

Properties of High Temperature Protection Coatings

E.E. Affeldt

MTU Aero Engines, Munich

Objective of the presentation

Why is it necessary to know the properties of the coatings?

How can one evaluate these properties?

Coatings used in Aero Engines

Typ

- TBC (Thermal Barrier Coating)
- Aluminide Pt-modified aluminide coatings
- MCrAlY coatings
- Abradable coatings

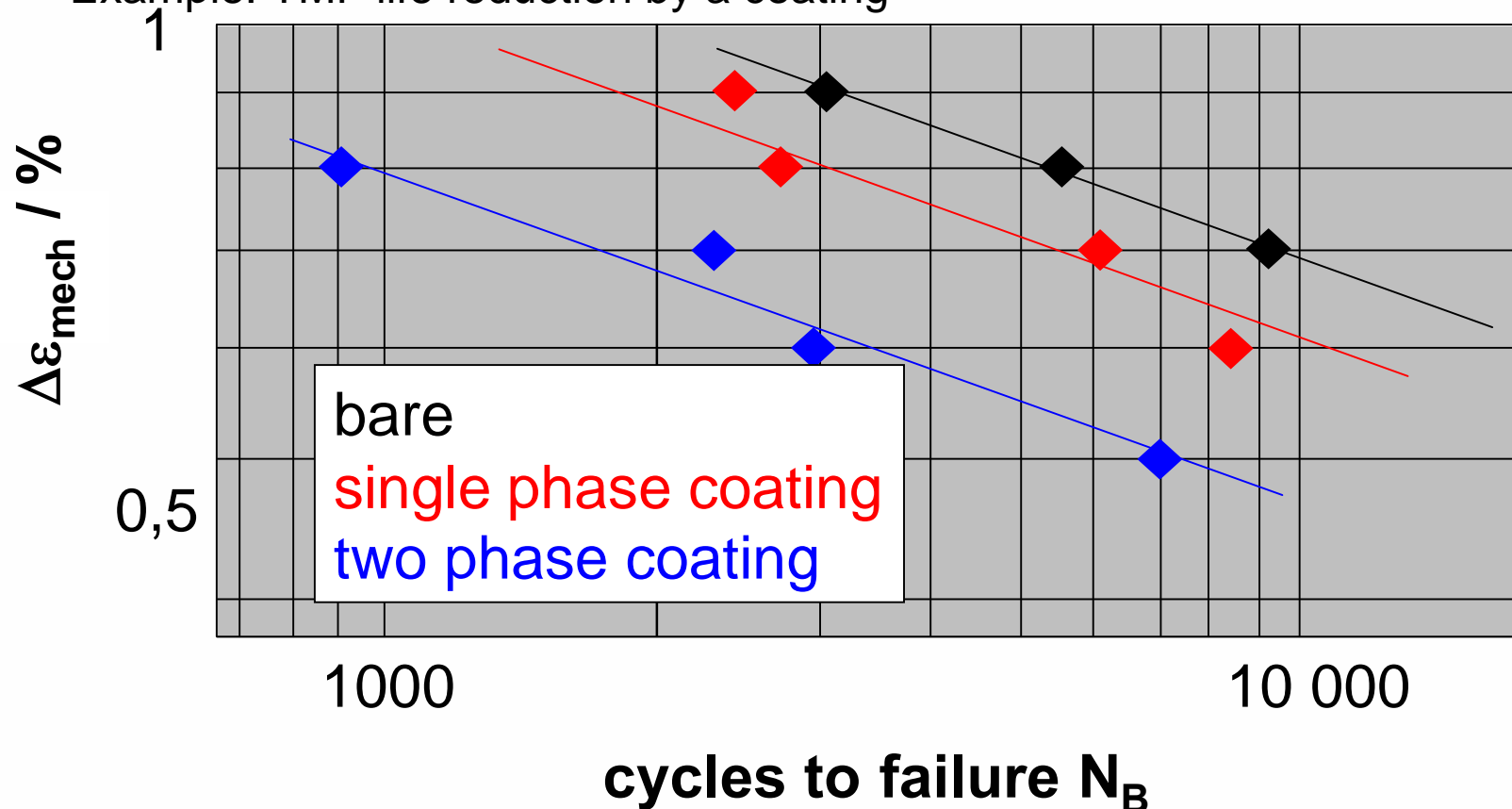
Task

- Reduction of temperature from gas to metal surface
- Oxidation protection / bond coat for TBCs
- Oxidation protection / bond coat for TBCs
- Fitting between rotating and static components

Which properties are needed and why ?

Besides the properties guaranteeing the intended functionality, it is often necessary to estimate the mechanical integrity over the life of the component. To do this the mechanical properties and the life of the coatings must be characterized.

Example: TMF life reduction by a coating



Explanation: Why is the life reduced by the coating?

The exemplified coating in the TMF diagram is an NiPt-aluminide coating. The life reduction is caused by

- brittle crack initiation in the coating, if the stress exceeds a critical values (fracture toughness)
- brittle cracking happens because the fracture toughness is low at temperatures below about 600°C and leads to cracks spanning over the whole coating thickness in one cycle.
- coating cracks propagate under cyclic loading into the substrate and reduce the life of the whole component / specimen.

>> prediction of cracking necessitates to calculate the coating stress and to compare it with the coating ductility

Special Complications by evaluating the properties of coatings:

coating is produced by diffusion, which causes:

- it has gradients
- it can hardly be produced as a stand-alone coating

specification allows a wide range of chemical compositions, which influences the behavior.

