# Manufacturing Ti-6Al-4V Aircraft Components at Lower Cost by Combining Beta-Forging and Electron Beam Additive Manufacturing

MAMA project (Metallic Advanced Materials for Aeronautics)

**05/24/21**

**Pauline MARTIN –** Materials Engineer

# Agenda.

# 1. Aims of the project

## Drastically reduce the manufacturing cost of mechanical structural aircraft parts made of Ti-6Al-4V

How ?

- Closed-die-forging above the β transus temperature ($T_\beta$ = 995°C)

- Hybridization → Combining closed-die forging with Electron Beam Additive Manufacturing (EBAM)

**Forging of large mechanical structural components**

# 2. Means implemented for the project

## β-field forging

Research press revamping (unique in EU)

- Increase of press load capacity

  *300 T → 1000 T*

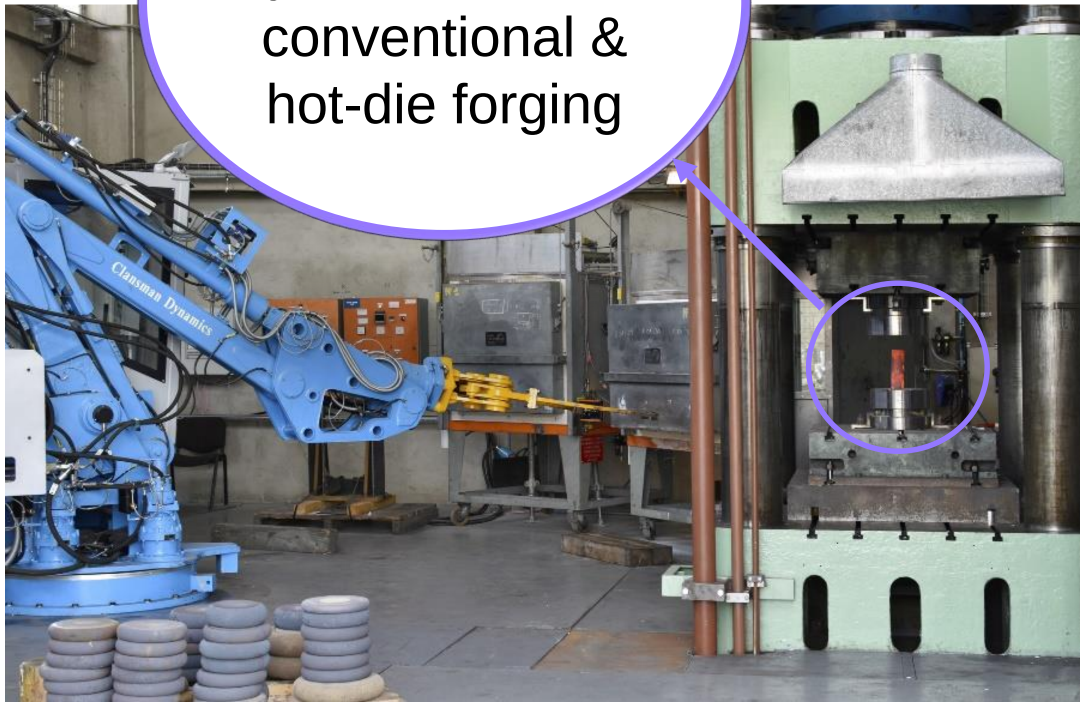
- Semi-automatic gripper arm

  *fast furnace to press transfer*

- Instrumentation of the process

  *temperature, load, displacement,…*

Built-in heating system for dies : conventional & hot-die forging



# 2. Means implemented for the project

## β-field forging
Preliminary tests

- Pancakes forging (temperatures, strains, ram speed)

  *best conditions for beta-forging*

- Box-like samples with cross ribs

  *Feasibility of beta-forging*



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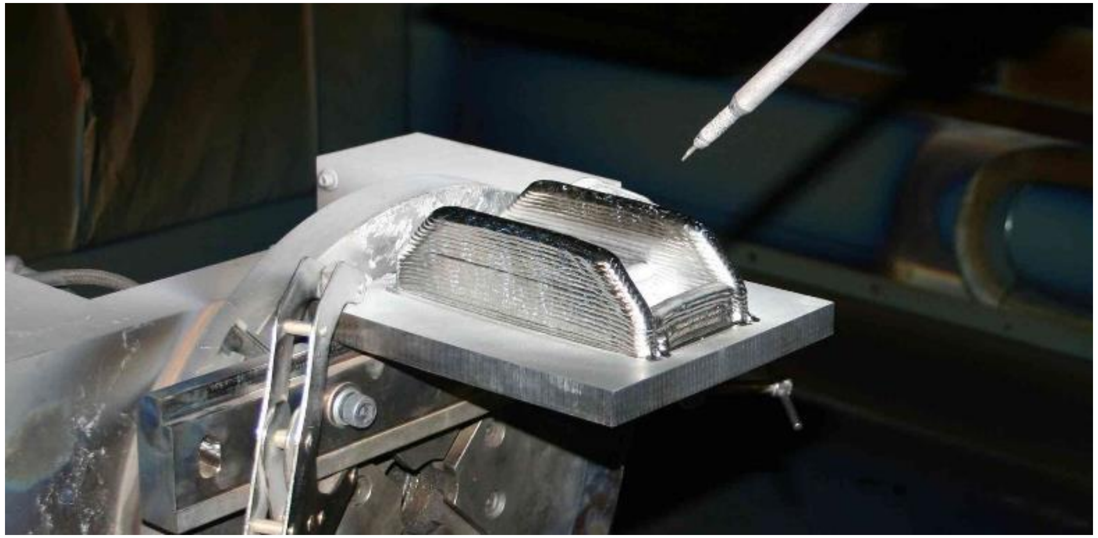
# 2. Means implemented for the project

## Hybridization (Forge + Print)



- EBAM (Electron Beam Additive Manufacturing)
- to be manufactured by Sciaky Inc.
- Additive manufacturing (forge + print) → Local addition of material on forged parts
- Mass and manufacturing cost reduction of the forged parts

*Sources : https://www.sciaky.com*

# 2. Means implemented for the project

## Numerical modelling

**heat transfer study**

- thermal balance measurement after forging by drop calorimetry

heat transfer coefficients

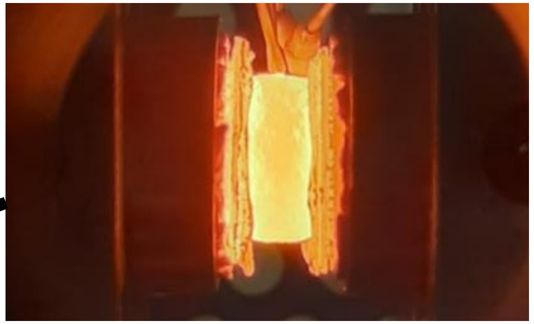
**Tribology**

- ring compression tests

Friction coefficient

**Rheology database**

- Isothermal compression



Rheological law

Ti-64 data-base

**Numerical simulation**

FORGE®

**First successful try**

# 2. Means implemented for the project



## Numerical modelling

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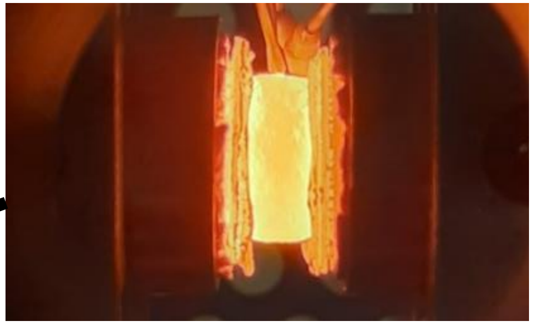


Rheological law

Ti-64 data-base

**Numerical simulation**

FORGE®

# First successful try

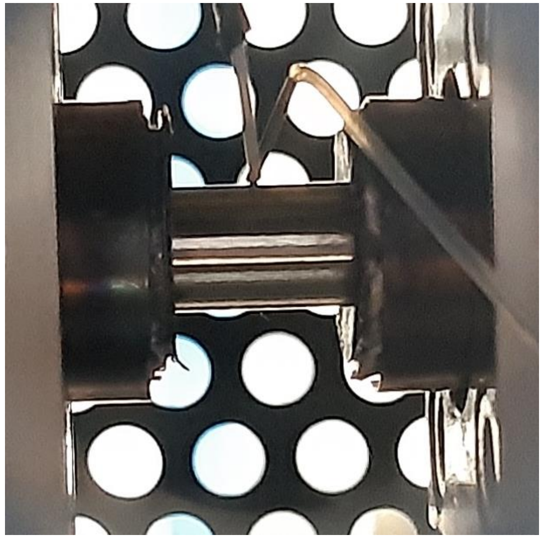
# 3. Rheological investigation

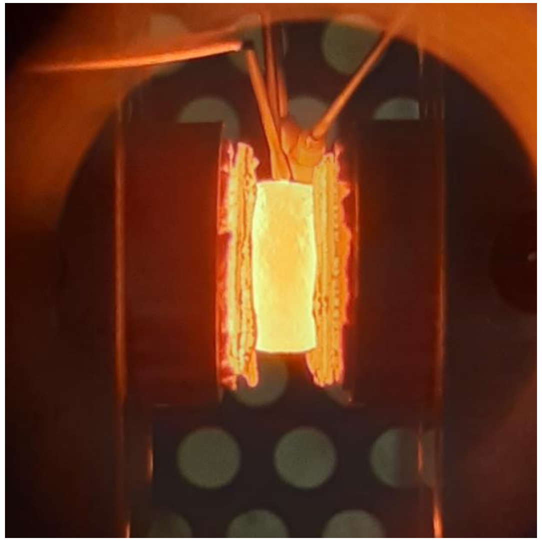
## Compression on the thermo-simulator Gleeble 3500

