New "strain-transformable" beta titanium alloys for improved resistance/ ductility/ strain hardening compromise

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Overview

Introduction

General background on Ti alloys

Design tools to develop new strain transformable Ti alloys

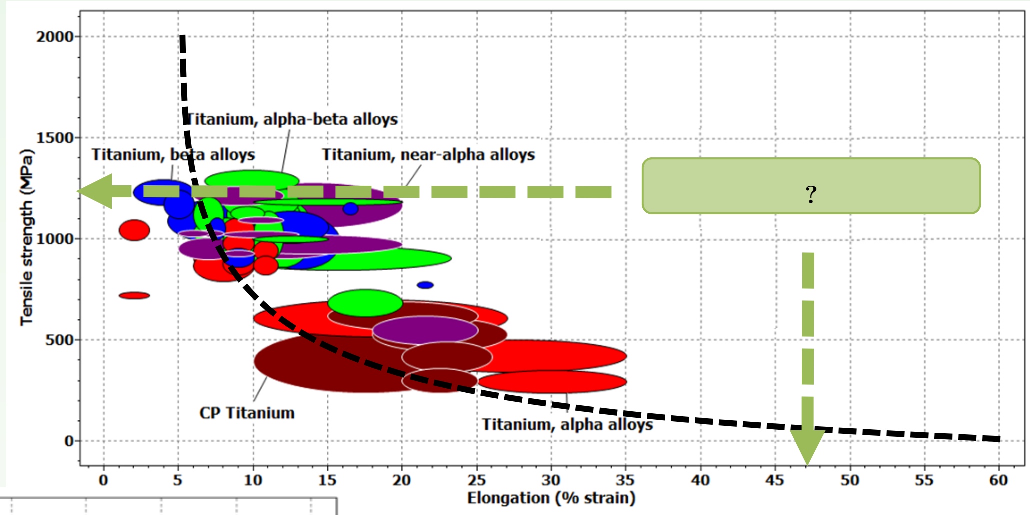
Strategies to improve mechanical properties

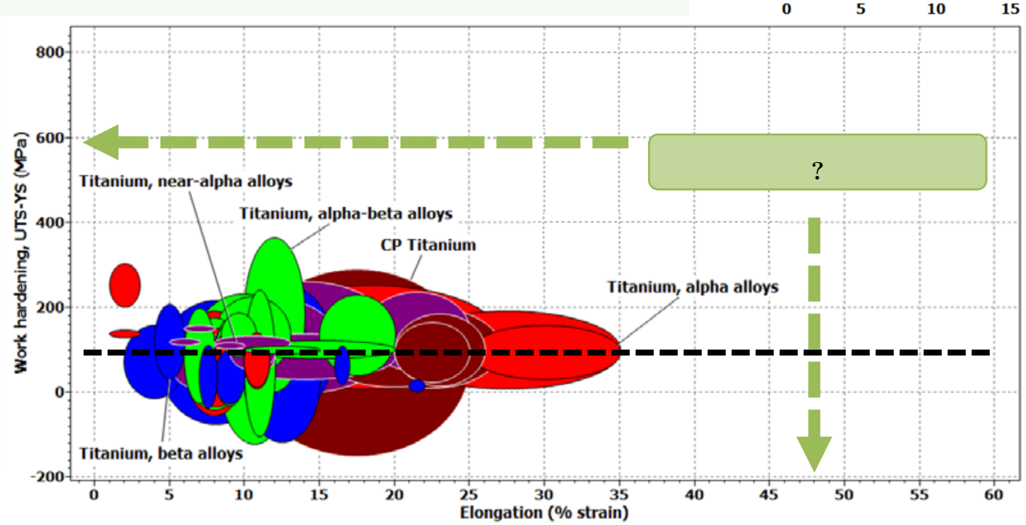
- ***Solid solution effect***
- ***Grain size***
- ***Precipitation***

Motivations

High Strength + low density + biocompatibility

BUT : lack of ductility





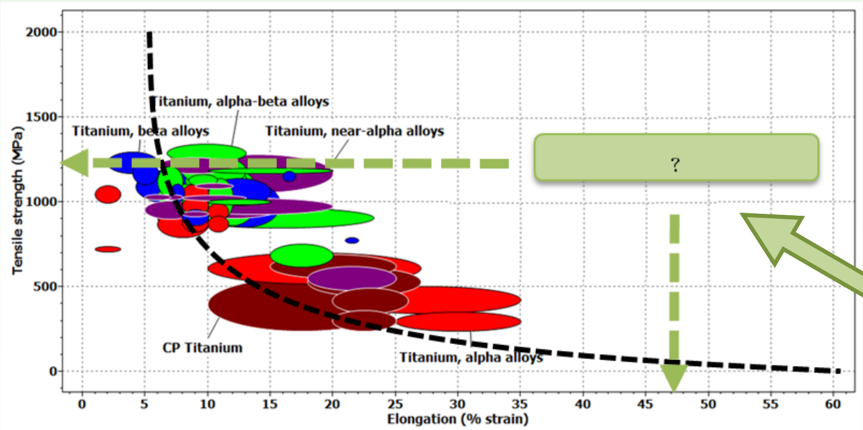
Lack of strain hardening

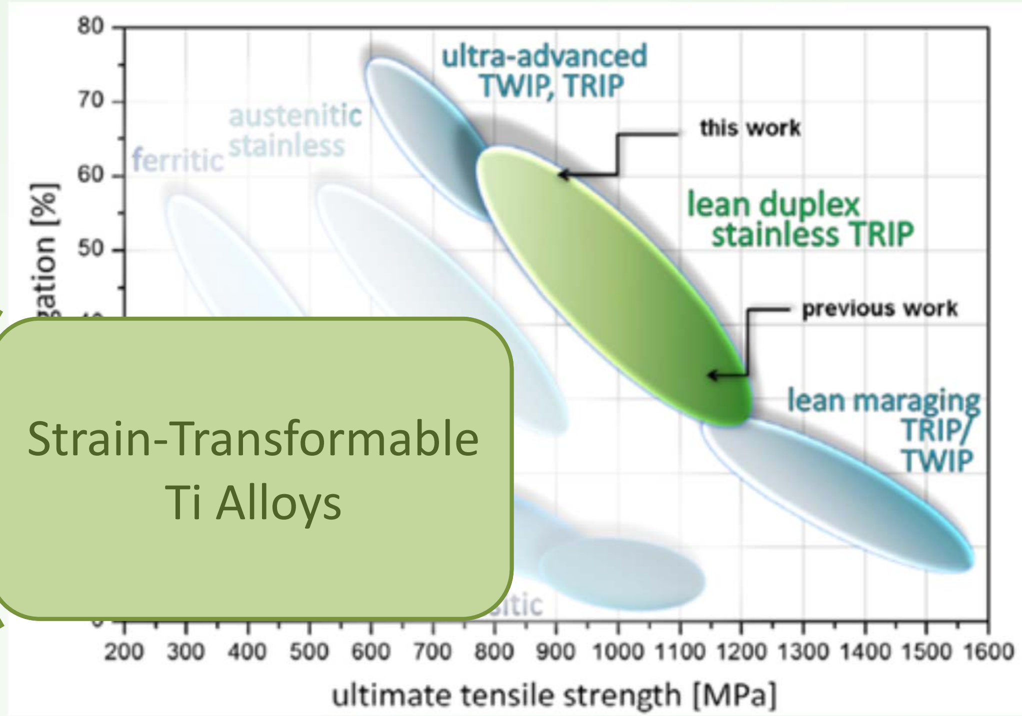
The chart of properties can be completed…

Inspiration may be taken from advanced STEELS technology

Twins and martensite interfaces can be efficient obstacles for dislocation glide

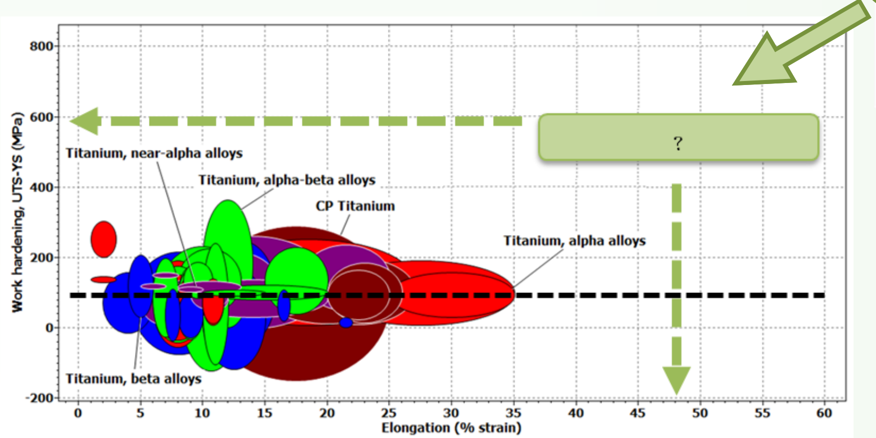
TRIP effects (Transformation Induced Plasticity)
TWIP effect (Twinning Induced Plasticity)





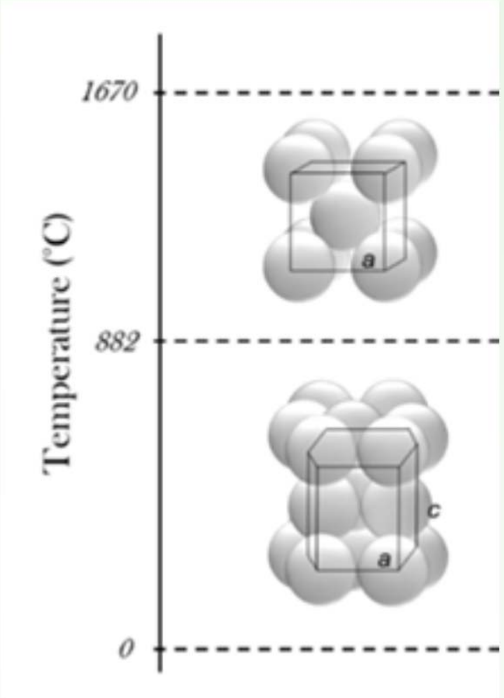
Strain-Transformable Ti Alloys

Ref: D. Raabe, Acta Mater.



Open question:
Are we able to « transfer » these approaches to titanium??