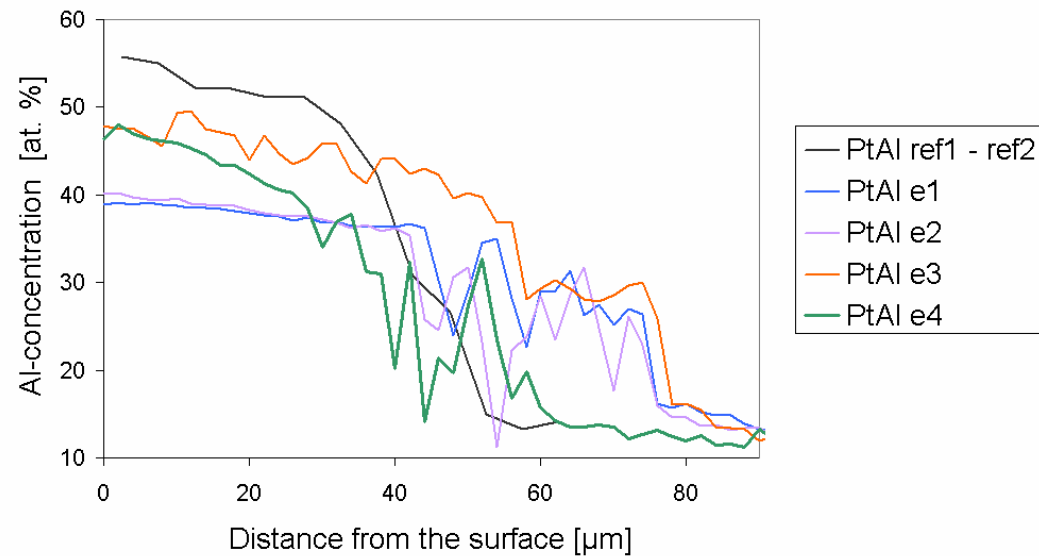
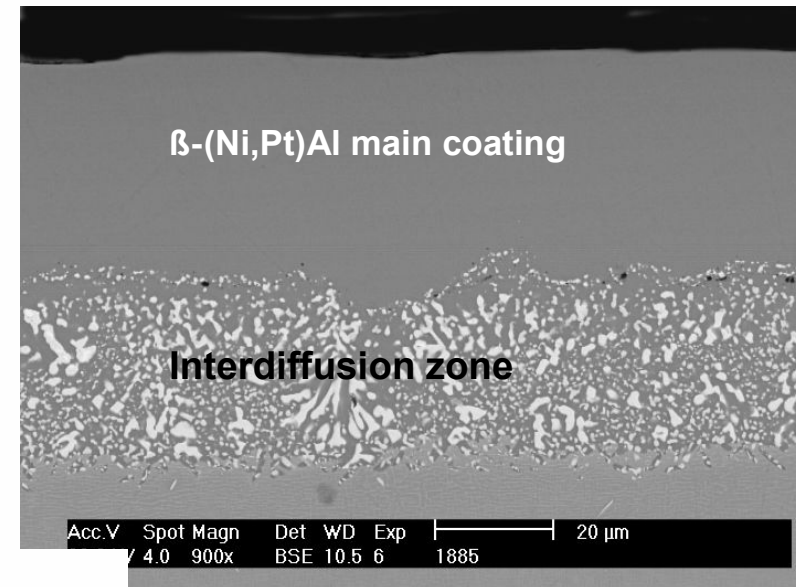
Characterisation of the coatings

typical single phase PtAl coating:

main coating

diffusion zone

substrate



Experimental techniques and results: Nanoindenter for the measurement of E – modulus, hardness, yielding

- the principle is similar to hardness measurement, but the information is more detailed
- diagram: load vs. indentation depth
- the information is in nano-range and can account for gradients etc.