• Academic partnership with National Engineering School of Tarbes

• Joule effect heating

• High capacity of heating and cooling control

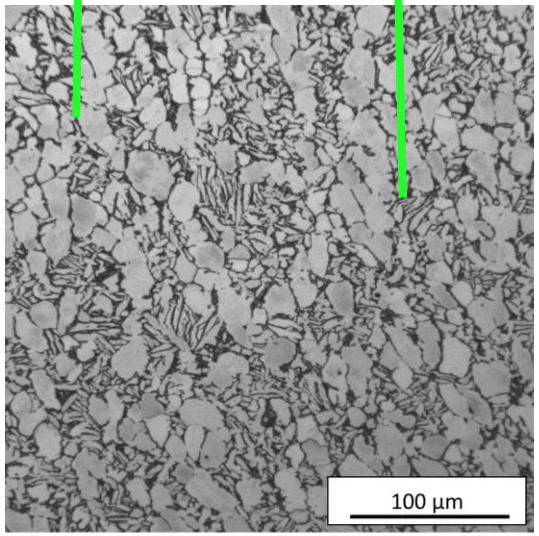


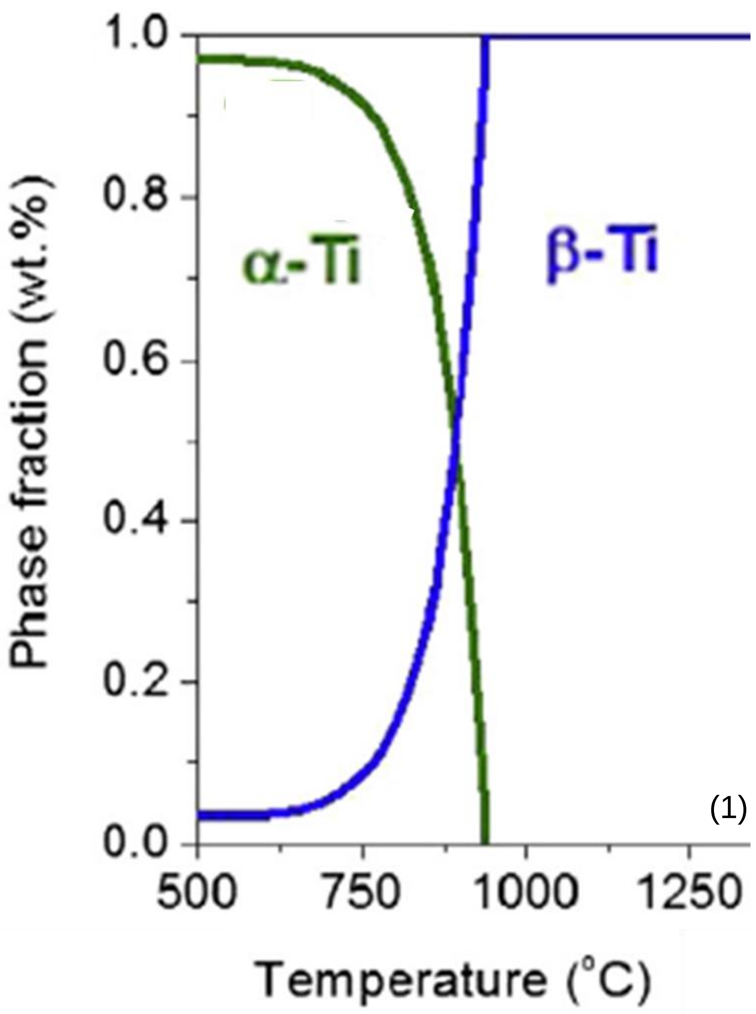
# 3. Rheological investigation

## Initial microstructure : bimodal

α nodules

α+β lamellae



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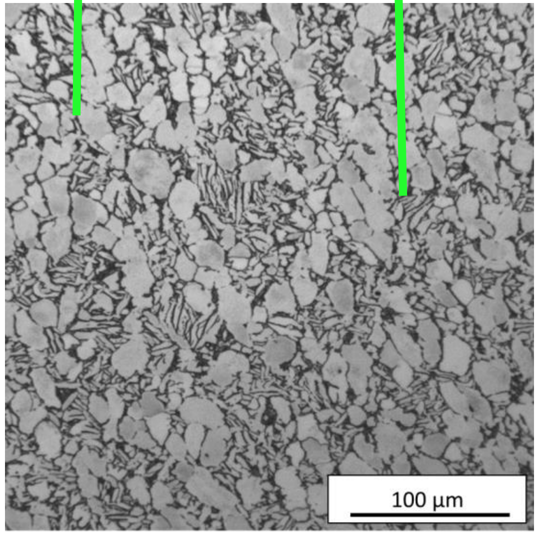
(1) J.H. Luan et al., J. Alloys Compd. 624 (2015) 170–178

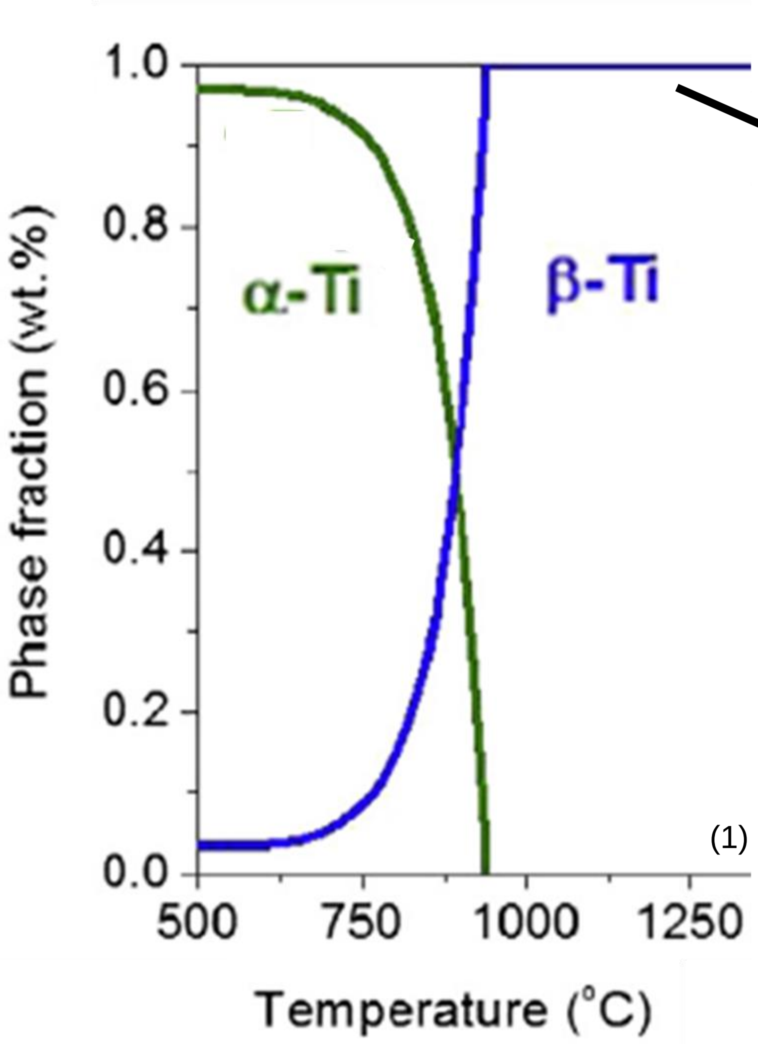
# 3. Rheological investigation

**Initial microstructure : bimodal**

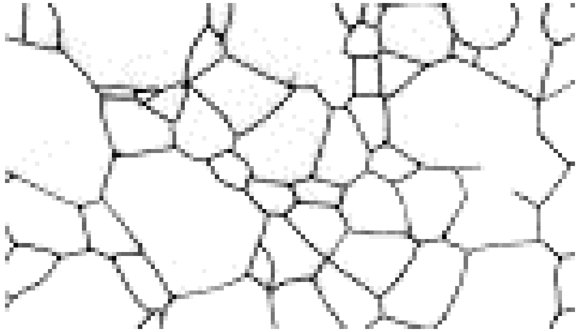
α nodules

α+β lamellae




**Equiaxed β-grains**





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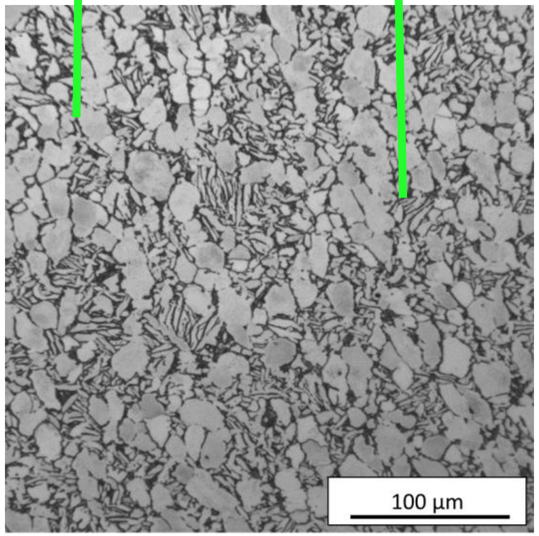
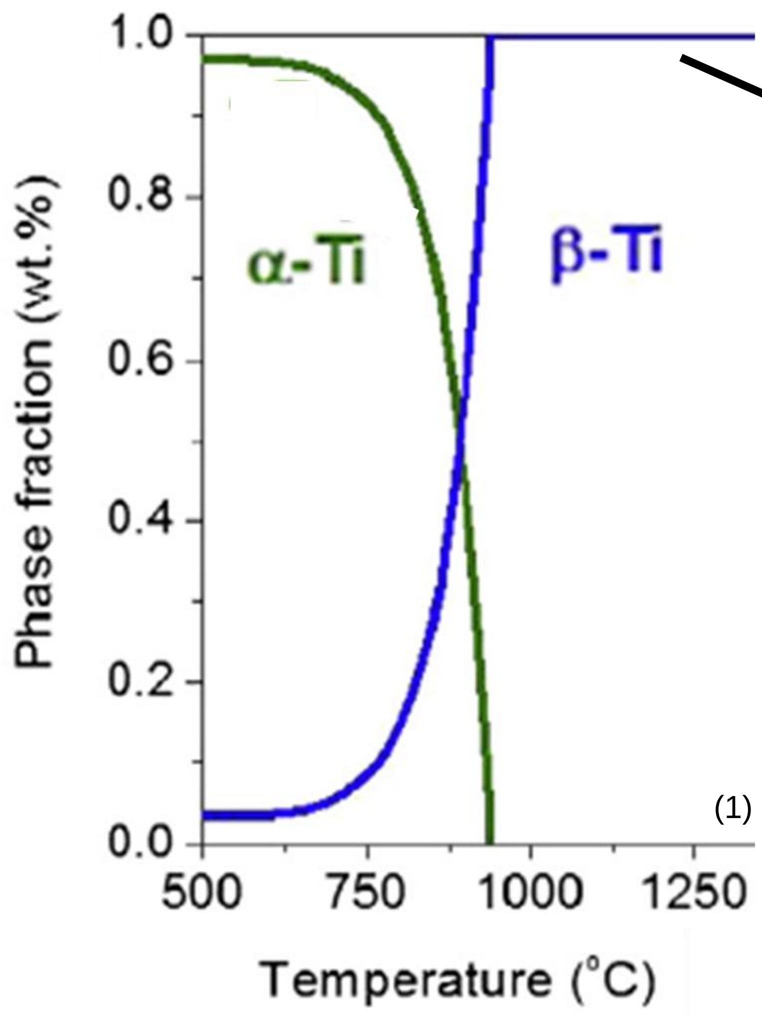
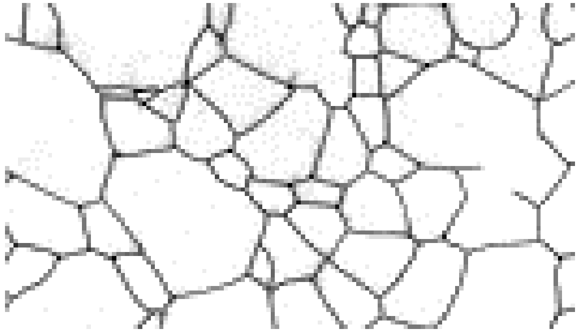
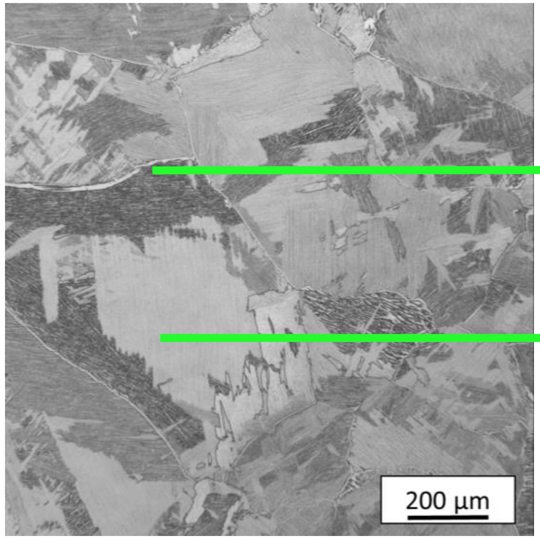



## Equiaxed β-grains



## Cooled microstructure




$\alpha_{GB}$

Colonies (α+β lamellars)



