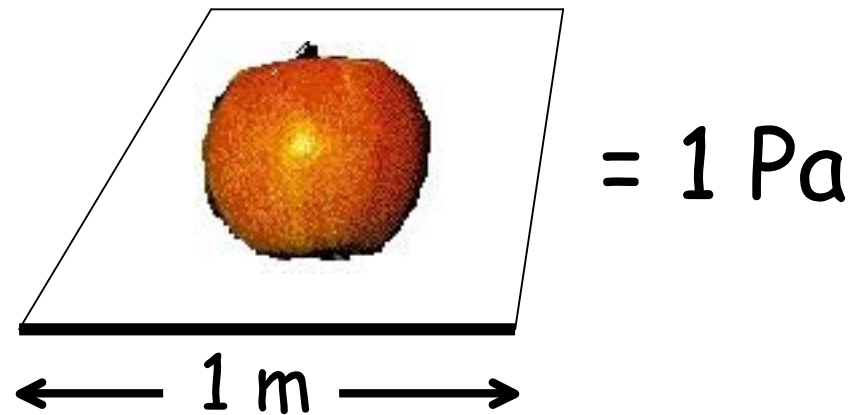


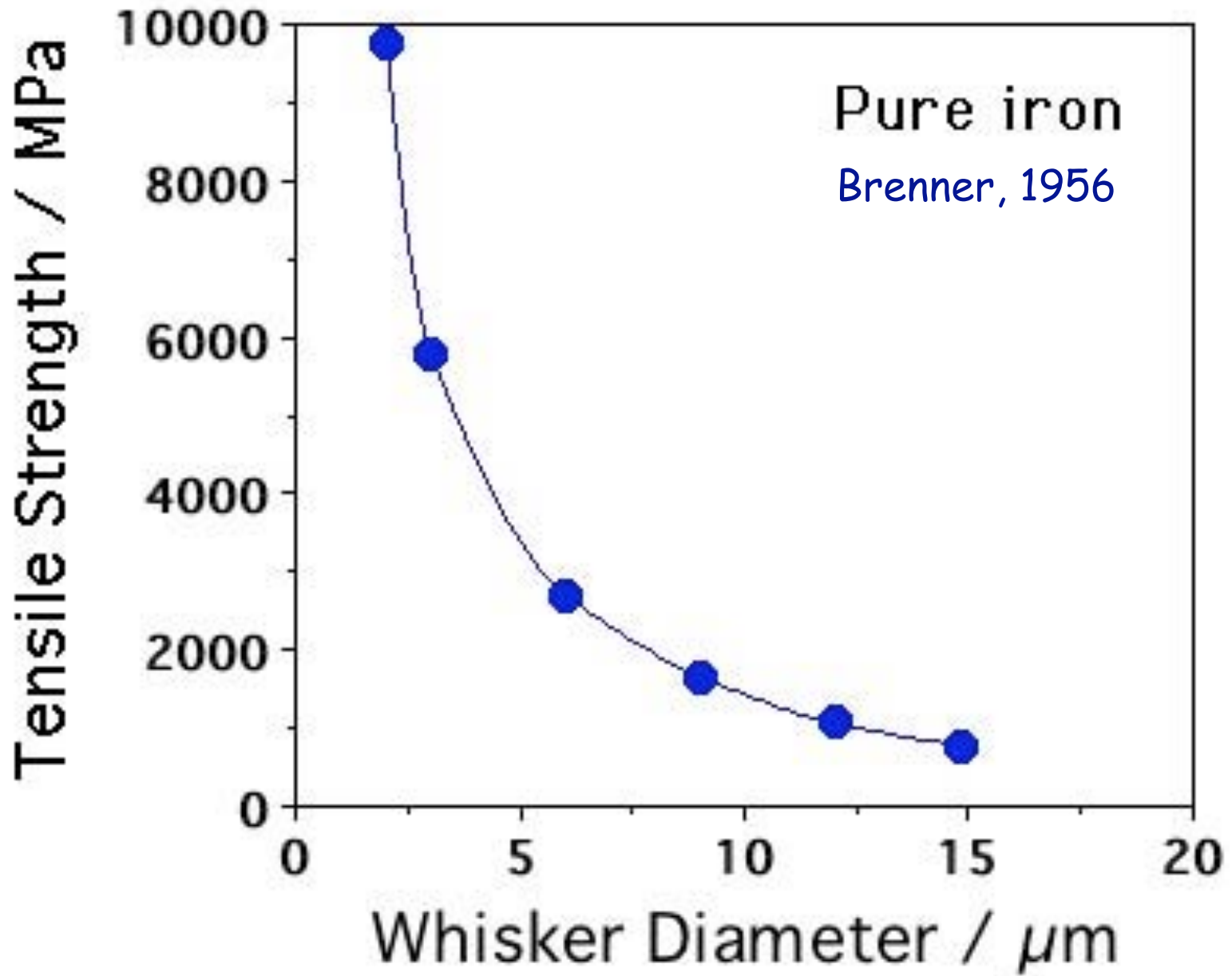
Large Chunks of Extremely Strong Steel

52nd Hatfield Memorial Lecture

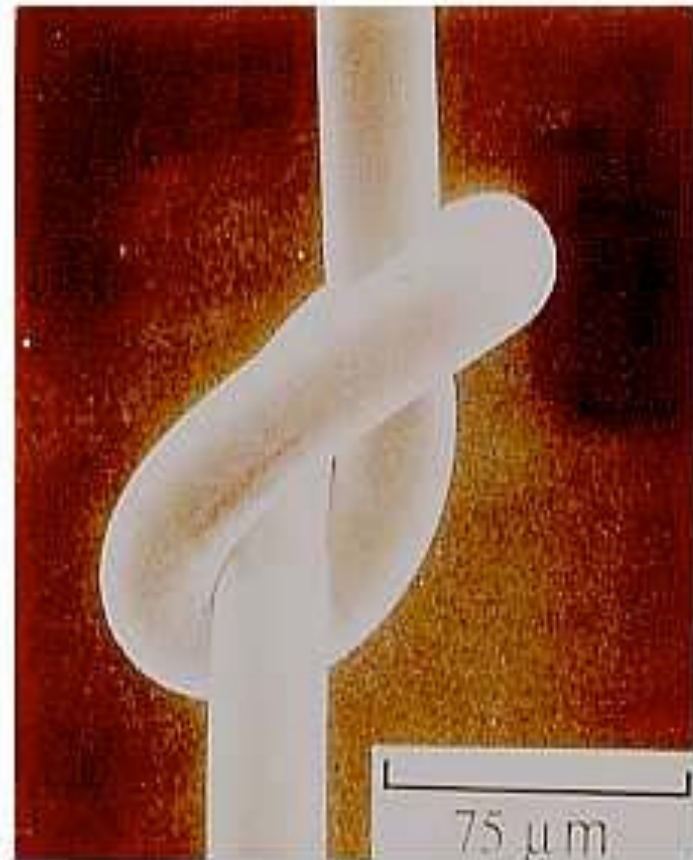
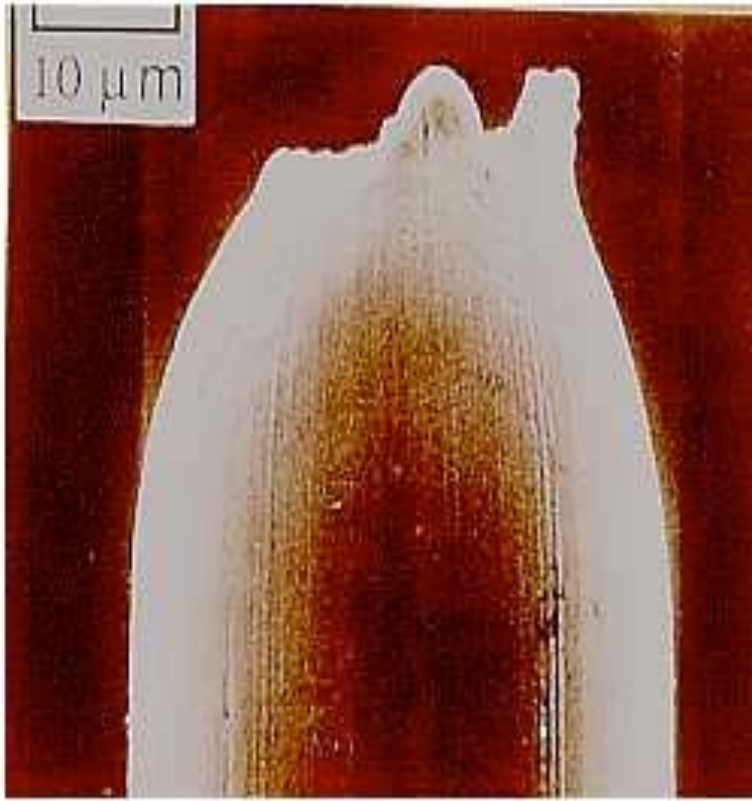


