Webinar: Novel high performance materials & components, 15th November 2022

Components' and Materials' Performance for Advanced Solar Supercritical CO_2 Powerplants

COMPASsCO_2

Novel Cr-based alloys strengthened by intermetallics for structural and coating applications at high-temperatures >800°C

Speakers:
Kan Ma (University of Birmingham)
Mathias Galetz (DECHEMA-Forschungsinstitut – DFI)

WP3 Development of Materials

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Outline

- Context: Concentrated Solar Power (CSP) and Cr-based materials (1min)

- Development of novel Cr-NiAl bcc-superalloys (9min)
  - Cr-NiAl alloy design with Fe addition: phase diagram calculations & microstructure validation
  - Microstructure stability at elevated temperatures
  - Mechanical properties at elevated temperatures

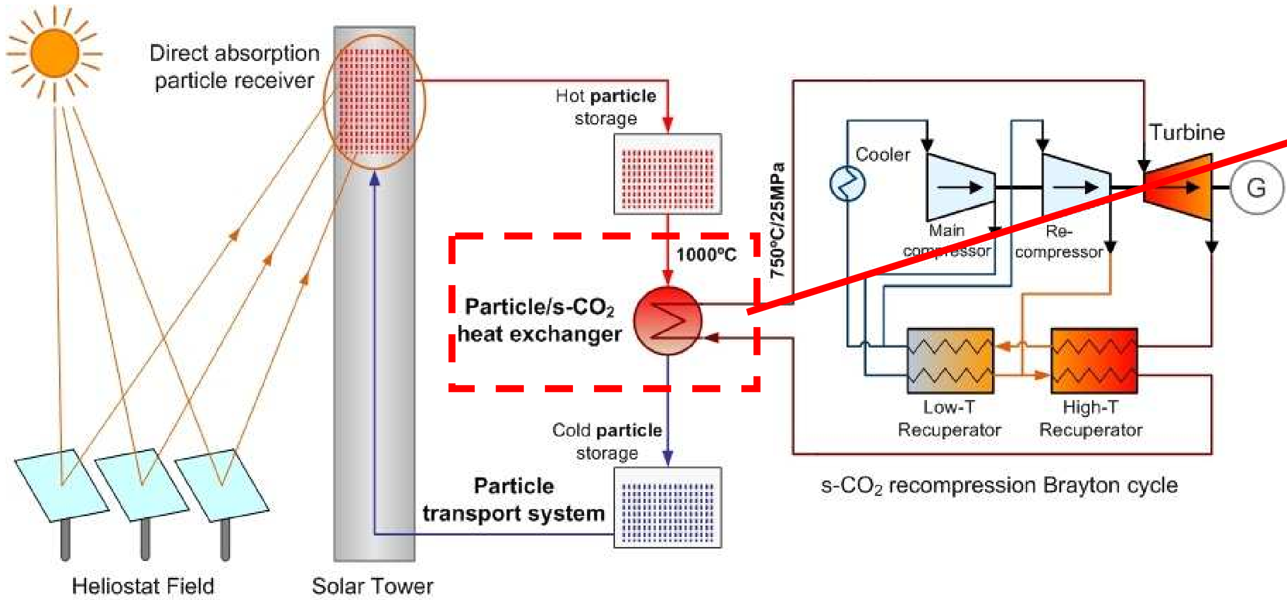
- Development of novel Cr-Si alloys and coatings (9min)
  - Alloy design
  - Advantages and Challenges of alloying by Si
  - Cr-Si slurry coating on Ni superalloys and austenitic steels

- Conclusions and perspectives (1min)

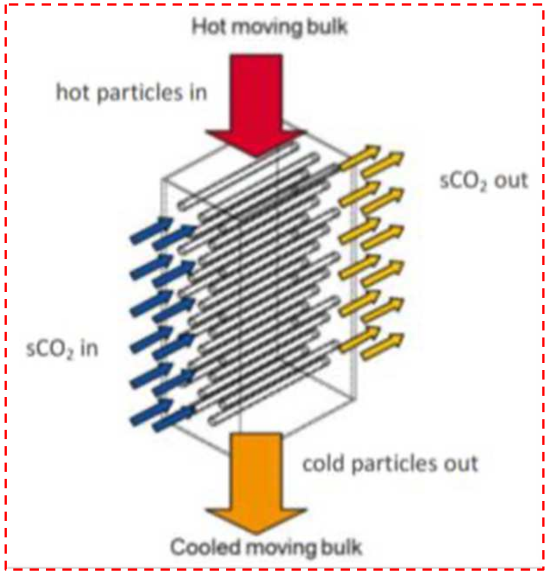
Context (1/2)

➢ Development of materials for HX tubes in advanced CSP

Advanced Concentrated Solar Plant (CSP)



Heat exchanger (HX)



Challenges of structural materials of HX:

- **High temperature >700°C (strength)**
- **s-CO_2 environment (corrosion)**
- **Erosion due to particles (wear)**
- High pressure ~20 MPa
- long-life behavior
- …

=> Cr-based materials

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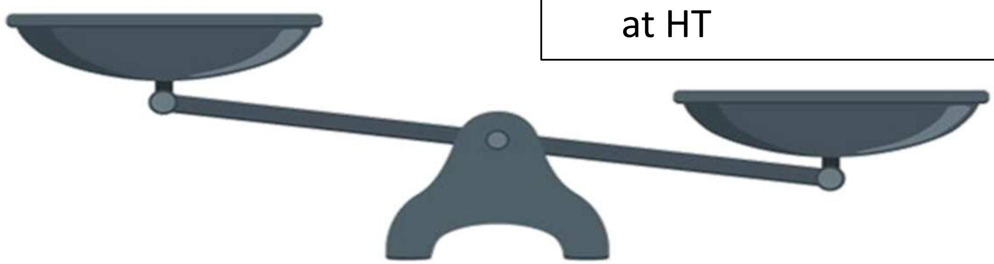
Context (2/2)