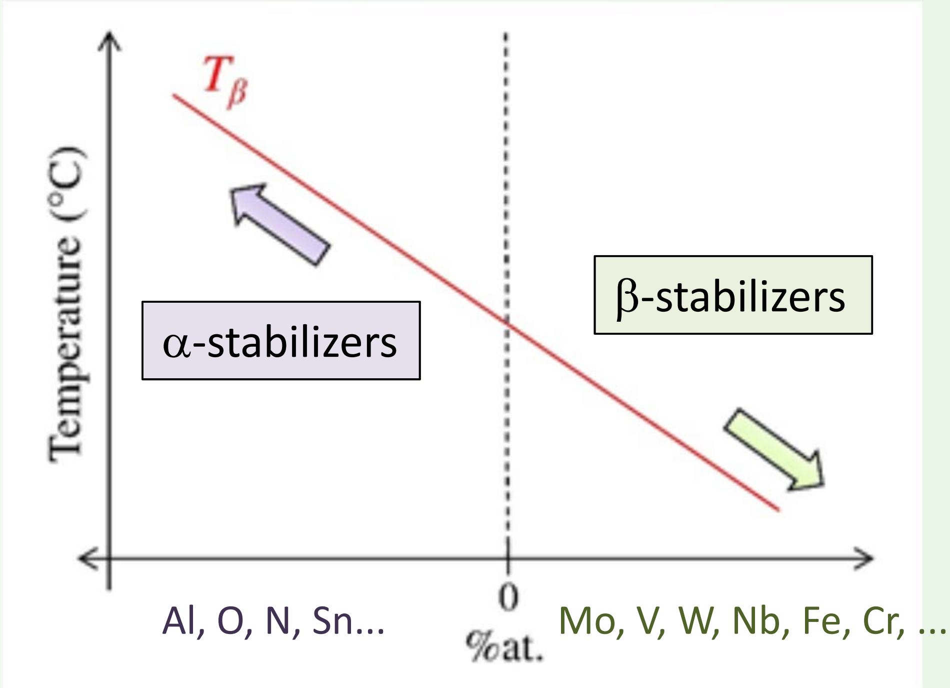
General background on Ti alloys



BCC
β-phase

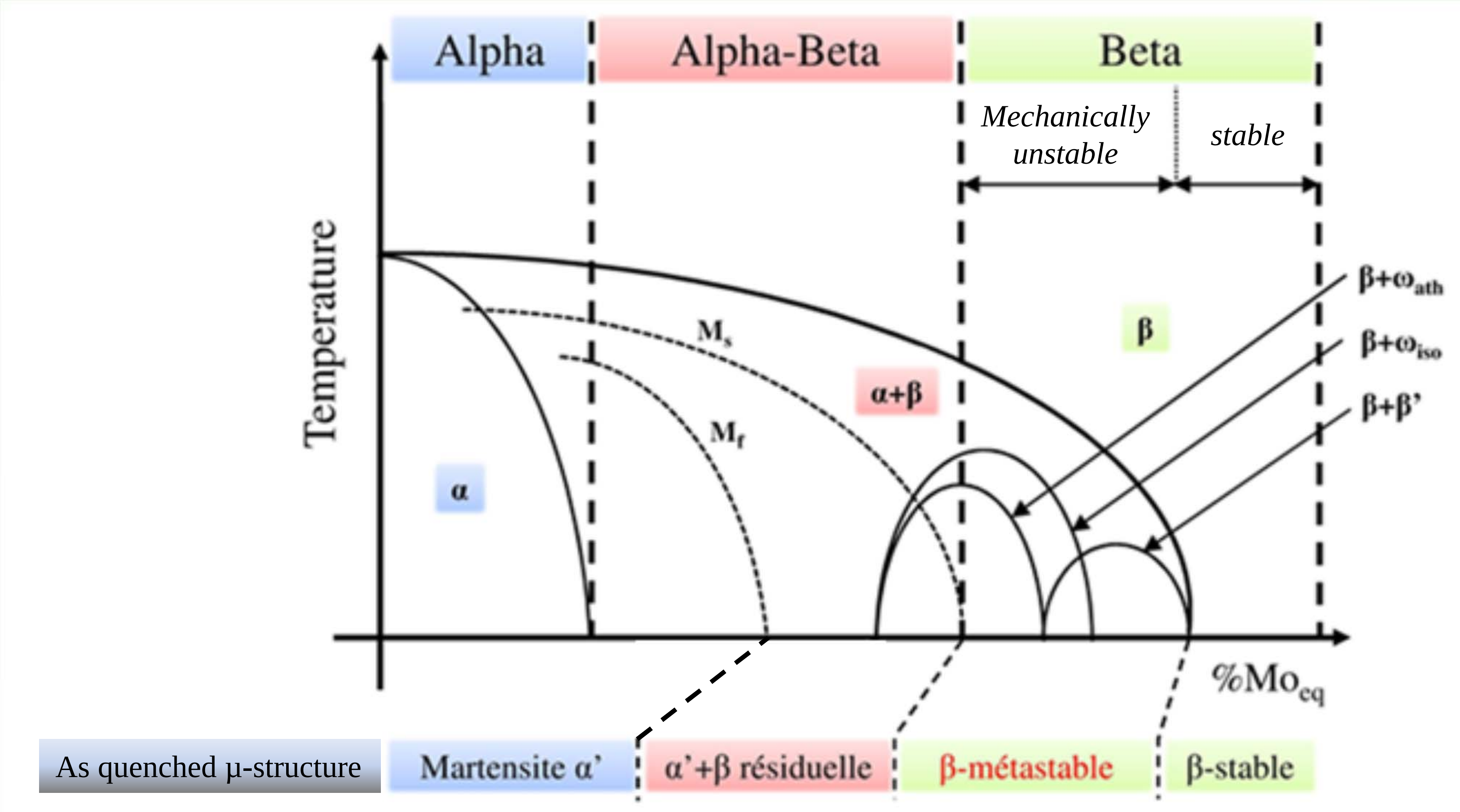
T_β — *Martensitic transformation*

HCP
α-phase



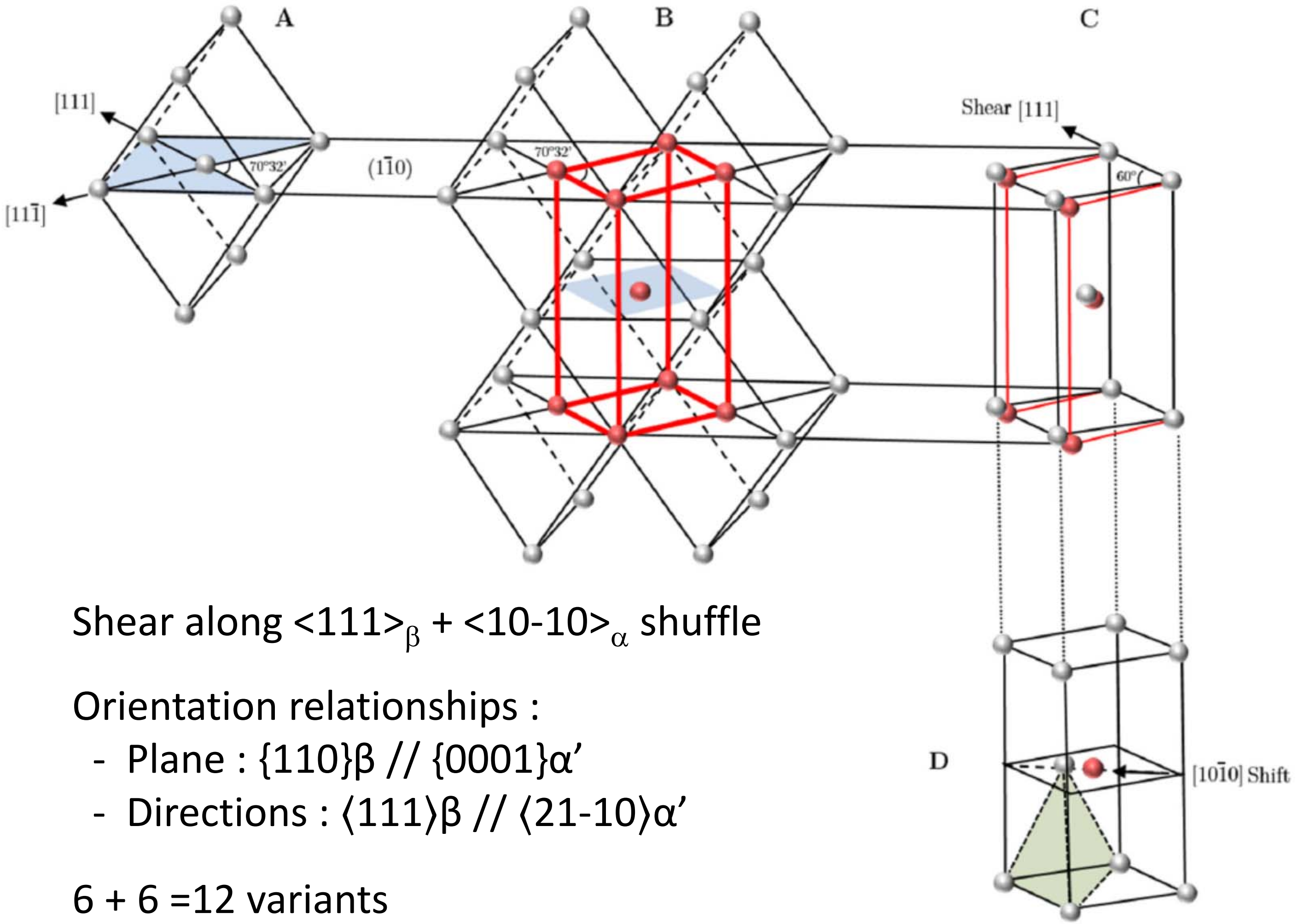
$$[Mo]_{eq} = [Mo] + 0{,}67\,[V] + 0{,}44\,[W] + 0{,}28\,[Nb] + 2{,}9\,[Fe] + 1{,}6\,[Cr]\ldots - 1{,}0\,[Al]\ldots$$

General background on Ti alloys



Potential transformation mechanisms of β-Ti alloys

β → α' (HCP) martensitic transformation



Shear along <111>$_{\beta}$ + <10-10>$_{\alpha}$ shuffle

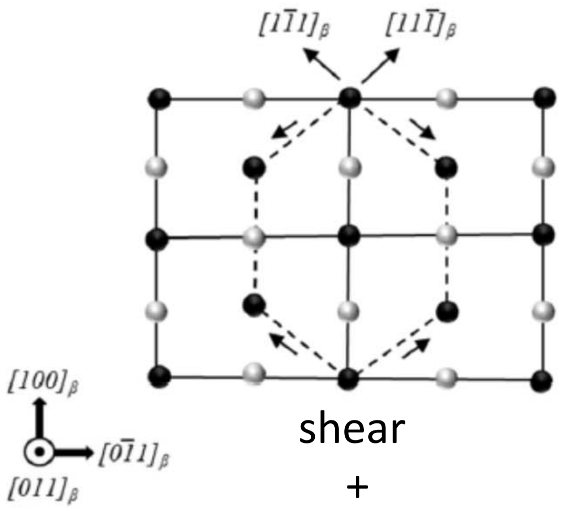
Orientation relationships :

- Plane : {110}β // {0001}α'
- Directions : ⟨111⟩β // ⟨21-10⟩α'

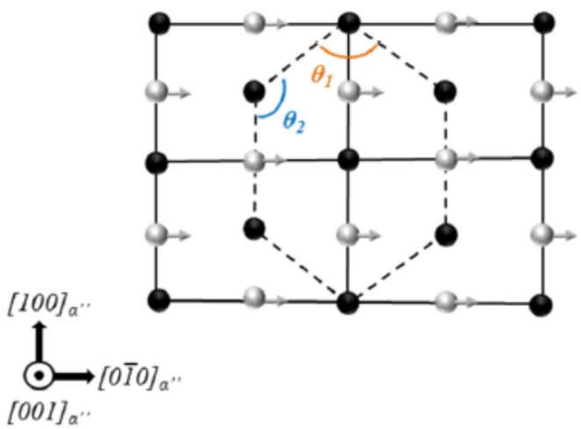
6 + 6 =12 variants

Potential transformation mechanisms of β-Ti alloys

β → α'' (orthorhombic) martensitic transformation

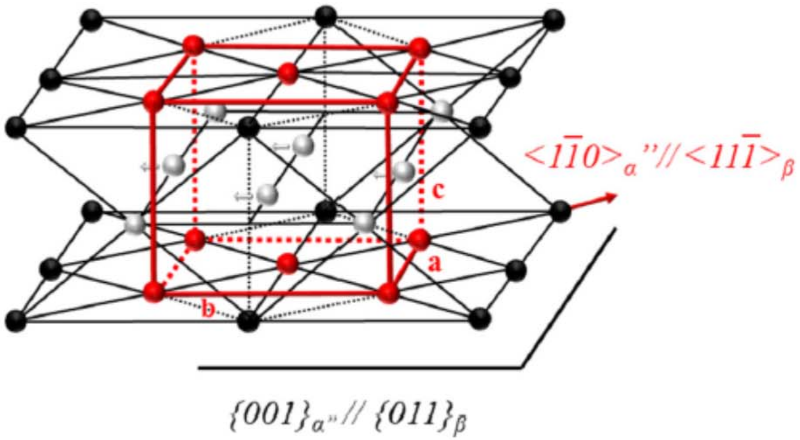


shear
+
shuffle



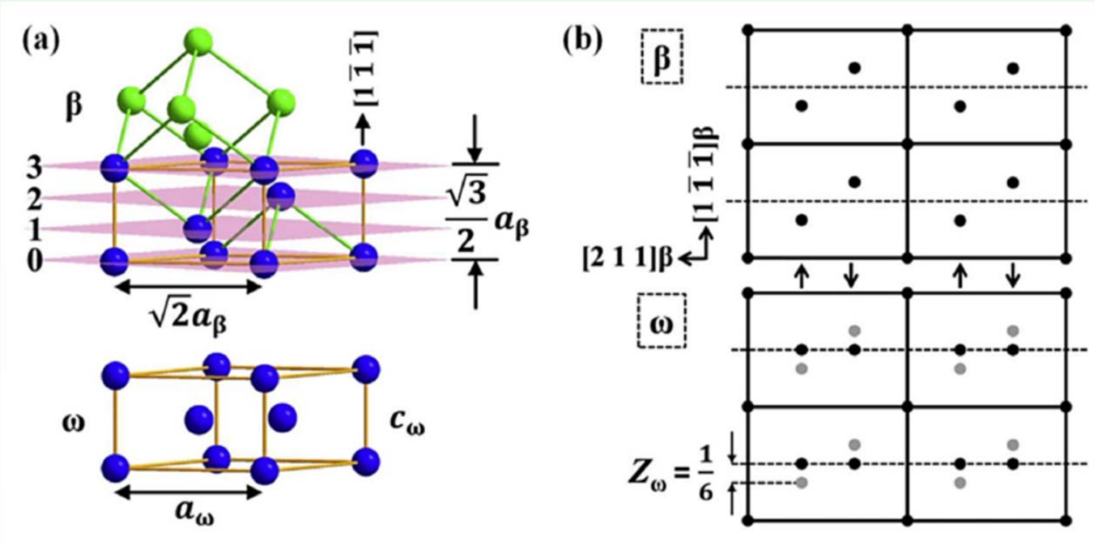
Shear is not completed to reach the 60° of hexagonal symmetry
→ Orthorhombic unit cell