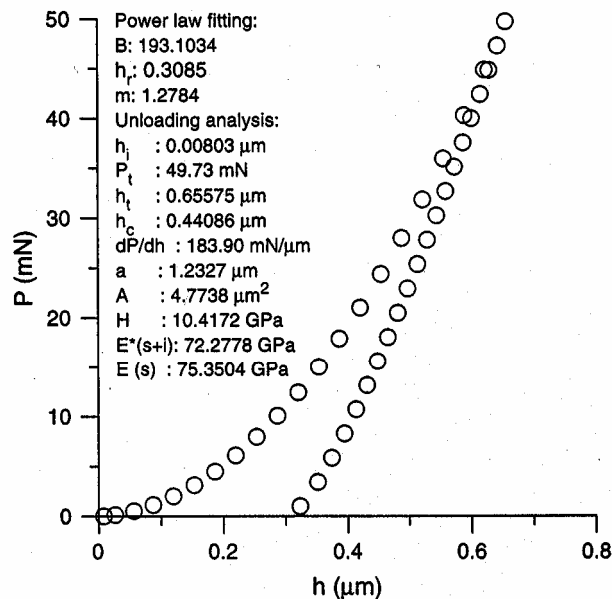
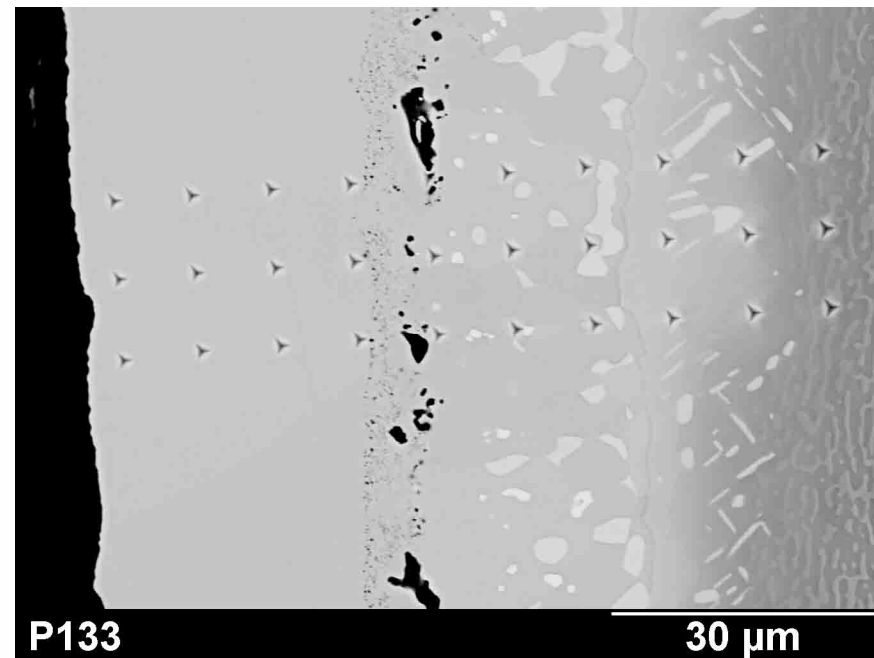
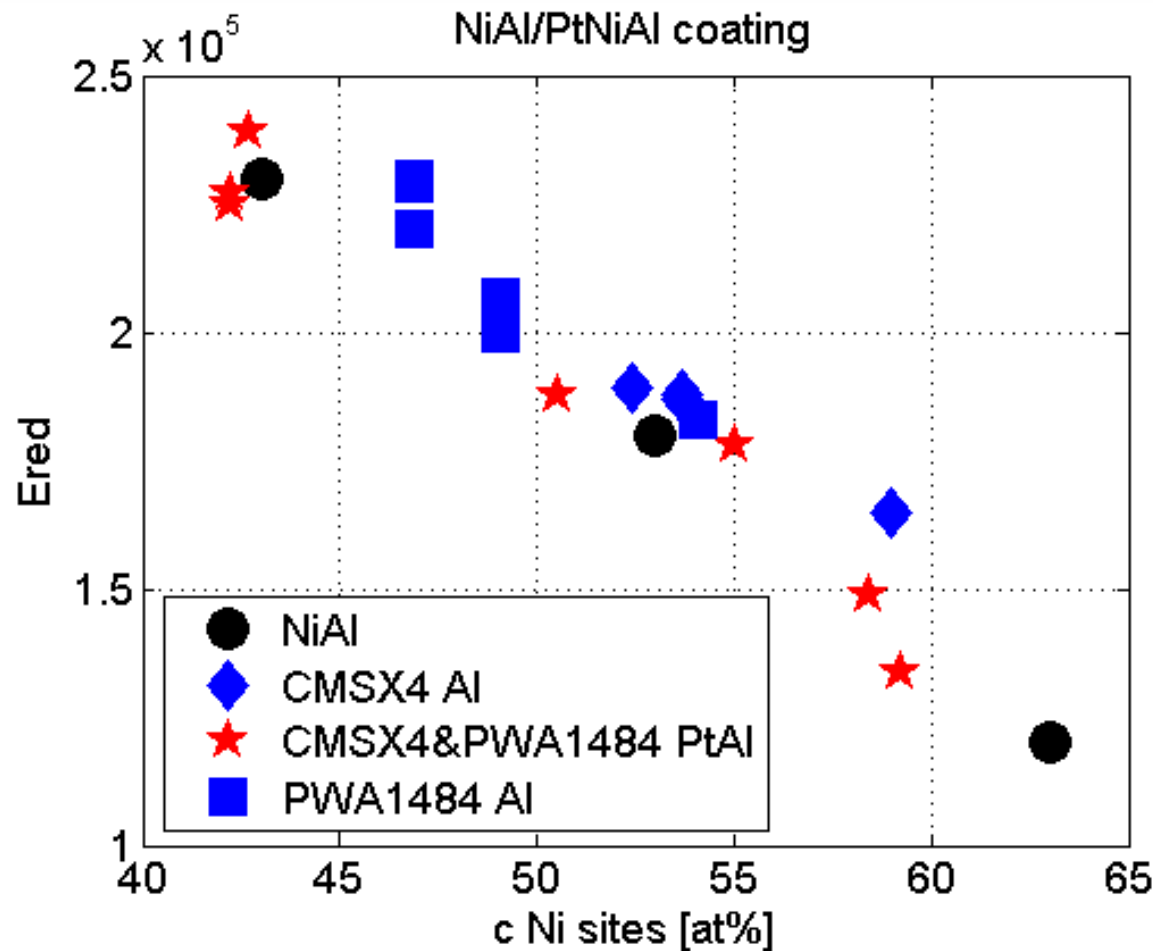


Fig. 3. Typical load–displacement curve with a Berkovich indenter on fused silica at 50 mN. The inset shows values of various quantities of interest. (Note: no area correction was applied for the analysis shown in the inset).



