Model-based description of the temperature-dependent strength of ferritic and austenitic ODS steels

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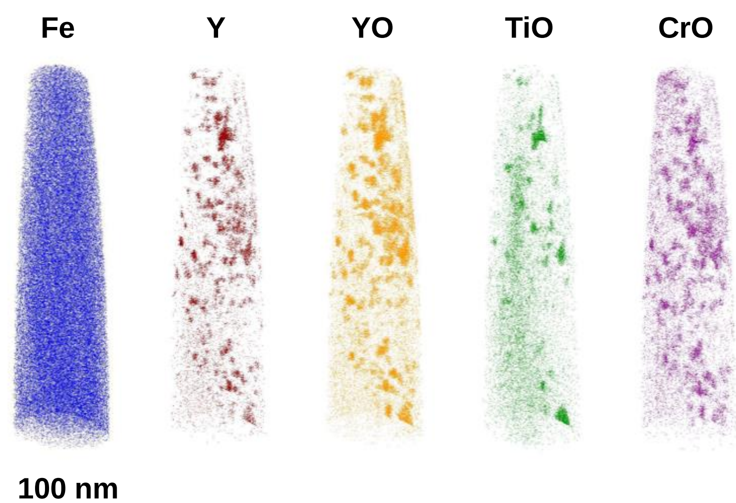


Motivation

Corrosion resistance

Creep resistance

Ferritic ODS steels

Ultrafine grain size

Stable microstructure

Suitable for high temperature applications
Nano-scaled oxide particles → nanoclusters

- Possible advantages of austenitic ODS steels
  - Higher corrosion resistance
  - Higher creep resistance due to crystal structure

➢ Identification of differences in mechanical properties of ferritic and austenitic ODS steels

Materials

- ODS steels with simple composition to enable comparison

Mechanical alloying

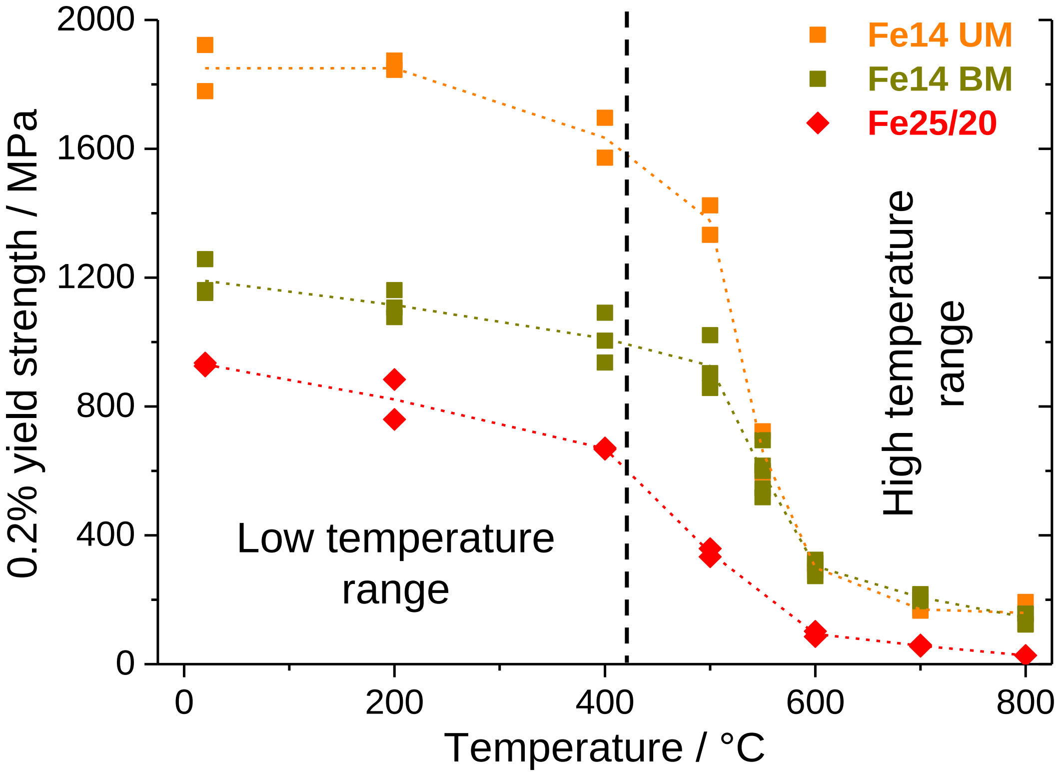
- **Ferritic** ODS steel
  - Fe-14Cr-0.4Ti-0.25Y_2O_3 (in wt.%)
  - Composition similar to 14YWT
  - Elemental powders and Y_2O_3 powder
  - Milling in an attritor
  - Investigated alloys:
    - **Fe14 UM** (unimodal grain size)
    - **Fe14 BM** (bimodal grain size)
- **Austenitic** ODS steel
  - Fe-25Cr-20Ni-0.4Ti-0.25Y_2O_3
  - Composition similar to the high temperature steel AISI 310
  - Elemental powders and Y_2O_3 powder
  - Milling in a planetary ball mill
  - Investigated alloy:
    - **Fe25/20**