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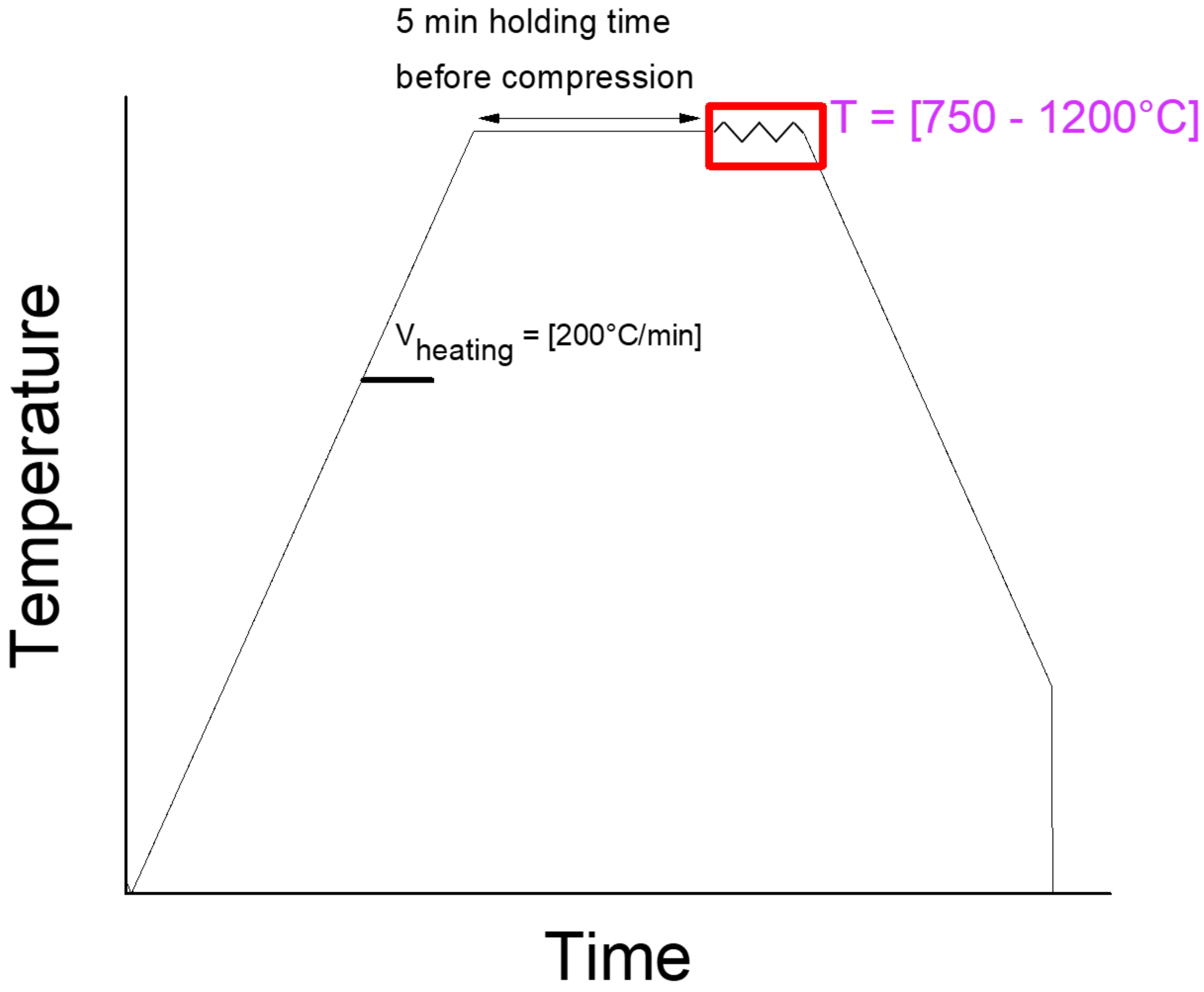
# 3. Rheological investigation

## First thermo-mechanical path investigated
(Isothermal conditions = IC)



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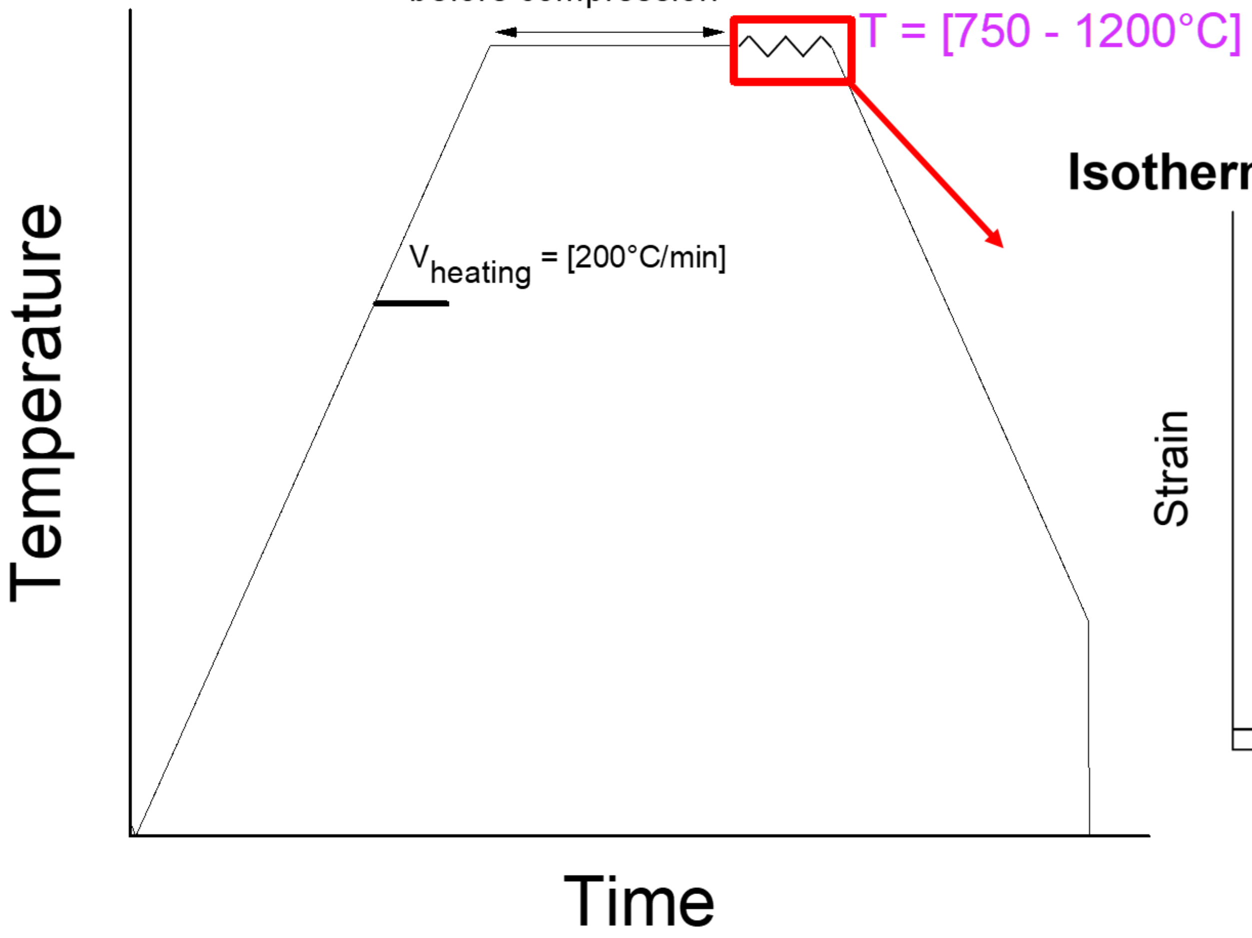
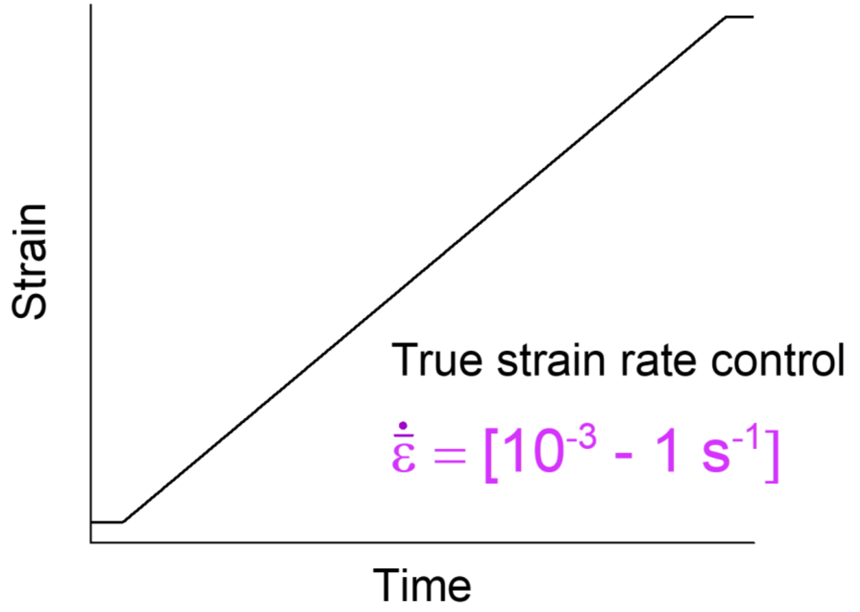
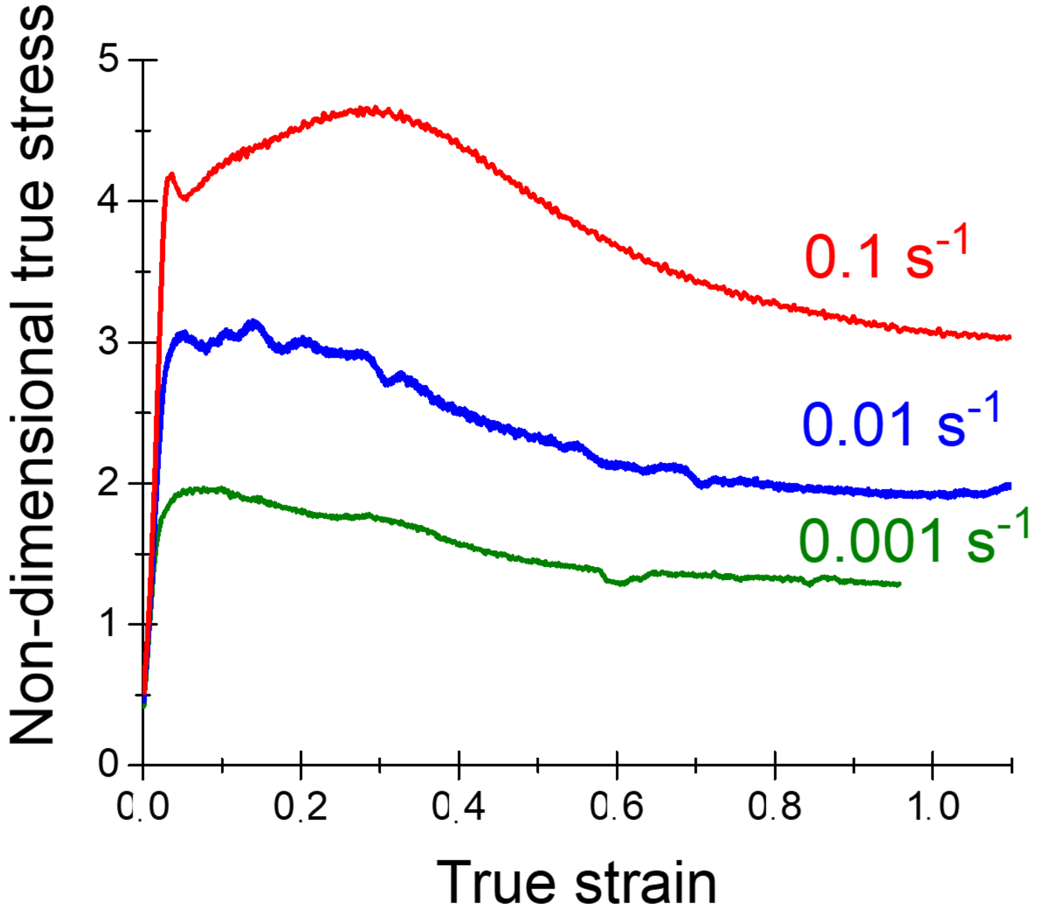


