High-temperature strength of $L1_2$-hardened Compositionally Complex Alloys

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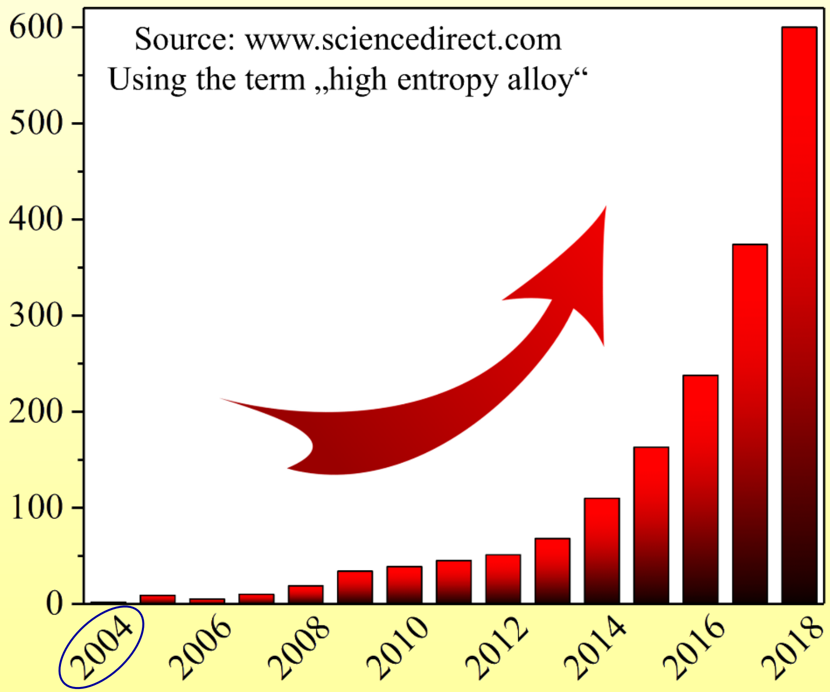
  - High Entropy Alloys (HEA)
  - Compositionally Complex Alloys (CCA)
- Base alloy $Al_{10}Co_{25}Cr_8Fe_{15}Ni_{36}Ti_6$ (in at.%)
- Modification by hafnium and molybdenum
- Mechanical characterization
- Discussion
- Summary

Introduction

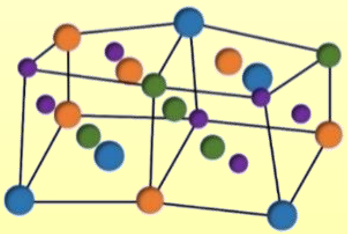
Increase of number of publications in the branche „high entropy alloys“



High entropy alloys

- ➢ At least 5 components
- ➢ Near equiatomic composition

$$S_{conf} = -R \cdot \sum_{i=1}^{n} (c_i \cdot \ln c_i)$$



- High strength
- High hardness
- Thermal stability
- Sluggish diffusion kinetics
- Oxidation and corrosion resistance

B. Cantor et al. „Microstructural development in equiatomic multicomponent alloys“ Mater. Sci. Eng. A (375-377)
J.W. Yeh et al. „Nanostructured high-entropy alloys with multiple principal elements: Novel alloy design concepts and outcomes“ Adv. Eng. Mater. (6)

Introduction

High entropy alloys
- Insufficient properties
- No solid-solution stabilization

Compositionally Complex Alloys

Multiphase microstructure as the prominent and promising feature

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AlCoCrCuFeNi
- More than 6 phases
- Phases with bcc-structure
- Brittle mechanical behavior

$Al_{10}Co_{25}Cr_8Fe_{15}Ni_{36}Ti_6$
- 3 phases left
- Fcc-structured matrix
- Good strength-ductility relation

