REORIENTATION INDUCED PLASTICITY (RIP) in Ti-6Al-4V:

Underlying mechanisms and resulting mechanical properties

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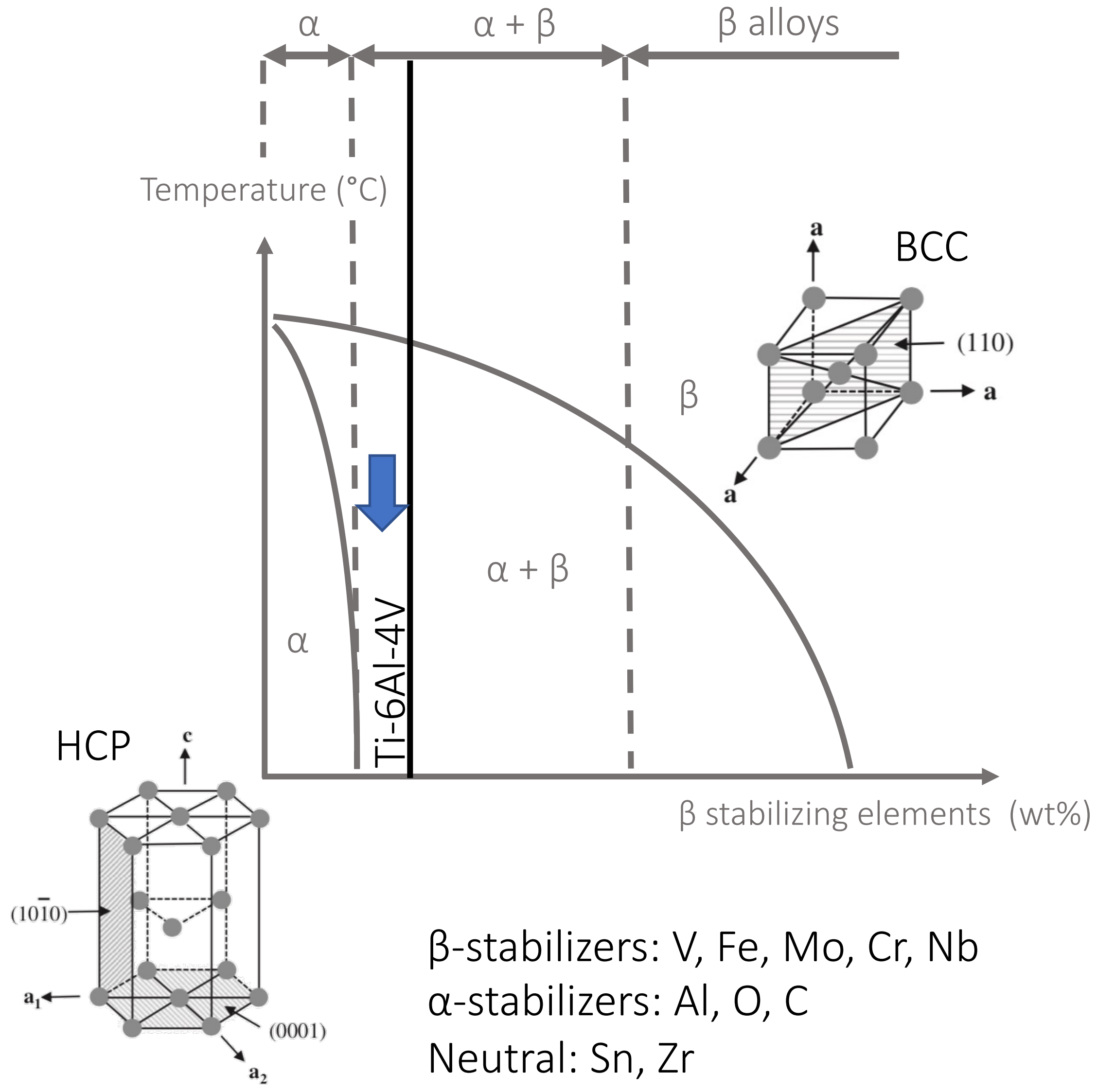
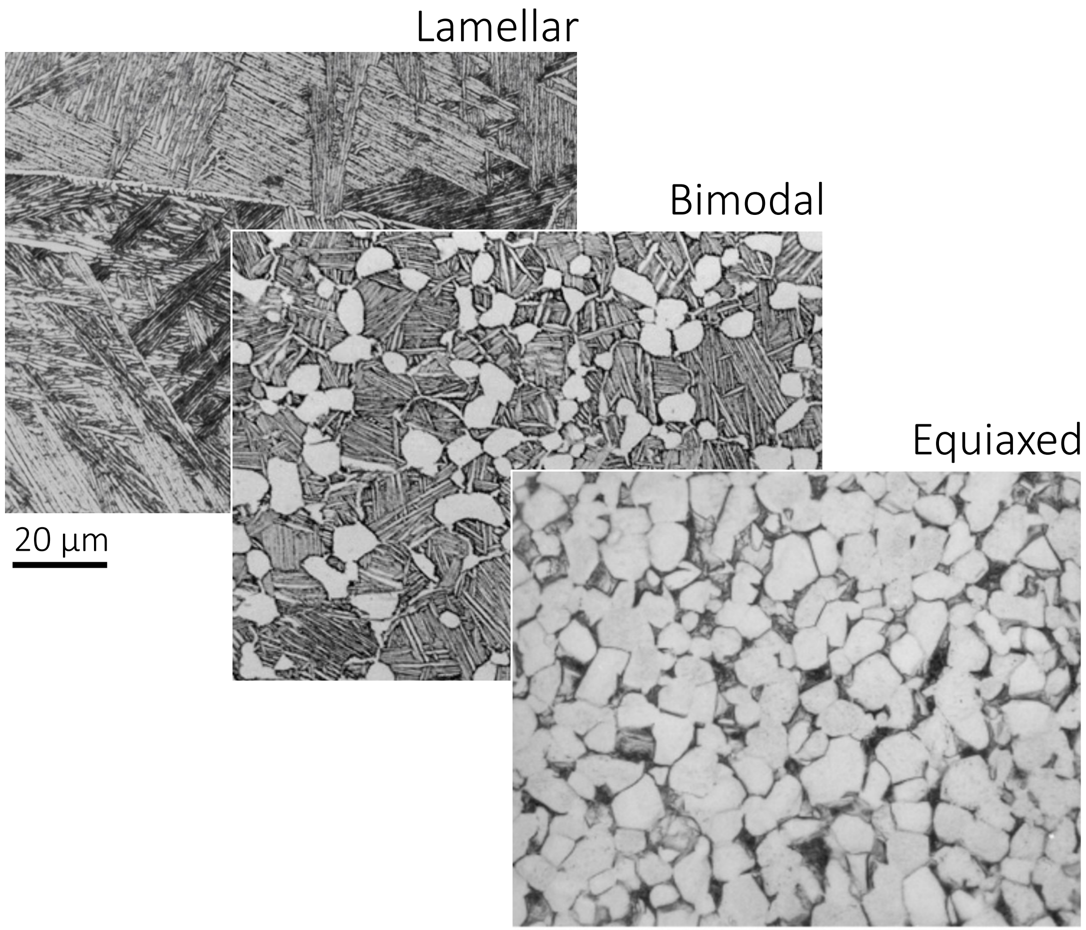
(α+β)Ti alloys offer a wide variety of microstructures



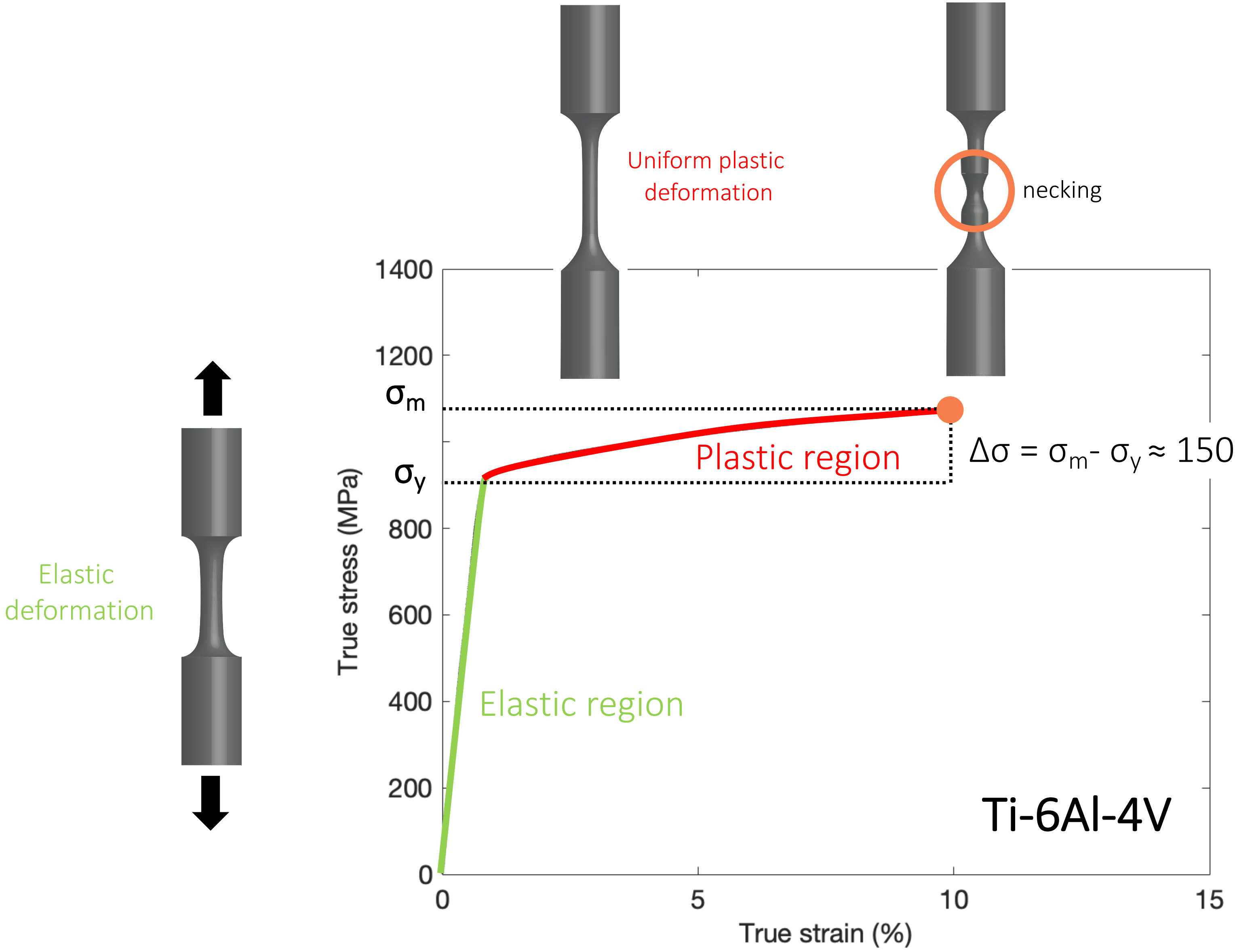
β-stabilizers: V, Fe, Mo, Cr, Nb
α-stabilizers: Al, O, C
Neutral: Sn, Zr



Mechanical properties depends on:

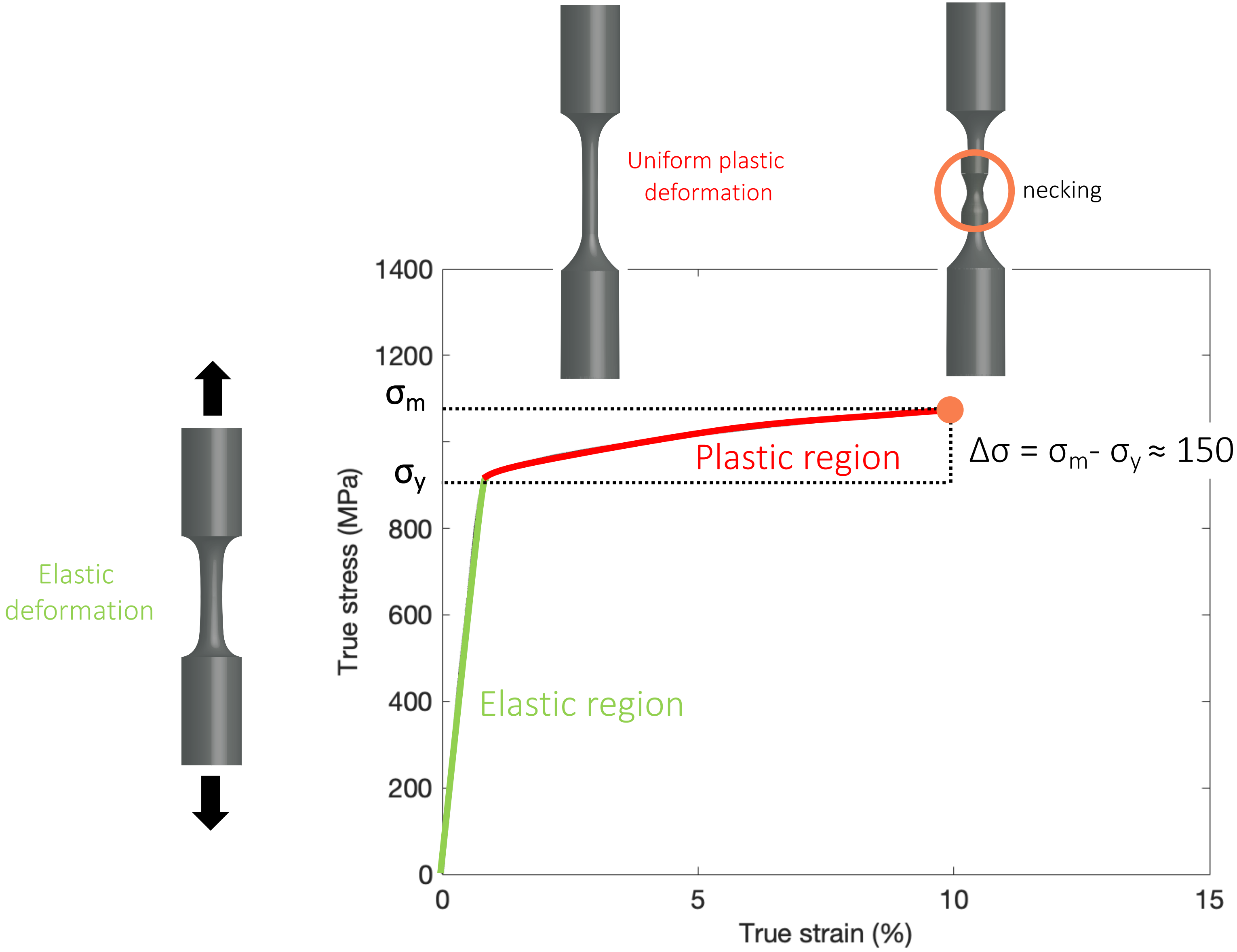
- nominal composition
- microstructure

(α+β) Titanium alloys generally exhibit a limited plastic deformation … and **a limited work-hardening**…



$\Delta\sigma = \sigma_m - \sigma_y \approx 150$ MPa ← WORK-HARDENING : Fairly low

