Single Crystal Nickel Based Superalloys for High Temperature Applications

- Microstructure, Properties, Anisotropy -

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Metals and Alloys

University Bayreuth

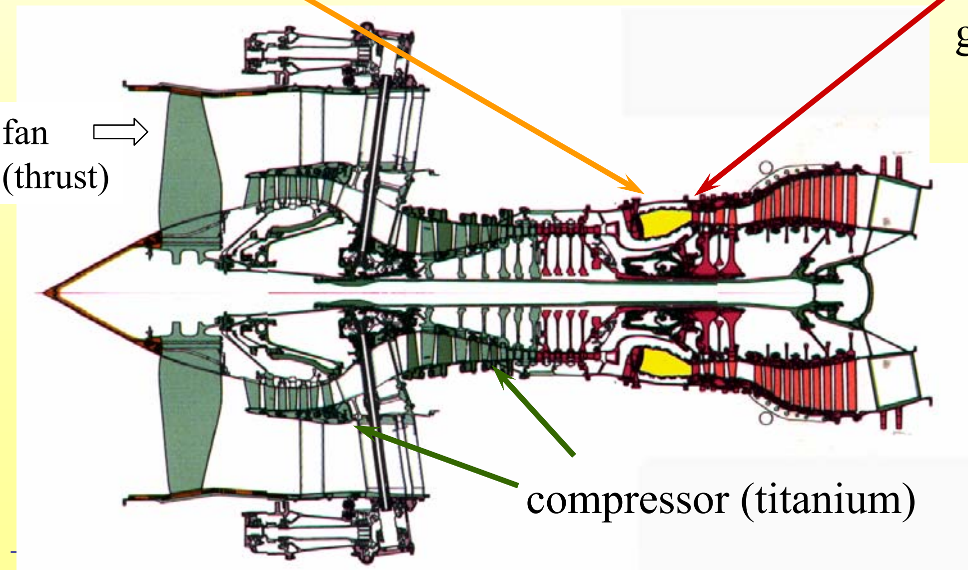
Content

- motivation: history, application field
- processing
- microstructure, misfit
- anisotropic properties (modulos, creep behavior)
- dislocations, stress induced diffusion
- Outlook (alloys with reduced density, platinum based superalloys)

TU-Berlin (SFB 339)
Uni Jena

Superalloys for Extreme Demands

Single crystal nickel based superalloys as material for **first rotating blades** after the **combustion chamber** in aircraft flight engines.



gas temp.: 1500°C

material: 1100°C

20.000 rpm

$\Rightarrow$ const. stress of about 100 MPa ($\approx$ 1 car/cm^2)

Big, Single Crystal Blade

Blade for stationary gas turbine for power production

$\approx$ \$ 40.000

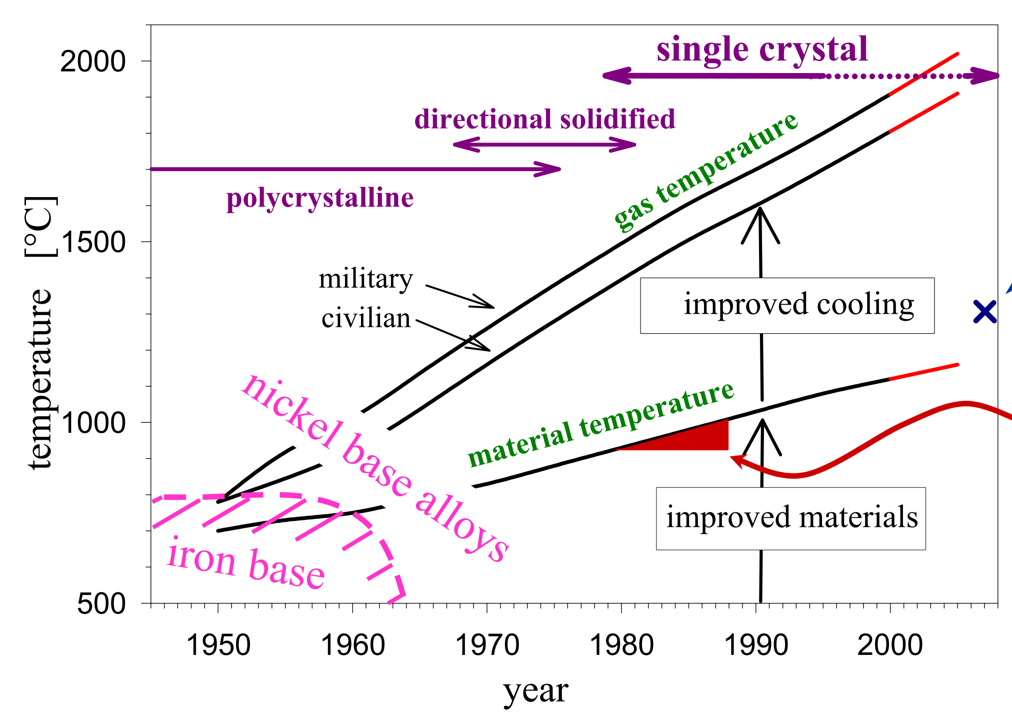
Coefficient of Efficiency

regular fuel car engine:	23%
diesel car engine:	27%
aircraft turbine:	30-35%
stationary gasturbine:	40%
gas and steam generation:	54%
gas + steam + long distance heating:	87%

$$\eta_{theor.}^{max} = \frac{T_{in} - T_{out}}{T_{in}} \Longrightarrow$$

increase of T_{in} increases coefficient of efficiency

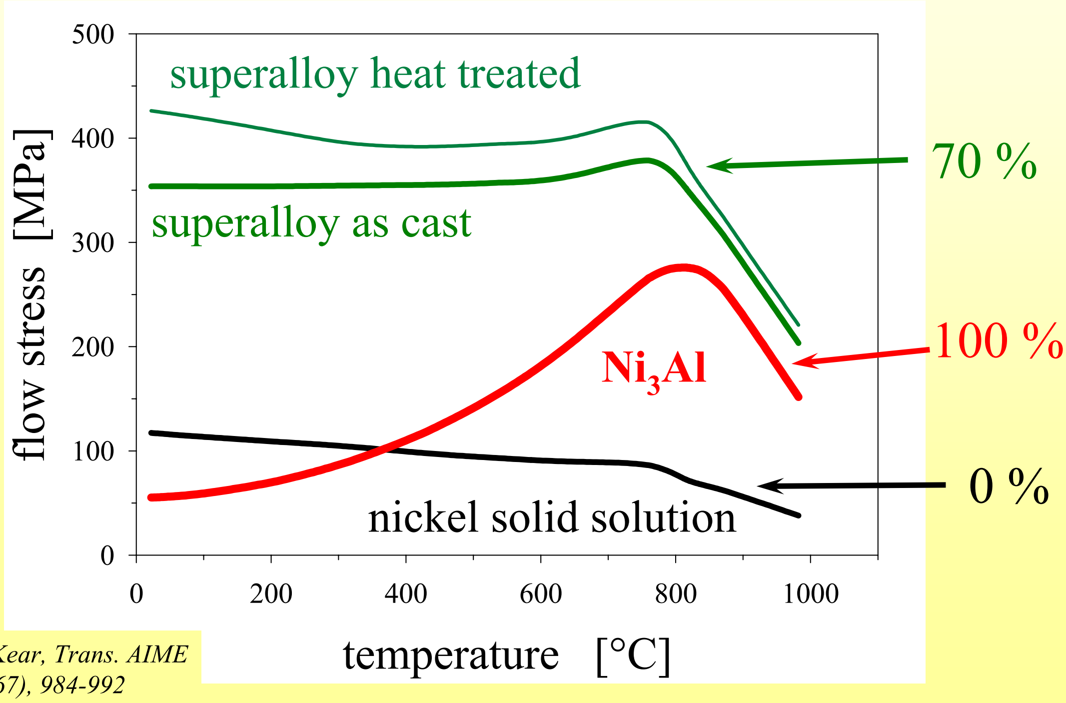
Increase in Temperature due to Improved Construction and Material



ceramics?? platinum base alloys?

