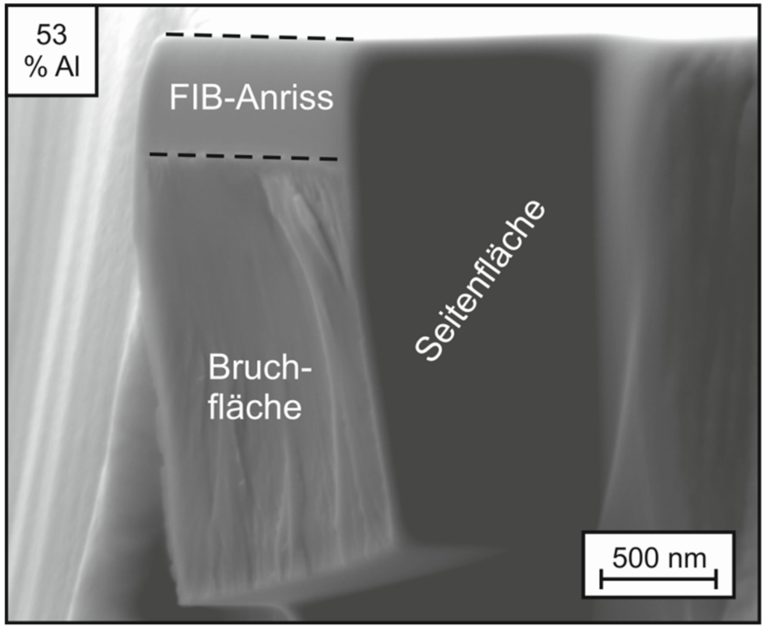


→ Pure brittle behaviour

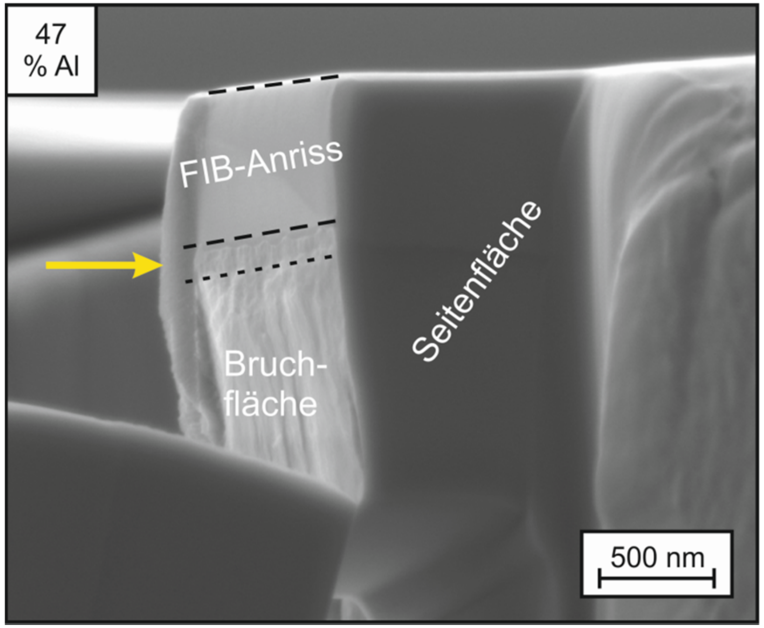
→ Plastic deformation occurs

Fracture surface

Al-rich NiAl

