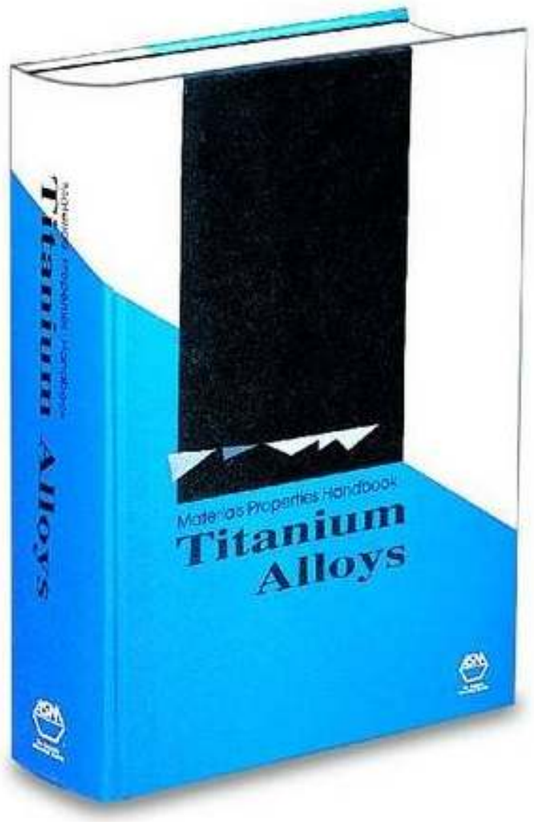
Introduction sur le TA6V

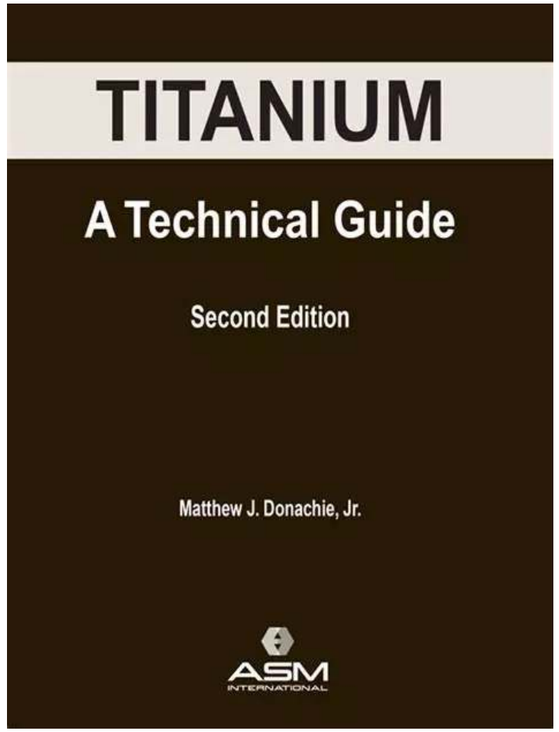
B. Appolaire
Université de Lorraine-CNRS, Institut Jean Lamour

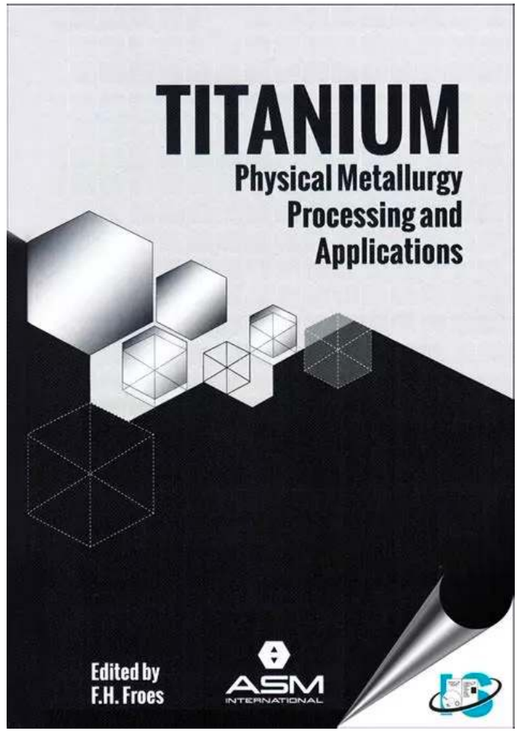
3/14/23

Sources

- Boyer, Welsch, Collings, *Materials Properties Handbook: Titanium Alloys*, 1984 (ed. 1994)
- Donachie Jr, *Titanium - A technical Guide*, 2000
- F.H. Froes, *TITANIUM - Physical Metallurgy, Processing and Applications*, 2015
- Y. Combres, Techniques de l'Ingénieur, M1 335, M2 355, M3 160, M557







Un des plus anciens et le plus courant

Le TA6V est actuellement l'alliage de titane le plus largement utilisé, représentant plus de 50 % du tonnage total des alliages de titane dans le monde

- L'industrie aérospatiale représente plus de 80% de cette utilisation
- La deuxième application la plus importante du TA6V concerne le médical (3% du marché)
- L'automobile, la marine et l'industrie chimique utilisent également de petites quantités de TA6V

Official U.S. Army News Release (May 17, 1954)

Public Information Office
Watertown Arsenal
Watertown 72, Massachusetts
WAtertown 4-8540, Ext. 452

FOR RELEASE
MONDAY, 17 MAY - AM PAPERS

NEW ALLOY
Hailed By Army
Titanium Compound May Add Striking Power To U. S. Ordnance

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TITANIUM STUDIES BRING NEW ALLOY

Light Material Developed by Army Reported as Tough as High-Strength Steel

Special to The New York Times.

WATERTOWN, Mass., May 16—Development of a new, light-weight titanium alloy possessing the toughness of high-strength steel was announced today by the Watertown Arsenal Laboratory, an Army center for titanium research.

Col. B. S. Mesick, commanding officer of the arsenal and co-ordinator of the Army titanium research program, said laboratory tests showed the alloy to be 40 per cent lighter in weight than high-strength steel. However, it is highly corrosion-resistant and has properties that compare favorably with those of steel used in making heavy weapons, tanks and armor plate.

While further tests must be made, the alloy is considered a potential substitute for steel in many ordnance components.

The alloy was worked out by Stanley Abkowitz, a member of the arsenal laboratory staff who was serving as a technical supervisor of a contract with the Armour Research Foundation of Chicago. The foundation is one of many agencies engaged in titanium research for the arsenal under Government contract.

The alloy shows tensile strengths up to 192,000 pounds for each square inch, or 42,000 pounds a square inch stronger than any commercial alloy of titanium now being produced.

It also is tougher and more pliable, permitting it to be shaped thus overcoming the brittleness factor that severely limits the use of commercial alloys.

Pourquoi le plus courant ?

Many alloys have been invented but have never seen significant commercial use.

Ti-6Al-4V alloy is unique in that it combines attractive properties

- *with inherent workability (which allows it to be produced in all types of mill products, in both large and small sizes),*
- *good shop fabricability (which allows the mill products to be made into complex hardware),*
- *and the production experience and commercial availability that lead to reliable and economic usage.*

Consequently, wrought Ti-6Al-4V became the standard alloy against which other alloys must be compared when selecting a titanium alloy (or custom designing one) for a specific application.

Ti-6Al-4V also is the standard alloy selected for castings that must exhibit superior strength.

It even has been evaluated in P/M processing.

Ti-6Al-4V will continue to be the most-used titanium alloy for many years in the future.

Donachie Jr

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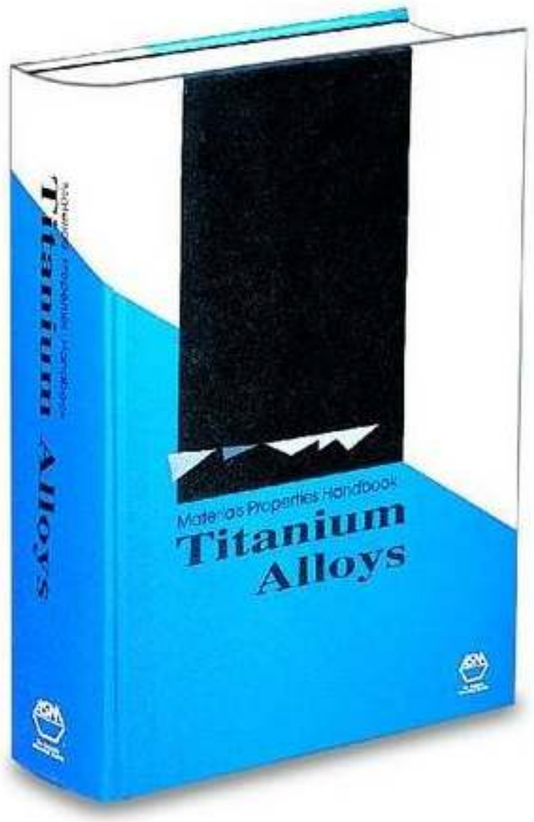

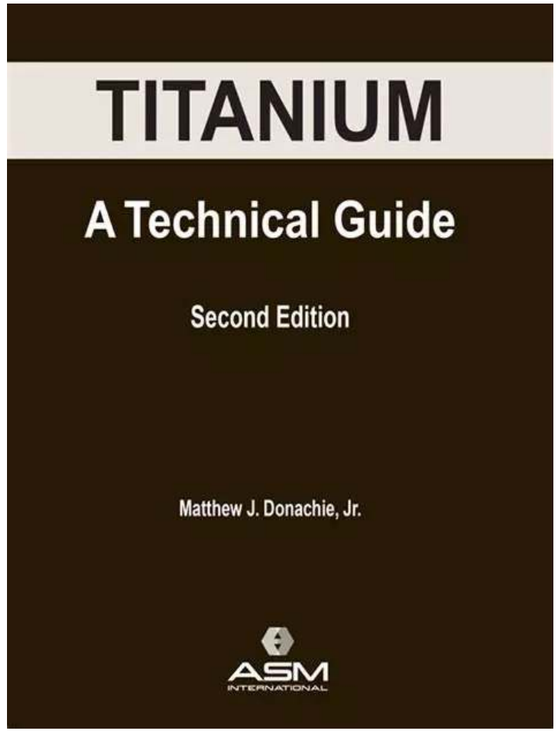

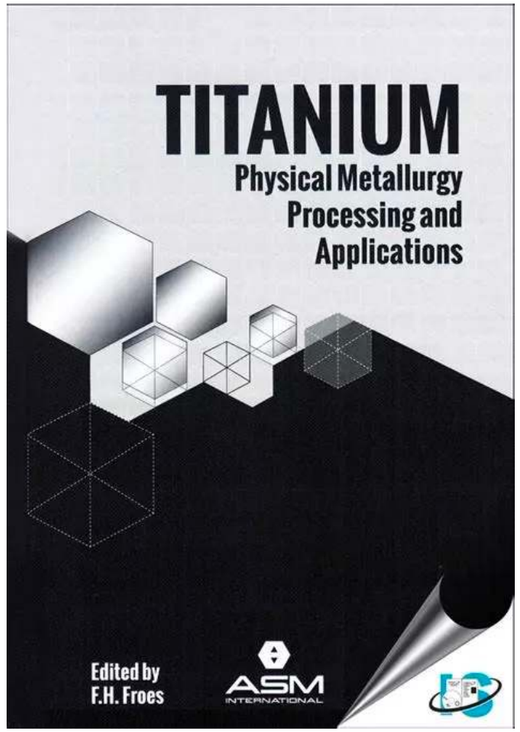

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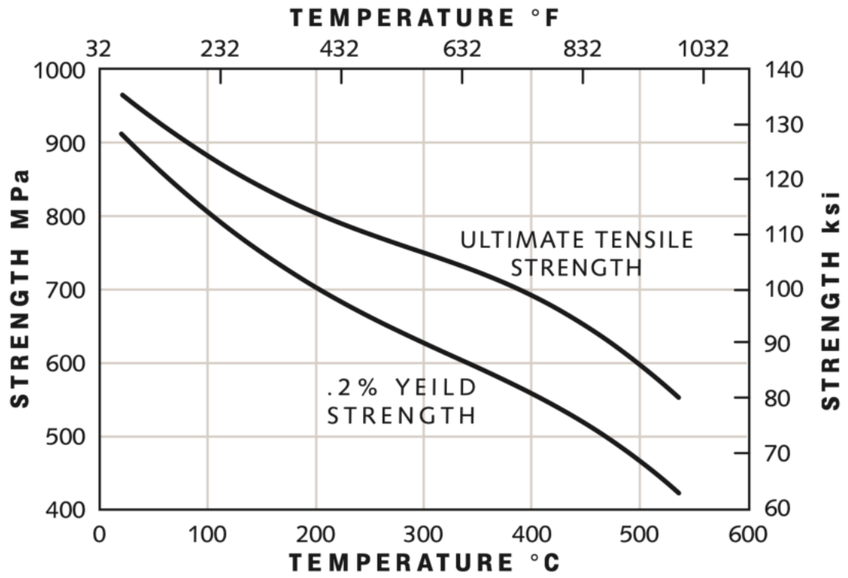
Propriétés

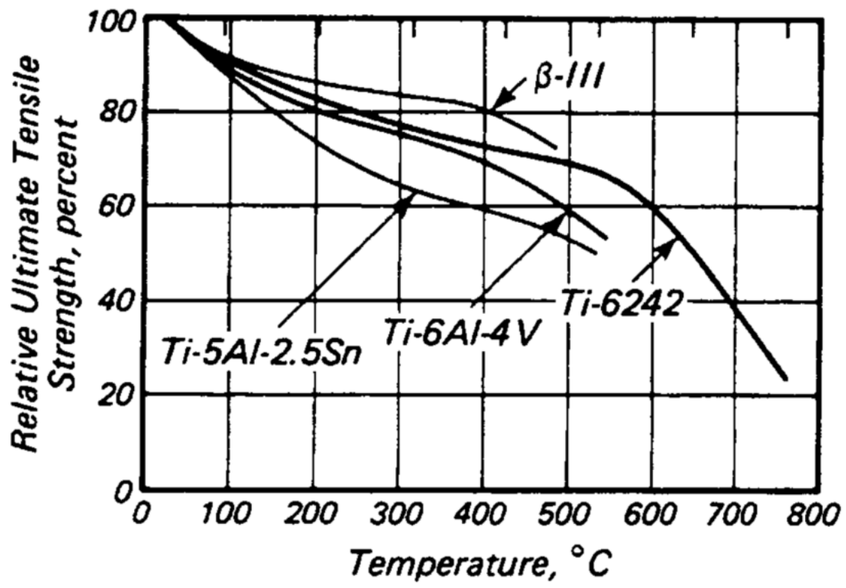
Conçu principalement pour une résistance élevée à des températures faibles à modérées

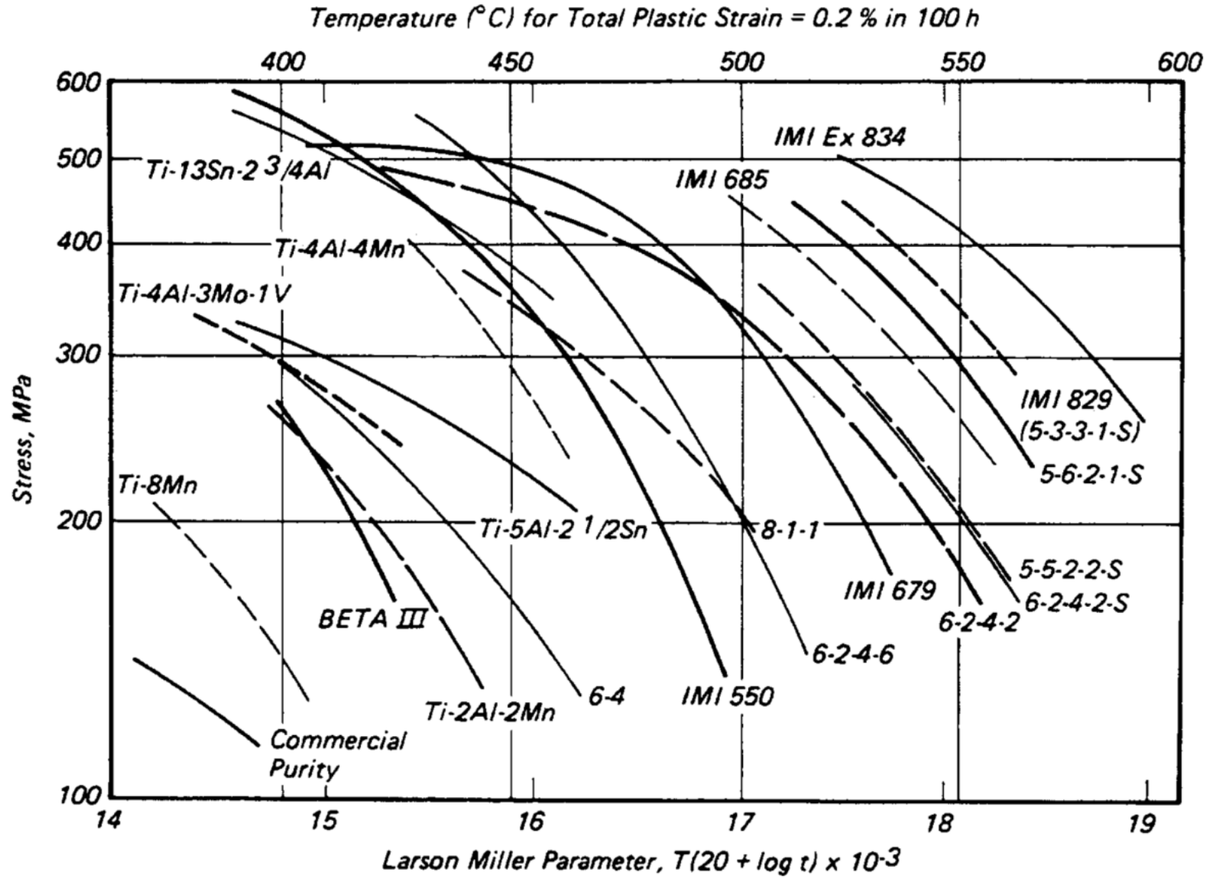
- résistance spécifique élevée
- une bonne résistance à la corrosion
- stabilité à des températures allant jusqu'à 400°C

Condition	Yield strength MPa	Yield strength ksi	Tensile strength MPa	Tensile strength ksi	Elongation at fracture, %
Mill annealed	945	137	1069	155	10
Duplex annealed	917	133	965	140	18
Solution treated and aged	1103	160	1151	167	13

Propriétés en température







Composition

Grade 5

- $c_{\mathrm{Al}} \in$ [5,5 – 6,75] %
- $c_{\mathrm{V}} \in$ [3,5 – 4,5] %
- $c_{\mathrm{O}} \in$ [800 – ~2000] ppm
  en fonction de l'application
- $c_{\mathrm{N}} \leq$ 0,05 %
- $c_{\mathrm{Fe}} \leq$ 0,25 %

Augmenter les teneurs en O et N

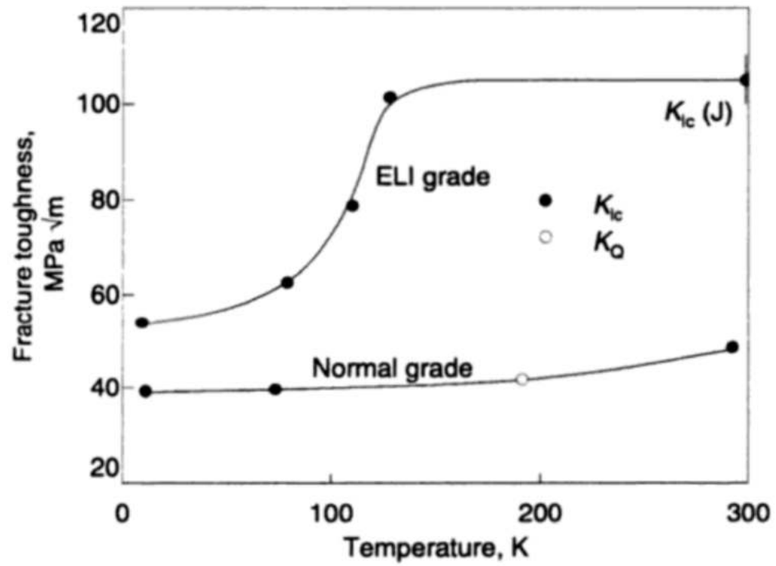
- augmente la résistance

Abaisser O, N et Al améliorent

- la ductilité
- la résistance à la croissance des fissures
- la résistance à la corrosion sous contrainte

Grade 23 ELI : Extra-Low Interstitial

- Faibles teneurs en O et en Fe
- Propriétés de tolérance aux dommages élevées, en particulier à des températures cryogéniques