Consolidation

- Field assisted sintering technique (FAST)
- 5 min at 1100 °C and 50 MPa

➢ Prevents coarsening of grains and nanoclusters

Temperature-dependent strength



- Compression tests
- Temperatures up to 800 °C
- Initial strain rate $\dot{\varepsilon} = 10^{-4}\ s^{-1}$

- Ferritic ODS steels have higher strength in the entire temperature range

- Drop of strength above 400 to 500 °C due to creep deformation

- Low temperature range
  - Superposition of strengthening mechanisms
  - Temperature dependency of shear modulus
- Creep models to describe high temperature strength

Calculation of yield strength

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$$\sigma_{\mathrm{dis}} = \alpha M G B \sqrt{\boldsymbol{\rho}_{\mathbf{dis}}}$$

Dislocation strengthening

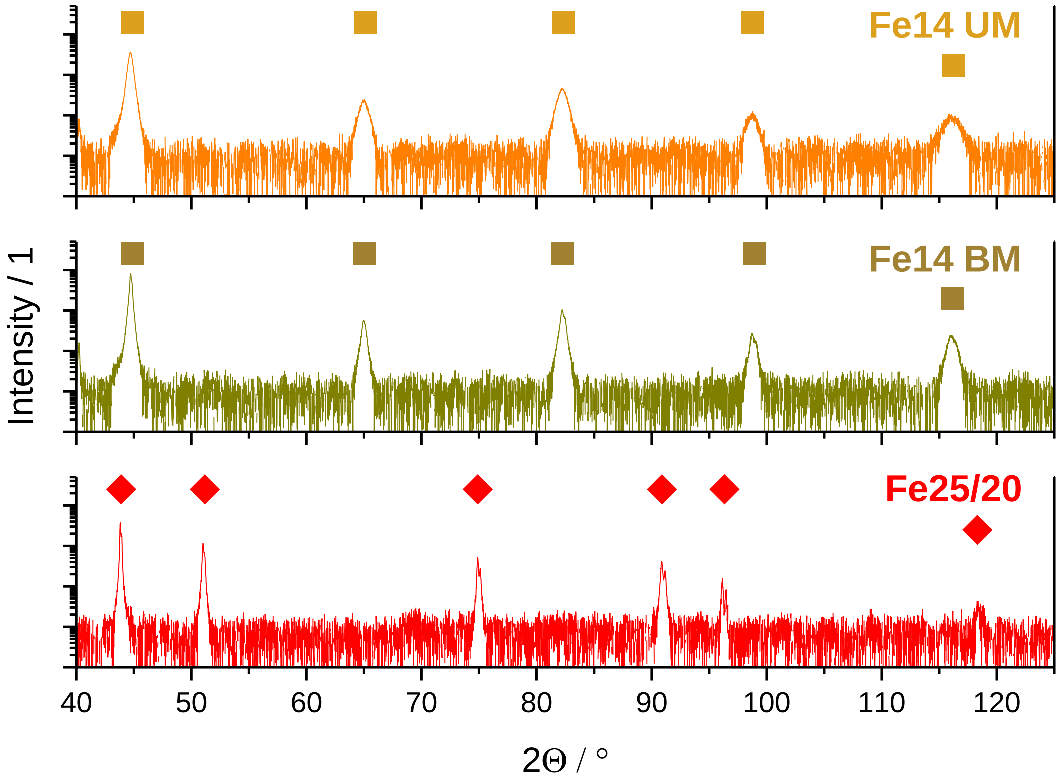
$$\sigma_{\mathrm{HP}} = \frac{k_{\mathrm{HP}}}{\sqrt{\boldsymbol{d}_{\mathbf{g}}}}$$