constant improvement 5-10°C/year

Why nickel based superalloys? Anomalous flow stress behavior of the intermetallic phase Ni_3Al:



Copley and Kear, Trans. AIME Vol. 239 (1967), 984-992

History

≈ 1980: Inconel 738 (polycrystalline) => 738 LC (single crystal)
50-60vol.% γ' phase, 3wt.% W, 0% Re
SRR 99, CMSX-6 (first generation)
60-70% γ', 9% W, 0% Re

≈ 1990: CMSX-4 (second generation)
> 70 % γ', 6% W, 3% Re

≈ 1995: CMSX-10 (third generation)
> 70 % γ', 6% W, 6% Re

Costly and time intensive heat treatment:
3-stage homogenization, controlled rapid cooling
2-stage aging

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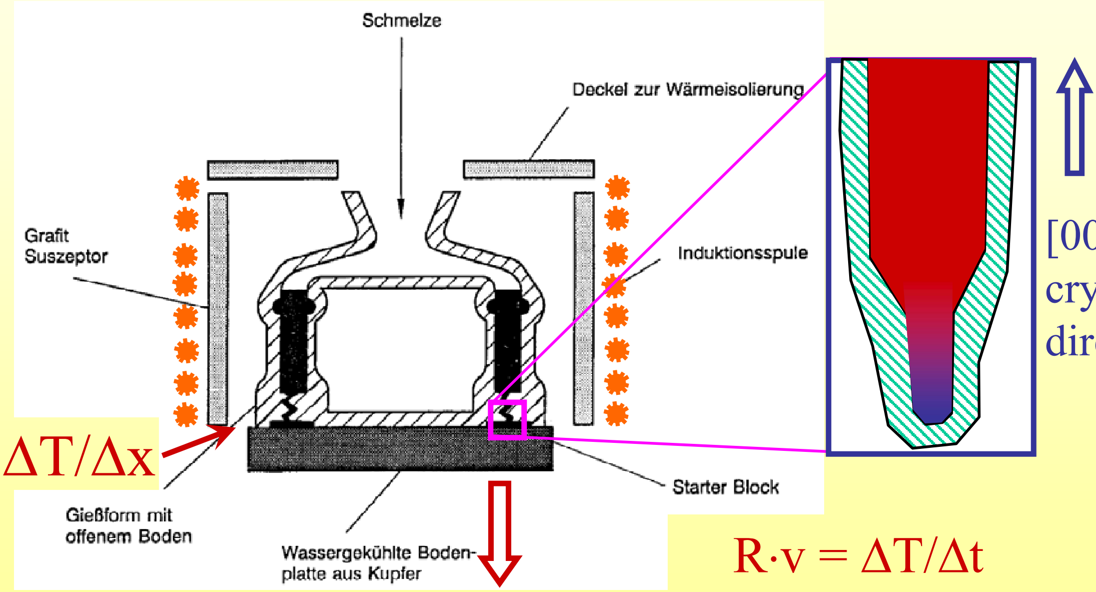
Single Crystal Growing



$R = \Delta T/\Delta x$

[001] crystal direction

$v = \Delta x/\Delta t$

$R \cdot v = \Delta T/\Delta t$ determines the dendrite spacing

alternative: seeding technique

Heat Treatment

example: CMSX-4 standard heat treatment

homogenization:
1 h @ 1280°C, 2 h @ 1290°C, 6 h @ 1300°C
cooling rate 150-400°C/min.

aging
6 h @ 1140°C für 6 h, 870°C für 16 h

if possible, combined with coating treatment

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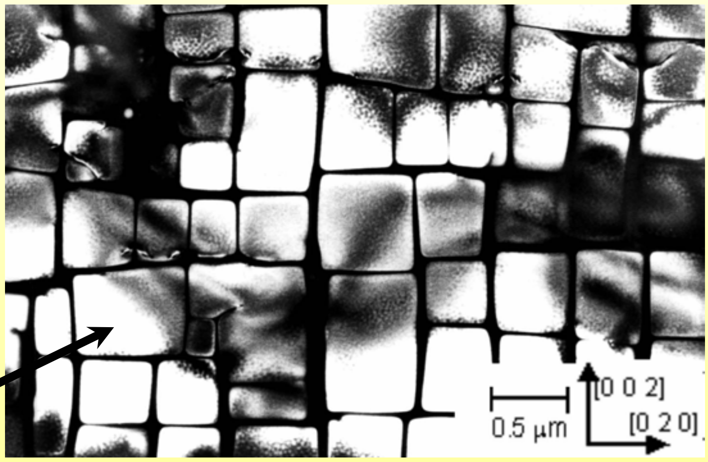
Microstructure

two-phase, single crystal:

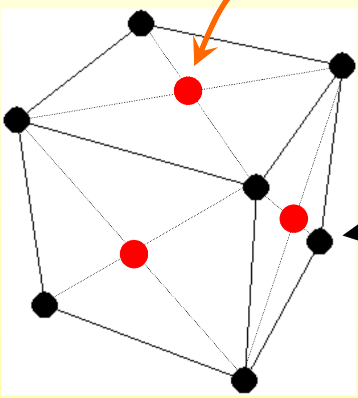
face-centred-cubic
matrix
(nickel solid solution)



Ni_3Al => fcc, but superlattice ordering, $L1_2$ or γ' Phase

dislocation free

Ni_3Al ⇔ nickel solid solution



nickel atoms in face centre

aluminium atoms on cube corners

$d_{Ni_3Al} = 358{,}0$ pm $\qquad d_{\text{nickel solid sol.}} = 358{,}7$ pm

in nickel solid solution → statistical distribution of atoms

Optimal Precipitation Hardening

- round particles (better than needle-shaped)
- high volume fraction
- finely dispersed
- small particles
- hard precipitates, soft matrix

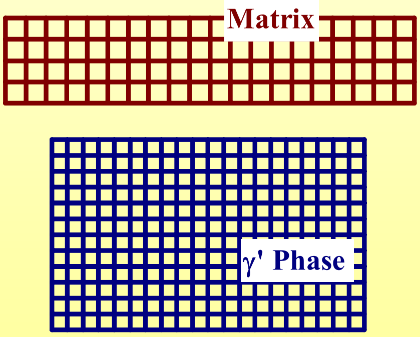
in text books no information given on optimum misfit

