MSE-422 – Advanced Metallurgy

Exercise 3: Ni alloys

FS 2024/25

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Creep behavior

- Ni alloys used for high temperature applications (Gas turbines and jet engines)

- **Long-term** creep resistance at T>800°C (service intervals 10’000-20’000 h)
- Resistant against thermo-fatigue

/www.airbus.com/

Creep behavior

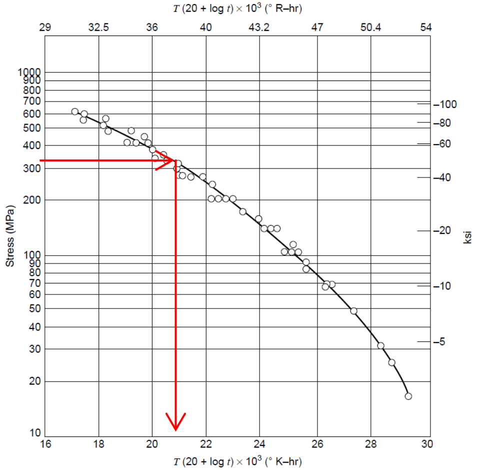
- Creep rupture tests at higher temperatures, comparable stress

- Shorter time periods
- Data extrapolation

  Larson-Miller parameter LMP $= T(C + log(t))$:

  For a specific stress the time to rupture is defined

  (depending on the temperature)



Creep behavior - Exercise 1

- The service life of turbine blade is on the order of years. A commonly used extrapolation procedure employs the Larson–Miller parameter, defined as: $LMP = T(C + log(t))$
- **Derive the Larson-Miller relation: LMP=** $\boldsymbol{T(C + log(t))}$

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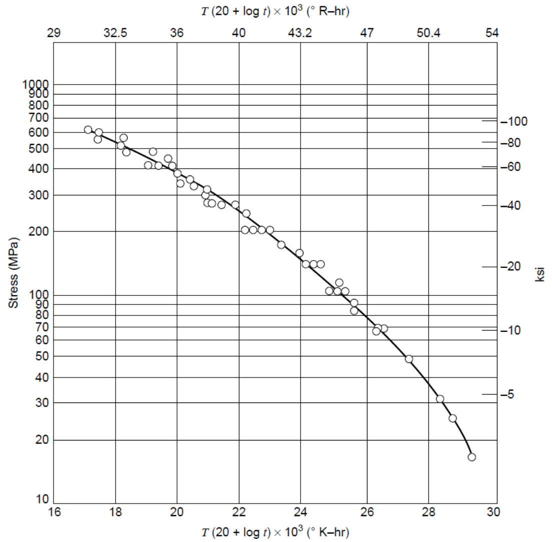

Creep behavior - Exercise 1

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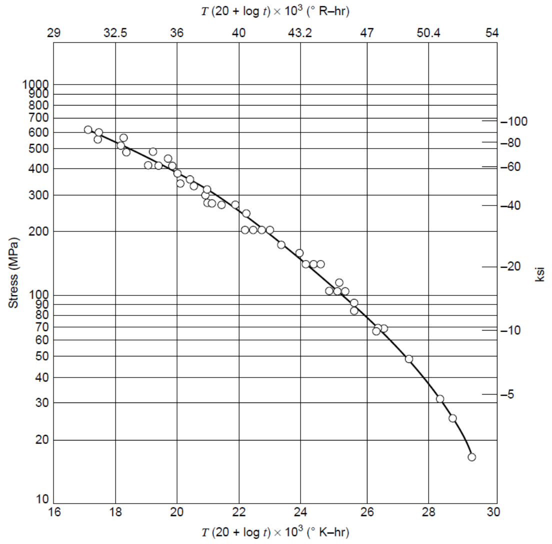
- **Derive the Larson-Miller relation: LMP= $T(C + log(t))$**

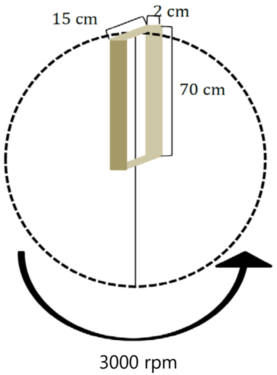
LMP= $T(C + log(t))$

- $\dot{\varepsilon} = \frac{1}{t} = A'e^{-\frac{\Delta H}{RT}}$
- $\frac{\Delta H}{RT} = (ln(A') + ln(\mathrm{t})) = (2.303\log(A') + 2.303log(t))$
- $\underbrace{\frac{\Delta H}{R*2.303}}_{\text{LMP}} = T(\underbrace{\log(A')}_{\text{C} \sim 20} + log(t))$