➢ Development of bcc-bcc superalloys

Property balance of Cr (bcc)

Advantages:
- High melting point (1907°C)
- Low price (<Ni, <other refractory metals.
- Good oxidation resistance.
- Good thermal conductivity.
- (low mass density)

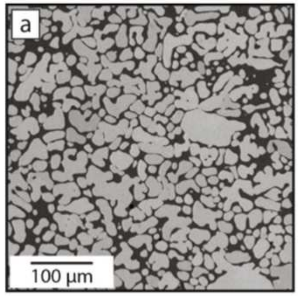
Drawbacks:
- Insufficient strength & creep resistance
- High DBTT (brittle @ RT)
- Nitrogen embrittlement at HT



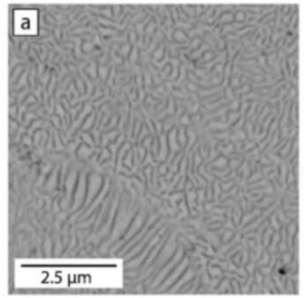
Approach 1

BCC-BCC → Cr (A2) strengthened by ordered bcc precipitates

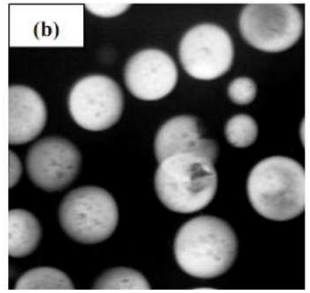
W-TiFe (A2-B2)[1]



Ti-TiFe (A2-B2)[2]

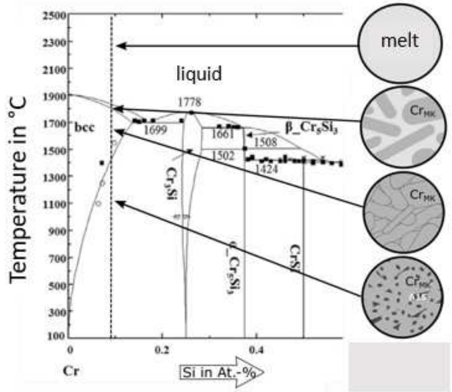


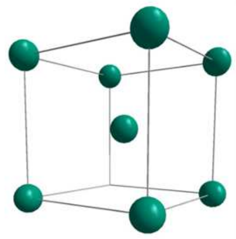
Fe-NiAl (A2-B2)[3]



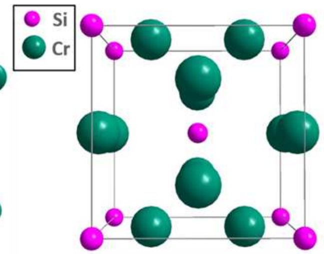
Approach 2

$Cr\text{-}Cr_3Si$ → Cr (A2) strengthened by A15 precipitates





bcc Cr_{ss}



A15 Cr_3Si

[1]A. Knowles et al. / Applied Materials Today 23 (2021) 101014
[2]A. Knowles et al. / Scripta Materialia 140 (2017) 71–75
[3]Z. K. Teng et al. / Scripta Materialia 63 (2010) 61–64

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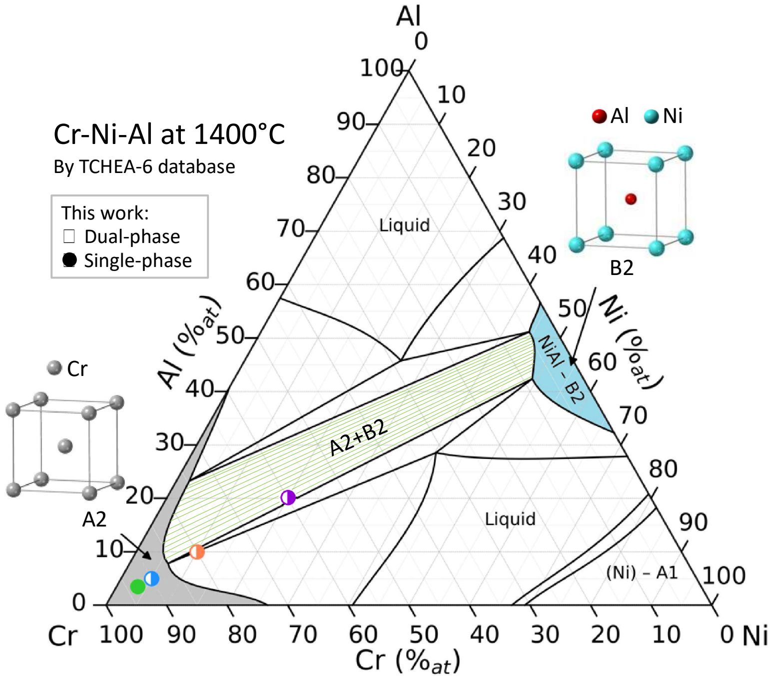
  - Cr-NiAl alloy design with Fe addition: phase diagram calculations & microstructure validation
  - Microstructure stability at elevated temperatures
  - Mechanical properties at elevated temperatures

- Development of novel Cr-Cr_3Si alloys (9min)
  - Alloy design
  - Hardness & DBTT?
  - Oxidation resistance
  - Slurry coating on Ni superalloys and austenitic steels