TA6V-Pd

- ~0,2 % Pd pour une meilleure résistance à la corrosion

Composition

Product specification(s)	Impurity limits, wt% max N	C	H	Fe	O	Max others, each or total	Alloying elements, wt%(a) Al	Sn	Zr	Mo	Others
Ti-6Al-4V (UNS R56400)											
Typical	0.05	0.10	(b)	0.3	0.2	…	6	…	…	…	4
Alloy Ti-P63 in AECMA standard prEN2530 for bars	0.05	0.08	0.01	0.3	0.2	0.4 total	5.5–6.75	…	…	…	3.5–4.5V
Alloy Ti-P63 in AECMA standard prEN2517 for sheet, strip, plate	0.05	0.08	0.012	0.3	0.2	0.4 total	5.5–6.75	…	…	…	3.5–4.5V
DIN 17851 (alloy WL3.7165)	0.05	0.08	0.015	0.3	0.2	…	5.5–6.75	…	…	…	3.5–4.5V
AMS 4905 (plate)	0.03	0.05	0.0125	0.25	0.12	(c), 0.005Y	5.6–6.3	…	…	…	3.6–4.4V
AMS 4906 (sheet, strip)	0.05	0.08	0.0125	0.30	0.20	0.4 total	5.5–6.75	…	…	…	3.5–4.5V
AMS 4911 (plate, sheet, strip)	0.05	0.08	0.015	0.30	0.20	(c), 0.005Y	5.5–6.75	…	…	…	3.5–4.5V
AMS 4920, 4928, 4934, and 4967 (rings, forgings, wires)	0.05	0.10	0.0125	0.30	0.20	(c), 0.005Y	5.5–6.75	…	…	…	3.5–4.5V
AMS 4954 (wire)	0.03	0.05	0.015	0.30	0.18	(c), 0.005Y	5.5–6.75	…	…	…	3.5–4.5V
ASTM B 265 (plate, sheet)	0.05	0.10	0.015	0.40	0.20	(c)	5.5–6.75	…	…	…	3.5–4.5V, 0.12–0.25Pd
ASTM F 467 (nuts) and F 468 (bolts)	0.05	0.10	0.0125	0.40	0.20	(c)	5.5–6.75	…	…	…	3.5–4.5V
Ti-6Al-4V-ELI (UNS R56401)											
AMS 4907 and 4930	0.05	0.08	0.0125	0.25	0.13	(c), 0.005Y	5.5–6.75	…	…	…	3.5–4.5V
AMS 4996 (billet)	0.04	0.10	0.0125	0.30	0.13–0.19	(d)	5.5–6.75	0.1 max	0.1 max	0.1 max	3.5–4.5V
ASTM F 135 (bar)	0.05	0.08	0.0125	0.25	0.13	…	5.5–6.75	…	…	…	3.5–4.5V
ASTM F 467 (nuts) and F 468 (bolts)	0.05	0.10	0.0125	0.40	0.20	…	5.5–6.75	…	…	…	3.5–4.5V

Composition

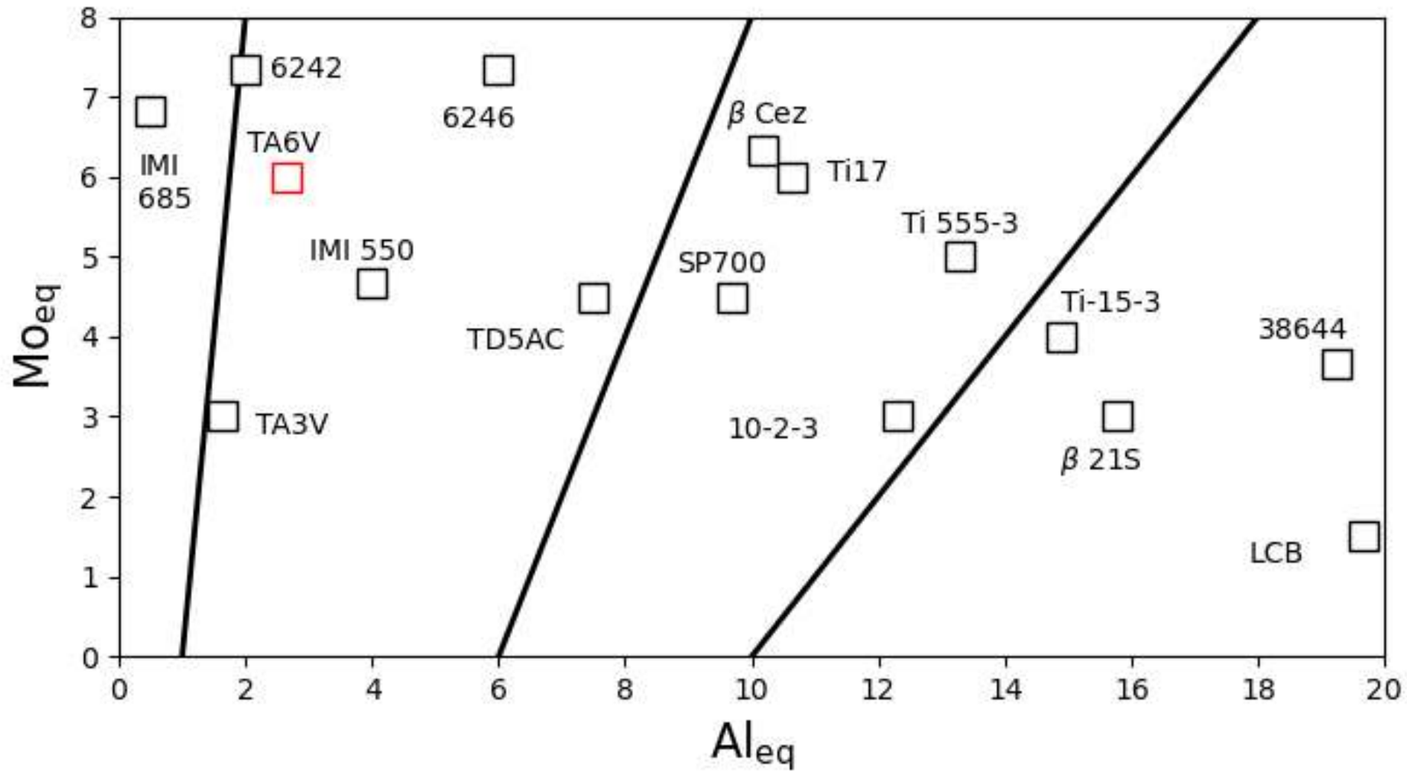
CHEMICAL COMPOSITION

ELEMENT	WEIGHT %					
	TIMETAL *6-4 ASTM Grade 5 Mil T-9047*		TIMETAL *6-4 ELI ASTM Grade 23 AMS 4981*		TIMETAL *6-4-.1Ru ASTM Grade 29*	
	Min.	*Max.*	*Min.*	*Max.*	*Min.*	*Max.*
Aluminum	5.5	6.75	5.5	6.5	5.5	6.5
Vanadium	3.5	4.5	3.5	4.5	3.5	4.5
Nitrogen	—	0.05	—	0.03	—	0.03
Carbon	—	0.08	—	0.08	—	0.08
Oxygen	—	0.20	—	0.13	—	0.13
Iron	—	0.40	—	0.25	—	0.25
Hydrogen	—	0.015	—	0.0125	—	0.015
Ruthenium	—	—	—	—	0.08	0.14
Resid. Elements, ea.	—	0.1	—	0.1	—	0.1
Resid. Elements, tot.	—	0.4	—	0.4	—	0.4

Composition : Al et Mo équivalents

Alloy classification and composition, wt.%	Aluminum equivalency, wt. % [Al]	[Zr]/6	[Sn]/3	$[Al]_{eq}$	Molybdenum equivalency, wt.% [Mo]	[Ta]/5	[Nb]/3.6	[V]/1.5	1.25[Cr]	1.25[Ni]	1.7[Mn]	1.7[Co]	2.5[Fe]	$[Mo]_{eq}$
Alpha and near-alpha alloys														
Ti-0.8Ni-0.3Mo	...	...	...	...	0.3	...	...	...	...	1.0	...	...	...	**1.3**
Ti-5Al-2.5Sn	5.0	...	0.8	**5.8**	...	...	...	...	...	...	...	...	...	...
Ti-8Al-1Mo-1V	8.0	...	...	**8.0**	1.0	...	...	0.7	...	...	...	...	...	**1.7**
Ti-6Al-2Sn-4Zr-2Mo-0.1Si	6.0	0.7	0.7	**7.4**	2.0	...	...	...	...	...	...	...	...	**2.0**
Ti-6Al-2Nb-1Ta-0.8Mo	6.0	...	...	**6.0**	0.8	0.2	0.6	...	...	...	...	...	...	**1.6**
Ti-2.25Al-11Sn-5Zr-1Mo	2.3	0.8	3.7	**6.8**	1.0	...	...	...	...	...	...	...	...	**1.0**
Ti-5Al-5Sn-2Zr-2Mo	5.0	0.3	1.7	**7.0**	2.0	...	...	...	...	...	...	...	...	**2.0**
Alpha-beta alloys														
Ti-6Al-4V	6.0	...	...	**6.0**	...	...	...	2.7	...	...	...	...	...	**2.7**
Ti-6Al-6V-2Sn	6.0	...	0.7	**6.7**	...	...	...	4.0	...	...	...	...	...	**4.0**
Ti-7Al-4Mo	7.0	...	...	**7.0**	4.0	...	...	...	...	...	...	...	...	**4.0**
Ti-4.5Al-5Mo-1.5Cr	4.5	...	...	**4.5**	5.0	...	...	...	1.9	...	...	...	...	**6.9**
Ti-6Al-2Sn-4Zr-6Mo	6.0	0.7	0.7	**7.4**	6.0	...	...	...	...	...	...	...	...	**6.0**
Ti-5Al-2Sn-2Zr-4Mo-4Cr	5.0	0.3	0.7	**6.0**	4.0	...	...	...	5.0	...	...	...	...	**9.0**
Ti-6Al-2Sn-2Zr-2Mo-2Cr	6.0	0.3	0.7	**7.0**	2.0	...	...	...	2.5	...	...	...	...	**4.5**
Ti-3Al-2.5V	3.0	...	...	**3.0**	...	...	...	1.7	...	...	...	...	...	**1.7**
Ti-10V-2Fe-3Al	3.0	...	...	**3.0**	...	...	...	6.7	...	...	...	...	5.0	**11.7**

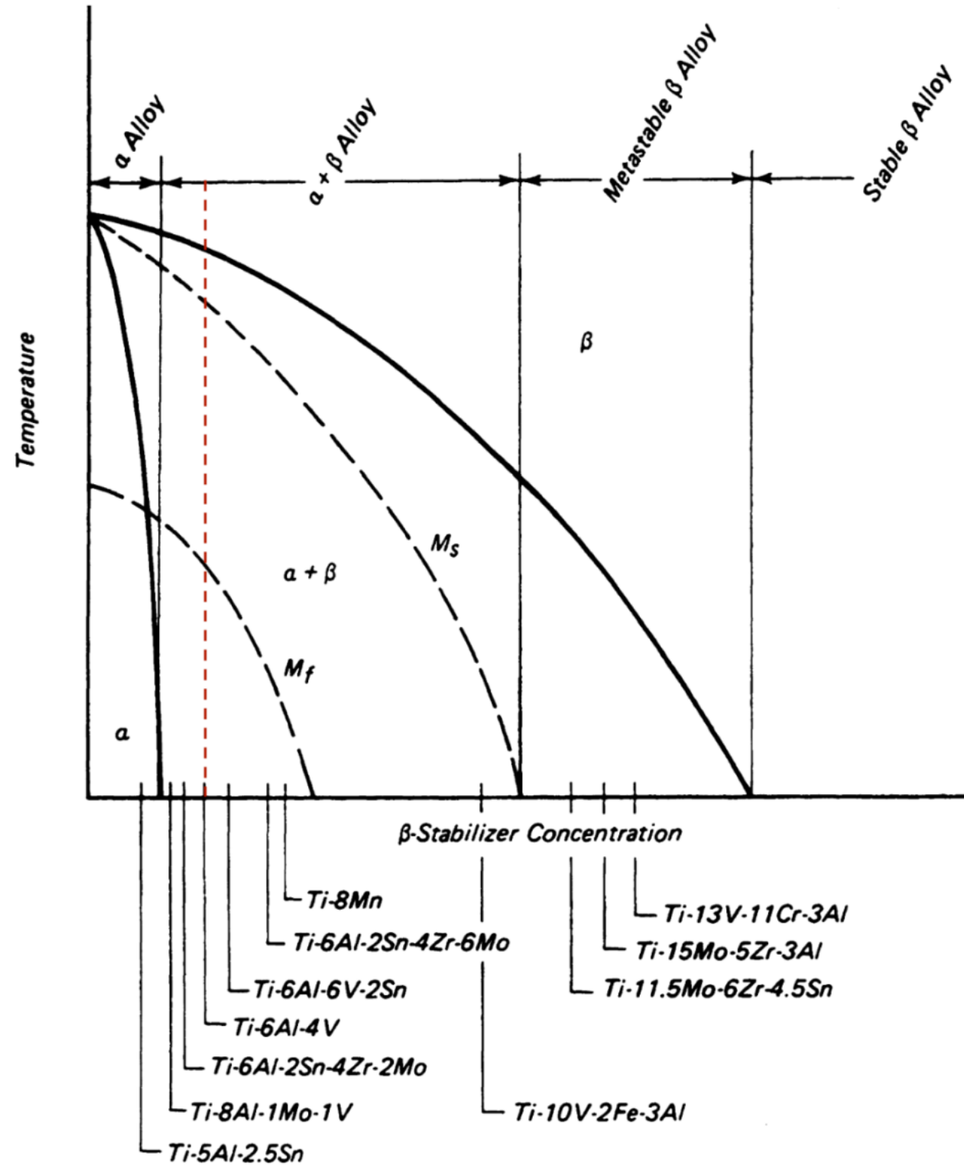
Composition : Al et Mo équivalents



Phases

Alliage $\alpha + \beta$

100% de martensite α' lors d'une trempe depuis β ($M_f > T_{\text{amb}}$)



Phases

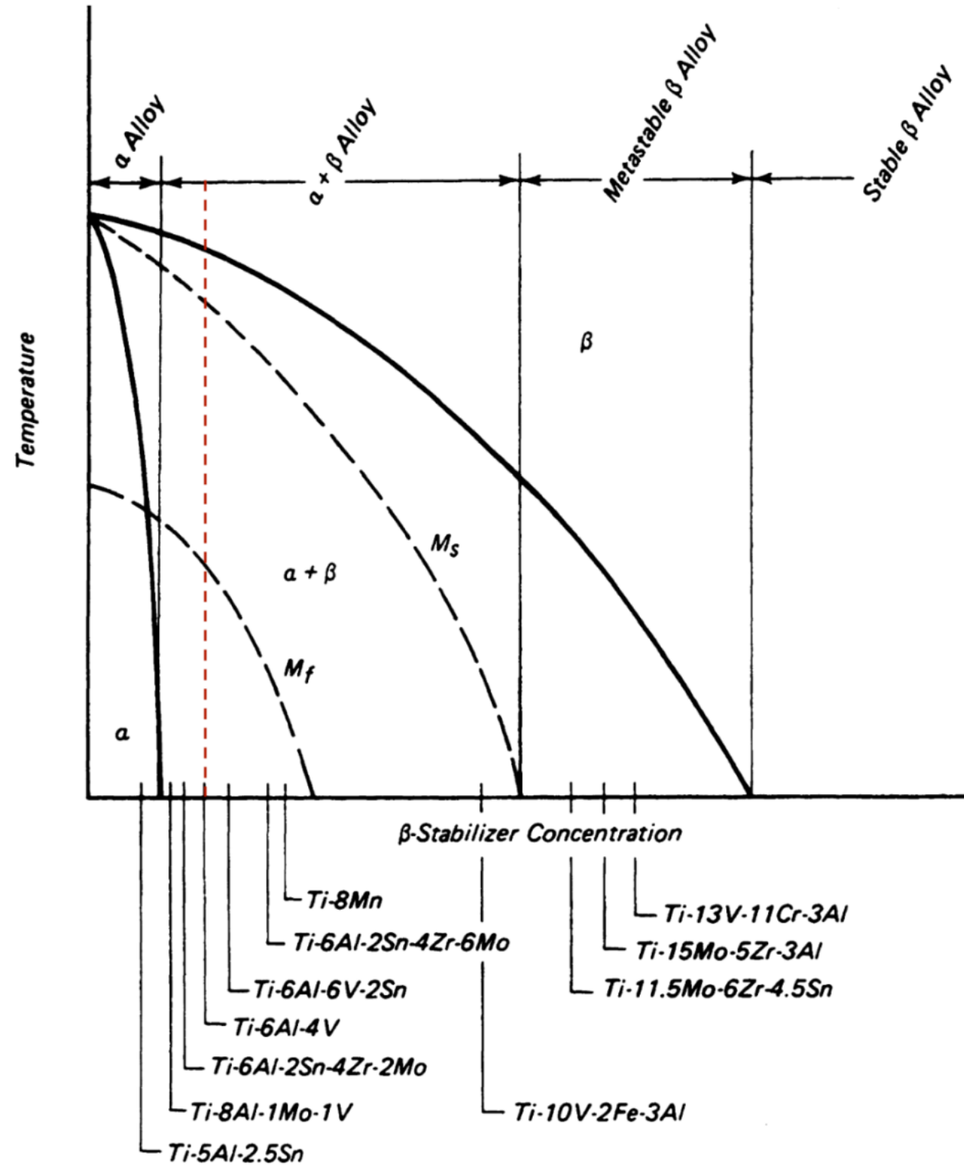
d'équilibre

Lorsque la température diminue

- $f_\alpha \nearrow$
- $c_{\mathrm{V}}^{\beta} \nearrow$

Suite à un refroidissement lent, à l'ambiante

- $f_\alpha \approx 90\ \%$
- β stable quand $c_{\mathrm{V}}^{\beta}(T_{\mathrm{amb}}) > 15\%$



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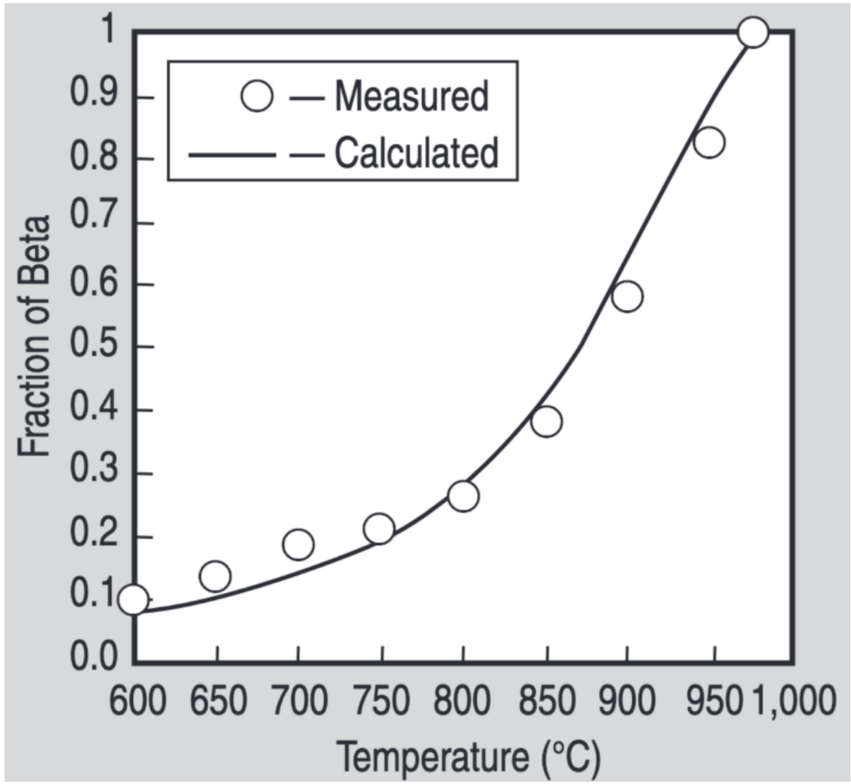
$$f_\alpha(T) = 0,925\left[1 - \exp\left(-8,5 \times 10^{-3}\Delta T\right)\right]$$

avec $\Delta T = T_\beta - T$

Prédictions CalPhaD



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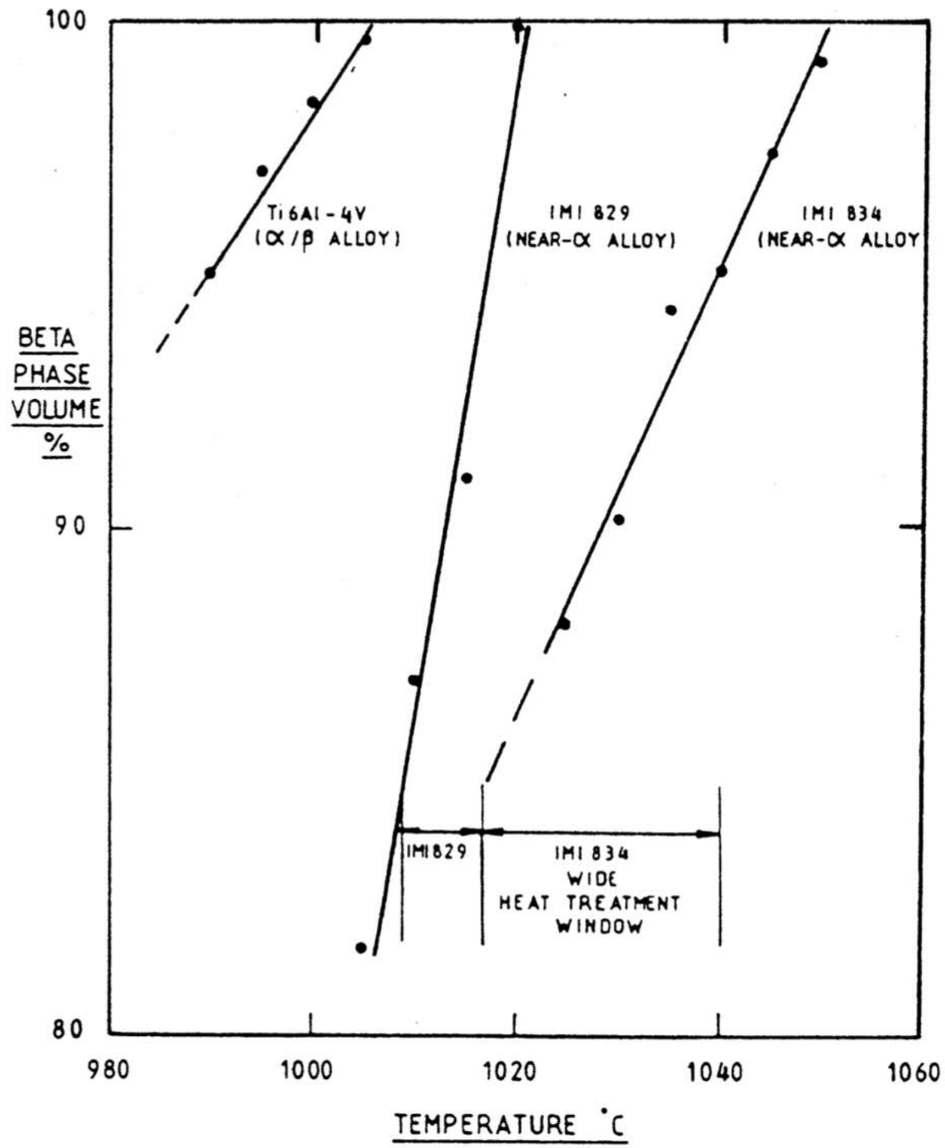