Creep behavior - Exercise 1

- A turbine blade for an aircraft is made of CM 247 LC with the composition reported in Table 1 and a density of 8.54 g/cm^3. The blade dimensions are 70*15*2cm^3 (Figure 1), the rotation speed is 3000 rpm and the working temperature is 800C.
- **Define the centrifugal force and, therefore, the stress to which the blade is subjected during the service assuming a point mass located at the extremity of the blade.**



Alloy	Cr	Co	Mo	W	Ta	Nb	Al	Ti	C	B	Zr	Others
CM 247 LC	8.1	9.2	0.5	9.5	3.2		5.6	0.7	0.07	0.01	0.01	1.4 Hf
IN 738 LC	16	8.5	1.7	2.6	1.7	0.9	3	3	0.11	0.01	0.05	
Rene 80	14	9.5	4	4			3	4.8	0.17	0.015	0.03	

Creep behavior - Exercise 1

EPFL

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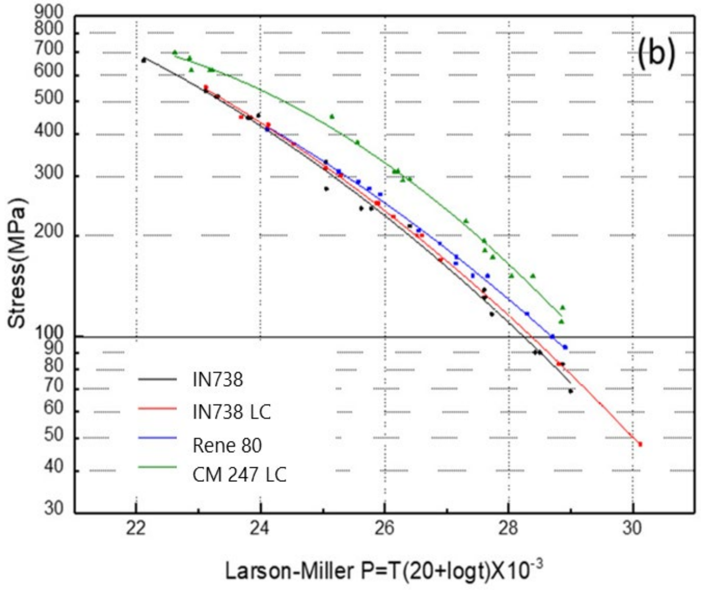
- **Define the centrifugal force and, therefore, the stress to which the blade is subjected during the service assuming a point mass located at the extremity of the blade.**

- $F_{centr} = m * a$
- $v = \omega * R$
- $a = v^2/R = \omega^2 * R$
- $\omega = (2\pi * rpm)/60$
- $m = \rho * A * R$

- $F_{centr} = \rho * A * R^2 * (2\pi * rpm/60)^2 = 1238$ KN
- $\sigma_{centr} = \frac{F_{centr}}{A} = 413\ MPa$

Creep behavior - Exercise 1

- The service life of turbine blade is on the order of years. A commonly used extrapolation procedure employs the Larson–Miller parameter, defined as: $LMP = T(C + log(t))$
- **Using the Larson-Miller diagram in Figure 2, define the lifetime of the blade of point a.**