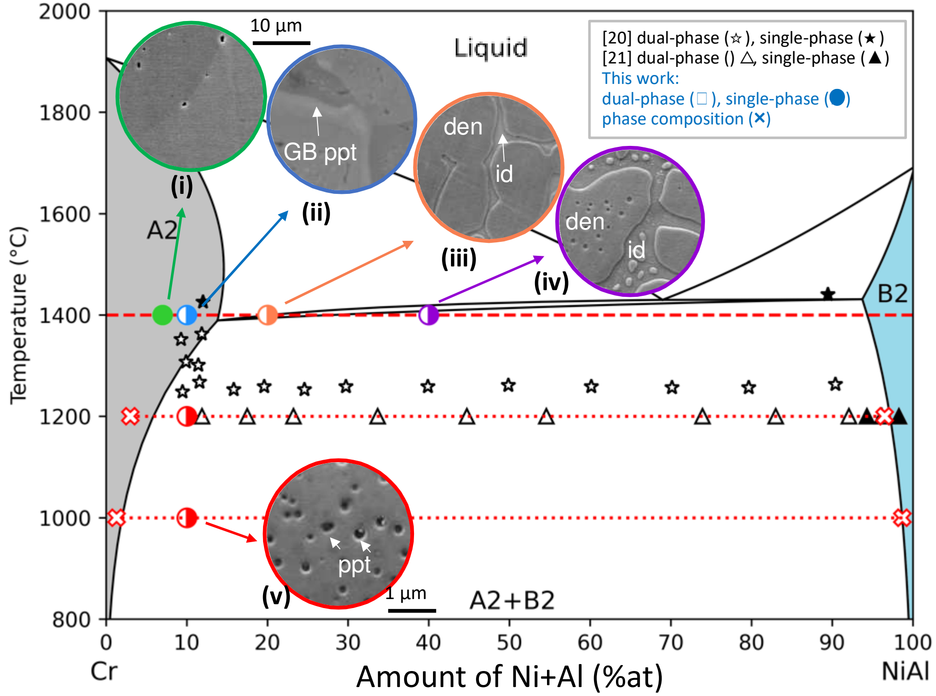
- Conclusions and perspectives (1min)

Novel Cr-NiAl bcc-superalloys

Alloy design instructed by phase diagram



- Phase diagram enabling the design of Cr-superalloys (Cr-NiAl)



- Discrepency of experiment and simulation on Cr-rich side in CALPHAD
- Limited solubility of Ni+Al limiting alloy design

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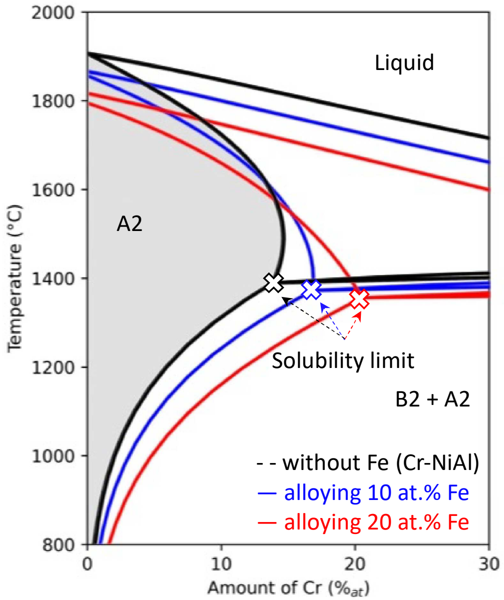
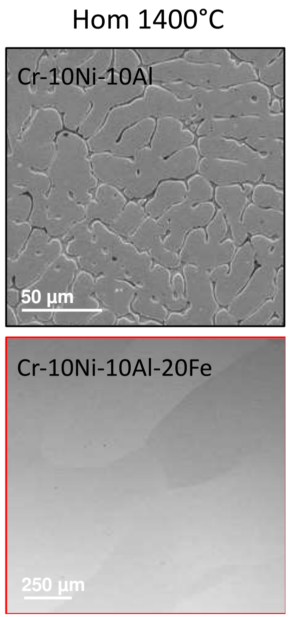
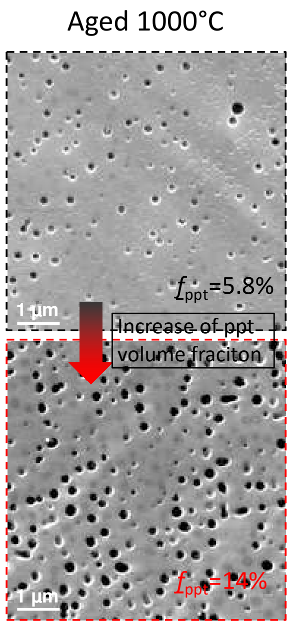
Novel Cr-NiAl bcc-superalloys

