➢ Single crystal Ni-based alloys - Part 1:

You recently joined an Aerospace company as a material expert, and you are responsible for the selection, processing and characterization of high-performance Ni and Ti alloys

a) Your team leader gave you the following scanning electron micrograph (Figure 3), which shows the cross section of a single crystalline turbine blade of the alloy CMSX-4 after 1'000 h of service with a maximum temperature of 950°C in an aero-engine. The alloy has the composition (in wt.%) given in Table 2.

Table 2: Chemical composition of CMSX-4;

Ni	Cr	Co	Mo	Al	Ti	Ta	Hf	Re
Bal.	6.5	9	0.6	5.6	1.0	6.5	0.1	3.0

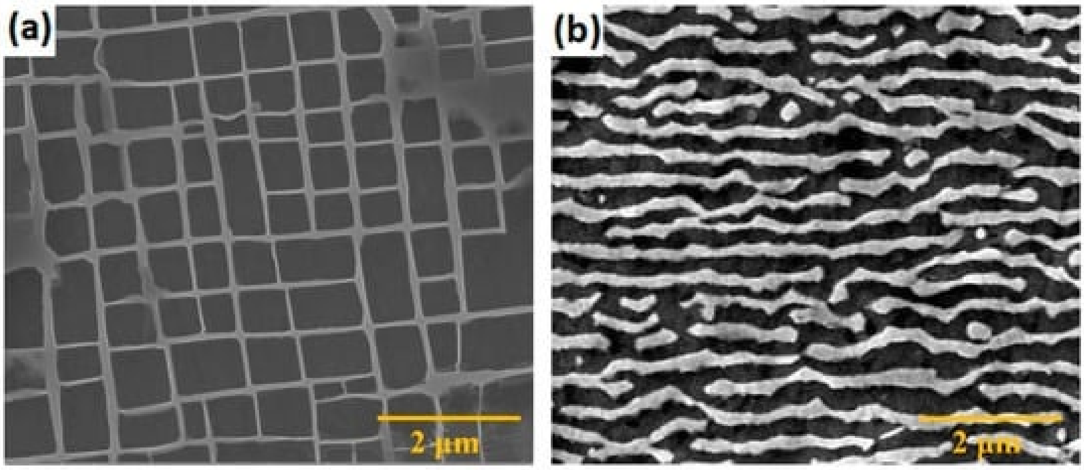

Figure 3. SEM – Cross section of a single-crystal turbine blade before and after 1'000 h of operation

- Name the phases that can be seen in the micrograph.
  γ/γ'

- Explain the role of the alloying elements Cr and Re.

  Cr: forms Cr-rich protective layer, solid solution strengthener (carbide former, less so in CSMX-4)

  Re: solid solution strengthener, delay coarsening of γ' (reduction of γ/γ' lattice misfit)

- Explain the microstructural changes that can be observed between the two micrographs. What is the common name for this phenomenon?

  Rafting;
  - **Directional coarsening is caused by the superposition of external load stresses and internal coherence stresses**
  - **If the γ'/γ lattice mismatch is positive ($a_\gamma < a_{\gamma'}$) □ type P**
  - **If the γ'/γ lattice mismatch is negative ($a_\gamma > a_{\gamma'}$) □ type N (most frequent case)**
  - **This results in different local stress fields in the γ channels perpendicular and parallel to the loading direction**

  These stress differences are the driving force for a directional diffusion; the γ' particles grow in the direction of the lower lattice distortion in the γ channels

b) Your team leader shares the results from stress rupture tests performed at different test parameters on Ni-based super alloy used for turbine blades (shown in Figure 4). Consider that LMP = T (ln(t) + c) × 10^{-3} and that the Larson miller parameter constant c is 25.

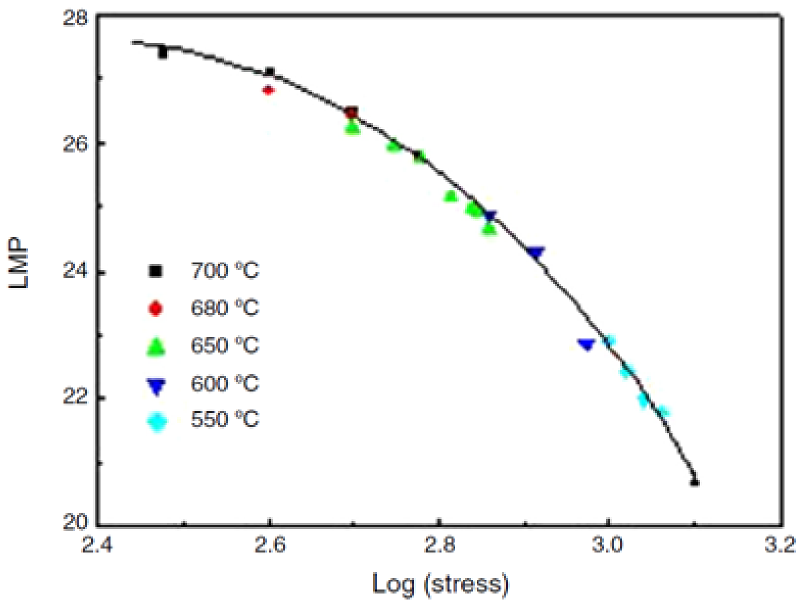

Figure 4. Larson Miller Parameter (LMP) correlation with stress obtained from stress rupture test of Ni-based super alloy.