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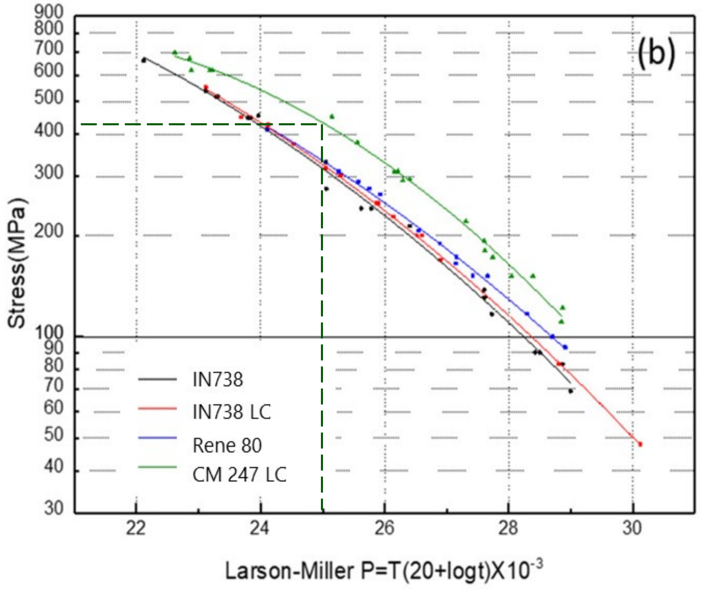
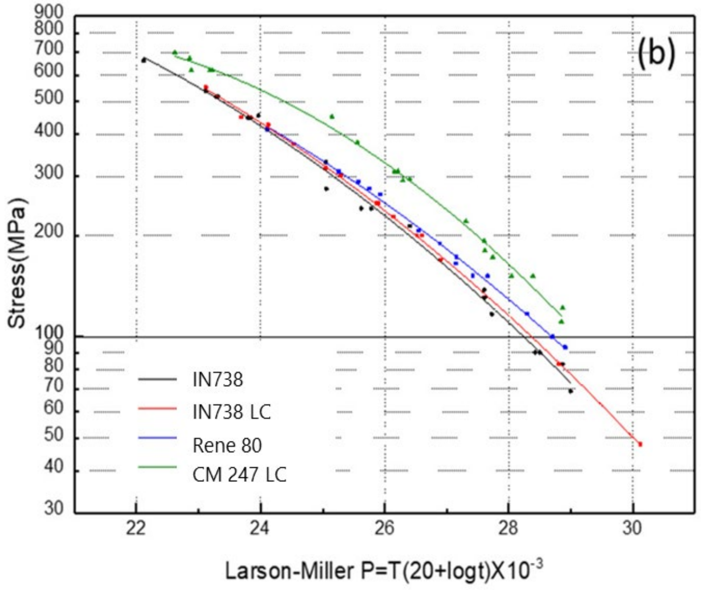


- LMP $= T(C + log(t))$
- $25 = 1073(20 + log(t)) * 10^{-3}$ → $t = 1995h$

Creep behavior - Exercise 1

- The service life of turbine blade is on the order of years. A commonly used extrapolation procedure employs the Larson–Miller parameter, defined as: $LMP = T(C + log(t))$
- **Define the variation of the time to rupture if the working temperature decreases to 750C (3000 rpm)**



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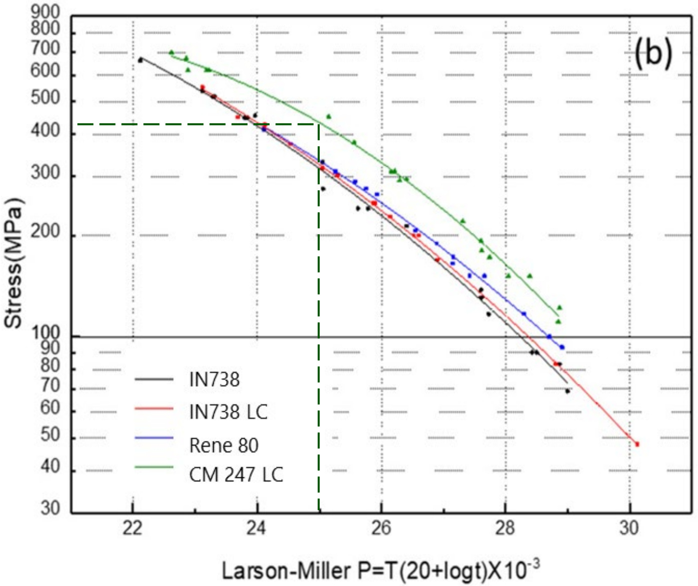
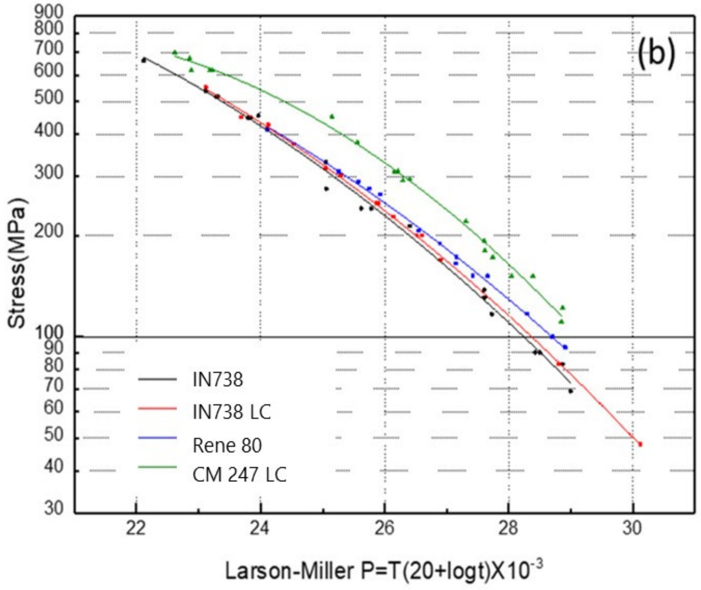