an apple weighs
1 Newton

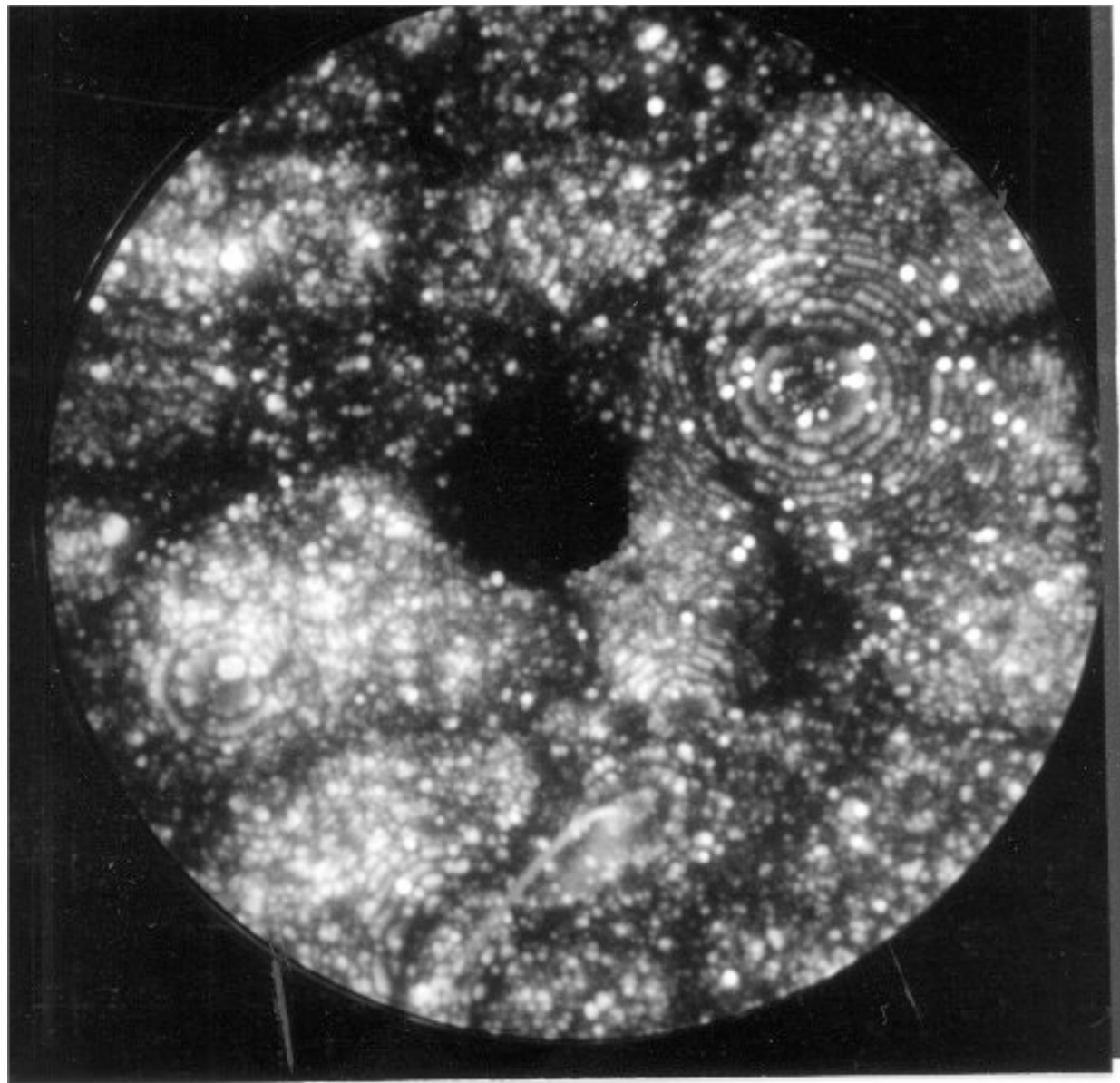


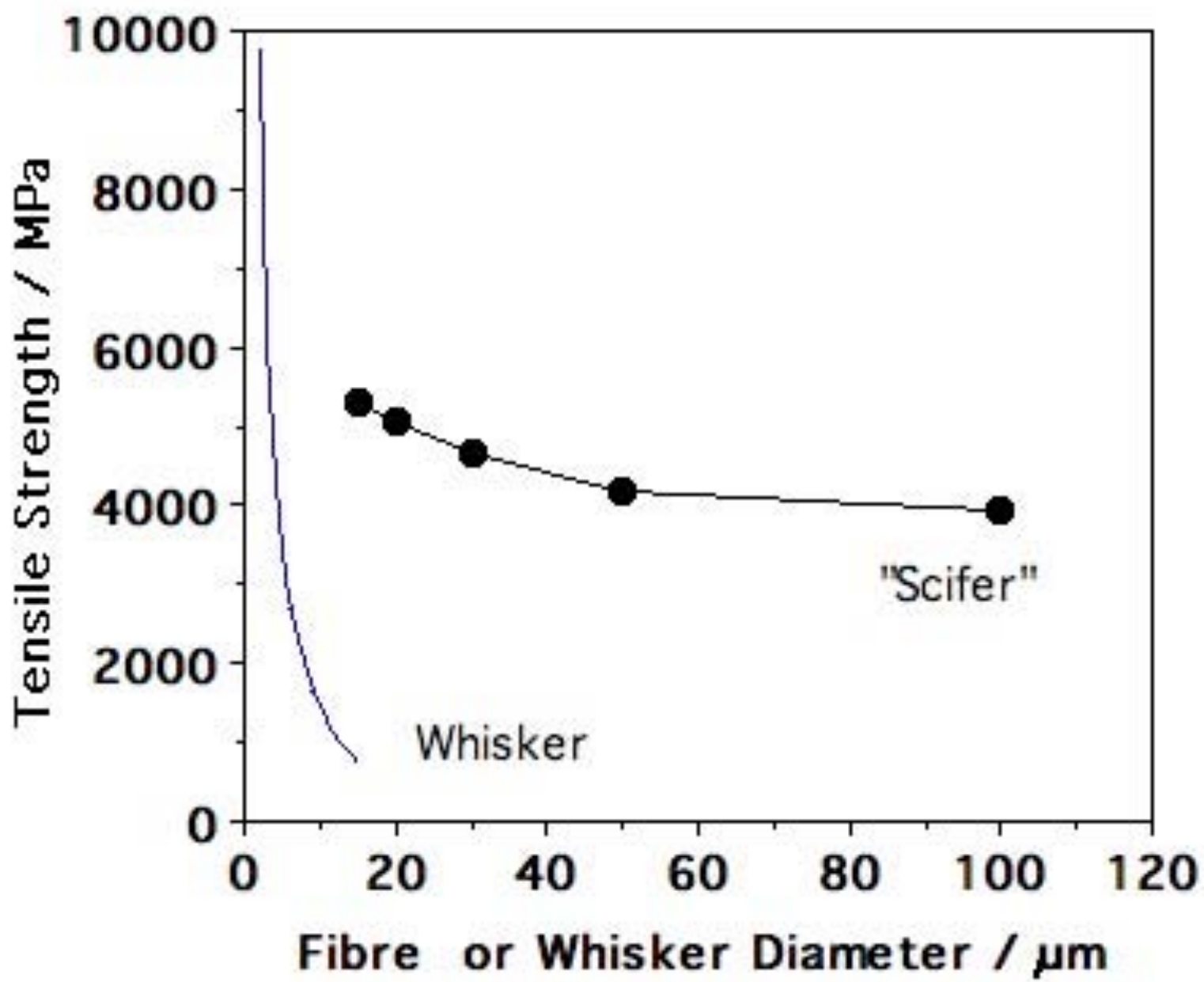


Scifer, 5.5 GPa and ductile



Kobe Steel



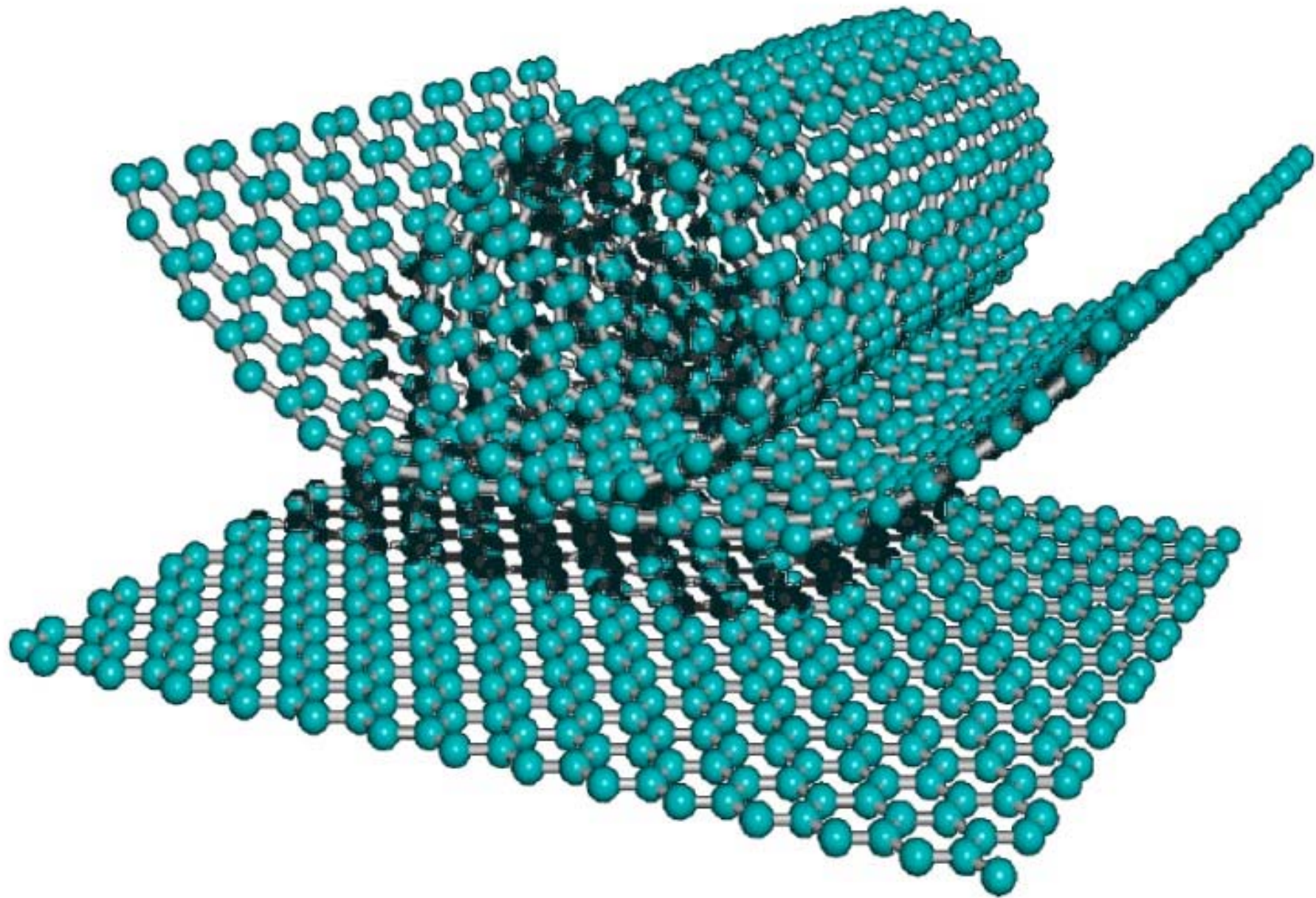


1 Denier: weight in grams, of 9 km of fibre

50-10 Denier



Scifer is 9 Denier



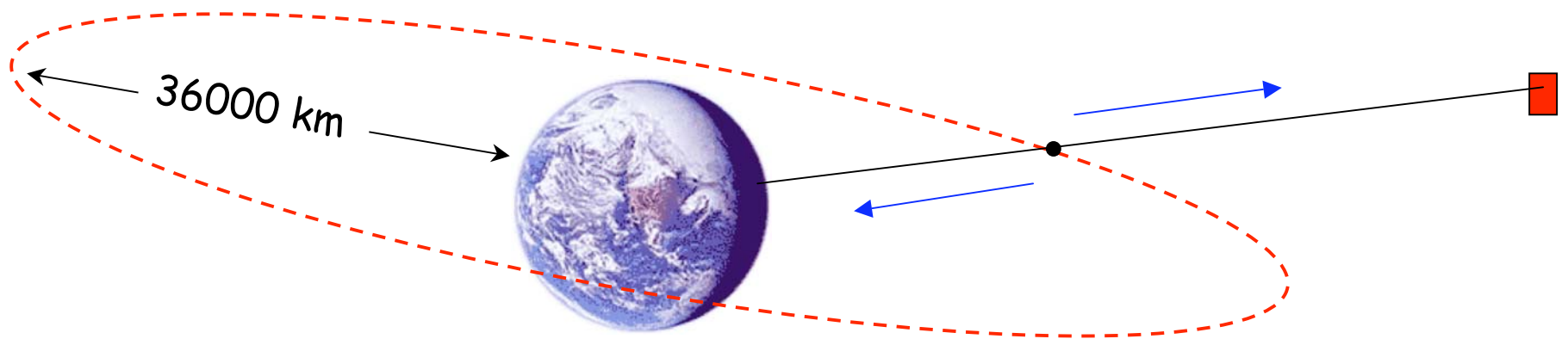
Morinobu Endo, 2004

Claimed strength of carbon
nanotube is 130 GPa

Edwards, *Acta Astronautica*, 2000

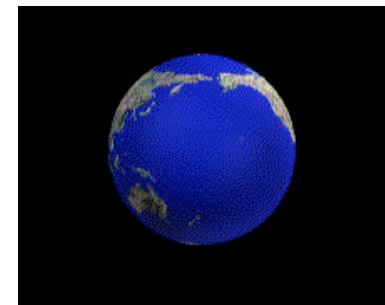
Claimed modulus is 1.2 TPa

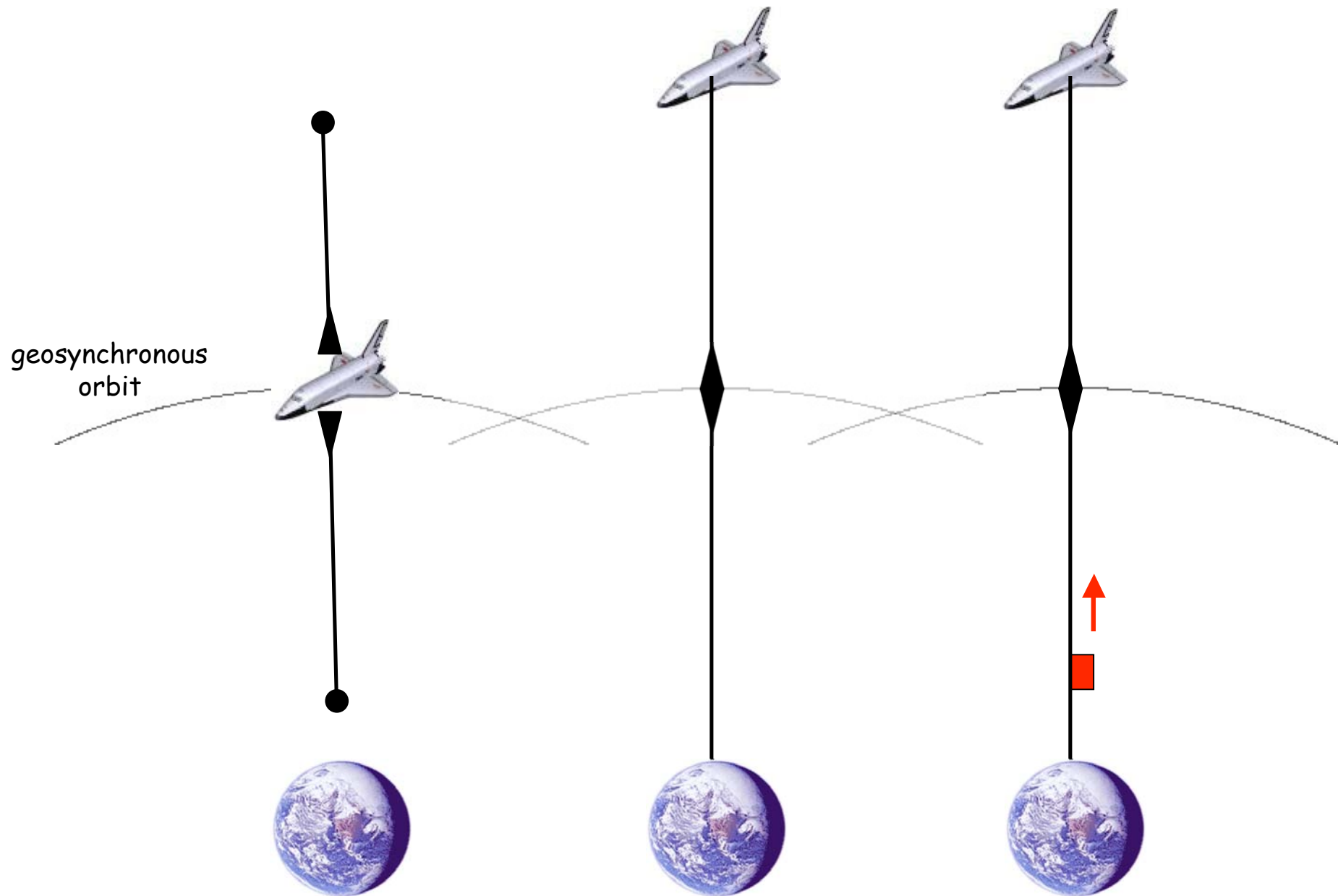
Terrones *et al.*, *Phil. Trans. Roy. Soc.*, 2004



tethered space elevator

Arthur C. Clark (1979)