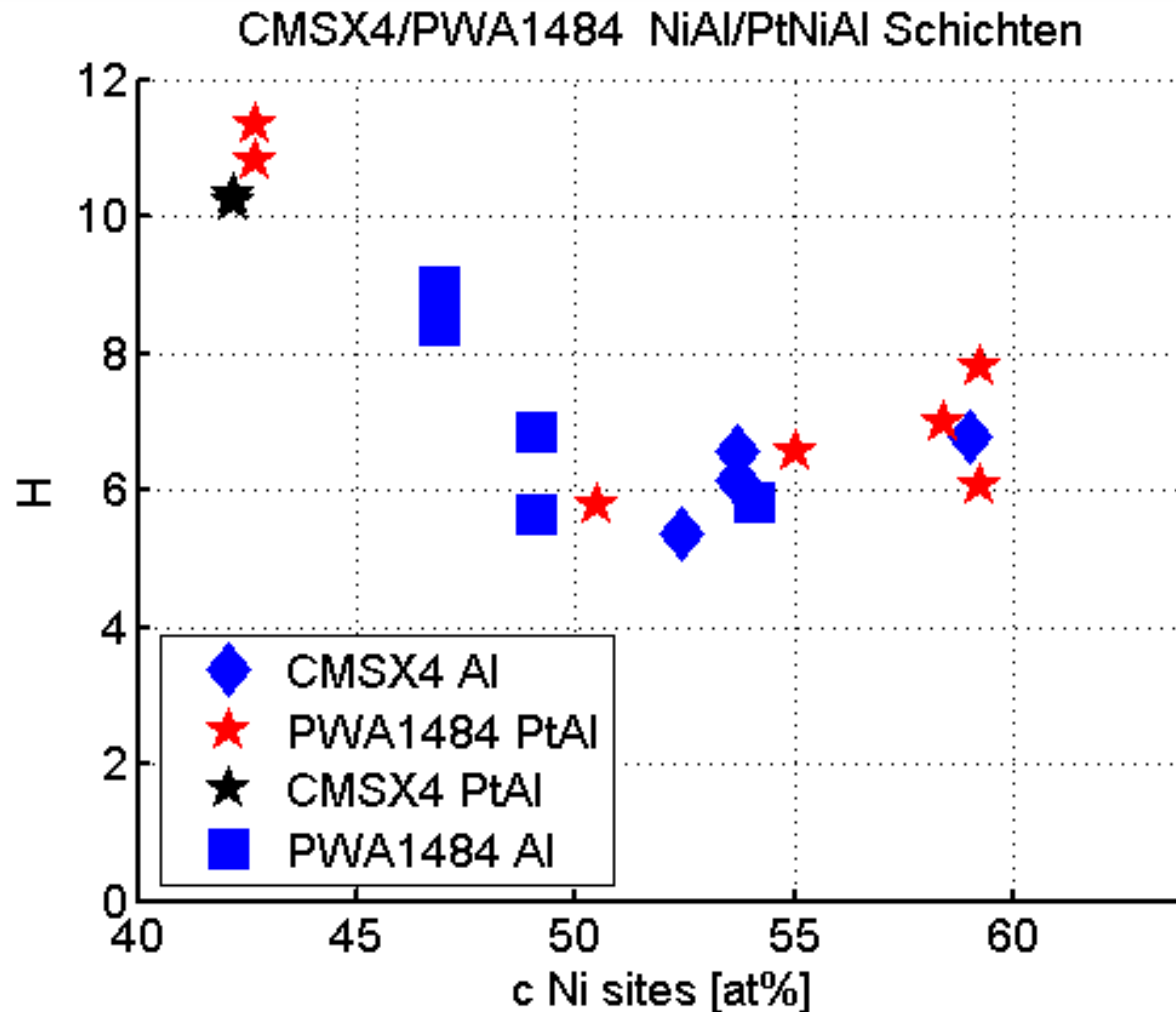
E- Modulus of aluminide coatings



The E-Modulus of NiAl is a function of the chemical composition. β -NiAl has an ordered structure, which compensates deviations from stoichiometry by vacancies or site substitution. This causes the dependence from the Al-concentration.

In NiAl-coatings other elements are soluble in the structure, especially Pt can substitute Ni. The results show that the E-modulus of NiAl-coatings can be estimated by a knowledge of the substitution.

