

Advanced Metallurgy – Exercise 3

Question 1:

The alloys Inconel 738LC (IN-738LC), CMSX-2, and CMSX-4 represent three generations of Ni-based superalloys, widely used for turbine blades in stationary gas turbines. Their chemical compositions (in wt.%) are listed in Table 1. While IN-738LC is a conventionally cast alloy, CMSX-2 and CMSX-4 are first- and second-generation single-crystal superalloys, respectively.

Alloy	Generation	Elements (wt.%)											
		Ni	Cr	Co	Mo	W	Re	Al	Ti	Ta	Zr	B	C
IN-738LC	Conventionally cast	bal.	16	8.5	1.75	2.6	—	3.4	3.5	1.75	0.05	0.01	0.13
CMSX-2	1st generation SX	bal.	8	4.6	0.6	8	—	5.6	1	6	—	—	—
CMSX-4	2nd generation SX	bal.	6.5	9.6	0.6	6.4	3	5.6	1	6.5	—	—	—

Table 1: Chemical composition of Inconel 738LC, CMSX-2 and CMSX-4 (in wt.%)

Figure 1 shows the Larson-Miller plots of the three alloys. Consider a turbine blade operating under high-temperature and high-stress conditions.

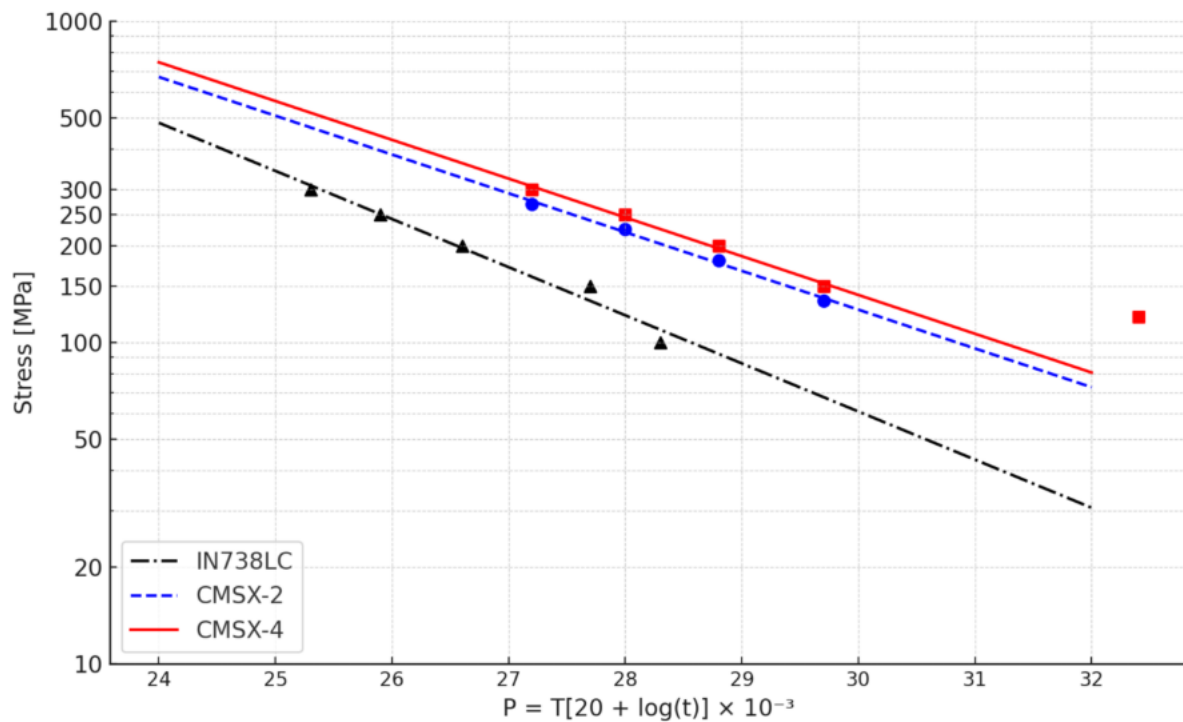


Figure 1. Larson-Miller diagrams of IN738-LC, CMSX-2 and CMSX-4

- a) Using the provided Larson-Miller plots:
- Calculate the service life of the turbine blade at a stress of 150 MPa and a temperature of 850°C if it is made from IN738LC
 - Calculate the gain in service life if the blade is instead made from CMSX-4.
- b) What are the primary metallurgical and mechanical reasons for the significant difference in creep life between IN738LC and CMSX-4? Consider the role of alloying elements and microstructure
- c) Why are Zr, B, and C included in IN-738LC but absent in CMSX-2 and CMSX-4?
- d) Considering their chemical compositions, explain the increased creep performance of CMSX-4 in comparison with CMSX-2.
- e) Figure 2 shows a scanning electron micrograph of heat-treated IN-738LC with the typical γ - γ' microstructure.
- Explain the terms "primary γ' " and "secondary γ' " precipitates in the context of IN-738LC. Discuss their roles in strengthening the alloy and indicate where they can be observed in the micrograph shown in Figure 2.
 - Define the term "antiphase boundary" as it relates to the γ' phase in Ni-based superalloys. Explain how antiphase boundaries contribute to the strengthening mechanisms of these alloys.