500 nm

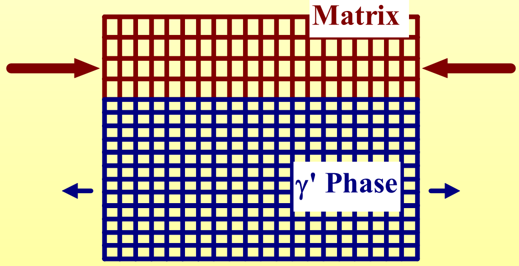
Constrained ↔ Unconstrained Misfit

Small difference in lattice parameter, $\Delta d/d \approx -(1-3)\cdot 10^{-3}$ resulting in a coherent interface and internal stresses:

$$\sigma = E\,\frac{\Delta d}{d} \approx 100 - 300\ \text{MPa}$$

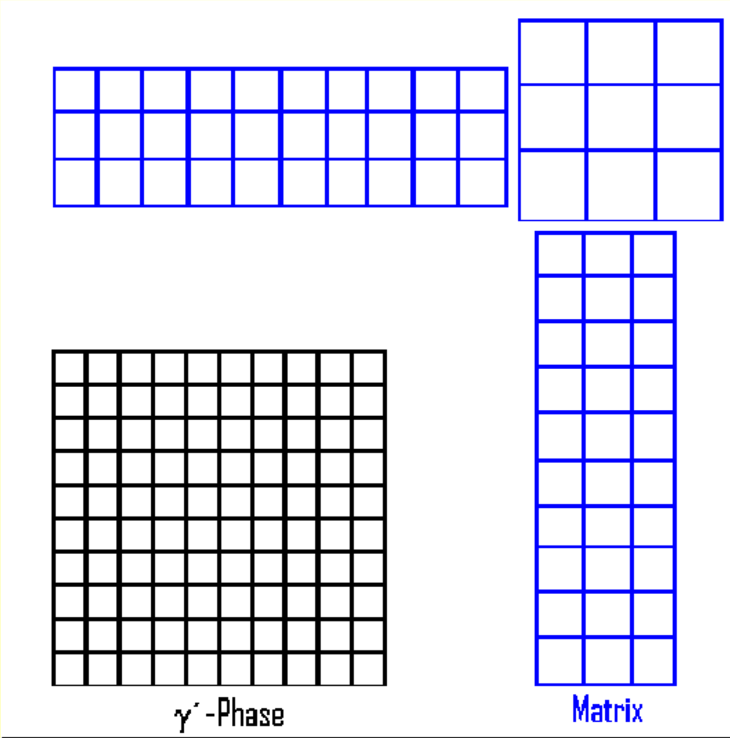


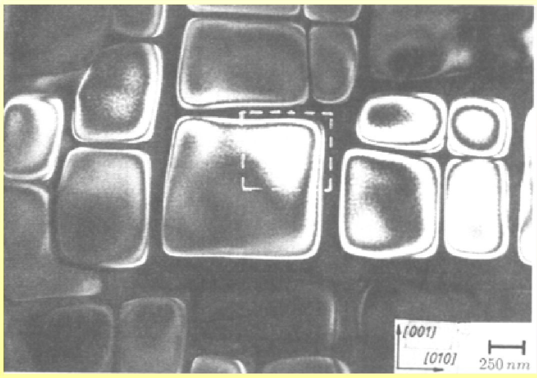
isotropic misfit



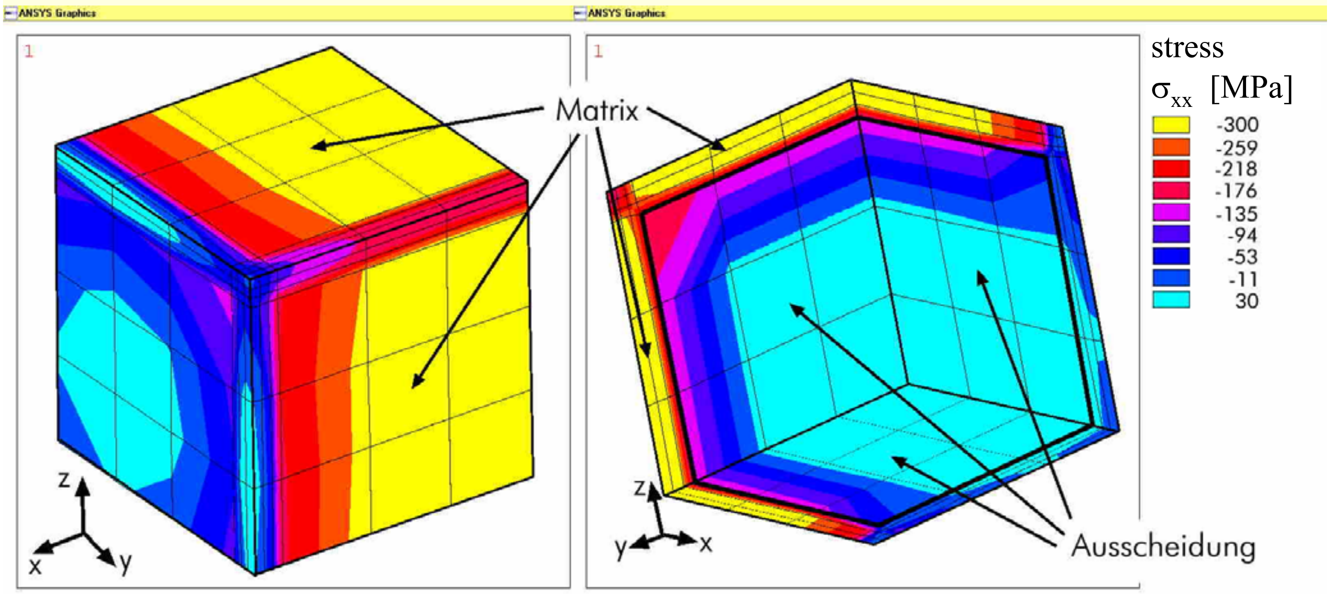
misfit dependent of planes taken for Bragg reflection