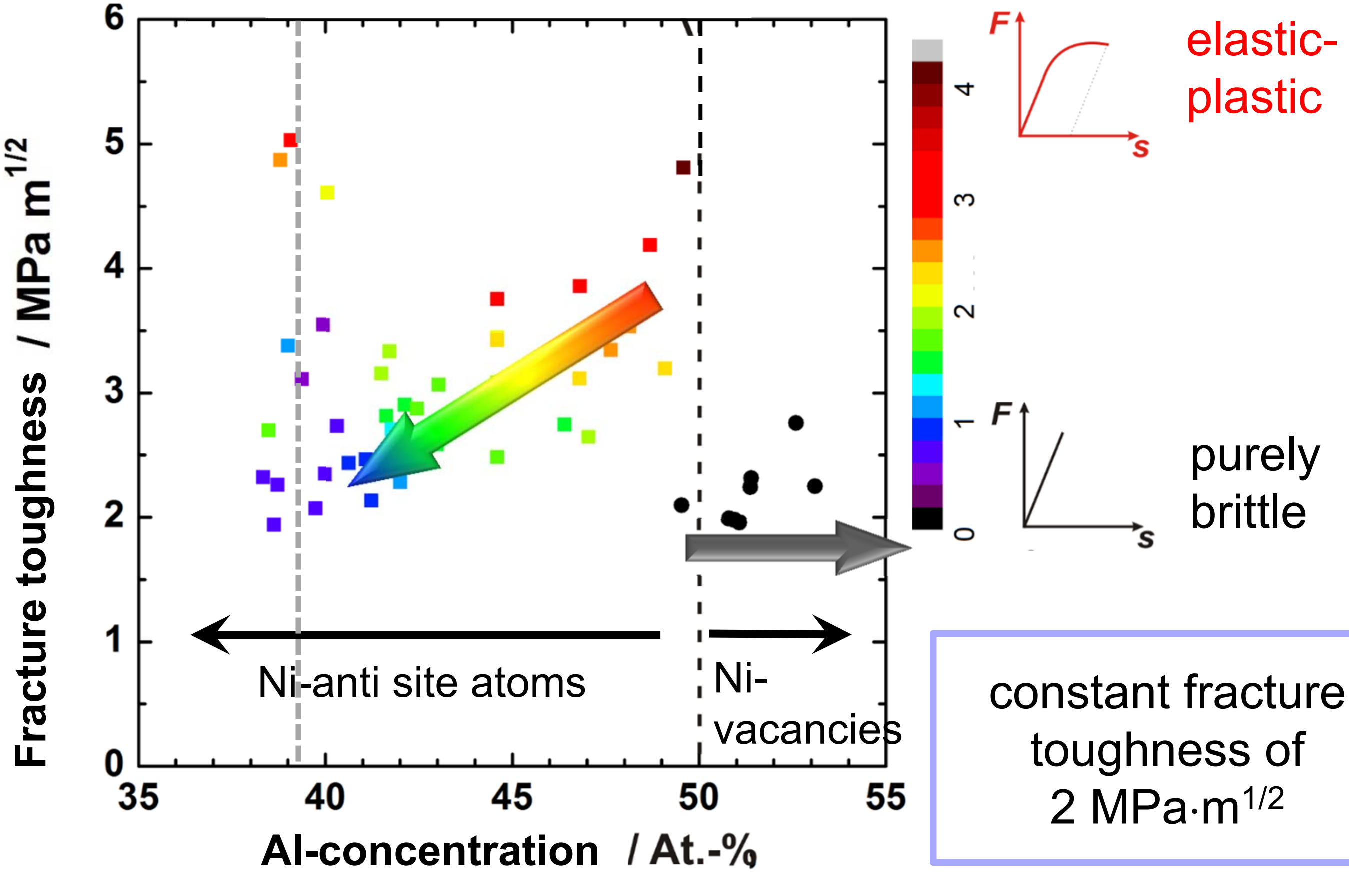


Ni-rich NiAl



→ Ni-rich NiAl: short period of stable crack growth

Influence of Al-content on Fracture Toughness in NiAl