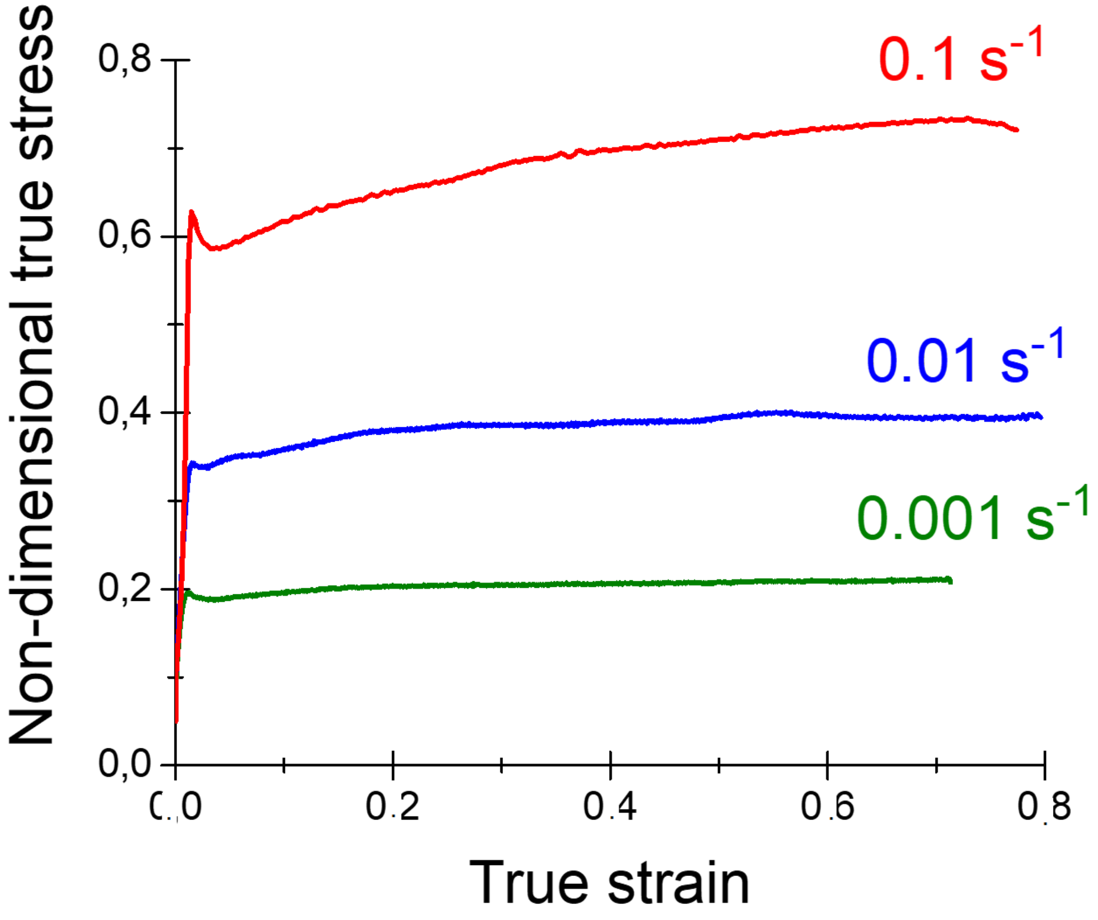



# 3. Rheological investigation

## α+β domain (850°C)

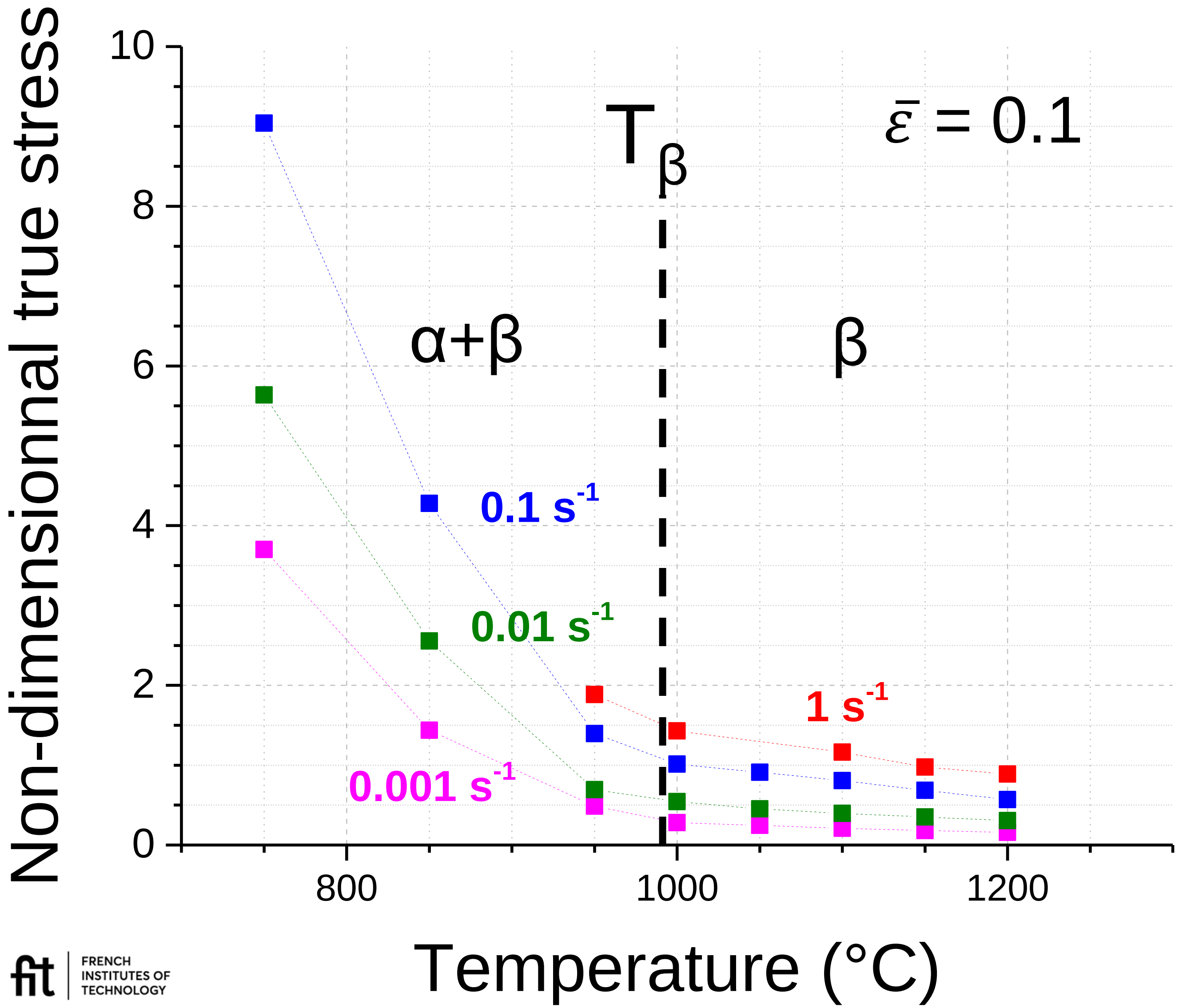



## β domain (1100°C)



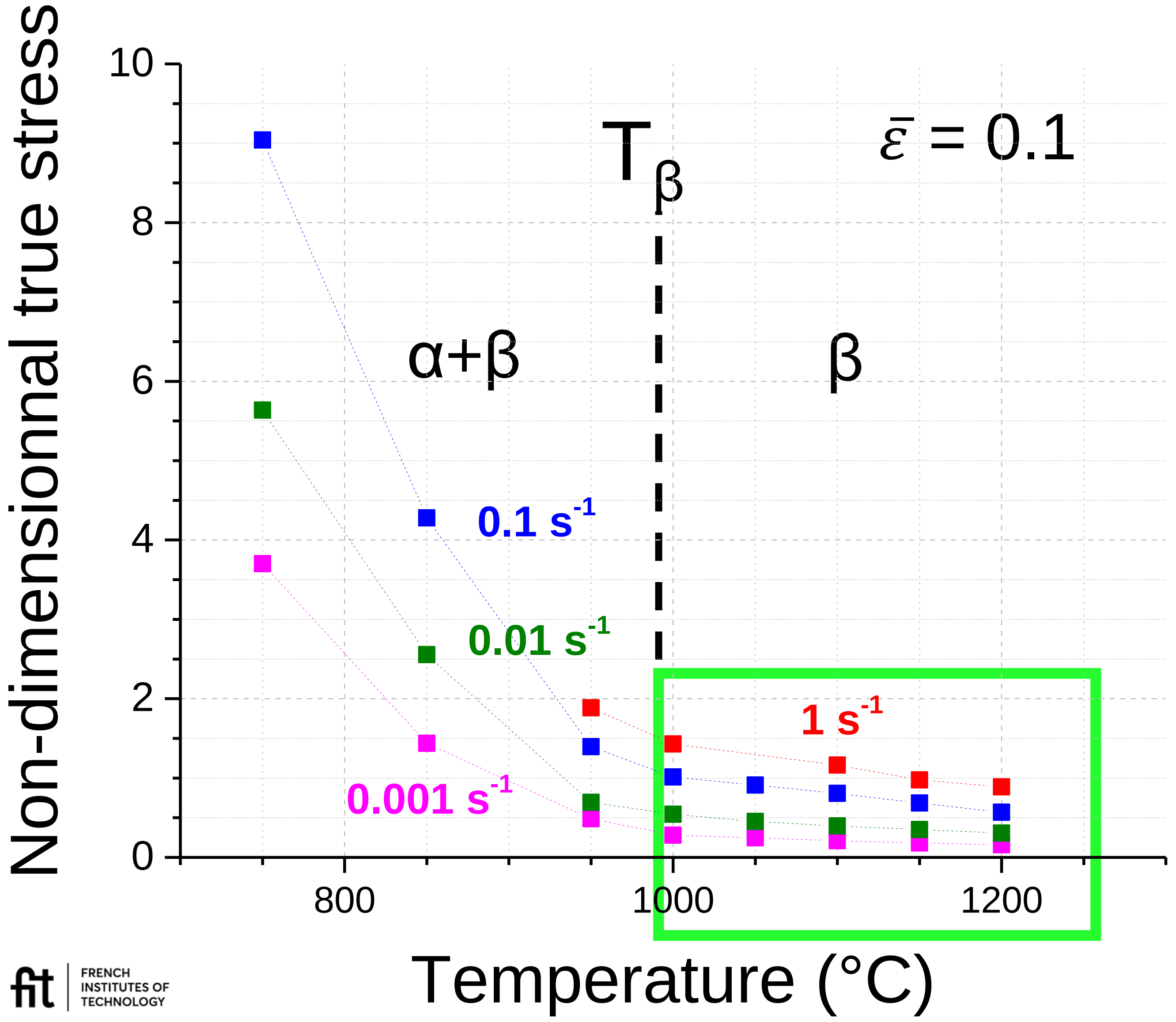

$T < T_\beta$ : **Stress peak** at low strain followed by **softening** at higher strain
$T > T_\beta$ : Almost constant flow stress