Two-Phase but 100% Coherent => Internal Stresses



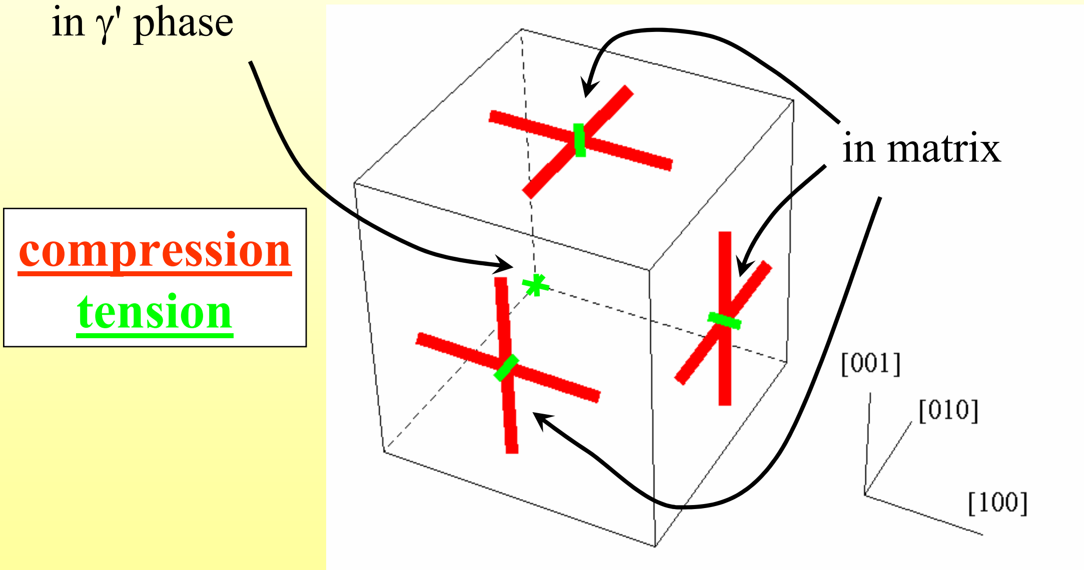


Stress Distribution



two views of 1/8 of the γ' cube with surrounding matrix

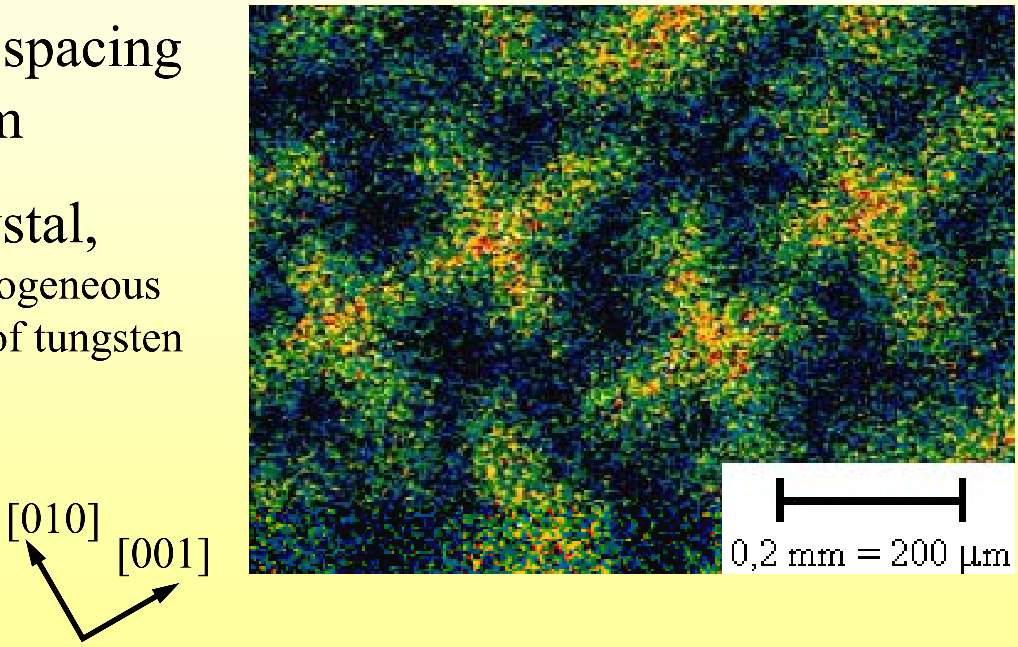
Stress Distribution Schematical



"Macrostructure"

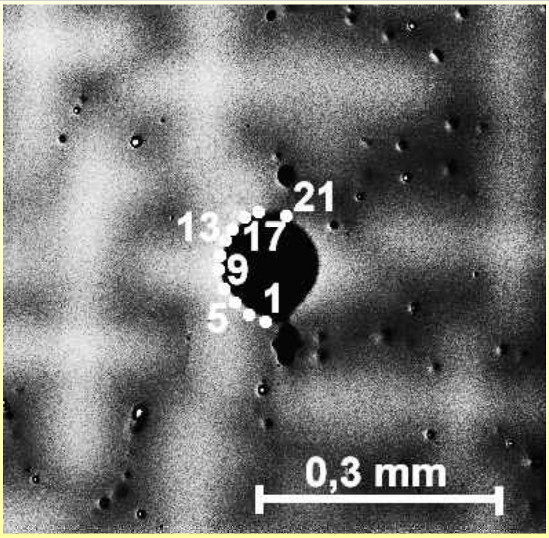
dendrite spacing
≈ 1/4 mm

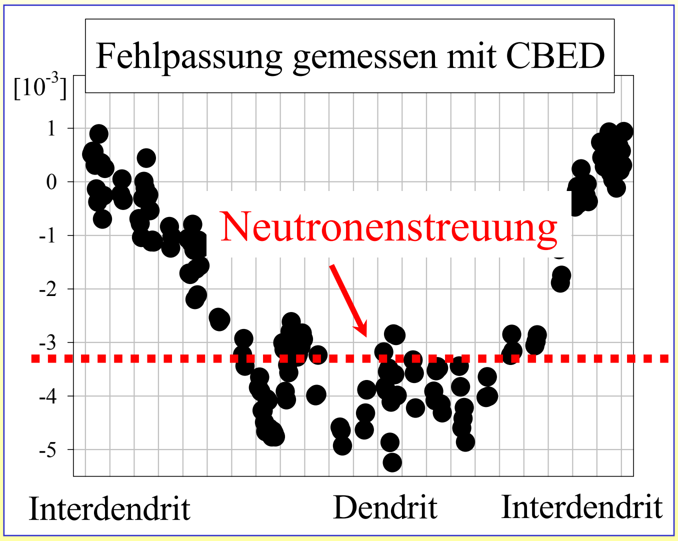
single crystal,
but no hgomogeneous distribution of tungsten and rhenium