- Cu

+ Ni

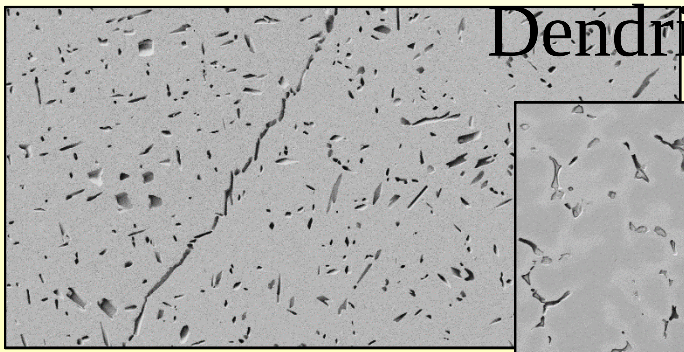
+ Ti

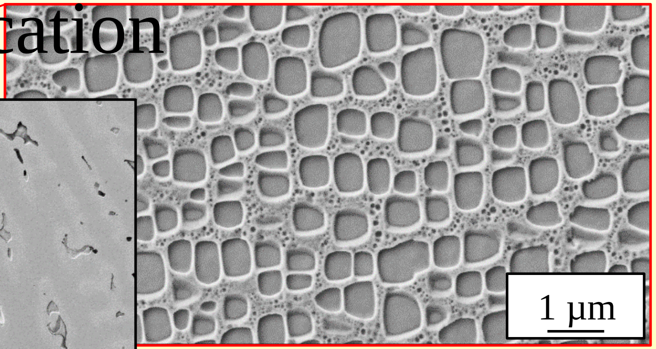
Base alloy

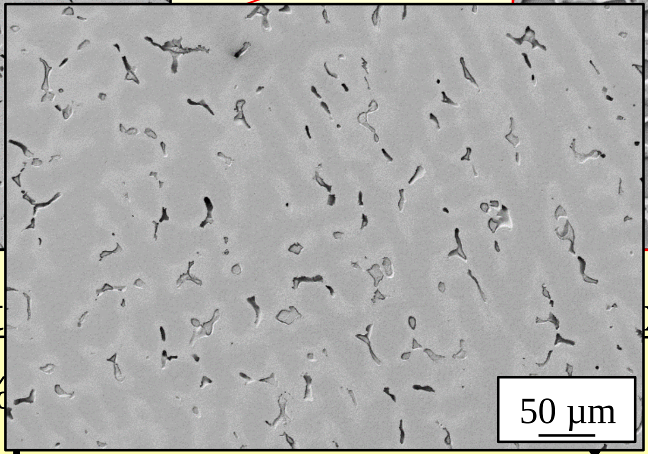
<u>C1-phase</u>

<u>γ/γ´-structure</u>

Dendritic solidification

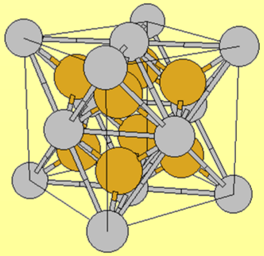






<u>Needle-like precipit</u>

- Al-rich (28 at.%
- cF12, Fm3m, **C1**
- Length up to 50 µm
- Volume content < 5 %



Homogenization:
1220 °C / 20 h
Annealing:
900 °C / 50 h

<u>x</u>

- Fcc-structure
- Fe-, Co-, Cr-rich

<u>γ´-particles (primary)</u>

- $L1_2$-structure
- Ni-, Al-, Ti-rich
- Edge length ~ 450 nm
- Volume content ~ 40 %

Impact of refractory metals hafnium and molybdenum

Base alloy

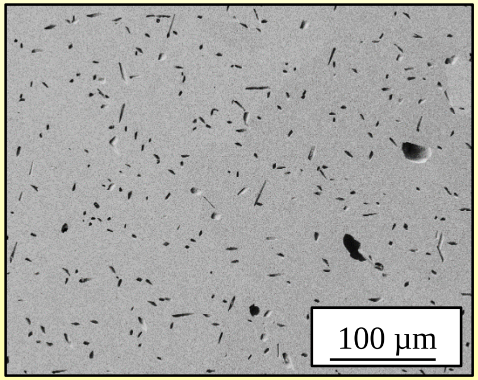
- Needle-like C1-phase
- Cubic γ´-particles