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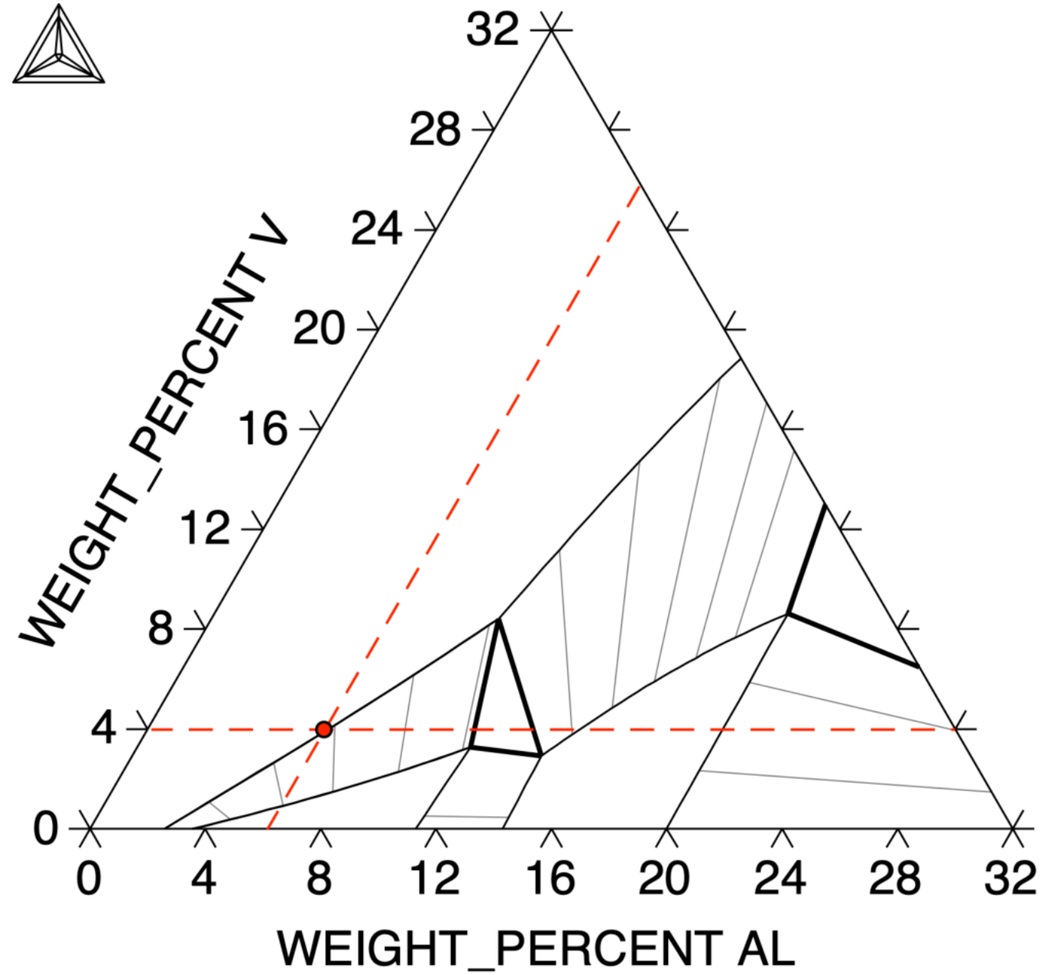

947°C

Phases

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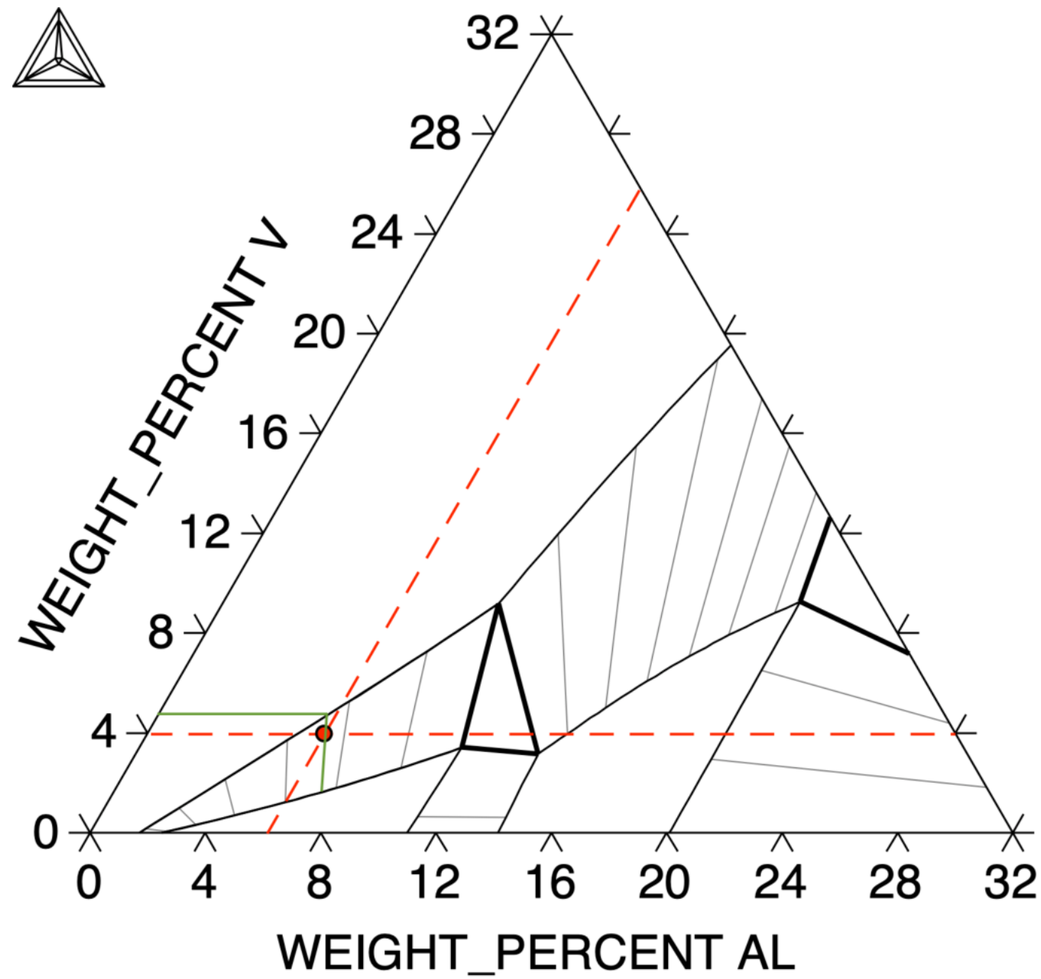

927°C

Phases

d’équilibre

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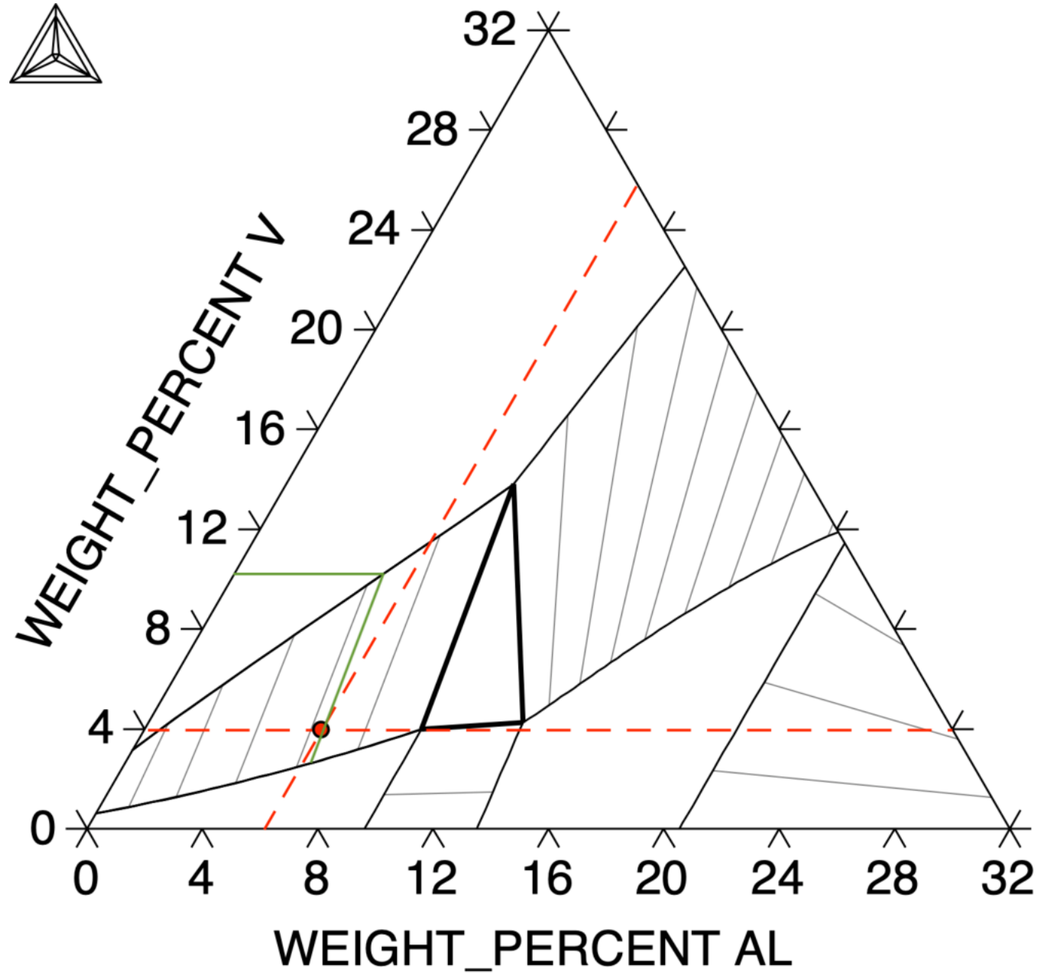
avec $\Delta T = T_\beta - T$

Prédictions CalPhaD



827°C

Phases

d’équilibre

Lorsque la température diminue

- $f_\alpha \nearrow$
- $c_{\mathrm{V}}^{\beta} \nearrow$

Suite à un refroidissement lent, à l’ambiante

- $f_\alpha \approx 90\ \%$
- β stable quand $c_{\mathrm{V}}^{\beta}(T_{\mathrm{amb}}) > 15\%$

Fraction de phase à l’équilibre [Castro, Seraphin, 1966] :

$$f_\alpha(T) = 0,925\left[1 - \exp\left(-8,5 \times 10^{-3}\Delta T\right)\right]$$

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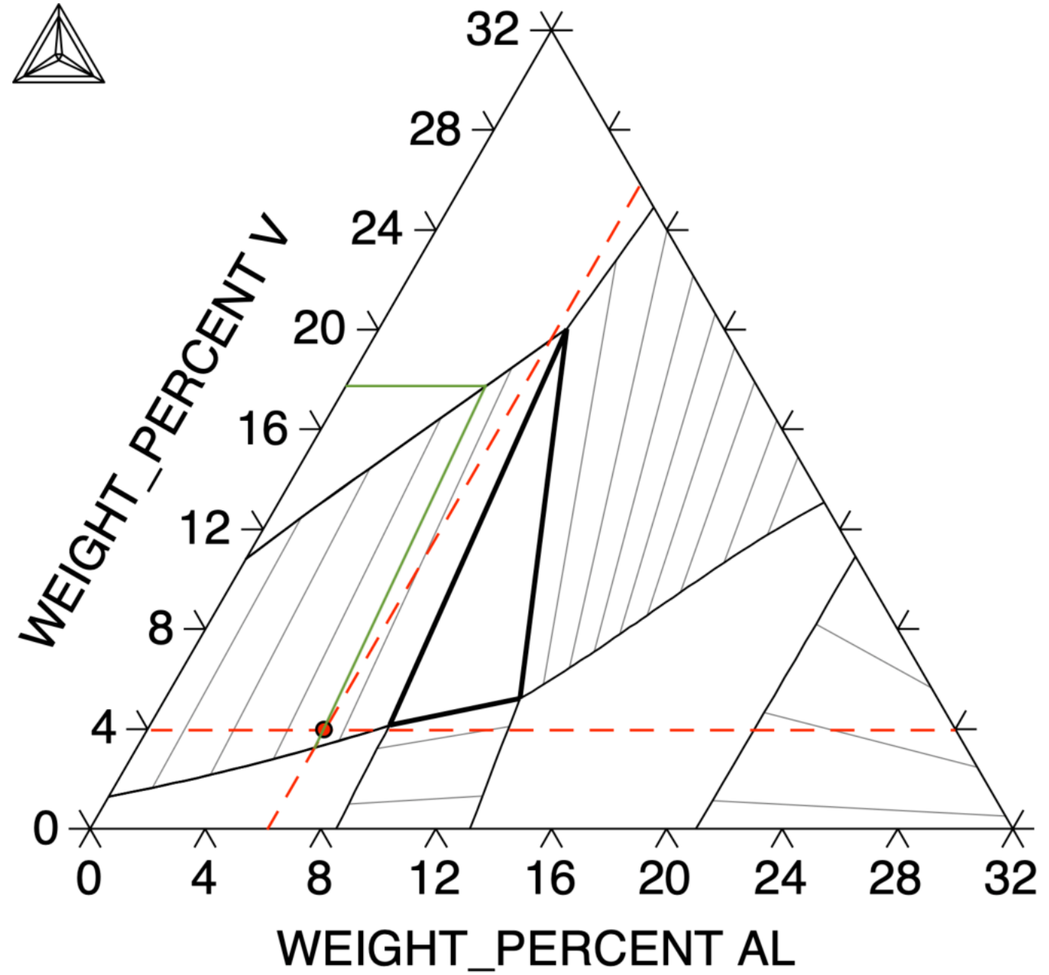
Prédictions CalPhaD



Phases

d’équilibre

Lorsque la température diminue

- $f_\alpha \nearrow$
- $c_{\mathrm{V}}^{\beta} \nearrow$

Suite à un refroidissement lent, à l’ambiante

- $f_\alpha \approx 90\,\%$
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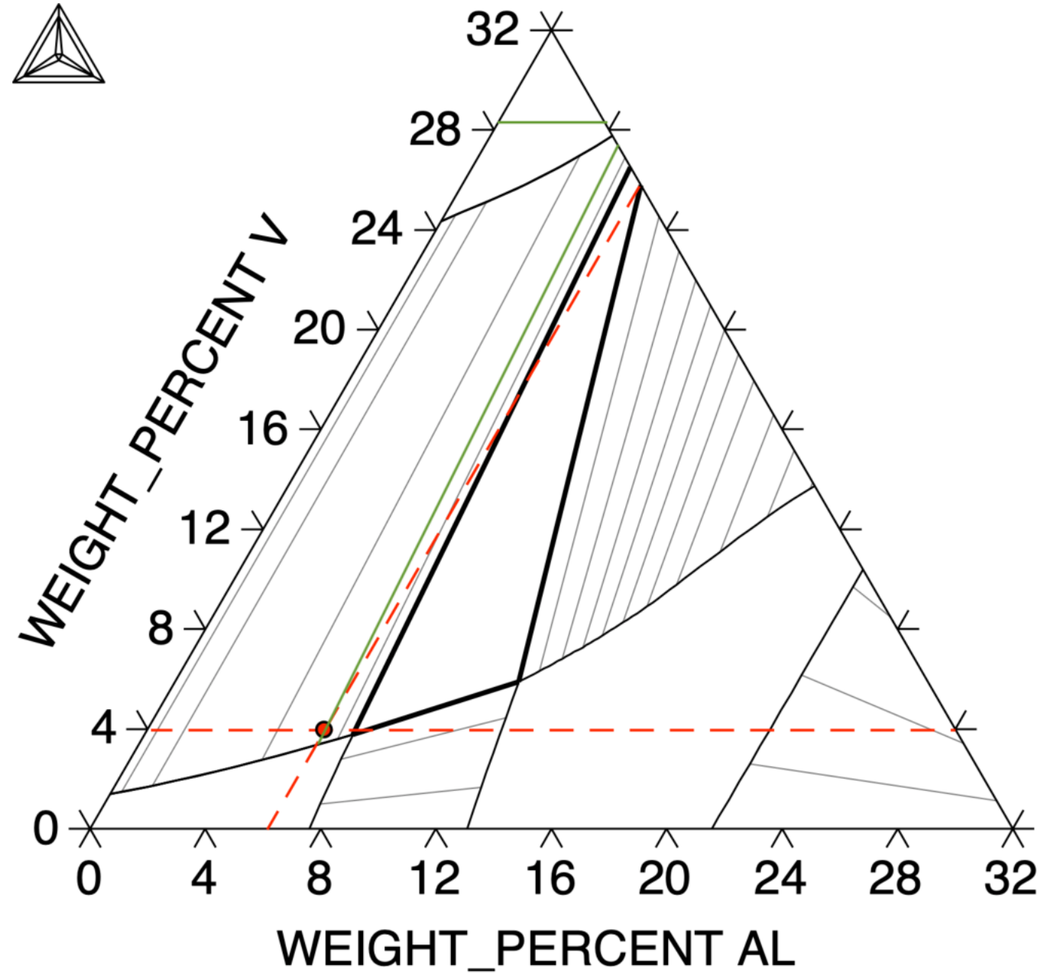
Fraction de phase à l’équilibre [Castro, Seraphin, 1966] :

$$f_\alpha(T) = 0,925\left[1 - \exp\left(-8,5 \times 10^{-3}\Delta T\right)\right]$$

avec $\Delta T = T_\beta - T$

Prédictions CalPhaD



Phases

d'équilibre ?