- $\text{LMP} = T(C + log(t))$
- $25 = 1023(20 + log(t)) * 10^{-3}$ $\quad t = 27542\ h$

Creep behavior - Exercise 1

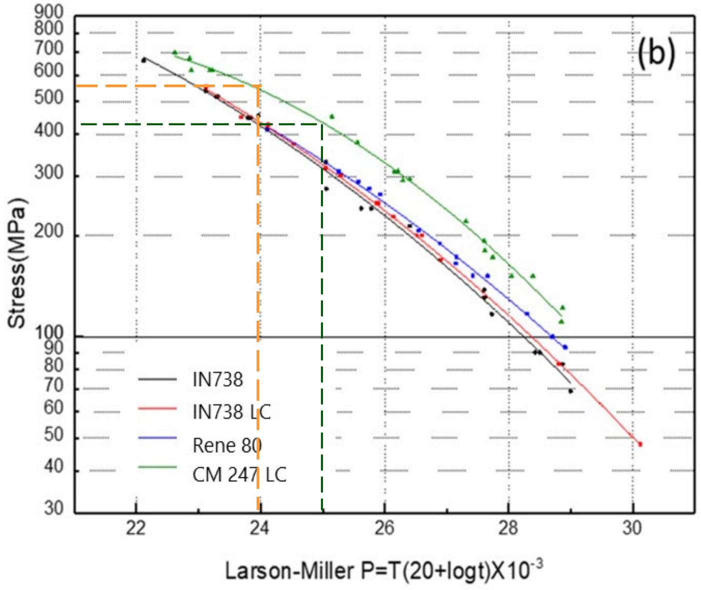
- The service life of turbine blade is on the order of years. A commonly used extrapolation procedure employs the Larson–Miller parameter, defined as: $LMP = T(C + log(t))$
- **Define the variation of the time to rupture if the rotation speed increases to 3500 rpm (800C)**



Creep behavior - Exercise 1

- The service life of turbine blade is on the order of years. A commonly used extrapolation procedure employs the Larson–Miller parameter, defined as: $LMP = T(C + log(t))$
- **Define the variation of the time to rupture if the rotation speed increases to 3500 rpm (800C)**

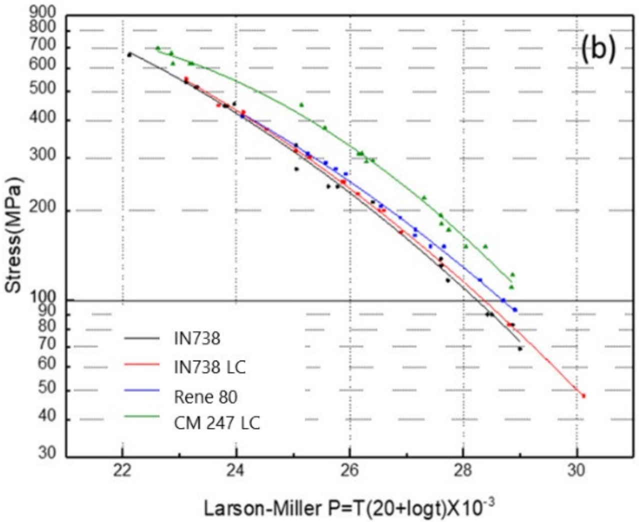
- $F_{centr} = \rho * A * R^2 * (2\pi * rpm/60)^2 = 1685$ KN
- $\sigma_{centr} = \frac{F_{centr}}{A} = 562\ MPa$
- LMP $= T(C + log(t))$
- $24 = 1073(20 + log(t)) * 10^{-3}$ → $t = 234\ h$



Creep behavior - Exercise 1

- Table 1 reports the composition of 4 different Ni-superalloys.
- **Explain the variation in the Larson-Miller diagrams observed in Figure 2**

➢ CM 247 LC highest creep resistance (longer time to rupture)



$$\text{LMP}= T(C + log(t))$$

Creep behavior - Exercise 1

EPFL

- Table 1 reports the composition of 4 different Ni-superalloys.
- **Explain the variation in the Larson-Miller diagrams observed in Figure 2**

- CM 247 LC highest creep resistance (longer time to rupture)
- Chemical composition:

- Lower Cr, Mo, C → lower formation of undesired TCP phases (brittle)
- Higher Co → lower formation of undesired TCP phases (brittle)
- Higher W → carbide former and solid solution strengthening
- Higher Ta → stabilization γ' and solid solution strengthening
- Higher Al → formation of γ'