Alloy design instructed by phase diagram



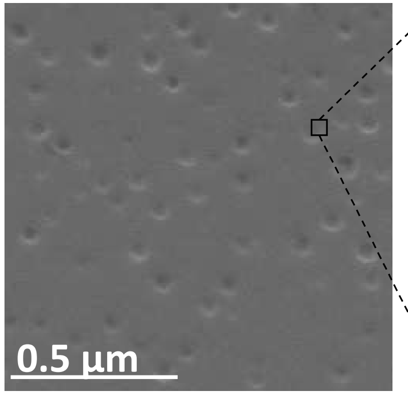


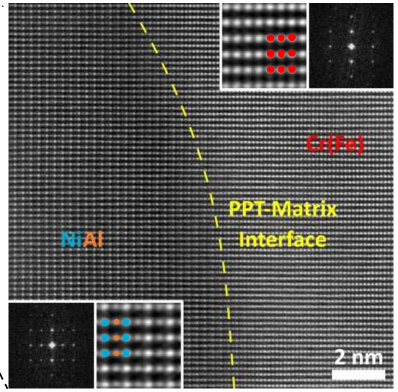


➢ Fe addition increasing the solublity of Ni+Al

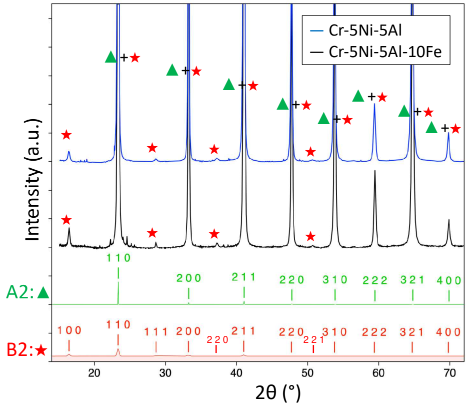
Novel Cr-NiAl bcc-superalloys

Microstructure characterisation

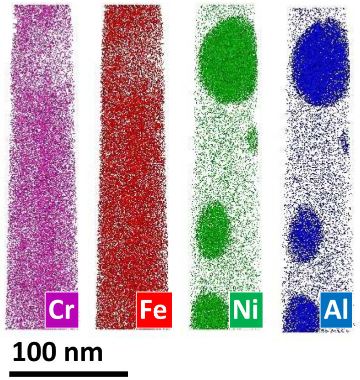


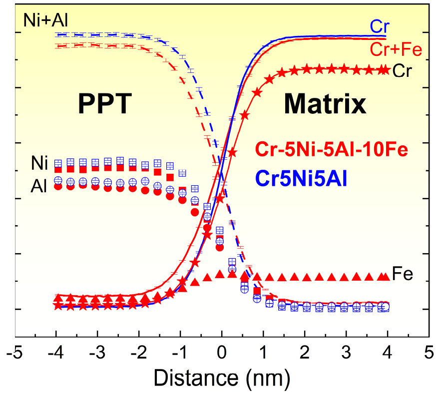


HR-STEM
(ePSIC - Diamond)

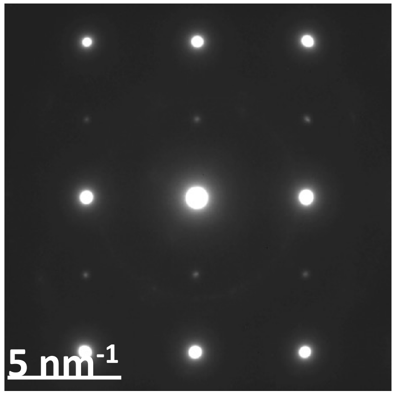


Synchrotron XRD
(I11 - Diamond)





Atom probe tomography
(University of Oxford)



- Fe additio …..

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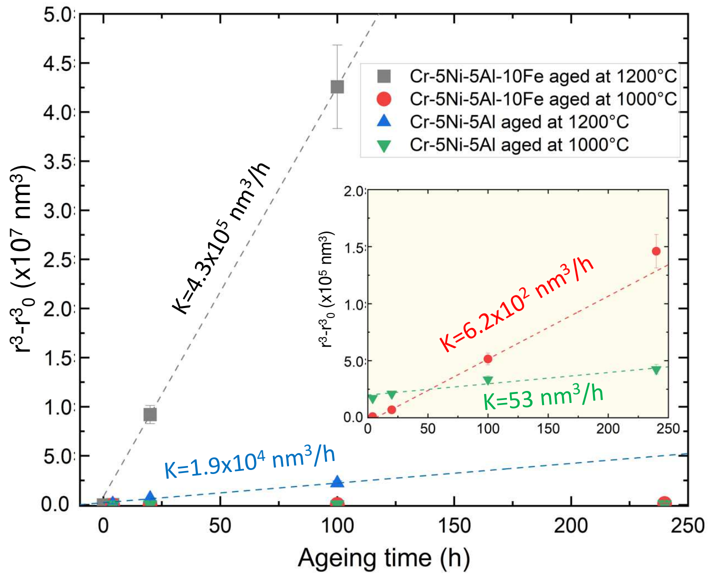
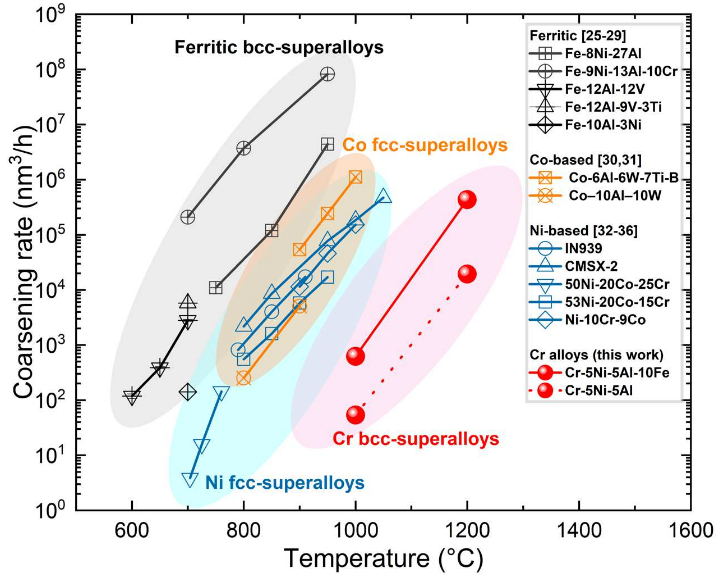
Novel Cr-NiAl bcc-superalloys