6 + 6 = 12 variants



Potential transformation mechanisms of β-Ti alloys

β → ω phase transformation

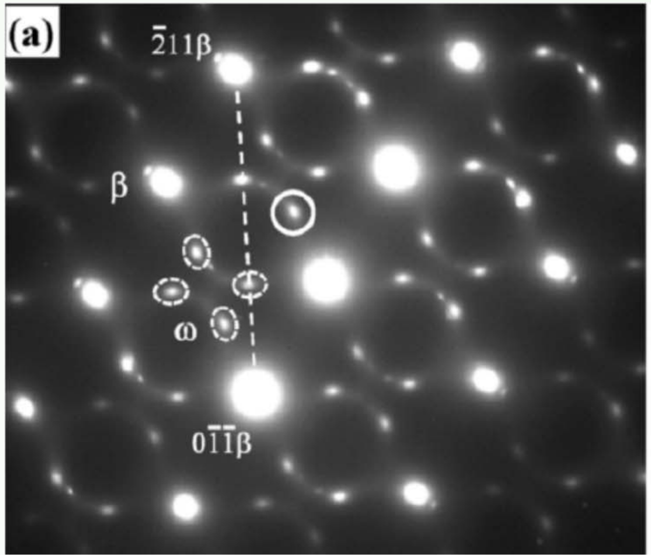


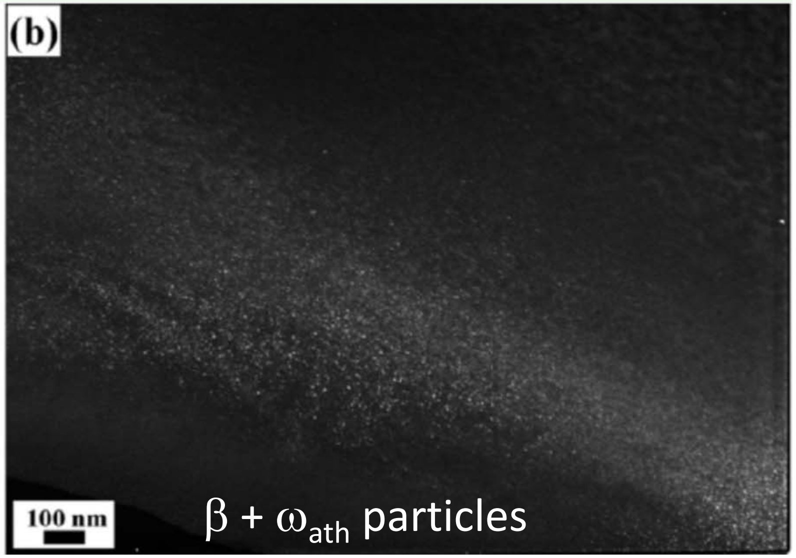
Shuffle
Displacive phase transformation
→ « athermal » ω phase

As quenched state

Diffuse scattering

High density of
very small particles





β + ω_{ath} particles

Potential transformation mechanisms of β-Ti alloys

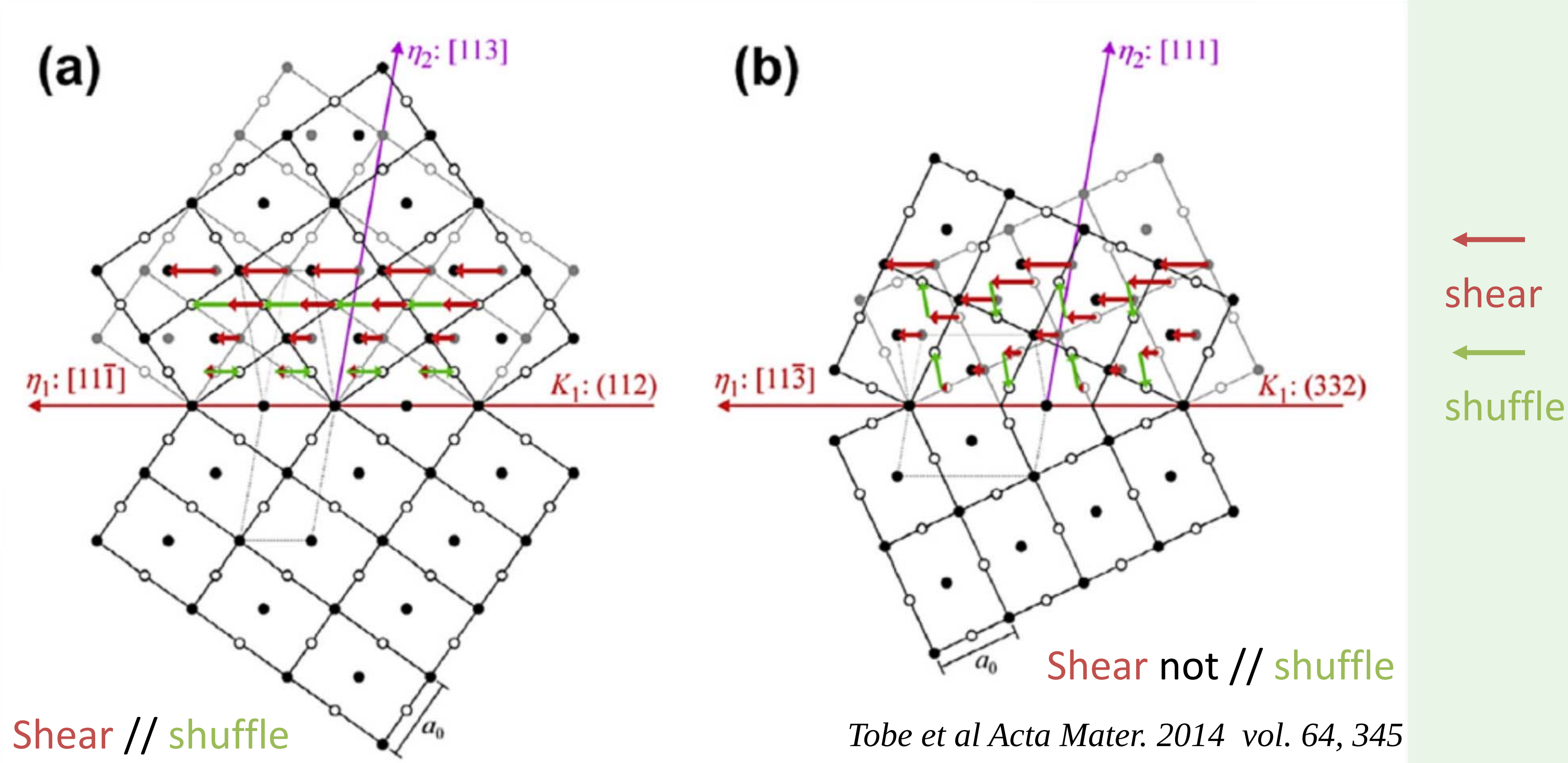
Twinning of the β phase : two possibilities

Conventional twinning mode of bcc metals | **Unconventional twinning mode of β-Ti alloys**

(112) [11-1]
12 twinning systems

shear = 0.3536

(332) [11-3]
12 twinning systems



Tobe et al Acta Mater. 2014 vol. 64, 345

Mainly observed in stable β phase

Mainly observed in metastable β phase

Deformation mechanisms in competition in BCC Ti-alloys

Depending on chemical stability →

- **Dislocations slip** (typically {110} <111> or {112} <111>)
- **Mechanical twinning** (either {112} <111> or {332} <113>)
- **Stress induced phase transformation** (α'' precipitation)

↓

Triggering

stress induced transformation/twinning mechanisms

Increase the CRSS associated with dislocations slip	***Decrease*** the CRSS associated with the stress induced transformation and twinning
Pre-deformation treatment ***Precipitation strengthening***	***Chemical composition*** ***(Ms position, β phase stability…)***

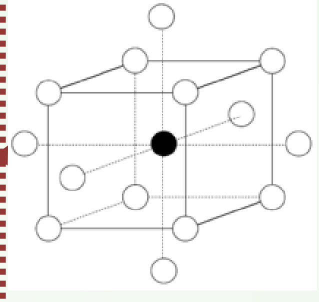
→ ***Main issue:*** **chemical (in)stability** of the titanium β phase

Design tools developed to predict occurrence of TRIP/TWIP deformation mechanisms

How to predict the stability of the β phase?

Inspired from a molecular model (LCAO)

Use of a cluster model

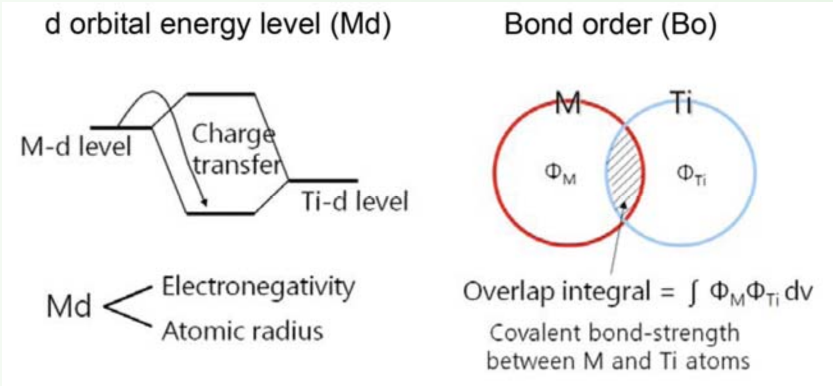


○ Ti atom

● Atom of the alloying element

Find relevant parameters to predict the β -phase stability

No prediction of the mechanical properties

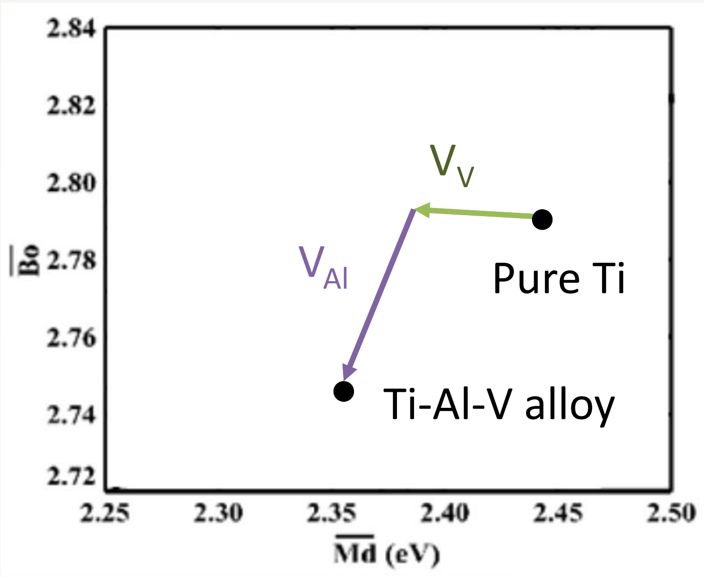


Stability

Cohesion

Design tools developed to predict occurrence of TRIP/TWIP deformation mechanisms

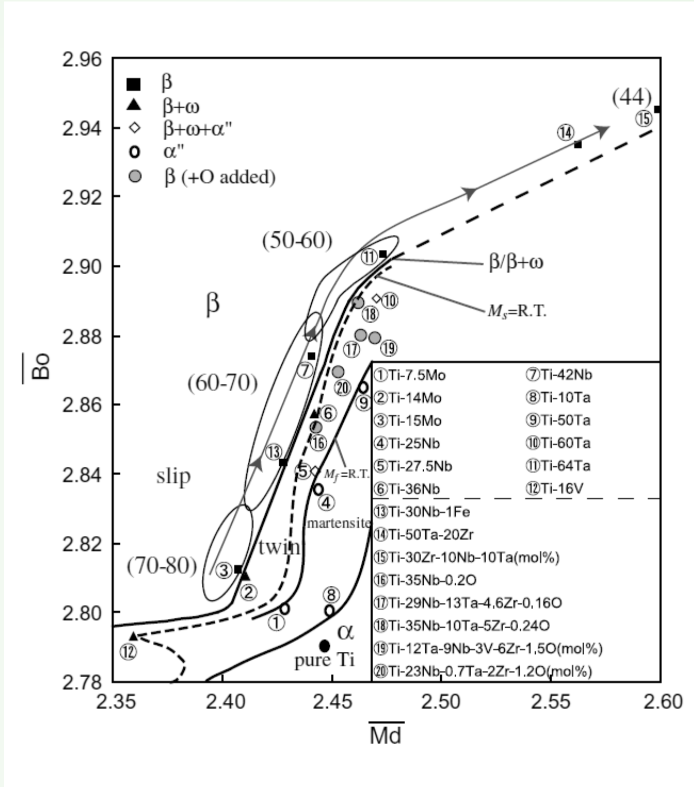
Alloying vectors defined



M. Morinaga et al, Titanium'92, Science and Technology - Volume I. TMS, 1992.

Experimental results can be reported on the chart :