Hall-Petch strengthening

$$\sigma_{\mathrm{OR}} = \frac{MGb}{\boldsymbol{d}_{\mathbf{p}}} \sqrt{\frac{6\boldsymbol{f}_{\mathbf{p}}}{\pi}}$$

Orowan strengthening

Dislocation density



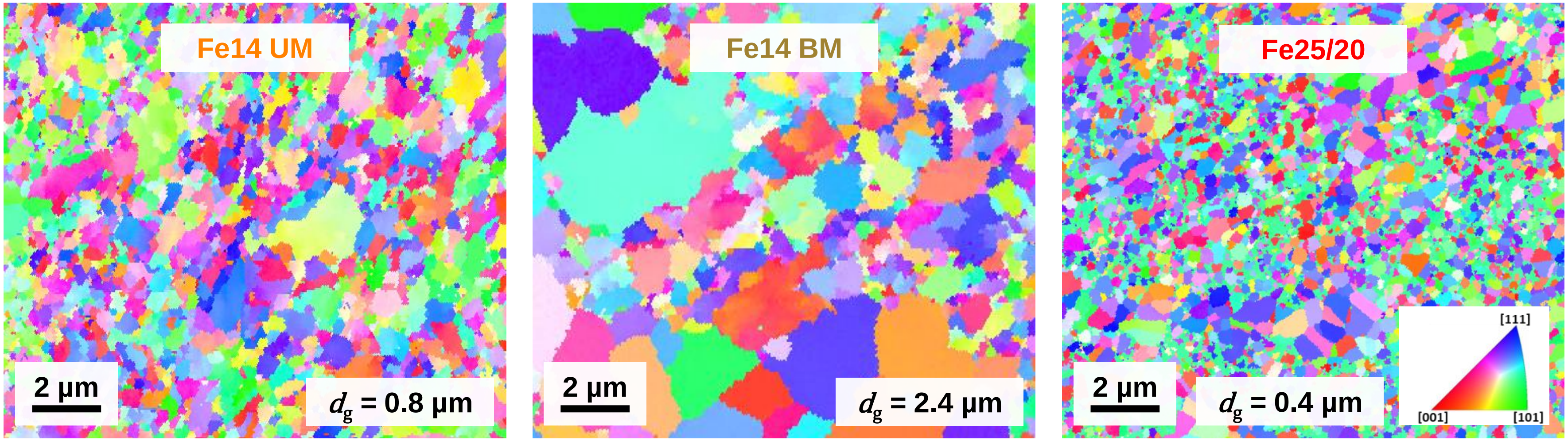
■ bcc

◆ fcc

- All ODS steels are single-phase after consolidation
- Differences in peak width → Williamson-Hall analysis
- Correction of device specific broadening and elastic anisotropy
- Dislocation density is ~ 10^{15} m^{-2} in ferritic ODS steels and ~ 10^{13} m^{-2} in **Fe25/20**

Strong recovery and/or recrystallization expected during consolidation of austenitic ODS steels