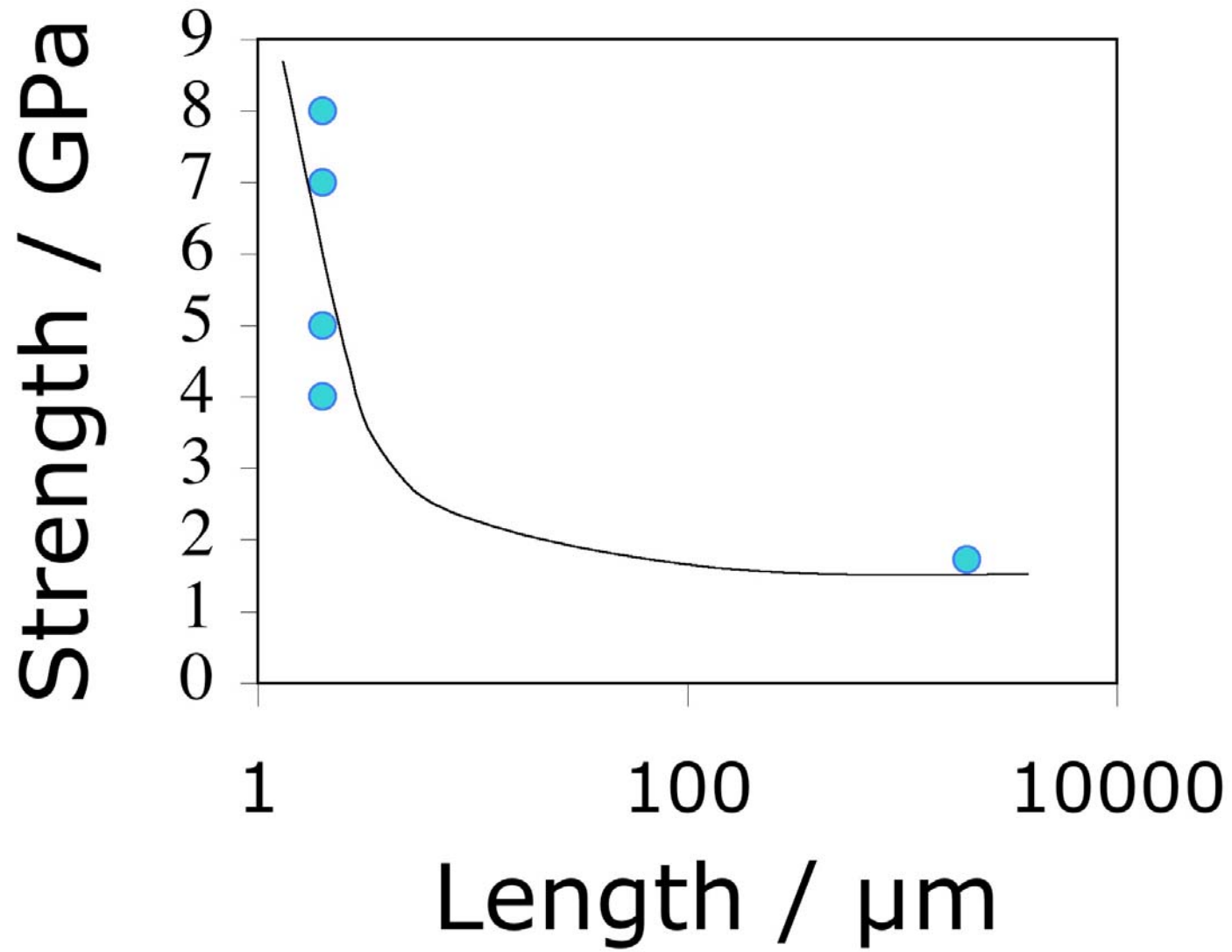




strength 130 GPa

modulus 1.2 TPa

	$J g^{-1}$	$m s^{-1}$
Dynamite	4650	6000
Nanotube	5420	21500



data from Pan *et al.* 1999, Yu *et al.* 2000

$$\Delta G = n \Delta g - kT \{ (N+n) \ln(N+n) - N \ln N - n \ln n \}$$

$$\frac{\partial \Delta G}{\partial n} = 0$$

$$\frac{n}{N} \approx \exp \left\{ - \frac{\Delta g}{kT} \right\}$$

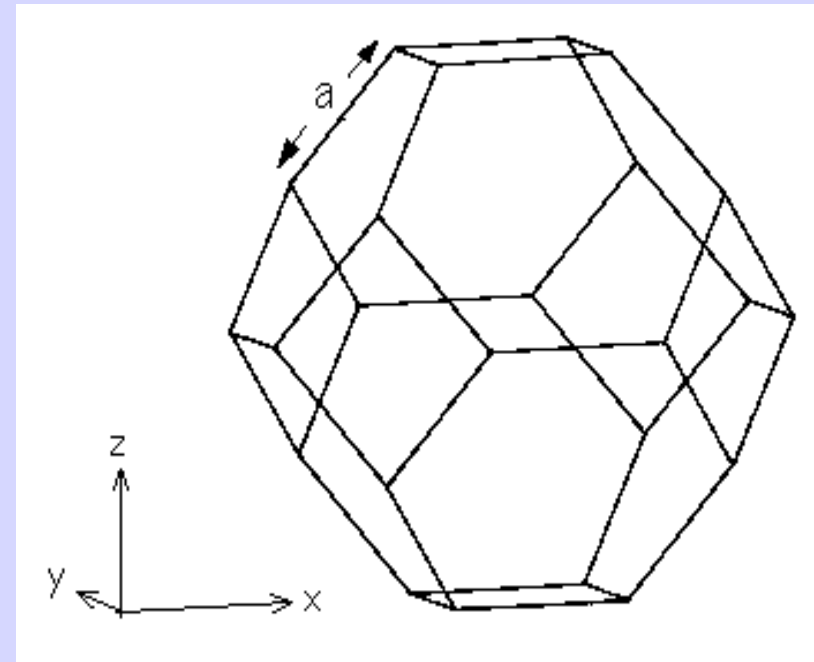
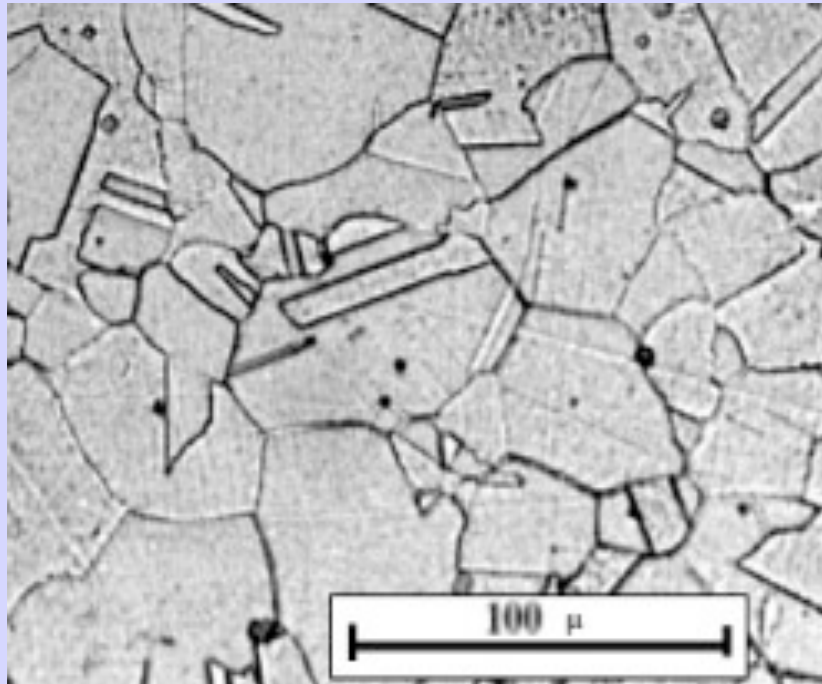
An equilibrium number of defects.

Strength of a nanotube rope 2 mm long is less than 2000 MPa

Summary

- Strength produced by deformation limits shape: wires, sheets...
- Strength in small particles relies on perfection. Doomed as size increases.

Smallest size that can be achieved in a polycrystalline substance?

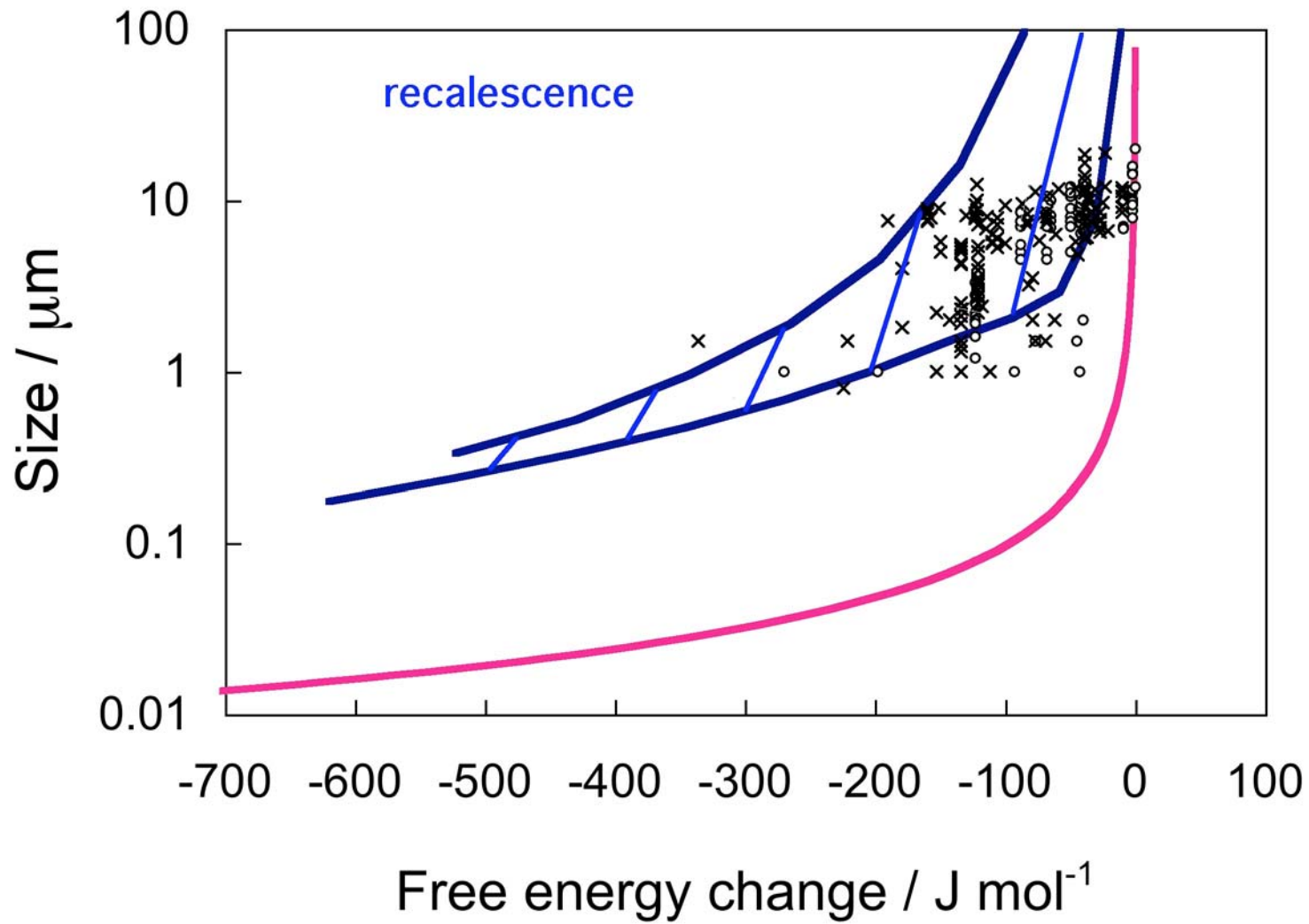


$$\Delta G_V = \sigma S_V$$

$$\Delta G_V = \sigma S_V$$

$$|\Delta G_V^{\gamma\alpha}| \geq \sigma_\alpha S_V^\alpha - \sigma_\gamma S_V^\gamma$$

$$|\Delta G_V^{\gamma\alpha}| \geq \frac{2\sigma_\alpha}{L_\alpha} - \frac{2\sigma_\gamma}{L_\gamma}$$



$$\Delta T^{max} \simeq \Delta H / C_{\gamma}$$

Yokota & Bhadeshia, 2004

Summary

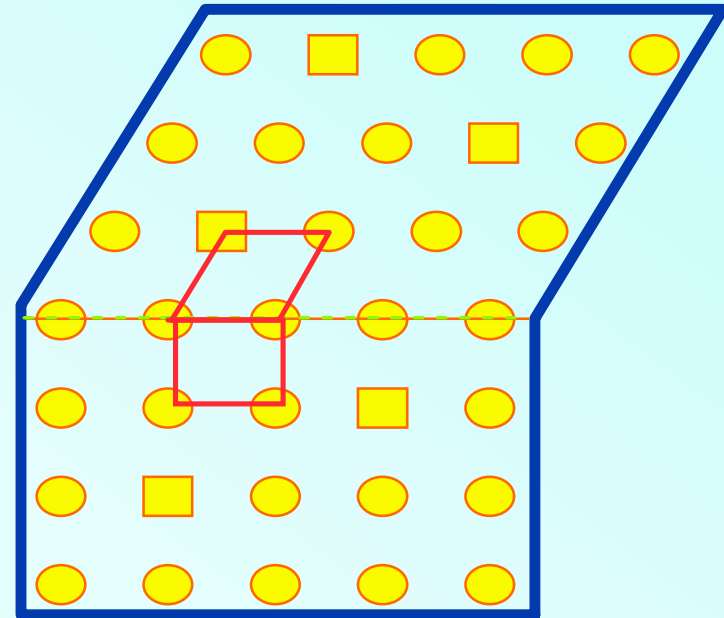
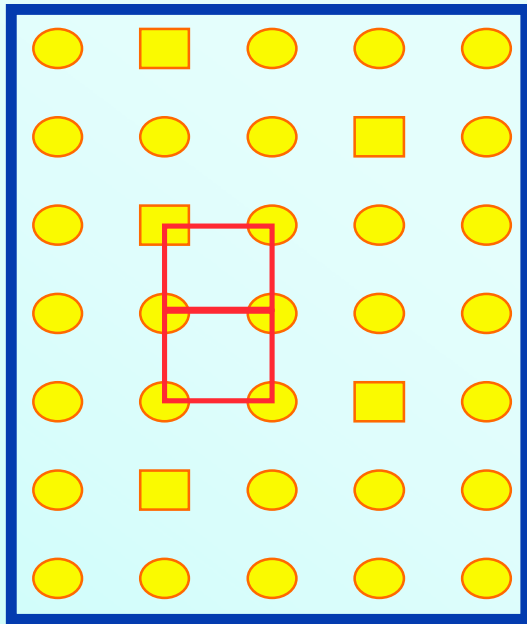
Thermomechanical processing
limited by recalescence

