Designing strong and ductile alloys
Intrinsic Bulk Nanostructuring via Confined Phase Transformation

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Department for Microstructure Physics and Alloy Design
## Structure of the Department

### Department for Microstructure Physics and Alloy Design

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- **Alloy Design & Thermomech. Processing**
  - new alloys
  - UFG alloys
  - thermomechanical
  - Steel microstructure

- **Theory & Simulation**
  - materials Mechanics
  - process models
  - crystal plasticity
  - transformation modeling

- **Diffraction & Microscopy**
  - textures
  - EBSD
  - TEM
  - 3D EBSD
  - in-stu SEM

- **Mechanics of Bio-Composites**
  - biomaterials
  - polymers
  - biological Materials
  - bone, chitin, teeth

- **Combinatorial Metallurgy & Processing**
  - rapid alloy Prototyping
  - advanced structural Materials
  - welding

- **Atomic-Scale Spectroscopy**
  - tomographic atom probe
  - functional materials
  - Nanostructures

- **Adaptive Structural Materials**
  - alloy design
  - mesoscale in situ characterisation
  - instable phases

**Services:** metallography, computer services, materials testing, materials technology

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Structure of the Department

Research mission, main fields of research and connections
Local phase transformations enable high strength of bulk metals.

- Advanced steels with displacive transformations (TWIP, TRIP)
- Nanocrystalline steels
- reverted nano-austenite steels
- Dual phase
- TRIP and complex phase
- Martensitic
- Advanced maraging-TRIP/TWIP nanoparticle hardened steels

**Inverse strength-ductility relation**

Design strain hardening only where needed.
Understanding the nanoscopic length scales and their effects

Pearlitic nanostructures finer than carbon nanotubes

> 6 GPa
Examples of intrinsically nanostructured alloys

Pearlite: the limits of strength

Nano-austenite reversion

Nanotwinning

Fe-based superalloy
Towards the limits of strength and strain hardening

~7 GPa

strength of blade martensite
strength of TWIP
strength of spider silk

Cooperation:
Neugebauer
Kirchheim

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Pearlite wire: the strongest ductile bulk material: 7 GPa
Towards the limits of strength: cold-drawn pearlitic steel

- Ferrite (~50 ppm C)
- Cementite (25 at.% C)

C isothermal concentration (7 at.%)

Cooperation:
Neugebauer
Kirchheim

Deformation-driven cementite dissolution - oversaturated ferrite
Structure and composition at grain boundaries: pearlite

→ lecture by Michael Herbig
→ poster by Li and Kirchheim
Examples

Pearlite: the limits of strength

Nano-austenite reversion

Nanotwinning

Fe-based superalloy
Solute segregation to martensite grain boundaries

Local phase transformation at grain boundary (martensite-to-austenite reversion confined to GB)
Solute segregation to martensite grain boundaries

- Element with high segregation tendency
- Reduce transformation temperature (e.g. from martensite to austenite)
- Prefer segregation over bulk precipitation (e.g. carbide)

Local phase transformation at grain boundary (martensite-to-austenite reversion confined to GB)
Structure and composition at grain boundary: Mn09, 450°C/10 min

Grain boundary <111> 6-7°
9Mn-2Ni-0.15Al-1Ti-1Mo (wt.%), aged 450°C/65h

Iso-conc. 10 at.%Ni 18 at.%Mn

Mn Ni Al C

Particle decorated martensite (bcc)

Interface region (fcc)

Phase formation at martensite interface
Near equilibrium partitioning at interface

Cooperation: Neugebauer

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Segregation plus confined phase transformation in Fe-Mn
Same effect even at dislocations?

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Extreme segregation at dislocations in Fe-Mn
Martensite relaxation & aging & nanoscale austenite reversion

650 MPa to 2 GPa

Making martensite ductile

400 °C aging:

precipitation + austenite reversion

Fe-13.6Cr-0.44C (wt.%)
Examples of intrinsically nanostructured alloys

Pearlite: the limits of strength

Nano-austenite reversion

Nanotwinning

Fe-based superalloy
Fe

\[ \tau_{tw} = \frac{\nu_{sf}\tau}{3b_s} + \frac{3Gb_s}{L_0} \]

APT

Funding: SFB 'steel-ab initio'
Examples

Pearlite: the limits of strength

Nano-austenite reversion

Nanotwinning

Fe-based superalloy
Fe-30%Mn-8%Al-1.2%C weight reduced alloys (10% less density)

Nanostructured Fe-based superalloy
Fe-Mn-Al-C weight reduced alloys (10% less mass density)

- Fe-Mn-Al-C alloys with k-carbides: 1.5 GPa, 80% ductility
- Thermal stability
- Deformation mechanisms depend on local composition
Conclusions

- Design alloys by self-organized nanostructuring

- Segregation plus confined phase transformation at defects

- Works for dislocations too?

- Deformation-driven mechanical bulk alloying leads to non-equilibrium phases approaching the theoretical limits of strength

- Designing stable nanocarbides enables weight-reduced ultra-ductile and thermally stable materials
Thanks for the attention