Lorsque la température diminue

- $f_\alpha \nearrow$
- $c_{\mathrm{V}}^{\beta} \nearrow$

Suite à un refroidissement lent, à l'ambiante

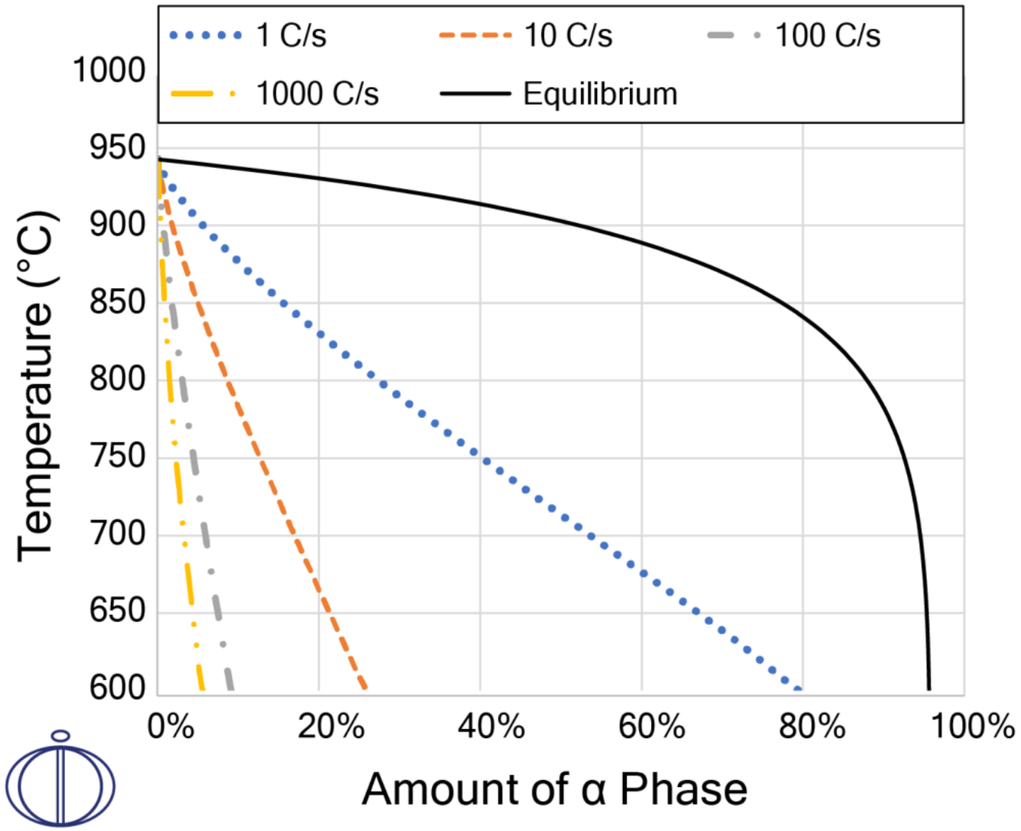
- $f_\alpha \approx 90\,\%$
- β stable quand $c_{\mathrm{V}}^{\beta}(T_{\mathrm{amb}}) > 15\%$

Fraction de phase à l'équilibre [Castro, Seraphin, 1966] :

$$f_\alpha(T) = 0,925\left[1 - \exp\left(-8,5 \times 10^{-3}\Delta T\right)\right]$$

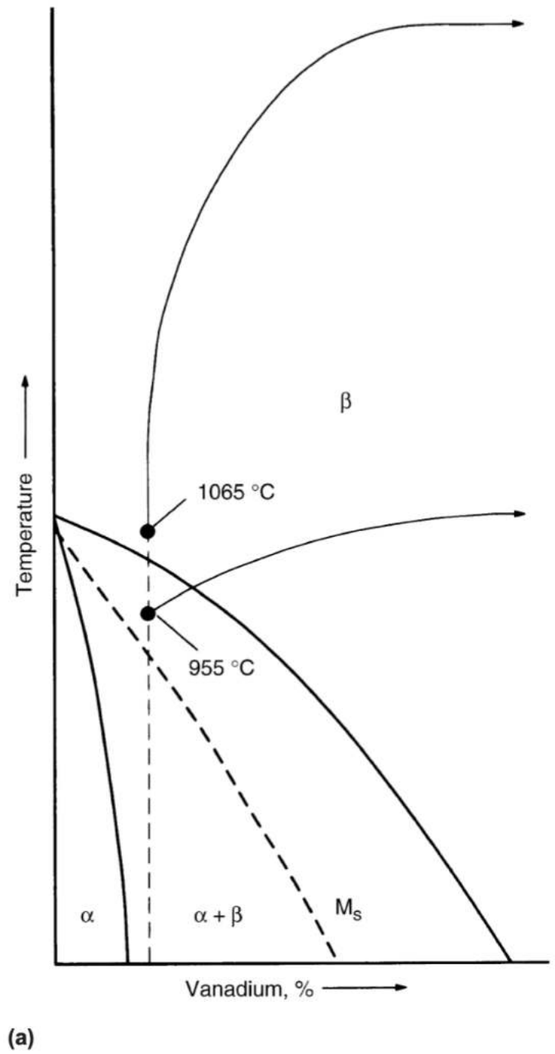
avec $\Delta T = T_\beta - T$

Prédictions CalPhaD

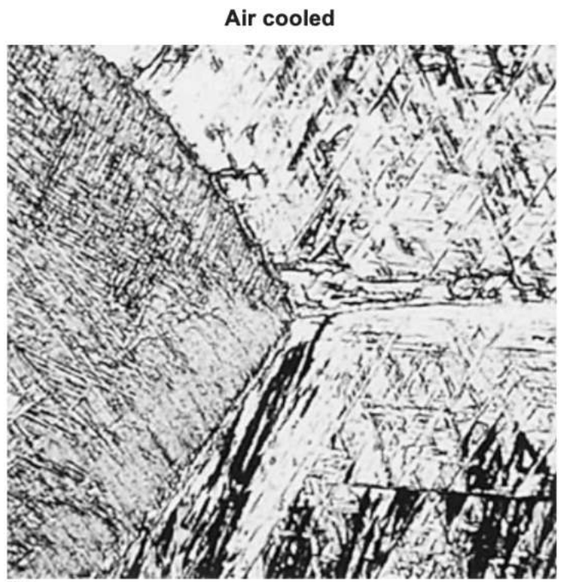


Microstructures

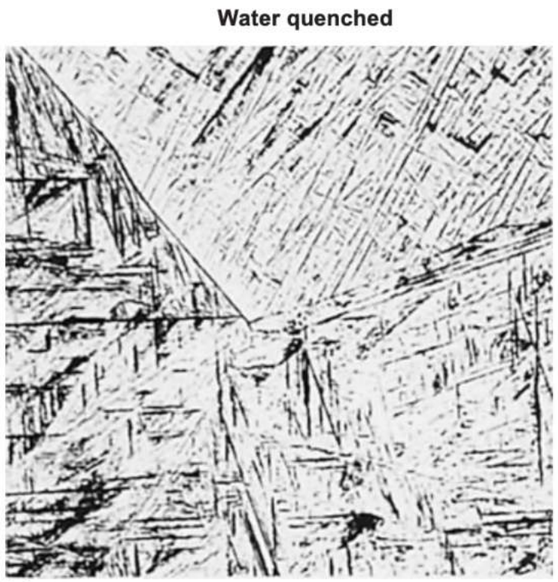
- Lamellaires
  - α
  - α'
- Équiaxe α
- Les deux (duplex)



(a)



(b)



(c)

(d)

(e)

Microstructures

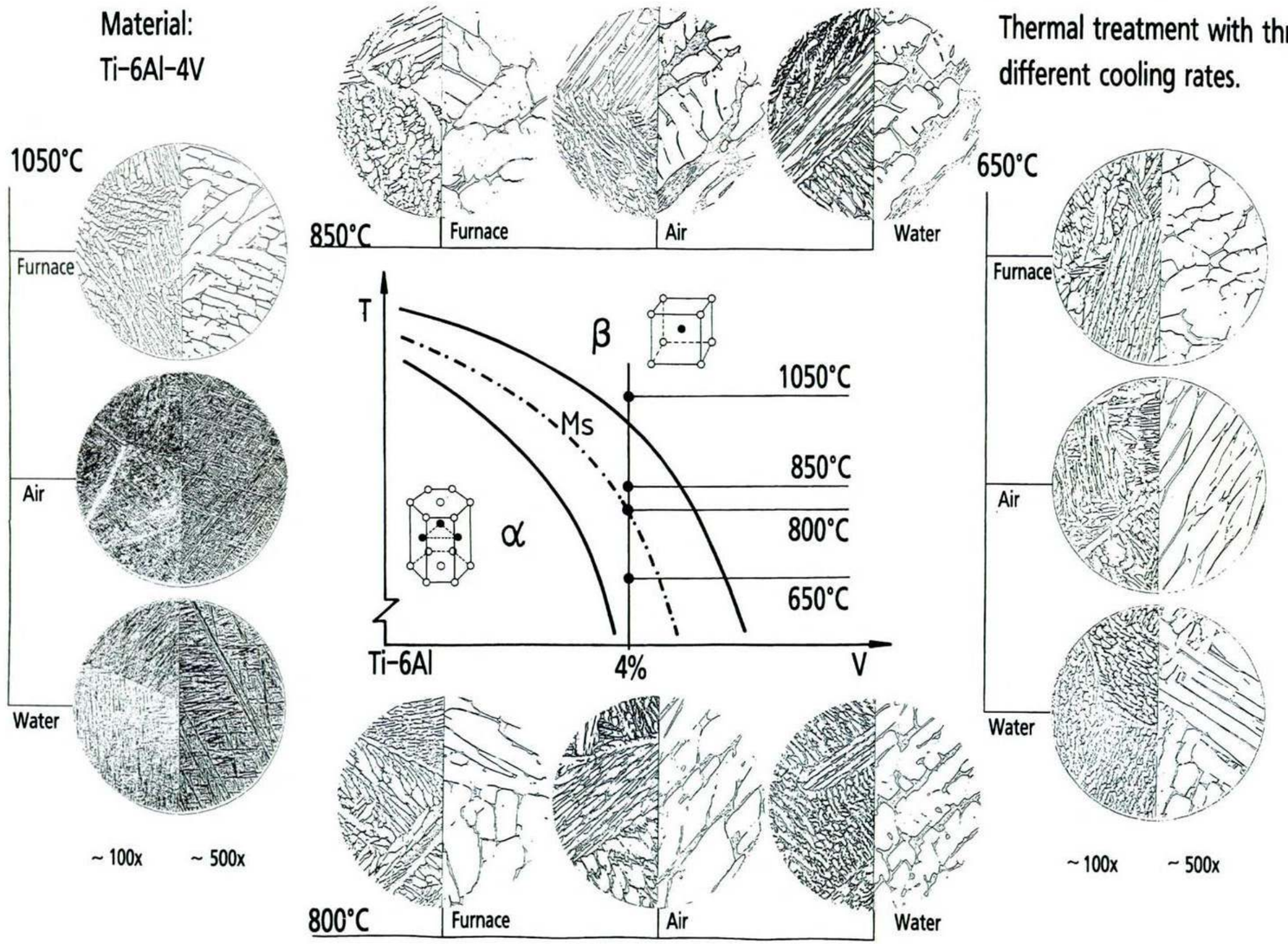
Lamellaires

Refroidissements depuis β

- lent = α (grossier)
- rapide = α' (fin)

Refroidissements depuis $\alpha + \beta$

- = α (grossier)

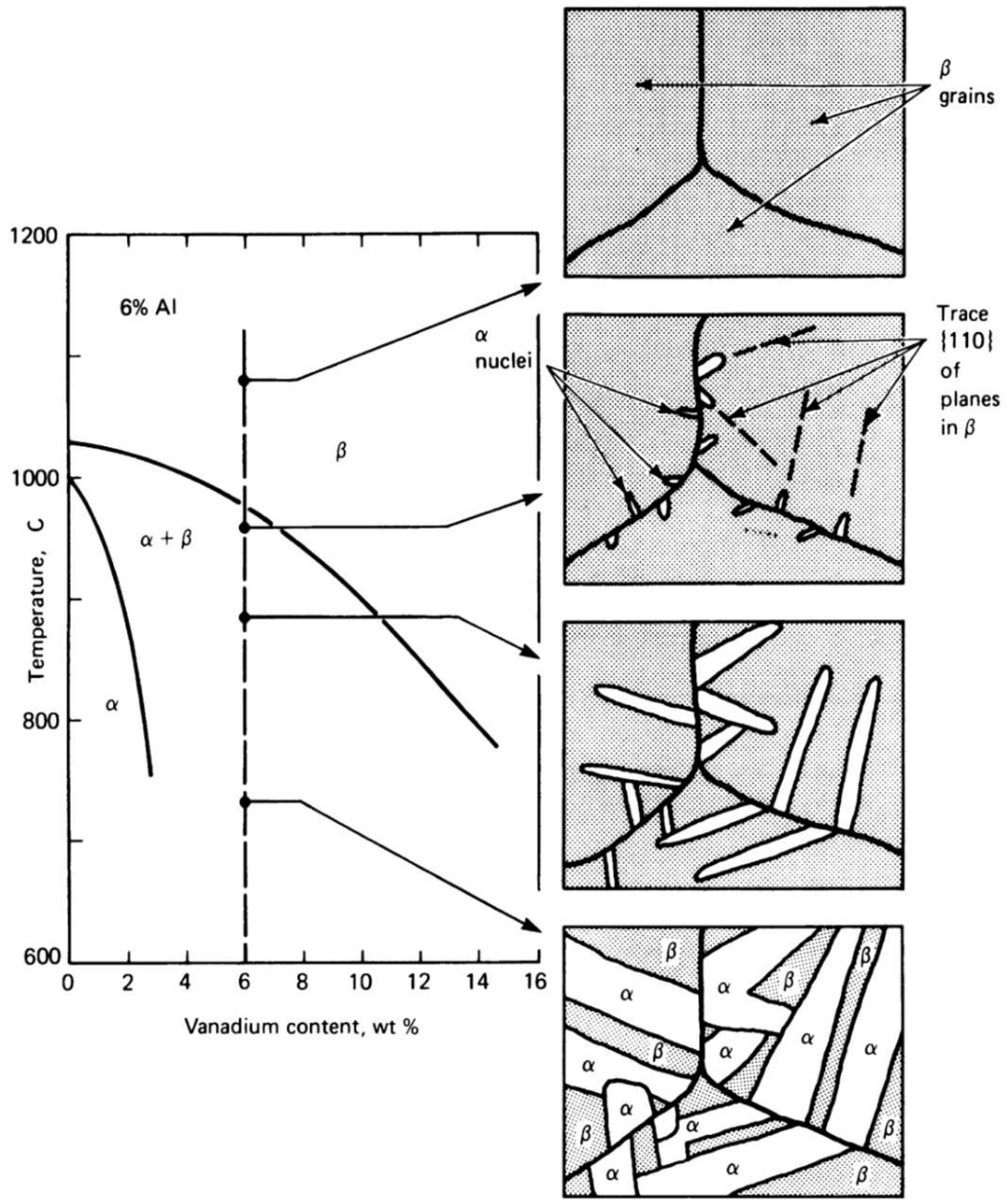


Microstructures

Lamellaires α

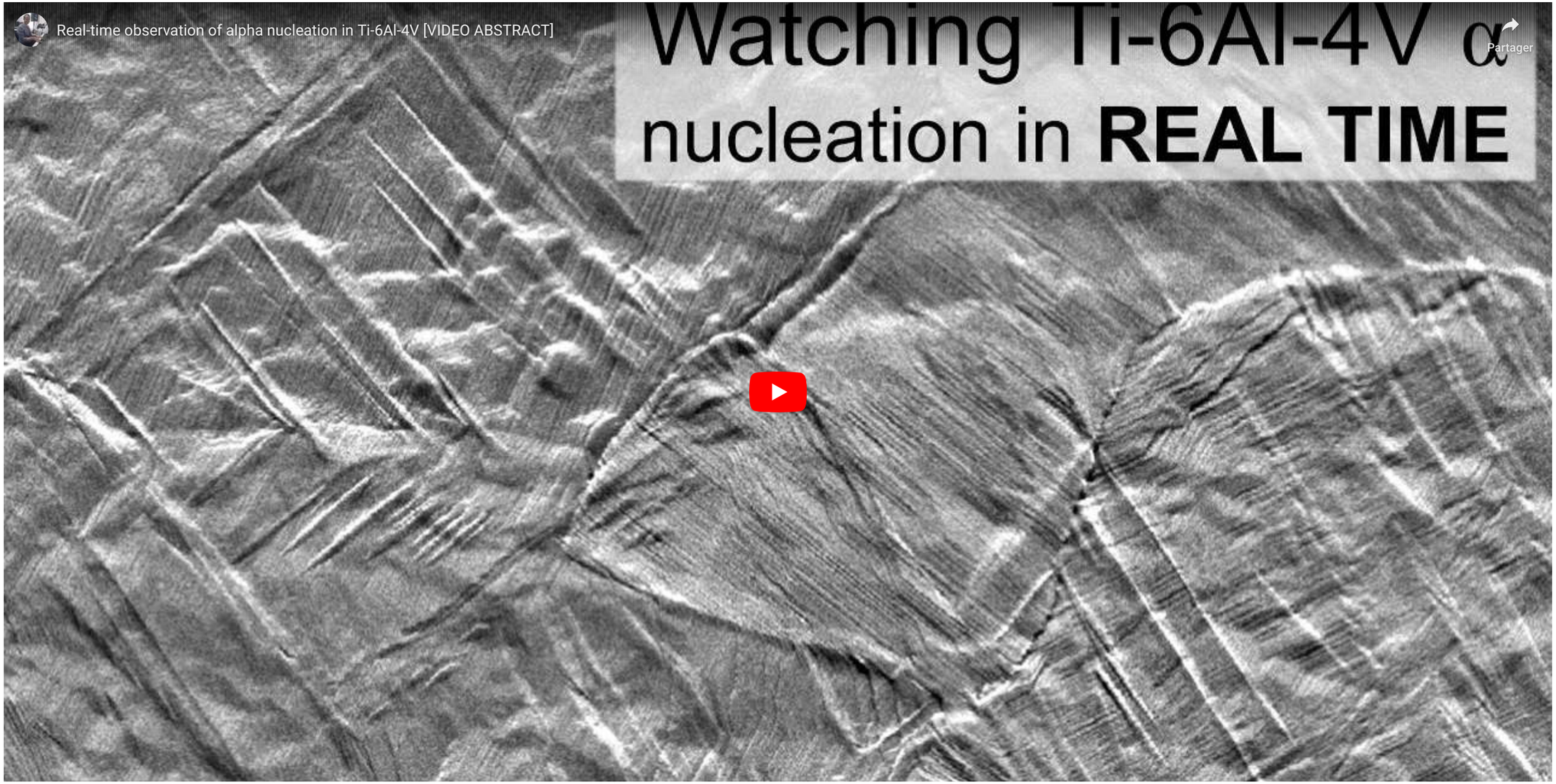
Refroidissements depuis β

- Germination aux jdg β
- Croissance des plaquettes vers l'intérieur
- Souvent en colonies