⇒ therefore local variation of misfit

Variation of Misfit due to Dendritic Segregation

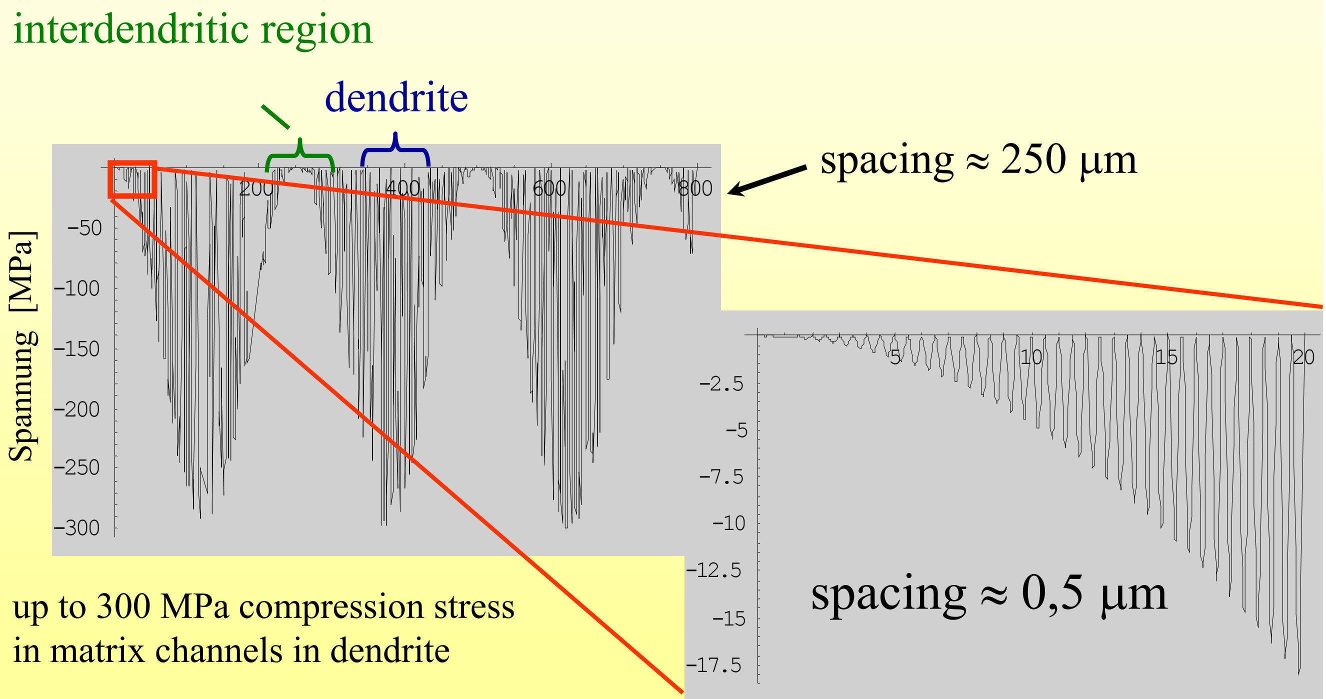




- negative misfit in dendrite
- close to zero in interdendritic region

Völkl, Glatzel, Feller-Kniepmeier; Acta mat. ***46*** *(1998) 4395*

Local Stress Variation



up to 300 MPa compression stress
in matrix channels in dendrite

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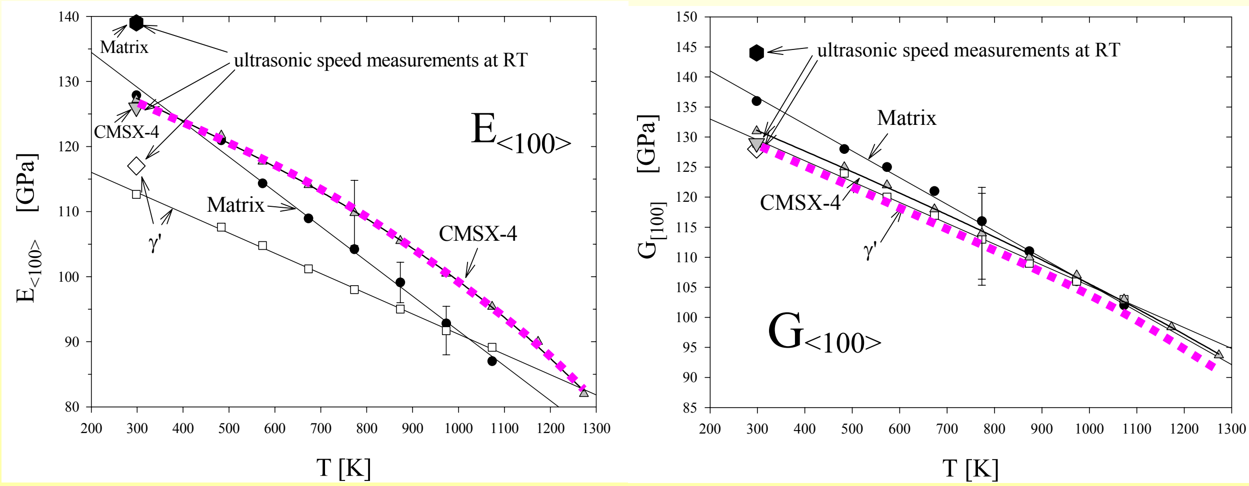
Elastic Anisotropy together with Misfit:

- Explanation for cuboidal γ' precipitates, with {100} phase boundary planes
- thereby very high volume fractions achievable

Temperature Dependence of Elastic Constants

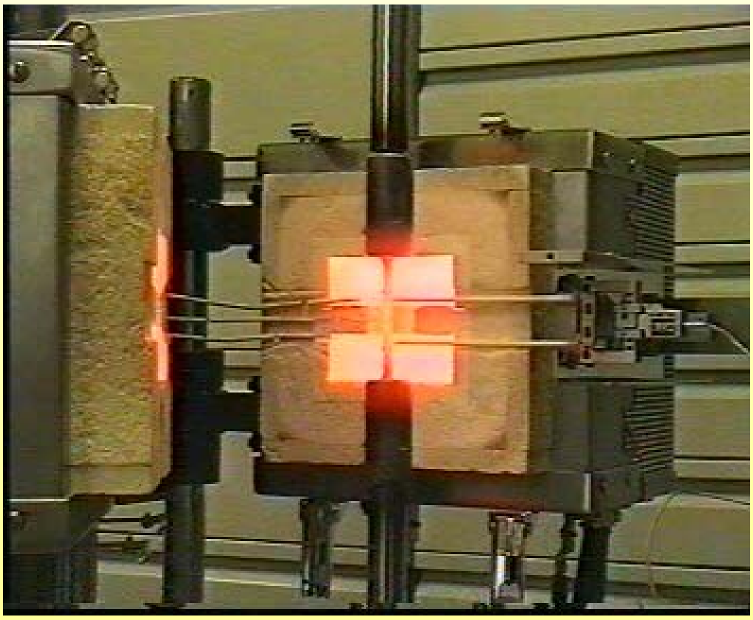


Important: anisotropy stays on the same high level of ≈ 2.8

Siebörger, Knake, Glatzel; Mat. Sci. Eng. ***A298*** *(2001) 26*

Creep Deformation

High Temperature Deformation up to 1400°C

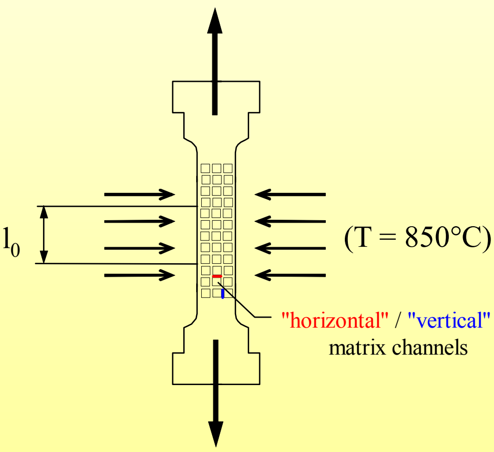


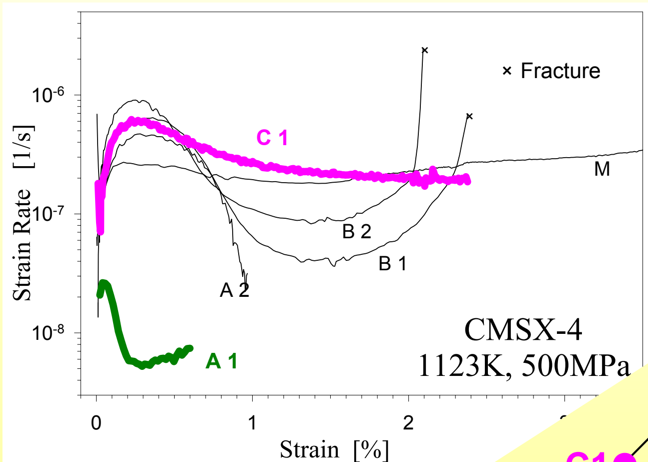
temperature and load are kept constant

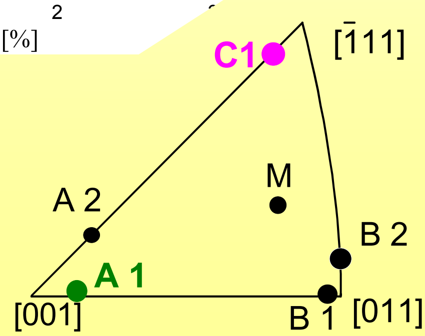
Orientation Dependence at 850°C

Single crystal with load axis parallel to [001]