X





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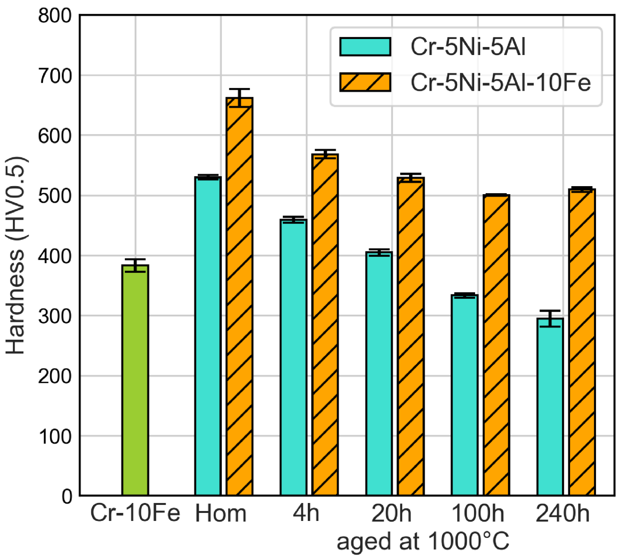
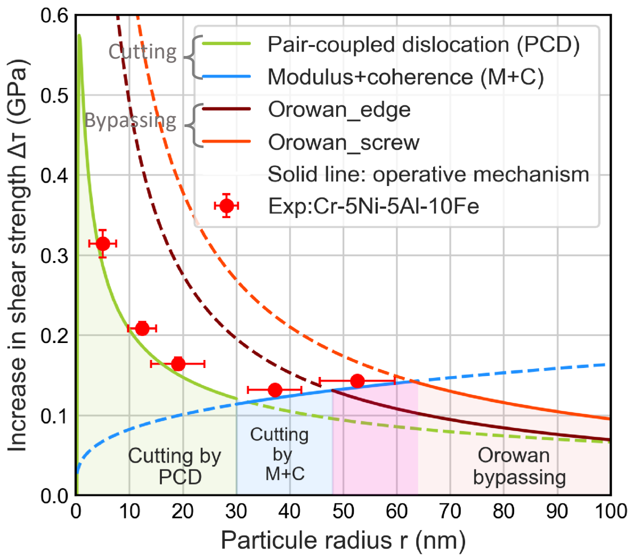
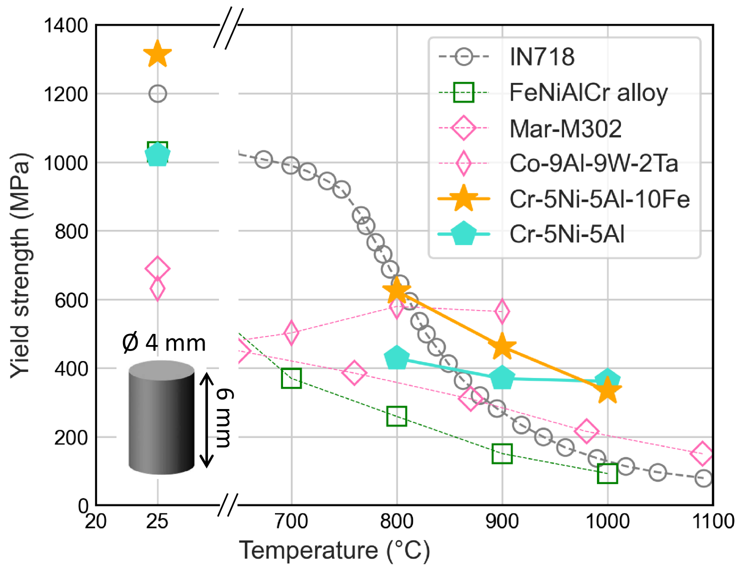
Novel Cr-NiAl bcc-superalloys

X







Conclusions

1. Low solubility of NiAl in Cr-matrix and uncertainty of current database for Cr phase diagram
2. Fe addition increasing the NiAl solubility
   - ➢ enables a homogenized microstructure and the tailoring of microstructure by heat treatment
3. Good thermal stability of B2-NiAl precipitates in Cr matrix
   - ➢ precipitate coarsening follows the LSW rule (controlled by diffusion)
   - ➢ small coarsening rate at the end-application (Concentrated Solar Plants) temperature range

Perspectives

- ❑ lattice misfit
- ❑ corrosion behavior
- ❑ deformation behavior

COMPASSCO2 project website
https://www.compassco2.eu

Tweets de @Co2Compa

k.ma@bham.ac.uk

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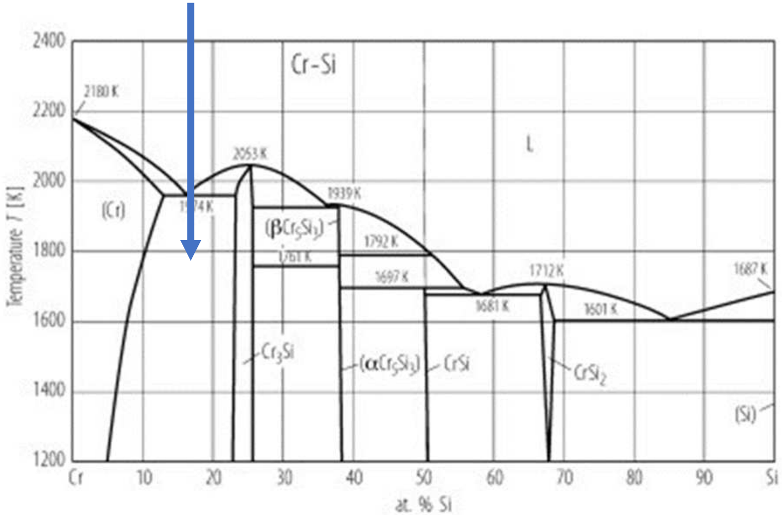
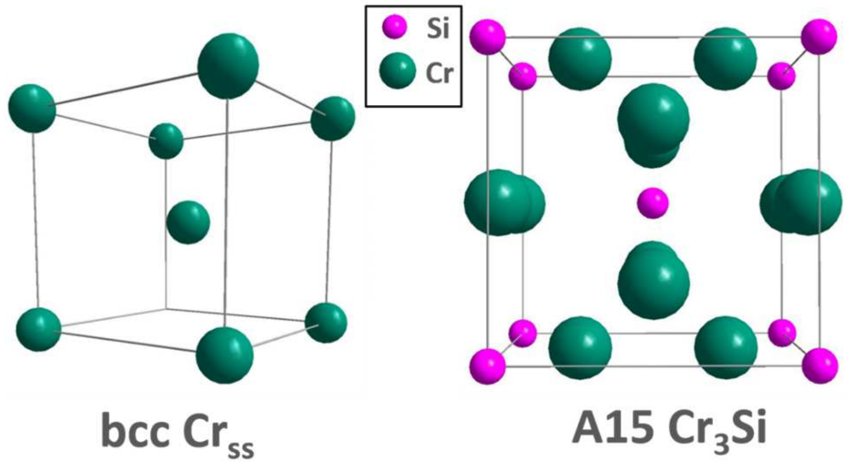
Design of Cr_{ss}-Cr_3Si alloys