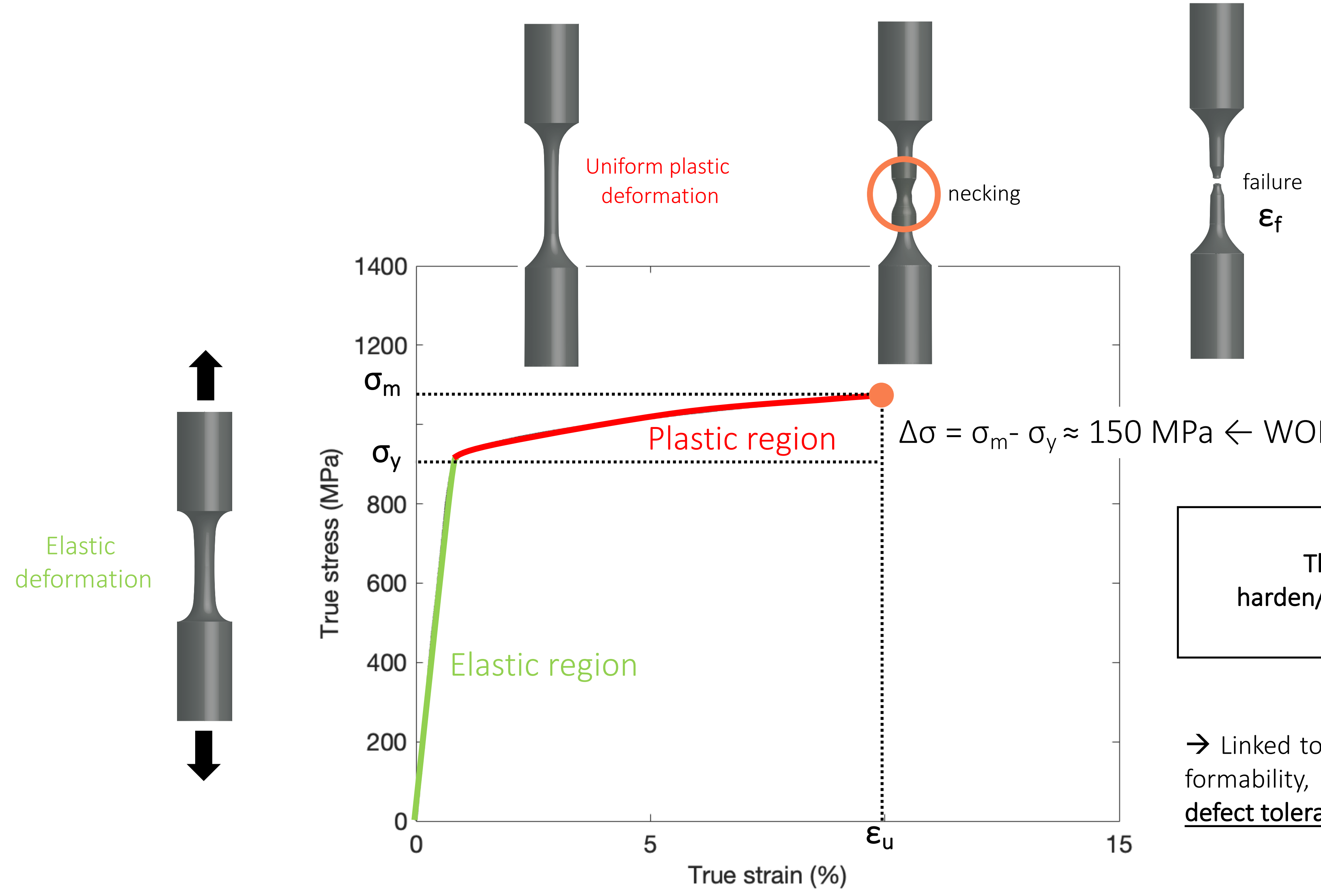
… and a limited work-hardening…



$\Delta\sigma = \sigma_m - \sigma_y \approx 150$ MPa ← WORK-HARDENING : Fairly low

Moderate capacity of the material to harden/consolidate during plastic straining

… and a limited work-hardening…



$\Delta\sigma = \sigma_m - \sigma_y \approx 150$ MPa ← WORK-HARDENING : Fairly low

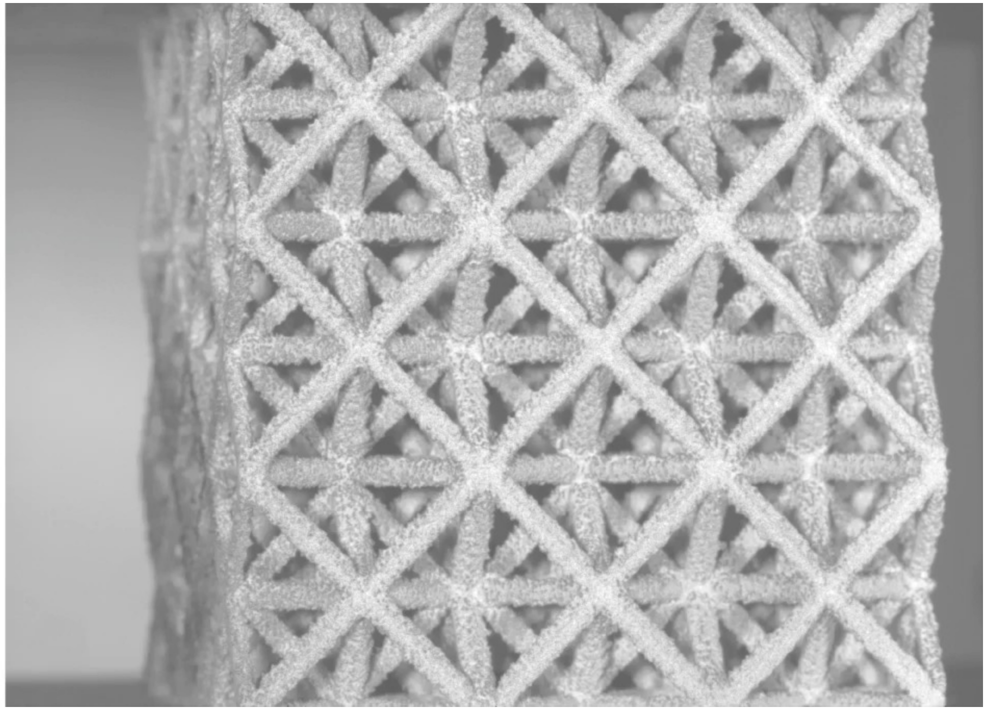
The capacity of the material to harden/consolidate during plastic straining

→ Linked to the uniform strain, **energy absorption**, formability, resistance to localized deformation, **defect tolerance** (in AM for example)

Nothing better than a good example:

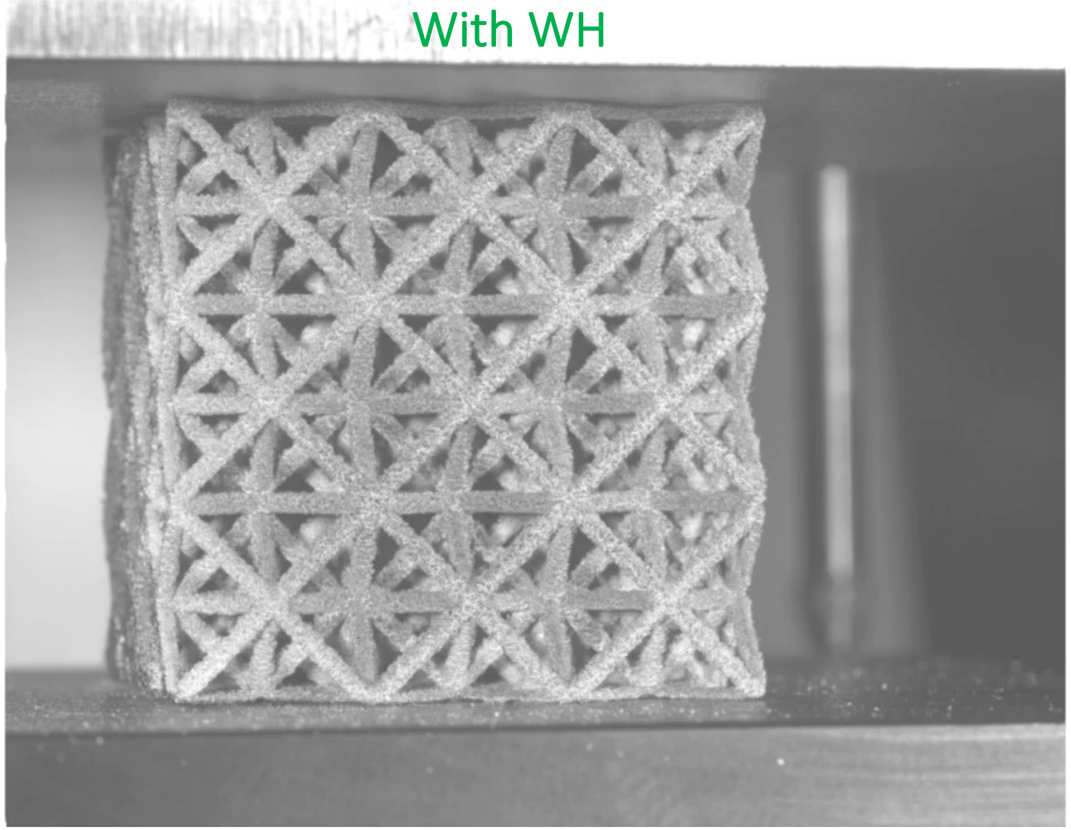
Lattice structures for high-energy absorption

Without WH



Low energy absorption capacity

With WH



High energy absorption capacity

Behaviour of β-metastable TWIP lattice structures

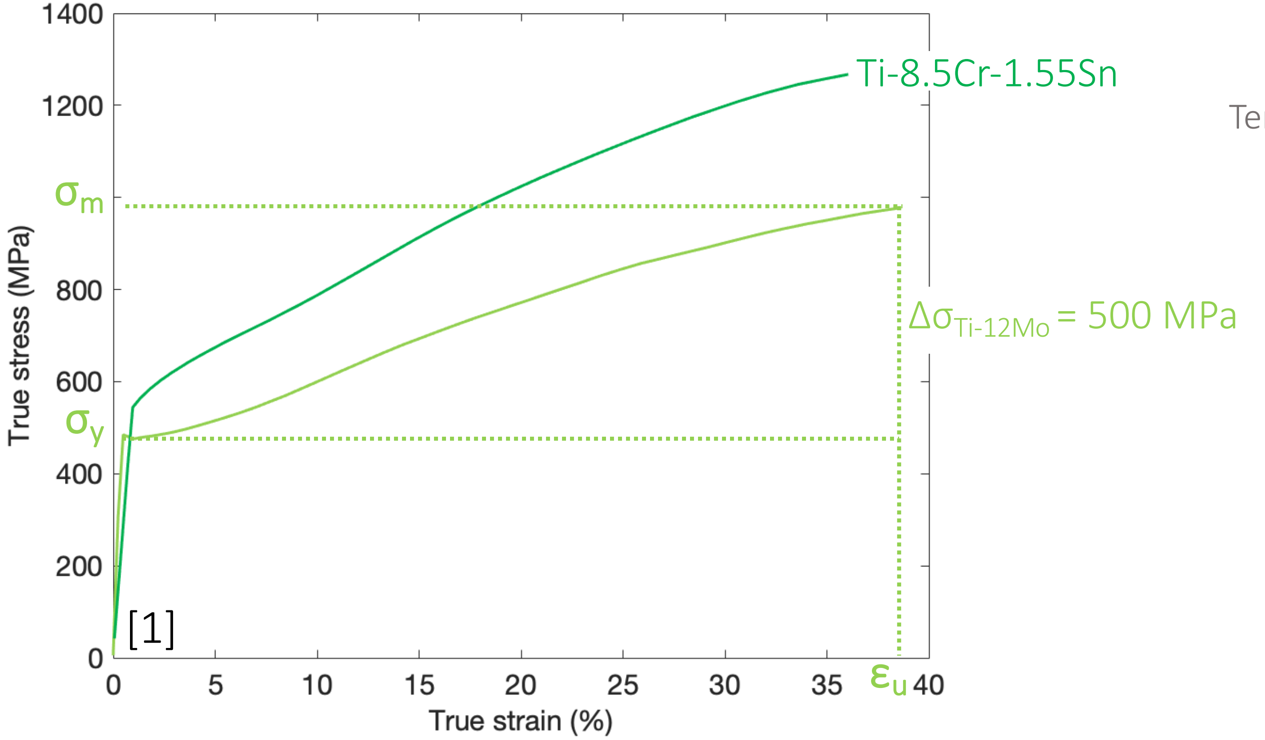
(Common work with SIMAP (Grenoble) on EBM pieces)

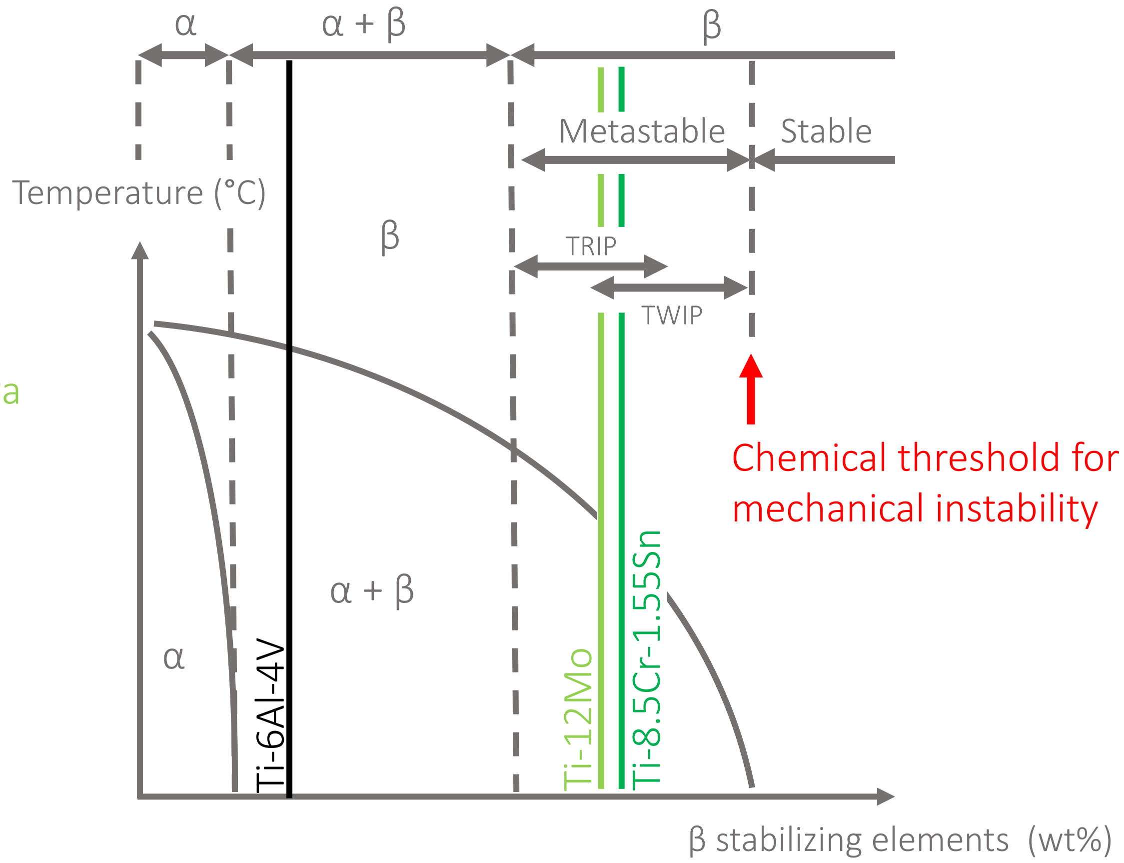
Duport et al., Scripta Materialia, 2022

➡ Strain-hardening as a key target !