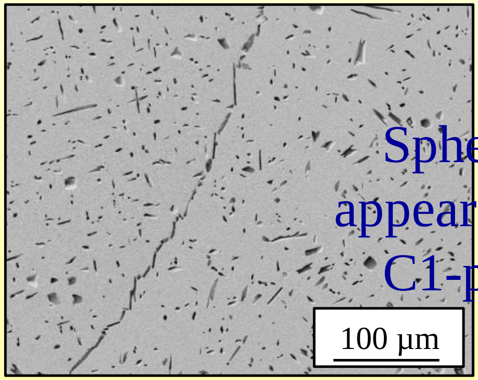
+ 1 at.% Mo

Solid-solution hardening

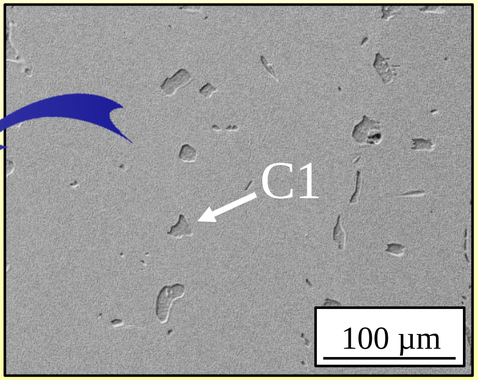
+ 0.5 at.% Hf

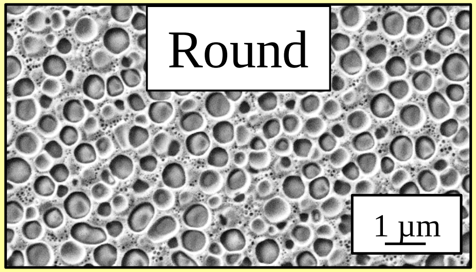
Stabilization of γ´

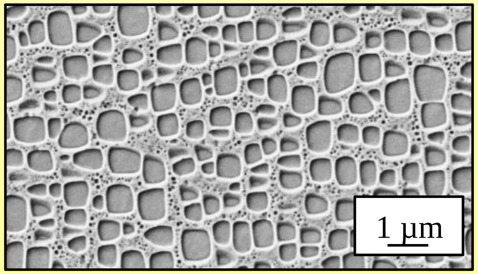


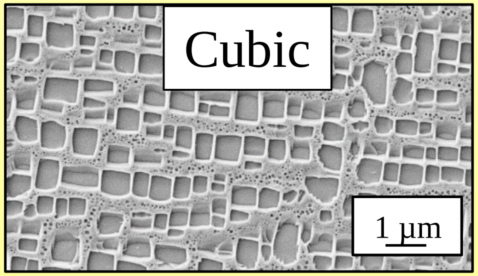


Spherical appearance of C1-phase







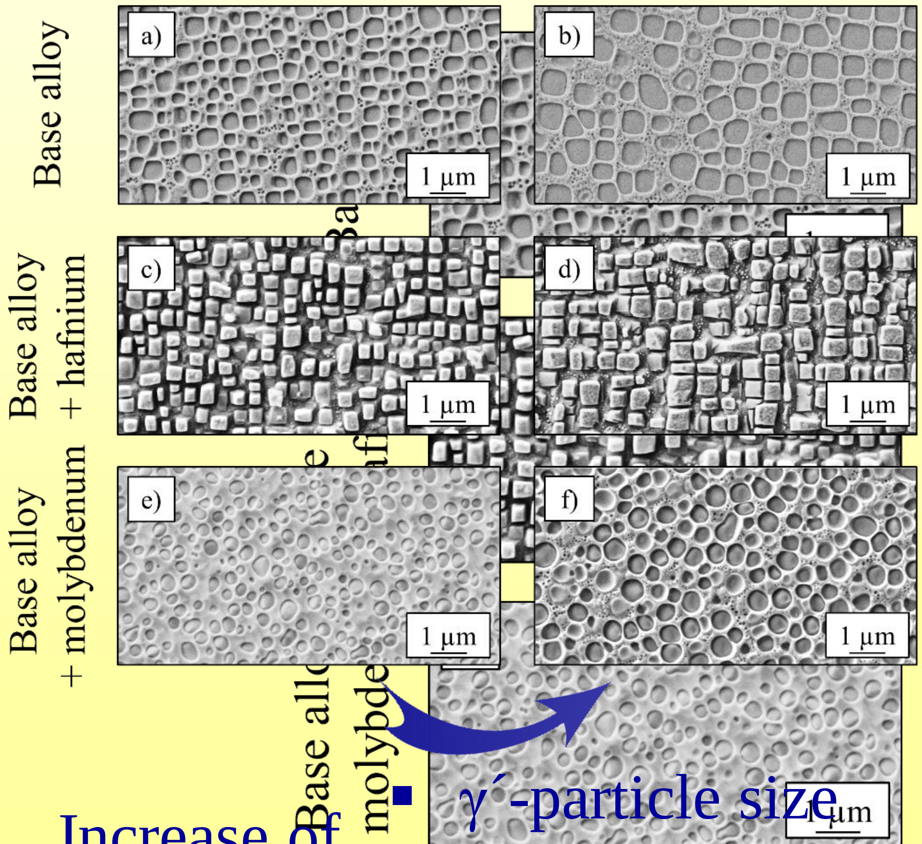


Following talk by Dr. Anna Manzoni

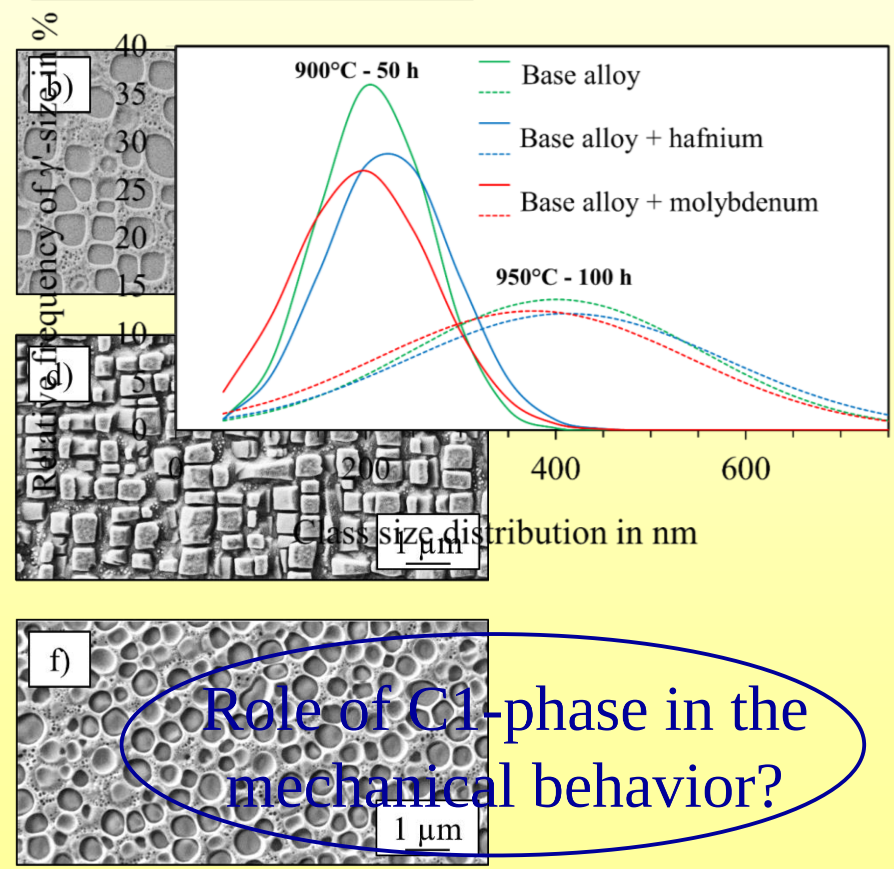
Heat treatment variation

900°C for 50 hours

950°C for 100 hours



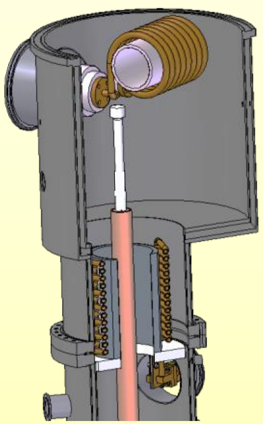
950°C for 100 hours



Role of C1-phase in the mechanical behavior?

Increase of
- γ´-particle size
- C1-volume fraction

Material & Methods



Vacuum induction furnace

- Directionally solidified (DS)

Heat treatment:

- Homogenization
ing
°C / 50 h
°C / 100 h
e cooling

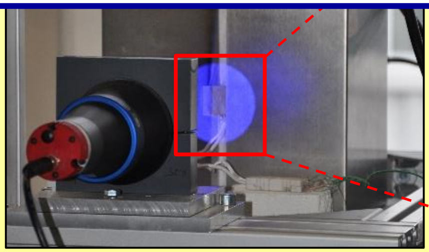
Two ways of comparing tensile tests:

Base alloy:
- DS
  CC
- 900 °C – 50 h
  950 °C – 100 h

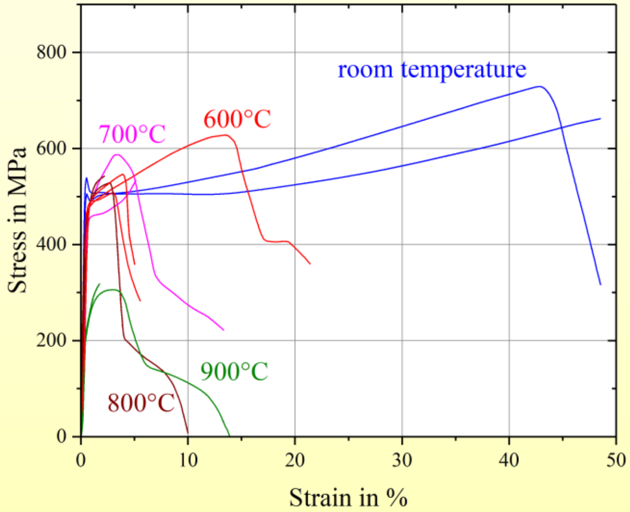
Direct. Solid.
950°C – 100 h:
- Base alloy
- Hf addition
- Mo addition

1.0 mm
Fl

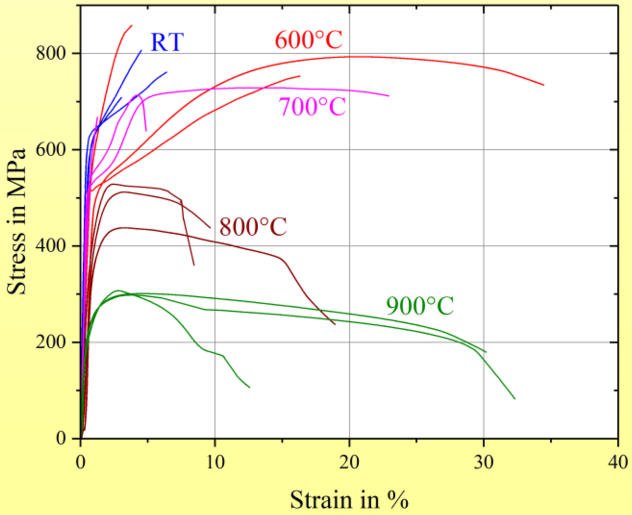
room temperature,
600 °C, 700 °C,
800 °C, 900 °C