# 3. Rheological investigation




↑ T and ↓ $\dot{\bar{\varepsilon}}$ → ↓ σ

# 3. Rheological investigation




↑ T and ↓ $\dot{\bar{\varepsilon}}$ → ↓ σ

$T > T_\beta$ → Low variation of σ with T

# 3. Rheological investigation

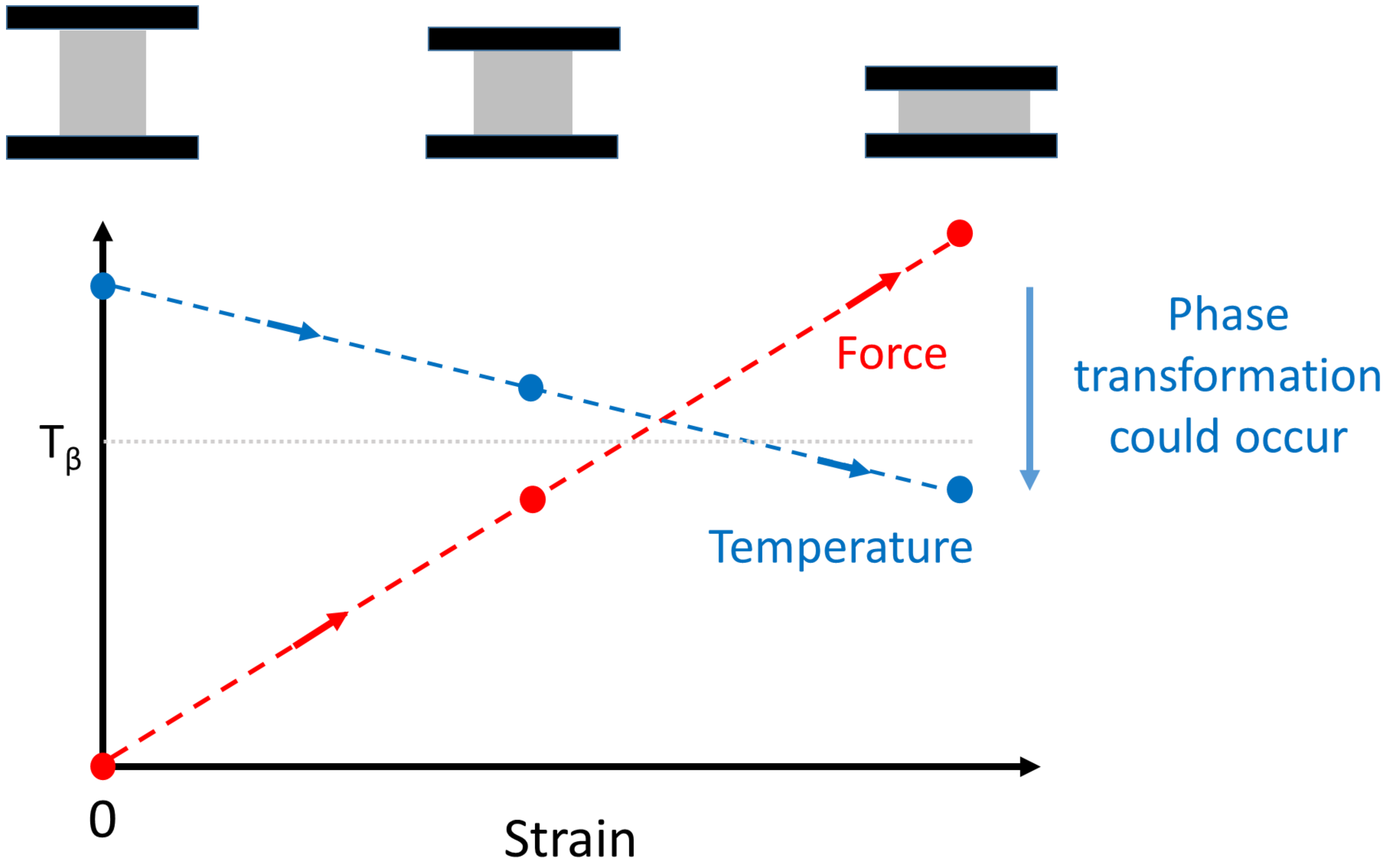
## Comparison between αβ and β forging

950°C

1100°C

# 3. Rheological investigation

In reality, temperature decreases during forging :



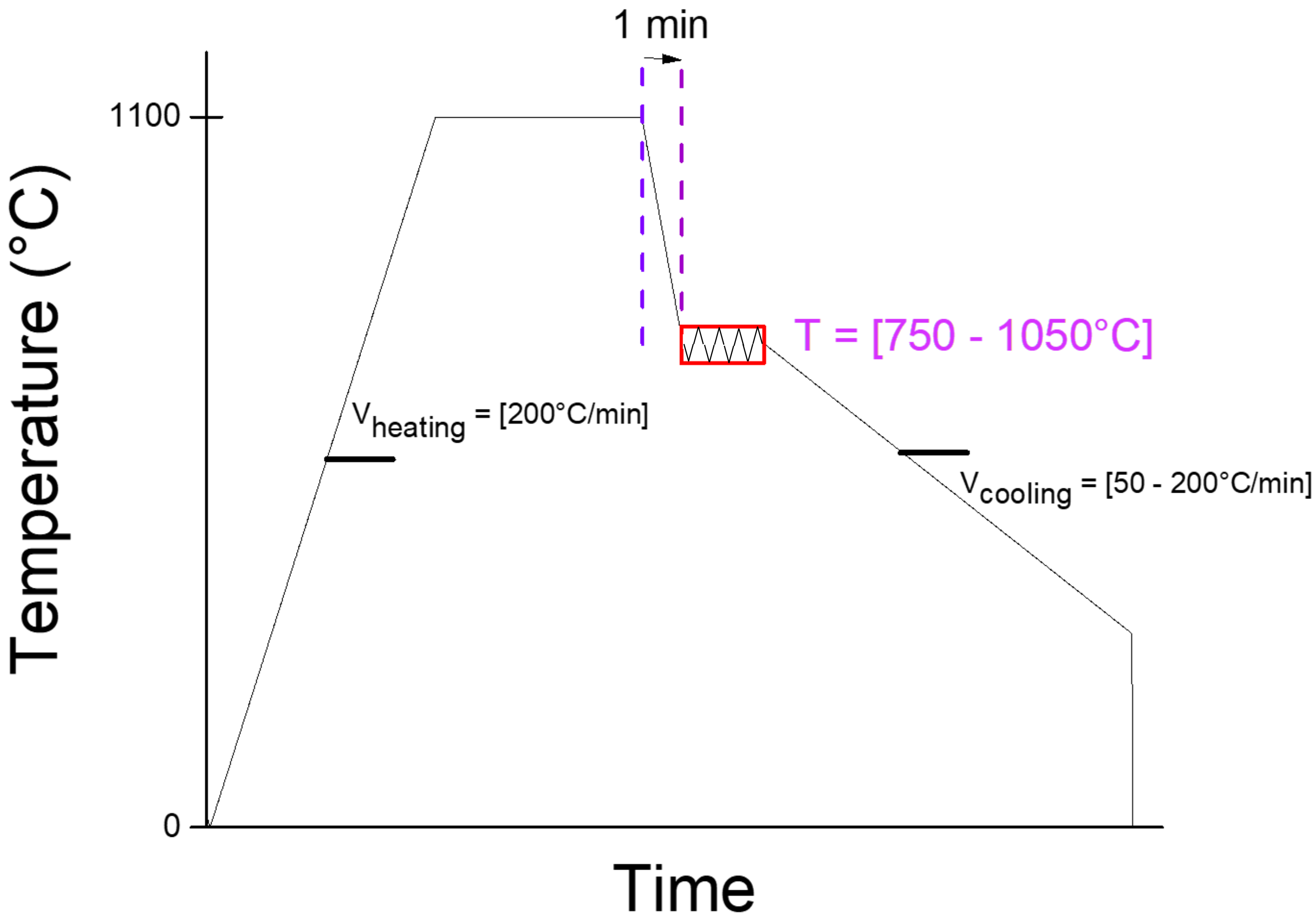
# 3. Rheological investigation

## Second thermo-mechanical path investigated

Non-isothermal conditions (Non-IC)