Conversely, the TWIP-assisted β-metastable alloys exhibit a very high WH but a low yield strength

Low σ_y, **outstanding WH and ε_u**

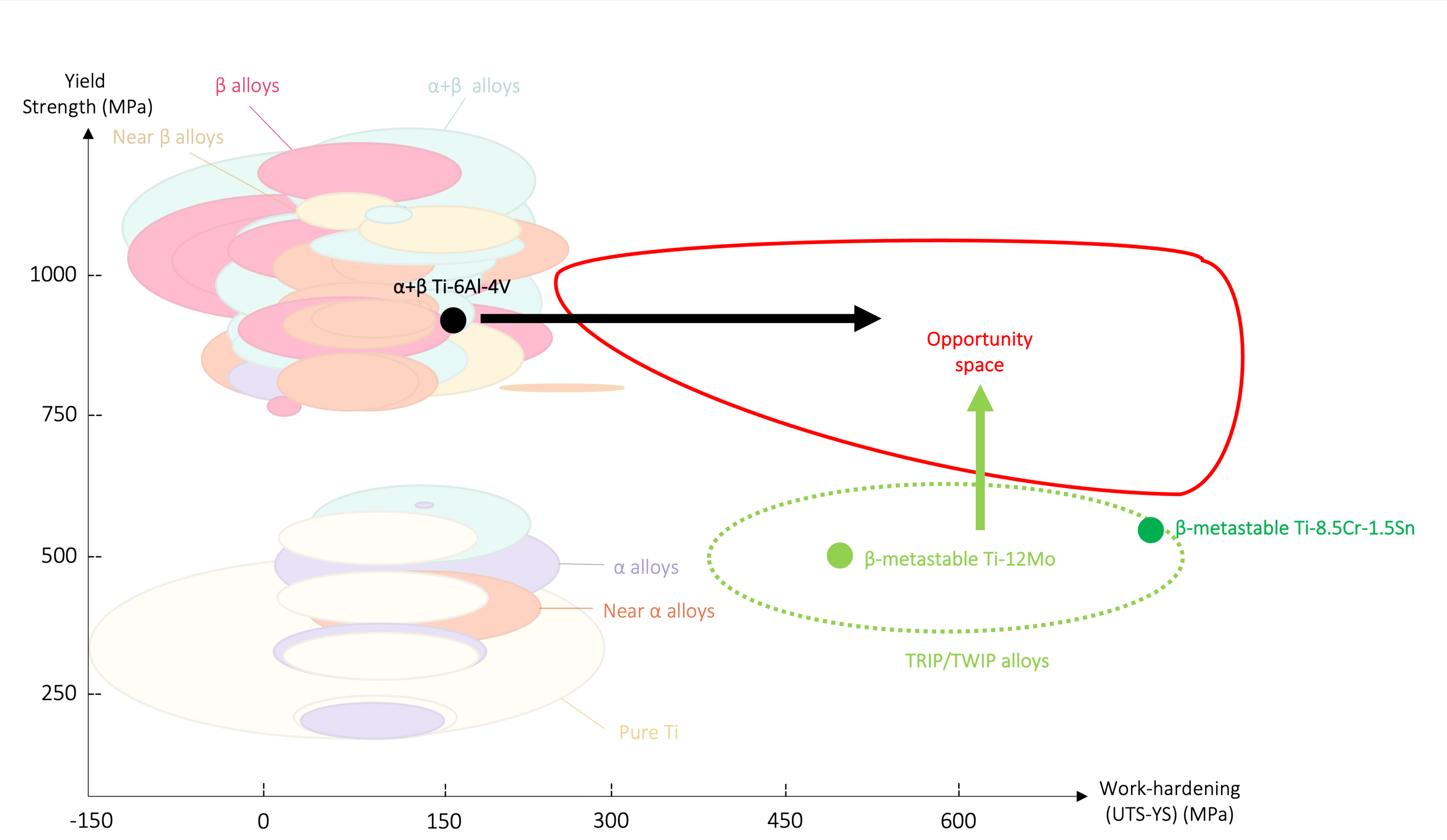




Chemical threshold for mechanical instability

[1] Brozek et al., *Scripta Materialia* (2016)

From the quest for **ideal σ_y and WH combination** of properties arises an **opportunity space** to be opened…



Outline/Goals

- Introduction
- Increasing the work-hardening of Ti-6Al-4V by Dual-Phase microstructures
- Understanding the Reorientation Induced Plasticity Effect and the role of martensite
- Can this be transferred to other Ti alloys? Generalisation and optimisation of the concepts developed on Ti-6Al-4V
- Design rules
- Conclusions

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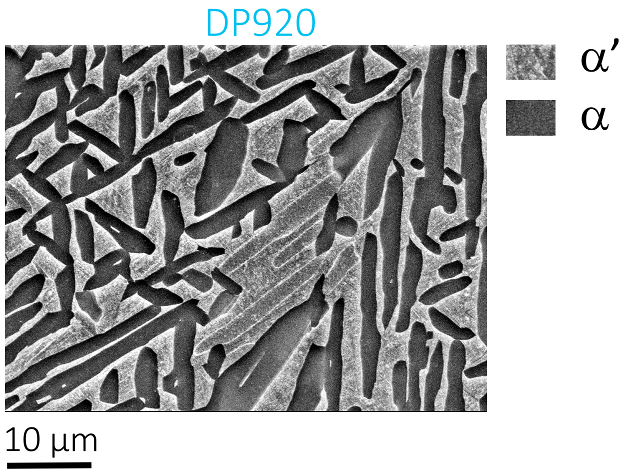
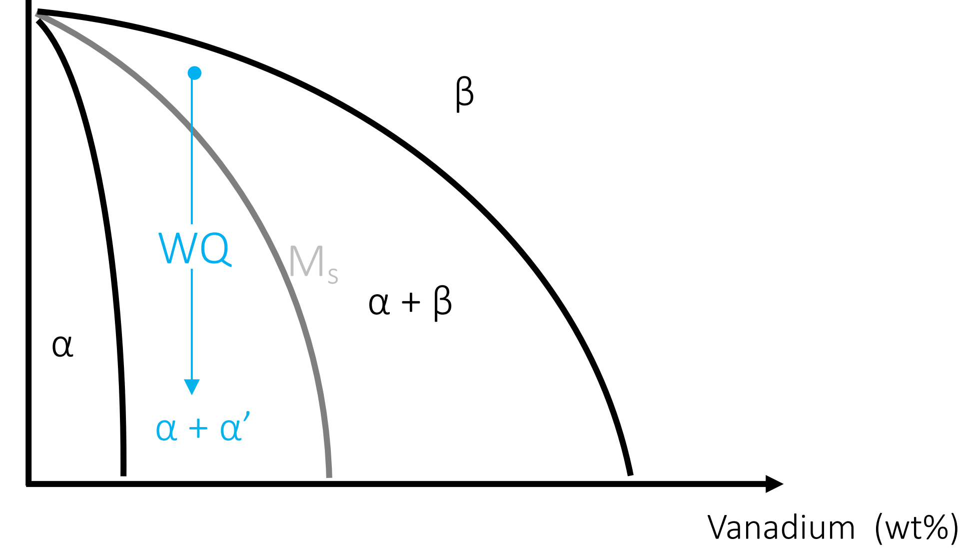
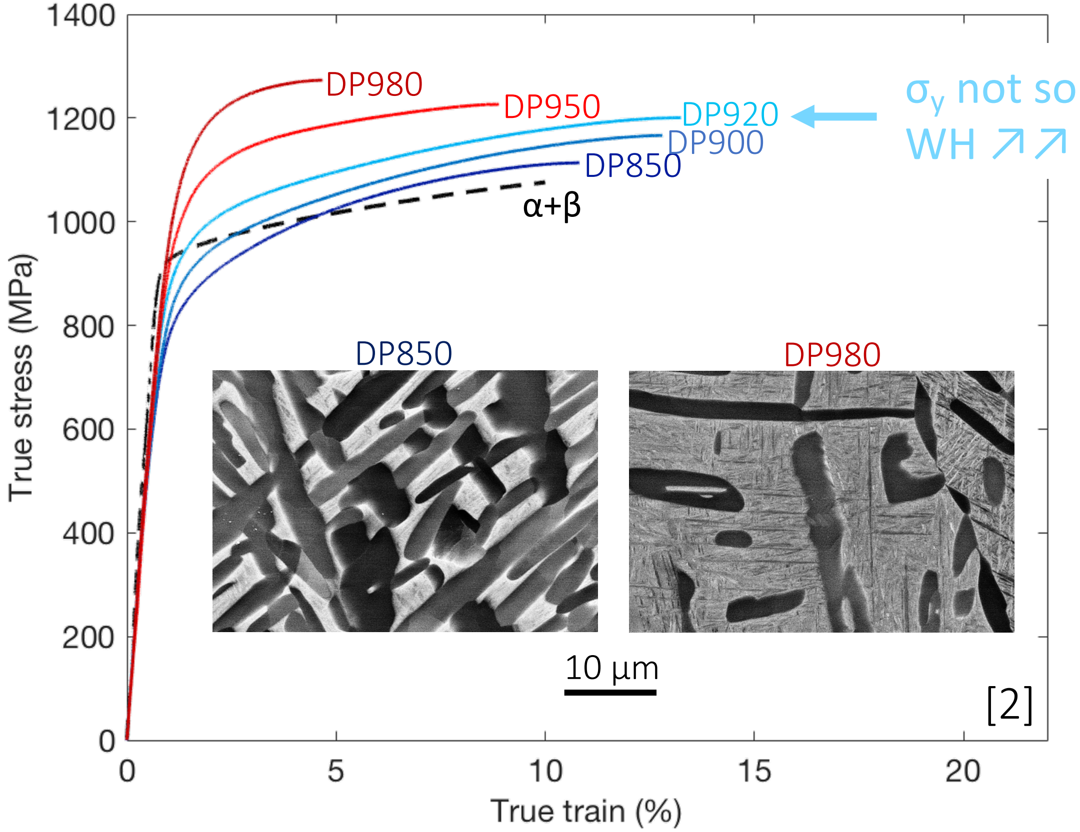
Dual-phase (DP) α-α' microstructures are proposed to improve the work-hardening of Ti-6Al-4V



Metastable phase with:

- Chemistry of the parent β phase
- Hexagonal structure

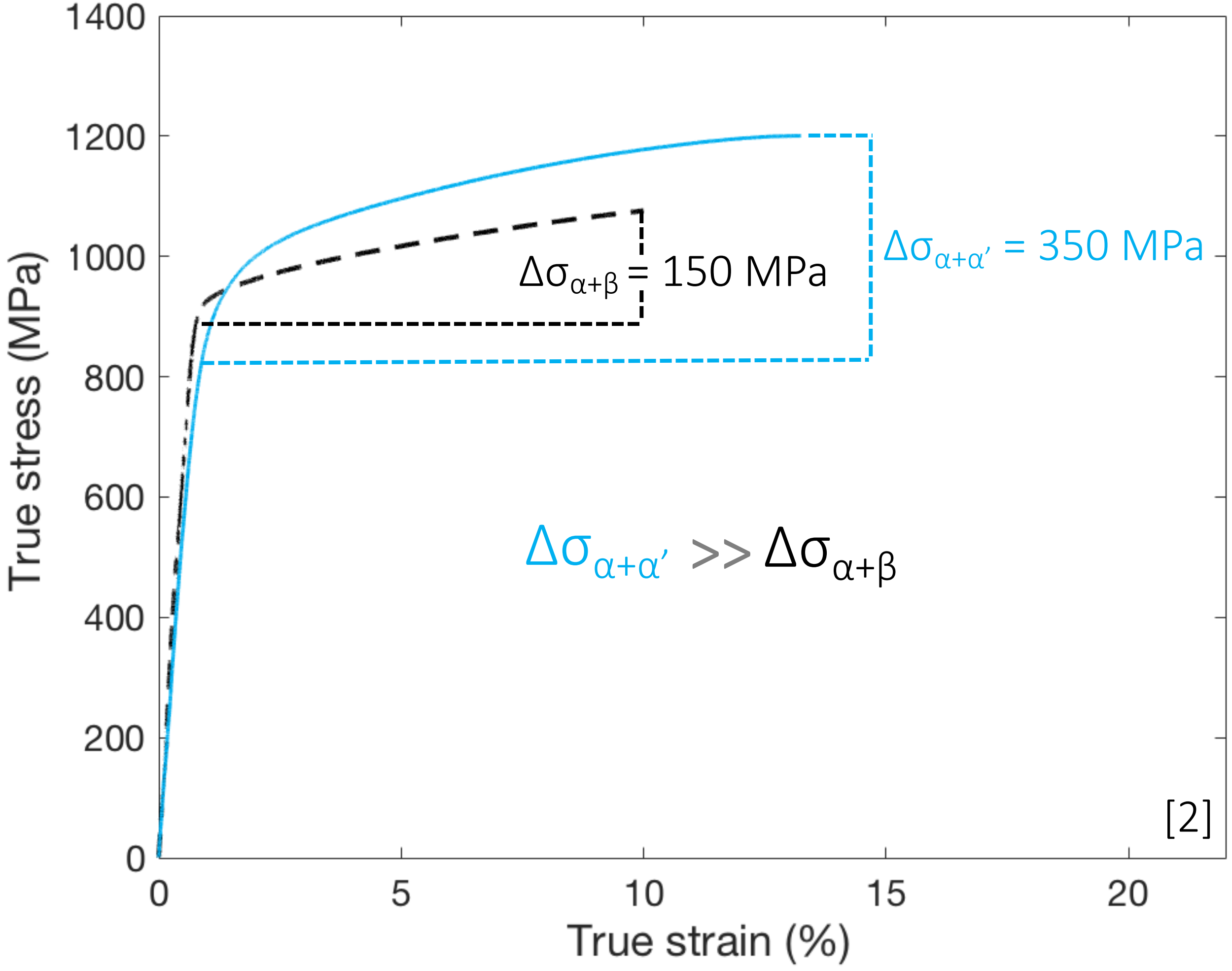




σ_y not so bad
WH ↗↗

[2] de Formanoir et al., MRL (2016)

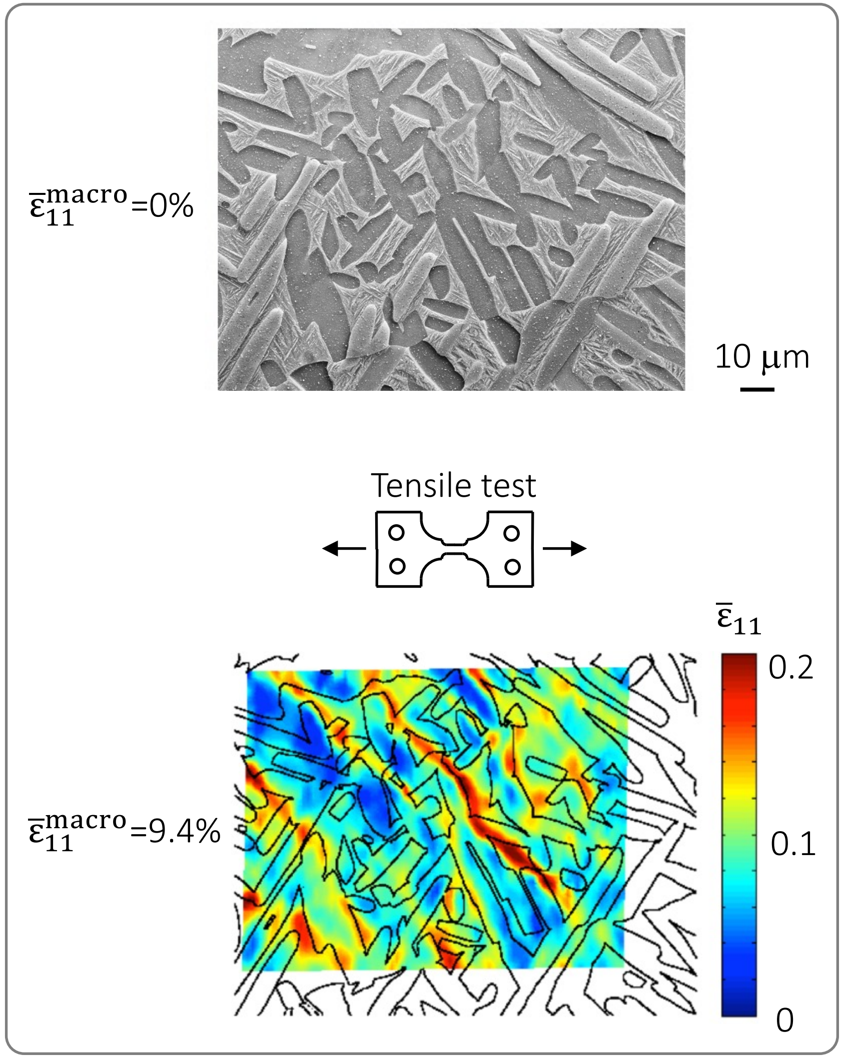
The work-hardening **is largely increased** (by 2 to 3 times) with the dual-phase α-α’ microstructures