- Approach: Cr-based materials alloyed with silicon
- Duplex Cr_2O_3-SiO_2 scale for high **oxidation&carburization resistance** precipitation of hard intermetallic silicides for **erosion&creep resistance**

Cr_{ss} + Cr_3Si



[Cr-Si Phase diagram of the Cr-Si system revised by Oka]

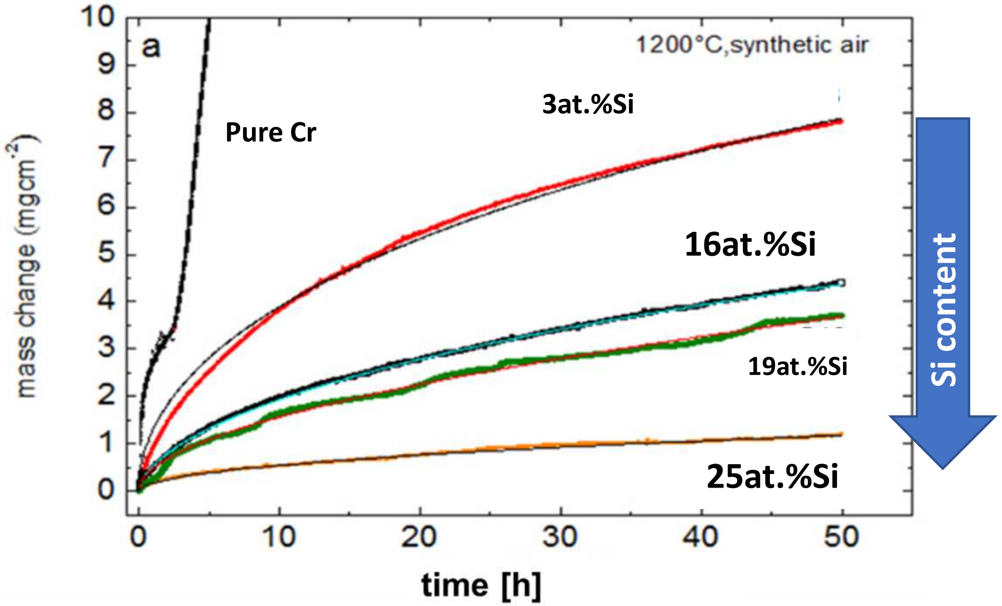


[A. S. Ulrich, PhD Thesis, University of Bayreuth, 2020]

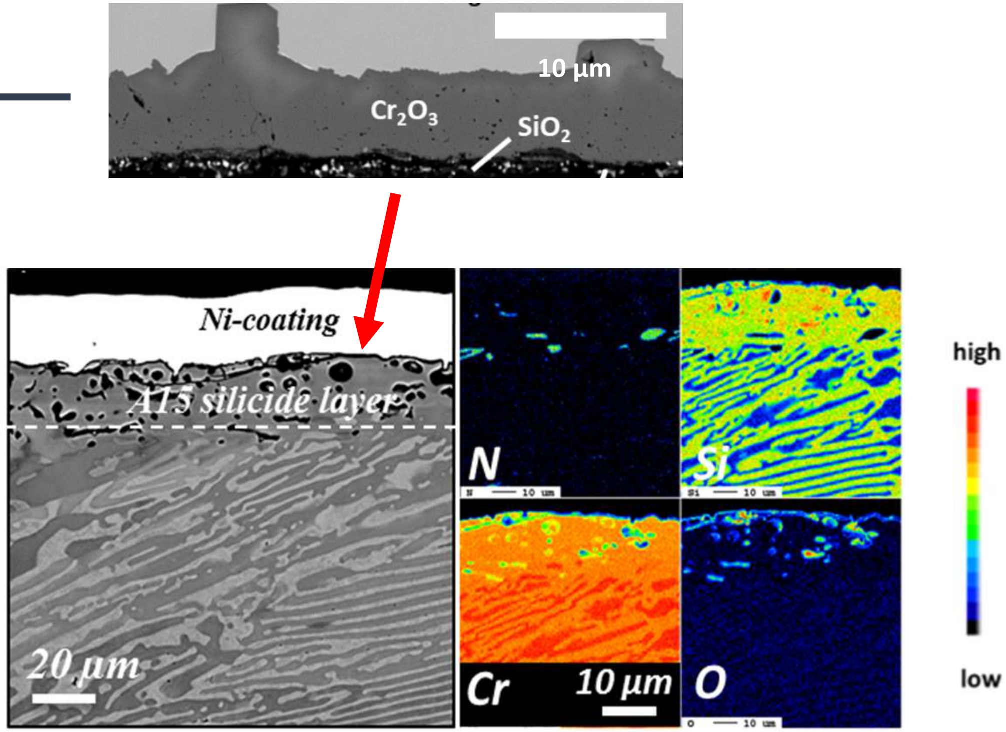
- Two phase microstructure: toughening bcc Cr_{ss} + strengthening A15 Cr_3Si precipitates

Alloying by Si: Advantages

50h @ 1200°C, air



Si decreases oxidation rate but also ductility



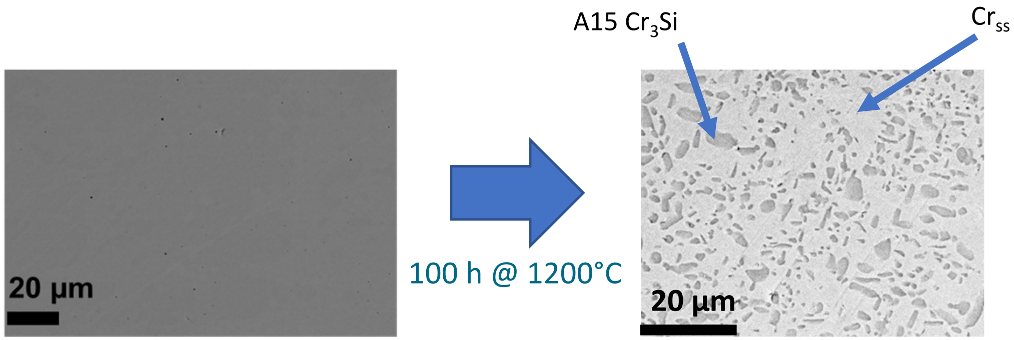
$Cr_{84}Si_{16}$: Layered oxid scale + continous A15 Cr_3Si layer acts as a barrier to nitration