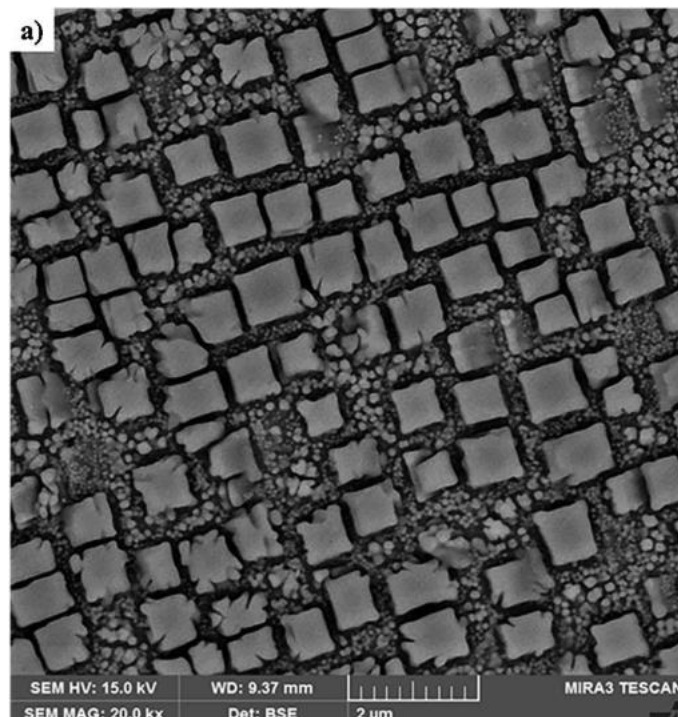


Figure 2. SEM – micrograph of IN-738LC after heat treatment

Question 2:

- a) The γ' -phase is important for the high-T performance of Ni superalloys.
 - Sketch the unit cell and give the basic stoichiometry of the γ' -phase.
 - What elements are the γ' -phase formers?
 - Explain why the γ' -phase provides an efficient strengthening effect at high-T
- b) Explain briefly why high-pressure turbine blades are produced from single crystal Ni-superalloys and not from wrought Ni alloys
- c) Why is $\langle 001 \rangle$ the preferred growth direction during single crystal fabrication
- d) Why does the amount of γ' in technical SX-Ni alloys typically not exceed 60 vol%?

Question3:

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.
- Name the phases that can be seen in the micrograph
 - Explain the role of the alloying elements Cr and Re.
 - Explain the microstructural changes that can be observed between the two micrographs. What is the common name for this phenomenon?

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

Table 2: Chemical composition of CMSX-4

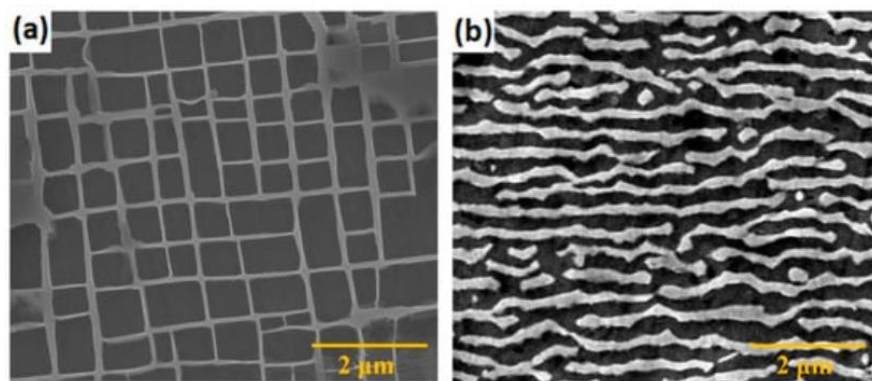


Figure 3. SEM – Cross section of a single-crystal turbine blade before and after 1'000 h of operation

- 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 $LMP = T (\ln(t) + c) \times 10^{-3}$ and that the Larson miller parameter constant c is 25.
- What stress can be applied so that the service life of the alloy at 500°C is 6000 h.
 - 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?

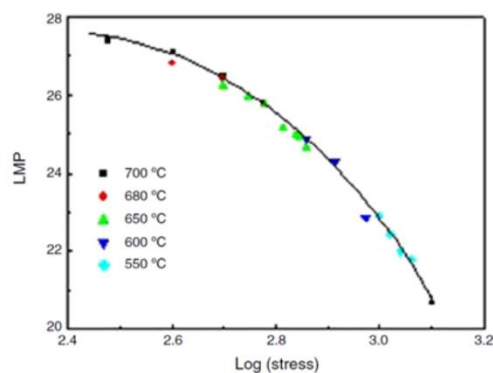


Figure 4. Larson Miller Parameter (LMP) correlation with stress obtained from stress rupture test of Ni-based super alloy.