constant load of 500 MPa

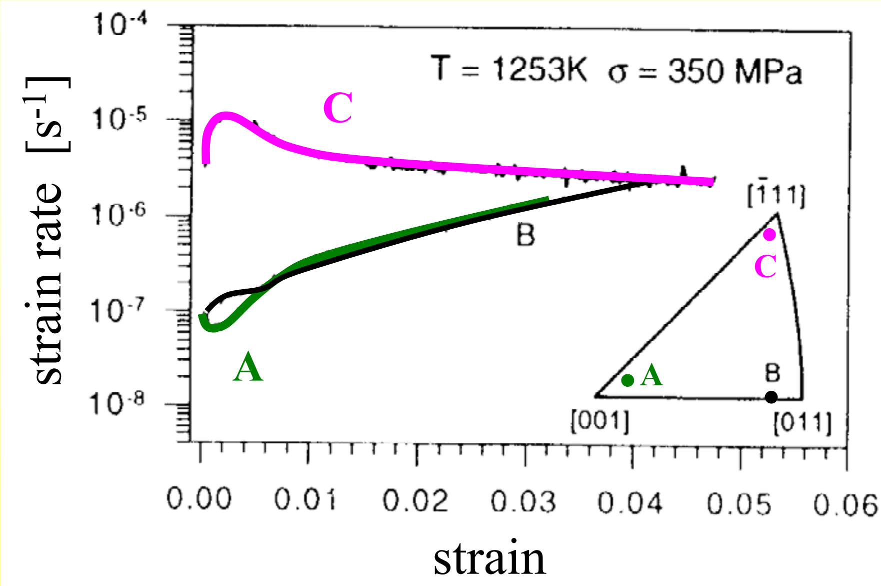






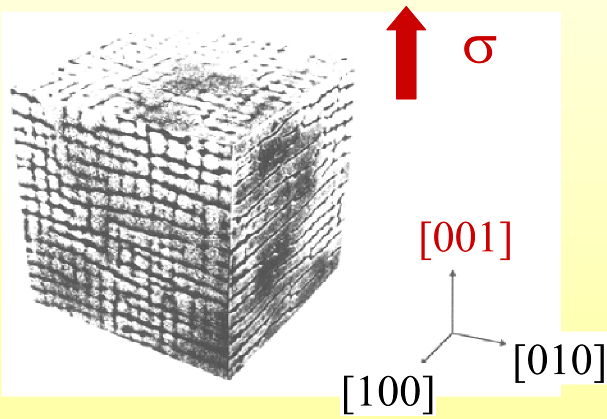
→ [001] orientation shows best creep performance

Orientation Dependence at 980°C

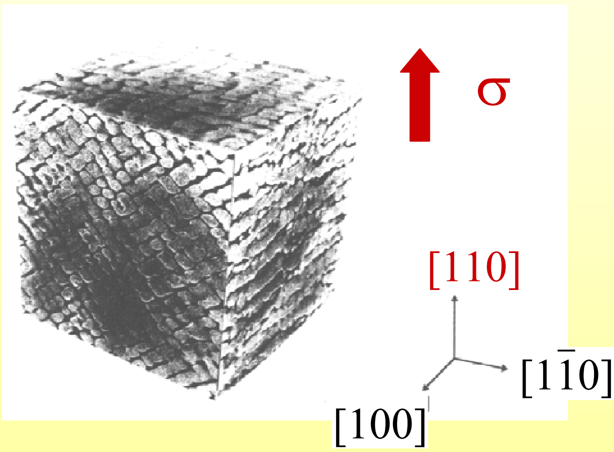


anisotropy has less influence at higher temperatures

Changes in Morphology
980°C, 350 MPa, 28 h



rafts with planes normal to the external [001] load axis



bars with long axis parallel to <100>

[001] crystal orientation:

- fastest growing direction +
- elastic soft +
- leads to {001} phase boundaries of the cuboidal γ' particles +
- direction of best creep properties +

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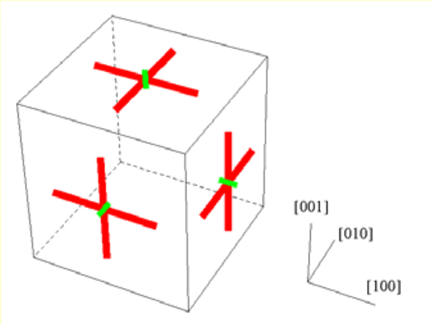
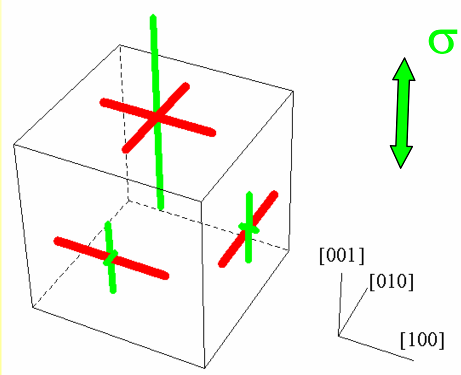
FEM calculation of stress distribution (pure elastic)



No external load
➔ high compression stresses in matrix channels parallel to the phase boundaries

compression
tension



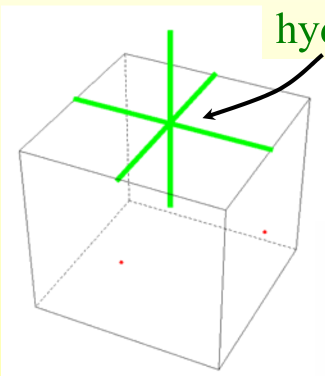
With an external load (500 MPa)
➔ high stress levels in horizontal channels; low stress levels in vertical channels

pure elastic at time t = 0

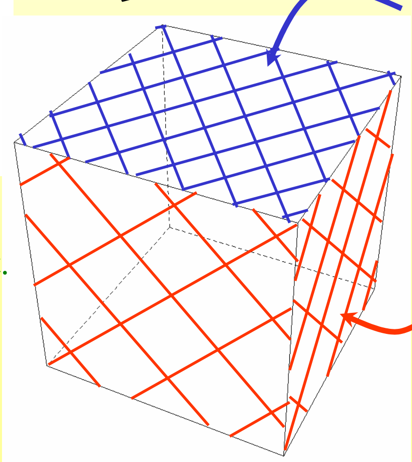
FEM calculations of stress distribution after creep (plastic deformation)

(Matrix according to Norton creep, γ' phase yields plastisch)

hydrostatic tension $p \approx \sigma_{ext.}$



dislocations networks:



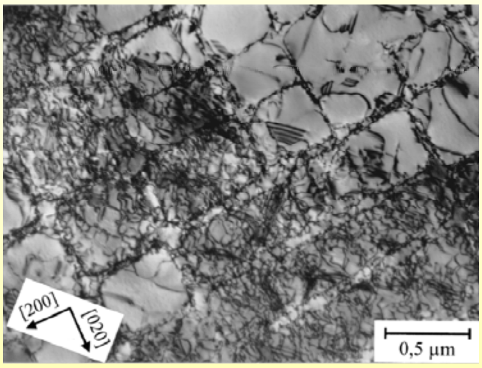
tension

$\sigma_{ext.}$

horizontaler channel:
High density of edge dislocations with additional half plane within γ' phase

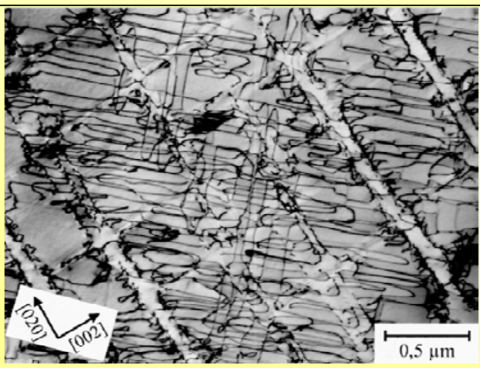
vertical channel:
network of LH- and RH-screw dislocations,
1/3 density

TEM Dislocation Structure:



cross section, $\varepsilon = 2.1$ %
external load normal to view plane
$\otimes$

look onto horizontal matrix channels, vertical channels edge-on.