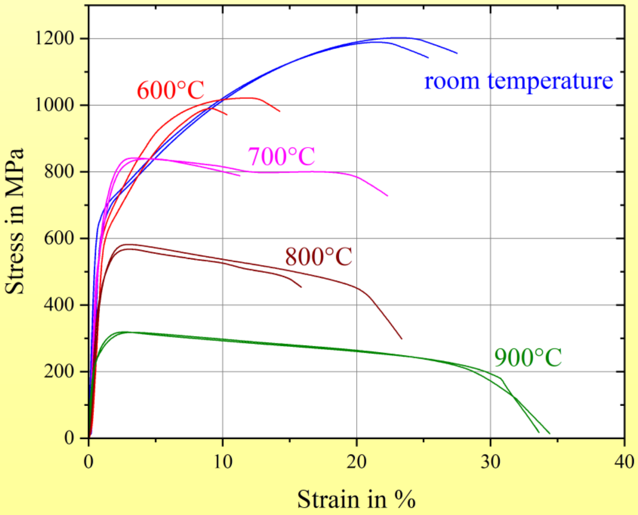
Tensile tests
1) Base alloy



CC
900 °C
50 h



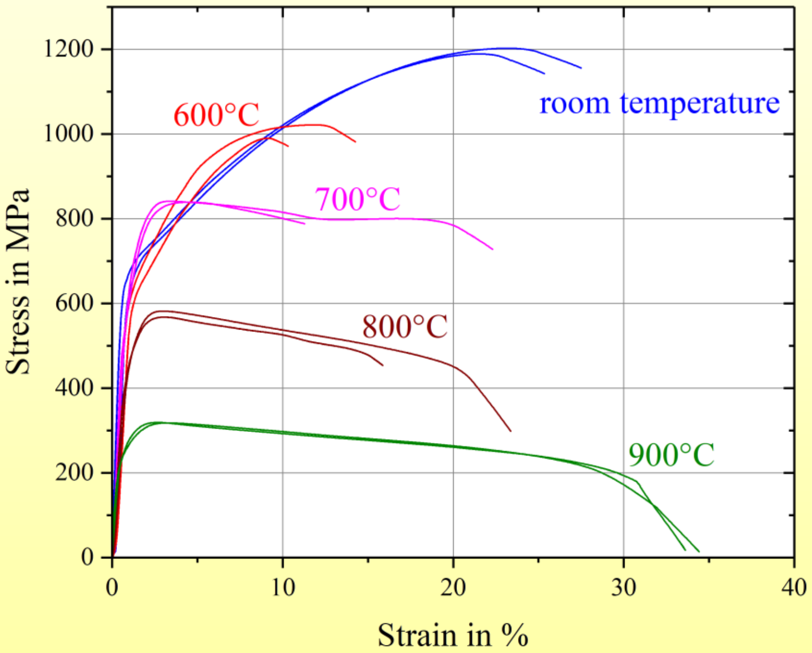
DS
950 °C
100 h



DS
900 °C
50 h

Tensile tests
1) Base alloy

Directionally **S**olidified: 900 °C / 50 h

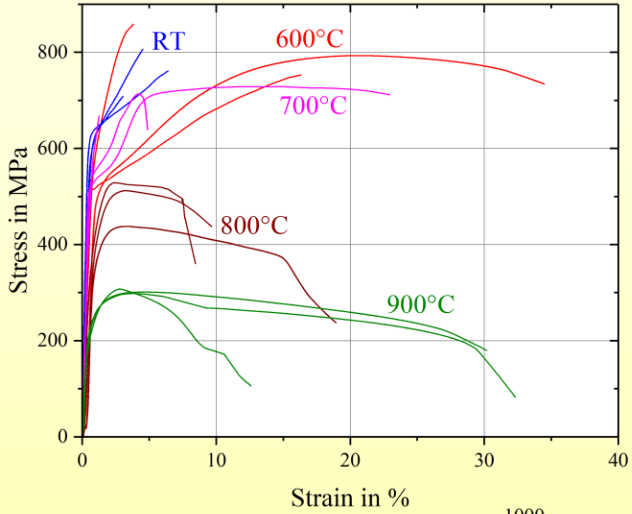


- High tensile strength
- Good strain to failure
- High reproducibility

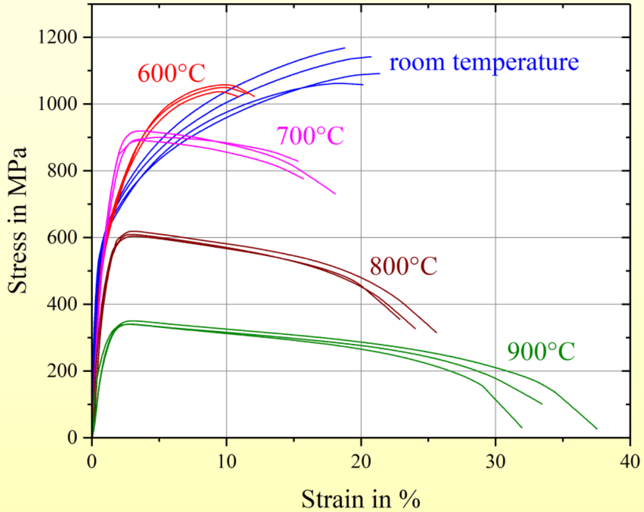
- Directional solidified grains in direction of load
- Decrease of needle-like C1-phase
- Decrease of γ´-particle size

	~23 °C	600 °C	700 °C	800 °C	900 °C
Ultimate tensile strength (in MPa)	1197 ± 6	1006 ± 16	840 ± 1	575 ± 7	319 ± 1
Strain to failure (in %)	27 ± 1	12 ± 2	17 ± 5	20 ± 4	34 ± 1