- What stress can be applied so that the service life of the alloy at 500°C is 6000 h.

  LMP = 773 (ln (6000) + 25)

  = 26049

  = 26000

  Log σ = 2.75

  σ = 562 MPa

- Additionally, your team leader wishes to have a safety factor of 10% considering the testing uncertainty. What will be your suggested stress for application of the alloy at 500°C is 6000 h?

  Considering the safety factor = 562 x 0.9 = 506 MPa

➢ Complementary exercise 1

a) Figure 5-a shows a single-crystalline (SX) turbine blade, which was made from the Ni-based superalloy CMSX-4 using the Bridgman furnace process (schematic Figure 5-b). During the casting process, the withdrawal velocity was set to 20 mm/min and the thermal gradient at the solid/liquid interface was set to 2500 K/m.

a)

b)

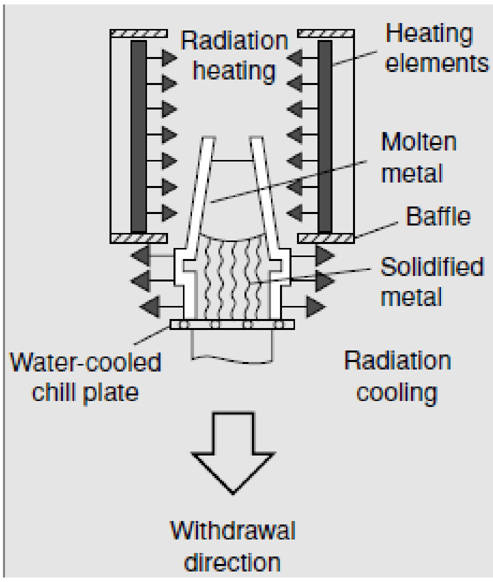

Figure 5: a) Single-crystalline turbine blade; b) schematic of the Bridgman furnace process;

- Explain the function of the 'pig-tail' in the lower part of the cast turbine blade.

- **Pig tail = single crystal selector: only one grain will reach the upper part of the casting mold. Since fcc-Ni grows fastest in (100) direction, a (100) grain will be selected.**

- Name and briefly explain two typical casting defects that would occur when increasing the withdrawal velocity to 40 mm/min.

- **High-angle GBs: if the withdrawal velocity is too high, the heat flow is not uniaxial anymore. The solidification front is curved and dendrites do not grow parallel anymore.**
- **Globular grains: nucleation of grains ahead of solidification front and growth in all directions.**

b) After casting, components fabricated from single-crystal superalloys undergo a complicated heat treatment designed to remove the microsegregation inherited from the casting process.

- Explain briefly why microsegregation occurs during casting of Ni superalloys.

- **Alloying elements have different solubility in solid and liquid phase (C_S and C_L) → partitioning coefficient $k=C_S/C_L$**
  a. **K<1 → enrichment of element x in the liquid**
  b. **K>1 → enrichment of element x in solid**

  The element x cannot diffuse quickly enough a) from the liquid to solid or b) out of solid into liquid

- What would be the implications of not heat-treating the cast components?

- **Formation of regions with (near) eutectic compositions and low melting point in the interdendritic regions → risk of liquation cracking upon heating**
- **Non-homogeneous element distribution and variation of physical and mechanical properties in the volume**

c) Creep samples from the single-crystal superalloys TMS-75 and TMS-82+ alloys were cast such that the compositions of the γ and γ'-Ni_3Al phases were on a common tie-line, so that the phase compositions remain invariant. The compositions of the two alloys (in wt.%) are given in *Table 3*. *Figure 6* shows the creep rupture life of the two alloys as a function of the fraction of the γ' phase present at 900°C and at 1100°C.

Table 3: Chemical compositions of TMS-82+ and TMS-75 (in wt.-%);

Alloy	Co	Cr	Mo	W	Al	Ti	Ta	Hf	Re	Ni
TMS-82+	7.8	4.9	1.9	8.7	5.3	0.5	6.0	0.1	2.4	Bal.
TMS-75	12.0	3.0	2.0	6.0	6.0	-	6.0	0.1	5	Bal.