Nano-hardness of aluminide coatings



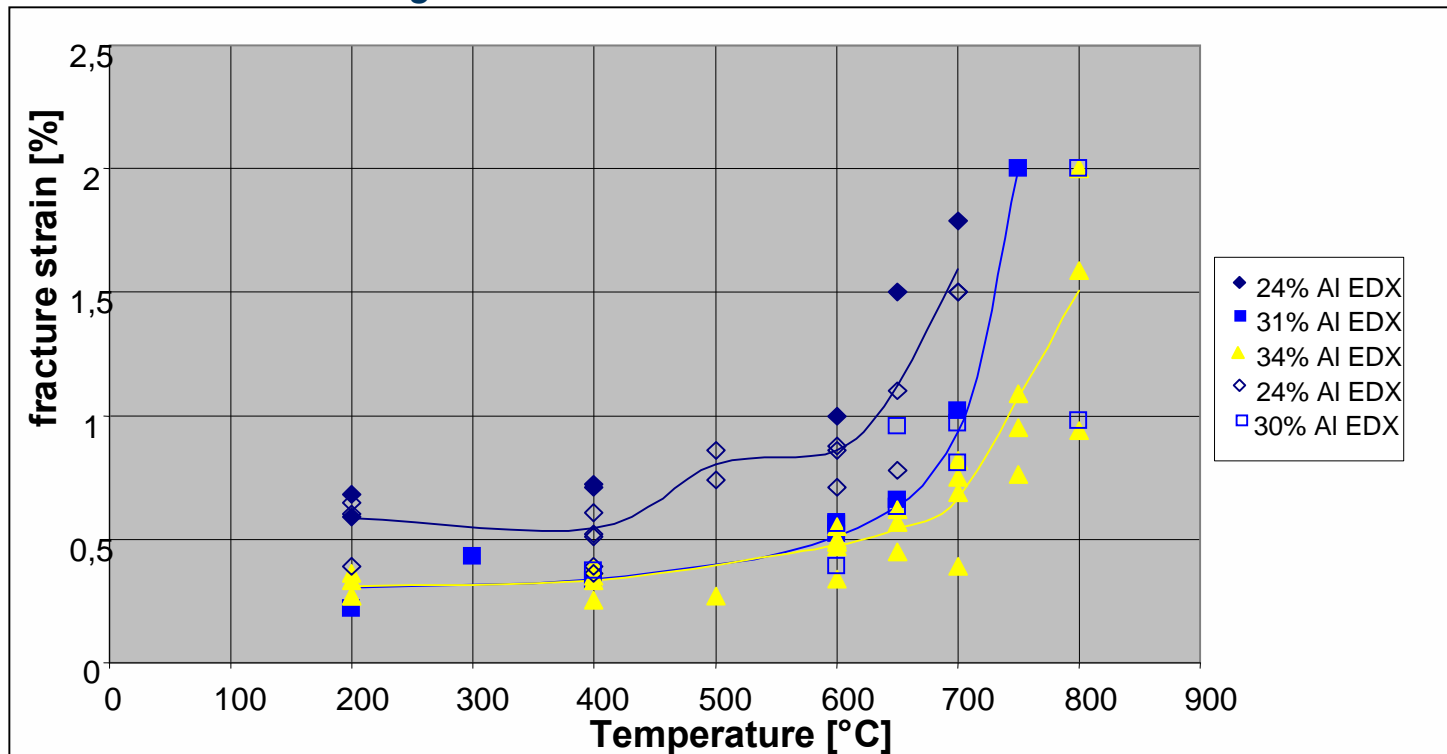
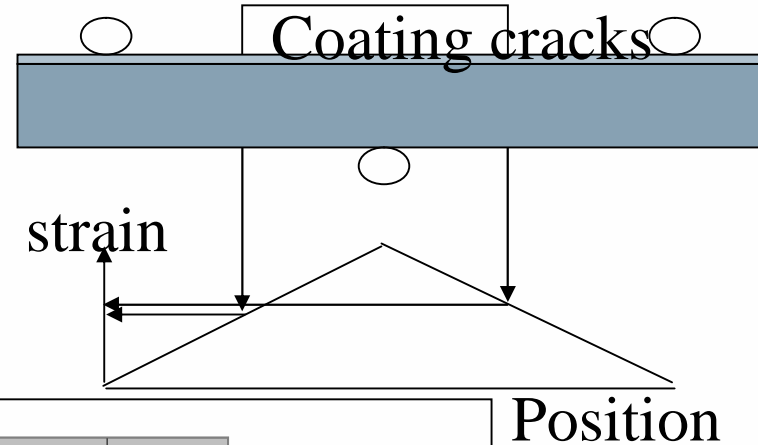
The nano-hardness of NiAl is a function of the chemical composition, too. The dependence of the hardness is similar to the dependence of the yield strength of NiAl from the Al-concentration. This indicates, that nano-hardness is a good indication of the yielding behavior.

The results show that the nano-hardness of NiAl-coatings can be correlated to the substitution, as shown for the E-modulus.

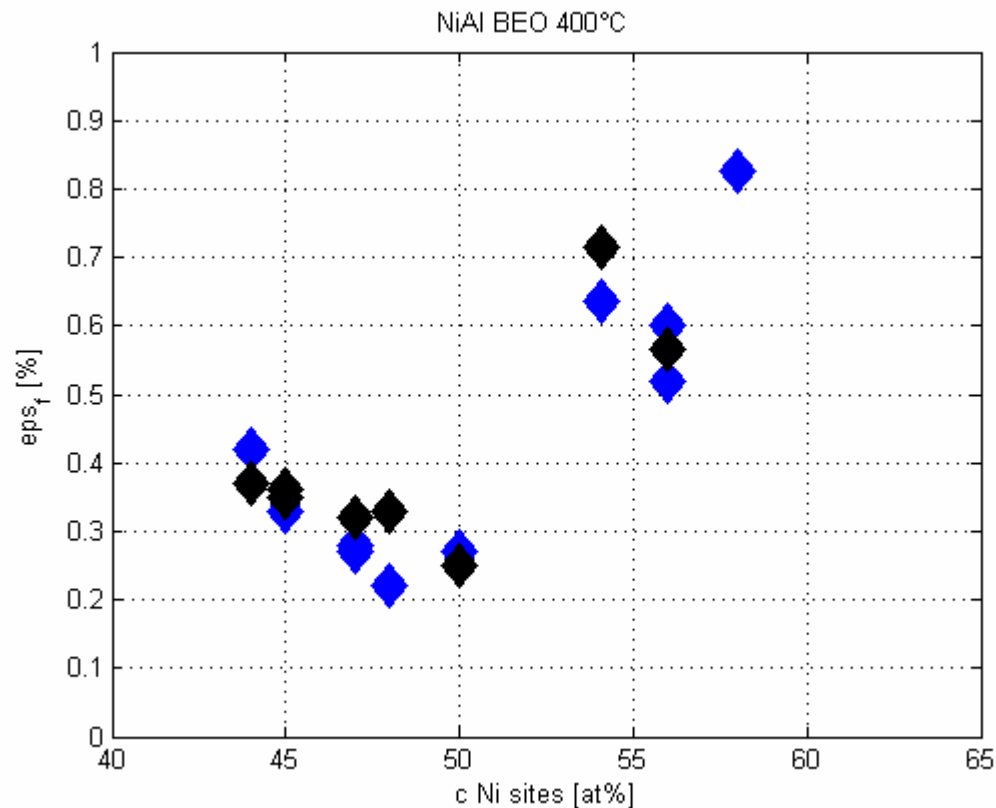
bending of coated substrates

ductility of the coatings

under bending the strain in the coating is linearly correlated to the position. Thus the lowest strain causing coating cracks can be evaluated from the boundaries of the cracked region.