[2] de Formanoir et al., MRL (2016)

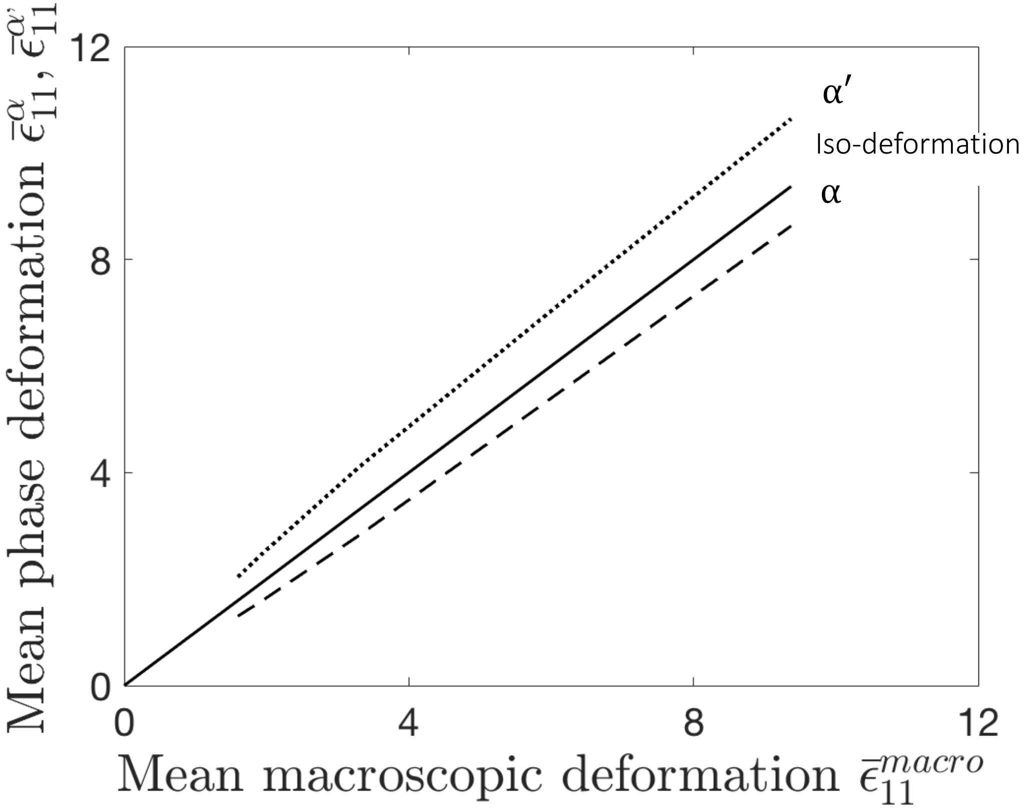
From a macroscopic point of view: The work-hardening may be attributed to a mechanical contrast between α’ and α

DIC measurements [3]



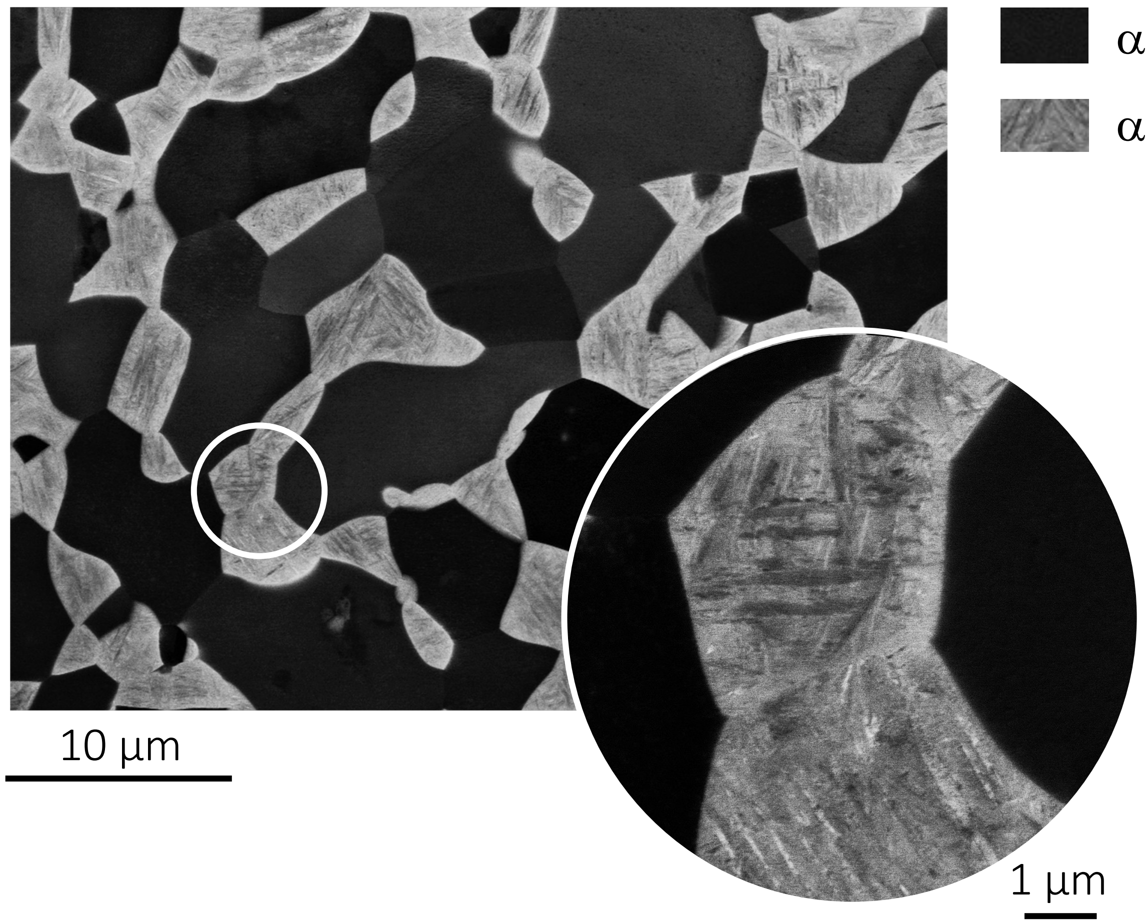
α′ deforms to a larger extent than the α phase

≈30% of strain difference between α and α’



[3] de Formanoir et al., *Acta Materialia* (2019)

But from a realistic point of view: The complexity of the α’ martensite needs to be investigated : role of α’/α’ interfaces?



The α’martensite is intrinsically a complex “divided” media

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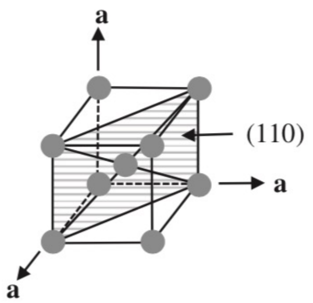
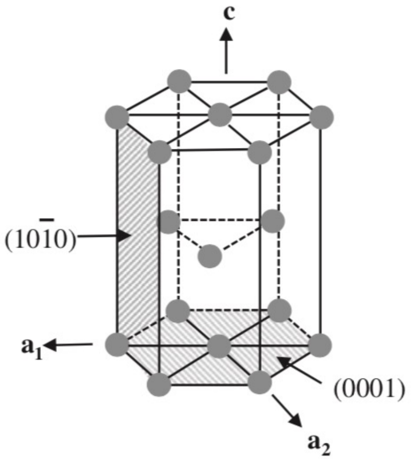
The Burgers orientation relationship (BOR) takes place between β and α’

parent β phase

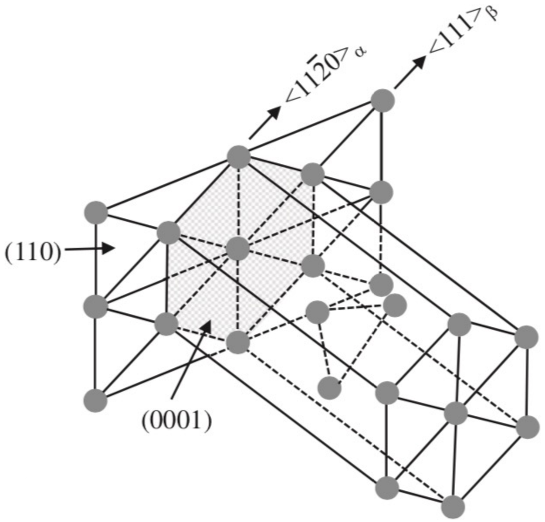


Phase transformation

daughter α’ phase



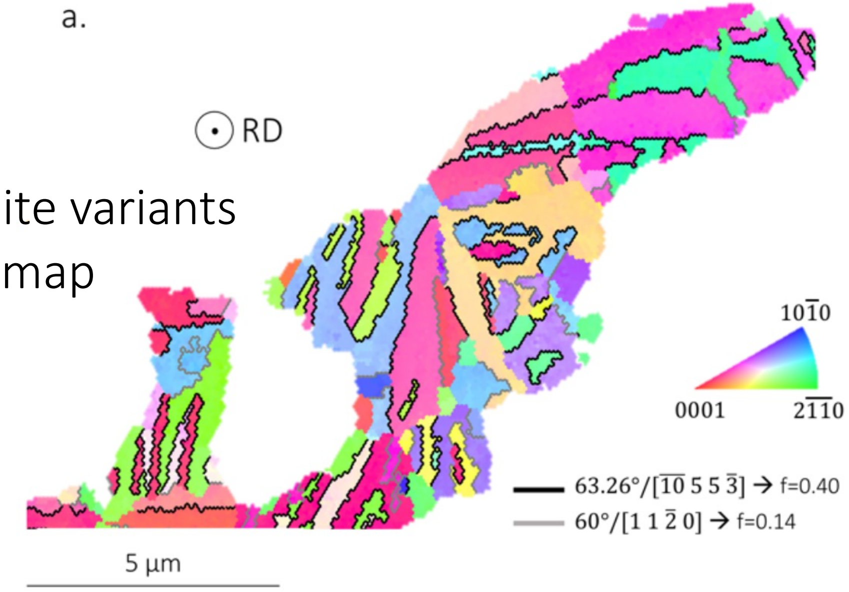
Burgers
orientation relationship



Variant n°	Burgers OR
1	$(011)_{\beta}//(0001)_{\alpha'}, [1\bar{1}1]_{\beta}/[11\bar{2}0]_{\alpha'}$
2	$(011)_{\beta}//(0001)_{\alpha'}, [11\bar{1}]_{\beta}/[11\bar{2}0]_{\alpha'}$
3	$(110)_{\beta}//(0001)_{\alpha'}, [\bar{1}11]_{\beta}/[11\bar{2}0]_{\alpha'}$
4	$(110)_{\beta}//(0001)_{\alpha'}, [1\bar{1}1]_{\beta}/[11\bar{2}0]_{\alpha'}$
5	$(1\bar{1}0)_{\beta}//(0001)_{\alpha'}, [111]_{\beta}/[11\bar{2}0]_{\alpha'}$
6	$(1\bar{1}0)_{\beta}//(0001)_{\alpha'}, [11\bar{1}]_{\beta}/[11\bar{2}0]_{\alpha'}$
7	$(101)_{\beta}//(0001)_{\alpha'}, [11\bar{1}]_{\beta}/[11\bar{2}0]_{\alpha'}$
8	$(101)_{\beta}//(0001)_{\alpha'}, [\bar{1}11]_{\beta}/[11\bar{2}0]_{\alpha'}$
9	$(10\bar{1})_{\beta}//(0001)_{\alpha'}, [1\bar{1}1]_{\beta}/[11\bar{2}0]_{\alpha'}$
10	$(10\bar{1})_{\beta}//(0001)_{\alpha'}, [111]_{\beta}/[11\bar{2}0]_{\alpha'}$
11	$(01\bar{1})_{\beta}//(0001)_{\alpha'}, [111]_{\beta}/[11\bar{2}0]_{\alpha'}$
12	$(01\bar{1})_{\beta}//(0001)_{\alpha'}, [\bar{1}11]_{\beta}/[11\bar{2}0]_{\alpha'}$

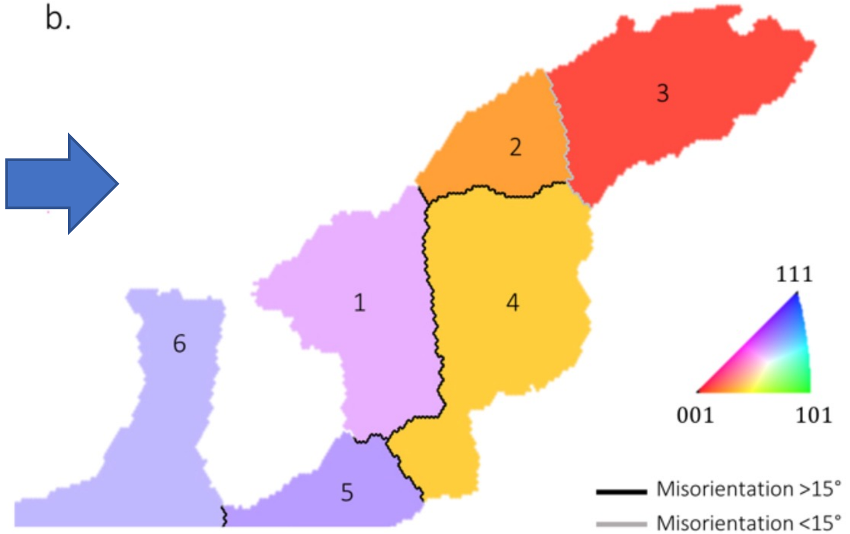
Far to be disordered: The non-deformed α’ is composed of parallel plates and two types of misorientations

a.



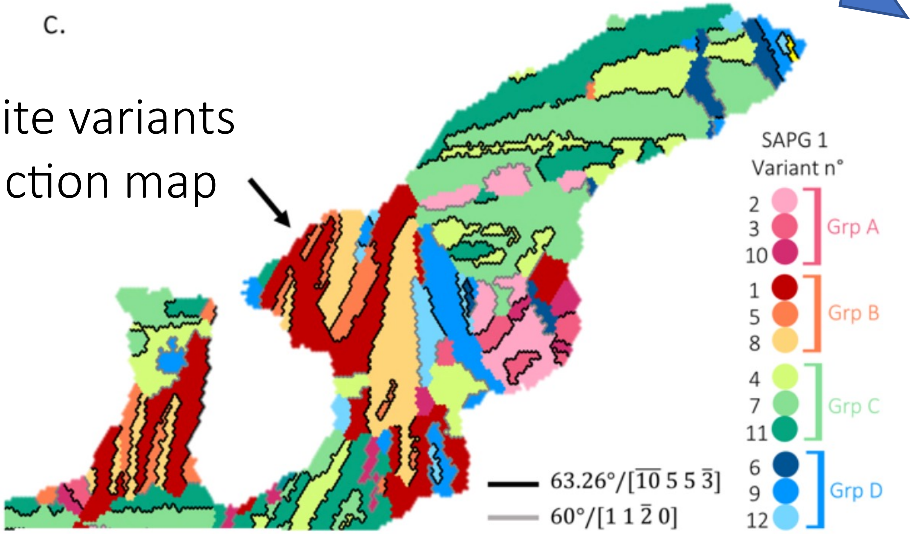
α’ martensite variants IPF map

b.



Parent β grain IPF reconstruction map

c.