Question 4:

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.

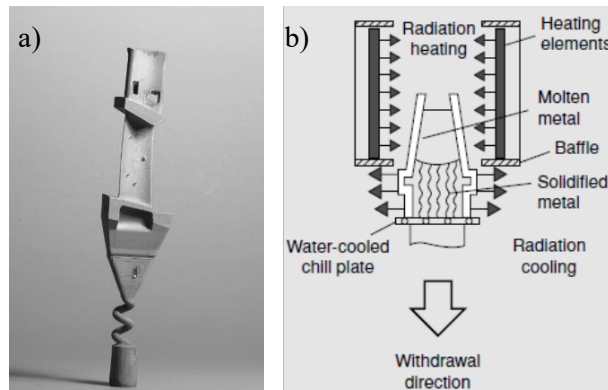


Figure 5: a) Single-crystalline turbine blade; b) schematic of the Bridgman furnace process

- Explain the function of the 'pig-tail' in the lower part of the cast turbine blade.
- Name and briefly explain two typical casting defects that would occur when increasing the withdrawal velocity to 40 mm/min.

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

Creep samples from the single-crystal superalloys TMS-75 and TMS-82+ alloys were cast such that the compositions of the γ and γ' -Ni₃Al 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.

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

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.

Table 4: Chemical compositions of TMS-82+ and TMS-75 (in wt.-%)

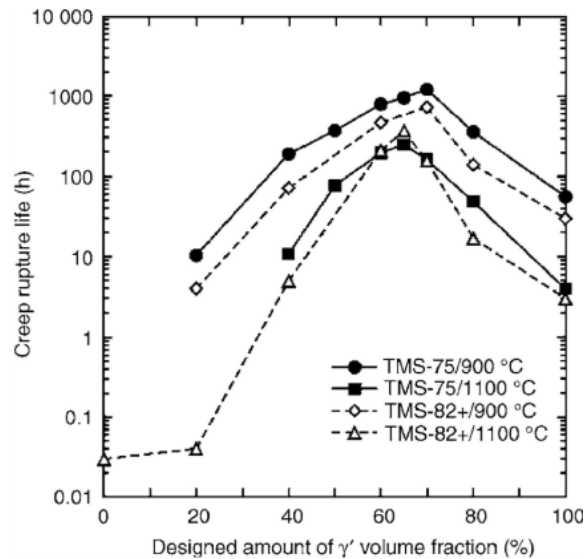


Figure 6: Creep rupture life of TMS-75 and TMS-82+ as a function of the fraction of the γ' phase
 $(\sigma = 392 \text{ MPa @ } T = 900^\circ\text{C}, \sigma = 137 \text{ MPa @ } T = 1100^\circ\text{C})$

Figure 7 shows the binary Ni-Al phase diagram.

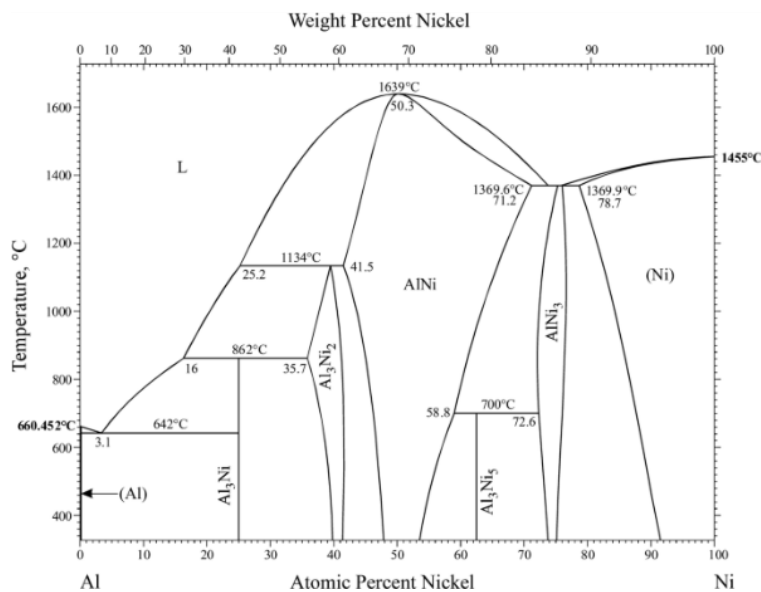


Figure 7: Binary Ni-Al diagram

- 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.
- Is the phase NiAl a Laves phase? Justify your answer.
- Explain why pure NiAl exhibits a poor ductility and, as a result, a high notch sensitivity at temperatures below 650°C .
- As a result of this low ductility, shape forming of NiAl using e.g. milling or turning is extremely challenging. Name and briefly explain an alternative method that could be used to fabricate parts with more intricate geometries such as turbine blades