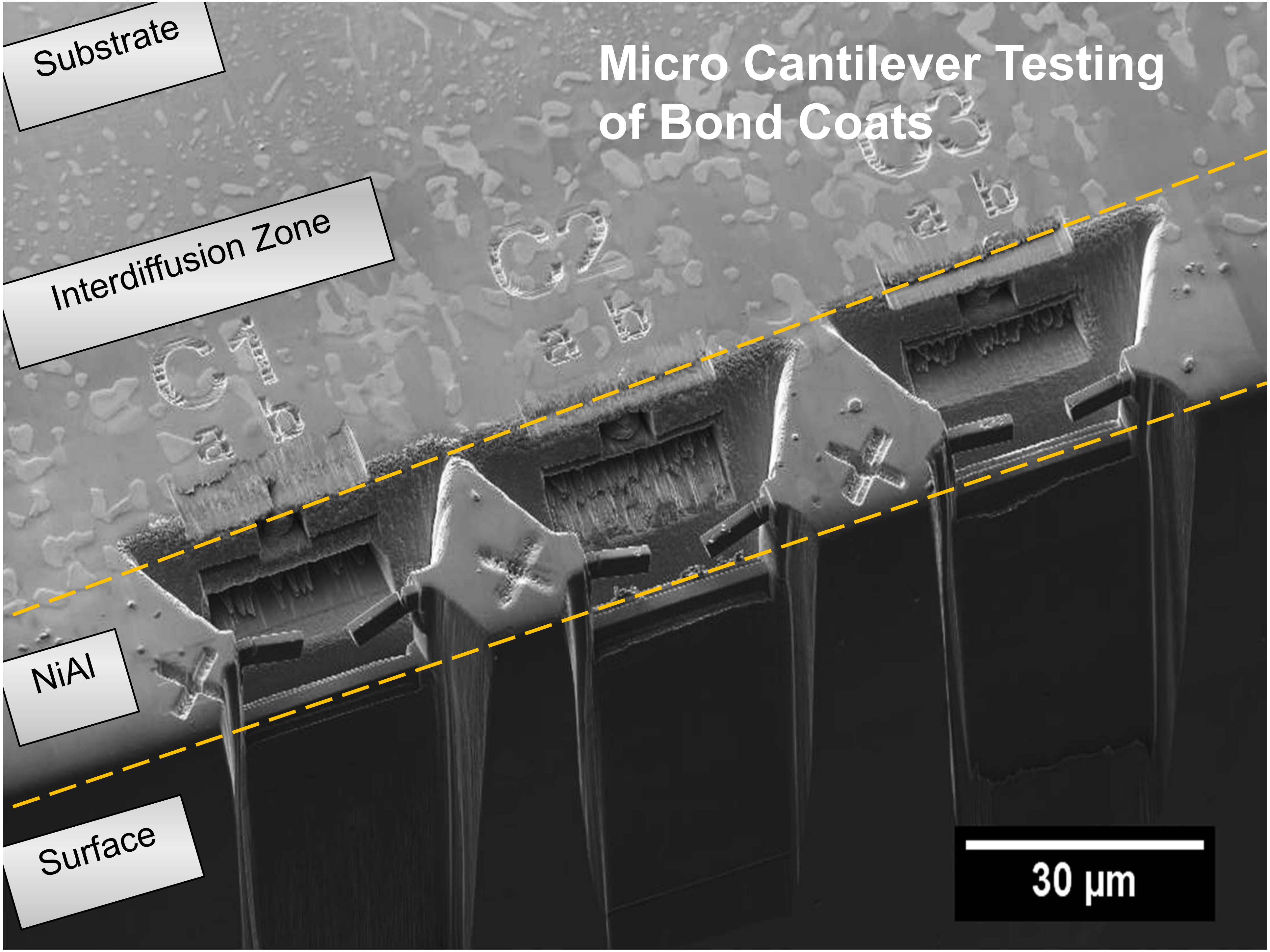


decreasing fracture toughness

constant fracture toughness of 2 $MPa \cdot m^{1/2}$

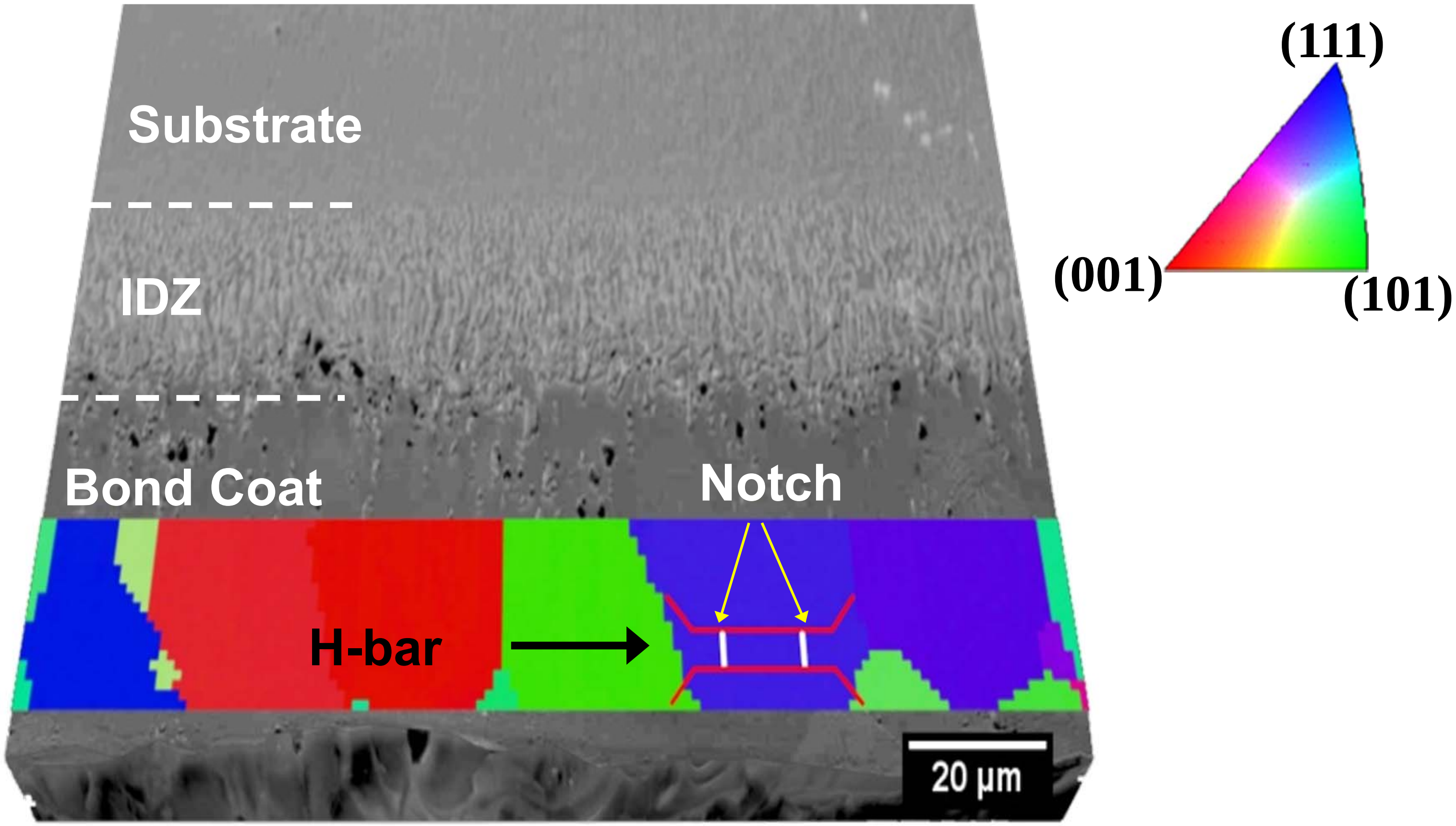
Ni-anti site atoms: plastic deformation

Ni-vacancies: no dislocation motion


Micro Cantilever Testing of Bond Coats
Substrate
Interdiffusion Zone
NiAl
Surface
C1
C2
C3
30 µm