Compression after temperature reduction

→ Approaching forging conditions

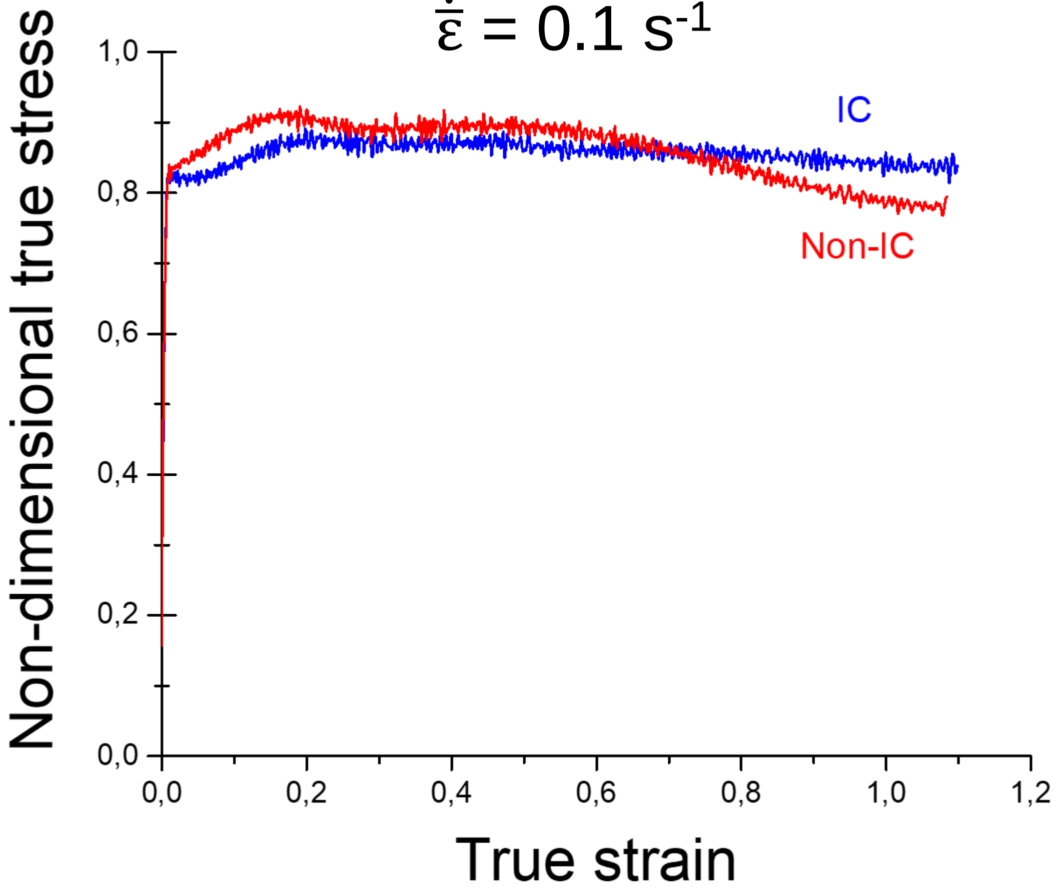


# 3. Rheological investigation

**Above $T_\beta$ :**

$T_{compression} = 1050°C$

$\dot{\varepsilon} = 0.1\ s^{-1}$

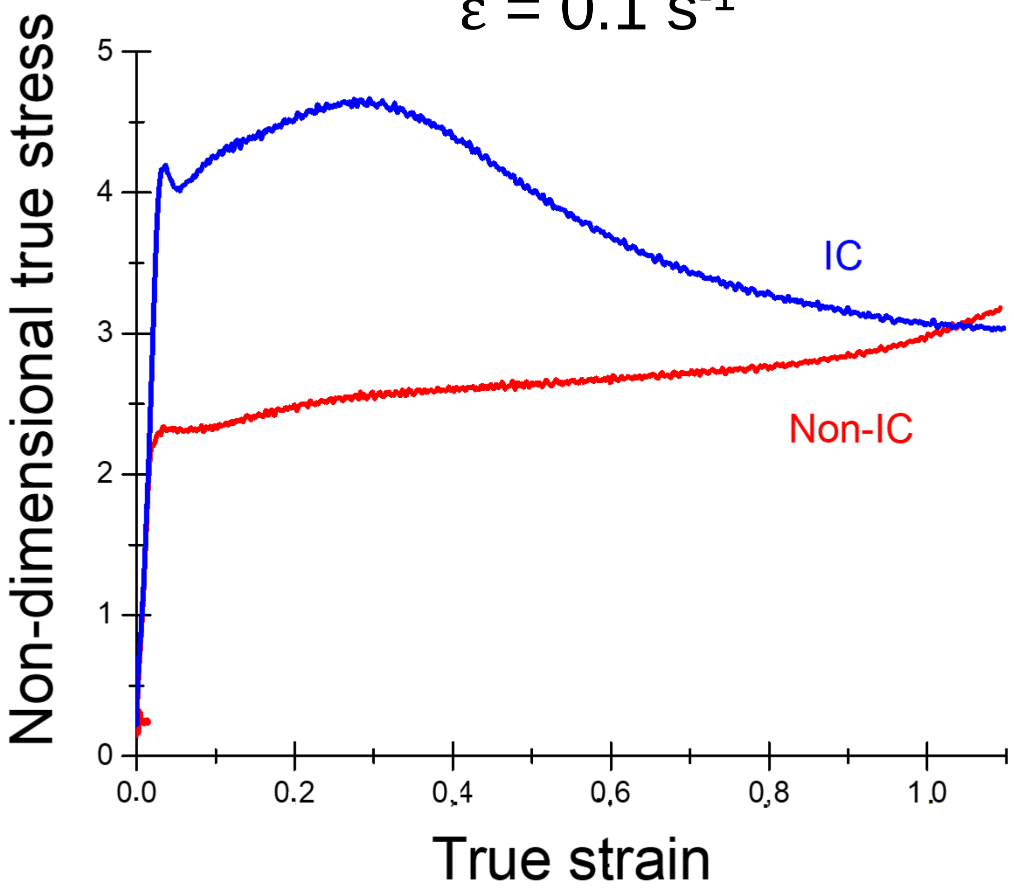



- Similar flow stress between IC and Non-IC

**Below $T_\beta$ :**

$T_{compression} = 850°C$

$\dot{\varepsilon} = 0.1\ s^{-1}$

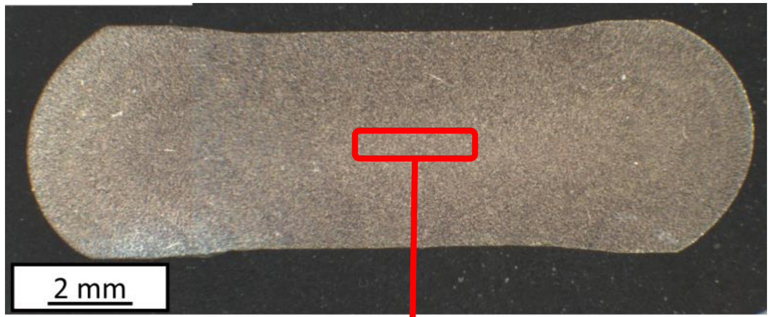


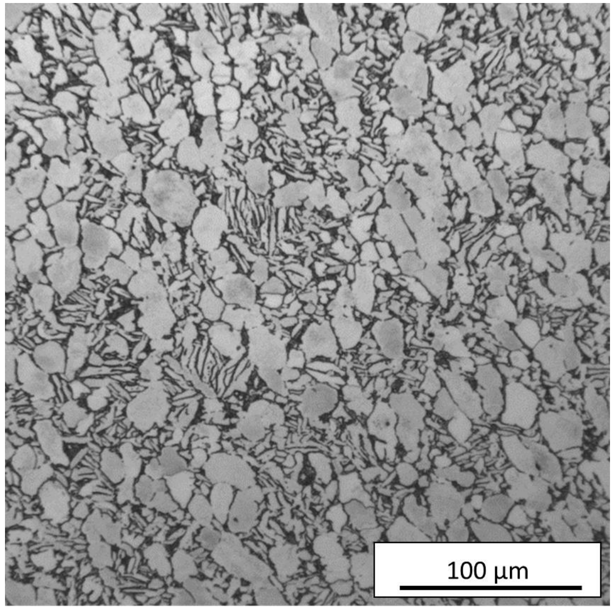

- Lower flow stress Non-IC

# 3. Rheological investigation

## (850°C – 0.1 $s^{-1}$)

IC




Compression direction

Bimodal microstructure



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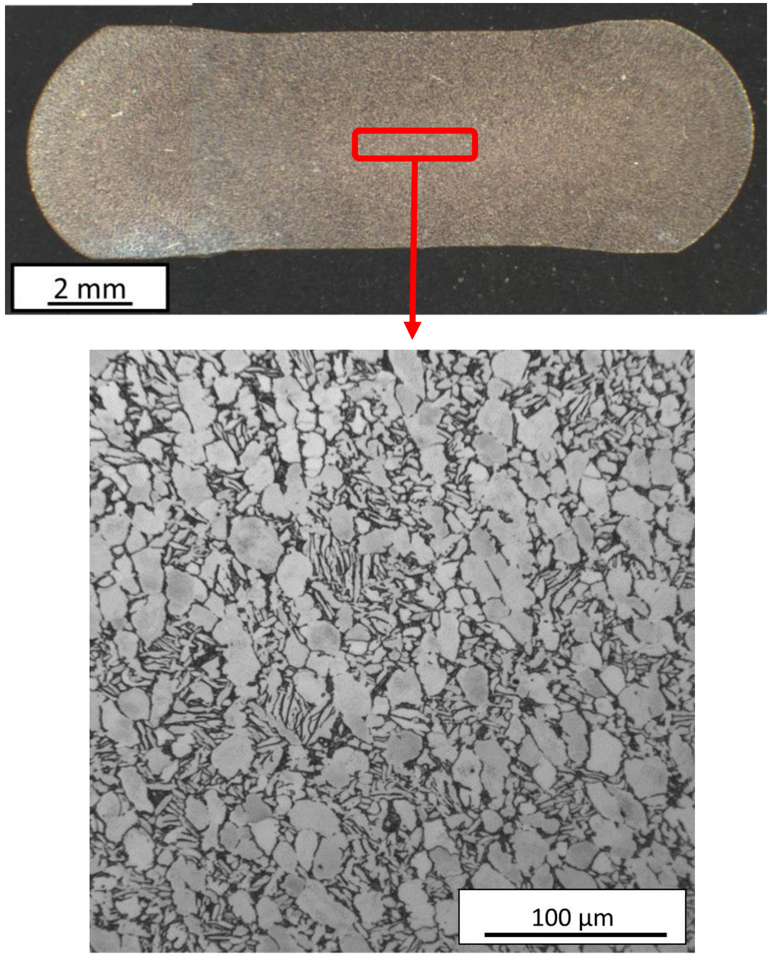
# 3. Rheological investigation