Alloy	Cr	Co	Mo	W	Ta	Nb	Al	Ti	C	B	Zr	Others
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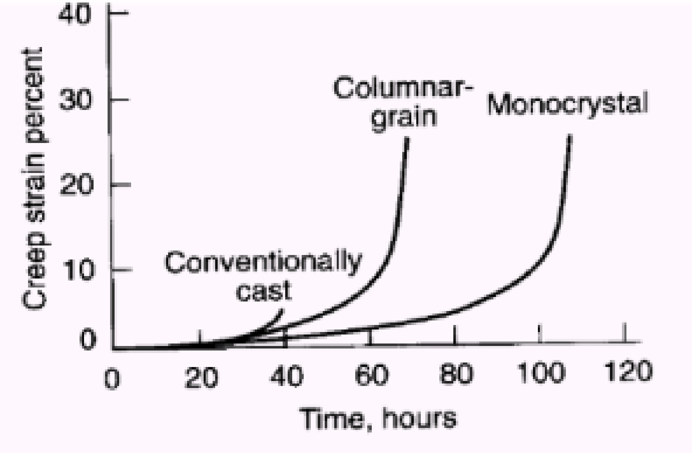
Creep behavior - Exercise 1

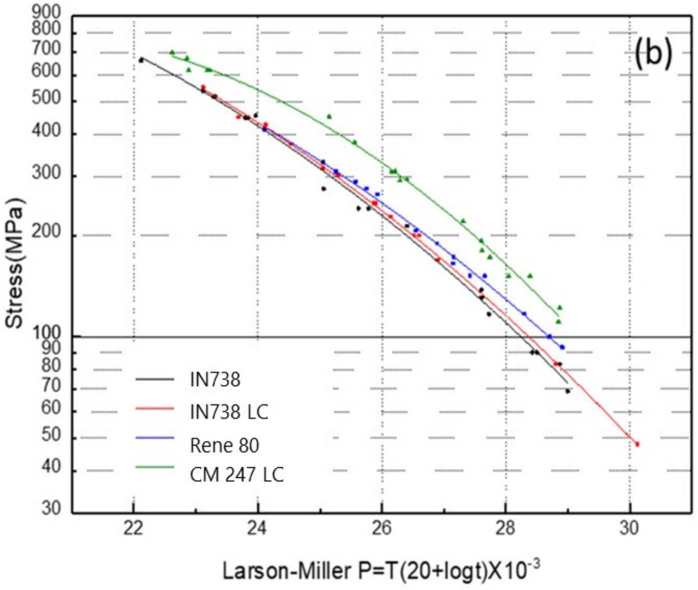
- Table 1 reports the composition of 4 different Ni-superalloys.
- **Explain the variation in the Larson-Miller diagrams observed in Figure 2**

- CM 247 LC highest creep resistance (longer time to rupture)
- **Fabrication process:**
- CM 247 LC → Directionally solidified alloy
- IN 738 LC → Conventionally cast alloy
- Rene 80 → Conventionally cast alloy



Creep behavior - Exercise 1

- The IN738 is applied for the blade production.
- **Define which temperature can be reached in order to achieve the same life time of point a but using the alloy IN738 (rpm: 3000) density 8.11**



Creep behavior - Exercise 1

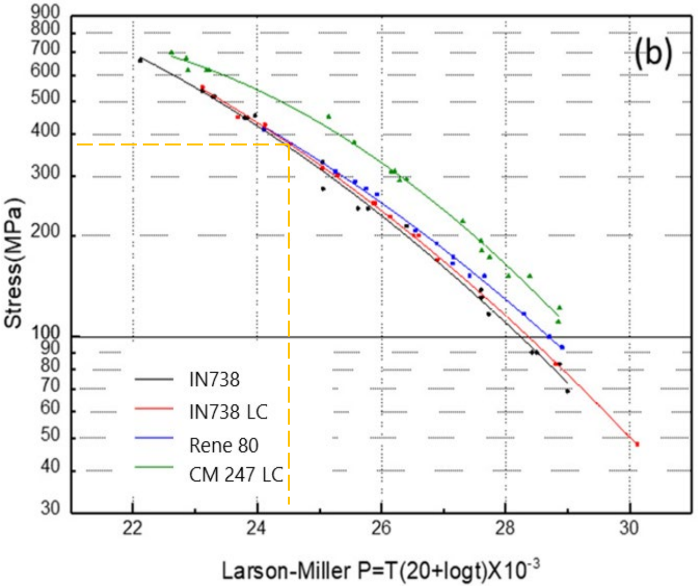
- The IN738 is applied for the blade production.
- **Define which temperature can be reached in order to achieve the same life time of point a but using the alloy IN738 (rpm: 3000) density 8.11**