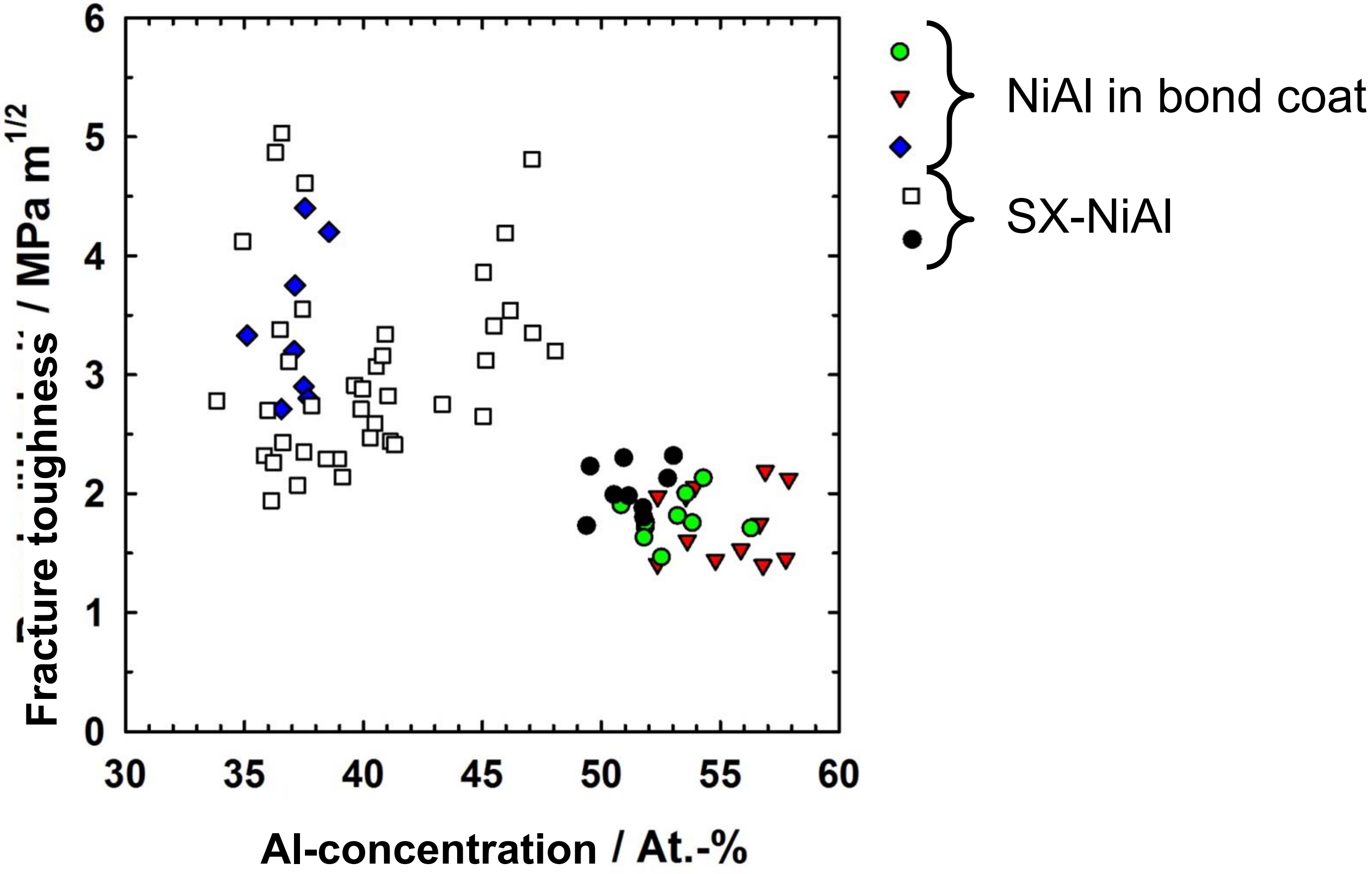
Micro-cantilever Testing of Bond Coats

Polycrystall



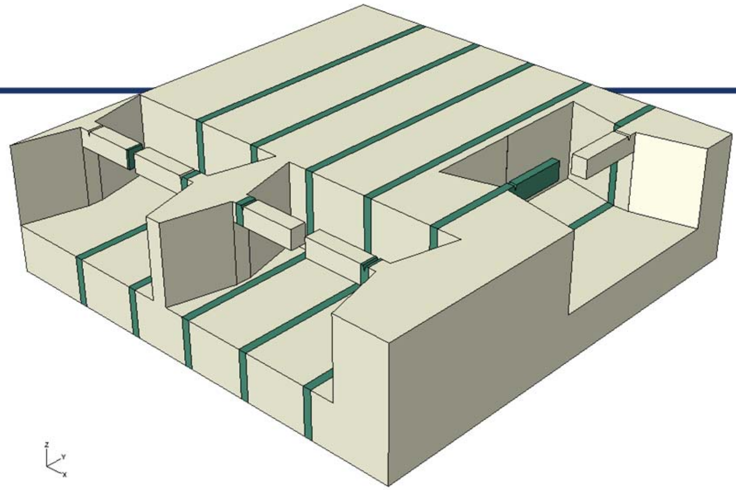
Positioning of cantilever in one grain

Comparison Between Bond Coats and SX-NiAl



→ Al-content affects also fracture toughness of bond coats

Conclusions

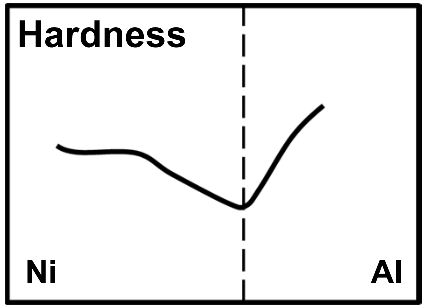


Microcantilever testing good method for measuring local fracture toughness

Graded SX-NiAl and bond coats