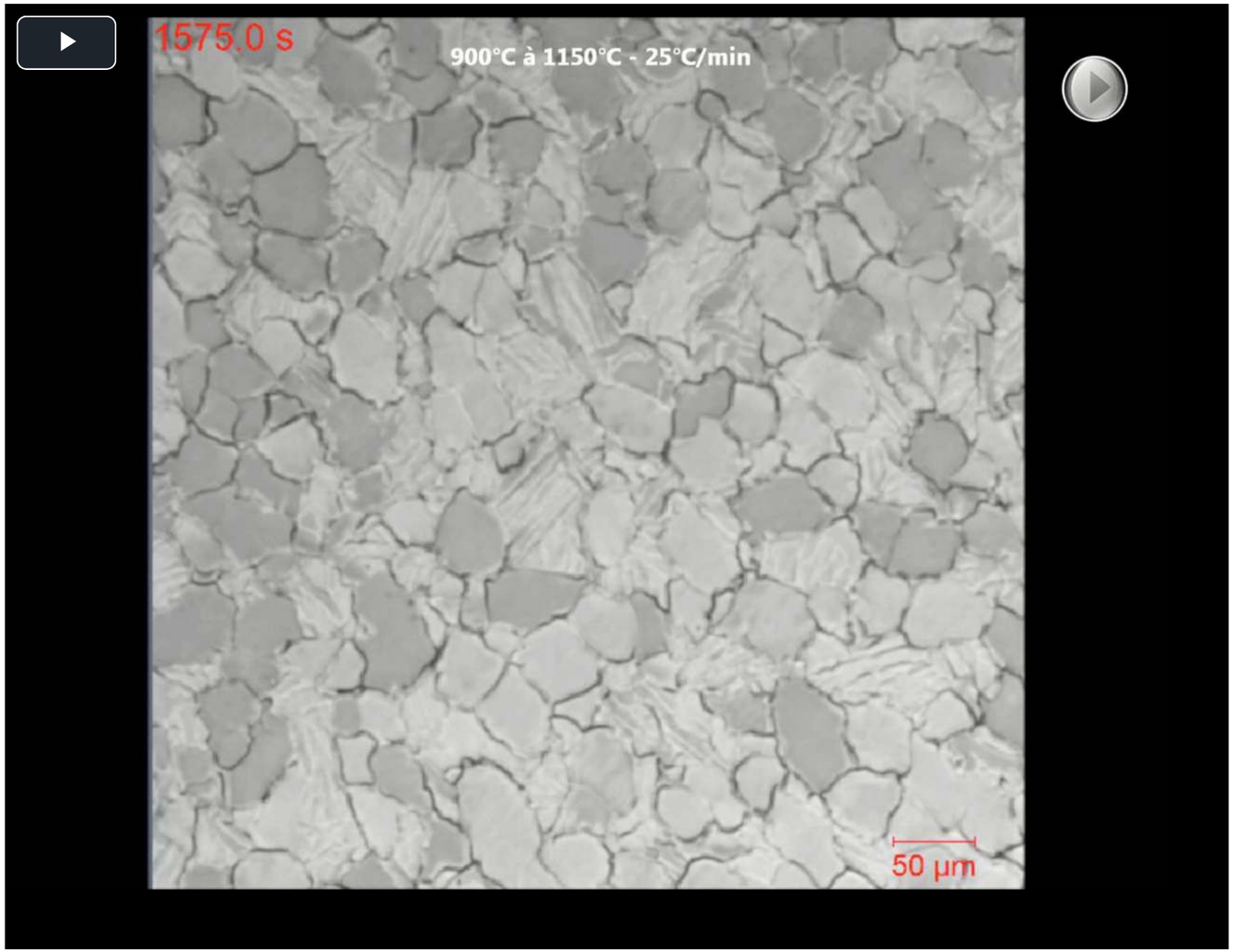
Microstructures

En direct de Manchester



Microstructures

En direct de Nancy

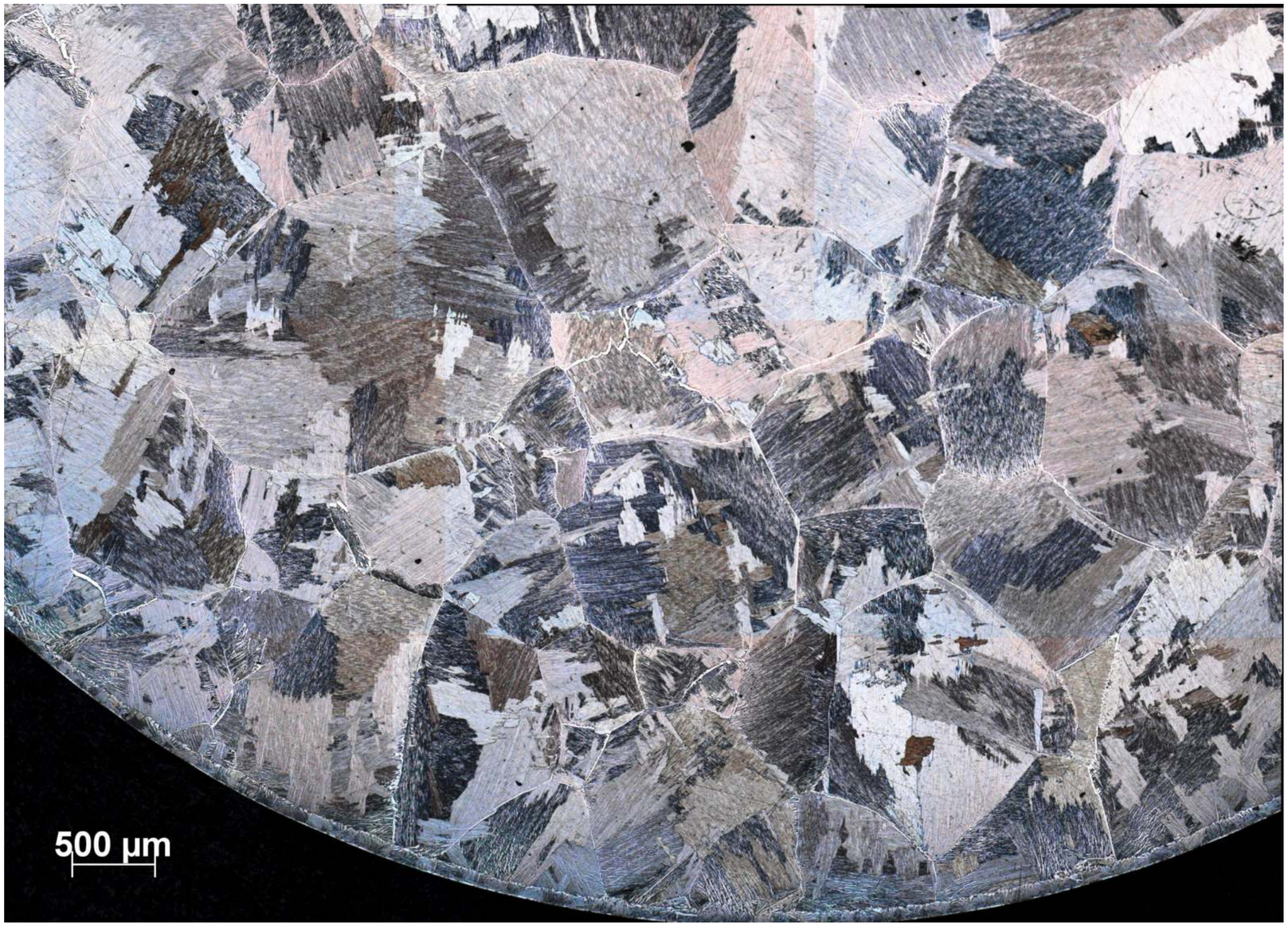


Florimonde Lebel 2010

Microstructures

Lamellaires α

Benoît Denand 2021

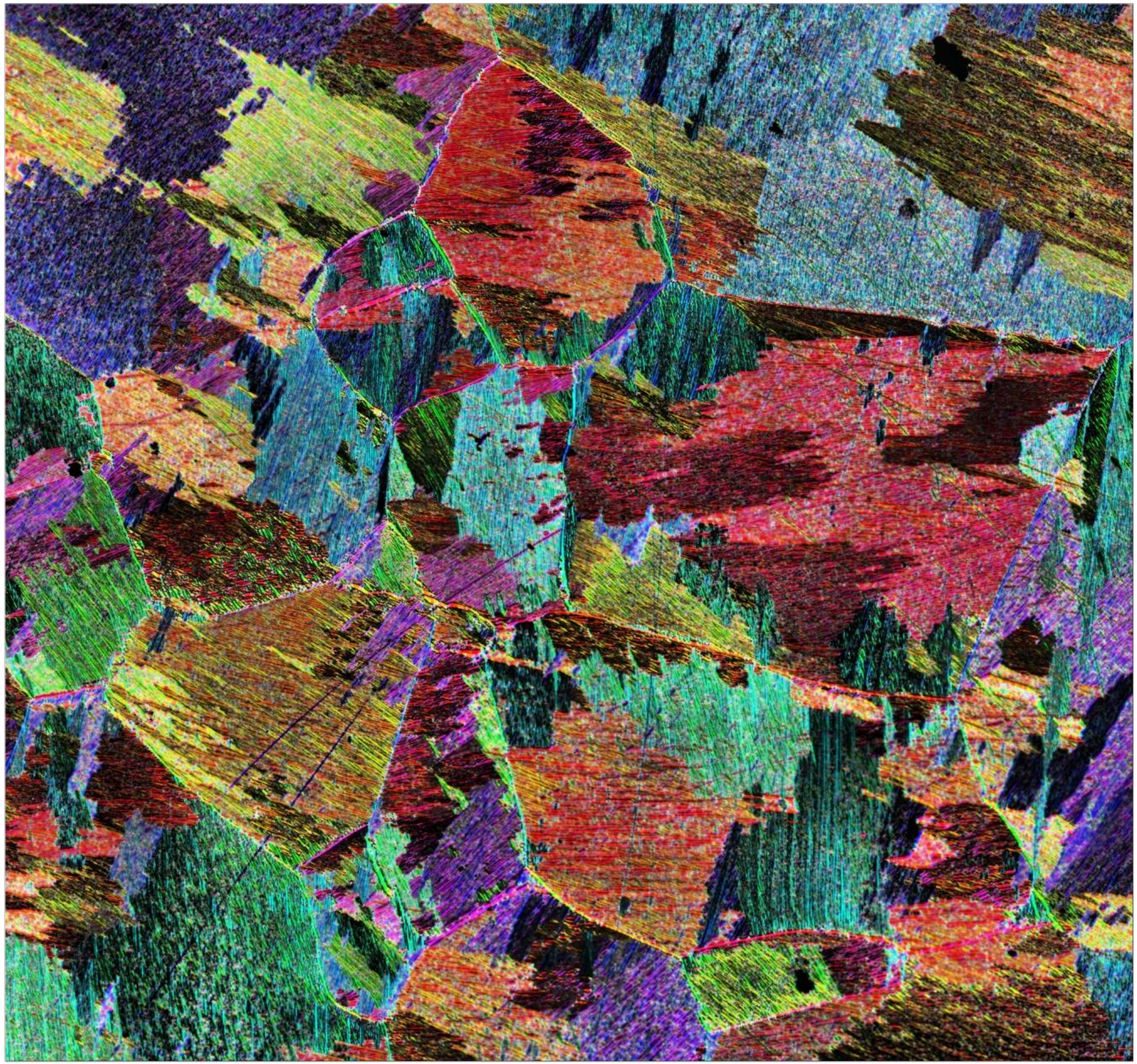


Microstructures

Lamellaires α

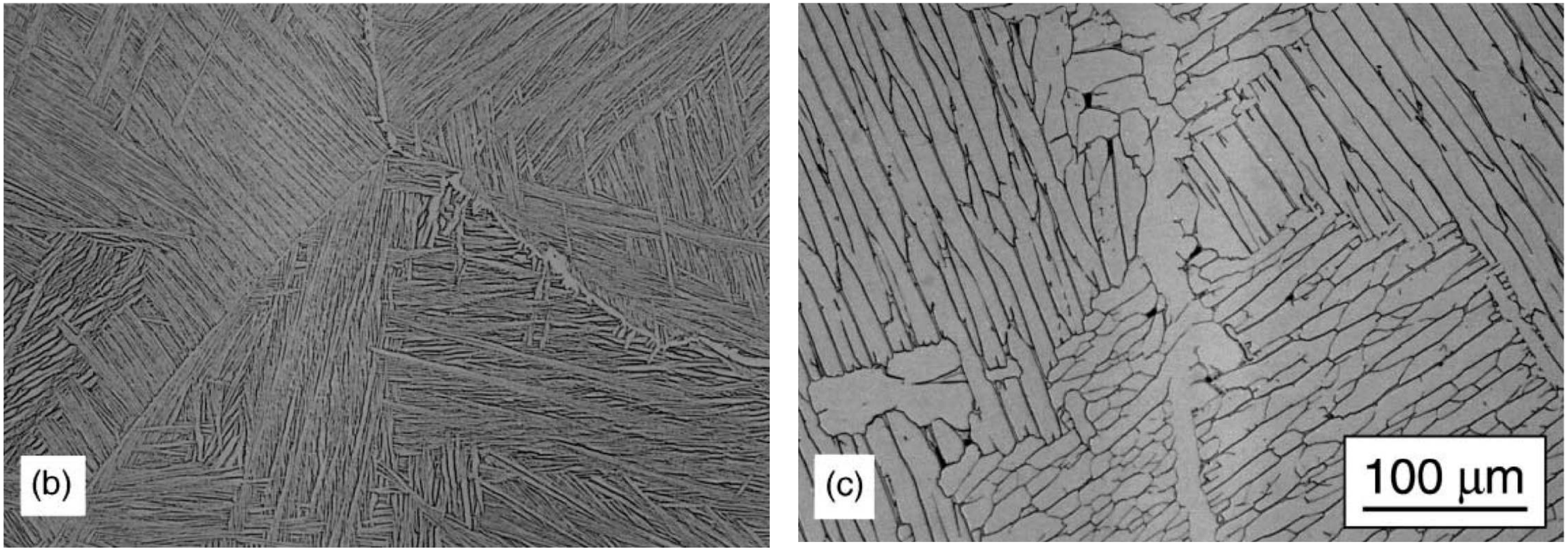
Benoît Denand 2021

(coloriage B Appolaire)



Microstructures

Lamellaires α



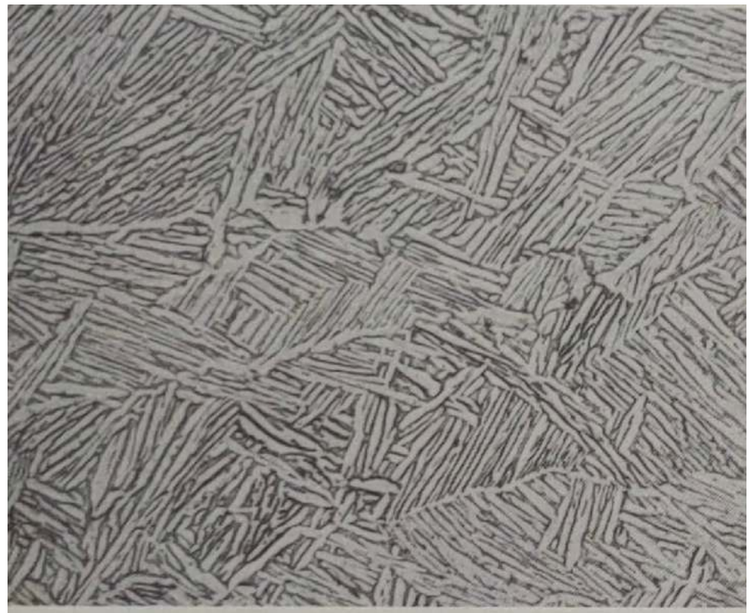
Semiatin, Bieler 2001

Microstructures

Lamellaires α : rien n'a changé

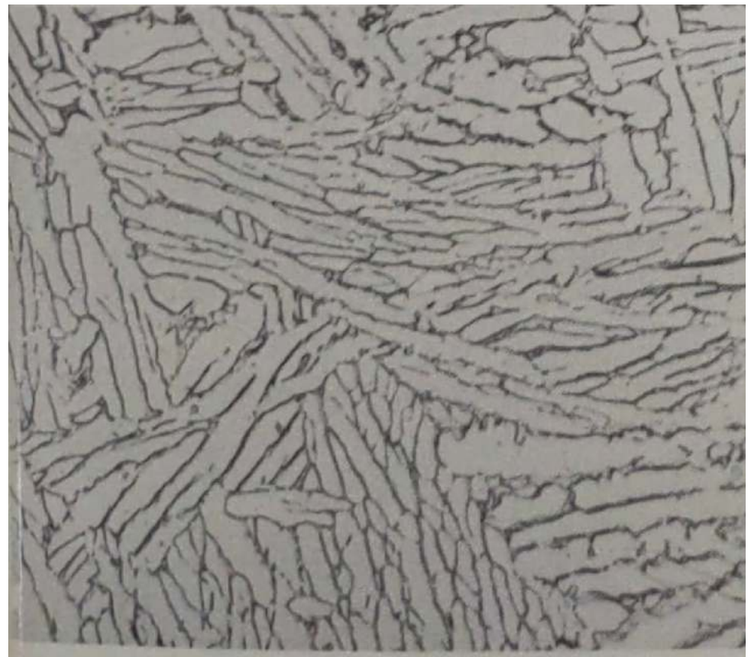
2 HF, 8 HNO_3, 90 H_2O 200×

2710 Ti-6Al-4V extrusion, heated for ½ hr at 1850 F (1010 C), air cooled, then heated for 1 hr at 1250 F (677 C), air cooled. Structure: acicular alpha (transformed beta); alpha at prior beta grain boundaries.



Kroll's reagent (192) 250×

2725 Ti-6Al-4V, forged at 1900 F (1038 C), above the beta transus, air cooled, annealed 2 hr at 1300 F (704 C), and air cooled. Coarse, platelike alpha (light) and intergranular beta phase (dark). See also 2726 and 2727.



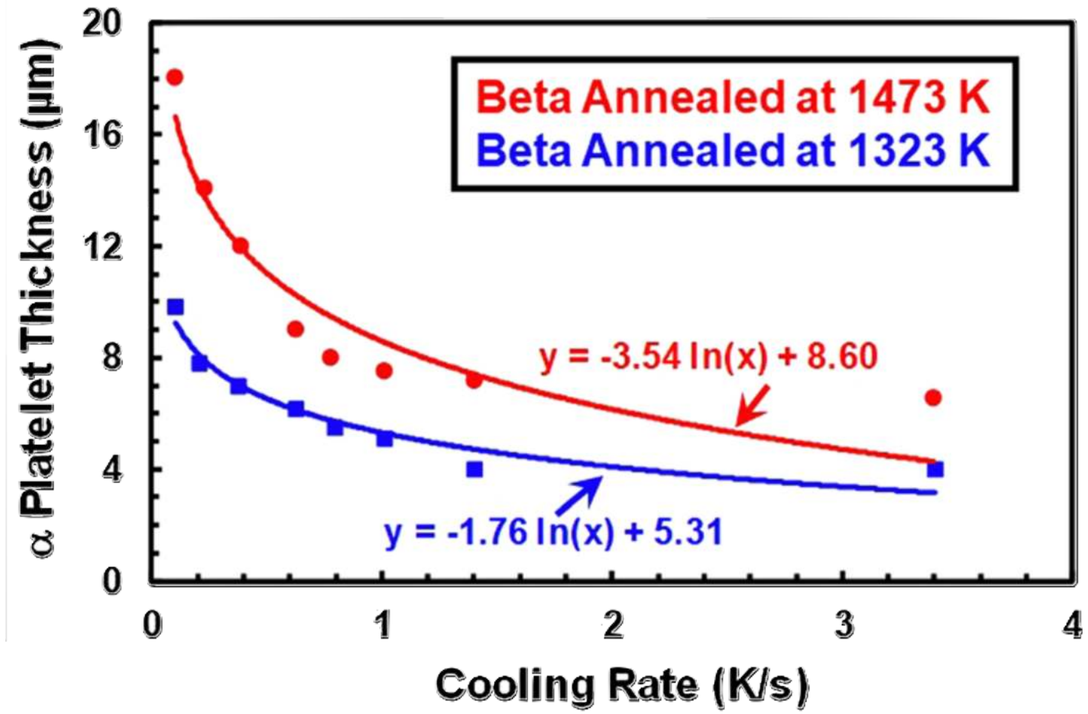
Kroll's reagent (192) 500×

2709 Ti-6Al-4V tube, 0.25-in. diam, annealed for 2 hr at 1300 F (704 C), furnace cooled at 300 F (167 C) per hour to 1000 F (538 C), and air cooled. The structure consists of transformed beta containing platelike alpha.

Atlas of microstructures of industrial alloys 1972

Microstructures

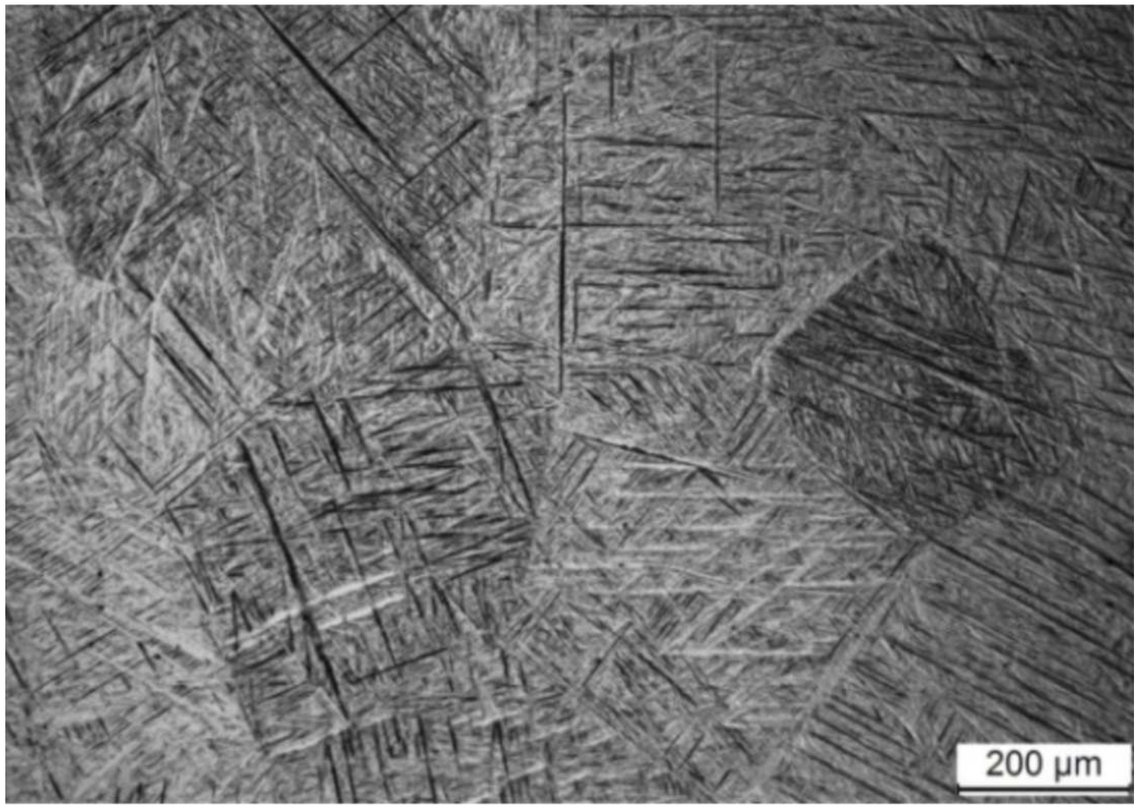
Lamellaires α

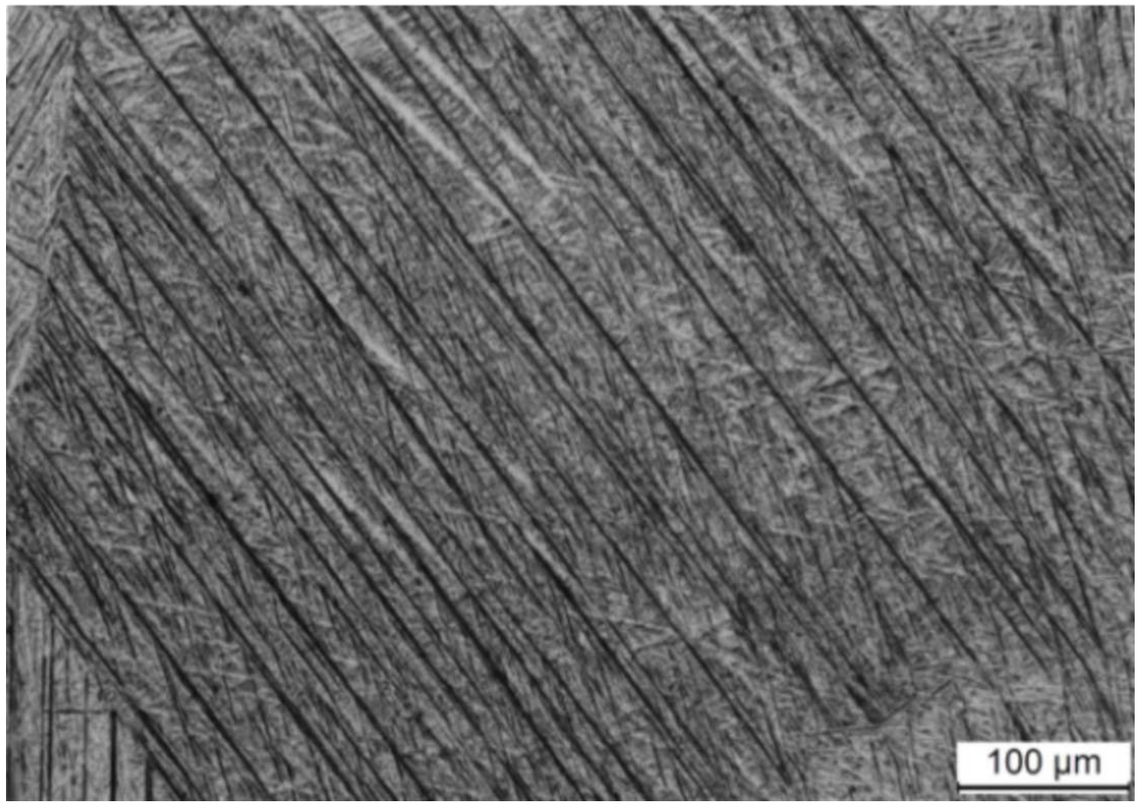


Semiatin 2020

Microstructures

Martensite α'