Phases *(as-quenched state)*
and deformation mechanisms



M. Abdel-Hady et al. Scripta Mat. 55 (2006) 477

Development of a new family of β-Ti alloys

TWIP/TRIP β-titanium alloys

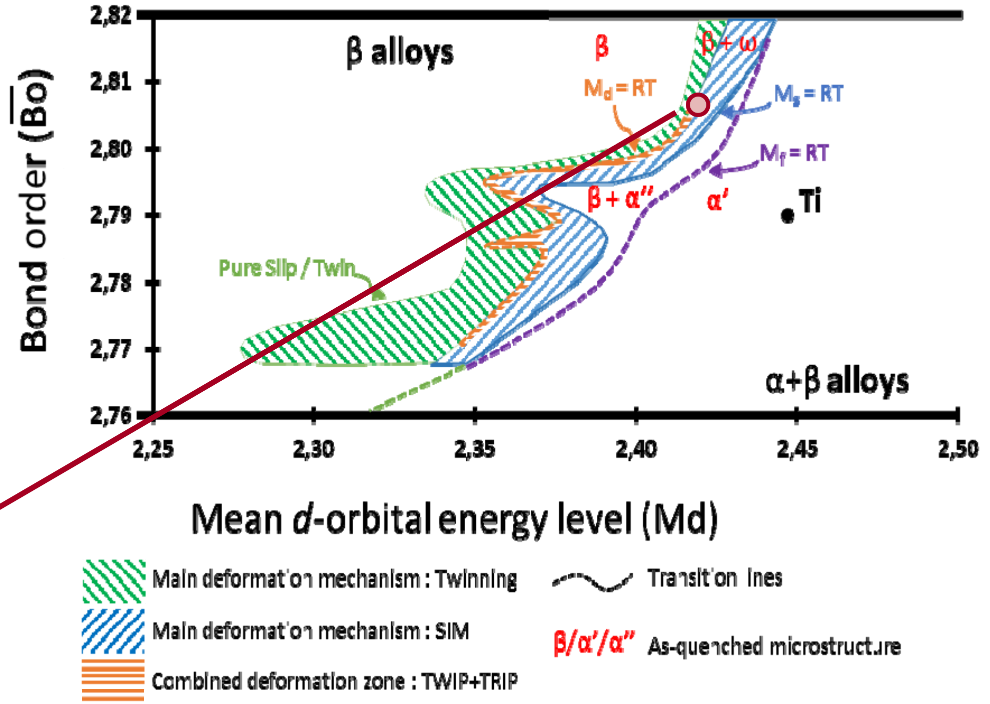
Compositional design based on d-electron approach

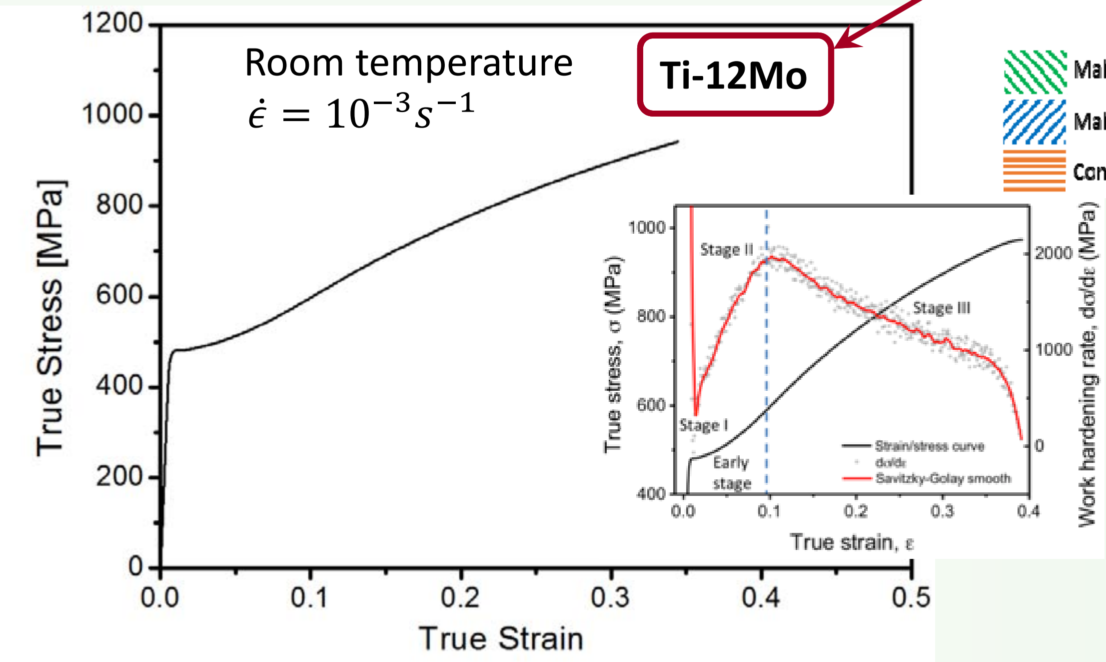
Control of the stability of the β phase

CRSS $_{Twinning}$ ≈ CRSS $_{Stress\ Induced\ Martensite}$

Design of "Model alloys"

Deformation Mechanisms Chart





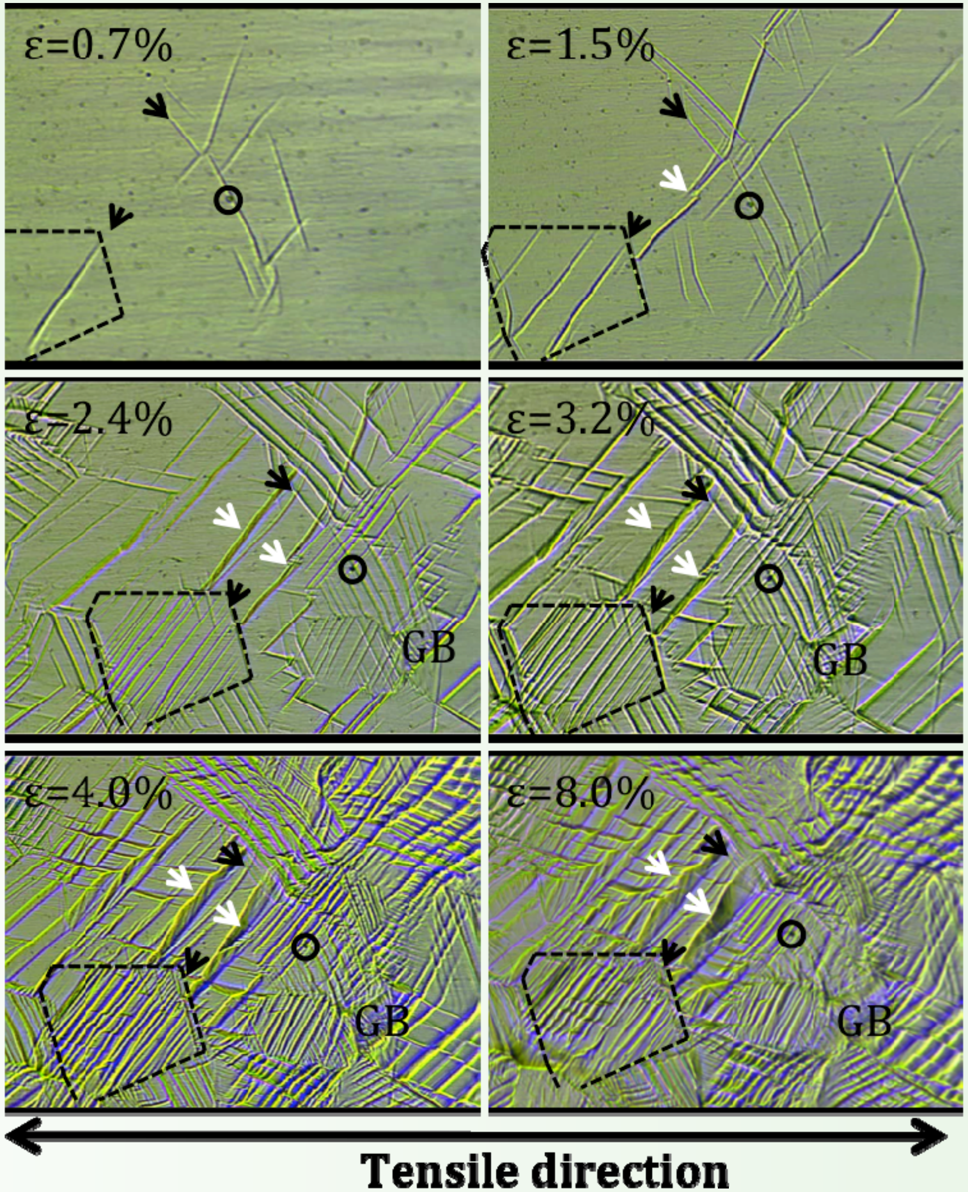
- High strength (over 1000 MPa)
- Excellent ductility (around 50% in total deformation)
- Improved strain-hardening

Deformation mechanisms : observations on Ti-12Mo

Optical Microscopy

↓

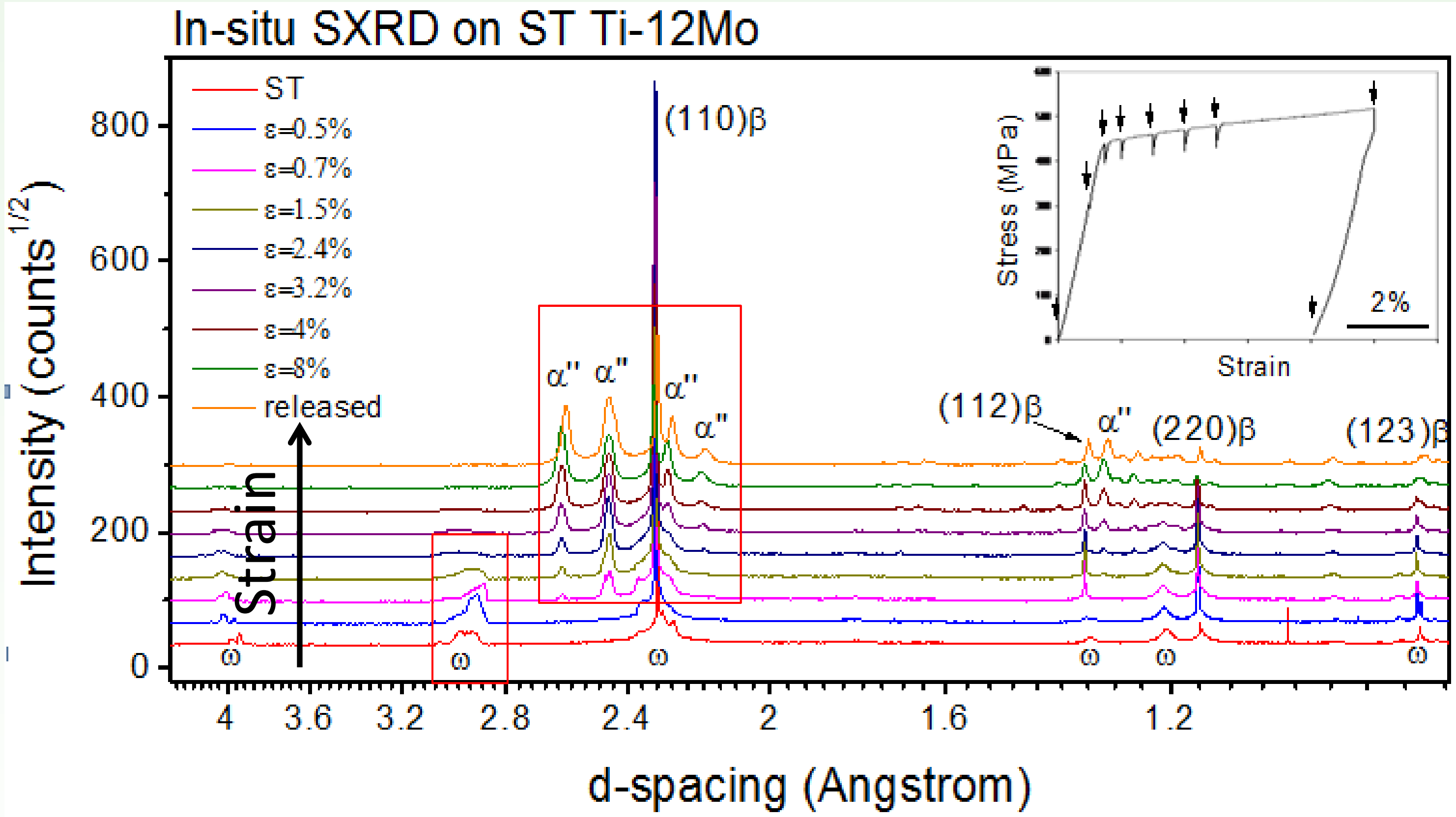
Intense Deformation bands



Deformation mechanisms : observations on Ti-12Mo

In-situ Synchrotron XRD investigation (ESRF, Grenoble)