Need to store the heat

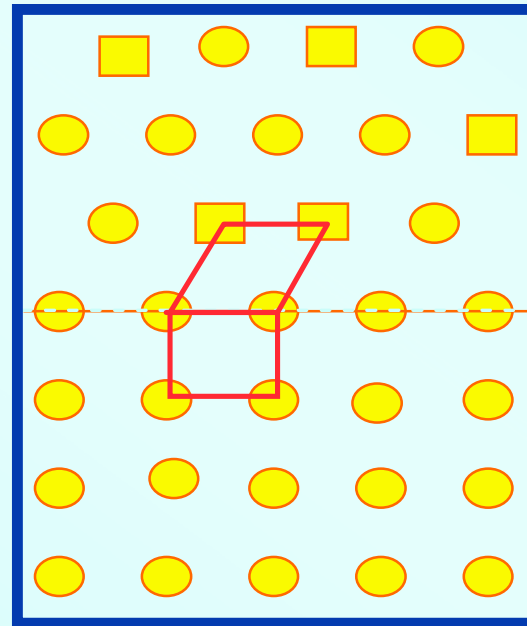
Reduce rate

Transform at low temperature

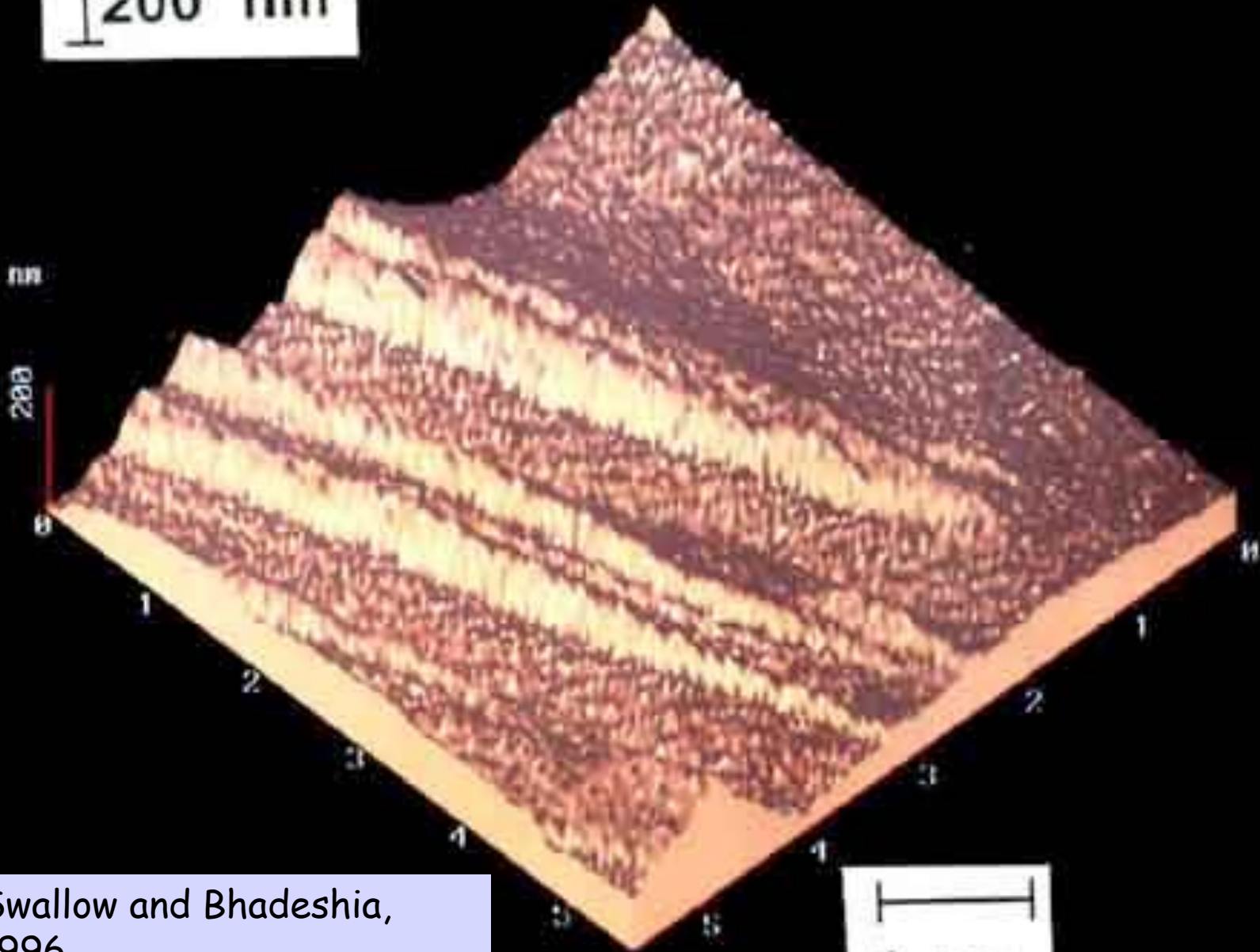
DISPLACIVE



RECONSTRUCTIVE



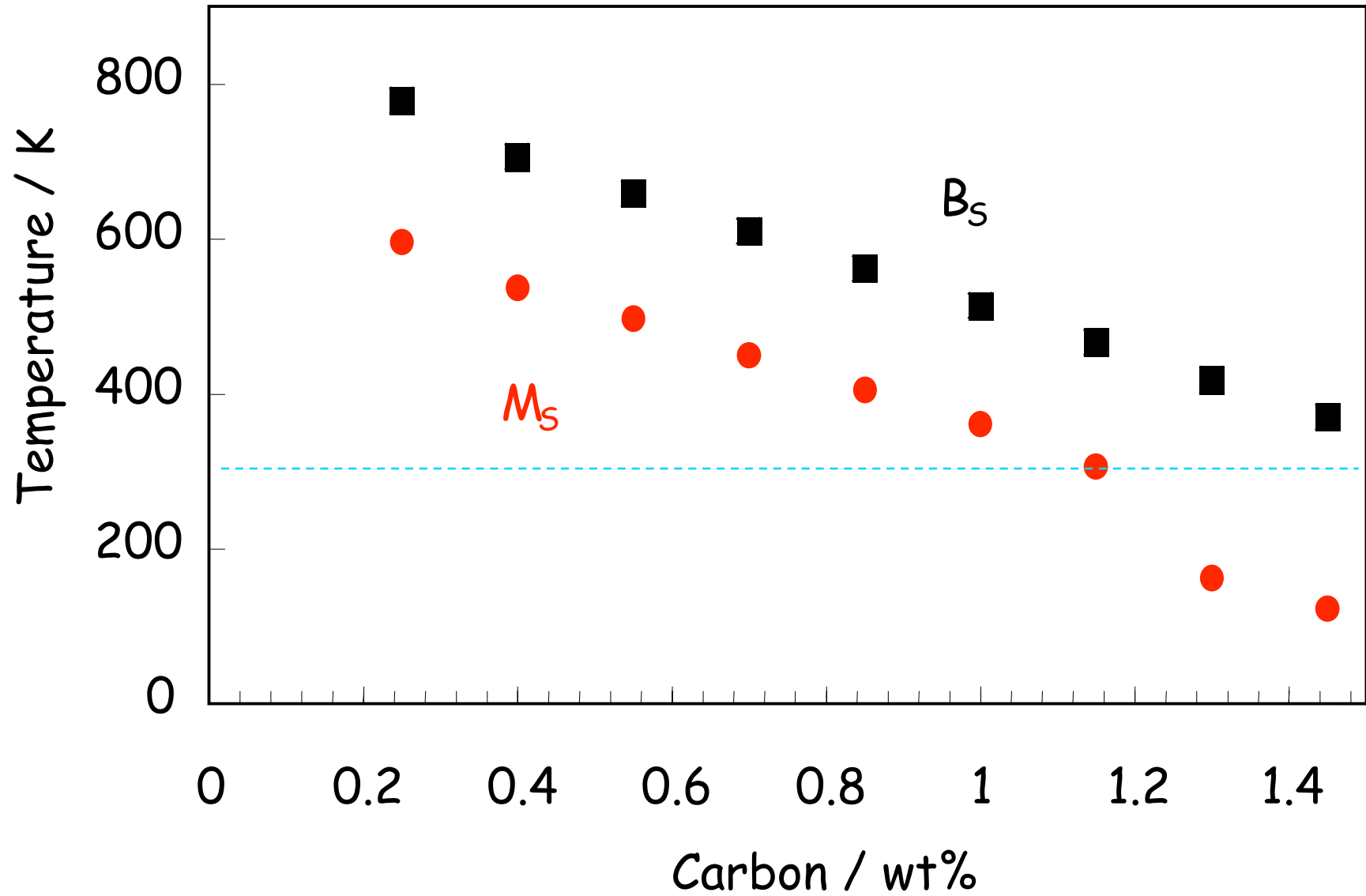
200 nm



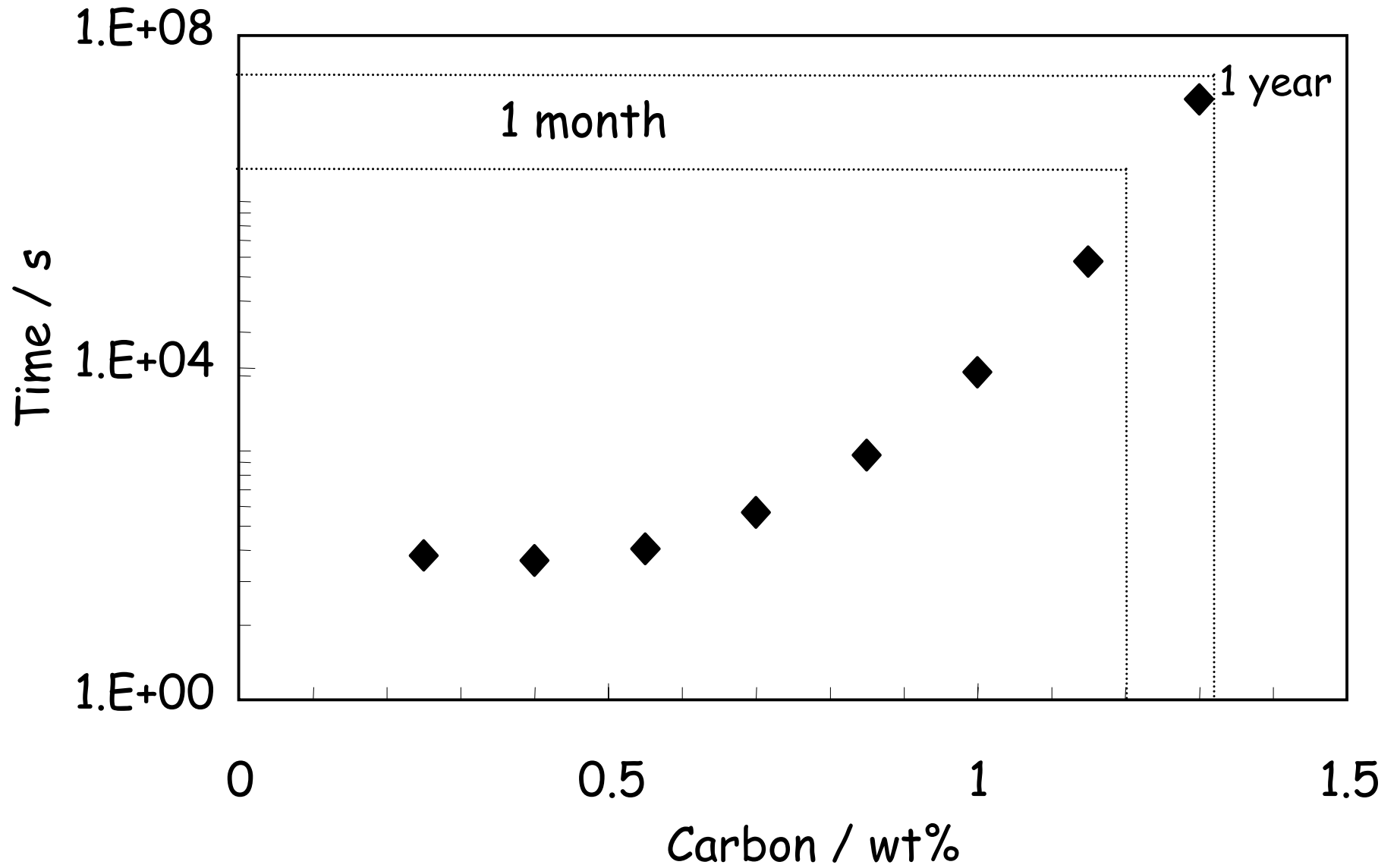
Swallow and Bhadeshia,
1996

1 μm

Fe-2Si-3Mn-C wt%



Fe-2Si-3Mn-C wt%



Low transformation temperature

Bainitic hardenability