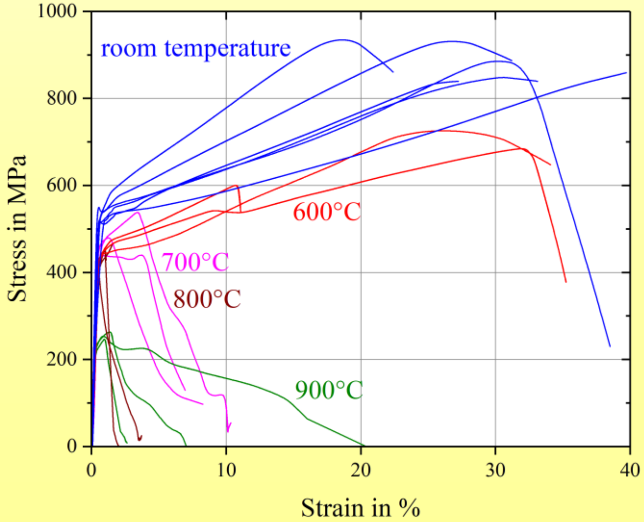
Tensile tests
2) Addition of Hf and Mo



Base alloy
DS
950 °C
100 h



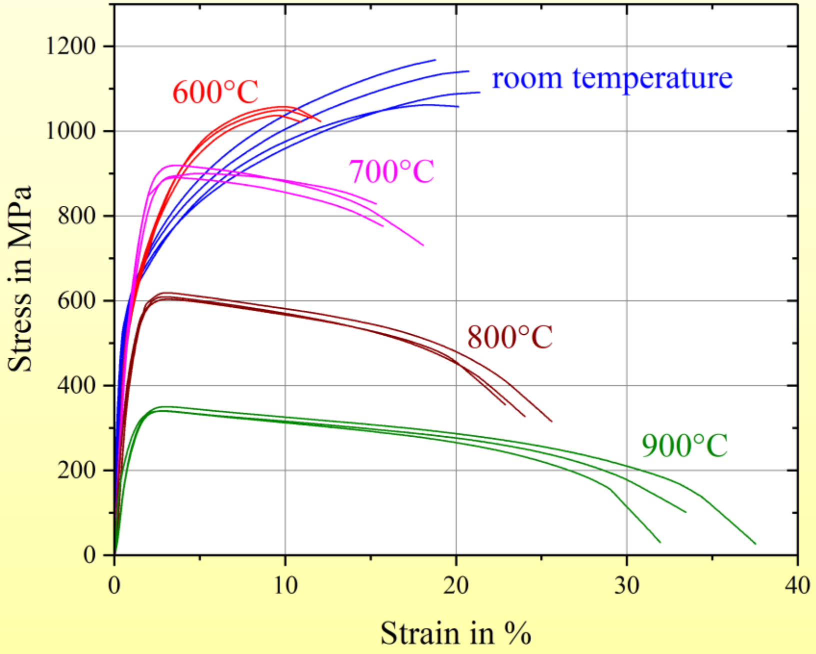
+ Hf
DS
950 °C
100 h



+ Mo
DS
950 °C
100 h

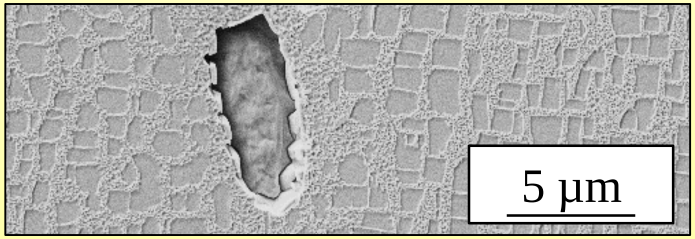
Tensile tests
2) Addition of Hf

$Al_{9,5}Co_{25}Cr_8Fe_{15}Ni_{36}Ti_6\mathbf{Hf_{0.5}}$



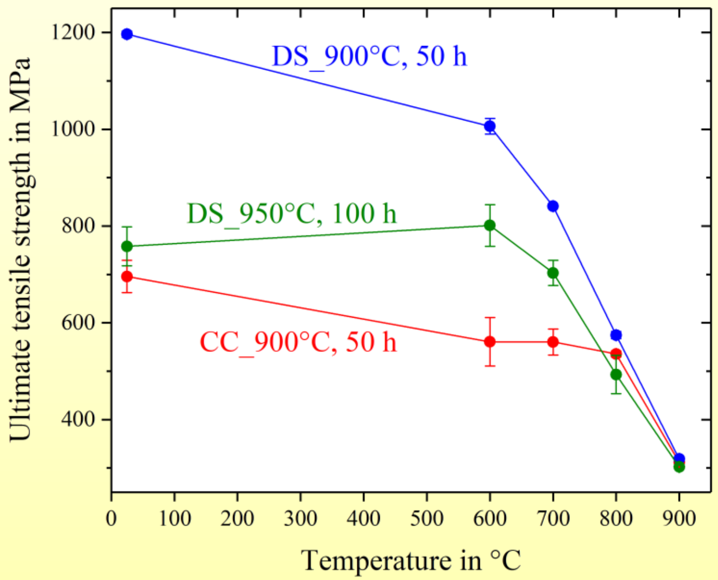
- High tensile strength
- Good strain to failure
- High reproducibility