➢ $F_{centr} = \rho * A * R^2 * (2\pi * rpm/60)^2 = 1175$ KN

➢ $\sigma_{centr} = \frac{F_{centr}}{A} = 392\ MPa$

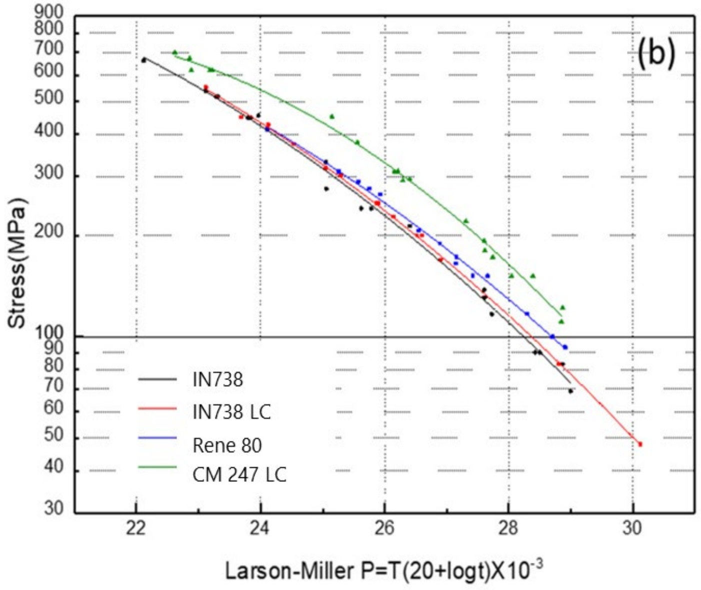
➢ LMP $= T(C + log(t))$

➢ $24.5 = T(20 + log(1995)) * 10^{-3}$ → T $= 779C$



Creep behavior - Exercise 1

- The IN738 is applied for the blade production.
- **Define which rotation speed can be reached to achieve the same life time of point a but using the alloy IN738 (800C)**



Creep behavior - Exercise 1

- The IN738 is applied for the blade production.
- **Define which rotation speed can be reached to achieve the same life time of point a but using the alloy IN738 (800C)**

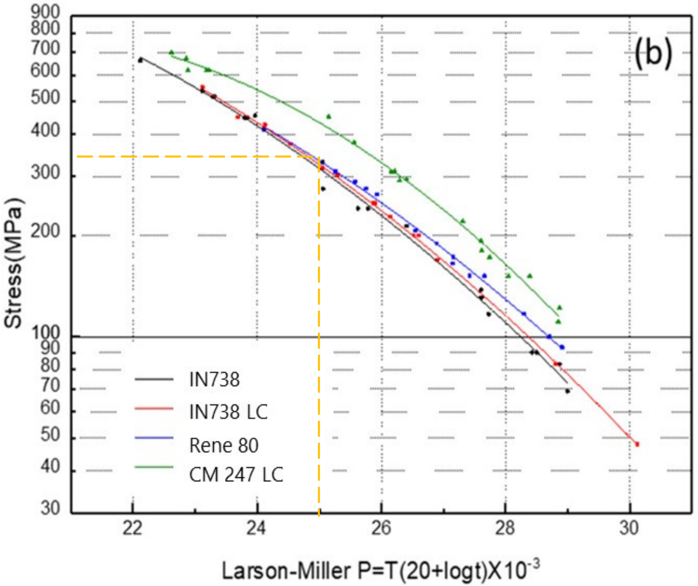
➢ $\text{LMP} = 1073(20 + log(1995)) * 10^{-3}$