## (850°C – 0.1 $s^{-1}$)

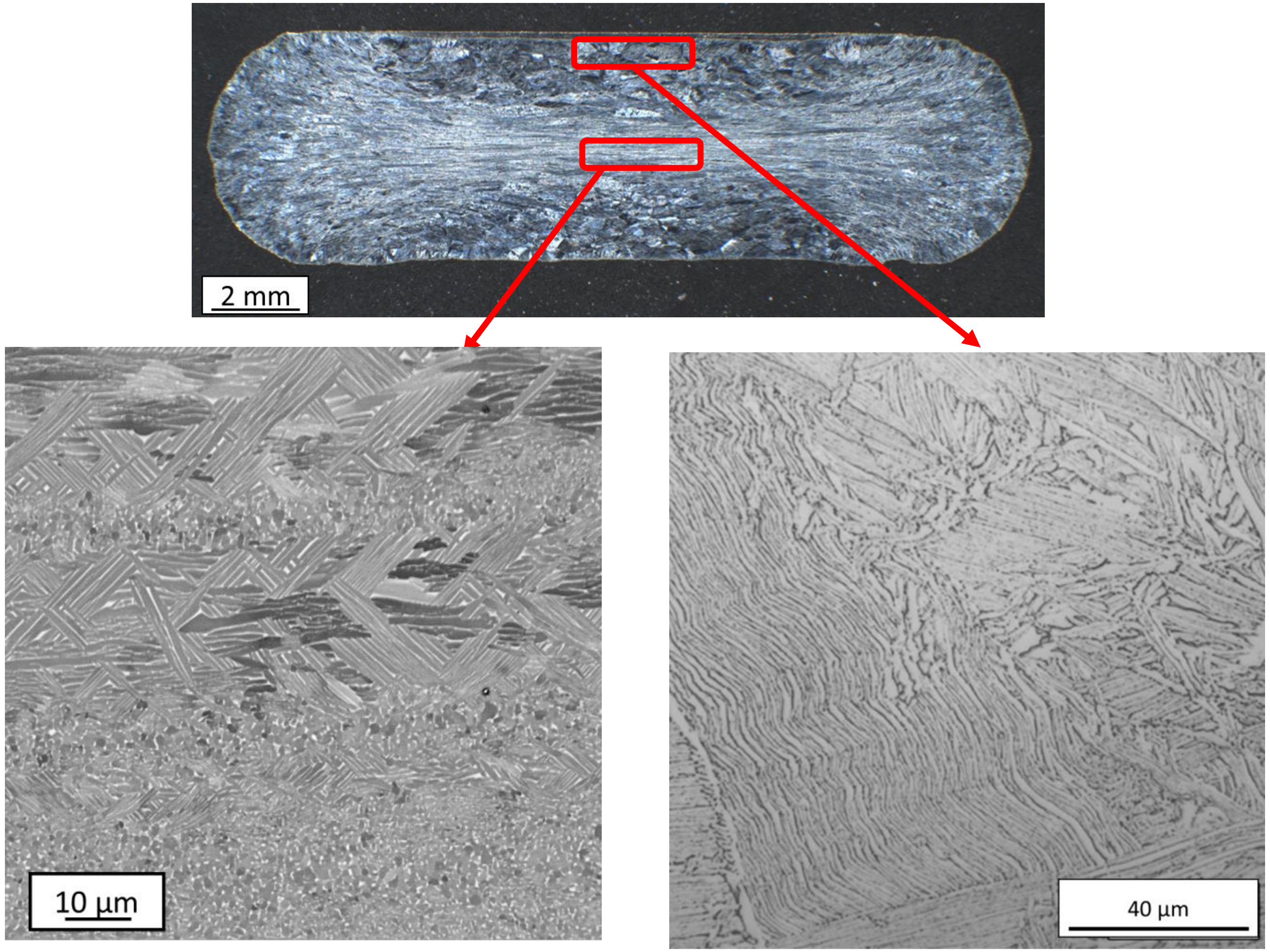


**IC**




Bimodal microstructure

**Non-IC**




Lamellae fragmentation

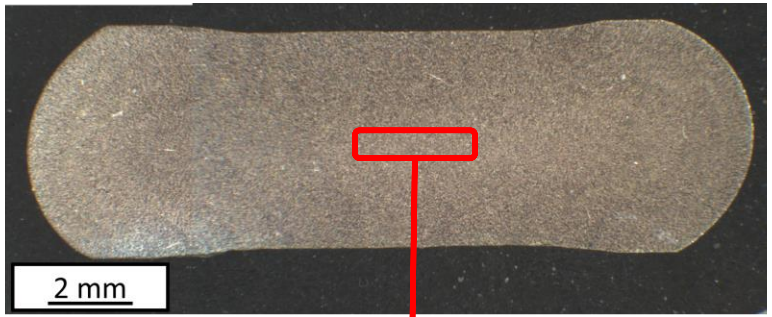
Kinked lamellae

Compression direction

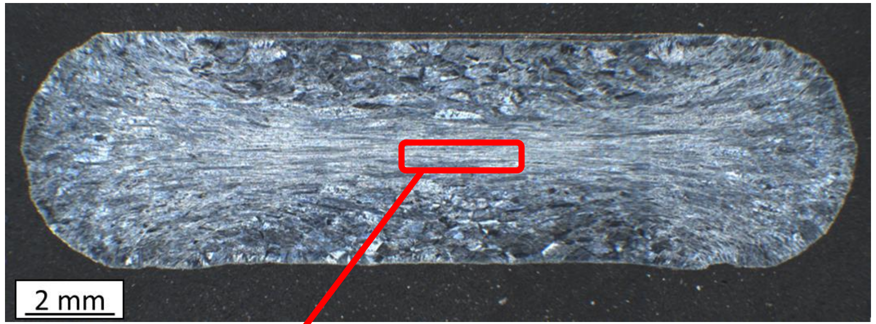
# 3. Rheological investigation

## (850°C – 0.1 $s^{-1}$)

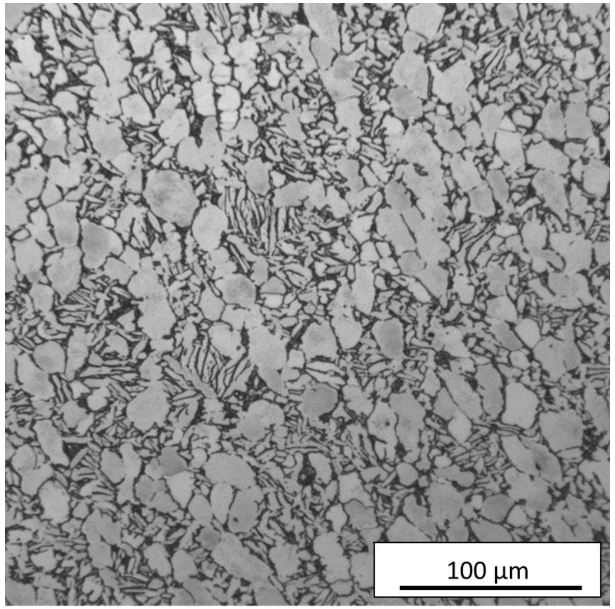
**IC**



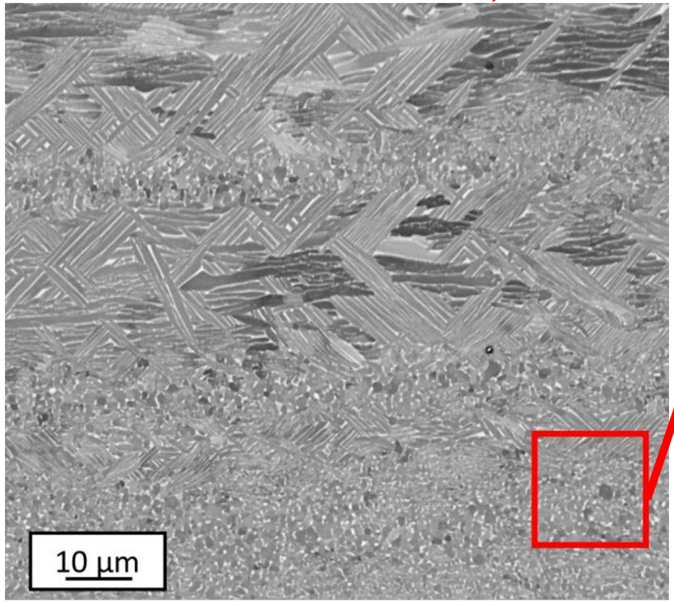

**Non-IC**



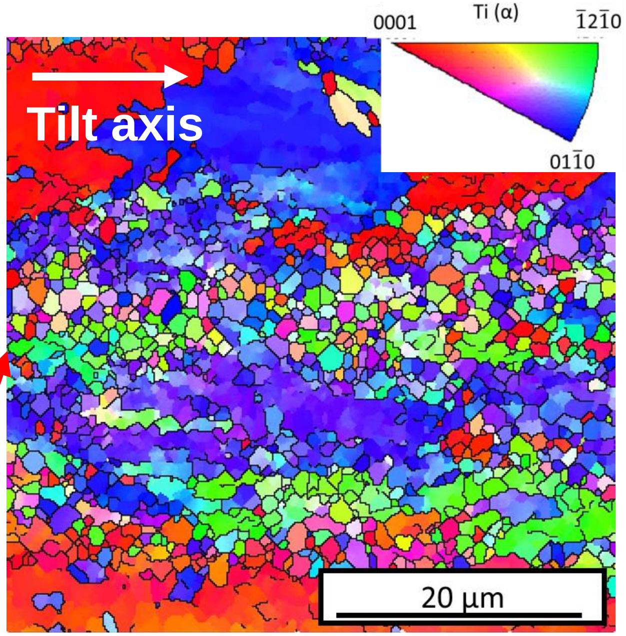

Compression direction




Bimodal microstructure




Lamellae fragmentation

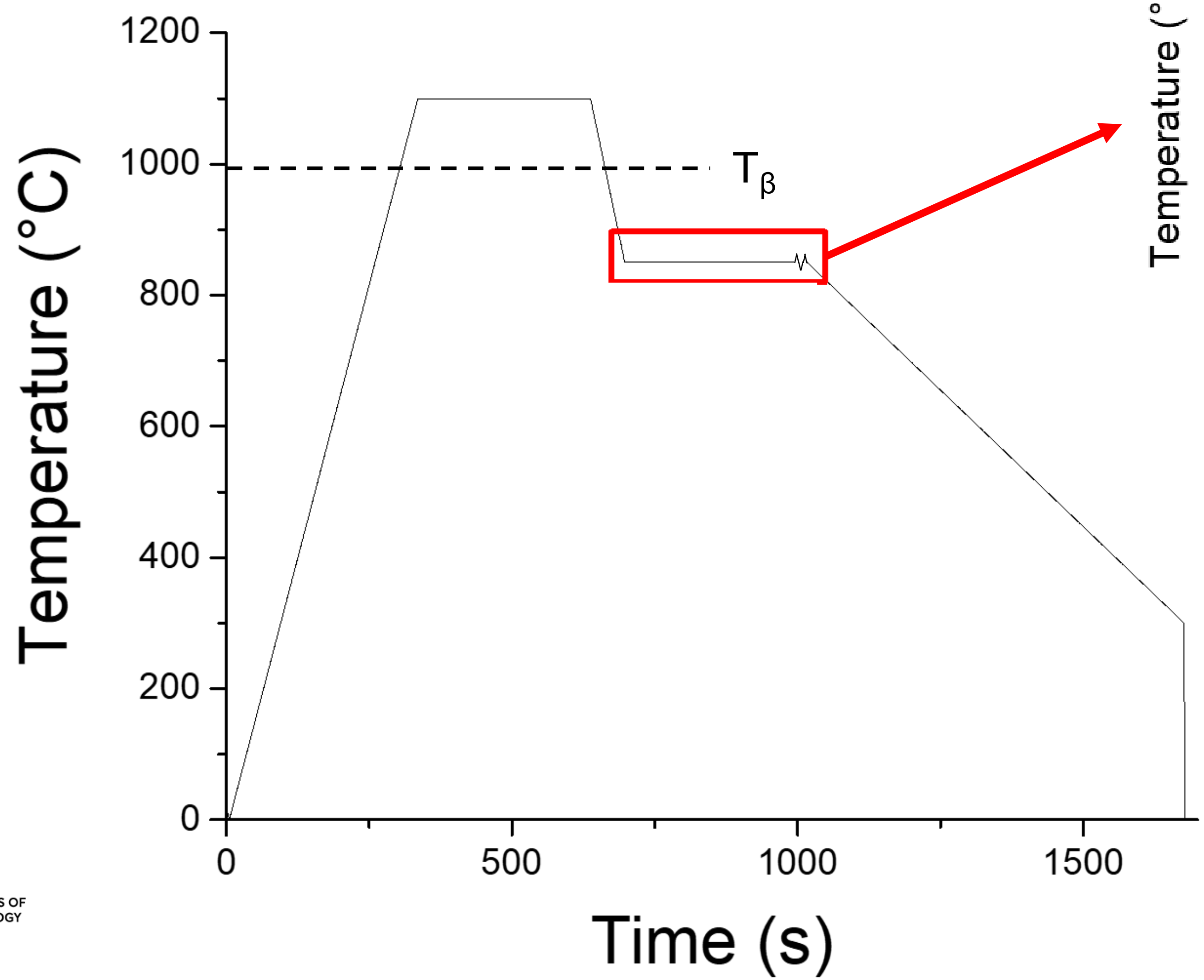


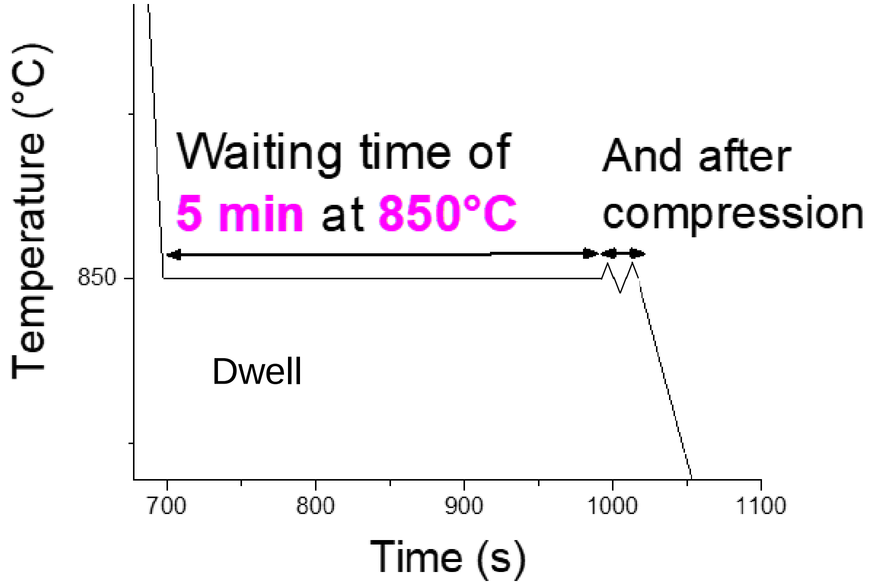

α recrystallization

# 3. Rheological investigation

## Stabilization time

Variation of holding time before compression



# 3. Rheological investigation

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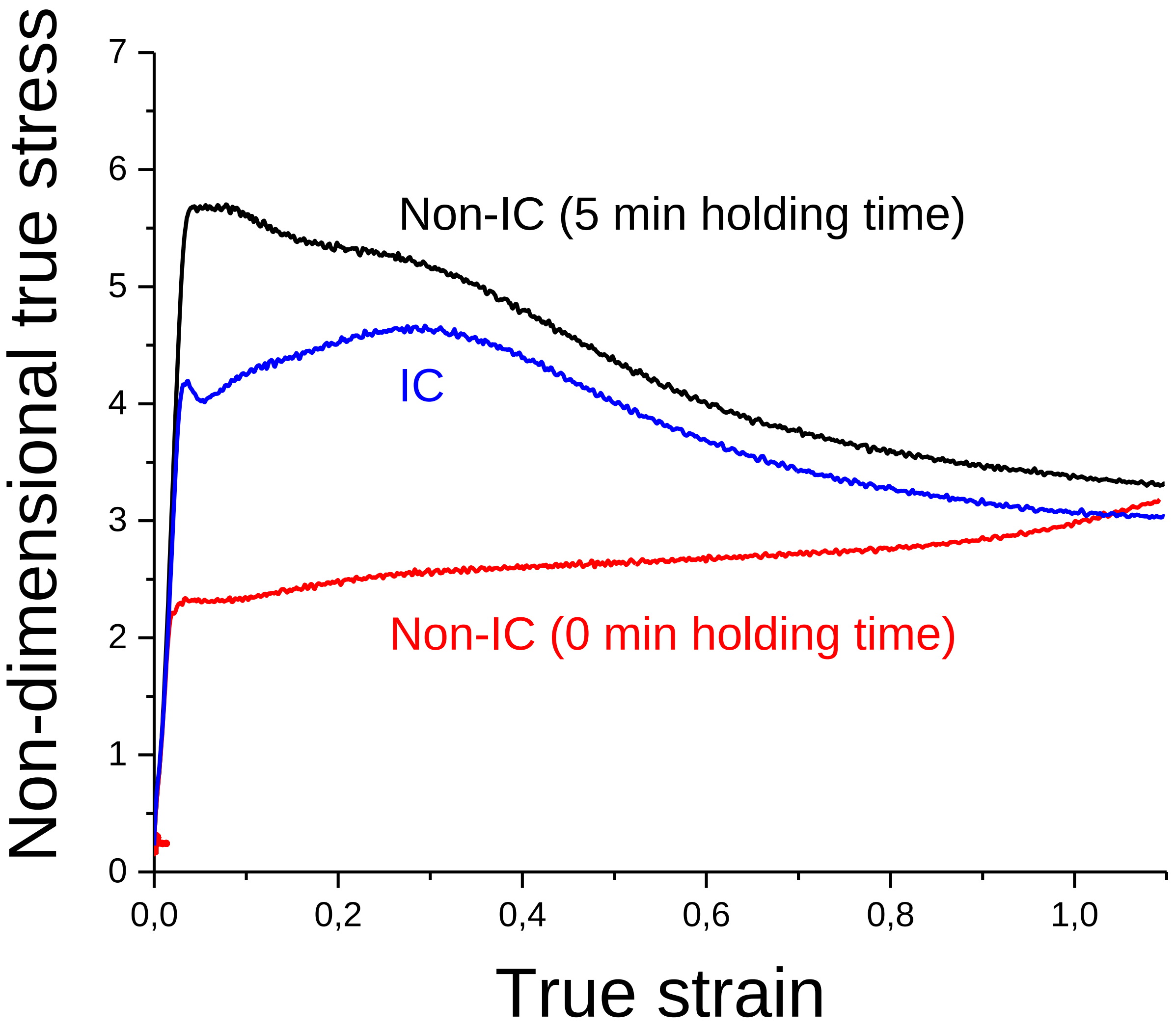
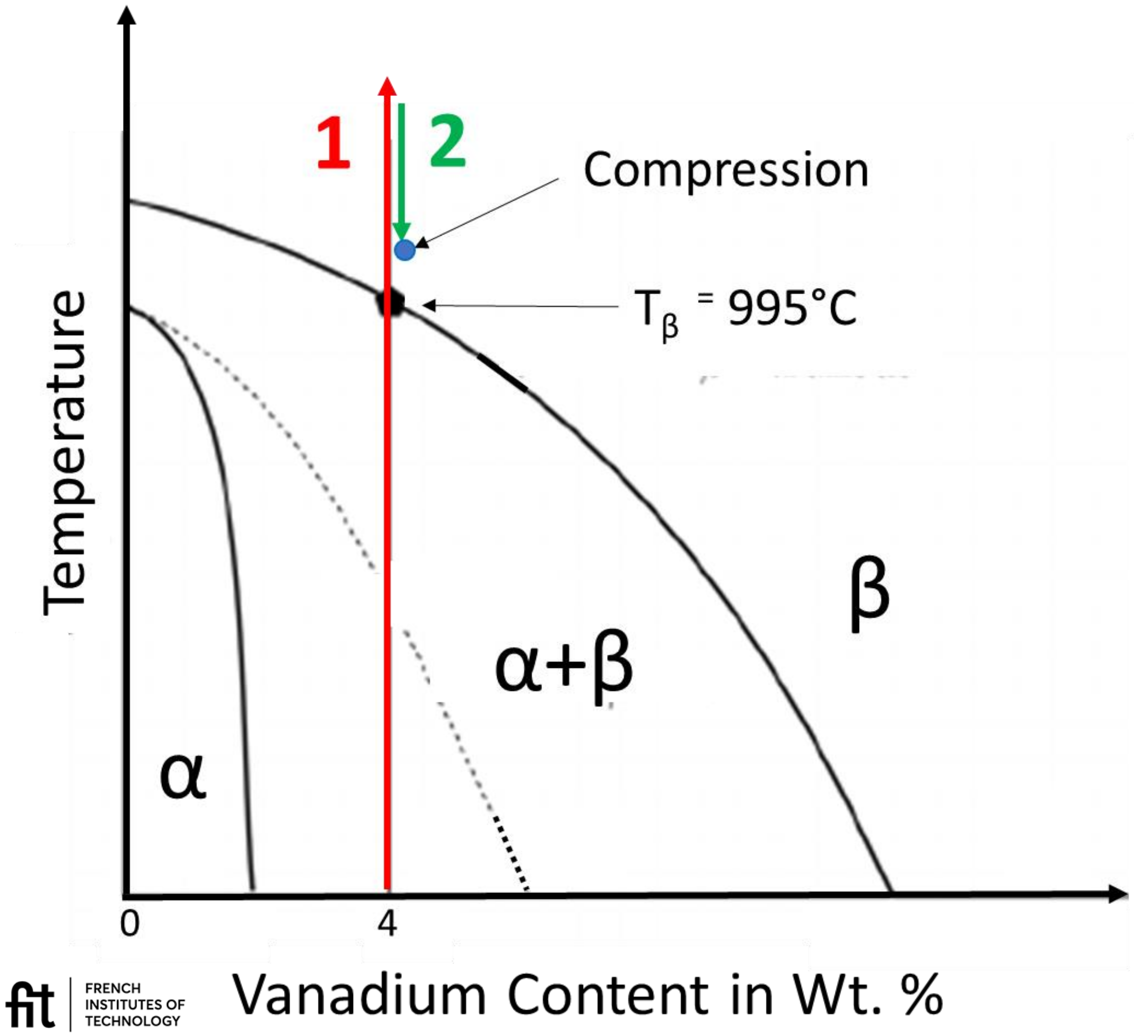