α’ martensite variants reconstruction map

Each parent β grains mostly transforms into **4 groups of 3 variants** separated by a unique misorientation at 63°

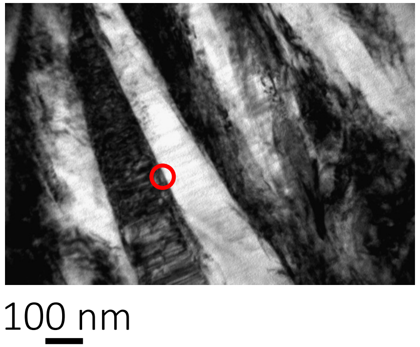
1 group = Self-Accommodated Plate Group (SAPG)

Compensation of their individual shape strain to **minimize the total transformation strain**

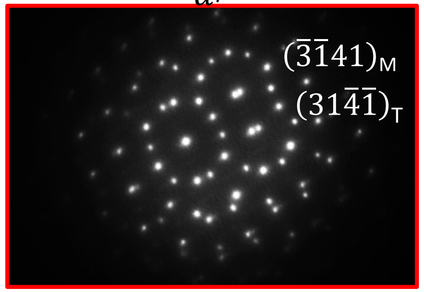
=

Self-accommodated martensite

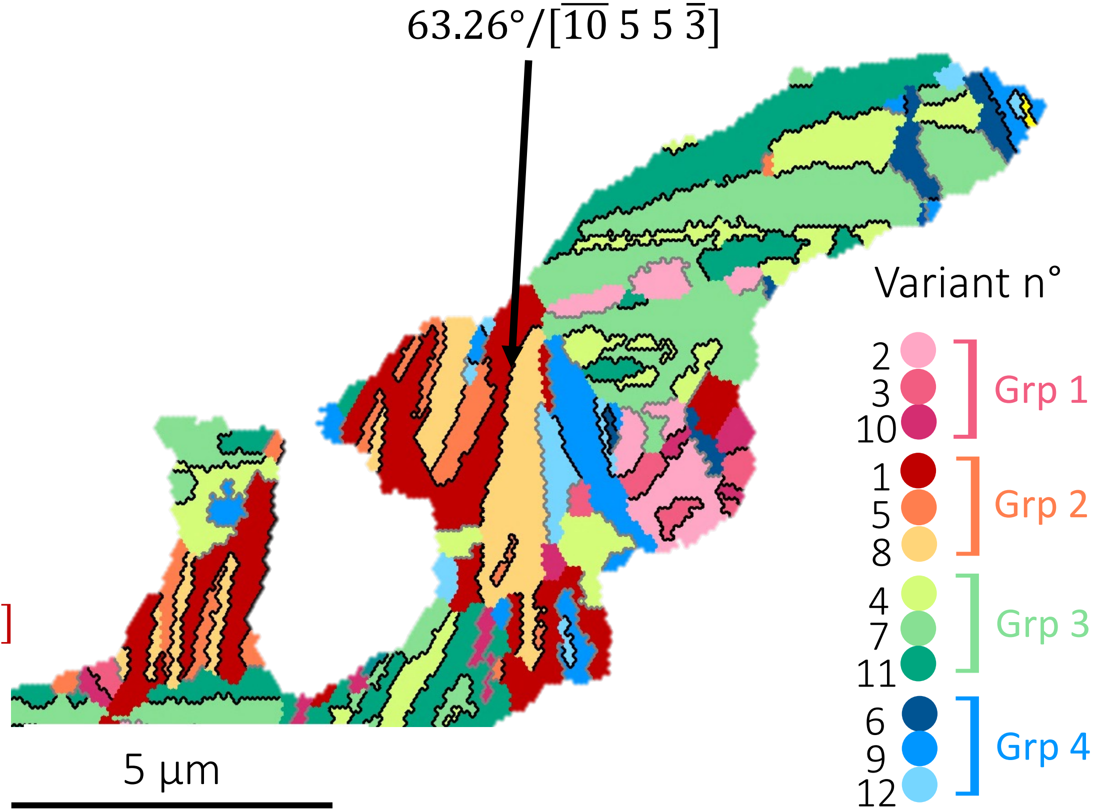
The martensite tends to organize itself into 4 SAPG of 3 variants that are :



$[4\,\bar{5}\,1\,\bar{3}]_{\alpha'}$ Type II twin (rational common axis)



- Separated by a unique misorientation at 63.26°/$[\overline{\mathbf{10}}\,\mathbf{5}\,\mathbf{5}\,\bar{\mathbf{3}}]$
- In twinning relationship on a $[4\,\bar{5}\,1\,\bar{3}]_{\alpha'}$ Type II twin. The intervariant plane is approximated by $(\mathbf{1}\mathbf{3}\bar{\mathbf{4}}\mathbf{1})_{\alpha'}$



▬ $63.26°/[\overline{\mathbf{10}}\,\mathbf{5}\,\mathbf{5}\,\bar{\mathbf{3}}]$

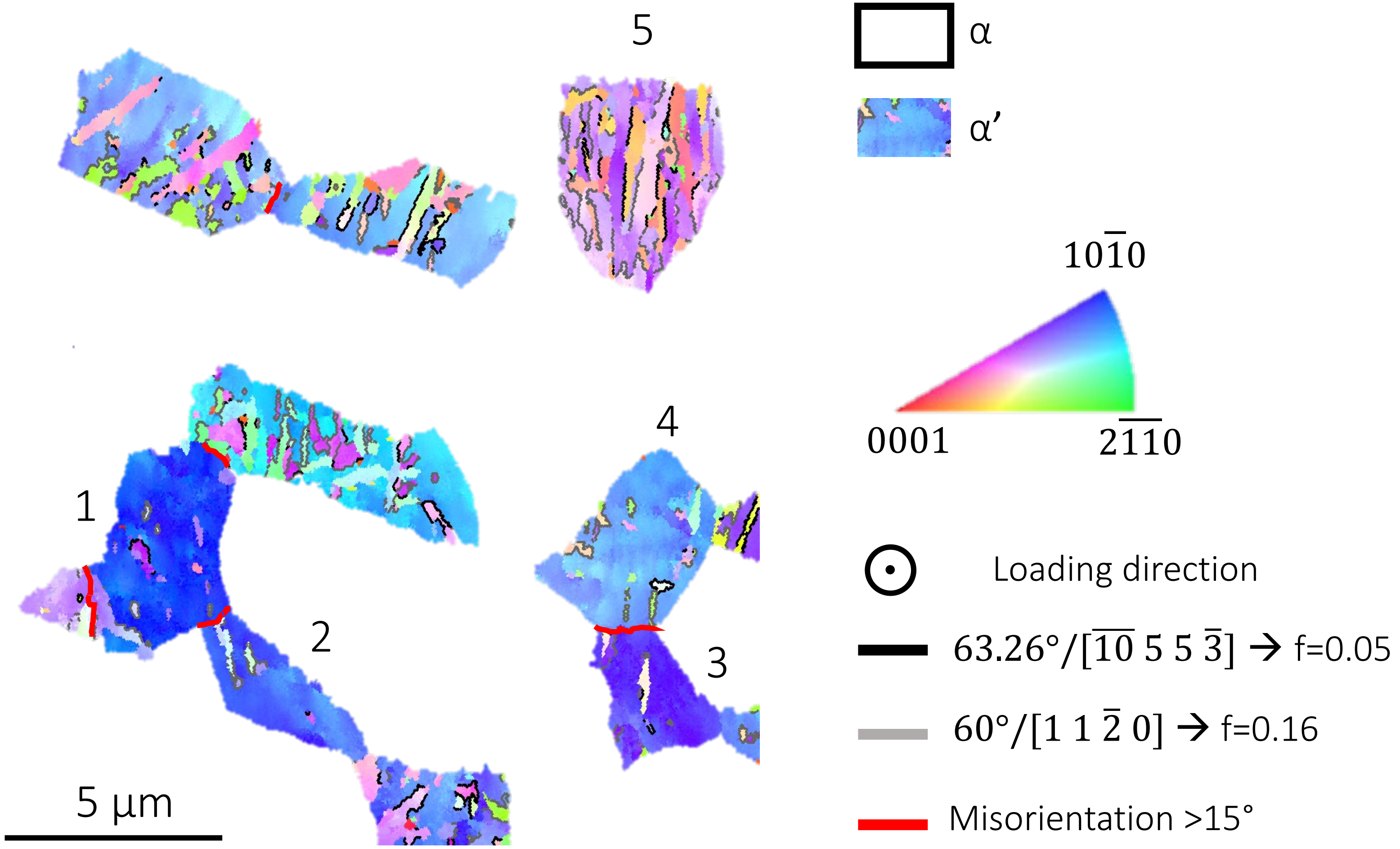
▬ 60°/$[1\,1\,\bar{2}\,0]$

Compensation of their individual
shape strain to **minimize the total**
transformation strain
=
Self-accommodated martensite

After deformation, the boundary length of $63.26°/[\overline{10}\ 5\ 5\ \bar{3}]$ has been drastically decreased in some grains : a totally new landscape in the deformed microstructure is formed

11% of deformation

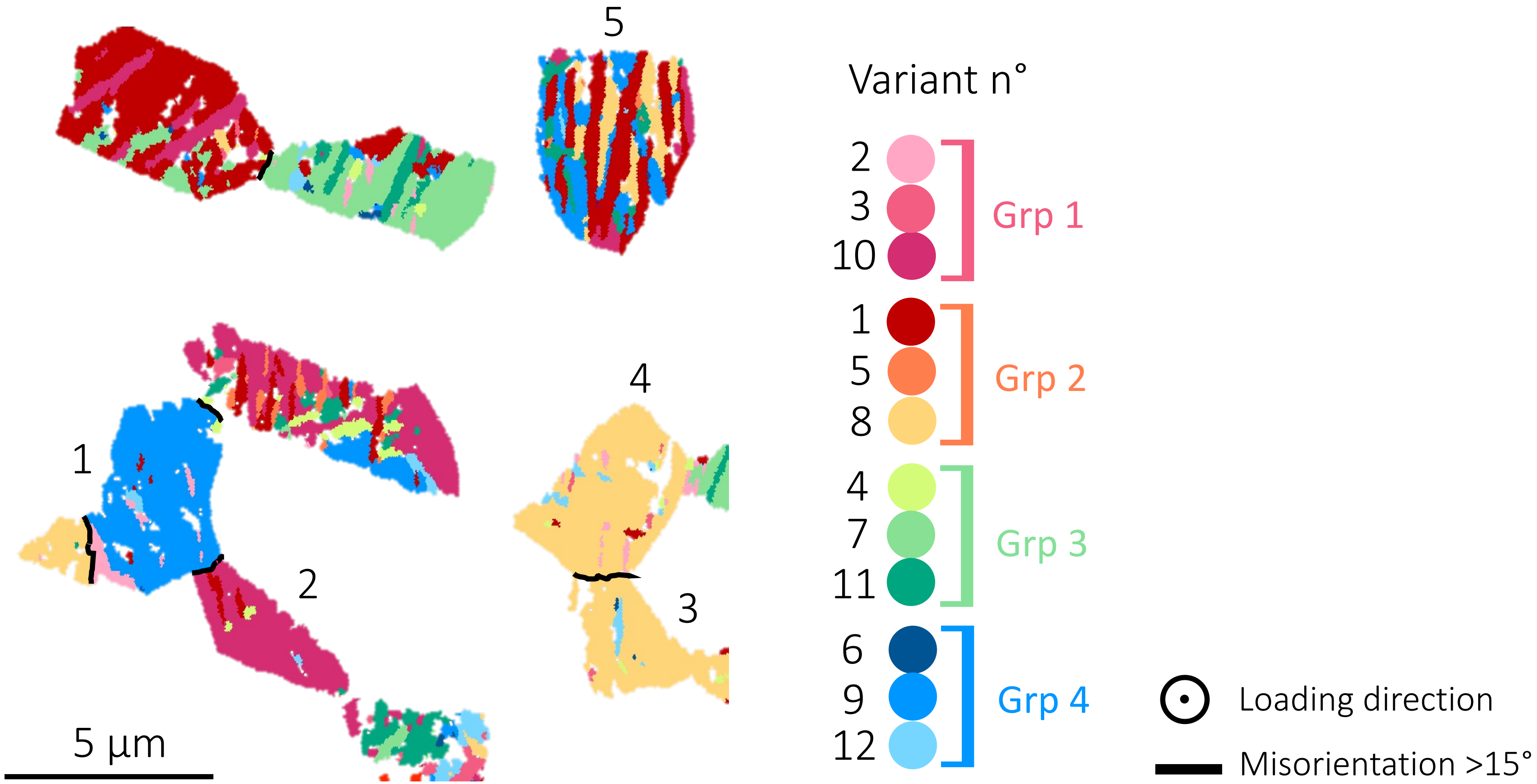
Inverse Pole Figure (IPF) map



Reorientation Induced Plasticity (RIP) occurs in the α’ at the SAPG scale but **several scenarios are coexisting** !

11% of deformation

α’ martensite variant reconstruction map



The Interaction Work (IW) is computed to confirm the occurrence of RIP

Macroscopic stress tensor

$$\mathrm{IW}_{\mathrm{Vi}} = Trace(\sigma \; * \; S_{Vi}^{T})$$

Interaction Work of a variant i

Shape strain of a variant i

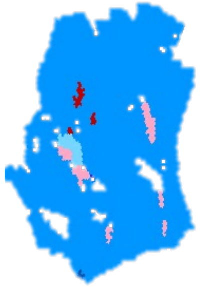
IW quantify the work of the shape strain of one variant in the tensile direction

→ Confirmation of RIP? Prediction? Why groups induce RIP and others do not?

<u>The striking point</u> : A given SAPG systematically induces complete reorientation if one variant displays IW>0 and 2 variants IW<0

Complete reorientation

1

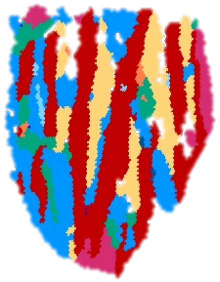


IW Ranking	1	2	3
Variant n°	9	12	6
IW	0.7	-0.2	-0.3

Grp 4

No apparent reorientation

5



IW Ranking	1	2	3	1	2	3
Variant n°	1	8	5	9	12	6
IW	0.4	0.2	-0.7	0.4	0.2	-0.7

Grp 2

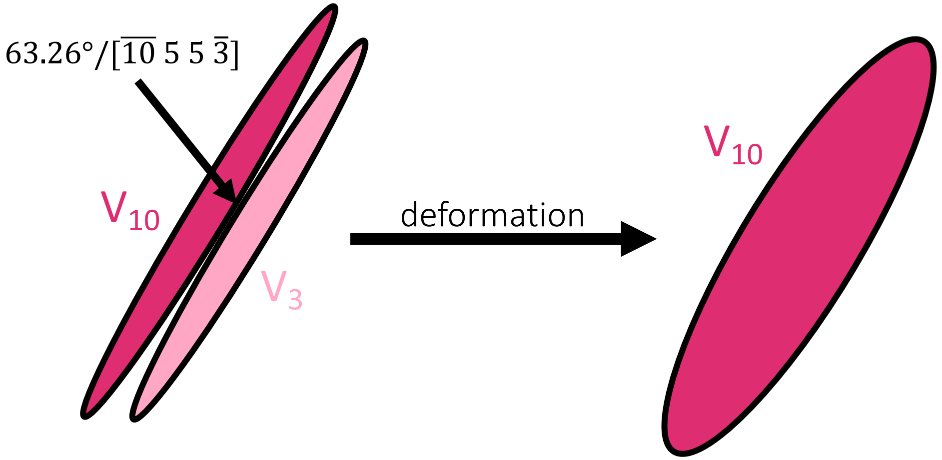
Grp 4

Variant n°

2 ●	Grp 1	
3 ●		
10 ●		
1 ●	Grp 2	
5 ●		
8 ●		
4 ●	Grp 3	
7 ●		
11 ●		
6 ●	Grp 4	
9 ●		
12 ●		