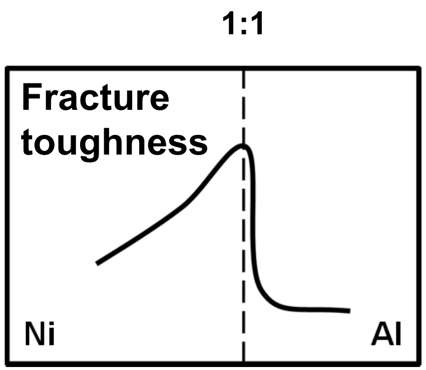
Nanoindentation

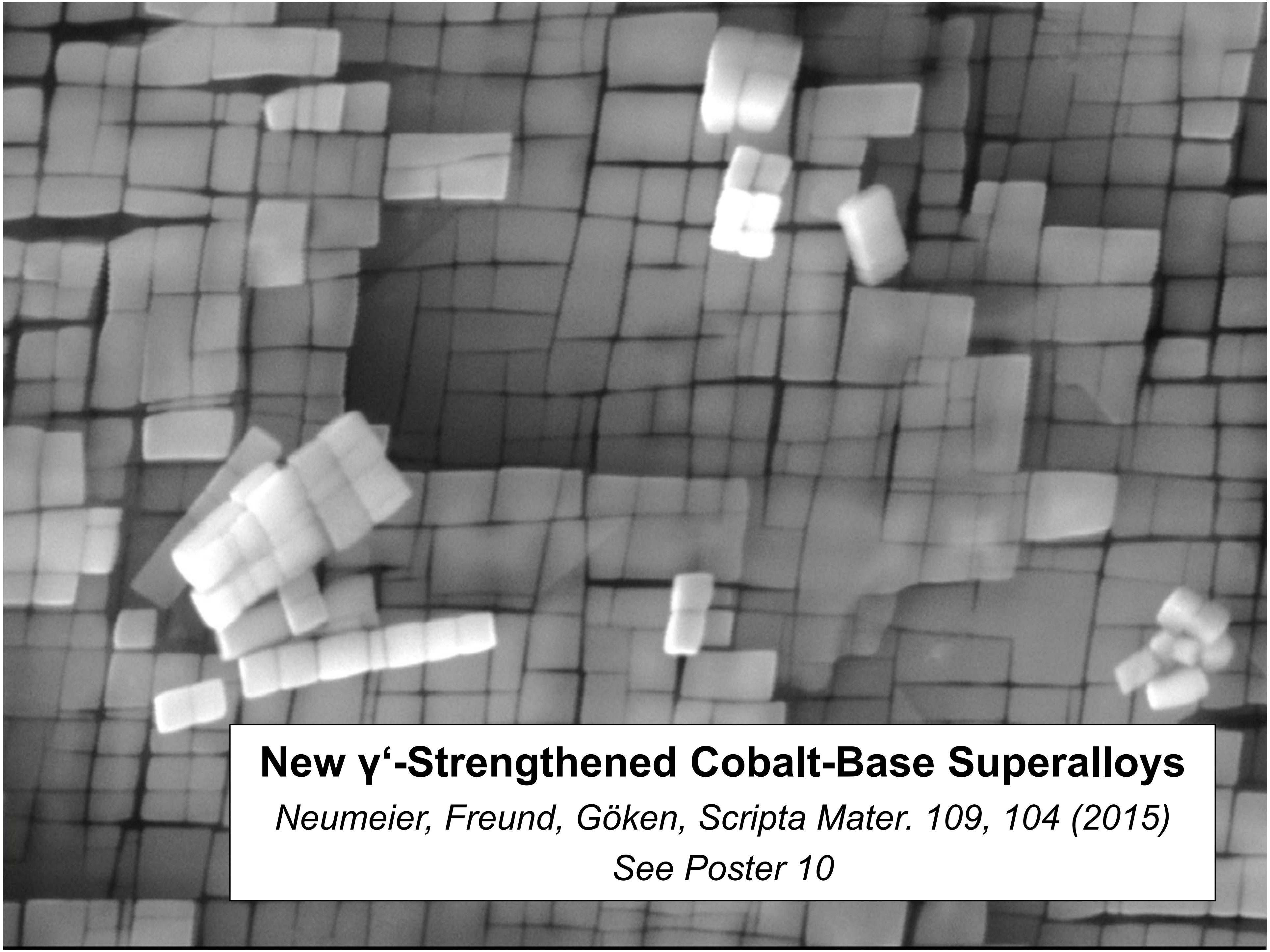
- Stochiometric Ni-50Al shows the lowest hardness



Micro cantilever tests

- Fracture toughness highest for stochiometric Ni-Al
- Al-rich NiAl shows a constant fracture toughness
- Ni-rich NiAl shows a decreasing fracture toughness with decreasing Al-content





New γ'-Strengthened Cobalt-Base Superalloys

Neumeier, Freund, Göken, Scripta Mater. 109, 104 (2015)

See Poster 10