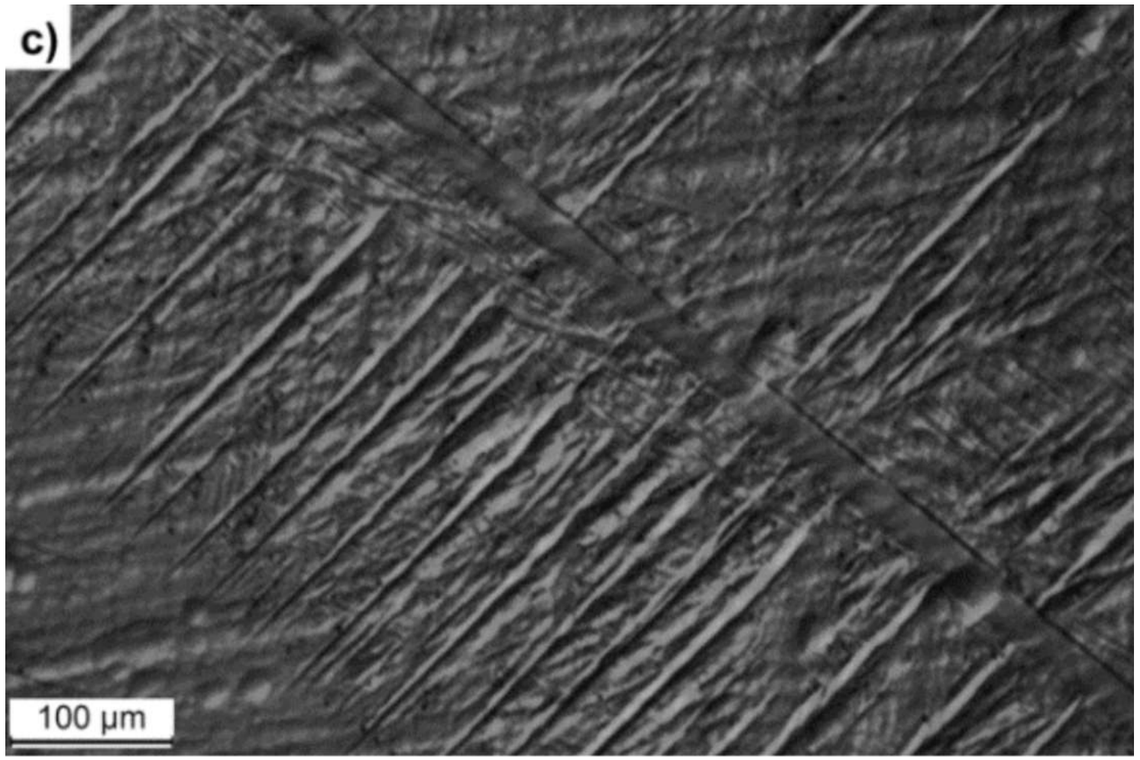


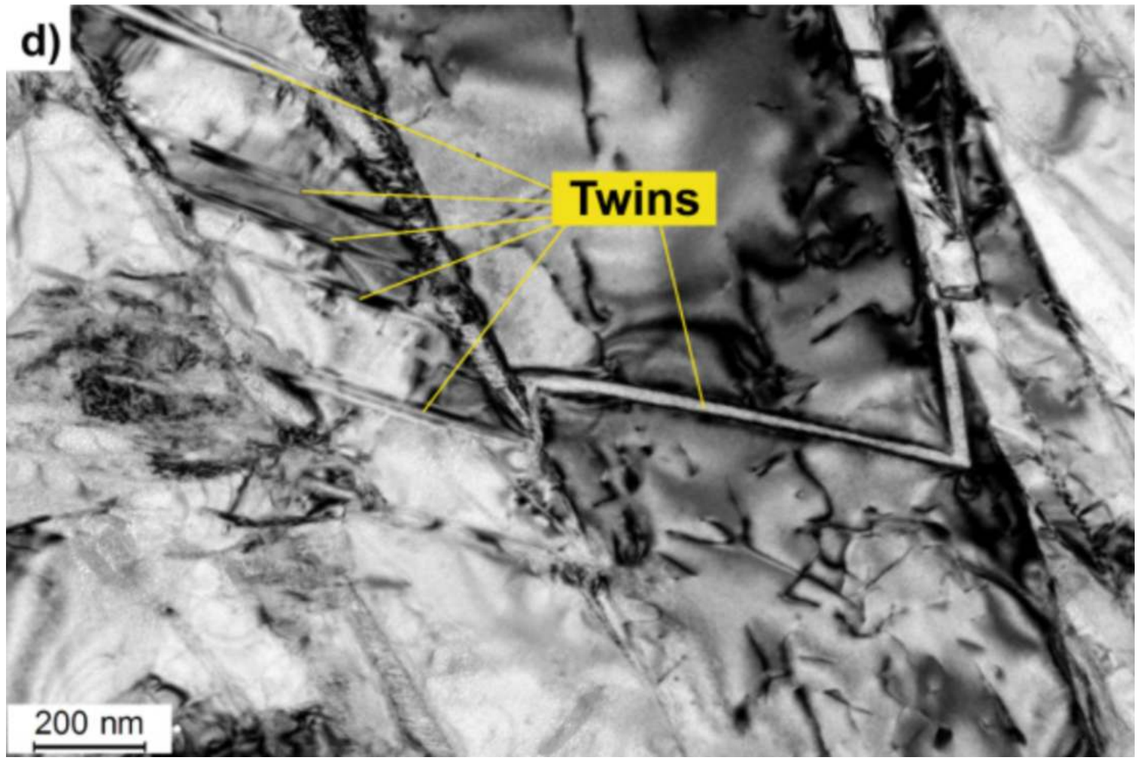


Motyka 2021

Microstructures

Lamellaires α'

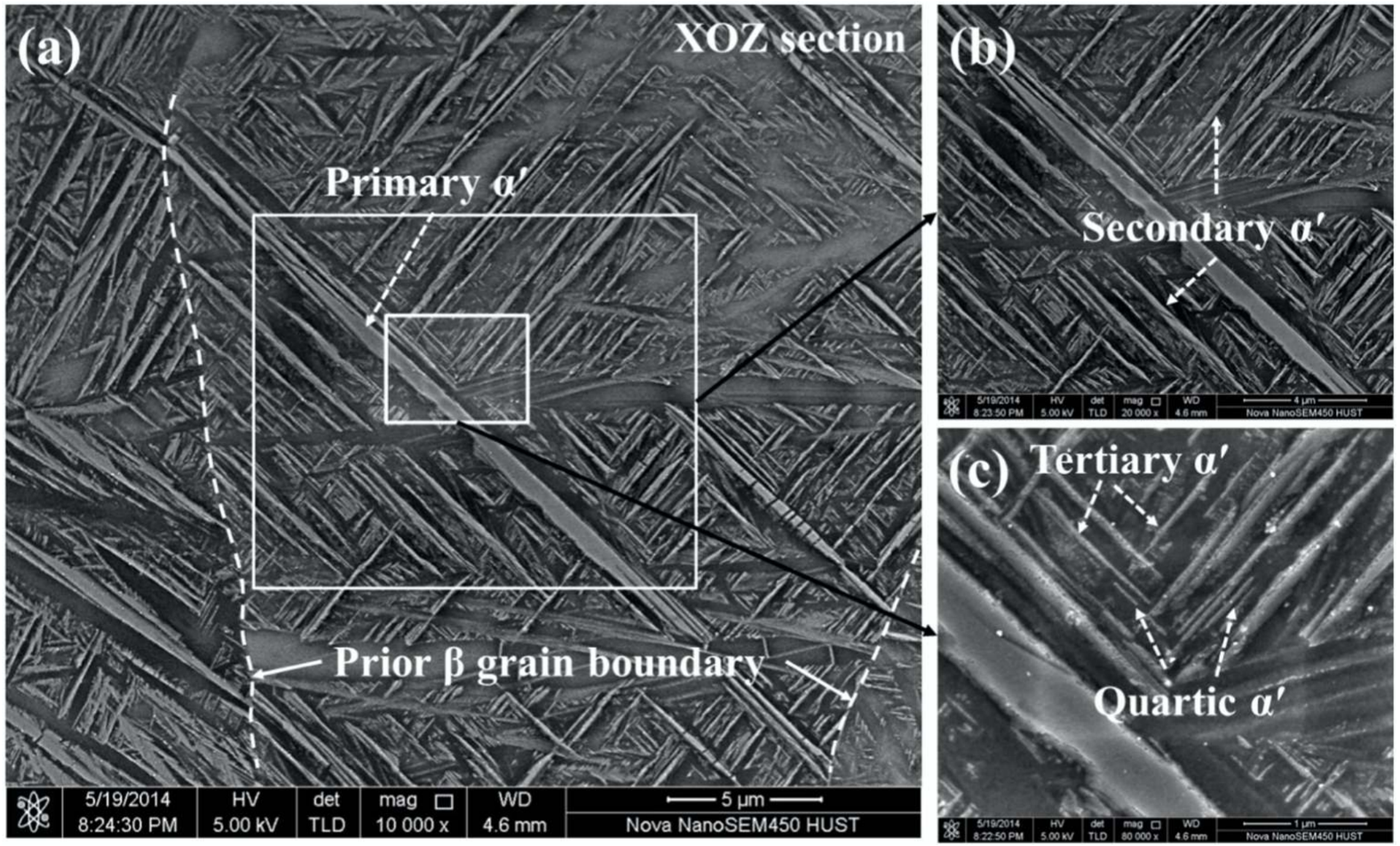




Motyka 2021

Microstructures

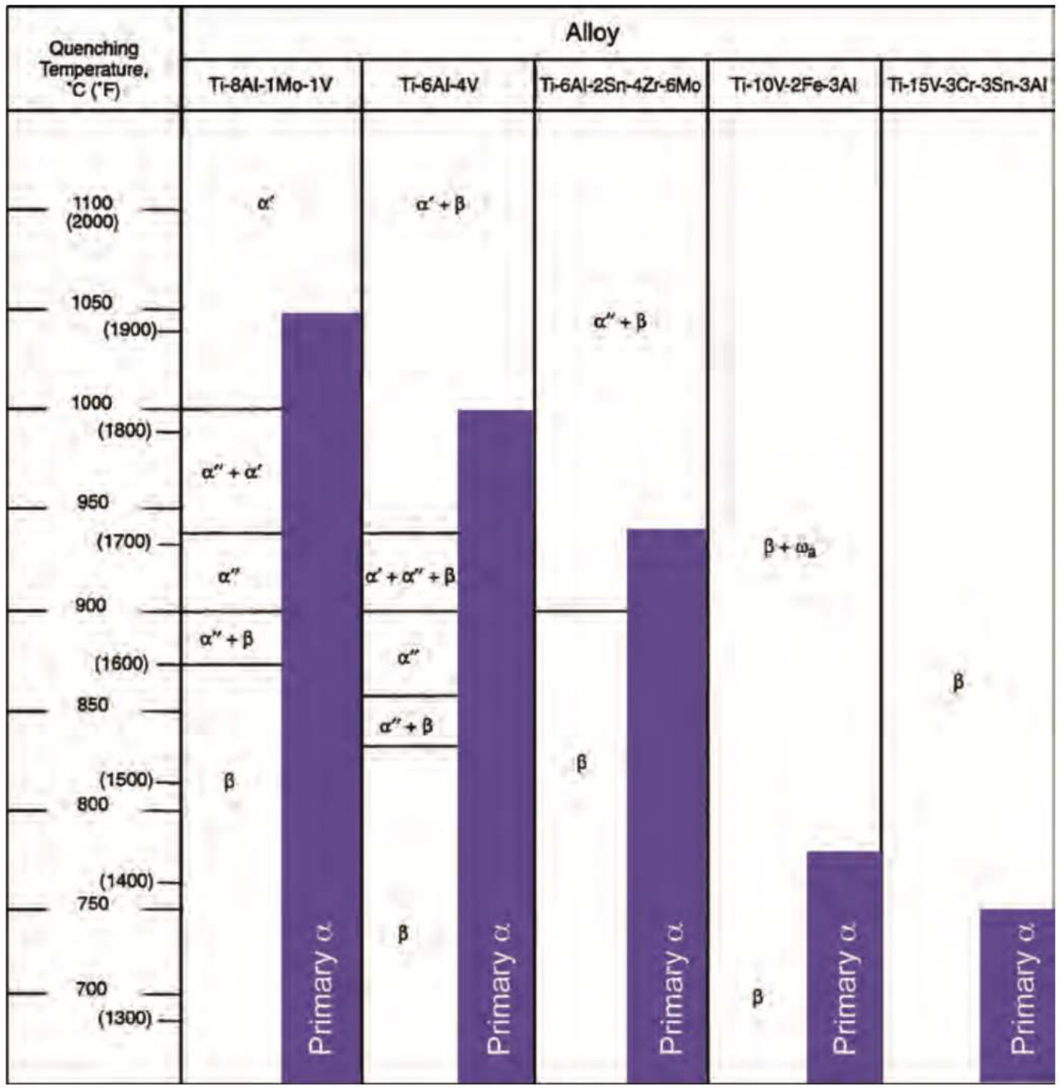
Lamellaires α'

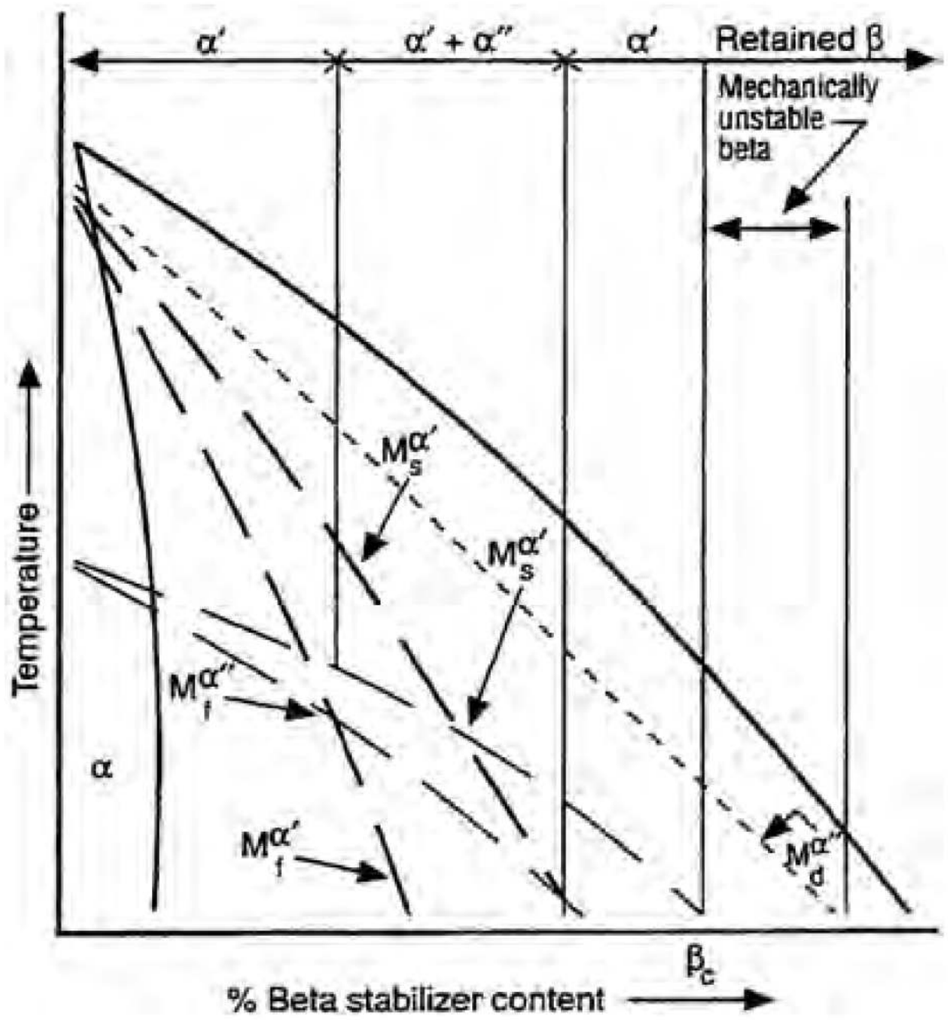


Yang, Yu et coll. 2016

Microstructures

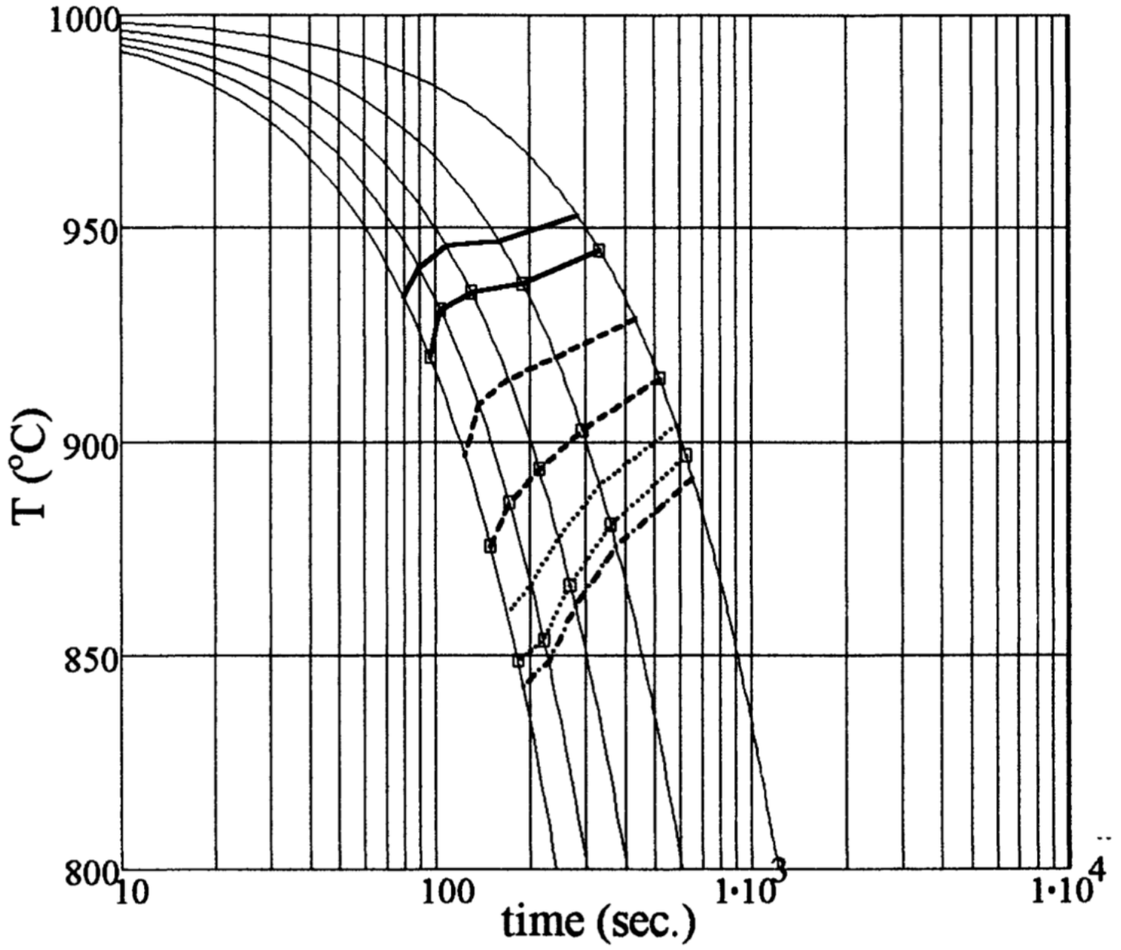
Martensite α'' (?)