- Increasing amount of Si: improved oxidation and nitridation resistance, but embrittlement

A. Soleimani Dorcheh, W. Donner, M. C. Galetz, Materials and Corrosion, 2014

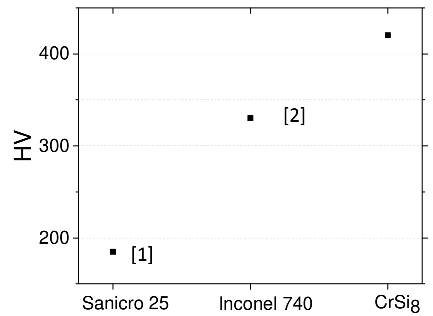
Heat treatable Cr_{ss}-Cr_3Si alloys

- Heat treatment 100 h @ 1200°C: diffusion controlled precipitation of Cr_3Si-phase



As cast: oversaturated single phase Cr_{SS} of $Cr_{92}Si_8$

$Cr_{92}Si_8$: Two-phase microstructure Cr_{ss} + A15 Cr_3Si



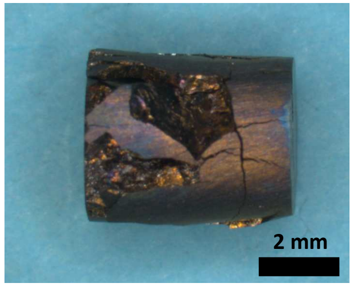
HV of $Cr_{90}Si_8$ compared to conventional materials*

[1] https://www.materials.sandvik.com, January 2022
[2] https://www.azom.com, January 2022

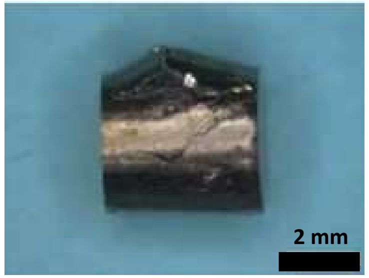
- Increased hardness by precipitation hardening → promising for improved erosion behavior

Challenge: Ductile to Brittle Transition Temperature

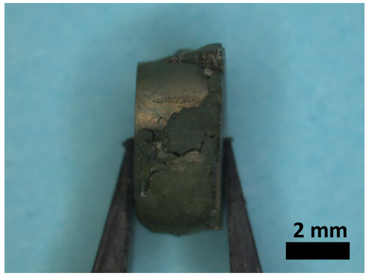
- DBTT was determined by compression tests at different temperatures



Fracture pattern for $Cr_{92}Si_8$ after compression test @ 500°C



Fracture pattern for $Cr_{92}Si_8$ after compression test @ 600°C



Fracture pattern for $Cr_{92}Si_8$ after compression test @ 700°C

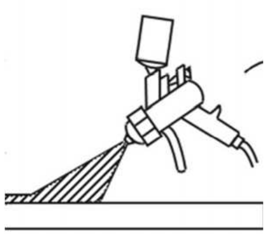
- Up to temperatures to 700°C very limited deformation → DBTT between 600°C and 700°C; no improvements by alloying with Fe and Ni
- <u>"Make or break" criteria for structural applications</u> → Development of Cr-Si coatings on state of the art materials as substrates

Process Chart of Cr-Si Slurry Coating

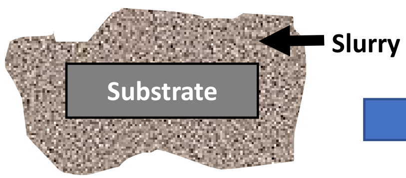
*Patent applied

➢ Newly developed coating process by the slurry technique for applying Cr-Si diffusion coatings

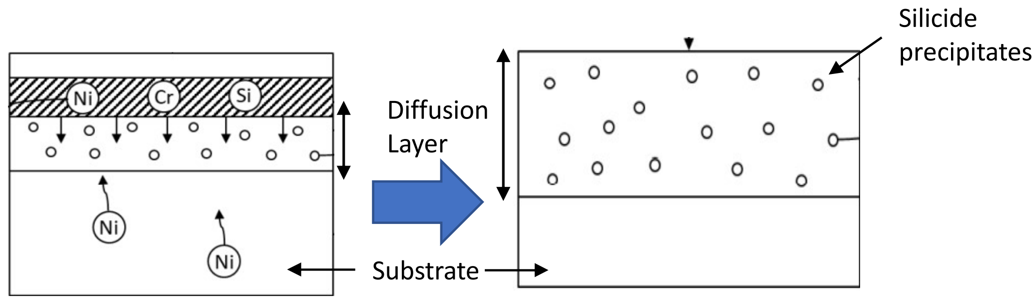
Slurry with particles + binder sprayed on substrate	Heat Treatment I - Removal of binder @ 350°C for 3 h	Heat Treatment II - Interdiffusion @ 1150-1200°C for 6 h	Enrichment of the substrate's surface by Cr-Si



R. Verma et al., Journal of Thermal Spray Technology (2016): 1289-1301



[M.C. Galetz, Coatings for superalloys (2015): 277-296]