Ductility



ductility as function of the atomic concentration on Ni-sites for 200°C and 400°C in NiAl coatings.

The strain to cause cracking in the coating – as a measure of ductility – shows a decrease with increasing Ni-concentration and reaches a minimum – for 50 at%. Then it increases, reaching a high ductility at about 58at%.

The behavior compares well to the hardness. This leads correlate it with the yield strength. It seems, that the onset of plasticity causes the formation of cracks in the coating.

summary of characterization so far

Nanoindentations enabled to evaluate the

- elastic behavior
- plastic behavior

as function of the chemistry of the coatings

Bending tests exhibited the

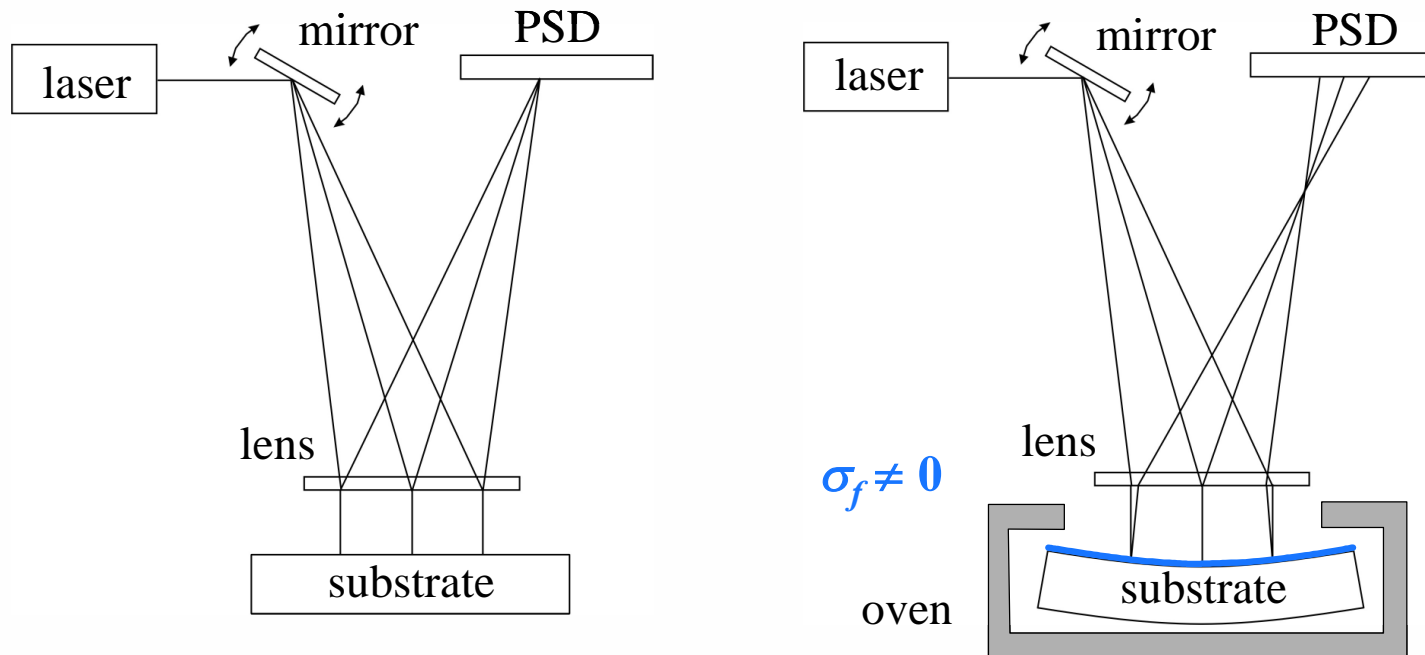
- ductility

as function of the chemistry of the coatings

Further necessary parameters to calculate the initiation of cracks in the coating are