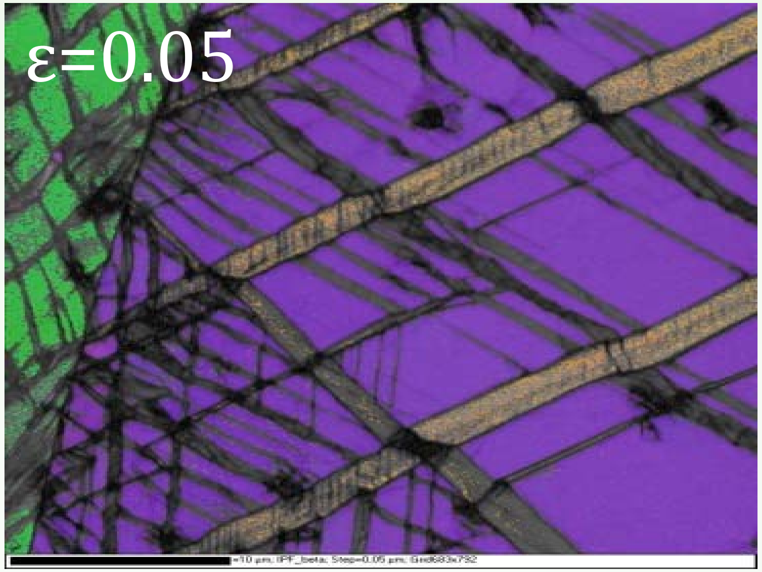
- 0% → 8% of deformation



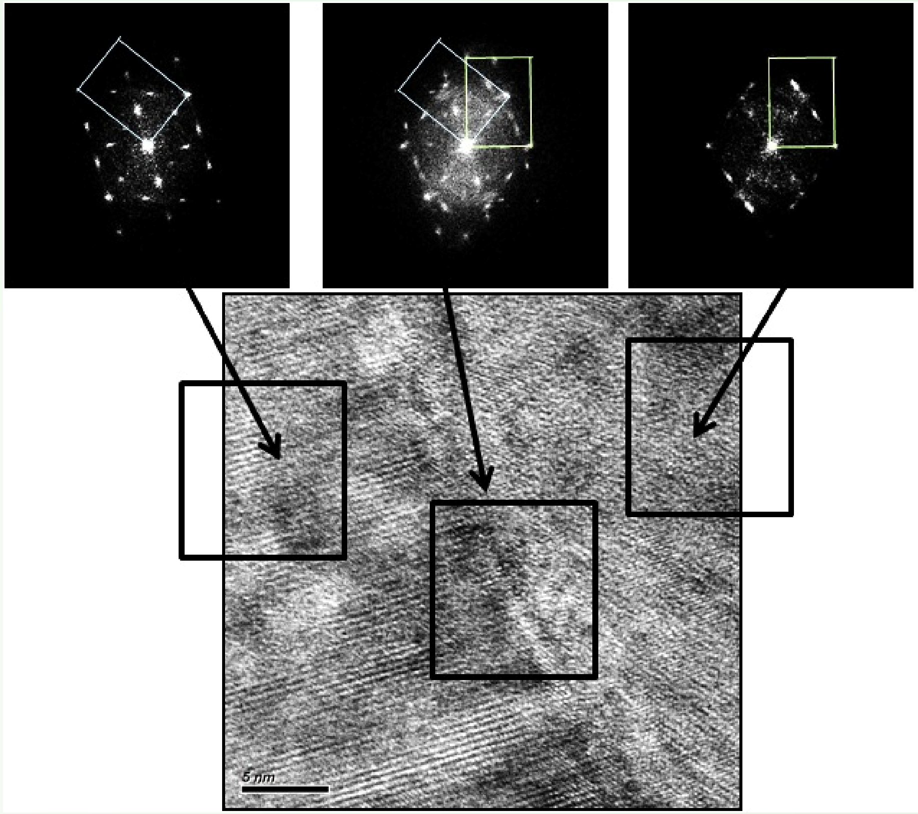
- Stress induced phase precipitations: ω phase from the very onset of the deformation, α'' phase is introduced at plastic range.