Grain size

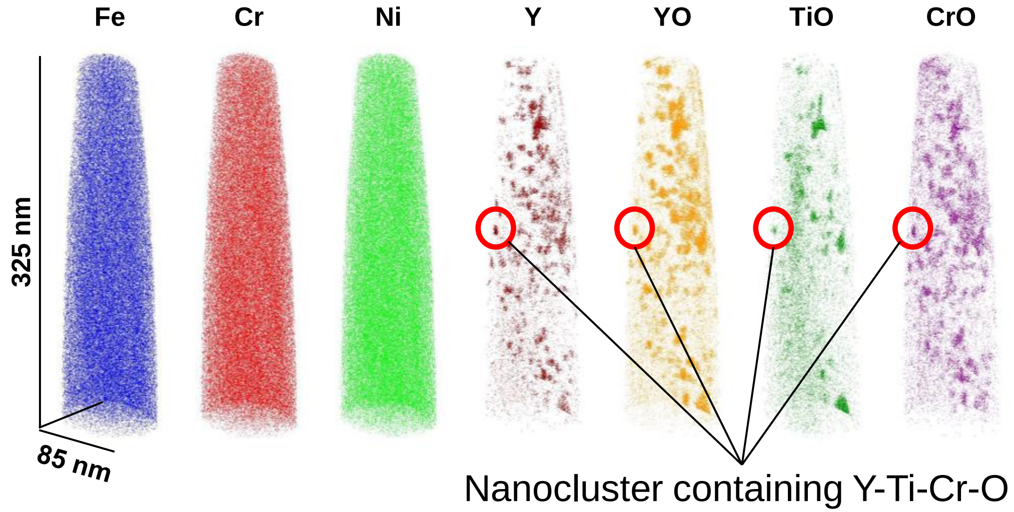


- Area normalized grain sizes analyzed by EBSD

- Austenitic ODS steel **Fe25/20** has smallest grain size
- **Fe14 BM** shows bimodal grain size distribution

Analysis of nanoclusters

3D reconstruction of a **Fe25/20** tip



- Analysis with atom probe tomography

- Nanocluster size is between 3 and 5 nm
- Volume fraction of particles is 0.06 to 0.08 vol.%
- Broad size distribution
- Inhomogeneous distribution of particles in the atom probe tips

Calculation of yield strength

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Orowan strengthening

- Additional contributions from Peierls stress and solid solution strengthening
- Superposition depends on strength and density of obstacles [1]

Lower limit → strong interaction of strengthening mechanisms

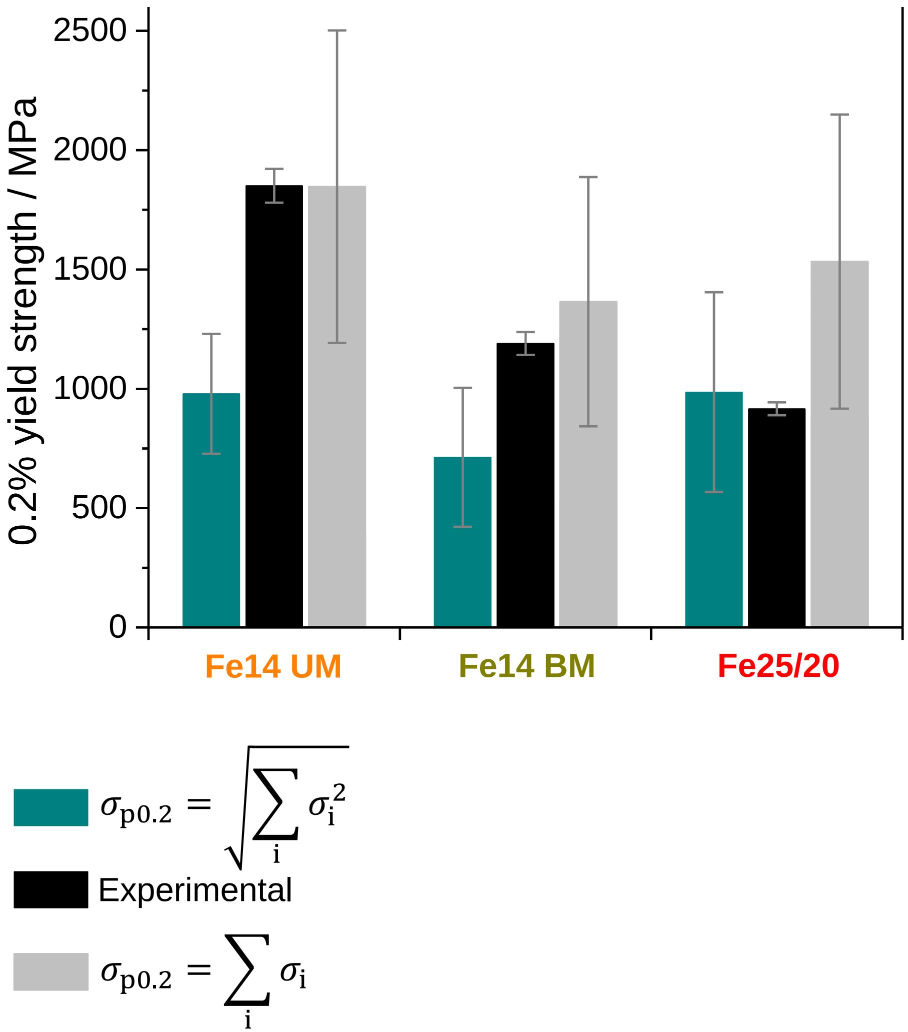
$$\sqrt{\sum_{\mathrm{i}} \sigma_{\mathrm{i}}^2} \leq \sigma_{\mathrm{p0.2}} \leq \sum_{\mathrm{i}} \sigma_{\mathrm{i}}$$