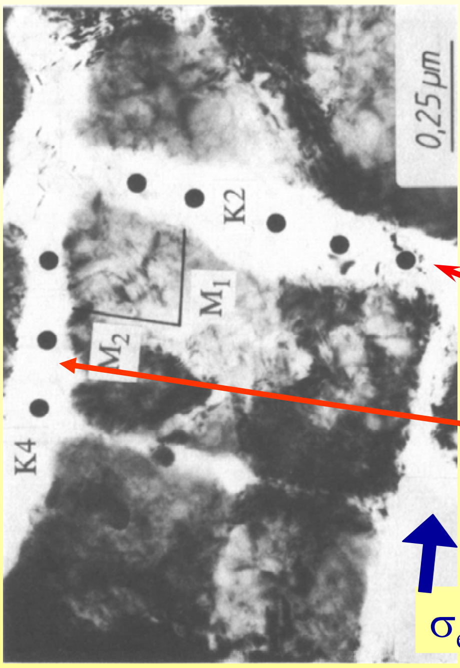


horizontal channel

longitudinal section
$\varepsilon = 1$ %

load axis

Stress Induced Diffusion (EDX-TEM)



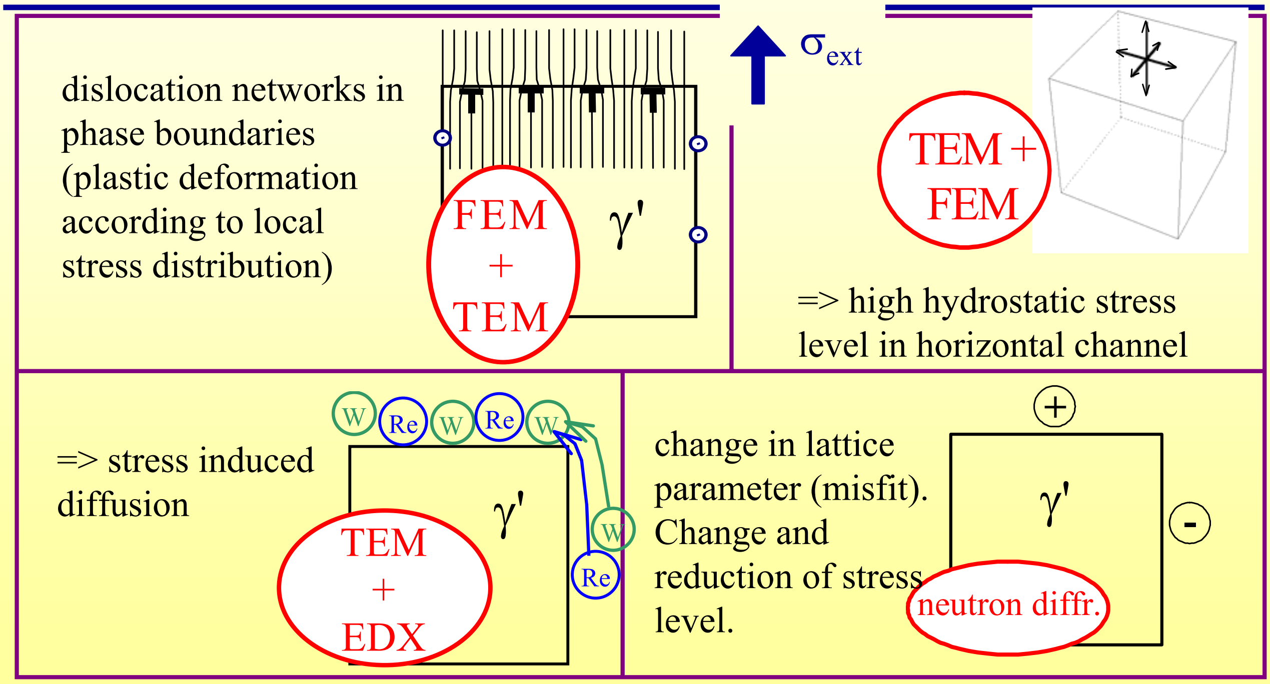
Large atoms diffuse from vertical to horizontal channel.

$$c_{\text{tungsten}}^{\text{horizontal channel}} = 1.2 \cdot c_{\text{tungsten}}^{\text{vertical channel}}$$

$\sigma_{ext.} \approx 500$ MPa

Schmidt and Feller-Kniepmeier, 1993 (SRR99, 760°C)

Summary: changes occuring durig creep



additionally: compostion variation dendrite – interdendritic region and morphology changes

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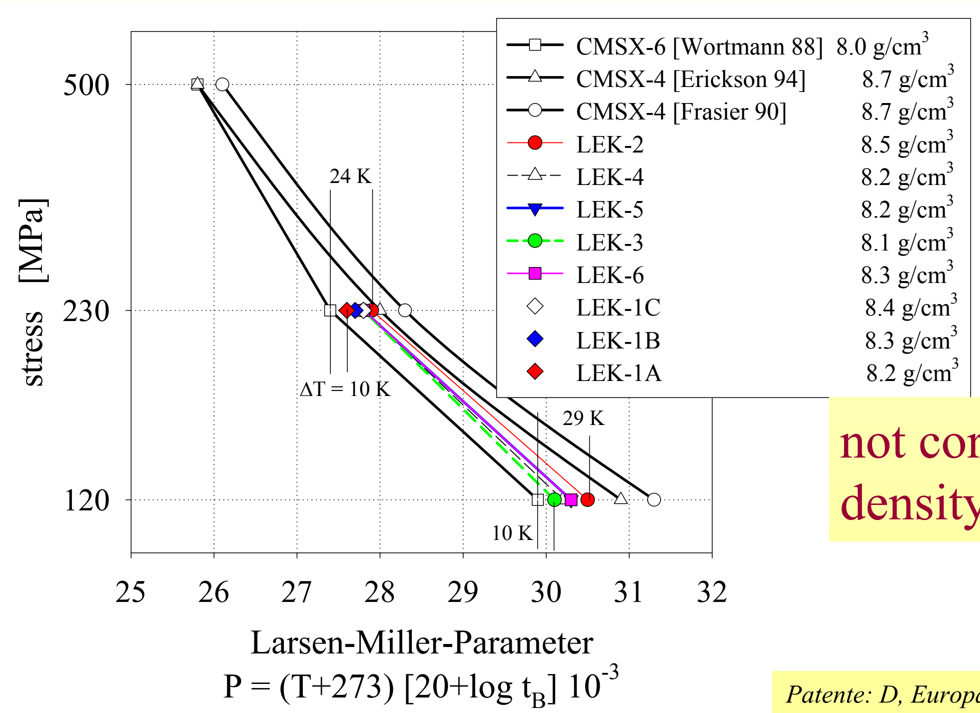
Outlook

- International patent (Glatzel, Mack, Wöllmer, Wortmann):
  Reduce W and Re content → reduced density, improved phase stability, larger temperature window for solution heat treatment, cheaper → LEK 94.
  Within GP 7000 engine for Airbus A 380.