Deformation mechanisms : observations on Ti-12Mo

Intense mechanical twinning

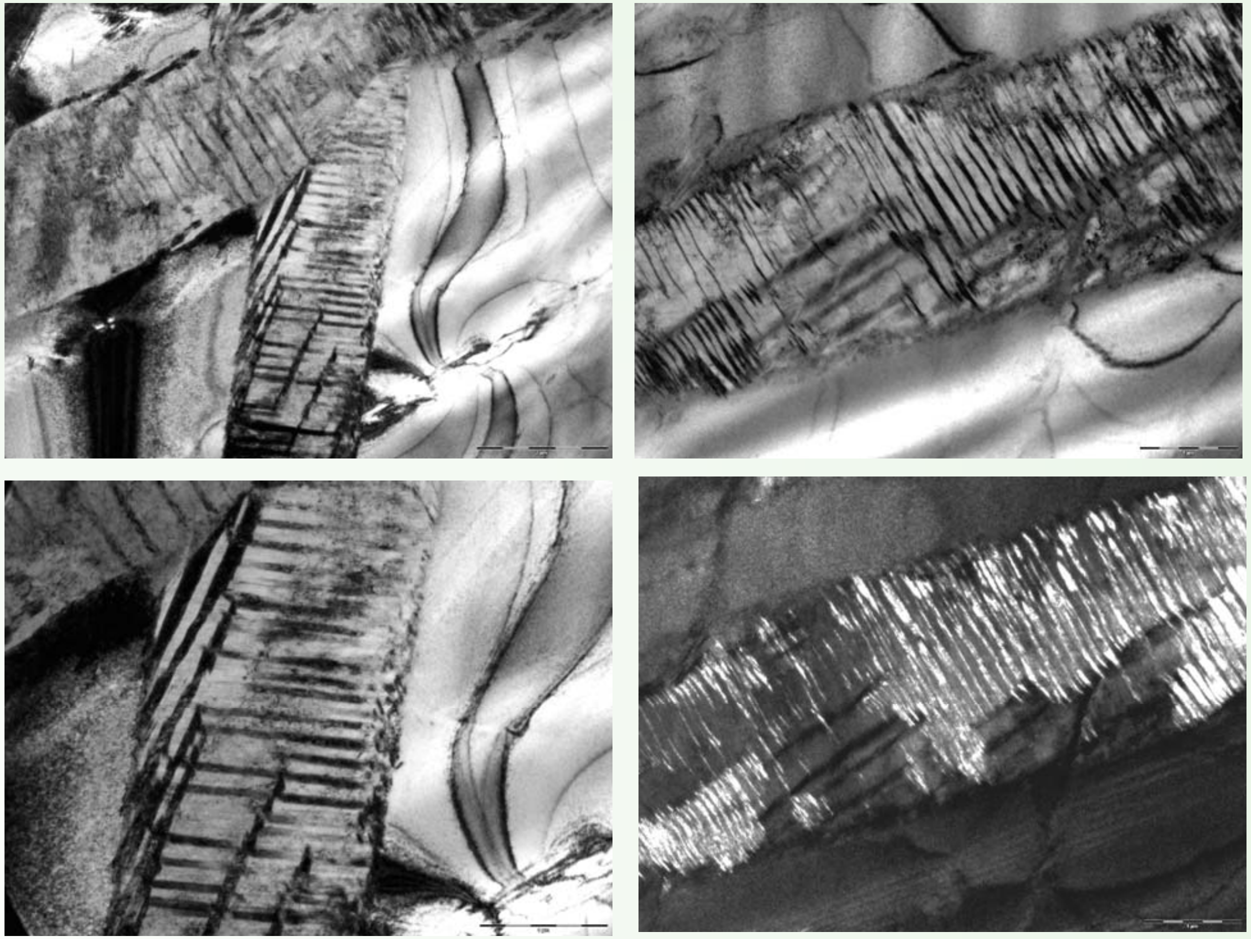


{332} <113> twinning type



Deformation mechanisms : observations on Ti-12Mo

A very complex microstructure at the nanometric scale

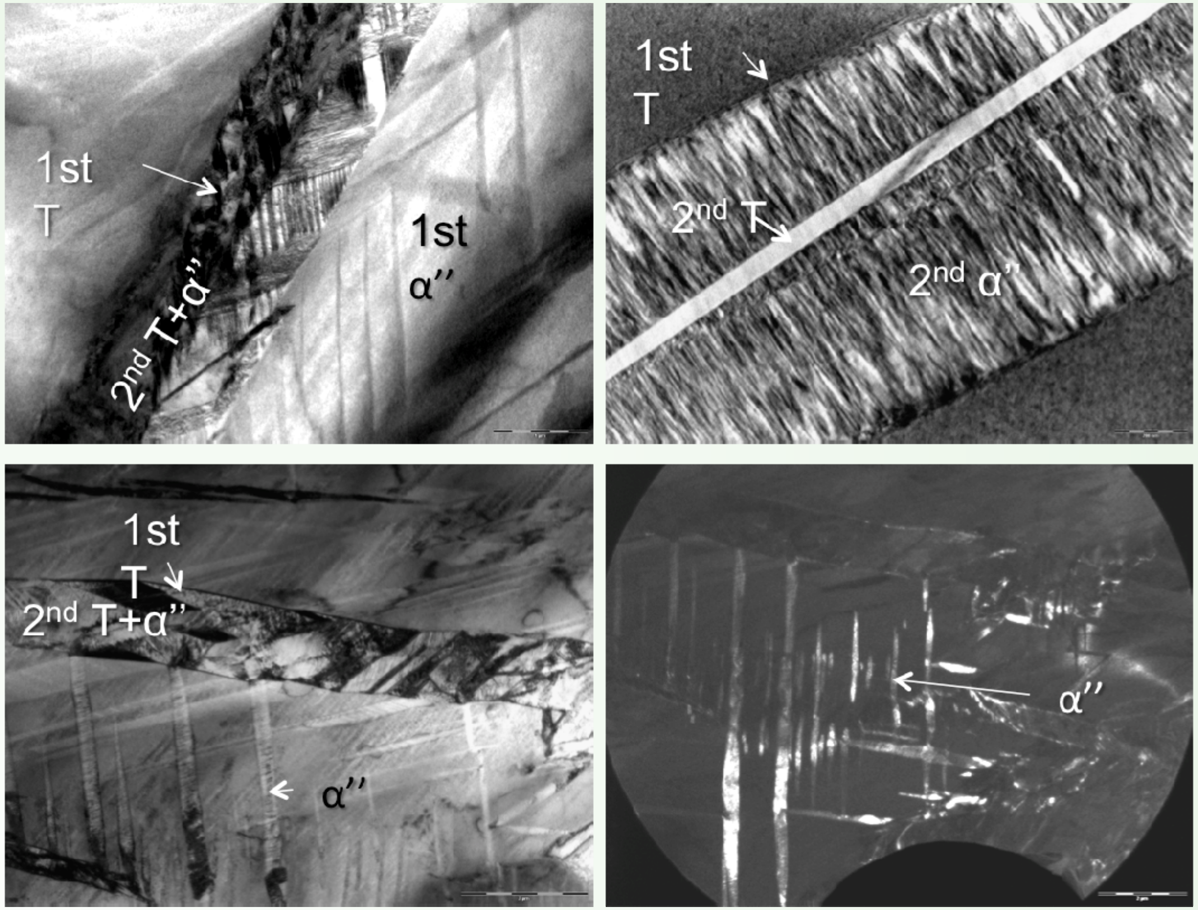


DEF<10%

Primary twins with 2^{ndary} twins inside

Deformation mechanisms : observations on Ti-12Mo

A very complex microstructure at the nanometric scale

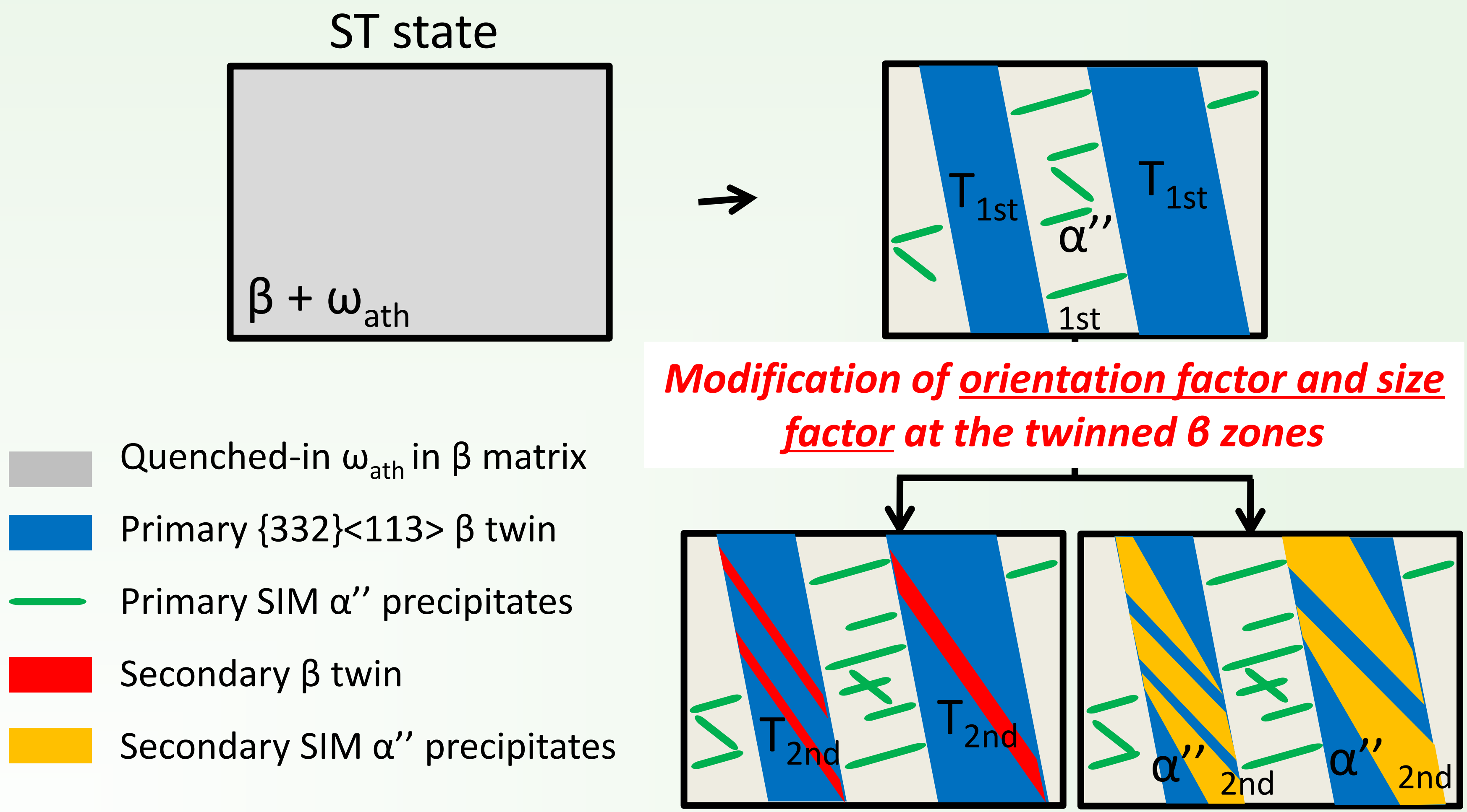


DEF<10%

Network of multi-level twins + SIM precipitation

Deformation mechanisms : observations on Ti-12Mo

Simple scheme of the plastic events during deformation

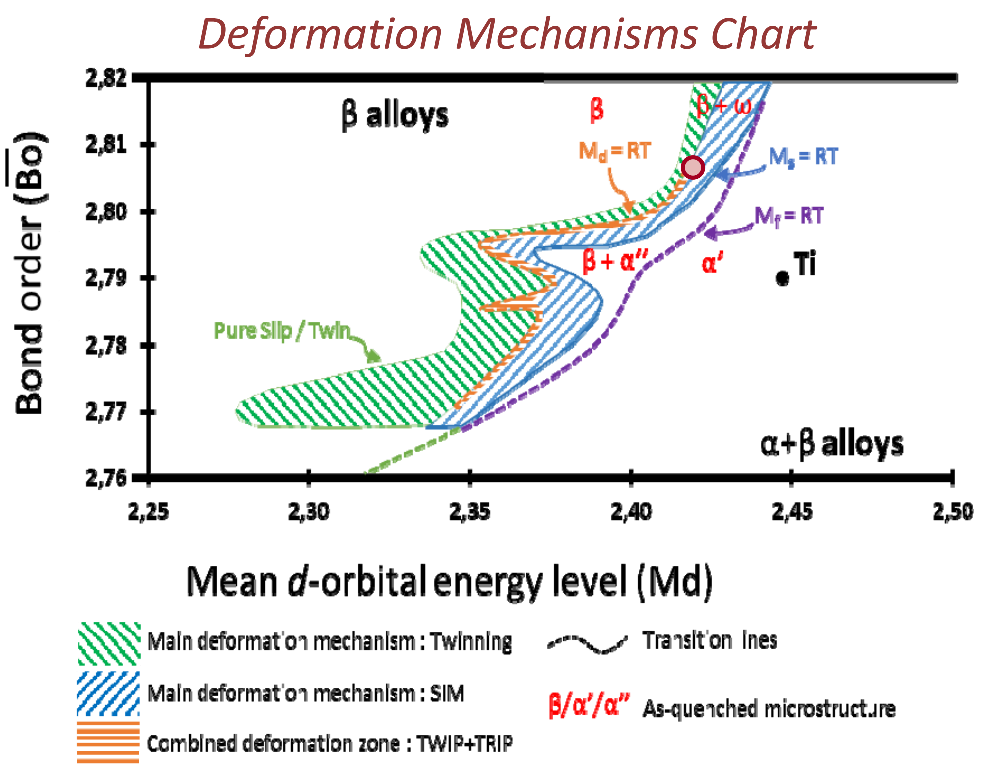


F. Sun, et al. Acta Mater 61 (2013) 6406.

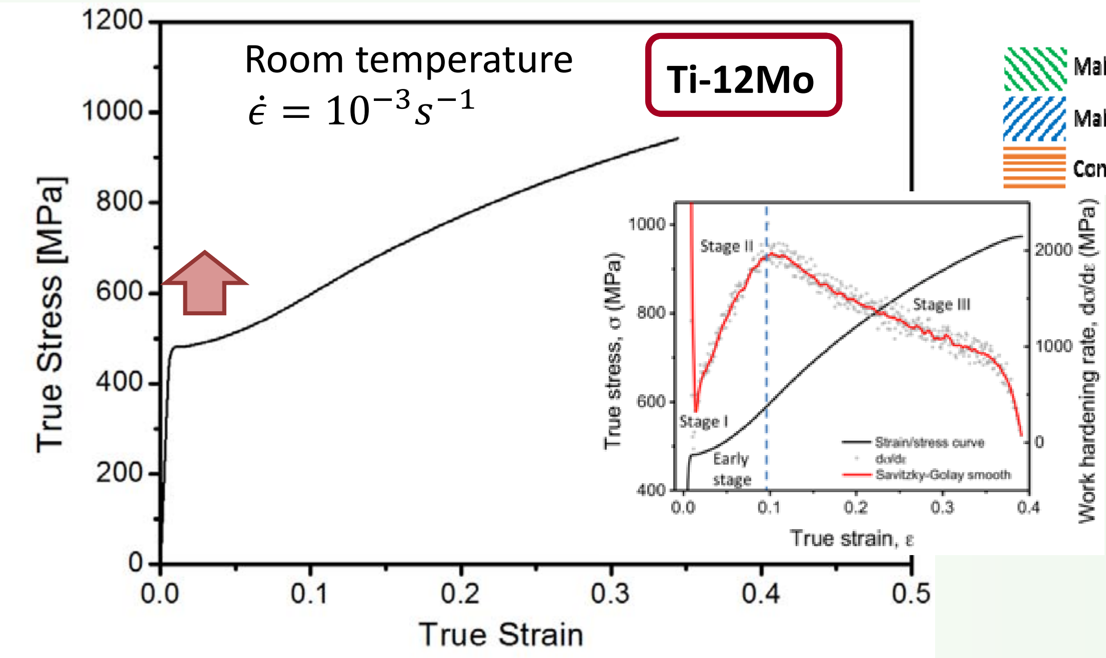
Development of a new family of β-Ti alloys

➡ TWIP/TRIP β-titanium alloys

Compositional design based on d-electron approach is **successful**



Design of "Model alloys"



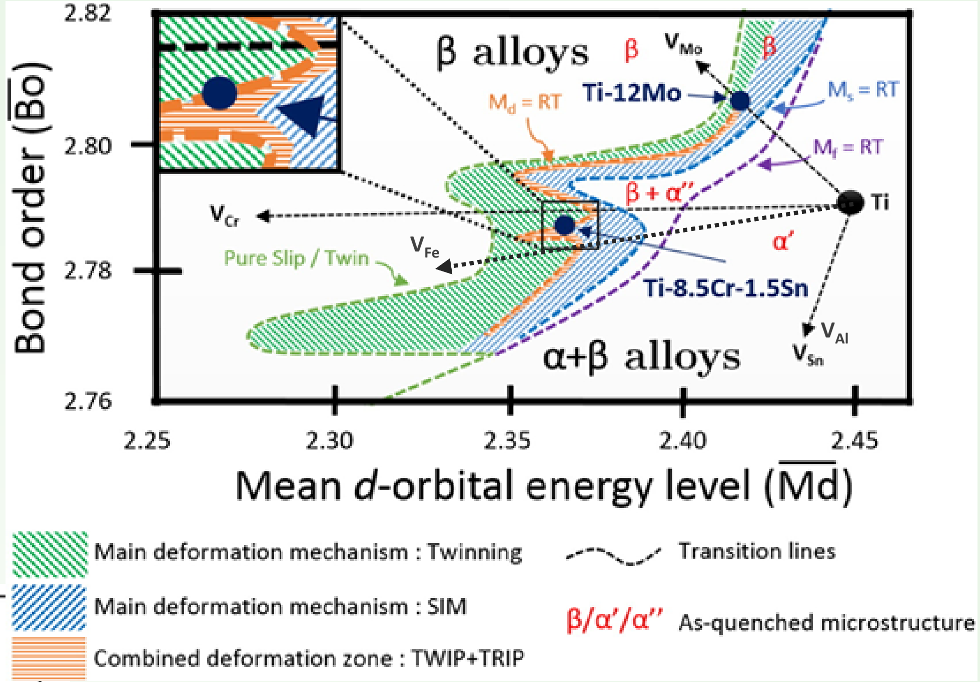
Does it work for other chemical compositions ?
Is it possible to optimize Yield stress by solid solution effect ?