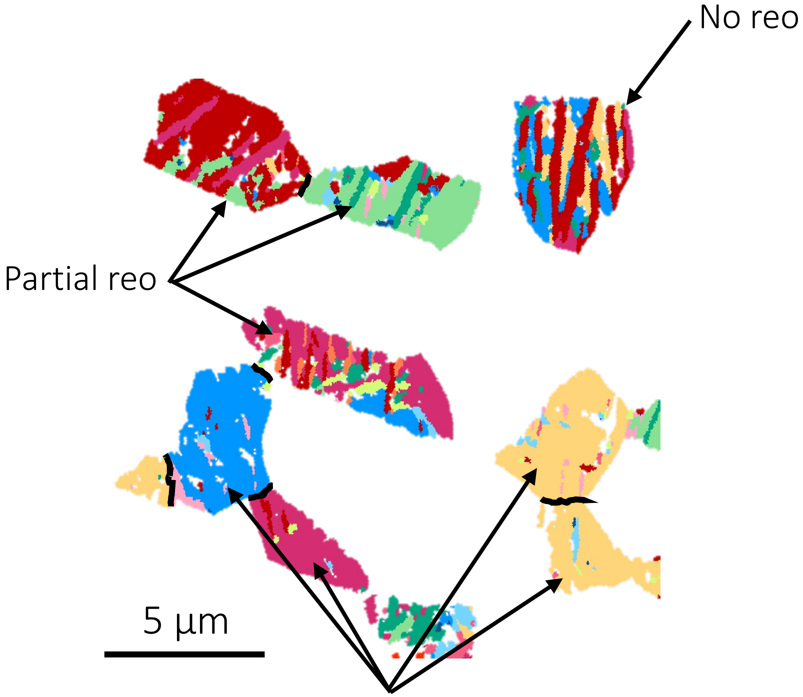
The generalization of the criteria for RIP occurrence to explain the different RIP scenarios

RIP occurrence is decided at the scale of 2 variants



V_{10} can grow at the expense of V_3
if $IW_{V10} > 0$ & $IW_{V3} < 0$

After deformation



Complete reorientation at the scale
of a parent β grain

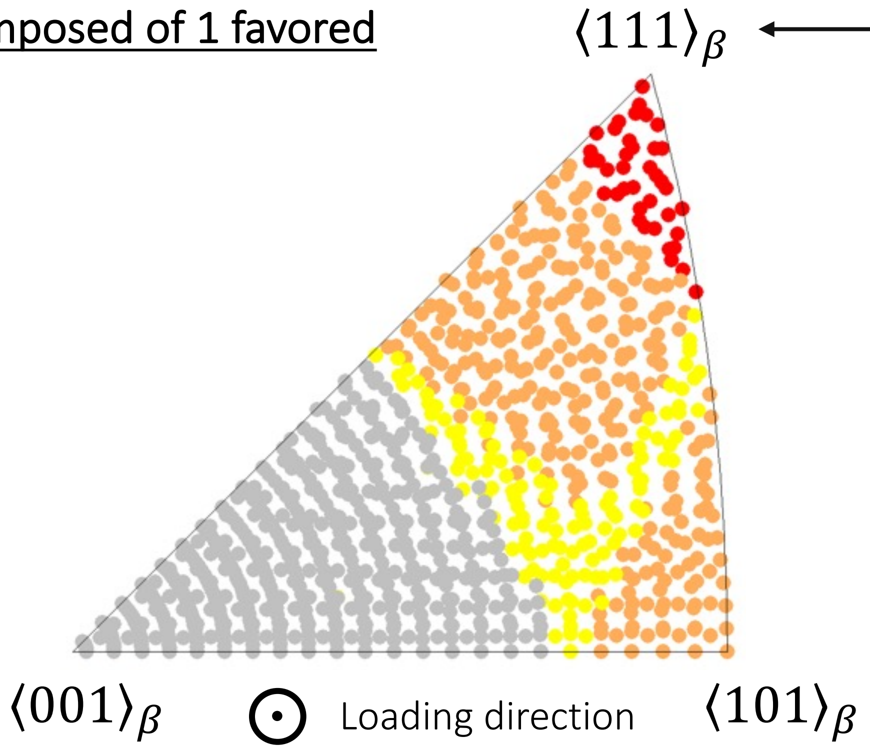
3 plasticity scenarios:
complete, partial or no reorientation

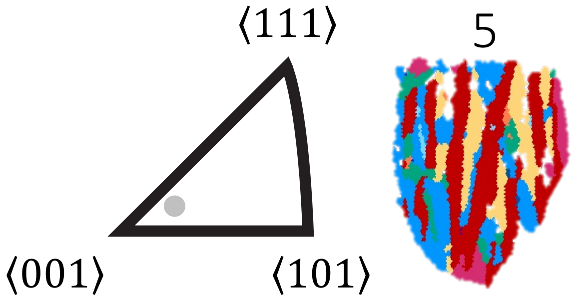
→ At the end, the plastic range consist in the <u>**co-deformation a heterogeneous α' media**</u>

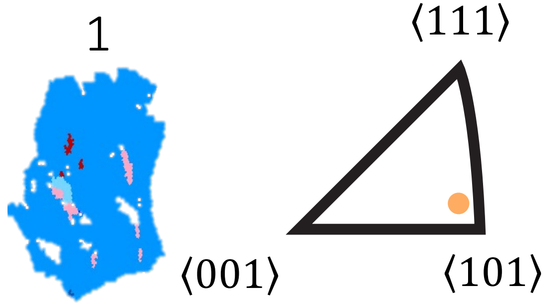
The **initial texture of parent β grain** plays statistically a major role in the occurrence of reorientation

- ● 0/4 self-accommodating groups **composed of 1 favored and 2 unfavored variants**
- 🟡 1/4
- 🟠 2/4
- 🔴 3/4

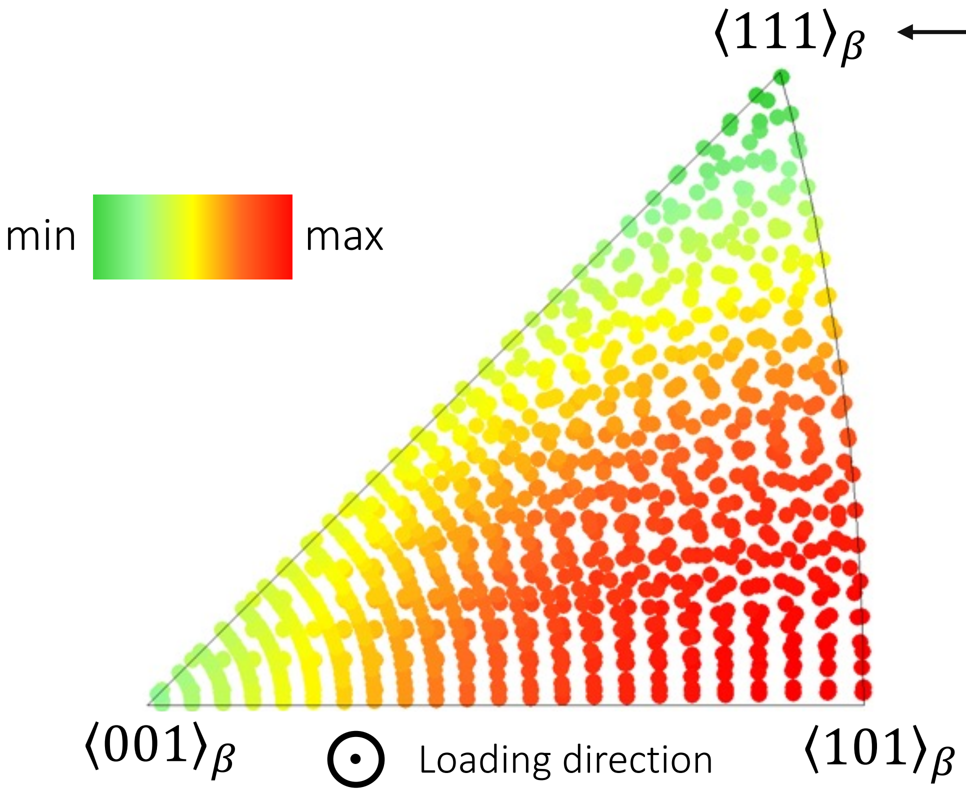
Highest probability to induce reorientation







The <u>**values of IW**</u> should also be taken into account



Highest probability but low IW

Best configuration for RIP occurrence

High probability and high IW

→ Predisposition for RIP occurrence can be “rather well” <u>predicted by texture analysis</u>

Is it sufficient to get martensite to get RIP effect ???

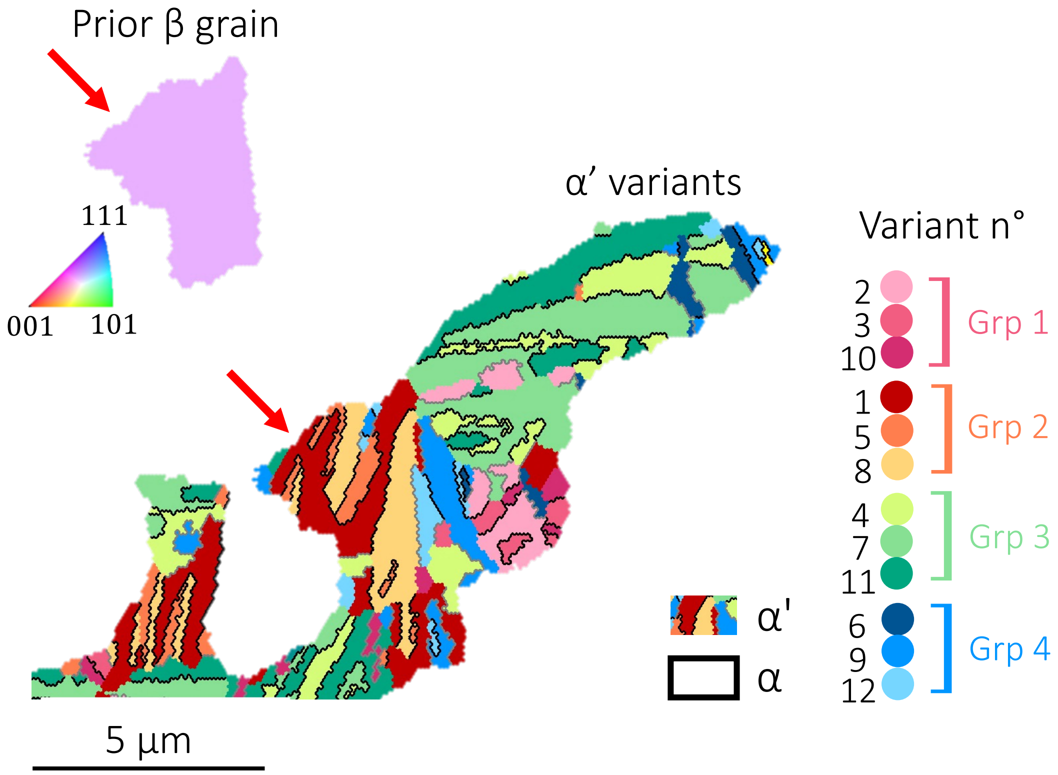
↓

Microstructure?

Chemistry?

Which microstructural features to trigger the RIP effect?

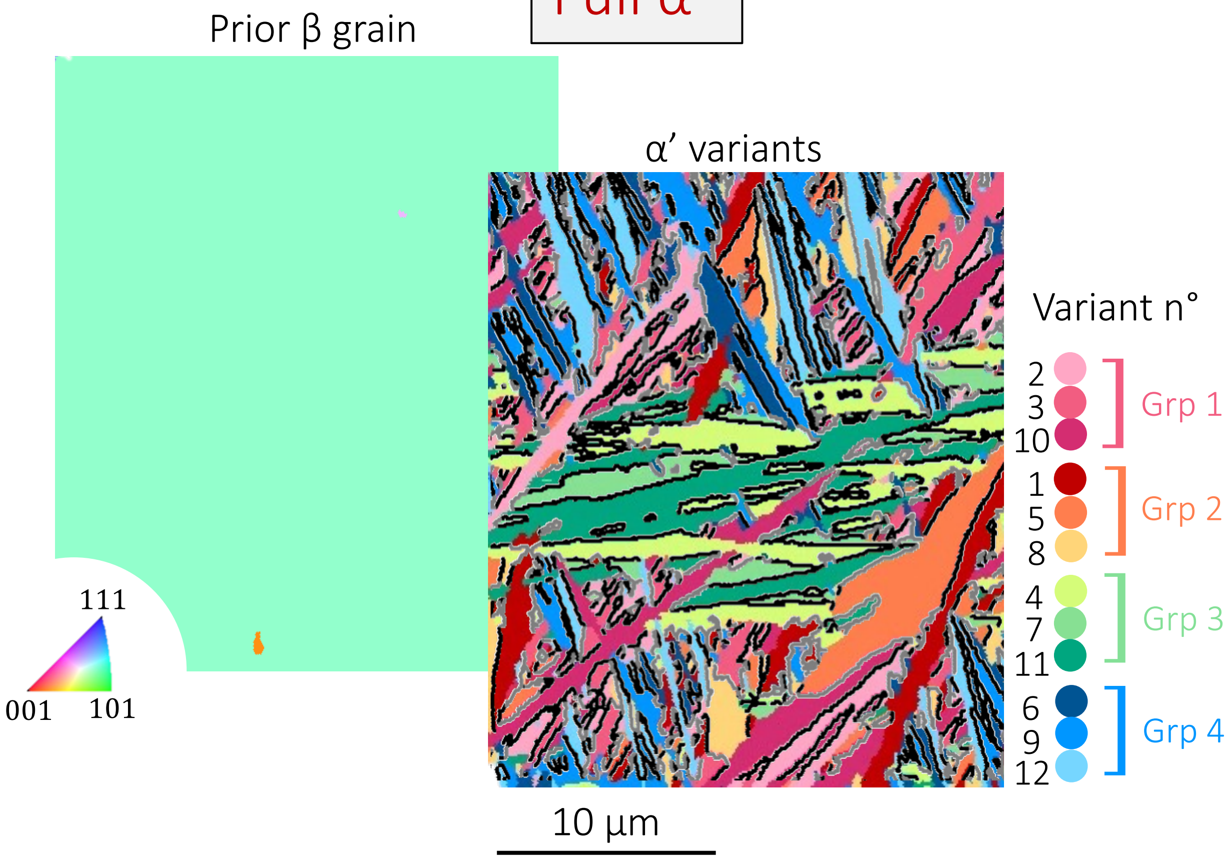
Dual-phase DP880



Almost only one self-accommodating group per parent β sub-grain

RIP effect in Ti-6Al-4V

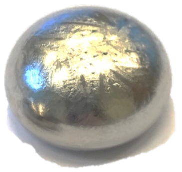
Full α’



Several **entangled** self-accommodating groups per parent β grain (“steric” effect)

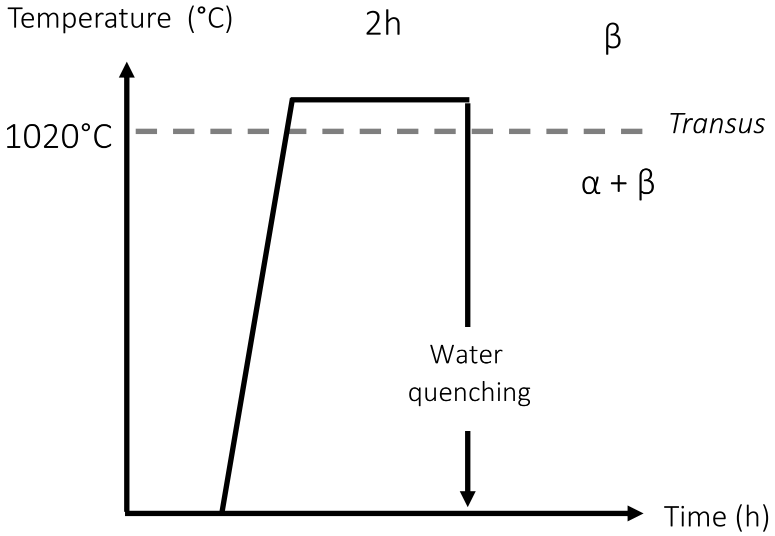
NO RIP effect in Ti-6Al-4V !!