→ $\text{LMP} = 25$

→ $\sigma_{centr} = 350\ MPa$

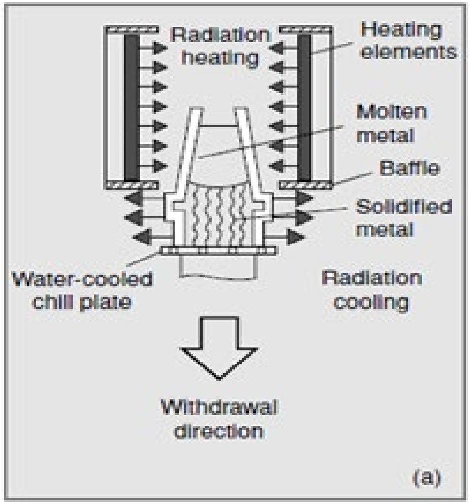
→ $F_{centr} = 350 * A = 1050\ KN$

➢ $F_{centr} = \rho * A * R^2 * (2\pi * rpm/60)^2$ → 2835 rpm



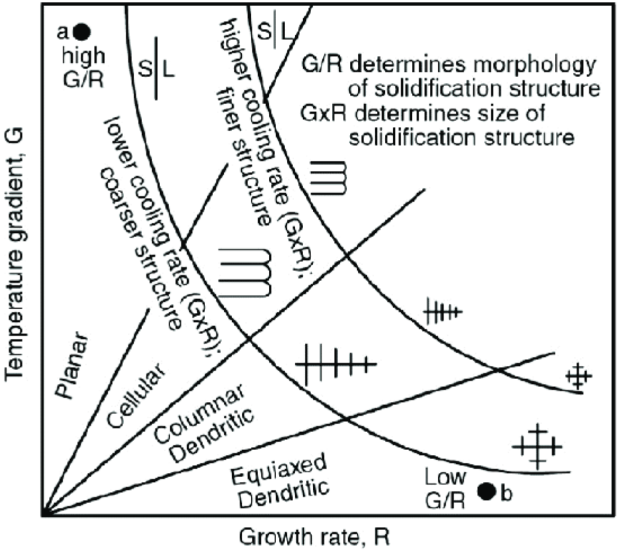
Single crystal parts

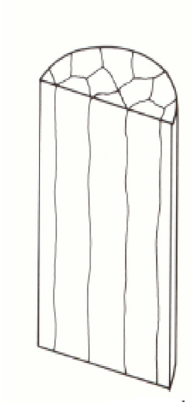
- The furnace consists of an upper melting chamber, a central mold chamber and a lower withdrawal chamber
- Need for careful control of the rate of heat removal from the casting (i.e. removal velocity of the casting from the furnace)
- The maximum withdraw velocity to avoid defects can be calculated

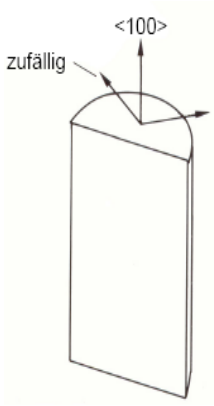


Single crystal parts

- Constant withdraw velocity of the mold:
  - Gradual progress of the solid-liquid interface
  - **High constant** thermal gradient (2000-4000 K/m) to produce large, elongated grains

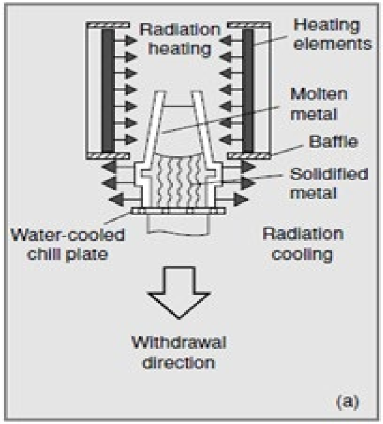


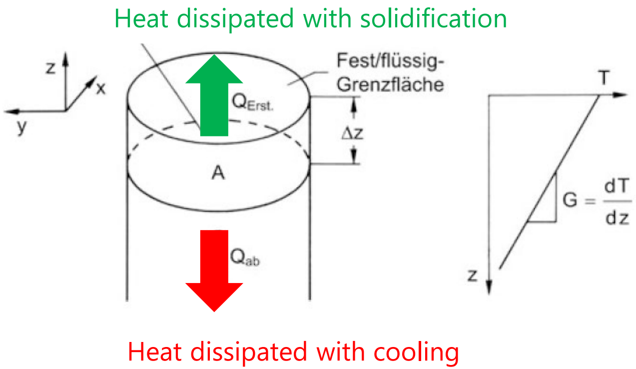




Single crystal parts – Exercise 2

- Estimate the maximum withdrawal velocity to obtain a single crystal turbine blade.