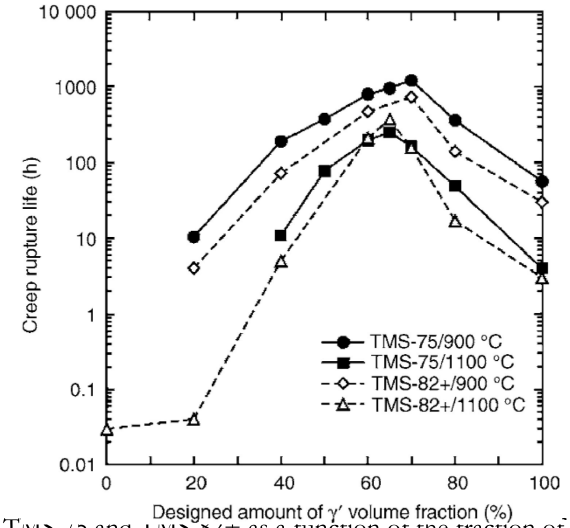

Figure 6: Creep rupture life of TMS-75 and TMS-82+ as a function of the fraction of the γ' phase (σ = 392 MPa @ T = 900°C, σ = 137 MPa @ T = 1100°C);

- Explain the general shape of the curves, i.e. the first increasing and then again decreasing creep rupture life with increasing γ' phase fraction. Why is the maximum creep resistance not imparted at a 50% fraction of γ' phase?

- **Increasing amount of γ' → increasing particle strengthening effect**
- **Beyond 60 vol% γ-channels (to which dislocation movement is constrained) become dis-connected and γ' regions are predominant (creep behavior of γ' intrinsically lower than γ)**

- Explain the in general higher creep rupture life of the TMS-75 alloy at γ' phase fractions below 60 vol%.

TMS-75: higher amount of mainly Co+Re

Co → reduces SFE + solid solution strengthening

Re → pronounced solid solution strengthener + reduction of γ' / γ-misfit → delayed coarsening of γ'

d) Figure 7 shows the binary Ni-Al phase diagram.

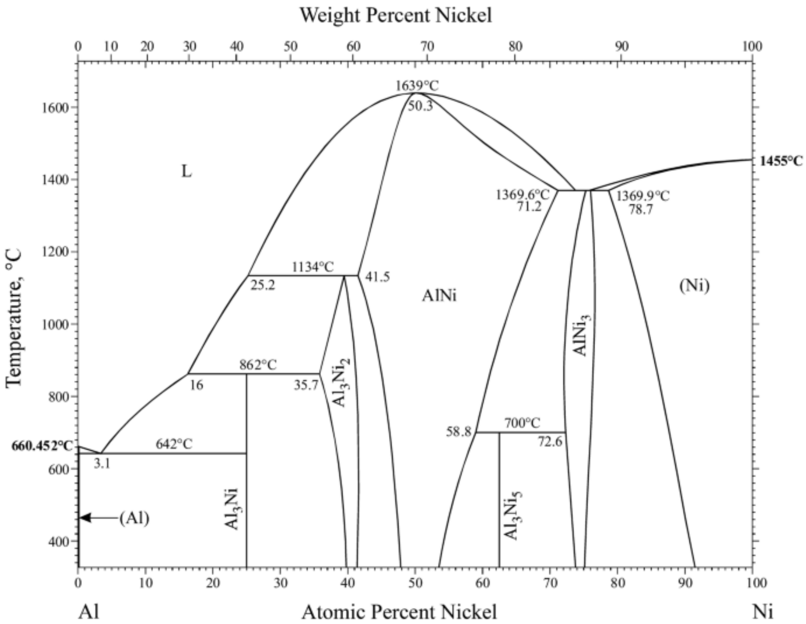

Figure 7: Binary Ni-Al diagram;

- Give two reasons why alloys with a composition of approximately 50 at.% Ni and 50 at.% Al are of interest as a replacement for Ni superalloys for high-temperature applications such as turbine blades.

- **Lower density**
- **Higher amount of Al and thus formation of dense Al_2O_3 layer C → protection against HT corrosion**
- **Higher melting point than Ni and Ni-alloys**

- Is the phase NiAl a Laves phase? Justify your answer.

- **It is not a Laves-phase**
- **Laves phases are of type A_2B or AB_2**
- **NiAl is not**

- Explain why pure NiAl exhibits a poor ductility and, as a result, a high notch sensitivity at temperatures below 650°C.

- **It is a B2 superstructure**
- **High Peierls stresse**
- **Availability of only 3 independent slip systems**

- As a result of this low ductility, shape forming of NiAl using e.g. milling or turning is extremely challenging. Name an briefly explain an alternative method that could be used to fabricate parts with more intricate geometries such as turbine blades.

- **Powder metallurgy could be an alternative:**
- **Fabrication of powder via e.g. EIGA**
- **Shape forming**
- **Sintering**