Upper limit → no interaction of strengthening mechanisms

- Furthermore, a discussion of uncertainties is necessary
- Uncertainties from literature data for constants and from experimentally determined parameters
- Orowan mechanism for smallest nanoclusters?

[1] Kocks et al., Progress in Materials Science (1975) 19

Calculation of yield strength



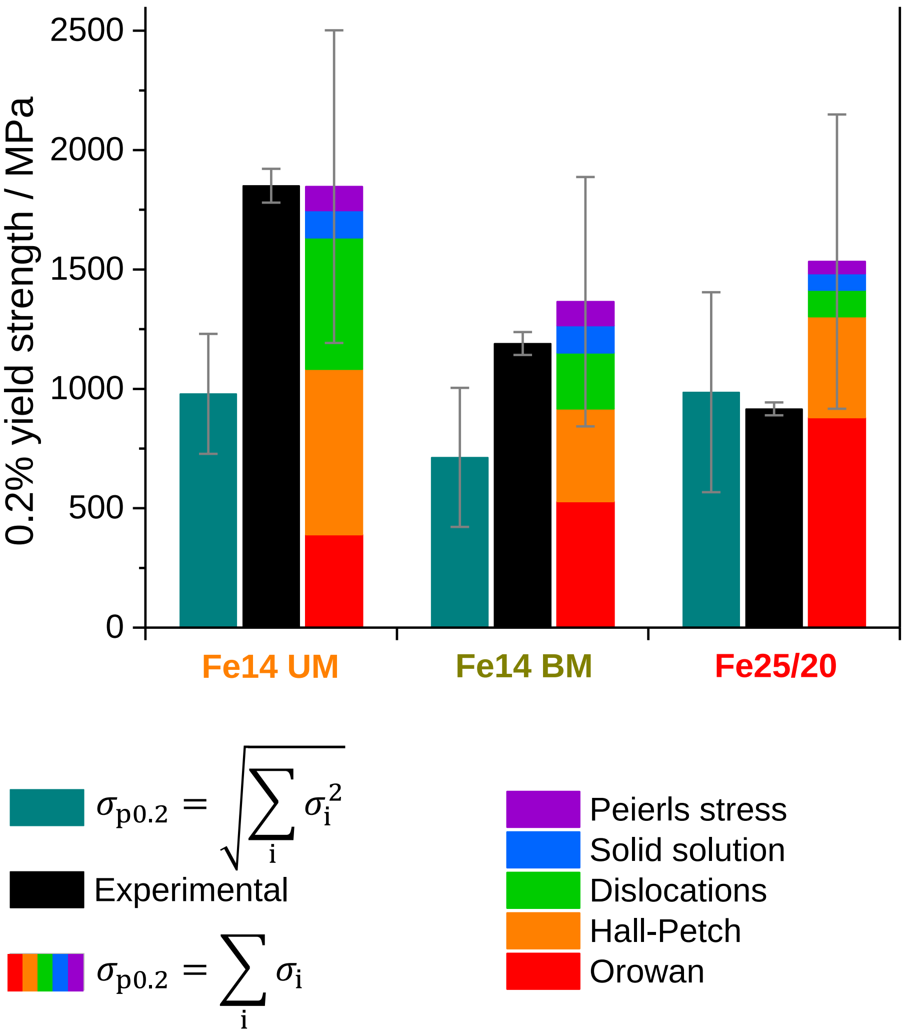
- Green and grey columns visualize the minimum and maximum calculated strength, respectively