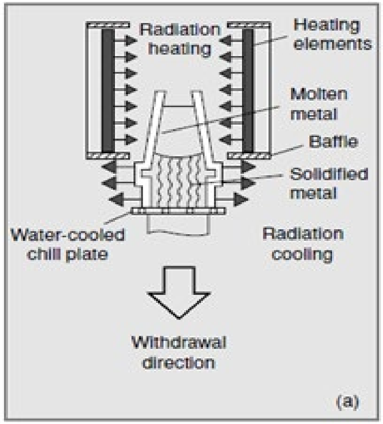


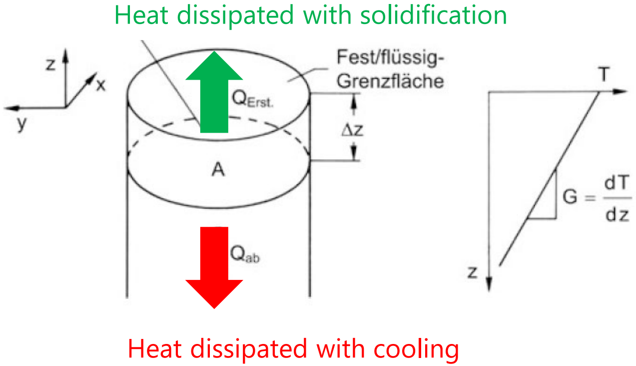


Single crystal parts – Exercise 2

- **Estimate the maximum withdrawal velocity to obtain a single crystal turbine blade.**

➢ Need for high **constant** thermal gradient → The heat dissipated into the already solidified material has to be as great as the heat generated during solidification.





Single crystal parts - Exercise 2

EPFL

- **Estimate the maximum withdrawal velocity to obtain a single crystal turbine blade.**

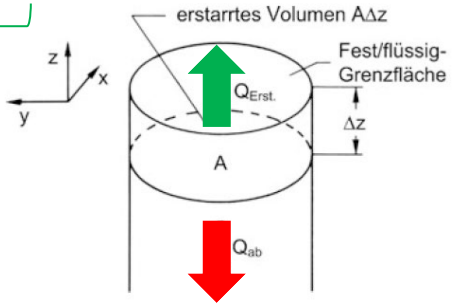
➢ Need for high **constant** thermal gradient → The heat dissipated into the already solidified material has to be as great as the heat generated during solidification.

➢ $$\dot{q} = \frac{Q_{ab}}{\Delta t * A} = \lambda * G \geq \frac{Q_{Erst.}}{\Delta t * A} = \frac{\Delta H * \Delta m}{\Delta t * A} = \frac{\Delta H * \rho * \Delta V}{\Delta t * A} = \frac{\Delta H * \rho * \Delta z}{\Delta t} = \Delta H * \rho * v$$

Heat dissipated upon cooling (for $\frac{Q_{ab}}{\Delta t * A} = \lambda * G$)

Heat dissipated due to solidification (for $\frac{Q_{Erst.}}{\Delta t * A} = \dots = \Delta H * \rho * v$)

Heat dissipated with solidification



Heat dissipated with cooling

➢ $$\lambda * G \geq \Delta H * \rho * v$$

➢ $$v \leq \frac{\lambda}{\Delta H * \rho} * G = 20\ mm/s$$

Single crystal parts - Exercise 2

- **What defects may occur in the turbine blade if this withdrawal velocity is exceeded?**

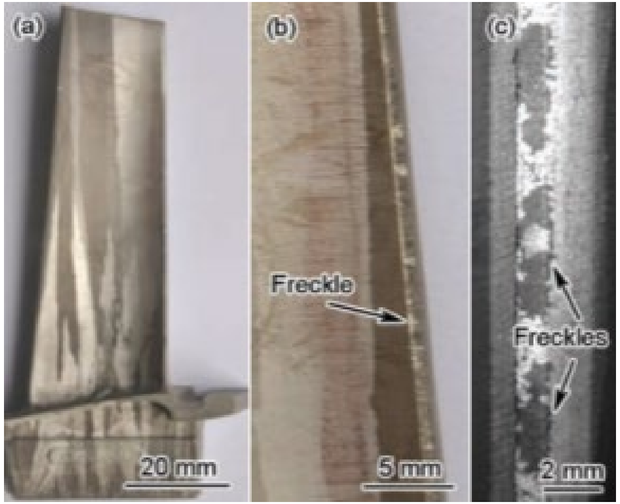
Single crystal parts - Exercise 2

EPFL

- **What defects may occur in the turbine blade if this withdrawal velocity is exceeded?**

➢ If the velocity is too high, solidification will not finish before the casting leaves the furnace → Temperature gradient also in the radial direction

- Non-parallel growth of dendrites: High-, low-angle GBs
- Freckles (equiaxed grains on the side)
- Globular grains



Single crystal parts - Exercise 2

- **How can the withdrawal velocity be increased to achieve a higher productivity?**

Single crystal parts - Exercise 2

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➢ Liquid metal or gas cooling (LMC): Immersion of the mold into a bath of liquid metal to increase the heat transfer rate

→ Higher solidification rate

→ Dendrite stem spacing reduction

→ Less contact time between the melt and the molding ceramic