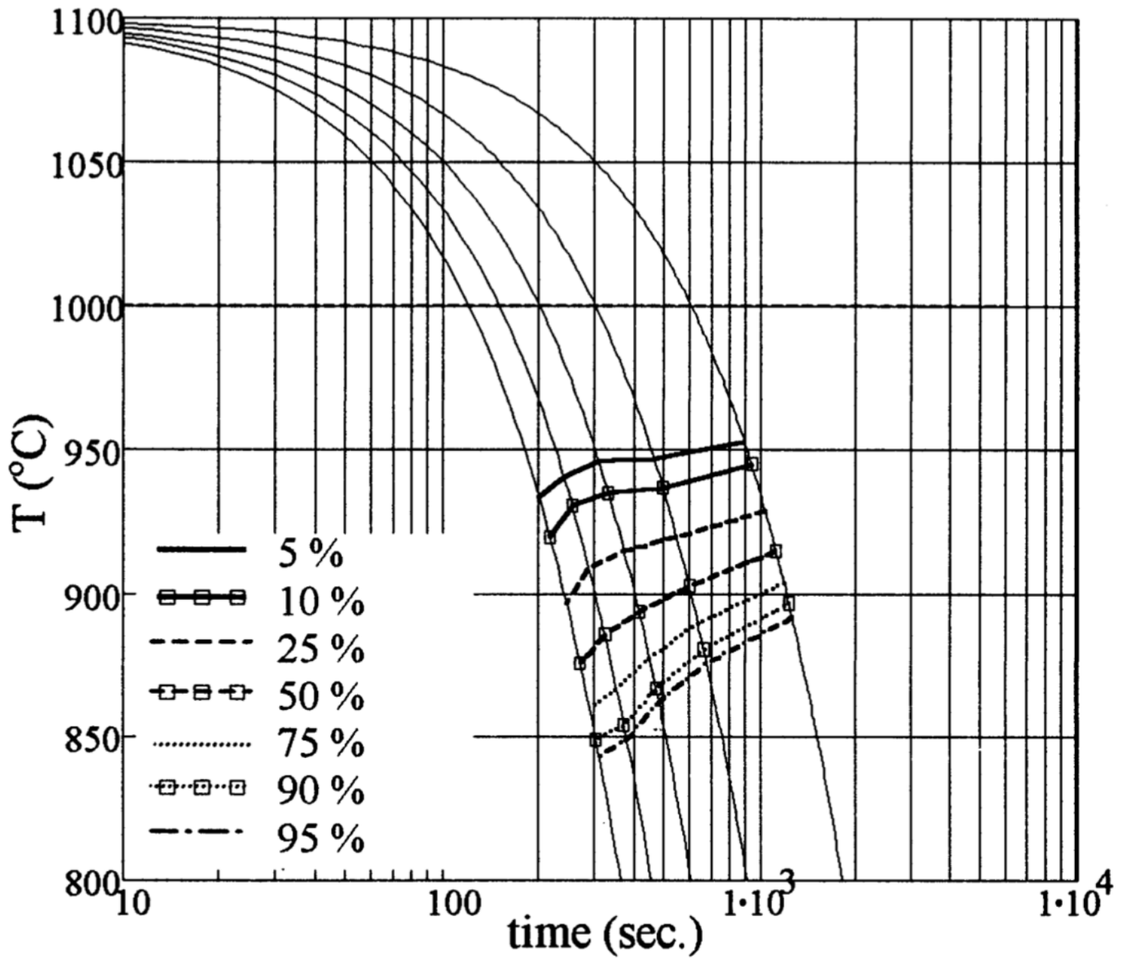




Microstructures

Cinétiques

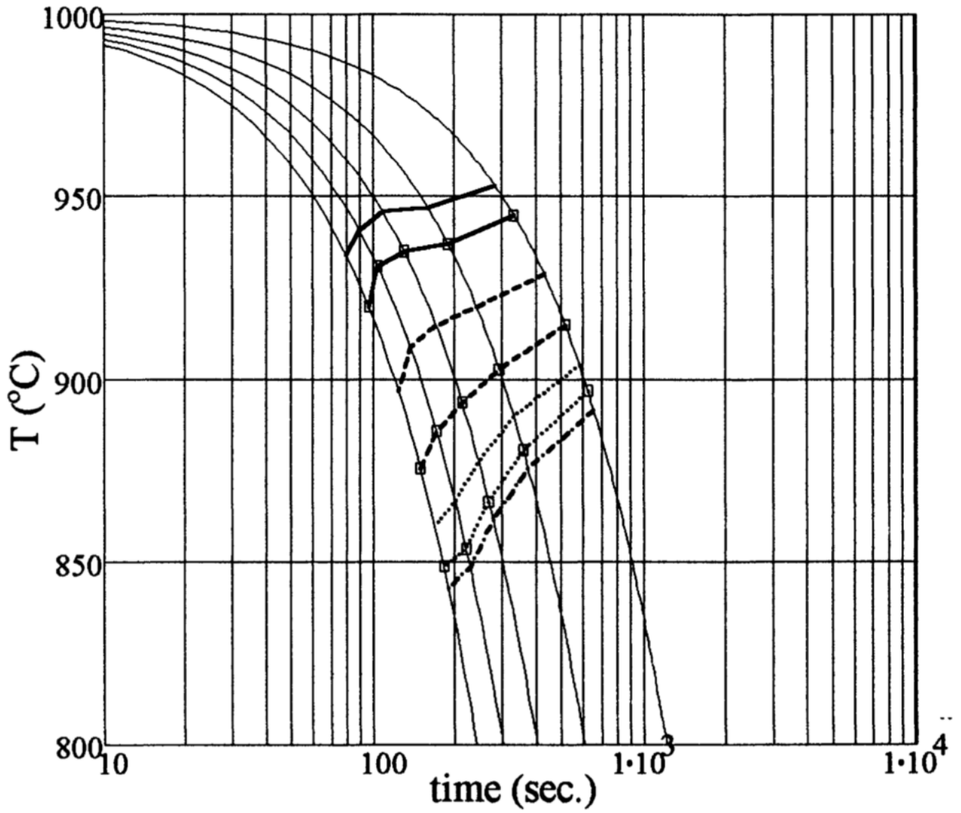


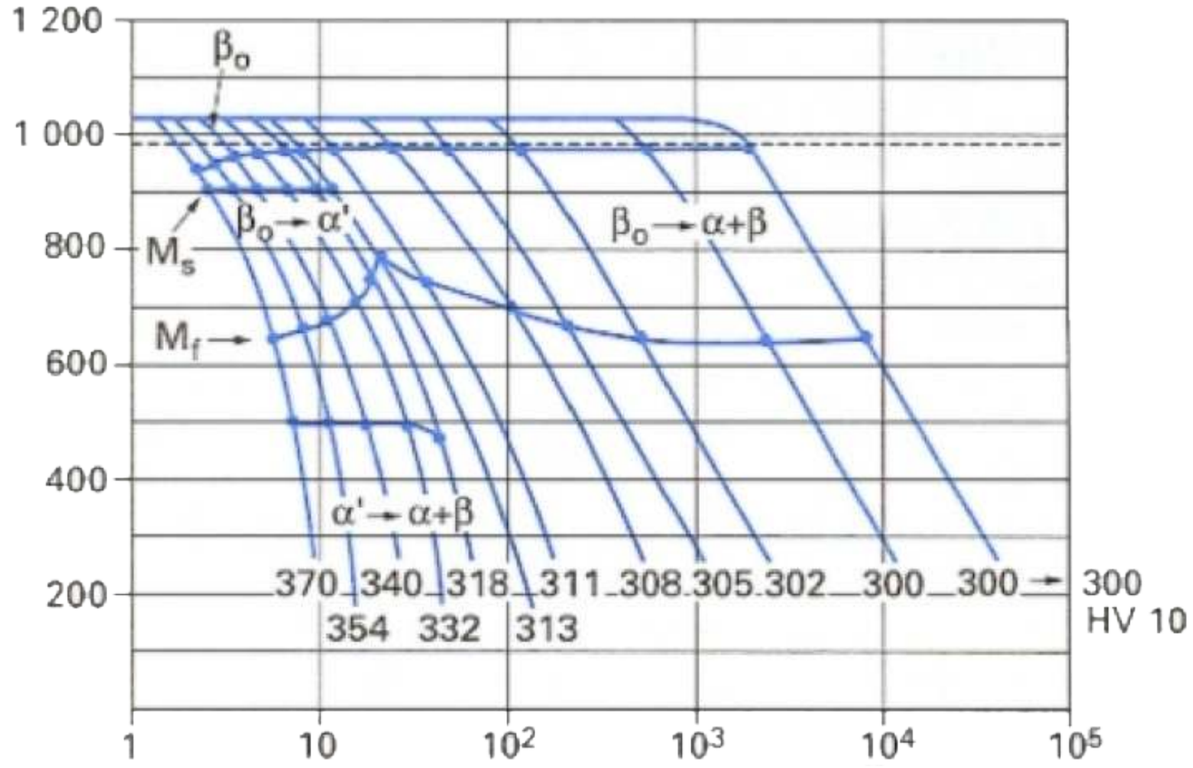


Malinov, Guo 2001

Microstructures

Cinétiques

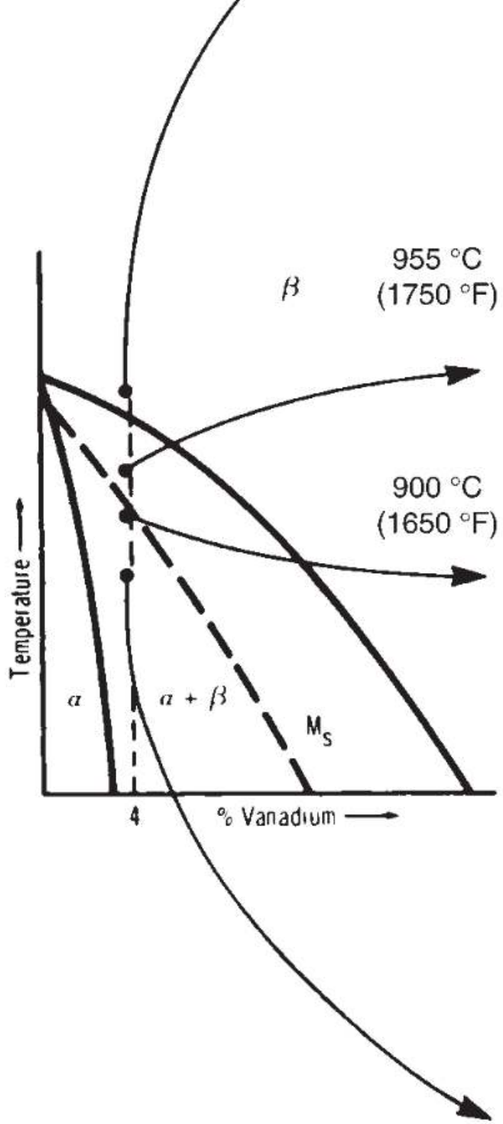




Y. Combres

Microstructures

Équiaxes ou nodulaires



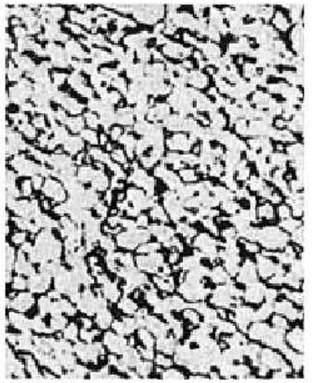

(b)

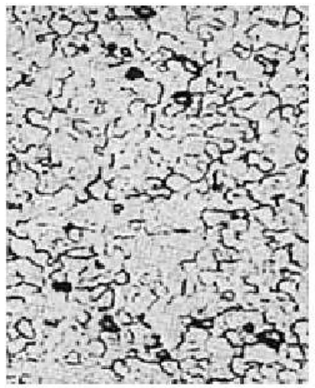

(f)


(j)

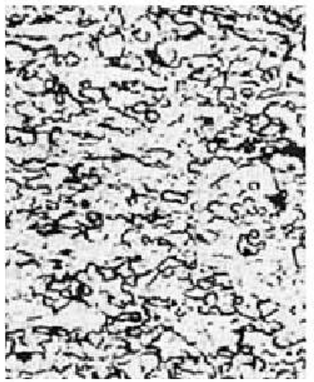

(c)


(g)


(k)

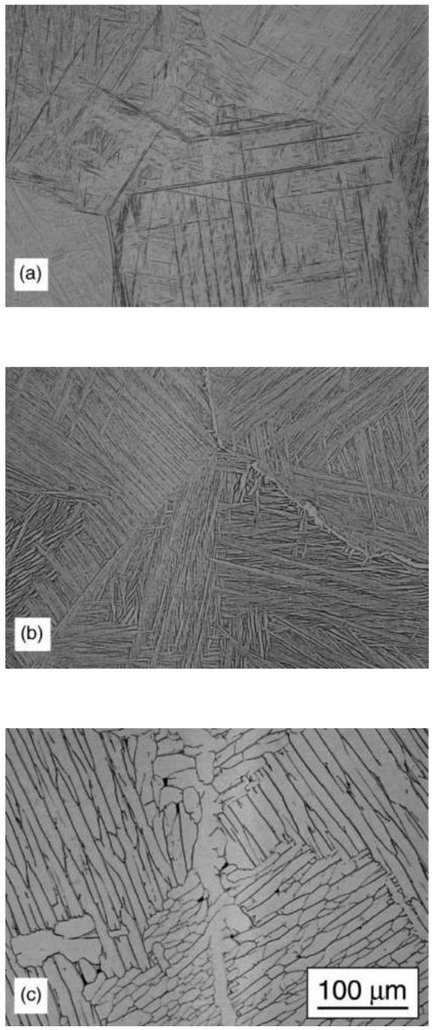

(d)


(h)


(l)

Microstructures

Équiaxes ou nodulaires



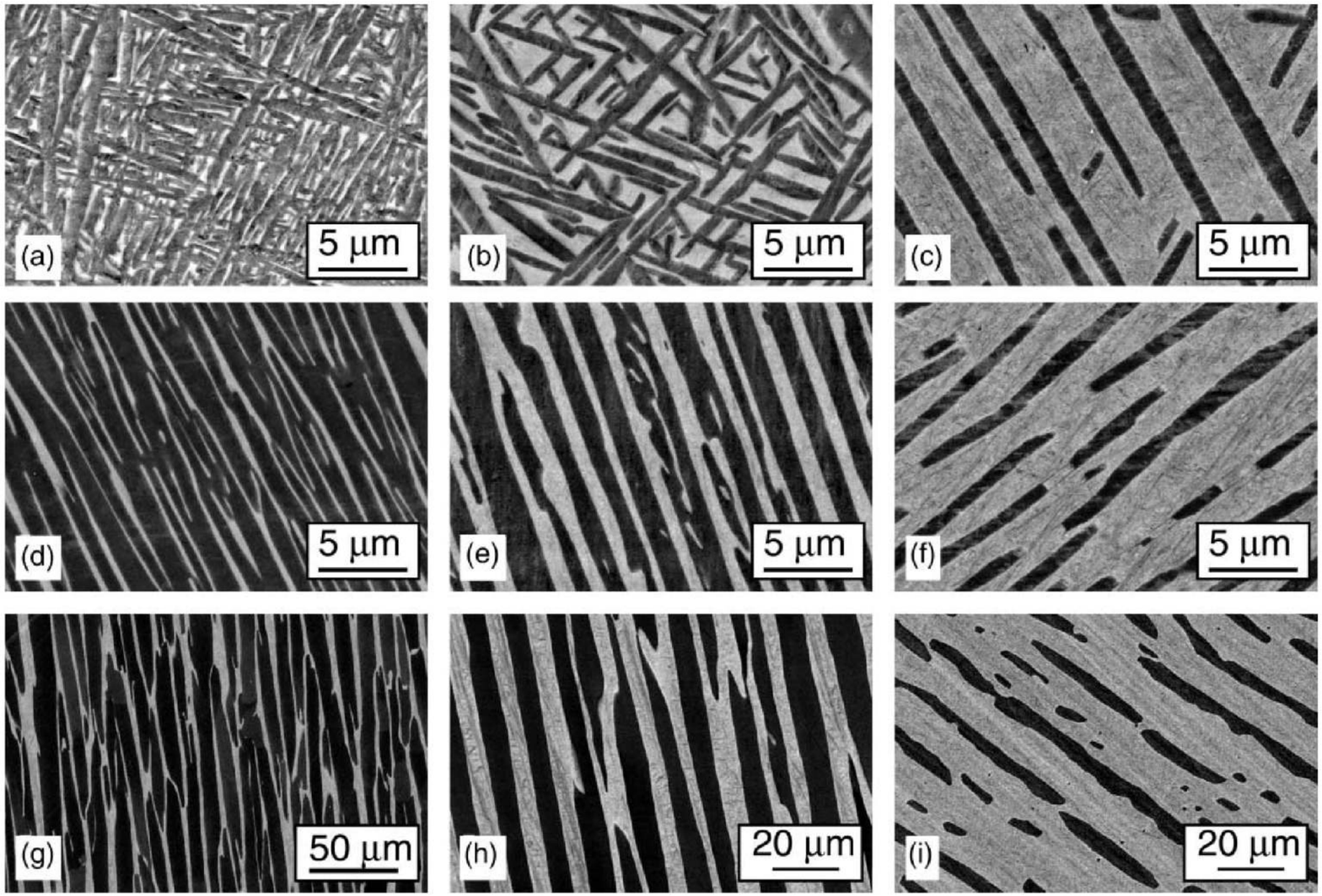
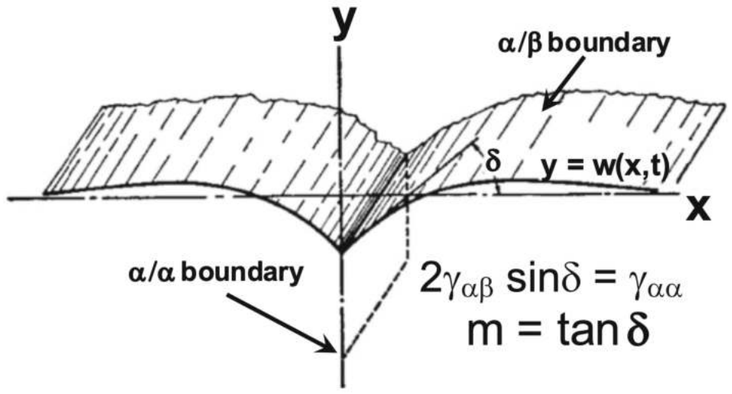


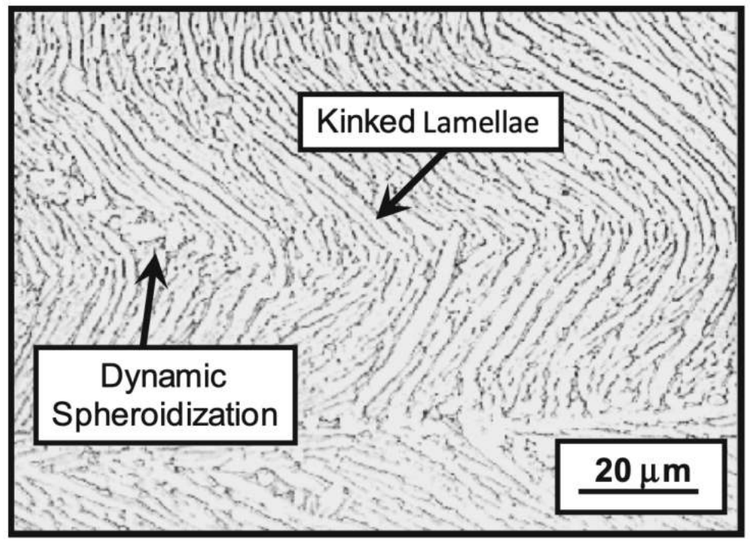
Fig. 2. Backscattered SEM micrographs of Ti–6Al–4V microstructures (a,b,c) A, (d,e,f) B, and (g,h,i) C developed during heating prior to hot deformation at (a,d,g) 815°C, (b,e,h) 900°C, or (c,f,i) 955°C.