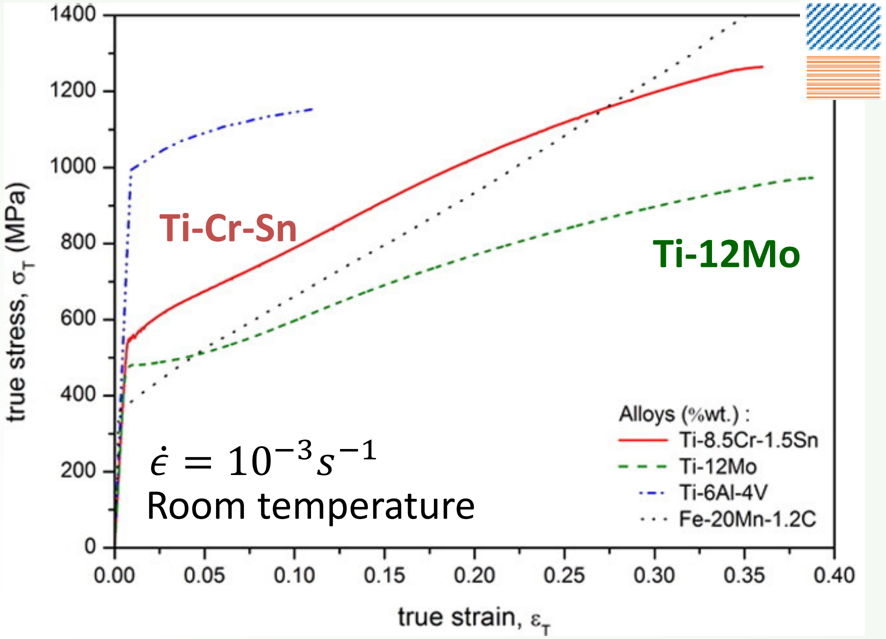
Solid Solution Effect

Ti-Cr-X alloys

Ti – 8.5 Cr – 1.5 Sn (wt%)

Brozek et al. Scripta Materialia 114 (2016) 60-64



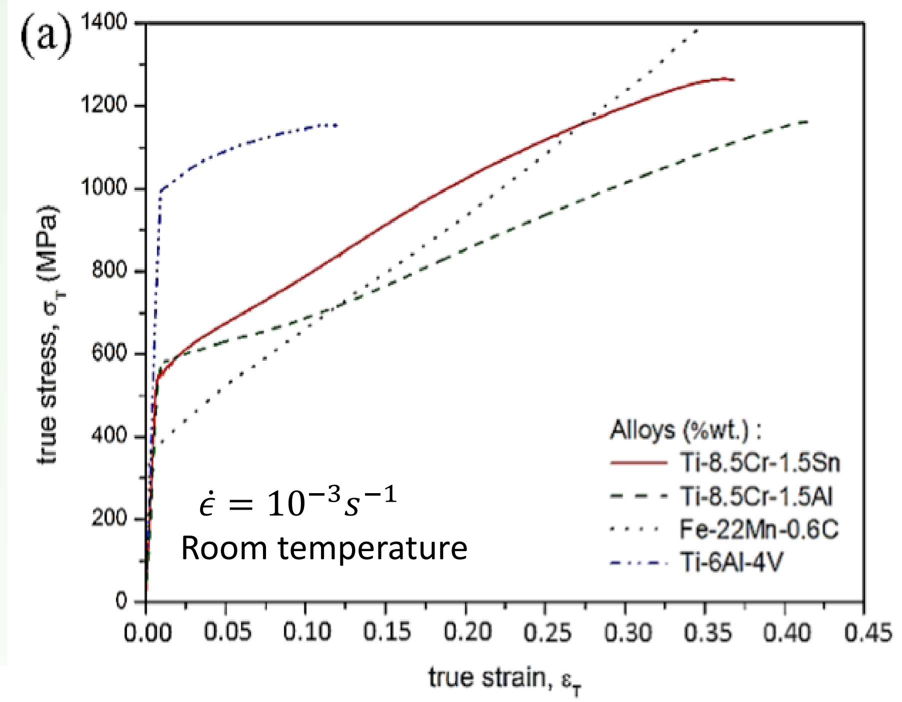


➡ ***Increase of Yield strength***

➡ ***Strain hardening and UTS are improved !!***

Solid Solution Effect

Substitution of Sn by Al in Ti-8.5Cr-1.5Sn



- ✓ Higher ductility (total elongation > 40%)
- ✓ UTS lower

but

- ✓ Very high work hardening rate
- ✓ SIM plateau

Ti-8.5Cr-1.5Al (TCA)

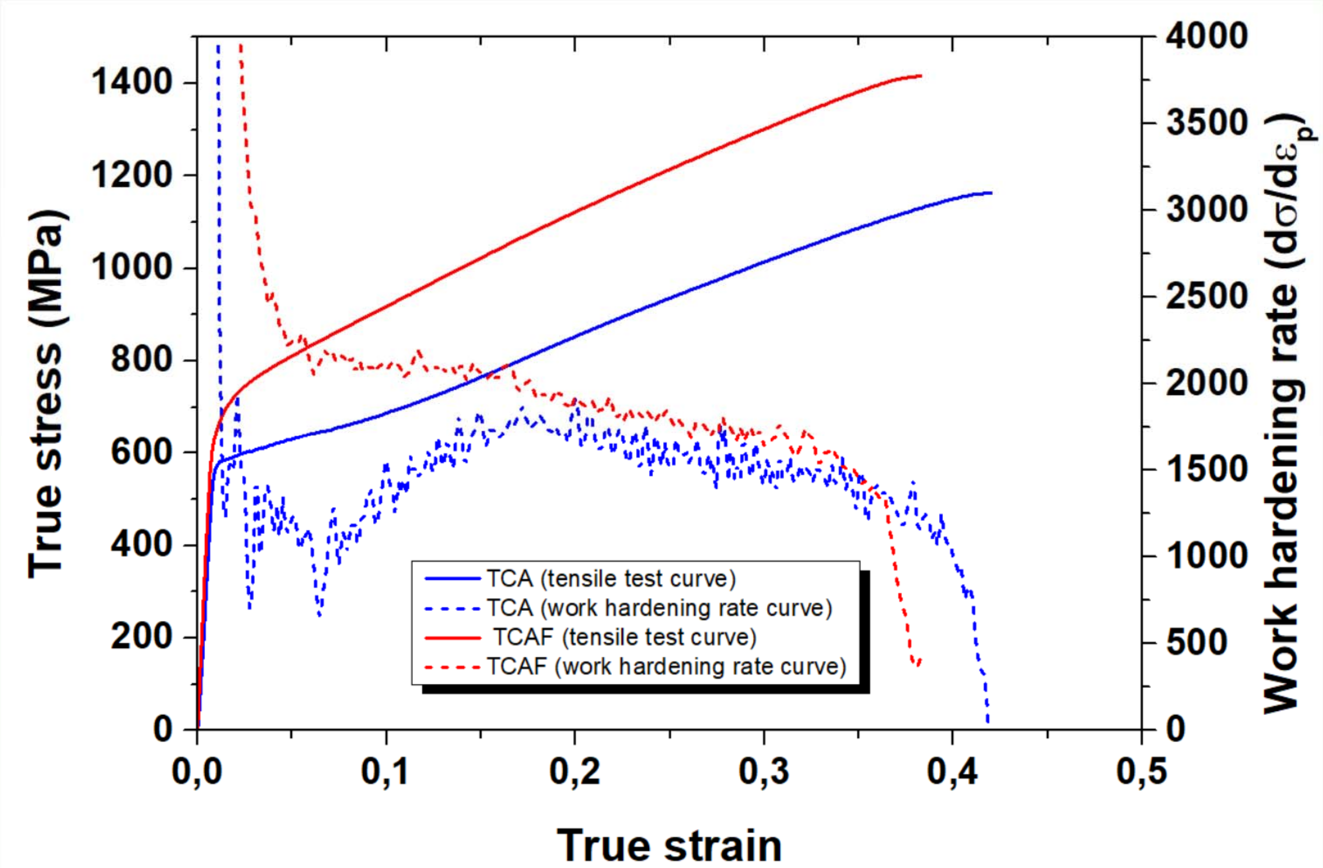
Addition of solute strengthening element (Fe)

Ti-7Cr-1Al-xFe (TCAF)

Fe addition (strong beta stabilizer and solute strengthening element) as substitute for Cr to increase σ_Y

Solid Solution Effect

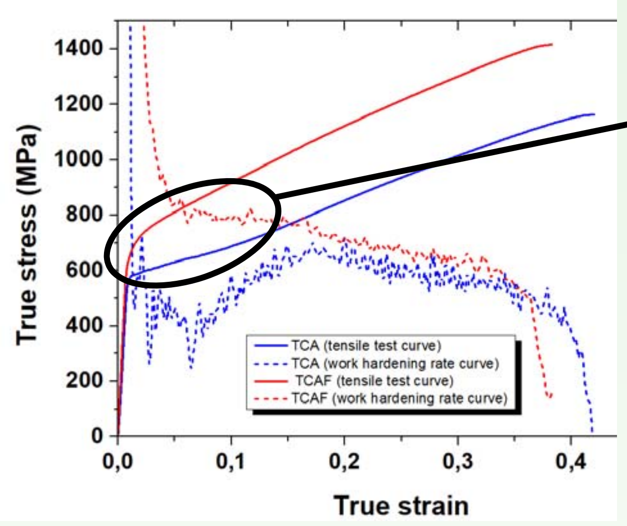
Ti-8.5Cr-1.5Al (TCA) → Ti-7Cr-1Al-xFe (TCAF)



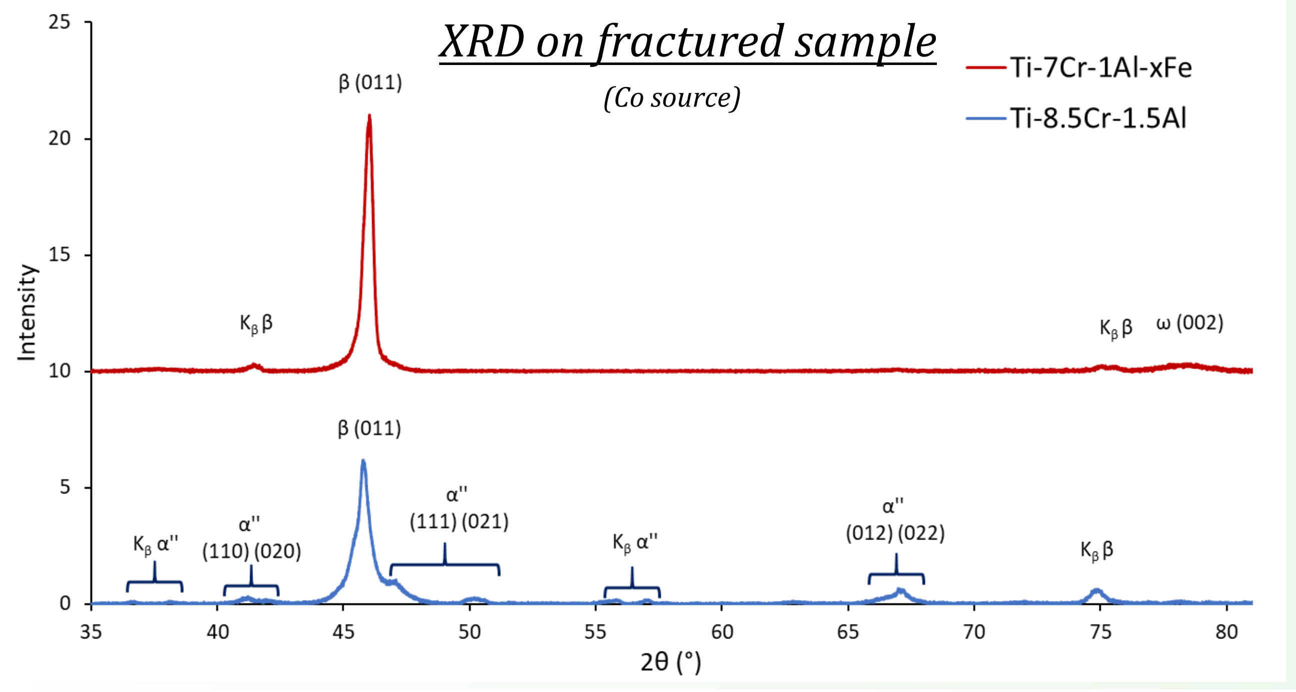
σ_Y = 570 MPa
UTS = 1160 MPa
ε_{hom} = 0.42