But !! The chemistry is the necessary condition to reach RIP effect

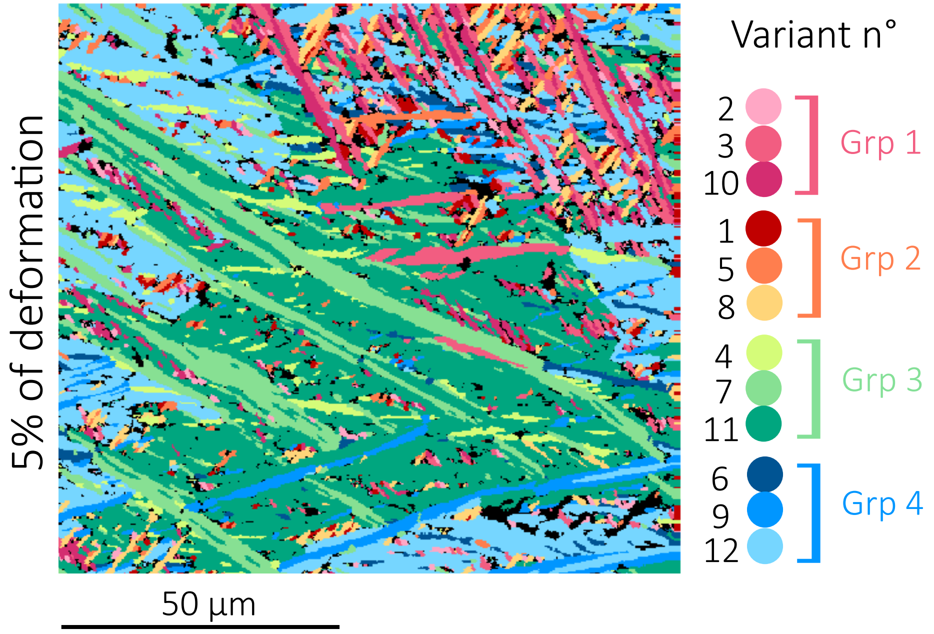


Ti-4.6Al-6.8V

+



α' martensite variant reconstruction map



RIP effect in full α' entangled microstructure!

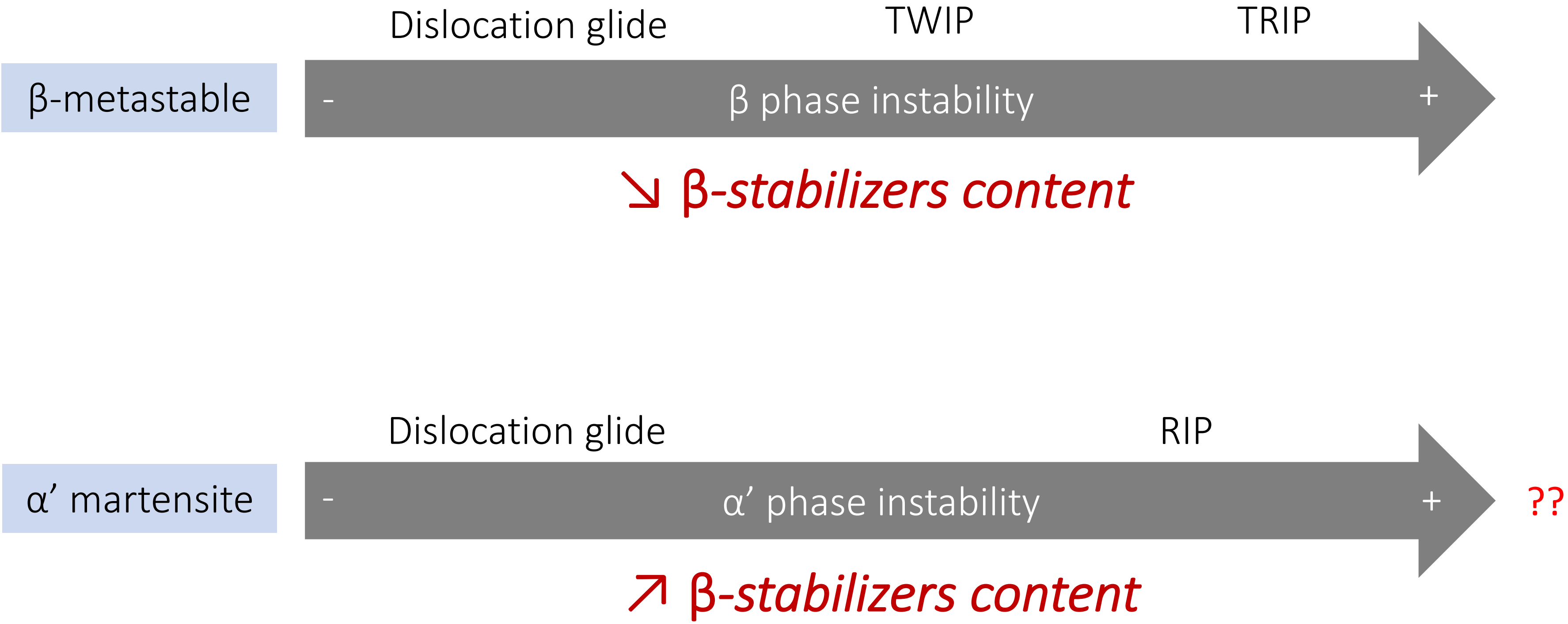
→ Chemistry : (interfaces mobility)

Necessary condition for RIP occurrence

→ Entanglement of the laths : (steric effects)

Limiting condition for RIP occurrence

As for the β-metastable alloys, the chemical instability dictates the deformation mechanisms… and RIP occurrence



Dislocation glide TWIP TRIP

β-metastable

\- β phase instability +

↘ *β-stabilizers content*

Dislocation glide RIP

α’ martensite

\- α’ phase instability +

??

↗ *β-stabilizers content*

The key-point relates to the $(13\bar{4}1)_{\alpha'}$ **interface mobility** which is **chemistry-dependent**

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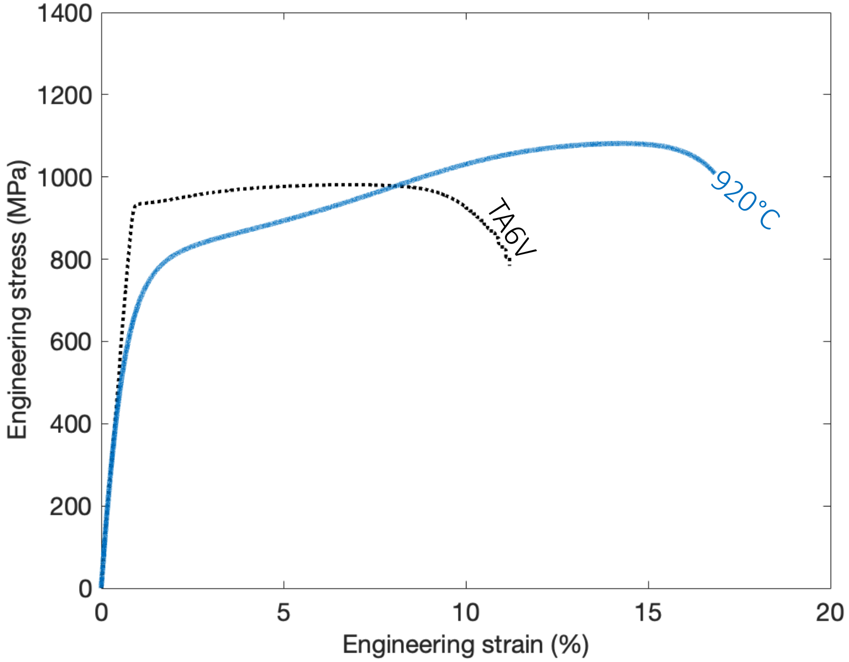
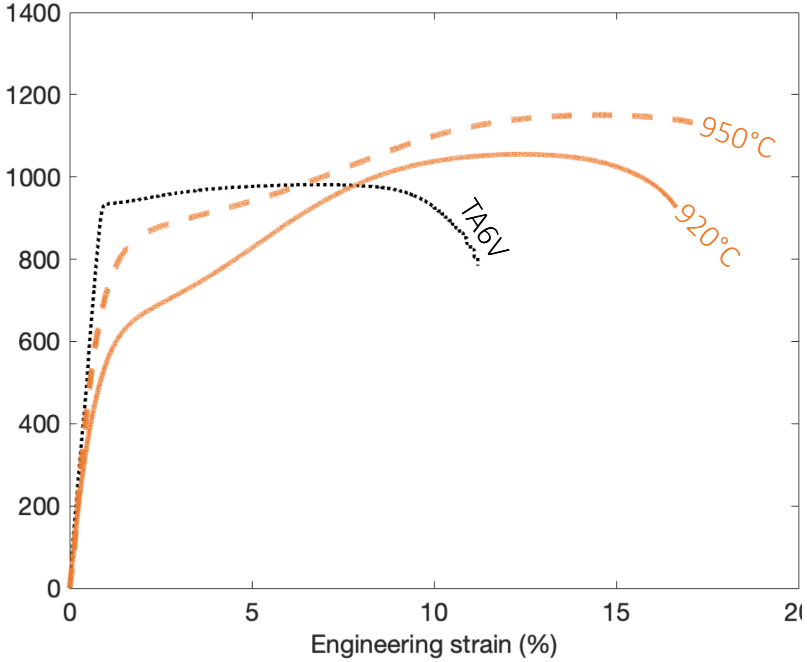
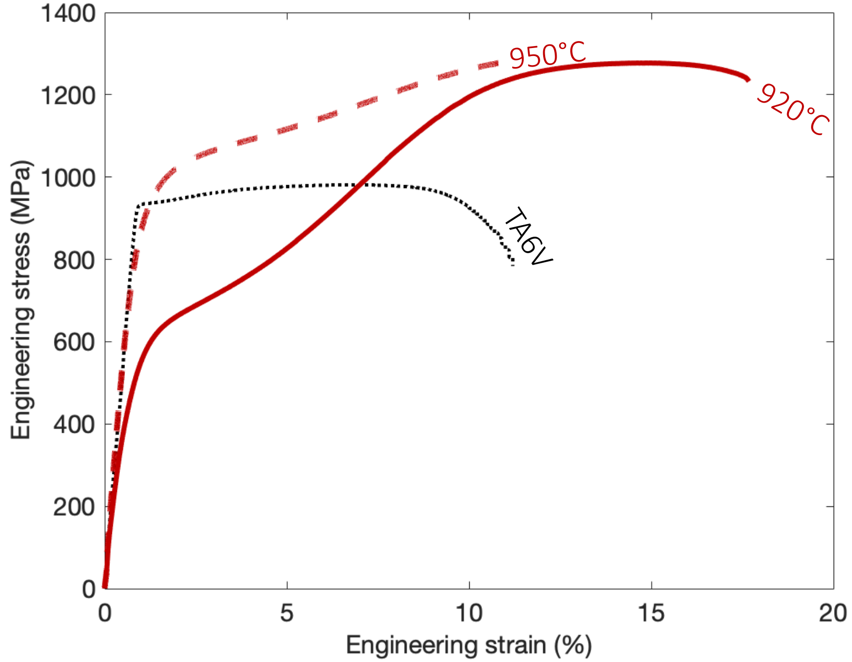
Winning strategy : the σ_y/WH compromise is extremely promising in some conditions


Ti-6Al-8V

	920
σ_y (MPa)	701
σ_m (MPa)	1241
ε_u (%)	14
WH (MPa)	540
Mo$_{eq}$	0.5

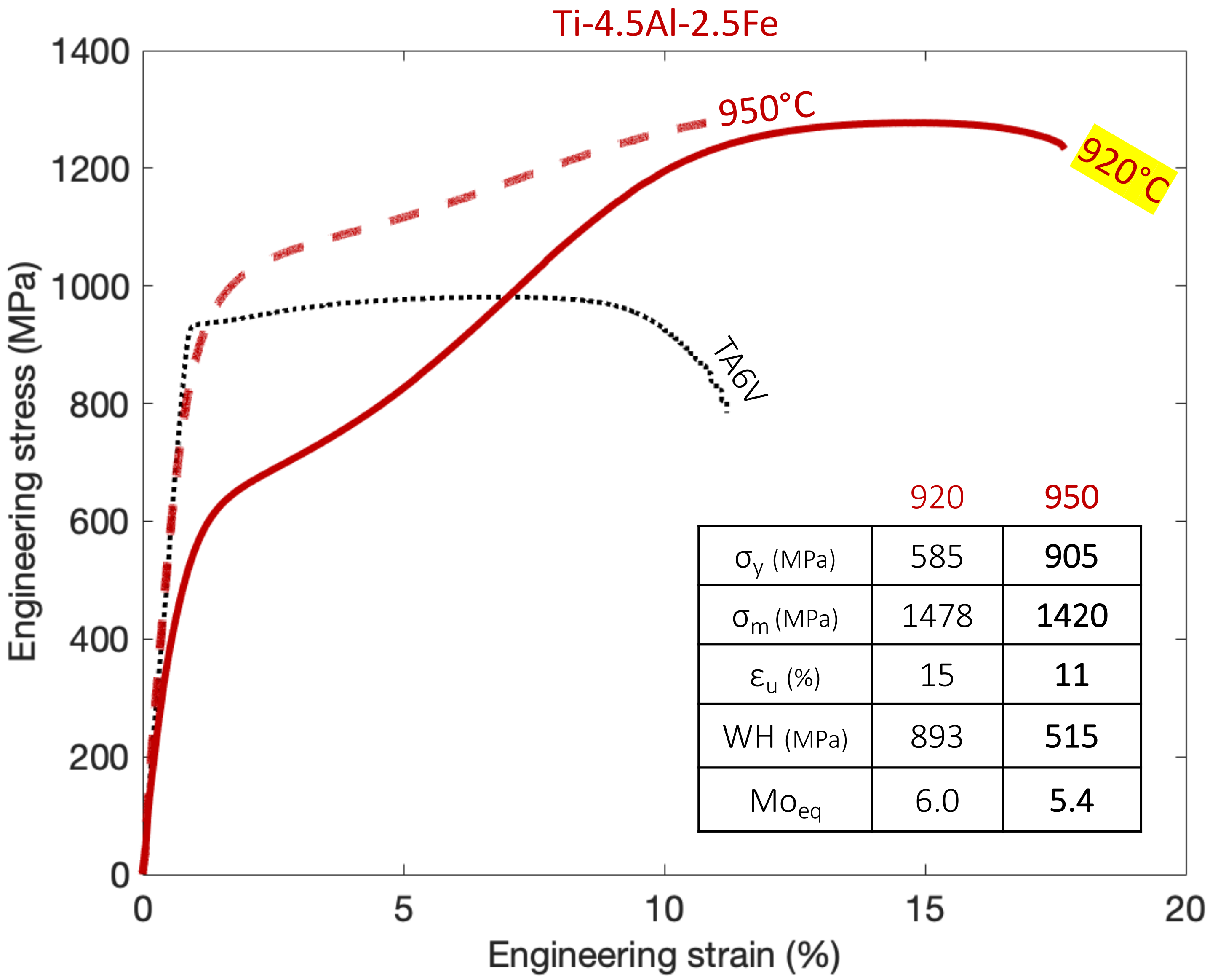

Ti-551

	920	950
σ_y (MPa)	588	750
σ_m (MPa)	1193	1329
ε_u (%)	13	15
WH (MPa)	605	579
Mo$_{eq}$	4.0	1.7