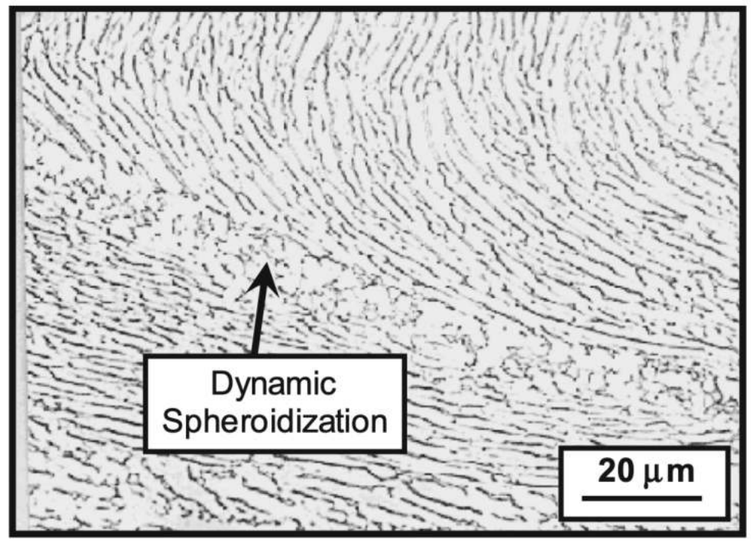
Semiatin, Bieler 2001

Microstructures

Équiaxes ou nodulaires



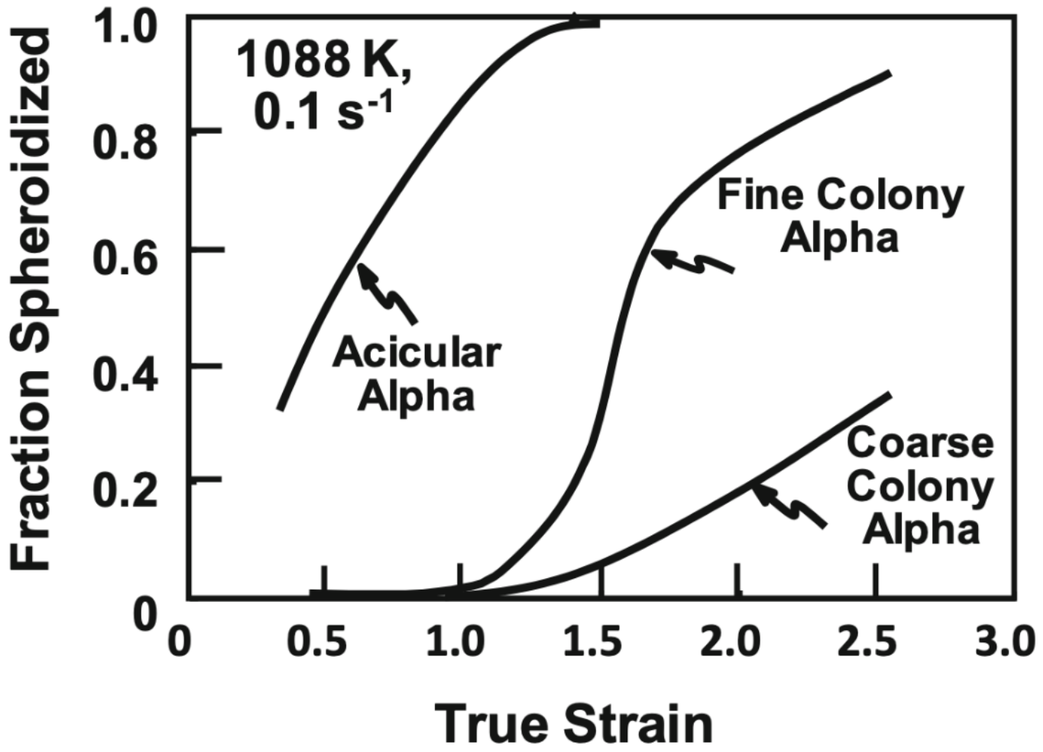


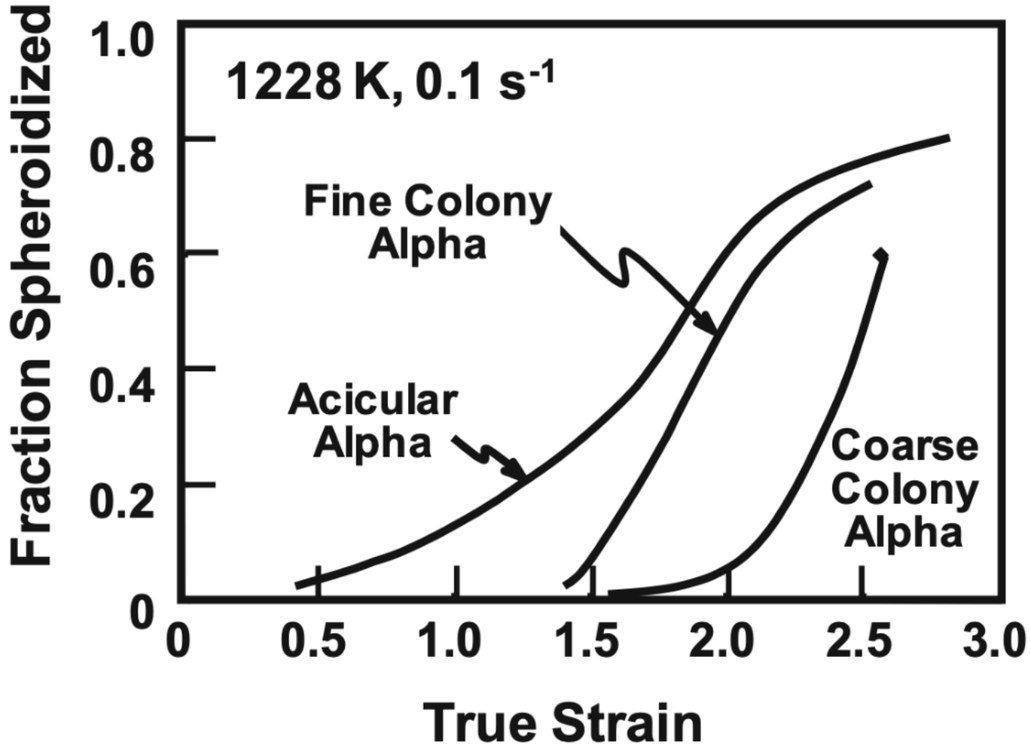


Semiatin 2020

Microstructures

Équiaxes ou nodulaires

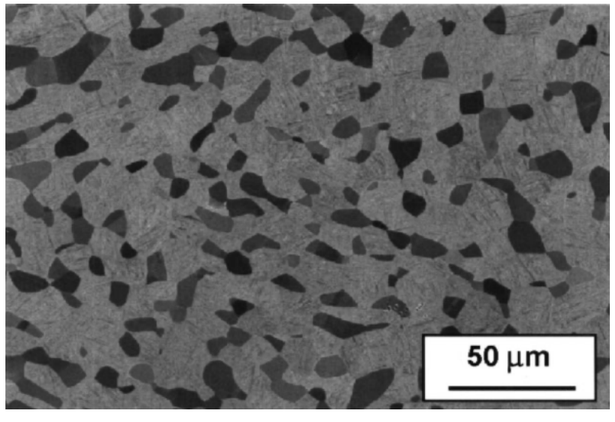




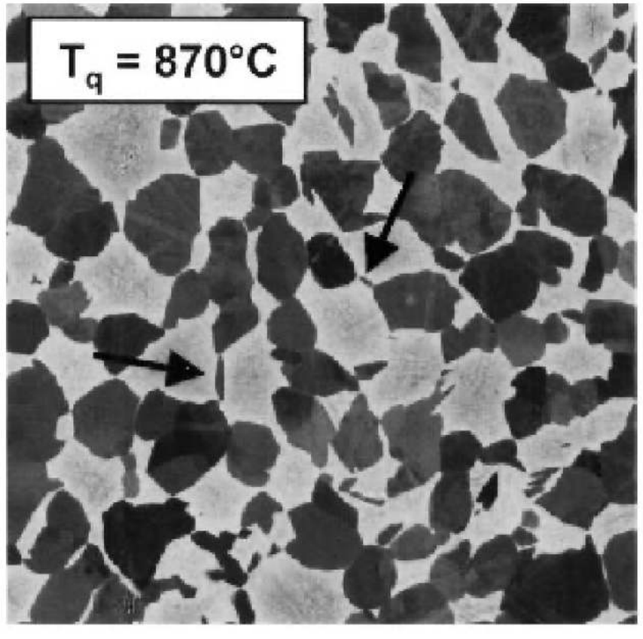
Semiatin 2020

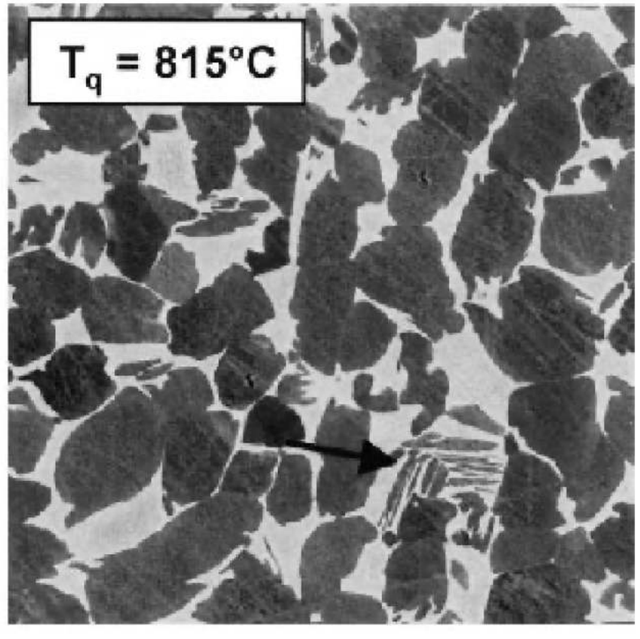
Microstructures

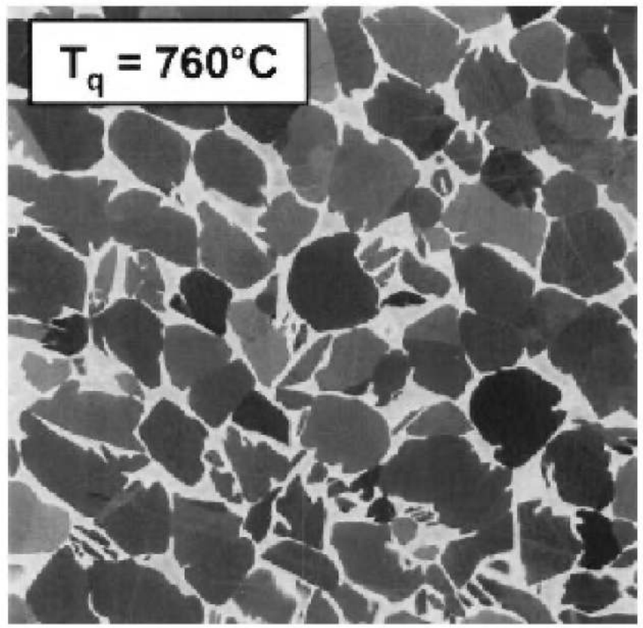
Bimodale

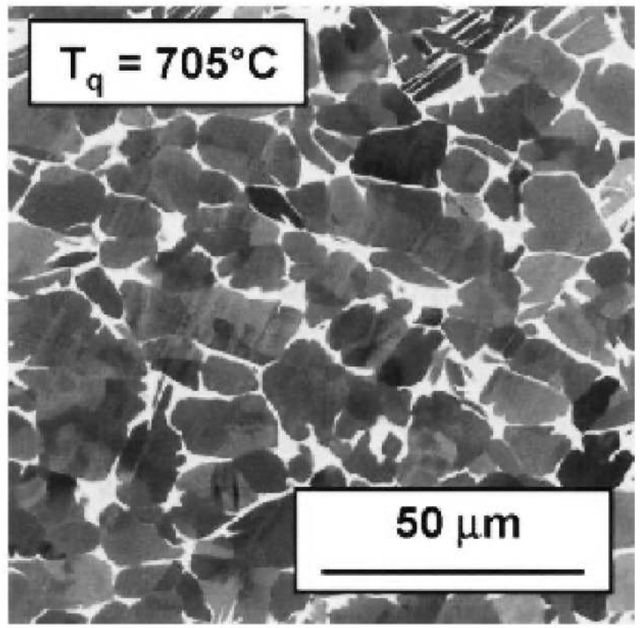


Semiatin, Kinsley 2003



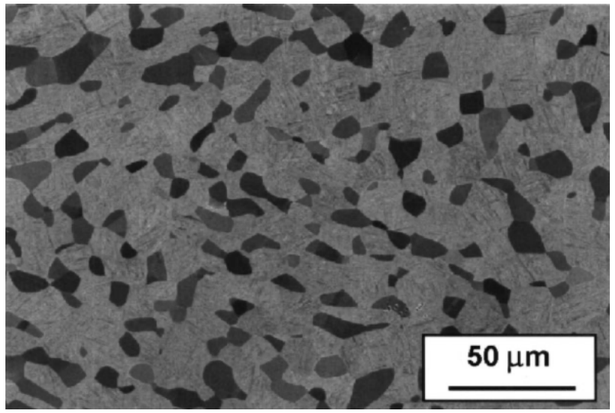




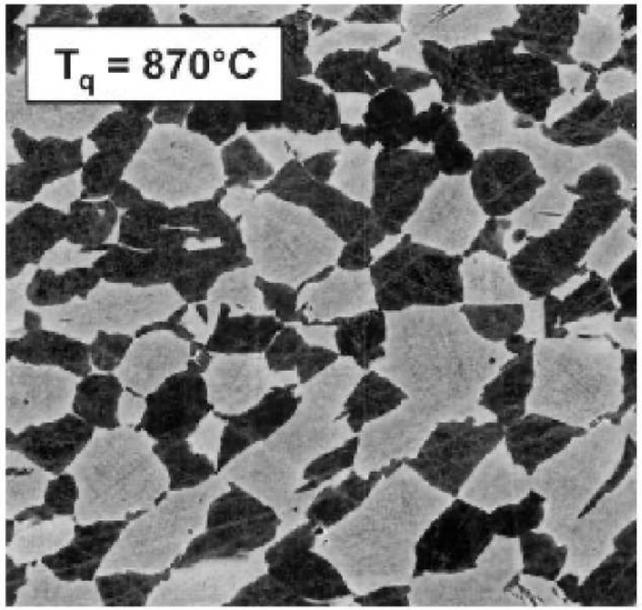


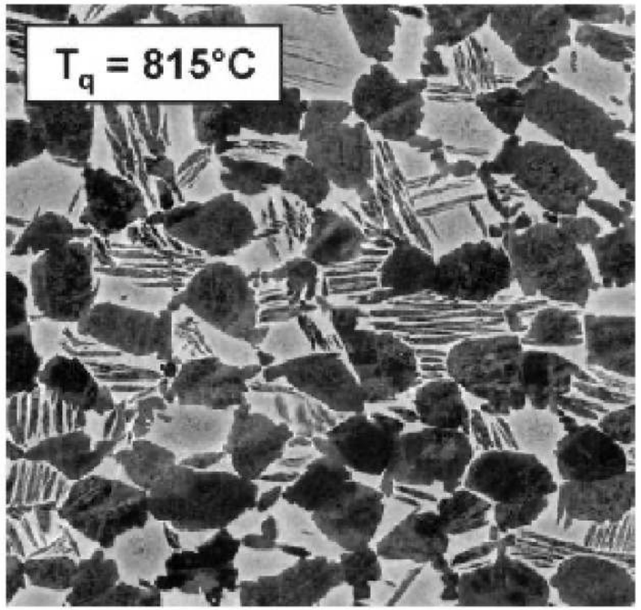
Microstructures

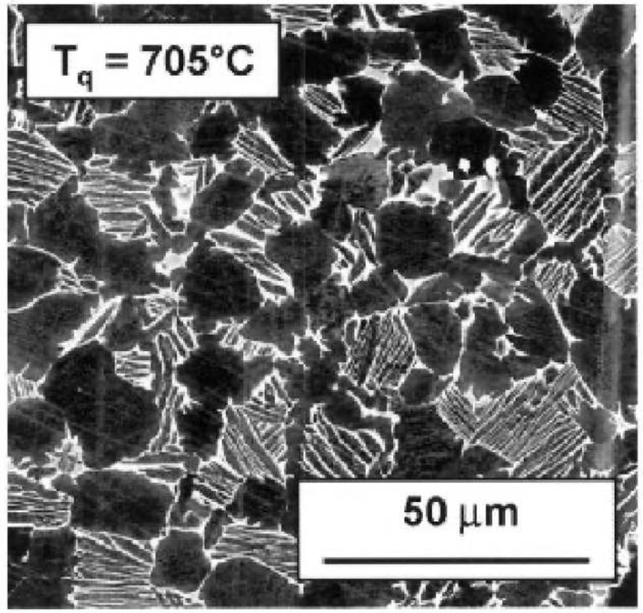
Bimodale



Semiatin, Kinsley 2003

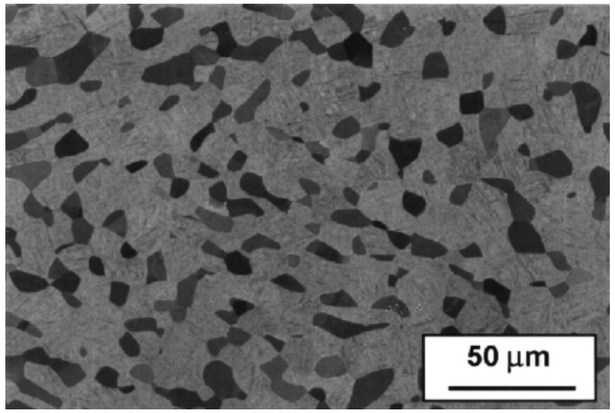




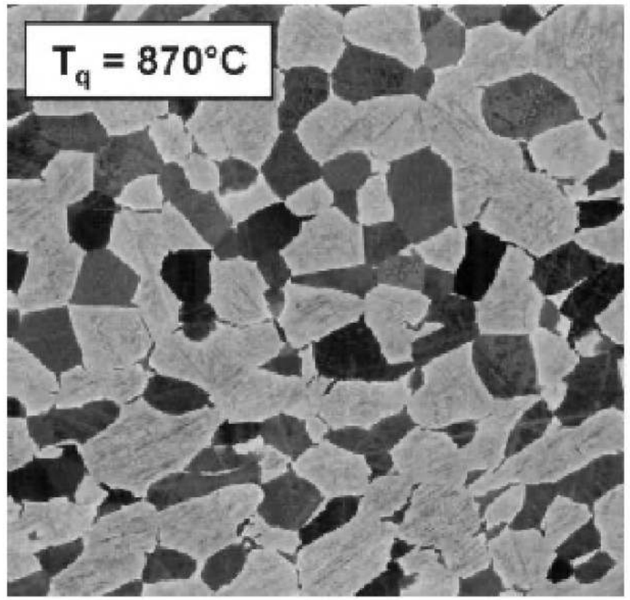


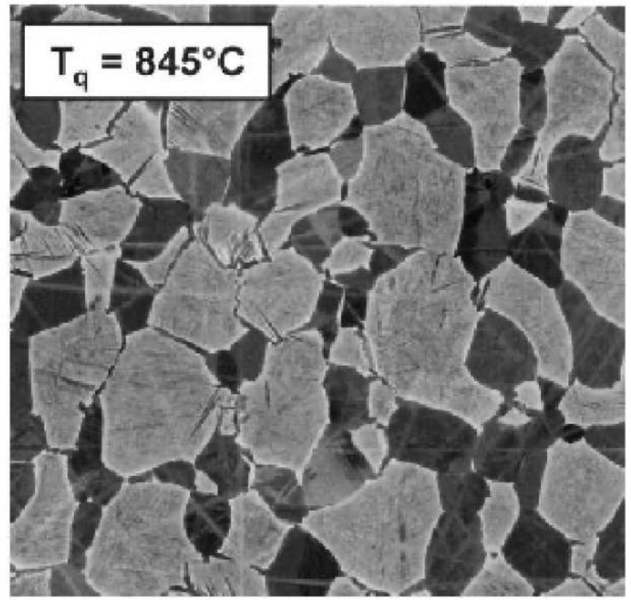
Microstructures

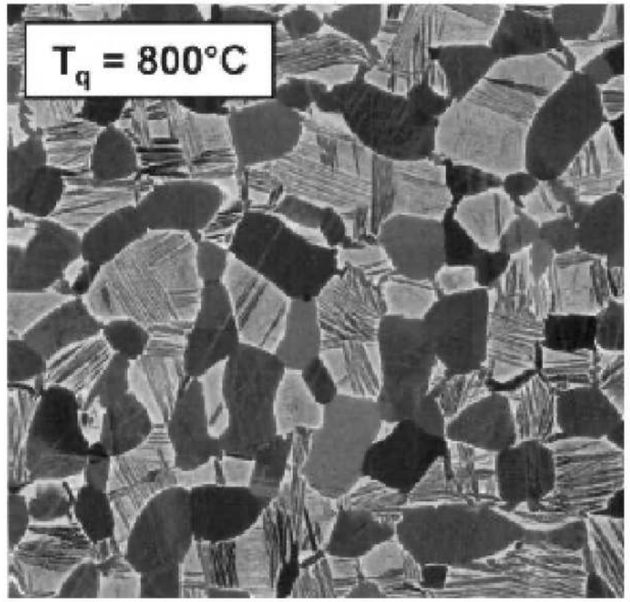
Bimodale

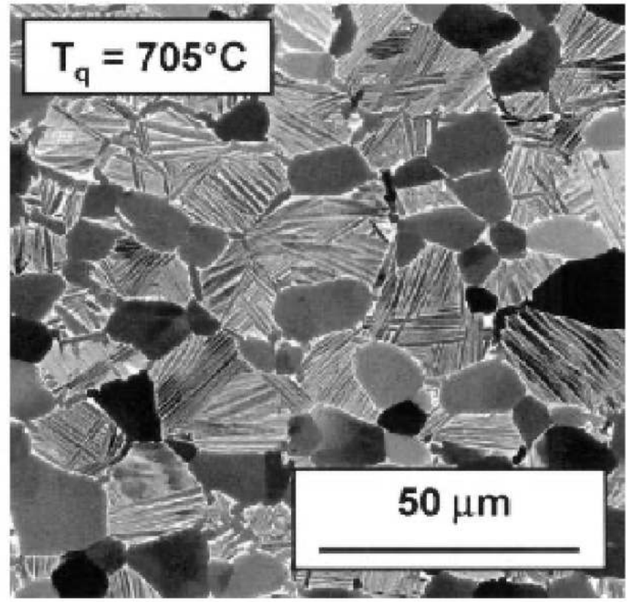


Semiatin, Kinsley 2003









Place aux spécialistes