- thermal expansion and relaxation of the coating

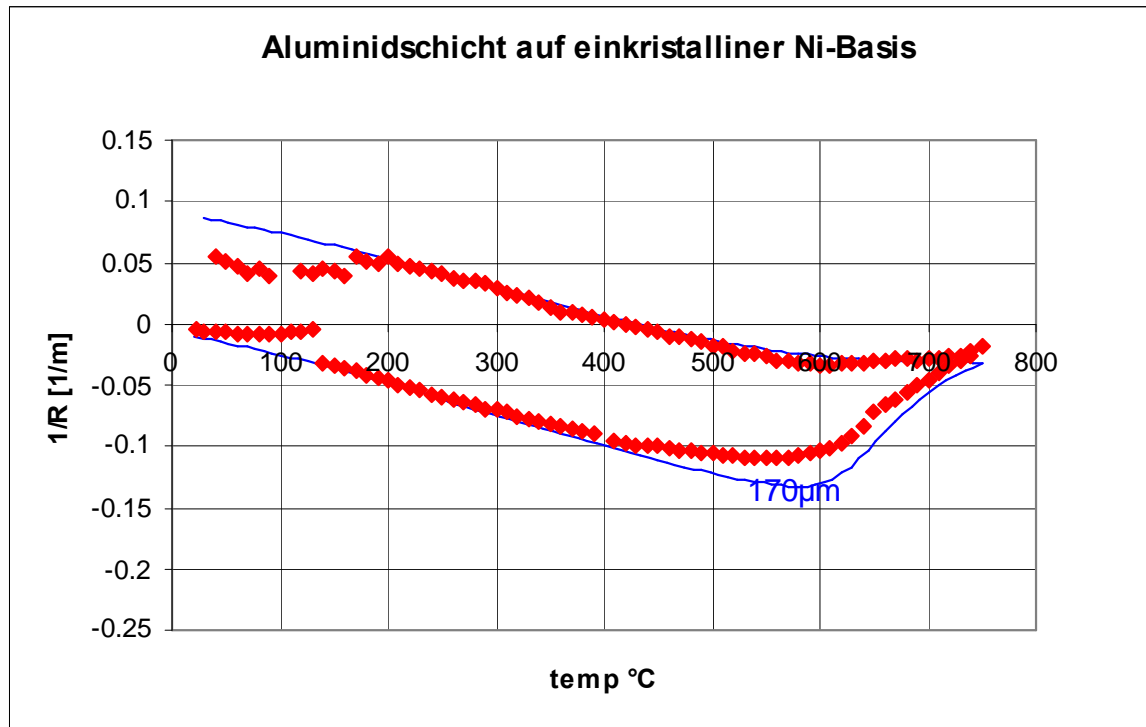
Schematic of substrate curvature measurement



$$\sigma_f = \frac{M_s h_s^2}{6 h_f} C$$

- film stress induces bending of the sample
- measurement of curvature C
➔ film stress as a function of temperature

Coating stress



testing: MPI/Uni Stuttgart, Arzt, Keller
specimen preparation and modeling:
MTU München, Affeldt

curvature of an aluminide-coated single crystal nickel base substrate

results:

- curvature starts at about 0, decreases with temperature, but increases for $T > 550^{\circ}\text{C}$ approaching 0
- during cooling it stays constant till $T < 550^{\circ}\text{C}$, then increases parallel to heating
- second cycle (not shown) coincides with cooling part

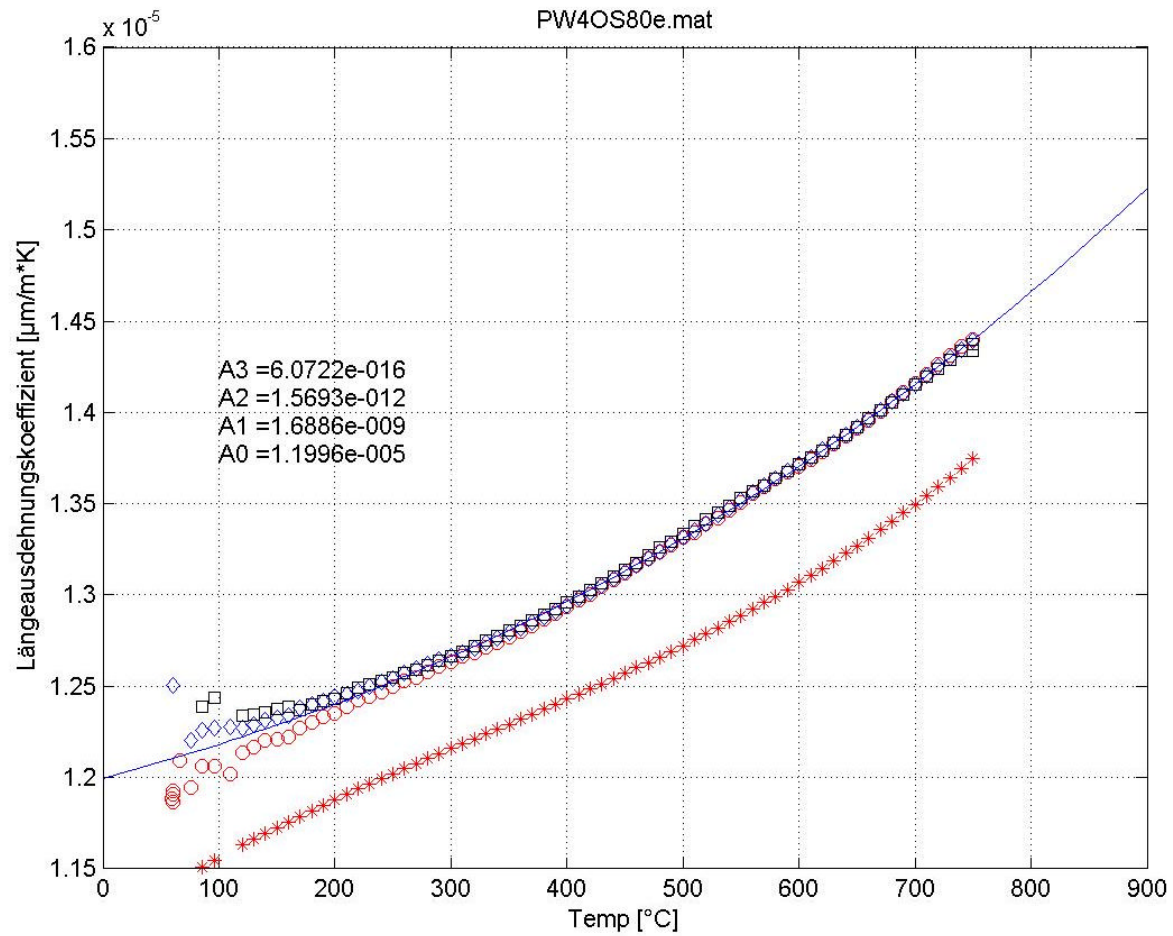
coating stresses

from substrate curvature the coating stresses can be deduced by means of the Stoney equation, which enables – for thin coatings on thick substrates – to calculate the coating stress with the coating thickness as the only necessary parameter of the coating.