TAFS

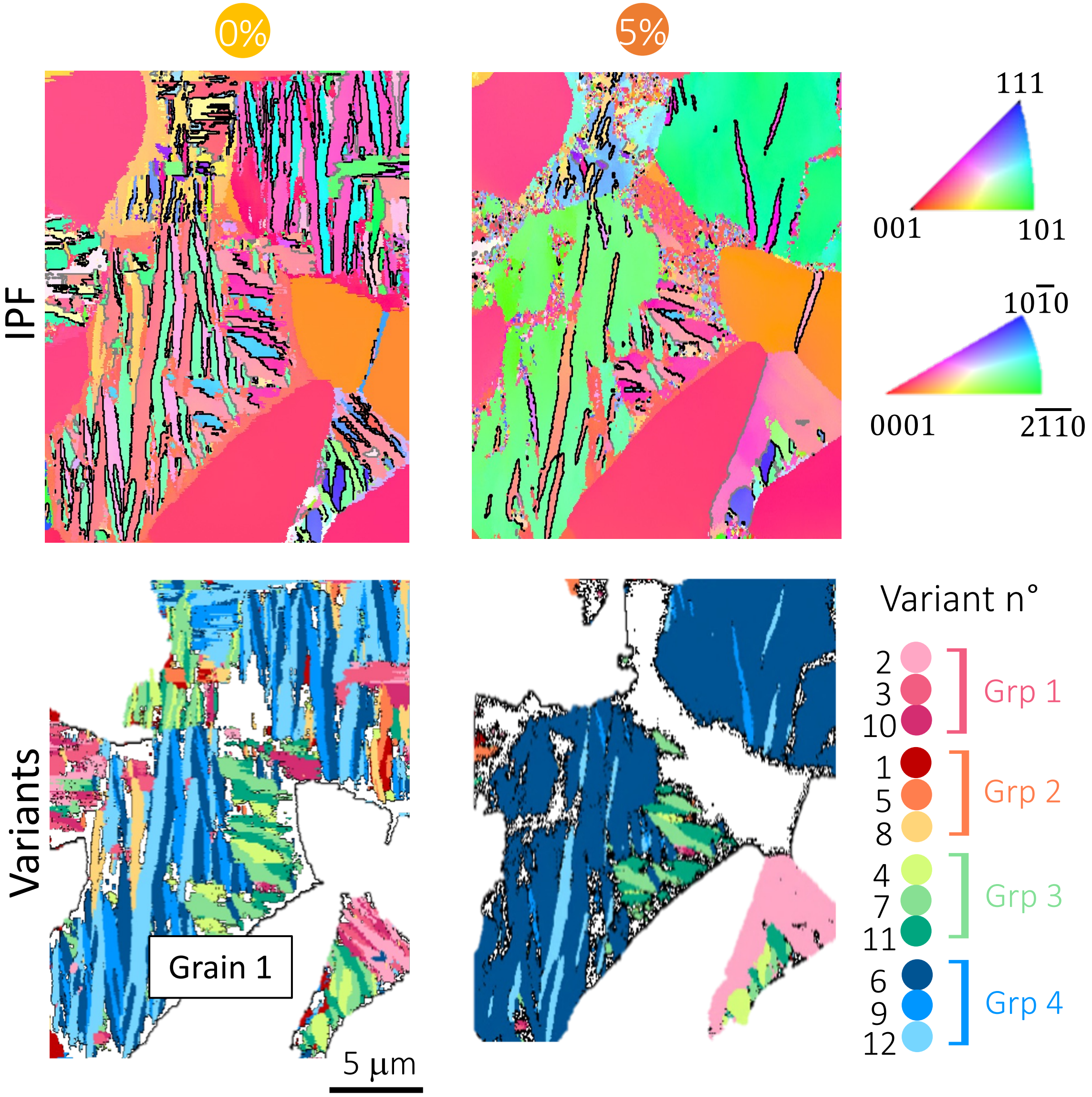
	920	**950**
σ_y (MPa)	585	**905**
σ_m (MPa)	1478	**1420**
ε_u (%)	15	**11**
WH (MPa)	893	**515**
Mo$_{eq}$	6.0	**5.4**

Is RIP triggered into TAFS 920°C?



	920	950
σ_y (MPa)	585	**905**
σ_m (MPa)	1478	**1420**
ε_u (%)	15	**11**
WH (MPa)	893	**515**
Mo_{eq}	6.0	**5.4**

TAFS 920°C follows the same IW rules to rationnalize RIP occurence

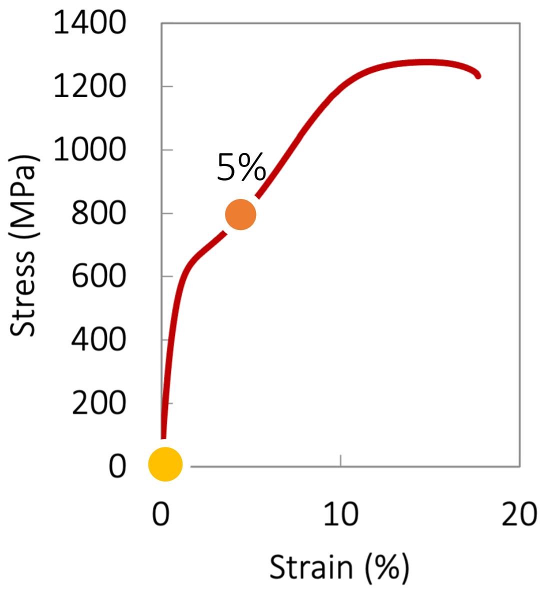


Grain 1

Variant n°	6	9	12	11	7	4
IW	0.7	-0.2	-0.1	-0.1	-0.3	-0.1

Grp 4 = RIP (variants 6, 9, 12)

Grp 3 = No RIP (variants 11, 7, 4)



Outline/Goals

- Introduction
- Increasing the work-hardening of Ti-6Al-4V by Dual-Phase microstructures
- Understanding the Reorientation Induced Plasticity Effect and the role of martensite
- Can this be transferred to other Ti alloys?
- Design rules
- Conclusions

Design rules to develop titanium alloys exhibiting WH by RIP

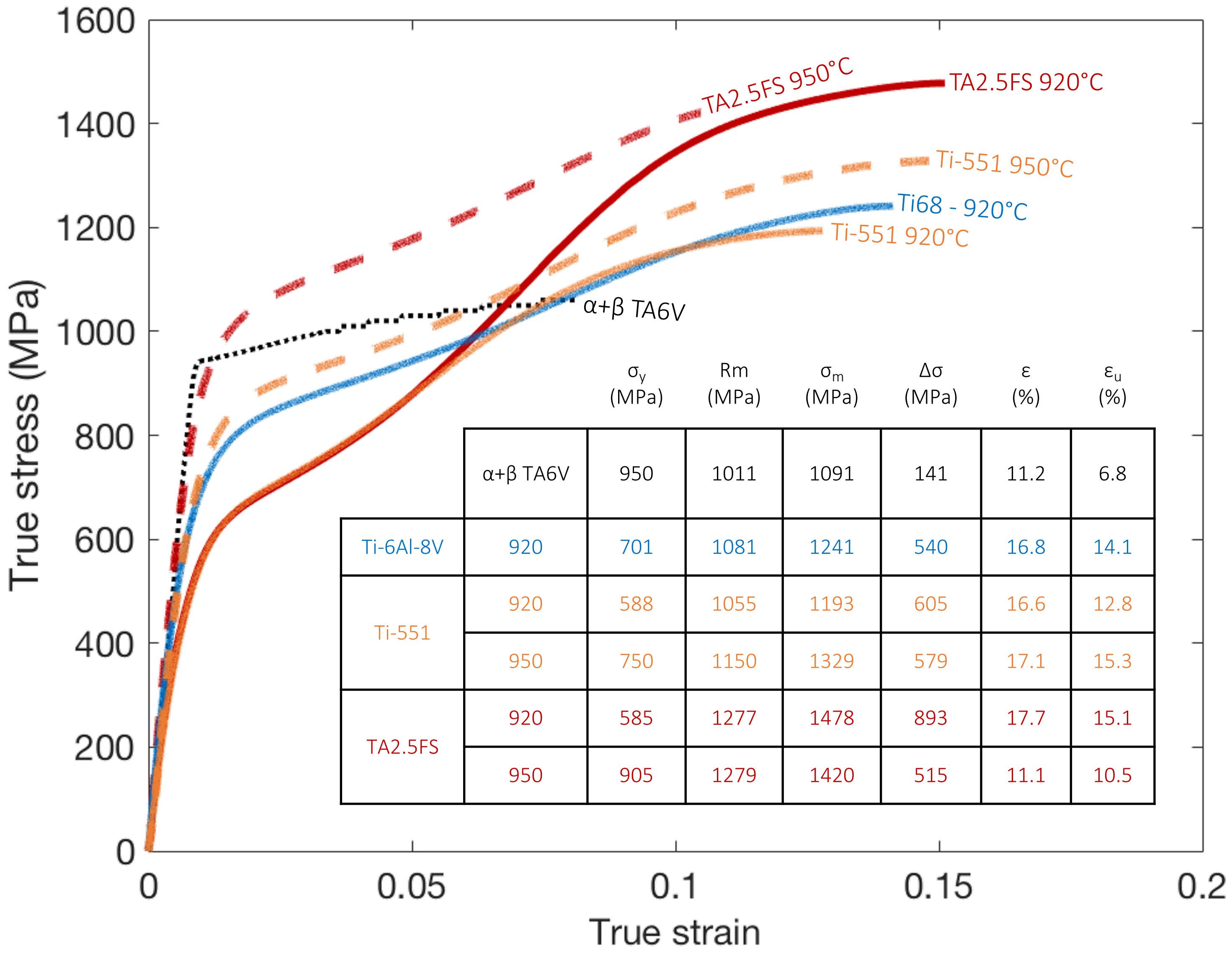
Design rules

α + β alloys to generate α’ (+ α + $\beta_{retained}$) microstructures

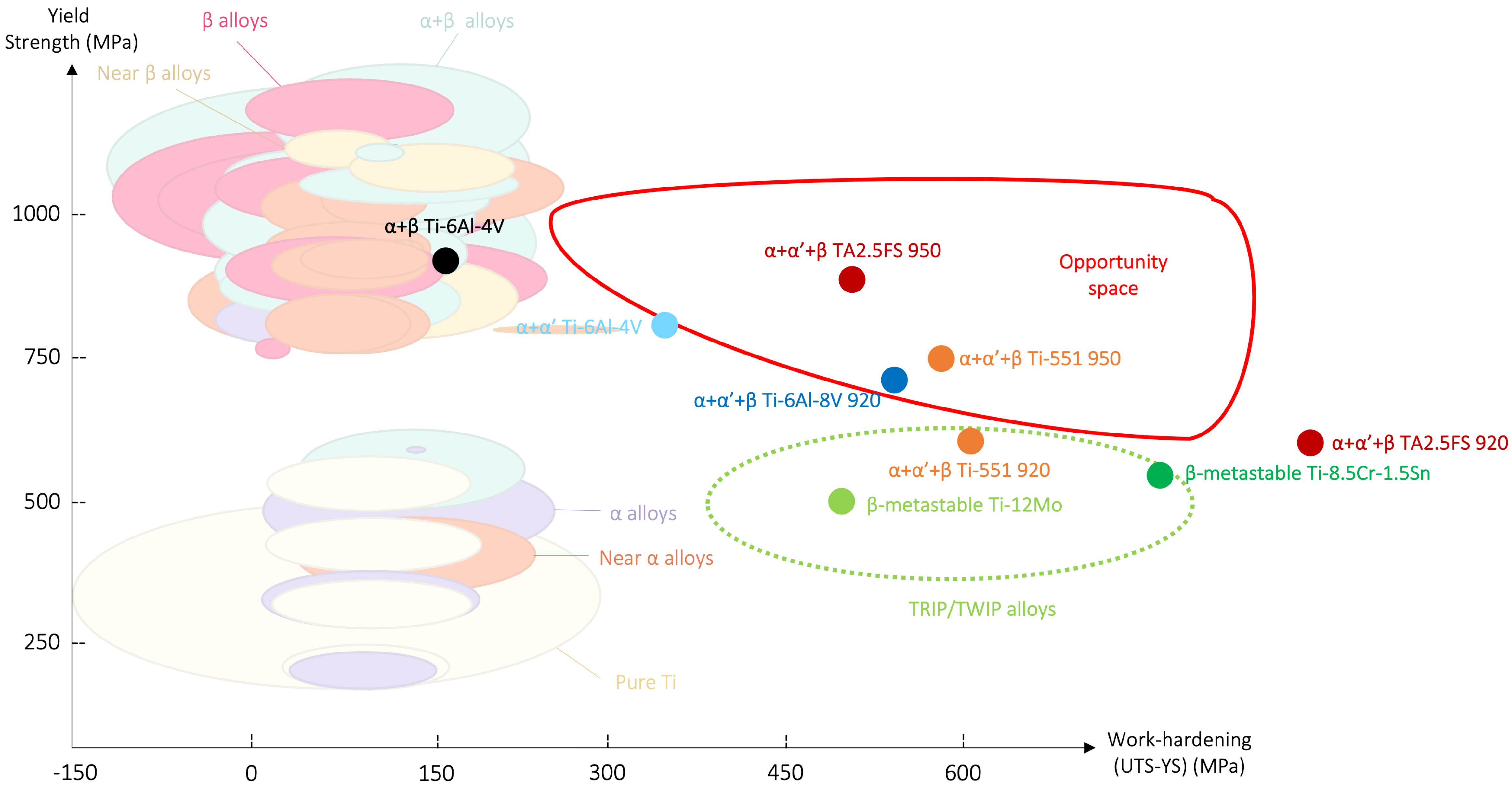
$Mo_{eq} \geq 0$ into α’

Limit the size of the martensite plates

DP treatment just below β-transus for maximizing σ_y without compromising ε



		σ_y (MPa)	Rm (MPa)	σ_m (MPa)	Δσ (MPa)	ε (%)	ε_u (%)
	α+β TA6V	950	1011	1091	141	11.2	6.8
Ti-6Al-8V	920	701	1081	1241	540	16.8	14.1
Ti-551	920	588	1055	1193	605	16.6	12.8
	950	750	1150	1329	579	17.1	15.3
TA2.5FS	920	585	1277	1478	893	17.7	15.1
	950	905	1279	1420	515	11.1	10.5


Yield Strength (MPa)
β alloys
α+β alloys
Near β alloys
1000
750
500
250
α+β Ti-6Al-4V
α+α' Ti-6Al-4V
α+α'+β TA2.5FS 950
Opportunity space
α+α'+β Ti-551 950
α+α'+β Ti-6Al-8V 920
α+α'+β TA2.5FS 920
α+α'+β Ti-551 920
β-metastable Ti-8.5Cr-1.5Sn
β-metastable Ti-12Mo
α alloys
Near α alloys
TRIP/TWIP alloys
Pure Ti
-150
0
150
300
450
600
Work-hardening (UTS-YS) (MPa)

Outline/Goals/Conclusions

- Increasing the work-hardening of Ti64 by Dual-Phase treatments

DP treatments are quite effective to increase the work hardening

- Understanding the Reorientation Induced Plasticity Effect and the role of martensite

Martensite cannot be considered as a monolithic block. This phase is self-organized and exhibits RIP that obeys specific rules.

- Can this be transferred to other Ti alloys? Generalisation and optimisation of the concepts developed on Ti-6Al-4V

Yes. High Mo_{eq} seems to be an important parameter to trigger RIP → key microstructural feature to combine WH + σ_y
The investigated alloys exhibits RIP, but also TRIP, TWIP and Twinning-assisted RIP

- Design rules

Sub-transus DP treatments on α+β alloys with $Mo_{eq} \geqslant 0$ into α'

To limit strain localisation effects into the martensite by reducing its size

To easily generate α+α' microstructures

To trigger WH by RIP effect into α'

Perspectives

- Micro-mechanic ✓ but meso-scale behaviour needs to be investigated: WH by RIP has been indirectly highlighted but not formally demonstrated yet.

- In-situ investigations to study more clearly the transitional pathway of RIP

- Complete the design strategy:

  Mo_{eq} criterion limit? Electronic stability criterion?

  → Strategy to simplify the investigation of the DPs: UFG strategy and Calphad methods

- Mechanical testing to highlight the beneficial impact of work-hardening by RIP effect on different mechanical properties: Bauschinger effect, impact test etc.

- 3D printing and DPs treatments need each other. Typical application : lattice structure for crush application.