- Sharp-edged γ´-particles
- Spherical shape of C1-phase

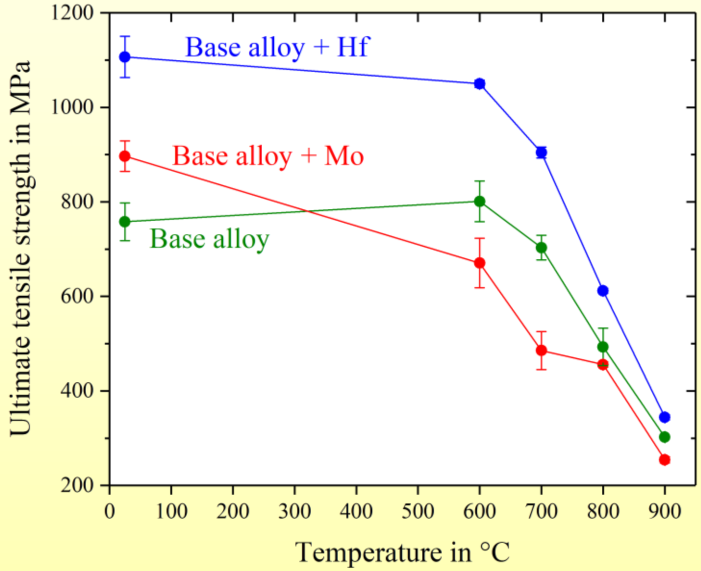


	~23 °C	**600 °C**	**700 °C**	**800 °C**	**900 °C**
Ultimate tensile strength (in MPa)	1107 ± 43	1050 ± 7	904 ± 12	612 ± 5	344 ± 5
Strain to failure (in %)	20 ± 1	12 ± 1	16 ± 1	24 ± 1	34 ± 2

Discussion



Detrimental impact of increasing needle-like C1-phase dominates bigger γ´-particles.



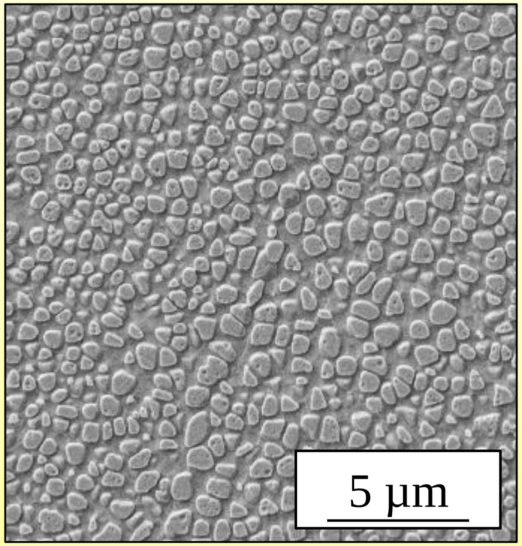
Spherical C1-phase improves mechanical properties compared to needle-like geometry.

Is a spherical form of C1-phase beneficial or less detrimental?

Outlook

Addition of Tungsten: $Al_9Co_{25}Cr_8Fe_{15}Ni_{36}Ti_6\mathbf{W_1}$

1220 °C / 20 h
900 °C / 50 h



2-phase microstructure!
No C1-phase!

Mechanical characterization will provide more information about the role of C1-phase

Summary

$Al_{10}Co_{25}Cr_8Fe_{15}Ni_{36}Ti_6$: γ´- and C1-phase change due to …

- ➢ Addition of elements in small amounts
- ➢ Variation of annealing treatment

Directional solidification increases the ultimate tensile strength: 72 % at 23 °C 80 % at 600 °C 50 % at 700 °C	Less needle-like C1-phase increases the ultimate tensile strength: 58 % at 23 °C 38 % at 600 °C 19 % at 700 °C	Hf-addition (spherical C1) increases the ultimate tensile strength: 46 % at 23 °C 31 % at 600 °C 29 % at 700 °C

C1-phase plays the important role for the mechanical behavior

➢ Gain more information about thermal & chemical stability

Thank you for your attention!