- DFG-Project "Platinbasissuperlegierungen":
  Pt-Al-Cr-Ni (+ Ta, + Ti) alloys can copy successful system of nickel based superalloys (coherent $L1_2$ ordered, cuboidal γ' particles with high volume fraction embedded in fcc-matrix)

LEK 94



not corrected with density!

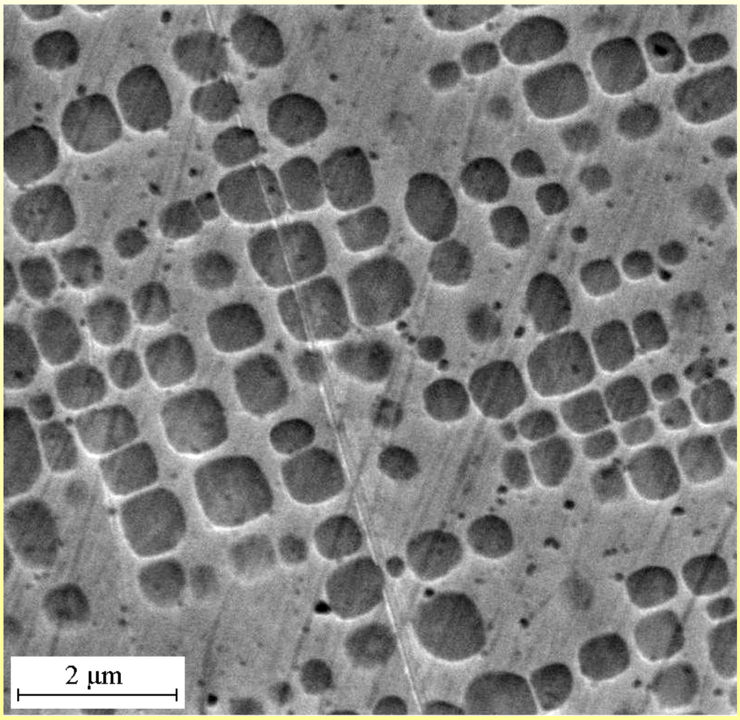
Patente: D, Europa, USA, Kanada, Japan

Microstructure
Platinum Based Superalloy

$Pt_{77}Al_{14}Cr_6Ni_6$

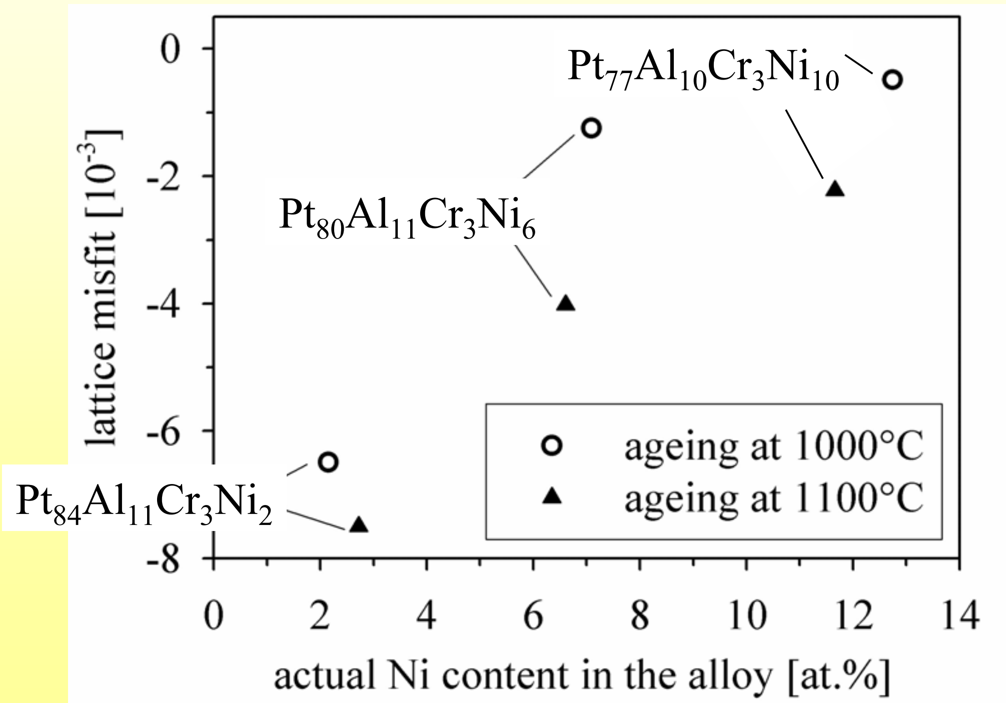
12h @1500°C +
120h @1000°C

CMSX-4, same magnification

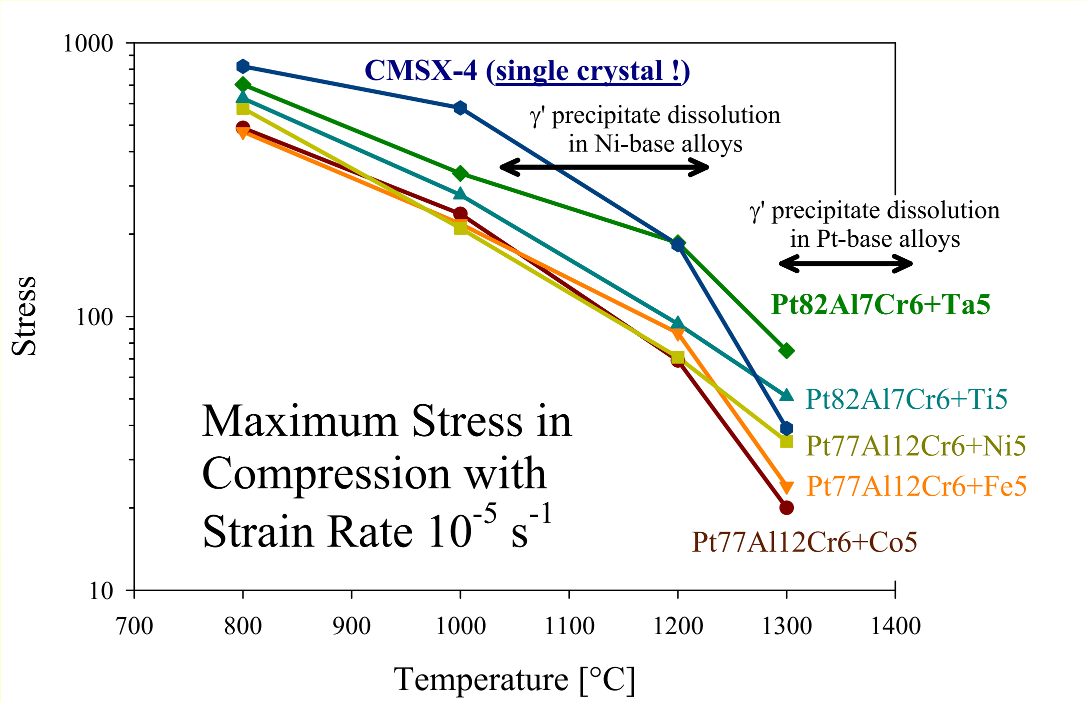


Hüller et al., Met.Mat.Trans. A, 36A (2005), 681

Misfit
Platinum Based Superalloys



Creep Properties
Platinum Based Superalloys



Juni 2005 Bayreuth