Linear superposition overestimates the experimentally determined strength

- Error bars symbolize uncertainties resulting from experimentally determined microstructural parameters

A range for the expected strength of an ODS steel can be calculated with the knowledge of microstructural parameters

Most important strengthening mechanisms



- Most important strengthening mechanisms in ODS steels are
  - Orowan strengthening
  - Hall-Petch strengthening
  - Dislocation strengthening (in ferritic ODS steels)
- Lower strength of austenitic ODS steels
  - Lower dislocation density due to recovery and/or recrystallization during consolidation
  - Lower Hall-Petch constant [1]: 0.3 vs. 0.6 MPa·$m^{1/2}$

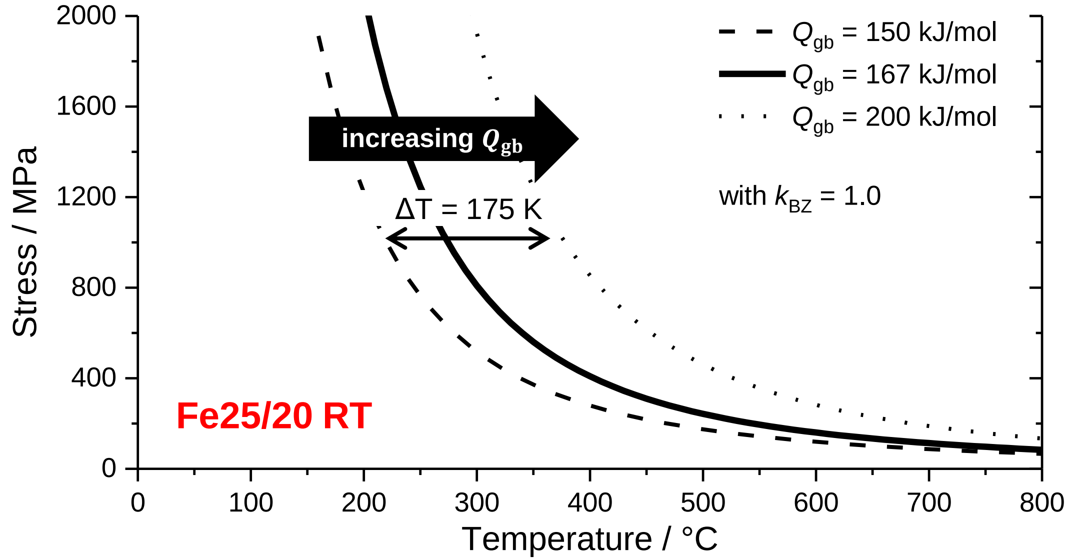
[1] Kashyap et al., Acta Materialia 50 (2002) 9

Strength at high temperatures

- Dislocation-based creep following Blum and Zeng [1]
- Annihilation and formation of dislocations at grain boundaries

$$\sigma_{\mathrm{BZ}} = \boldsymbol{k}_{\mathbf{BZ}} \cdot G \left(\frac{\pi(1-\nu)M^9}{1.2^4}\right)^{\frac{1}{8}} \cdot \left(\frac{k_{\mathrm{B}}T}{G\delta_{\mathrm{gb}}\boldsymbol{D}_{\mathbf{gb0}}} \cdot \dot{\varepsilon}\right)^{\frac{1}{8}} \cdot \exp\left(\frac{\boldsymbol{Q}_{\mathbf{gb}}}{8RT}\right) \cdot \left(\frac{d_{\mathrm{g}}}{b}\right)^{-\frac{1}{2}}$$