Reasonable transformation time

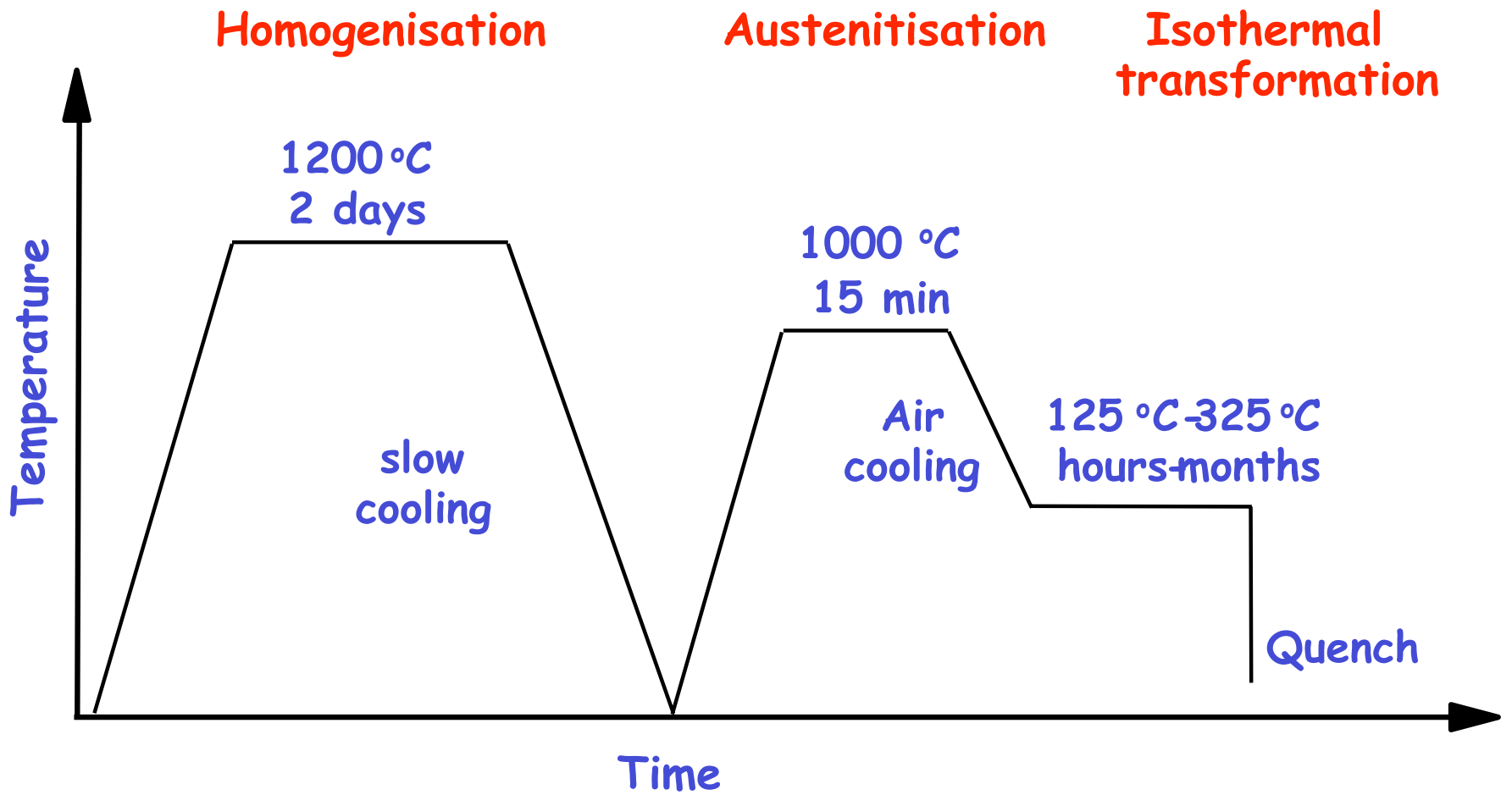
Elimination of cementite

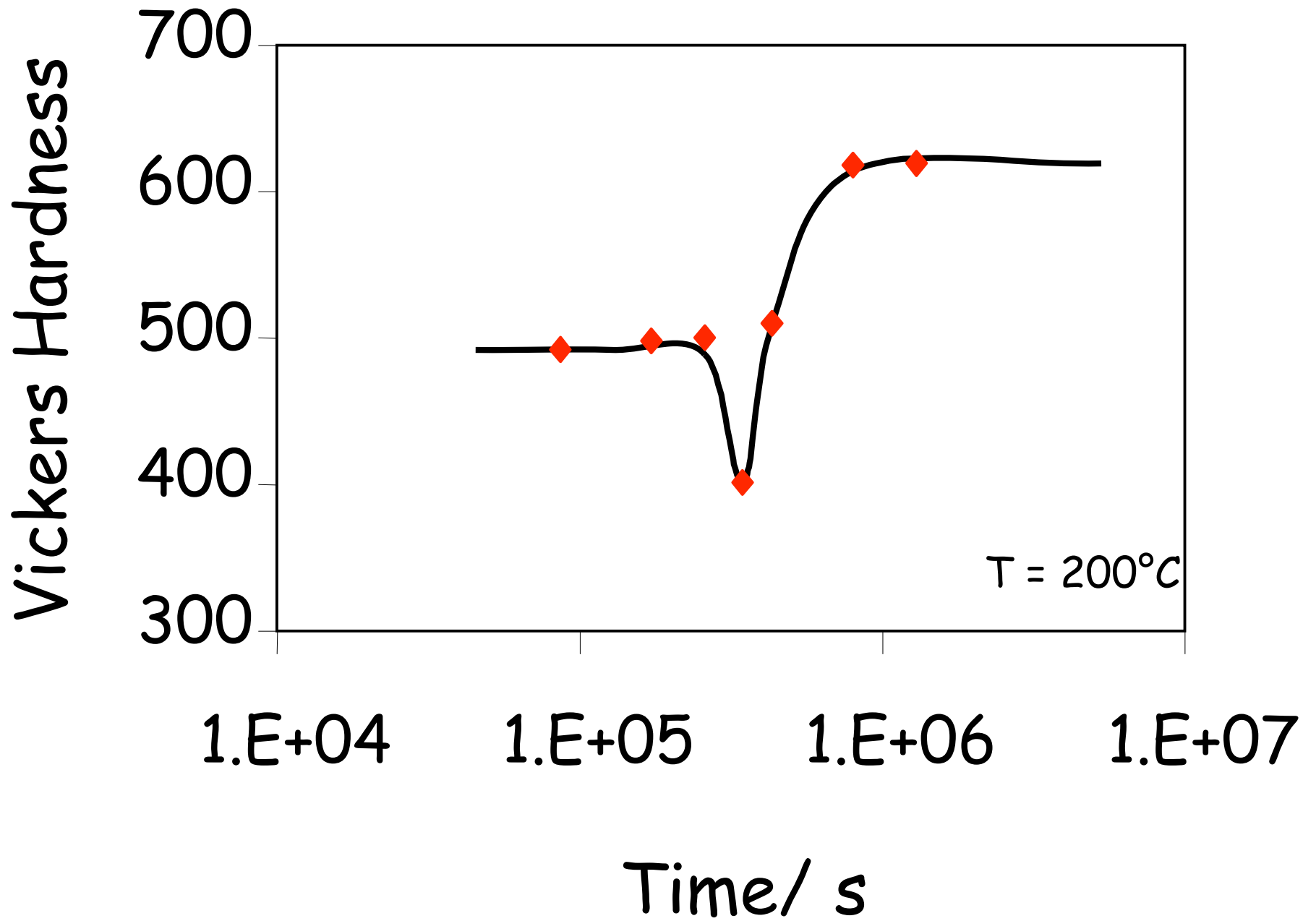
Austenite grain size control

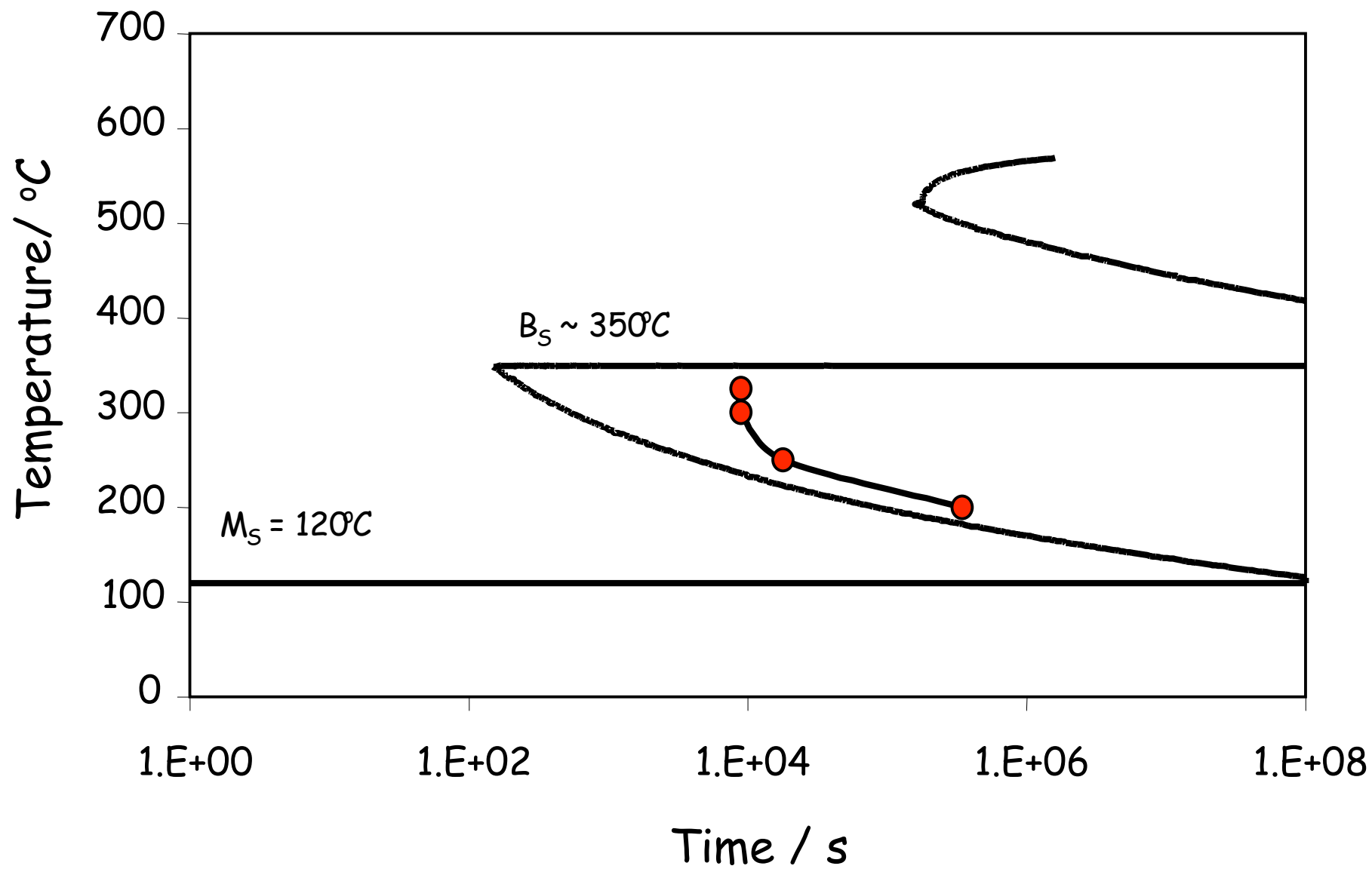
Avoidance of temper embrittlement

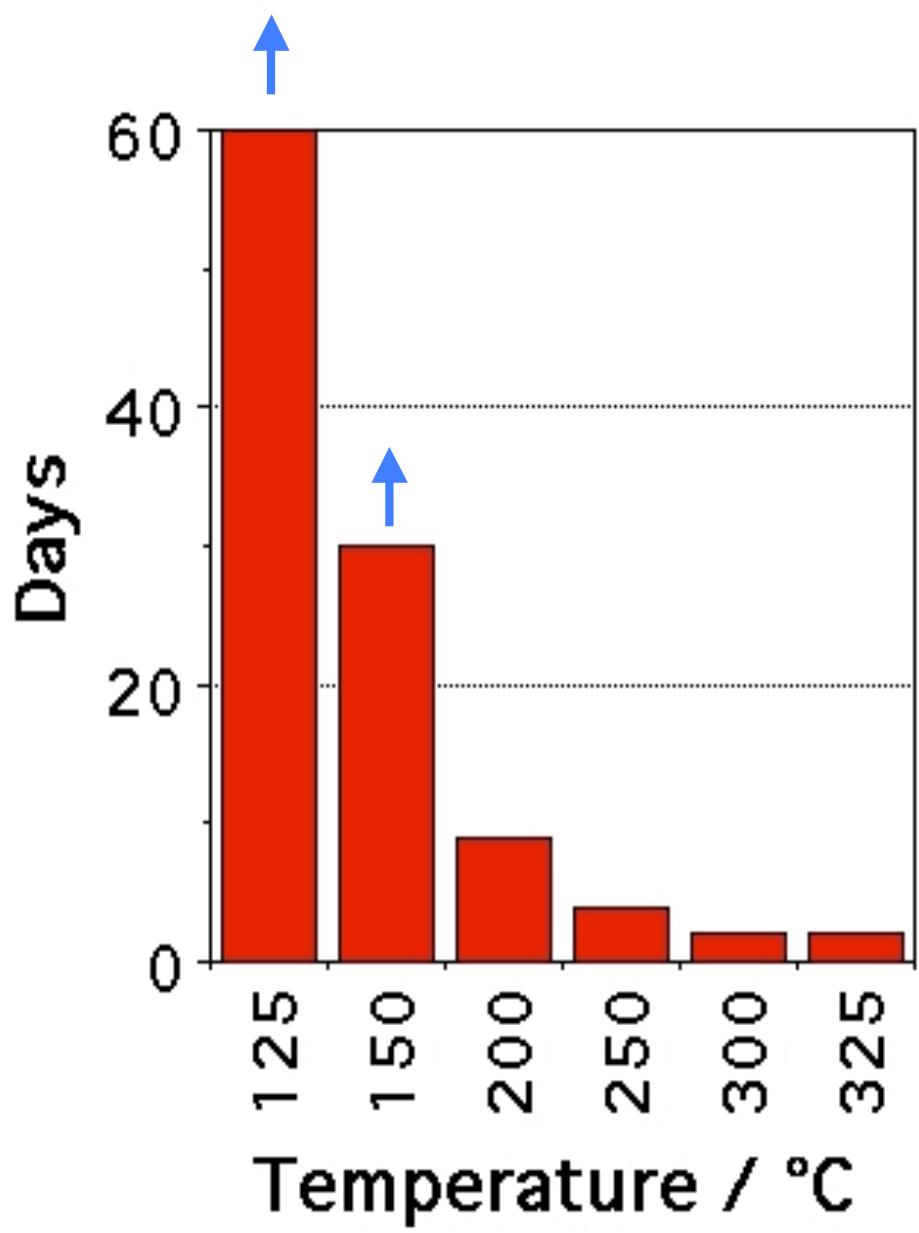
wt%

C	Si	Mn	Mo	Cr	V	P
0.98	1.46	1.89	0.26	1.26	0.09	< 0.002





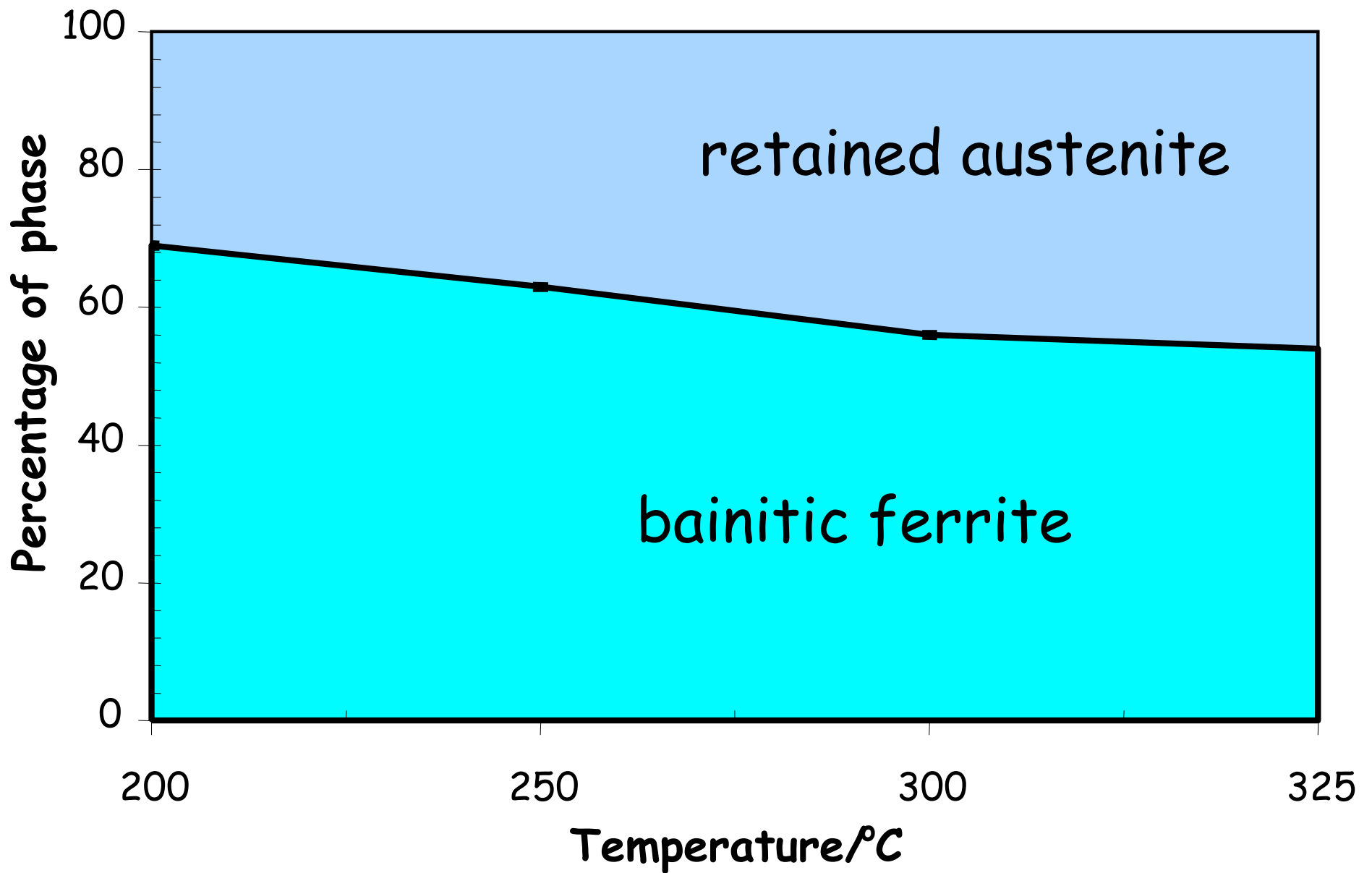


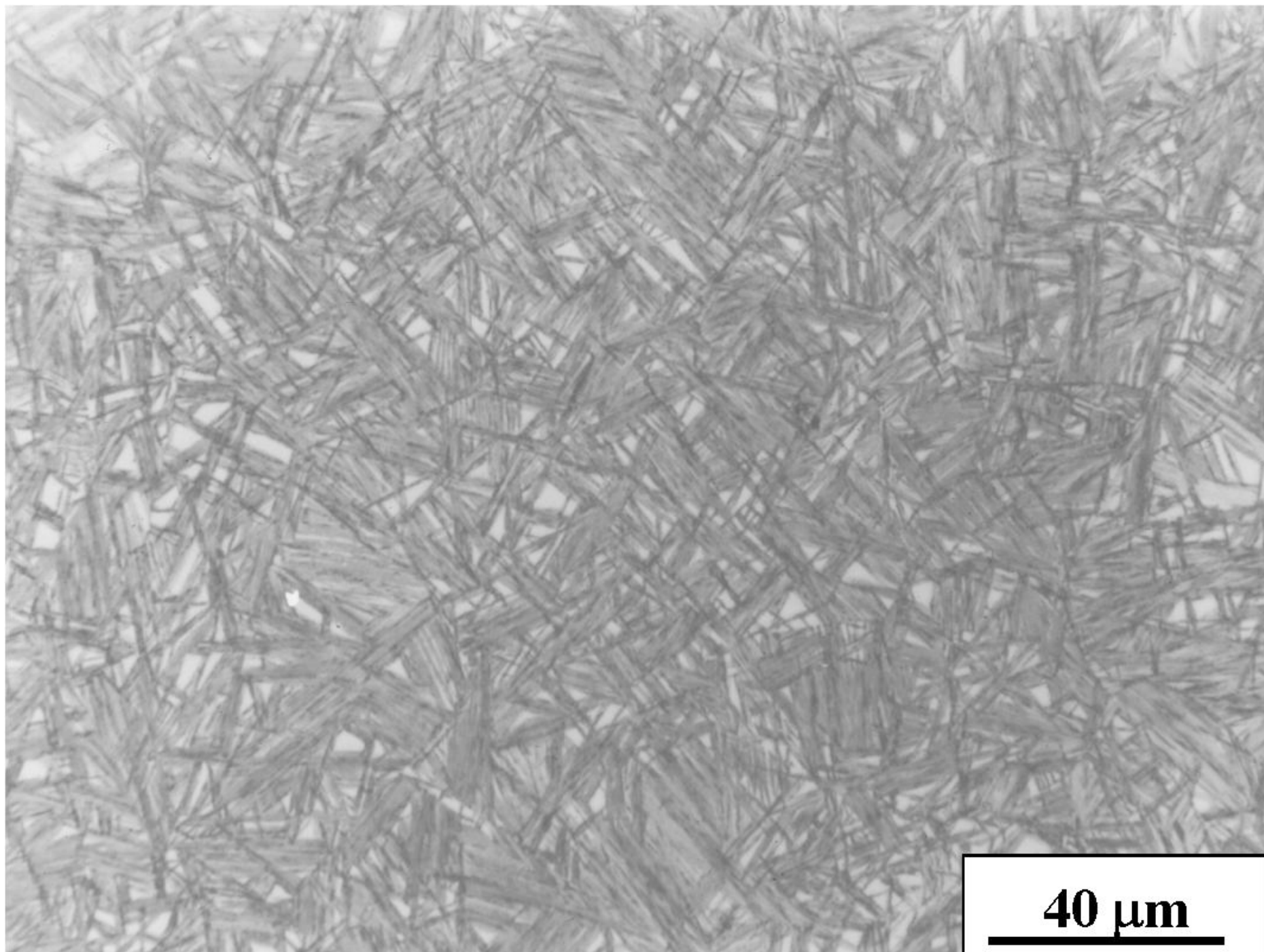