# Key takeaways

## Rheological behaviour



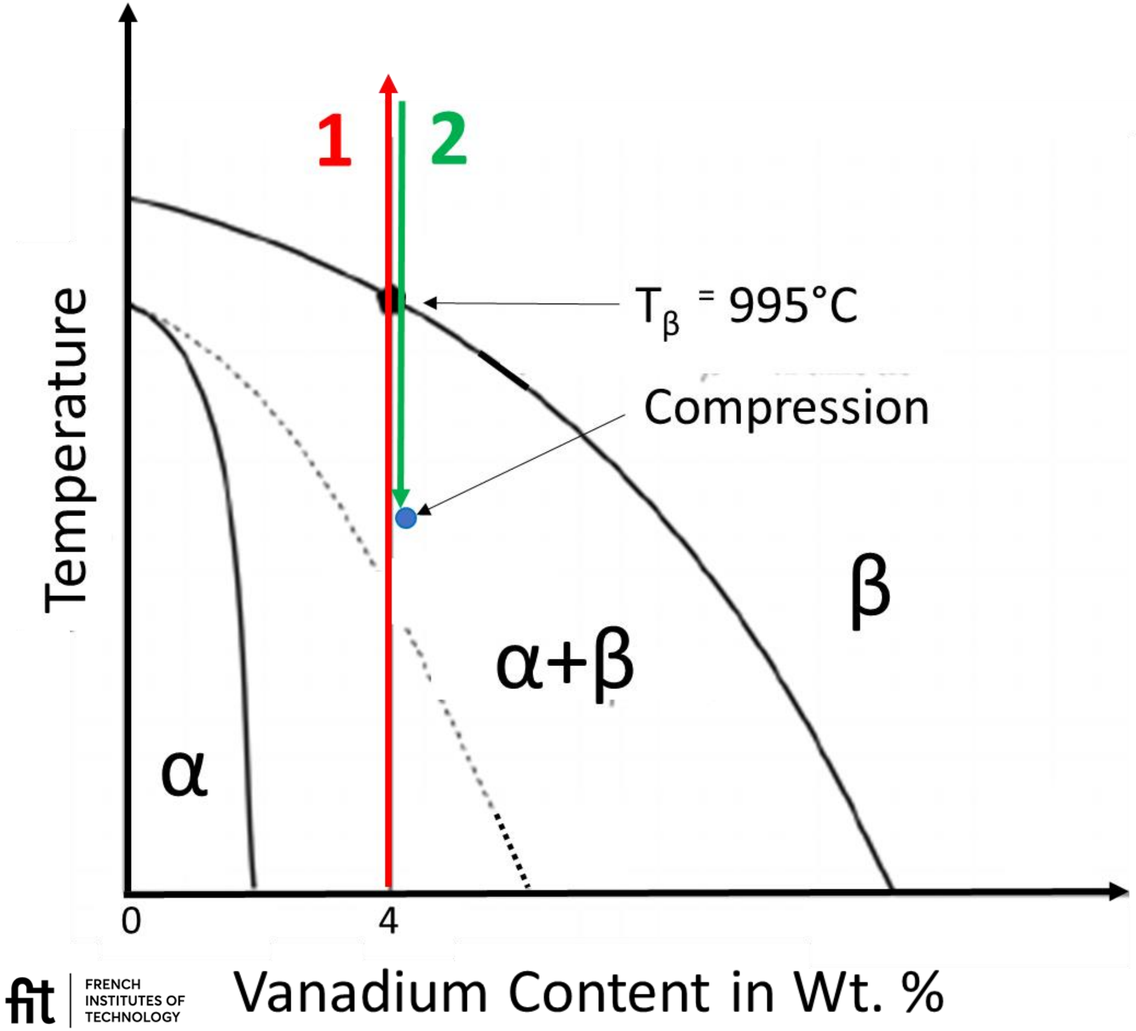

Same rheological behaviour than IC

Same microstructure tested

*Equiaxed β grains*

# Key takeaways

## Rheological behaviour




**With holding time**

- Higher flow stress than IC
- Stabilized microstructure

**Without holding time**

- Lower flow stress than IC
- Unstabilized microstructure

*Phase transformation during compression*

*Lamellae fragmentation and α recrystallization*

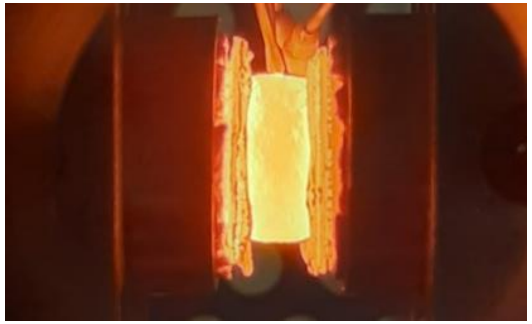
→ Reduction of flow stress is beneficial for forging

# Key takeaways

## Industrial context

**Rheology database**

- Isothermal compression



→

**Numerical simulation**

FORGE®

→

**First successful try**

*When developing a rheology database for β-forging of Ti-64, care should be taken to the transition time between the solutionizing temperature and the deformation temperature*

# Thanks for your attention