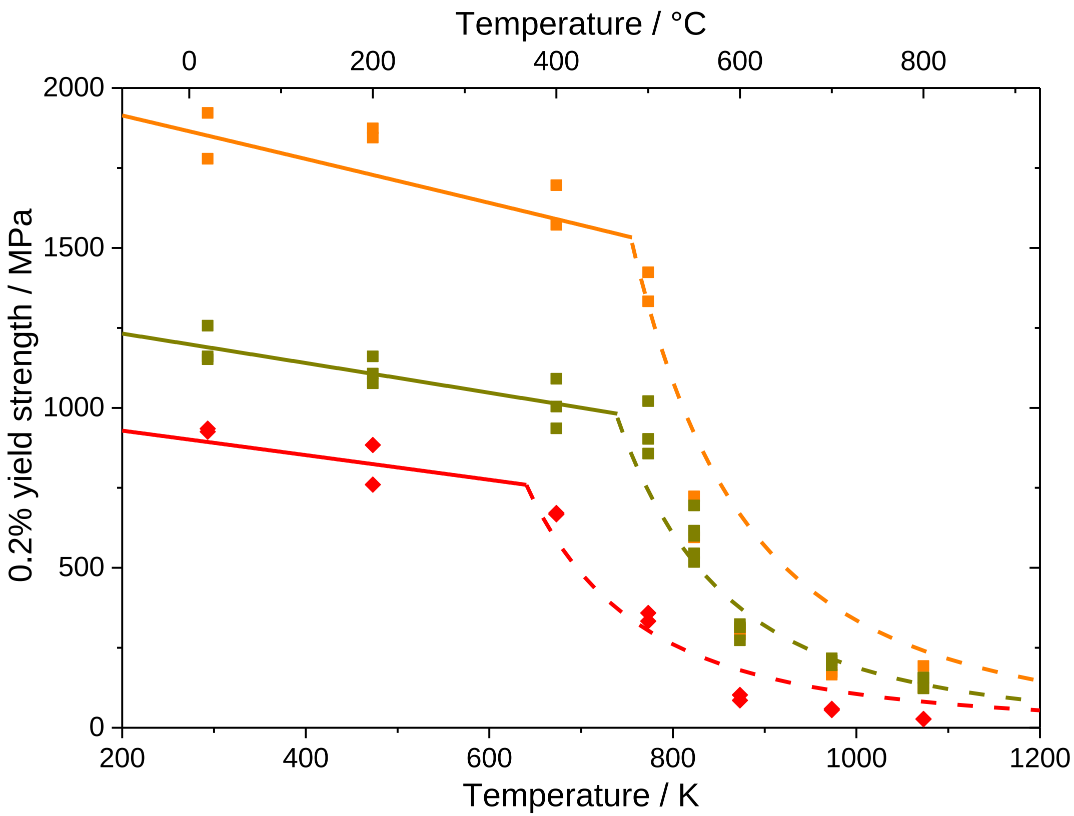
- Influence of $\boldsymbol{Q}_{\mathbf{gb}}$



- $\boldsymbol{D}_{\mathbf{gb0}}$ has a similar influence
- $\boldsymbol{Q}_{\mathbf{gb}}$ can be used for a least square fit of the curve to experimental data
- $\boldsymbol{k}_{\mathbf{BZ}}$ is used in a second step

[1] Blum and Zeng, Acta Materialia, 59 (2011) 15, 6205-6206

Model-based description of the yield strength



- Low temperature range
  - Linear superposition of strengthening contributions
  - Fitting to experimental data by a linear scaling factor
- High temperature range
  - Fitting to experimental data by varying the activation energy Q_{gb} and k_{BZ}
  - Obtained values are in a reasonable range for ODS steels

B&Z model can be used to describe the strength at high temperatures
Dislocation-based creep can be assumed

Conclusions

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- Austenitic ODS steel shows lower strength due to lower contributions from dislocation strengthening and Hall-Petch strengthening

- In the low temperature range, yield strength can be described by the superposition of strengthening mechanisms
- Experimental uncertainties and unknown interaction of strengthening mechanisms has to be taken into account

- In the high temperature range the drop in yield strength can be described dislocation-based creep following the Blum & Zeng model
- The activation energy Q_{gb} and the constant k_{BZ} are used to fit the calculation to experimental data

Thank you for your attention!

DFG

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