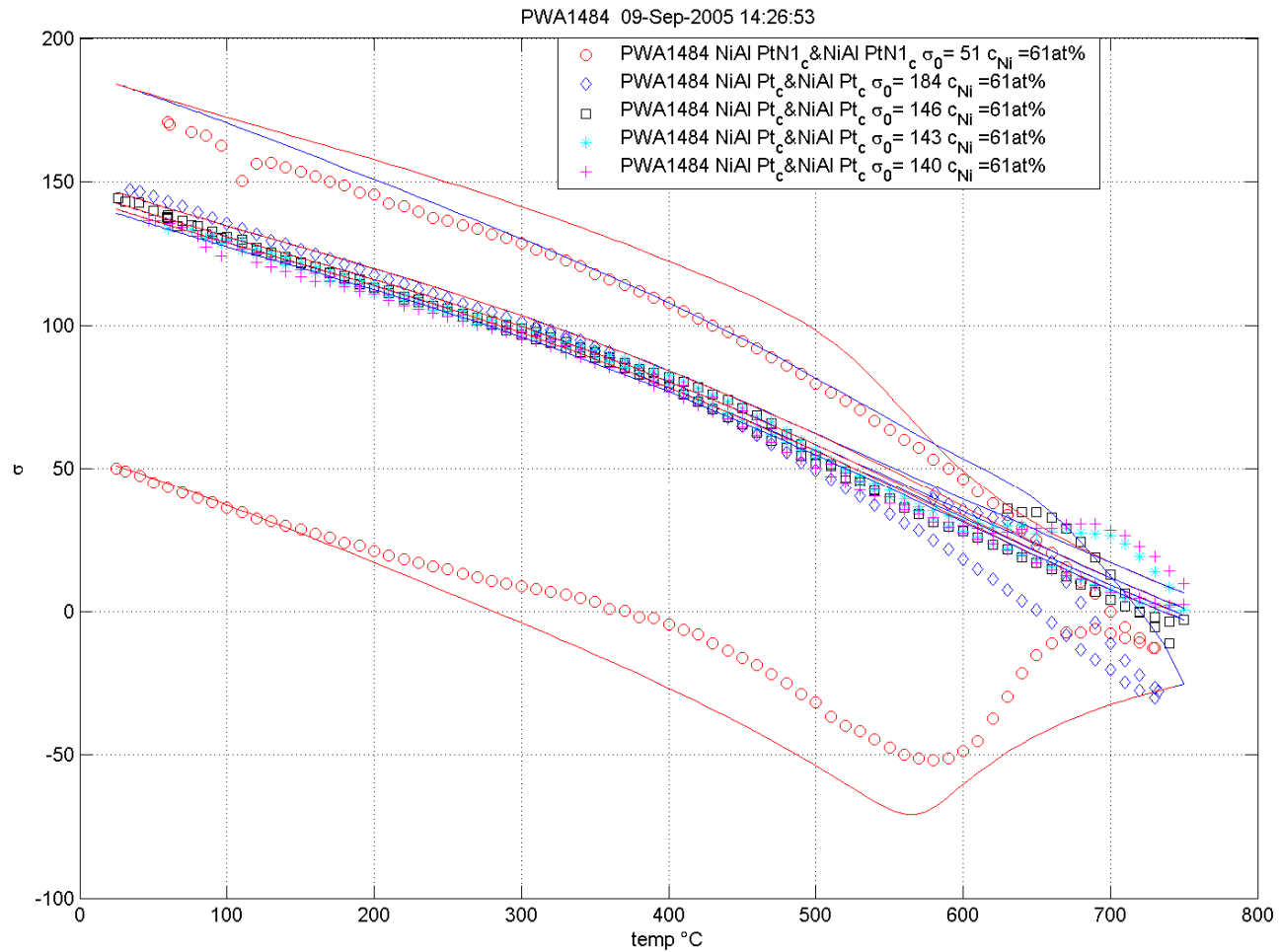
The stresses in the low temperature part are controlled by the the thermal expansion of the coating and the substrate, by means of the elastic constants of the coating, the thermal expansion can be deduced from the measurement.

The high temperature part shows relaxation of the coating. Based on literature data, it is possible to verify the relaxation of the coating

thermal expansion as deduced from the substrate curvature



Comparison of calculated and measured stresses



Summary and discussion

It was shown how the mechanical properties of diffusion coatings can be evaluated:

- elastic behavior
- plastic behavior
- thermal expansion
- ductility
- relaxation / creep could be estimated more information would be helpful.

All properties are strongly dependant on the chemistry. Even within the single phase range the properties can typically vary systematically by a factor of two. This variation is possible within the allowed specification limits of the coatings. Nevertheless the Nanoindentation can be used to characterize individual coatings and the correlation with the chemistry enables to describe all properties necessary to calculate the stresses in the coating and the ductility of it. Thus the prediction of crack initiation in the coatings is possible.