σ_Y = 650 MPa
UTS = 1415 MPa
ε_{hom} = 0.38

Solid Solution Effect



SIM Plateau vanished with addition of Fe



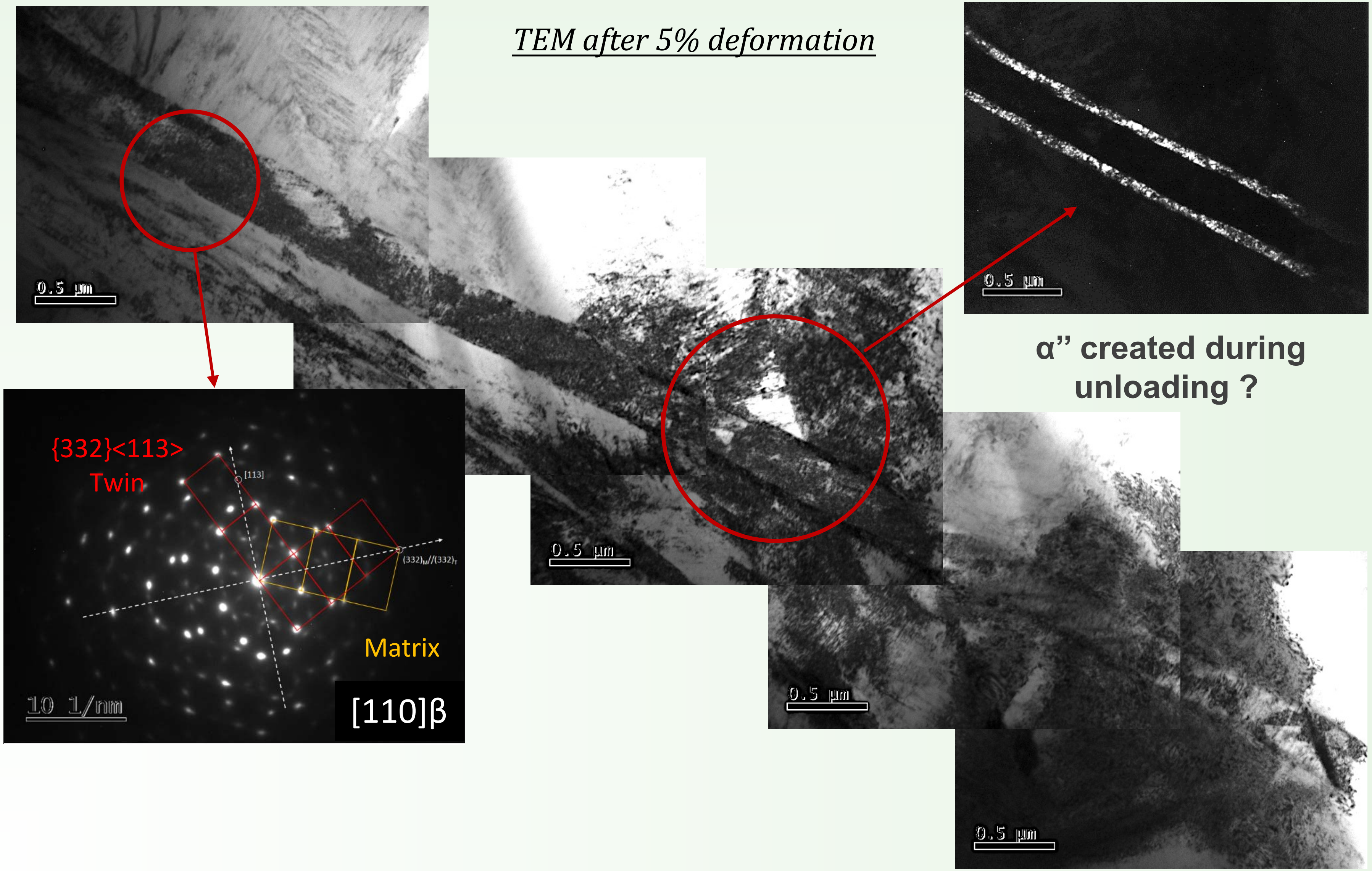
Ti-7Cr-1Al-xFe

No α'' on XRD or TEM

No TRIP effect ...

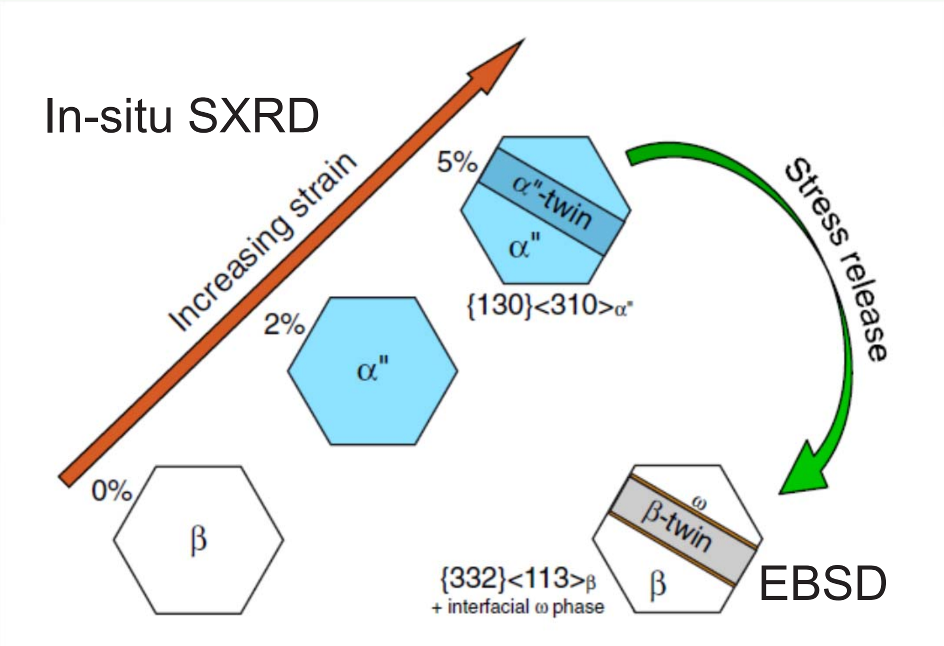
Solid Solution Effect

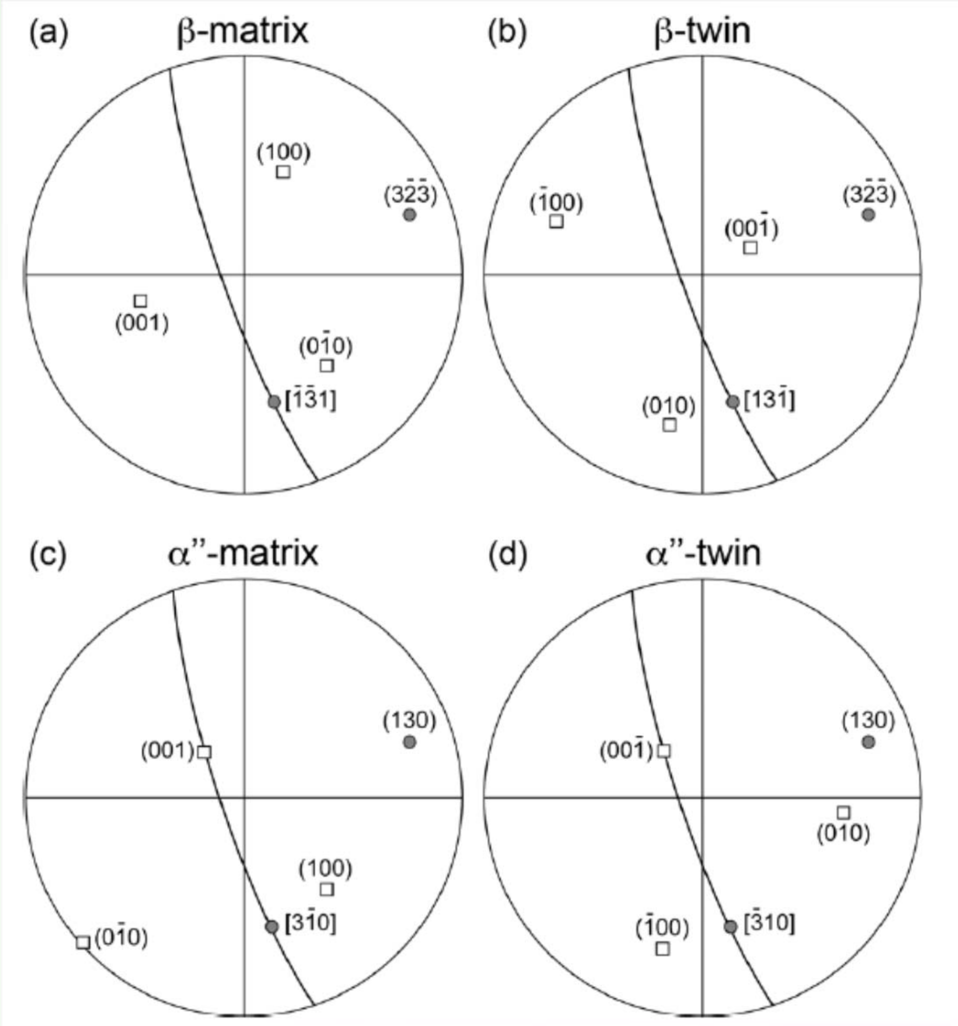
Evidence of TWIP effect :



{332}<113>twinning mechanism involving SIM ?

Reversion of a Parent {130}<310>$_{\alpha''}$ Martensitic Twinning System
at the Origin of {332}<113>$_{\beta}$ Twins Observed
in Ti-27Nb beta-metastable alloy



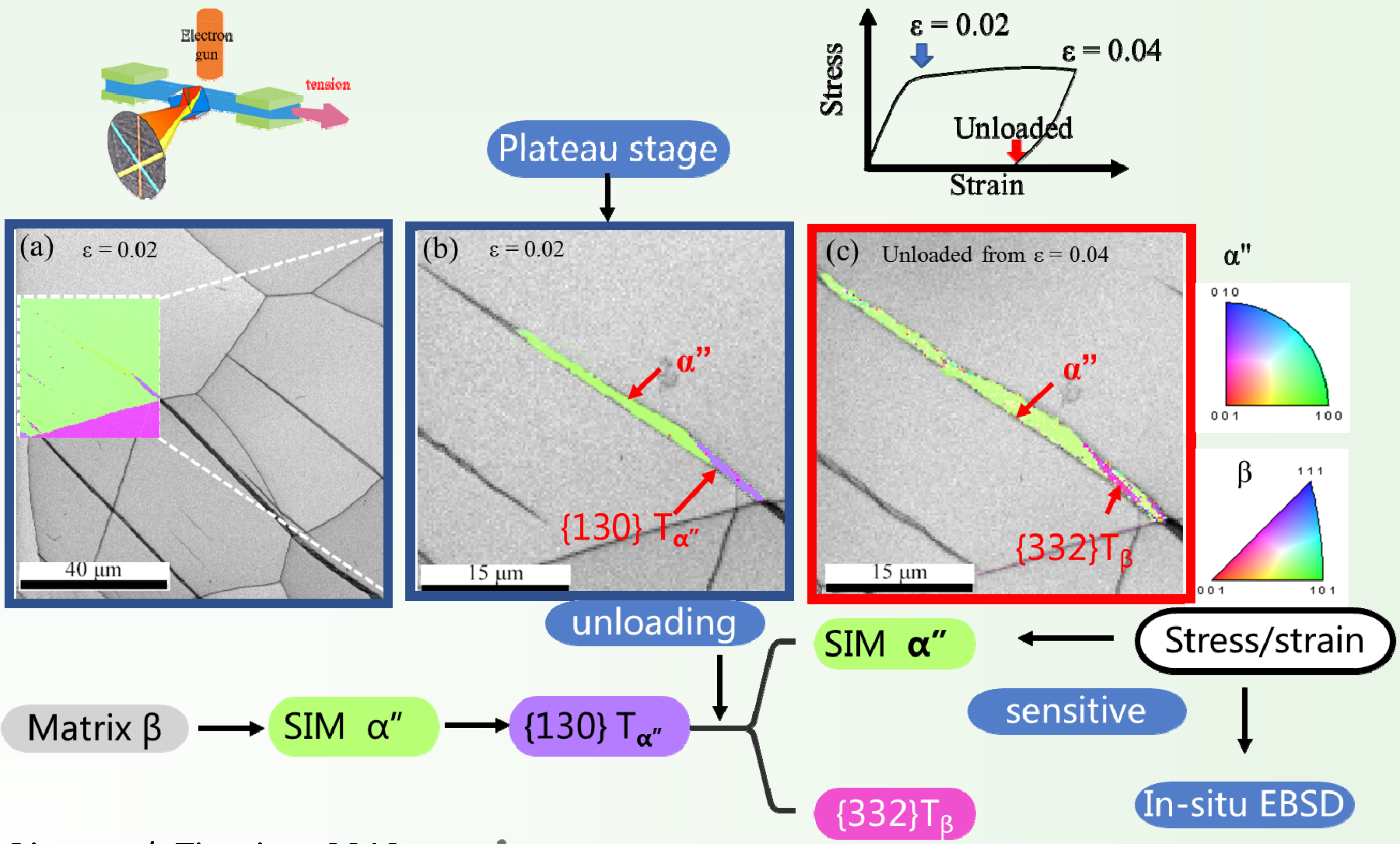


P. Castany et al, Phys. Rev. Lett. 117 (2016)

Twinning mechanism involving SIM ?

In-situ EBSD

Ti-12Mo alloy tensile test



B. Qian et al, Titanium 2019

Conclusion

Alloy design

- Strategy based on d-electron parameters is successful
- TRIP/TWIP Ti alloys can be design with very good mechanical properties
- The synergetic effect between the deformation mechanisms have to be better understood
- The origin of the {332}<113> twinning mode seems to be connected to mechanical twinning of the SIM + reverse transformation

Microstructure improvement

- Solid solution effect :
  - effective improvement of mechanical properties
  - TWIP effect alone can be effective for good mechanical properties

IRCP Institut de Recherche de Chimie Paris

Thank you for your attention

~

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