➢ Enrichment of Cr and Si in surface zone to specifically modify the properties

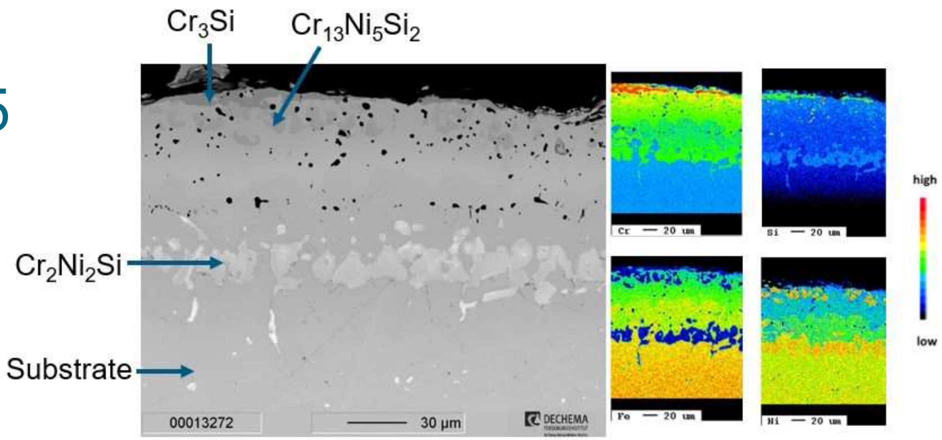
Cr-Si Coatings: Cross-sections

<u>Austenitic steel</u>: Sanicro 25

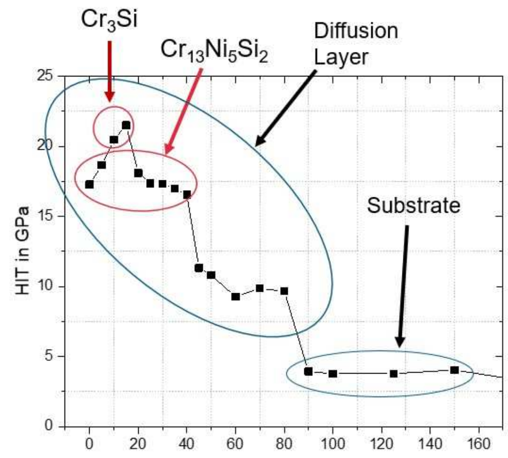
- Enrichment of Cr and Si in a layer of about 100 µm
- Diffusion layer: high increase of hardness compared to substrate

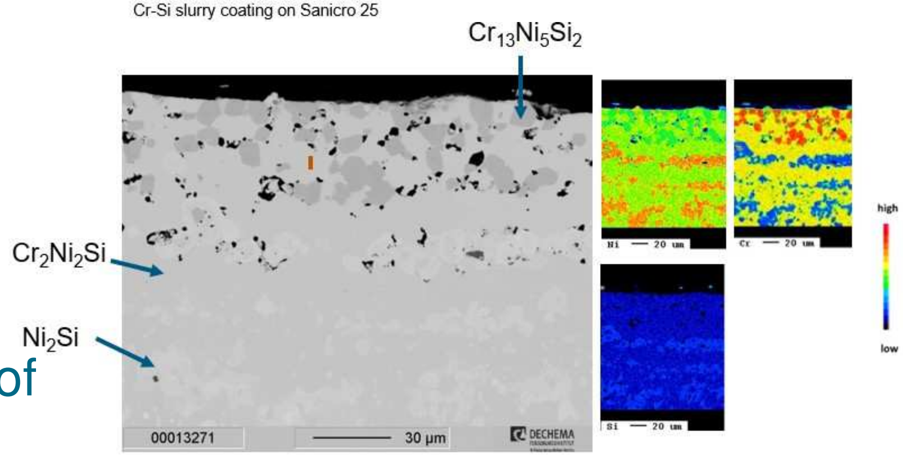
<u>Ni-based alloy</u>: Inconel 740

- Enrichment of Cr and Si in a layer of about 200 µm
- Diffusion layer: high increase of hardness compared to substrate

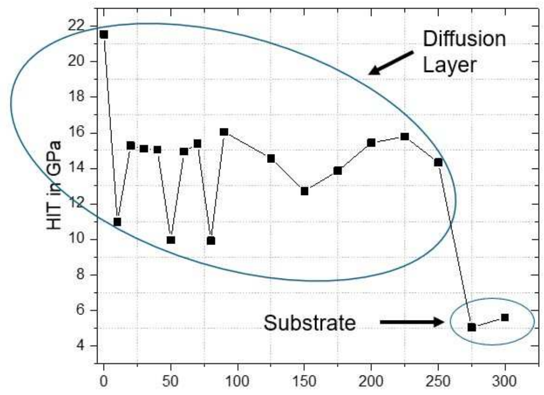


Cr-Si slurry coating on Sanicro 25



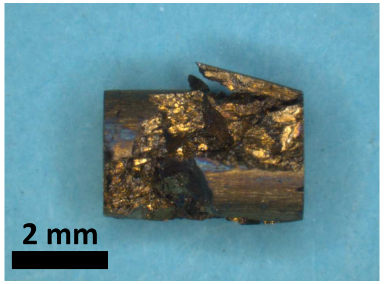


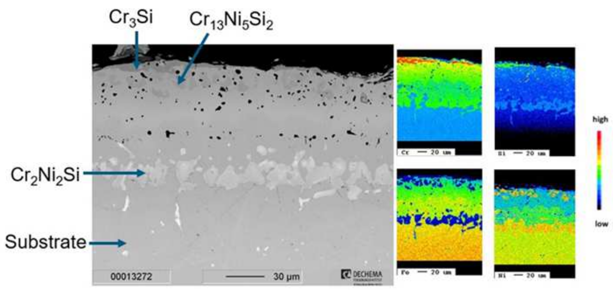
Cr-Si slurry coating on Inconel 740



Conclusions and next steps

- Cr-Si alloys show high potential for high temperature applications
- Mechanical properties and in particular DBTT remains „make or break“ criteria for structural applications





Cr-Si slurry coating on Sanicro 25

- CSP-application: Use Cr-Si in the form of diffusion coatings on state-of-the-art materials: Novel slurry process successfully developed

- Next Step: Testing of coatings in CSP heat exchanger environment

COMPASSCO2 project website
https://www.compassco2.eu

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