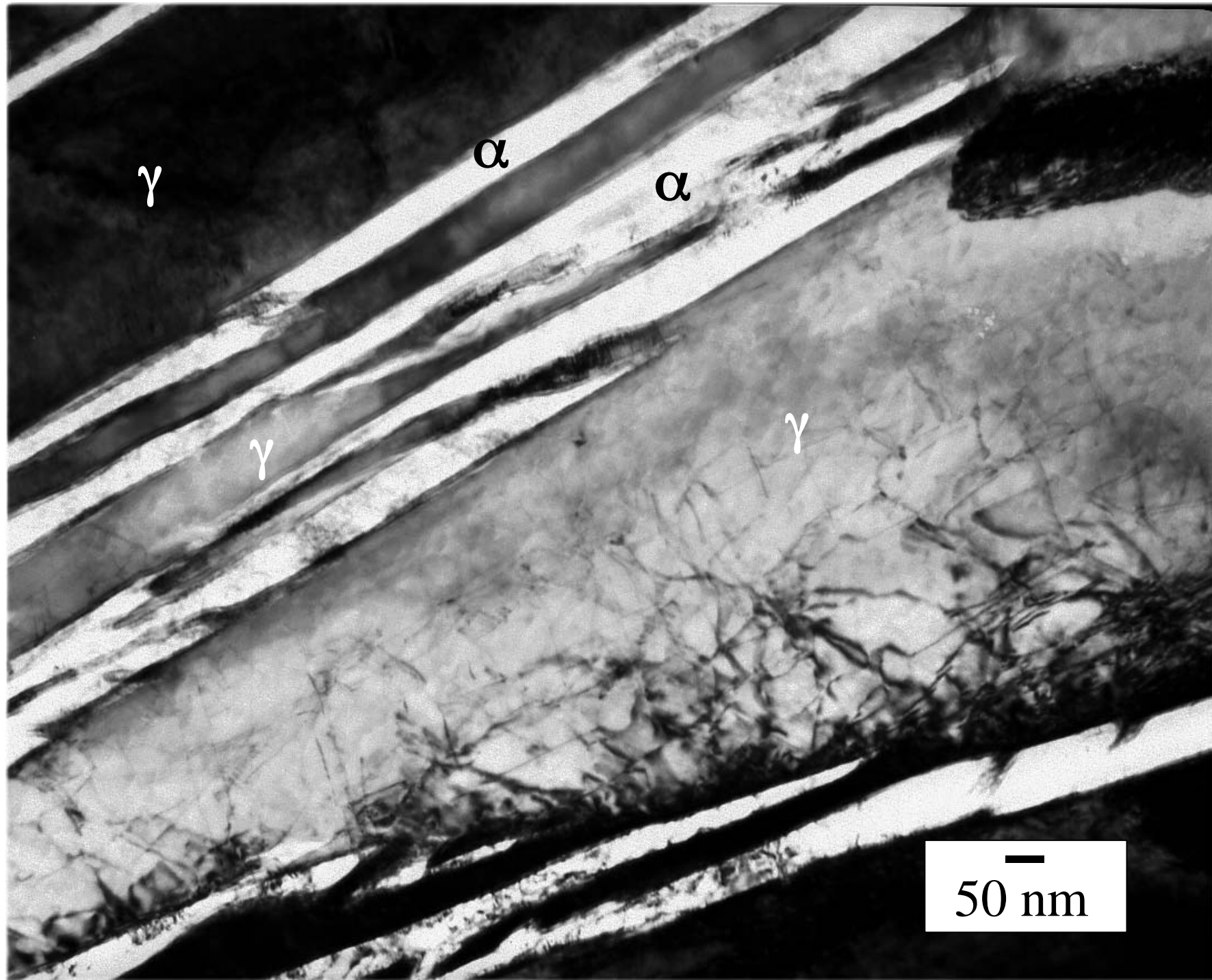
Cooking
temperature?

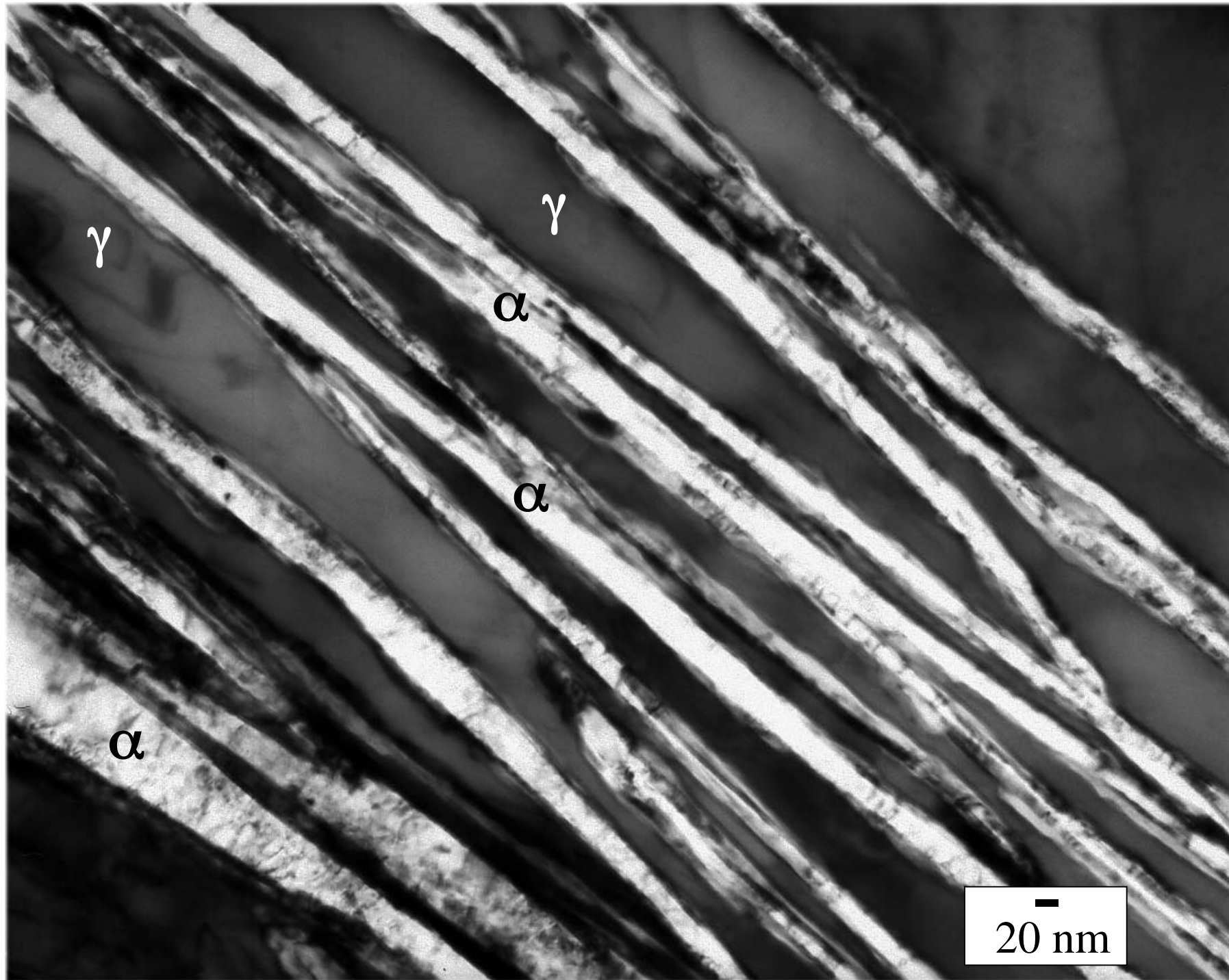
180 to 220 °C





40 μm





Conclusions

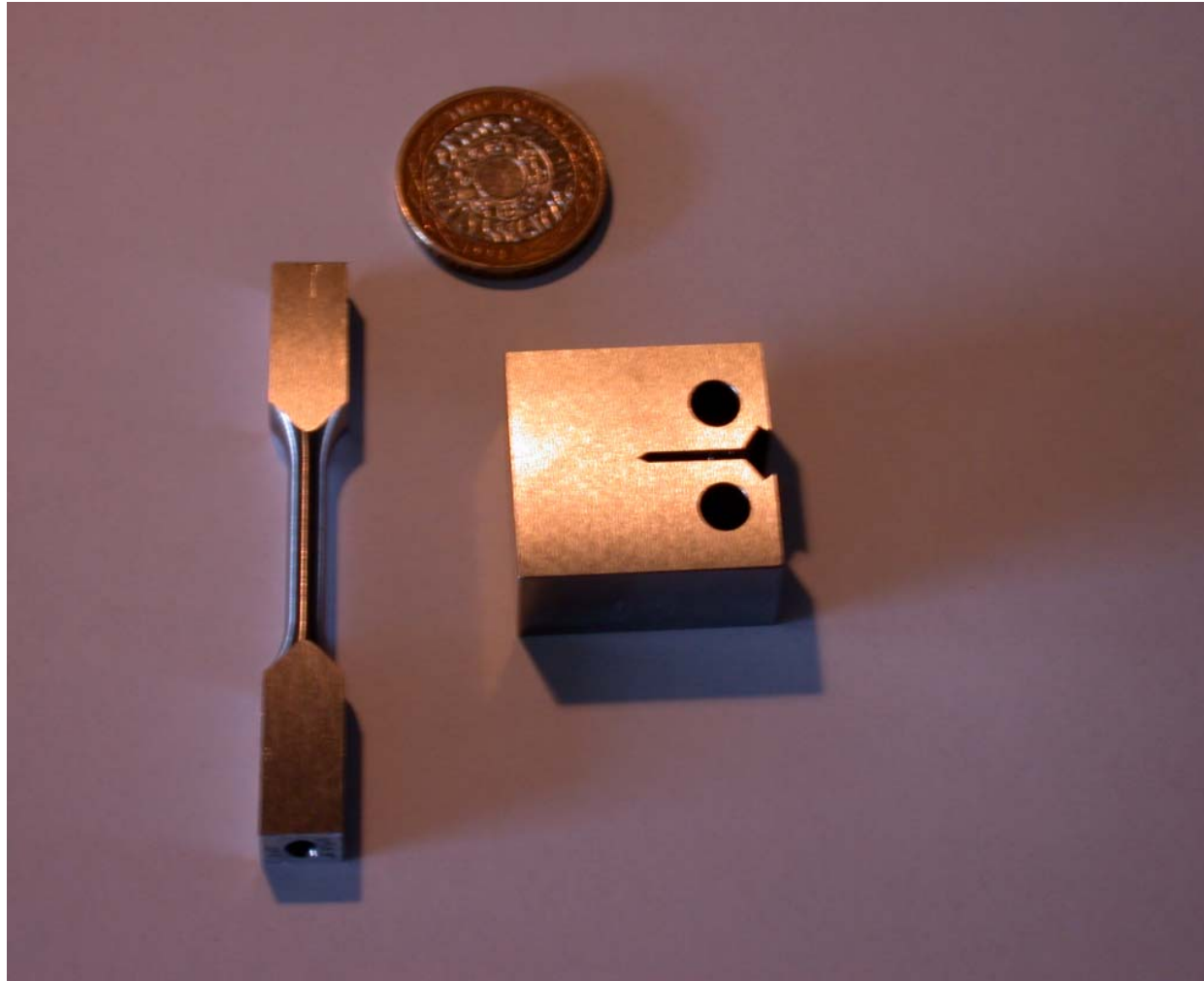
Low temperature transformation: $0.25 T/T_m$

Fine microstructure: 20-40 nm thick plates

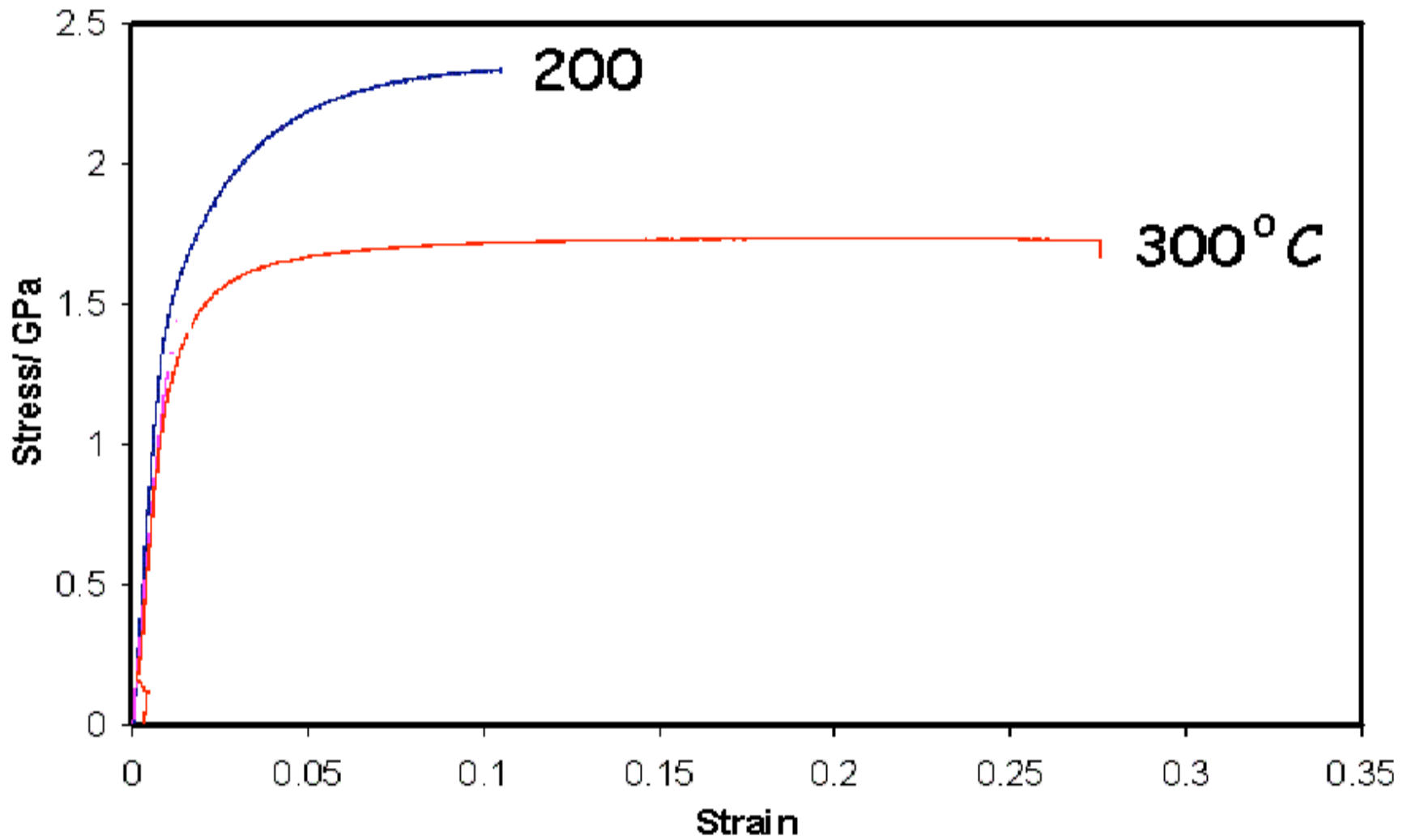
Carbide-free

Designed using theory alone

Typical mechanical properties:



2300 MPa, $27 \text{ MPa m}^{\frac{1}{2}}$



Faster Transformation

C	Si	Mn	Mo	Cr	V	P
0.98	1.46	1.89	0.26	1.26	0.09	< 0.002

Cobalt (1.5 wt%) and aluminium (1 wt%) increase the stability of ferrite relative to austenite

Refine austenite grain size

200°C

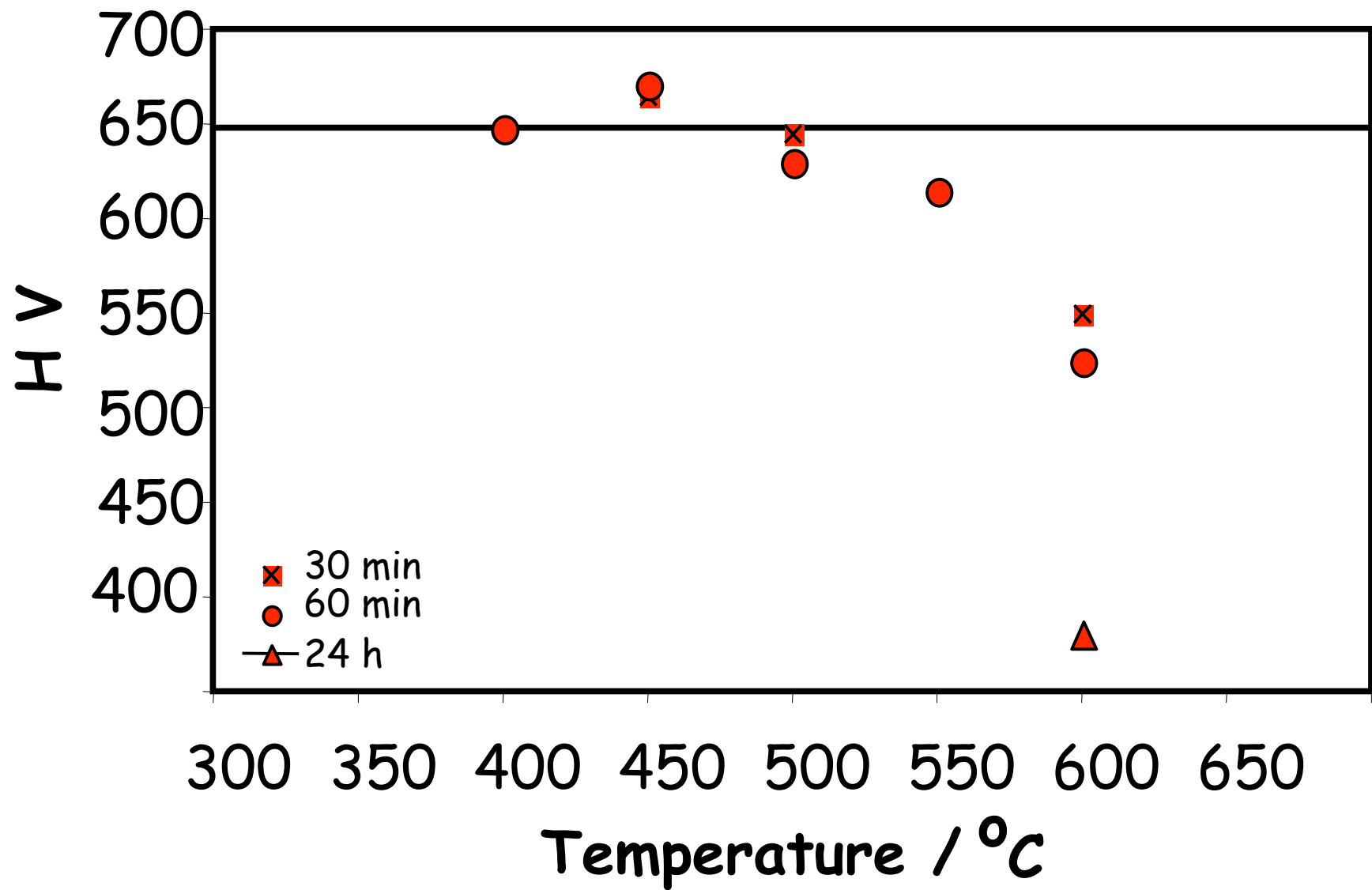
Steel	Beginning	End	% Bainite	HV
Original	4d	9d	69	618
Co	2d	5d	79	690
Co+ Al	16h	3d	78	690

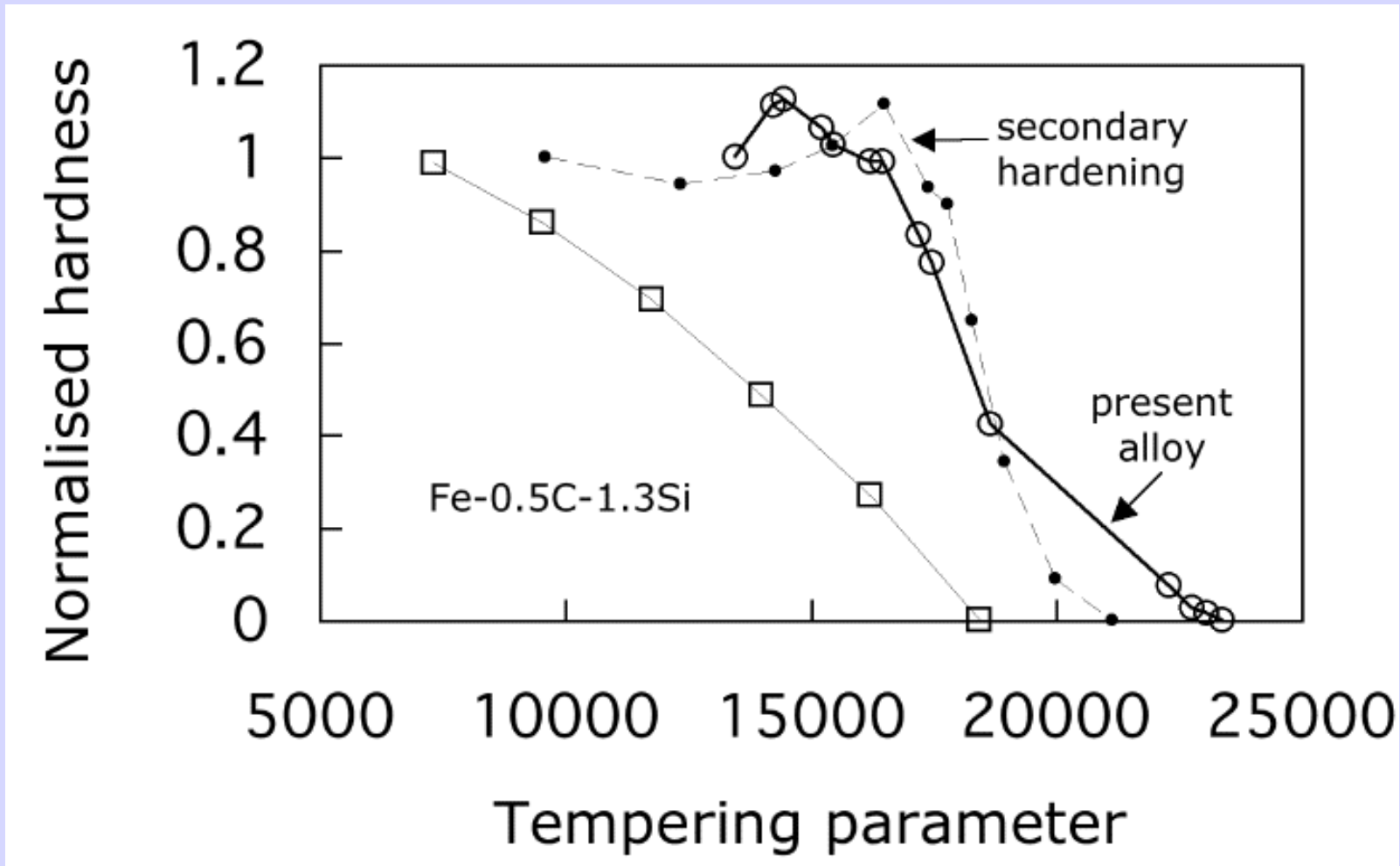
250°C

Original	5h	3/4d	63	550
Co	4h	11h	77	640
Co + Al	1h	8h	76	640

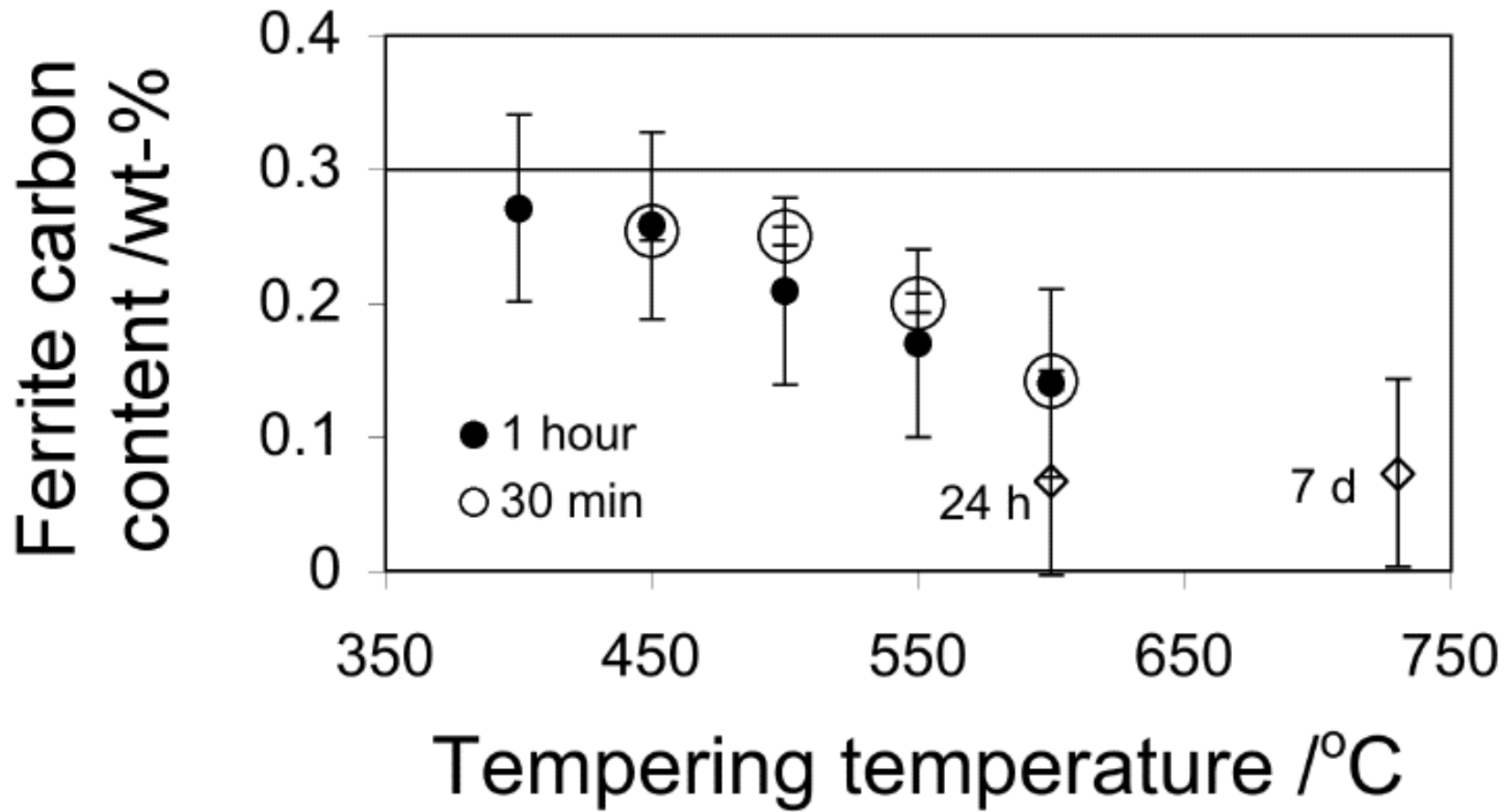
300°C

Original	2.5h	1/2d	55	420
Co	1h	5h	66	490
Co + Al	0.5h	4h	66	490

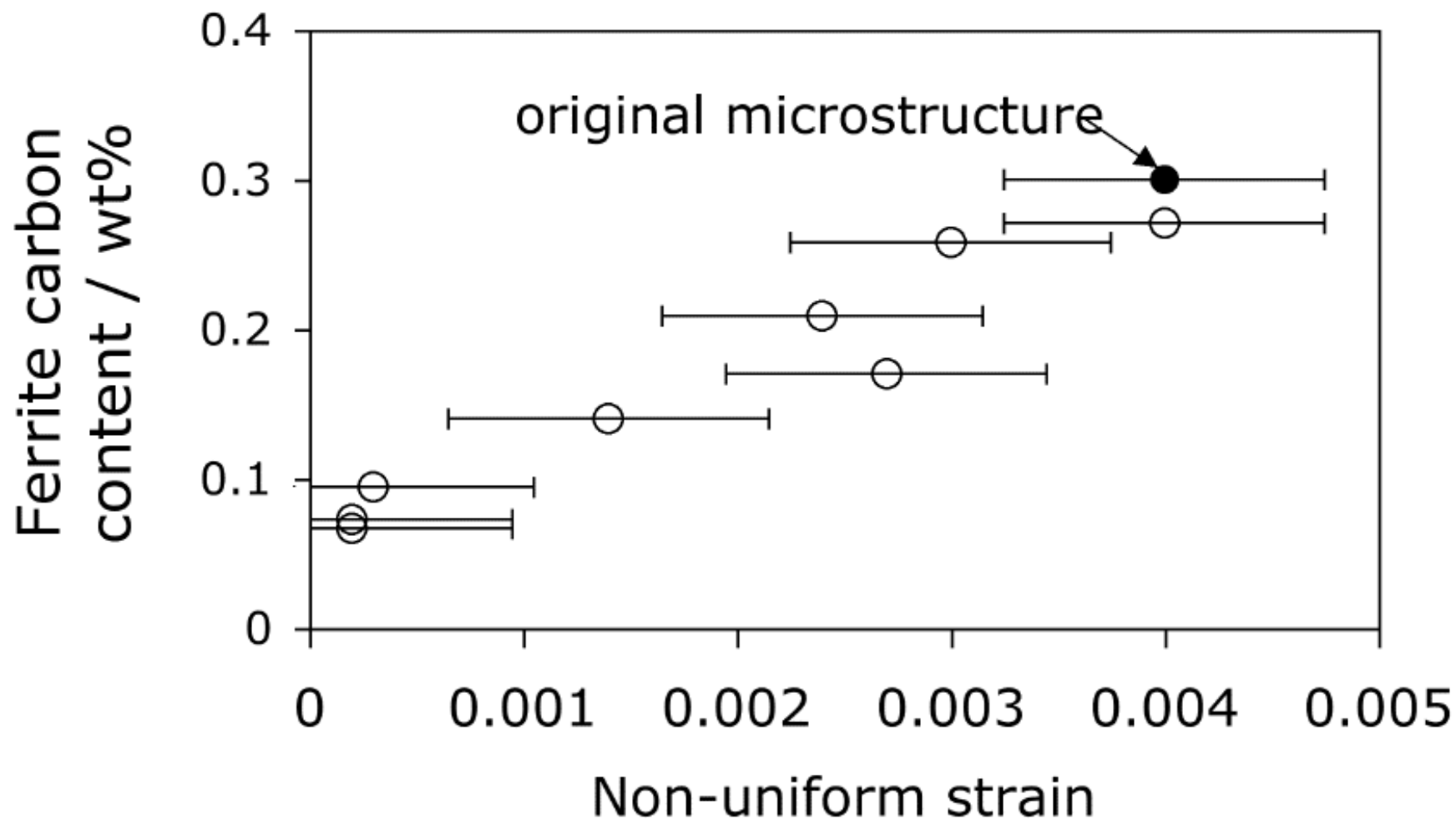


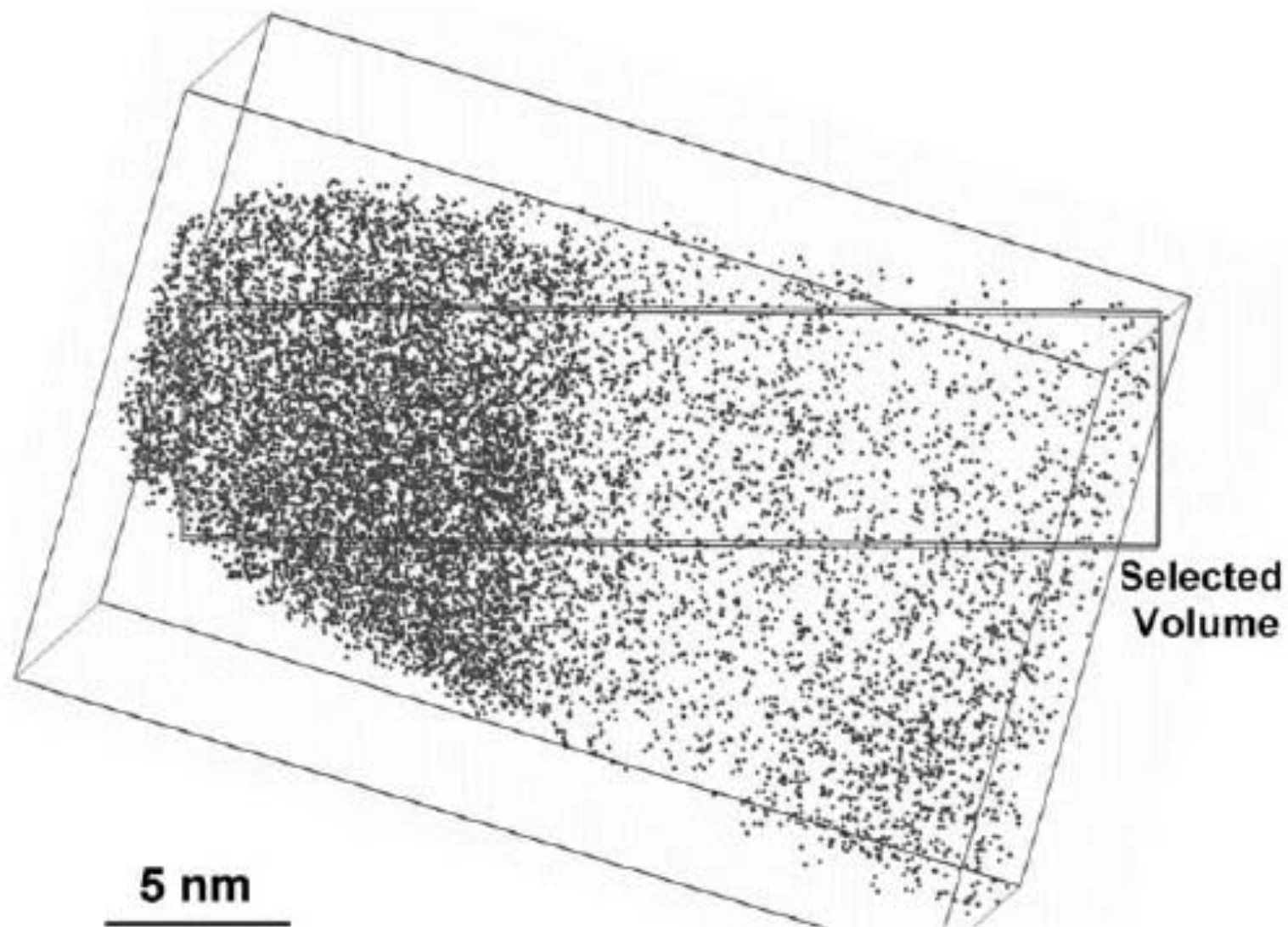


Fe-0.34C-5.08Cr-1.43Mo-0.92V-0.4Mn-1.07Si wt%

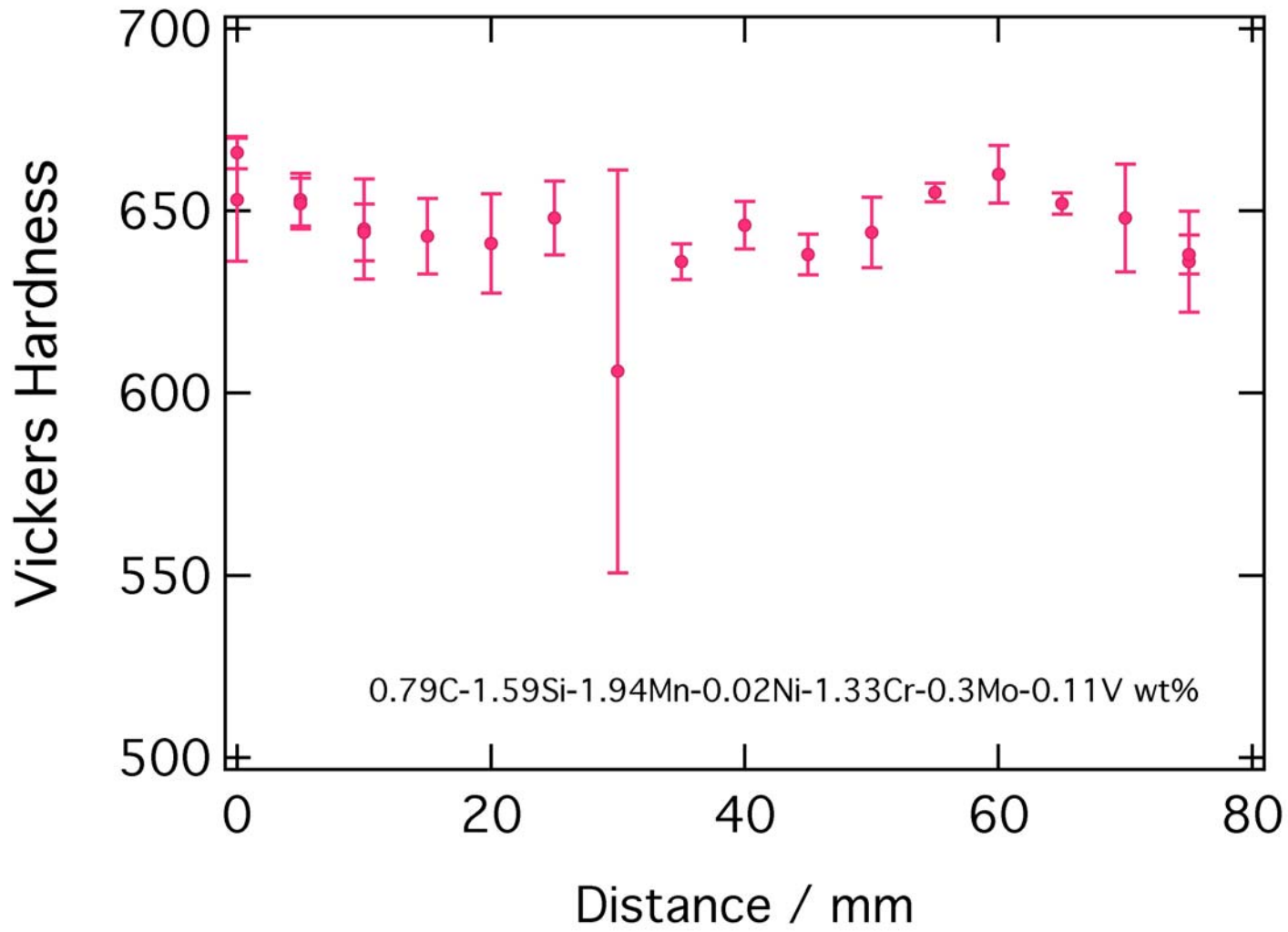


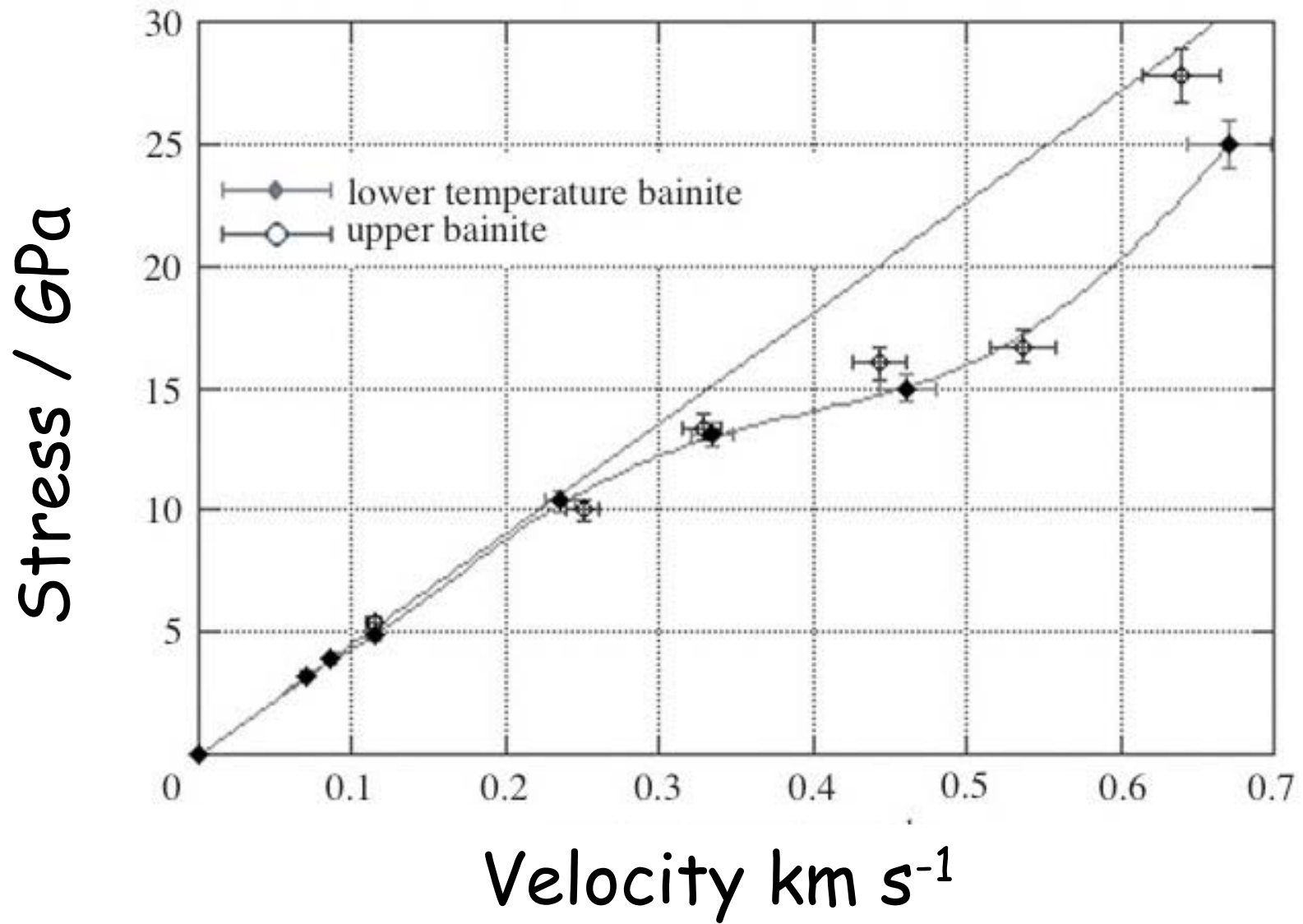
excess carbon in solid solution in ferrite !





Peet, Babu, Miller, Bhadeshia, 2004





Hammond and Cross, 2004



GRP

mild steel

"superbainite"

vehicle steel

GRP

Peter Brown (DSTL)

Dave Crowther (QinetiQ)



"more serious battlefield threats"



250

DM 1539

23

35

37

25

36

38

24

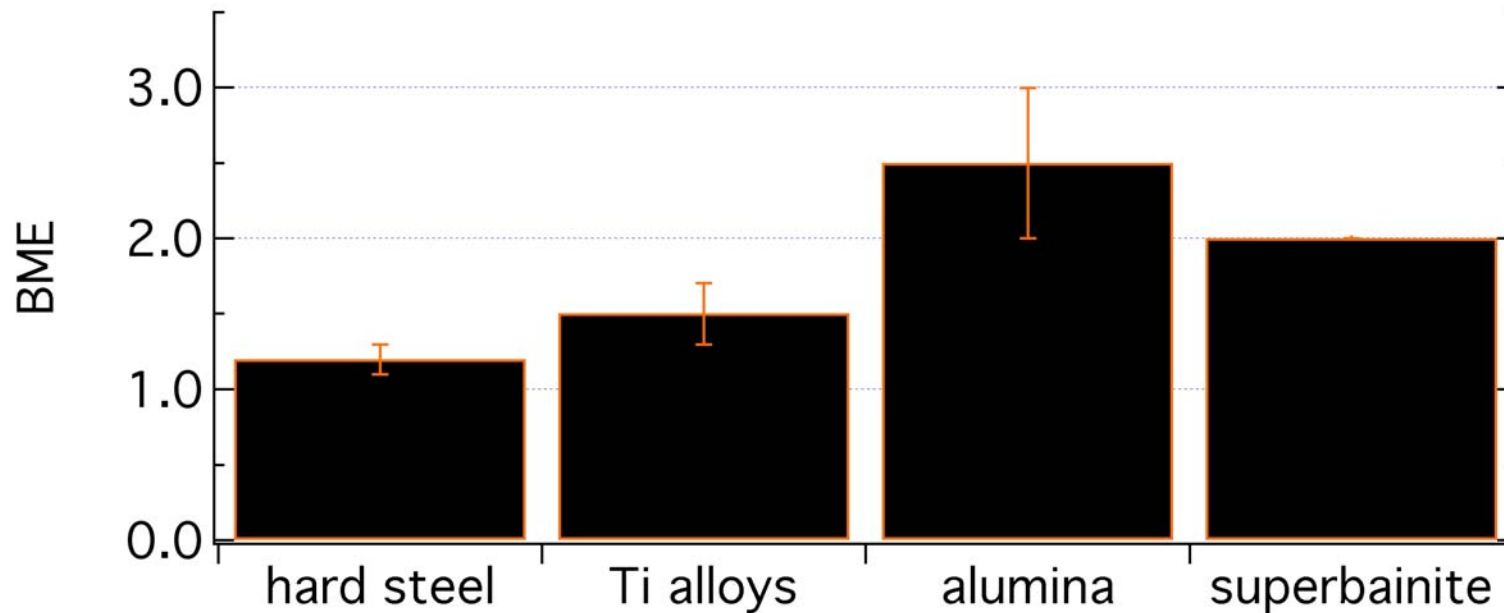
27

590 HV

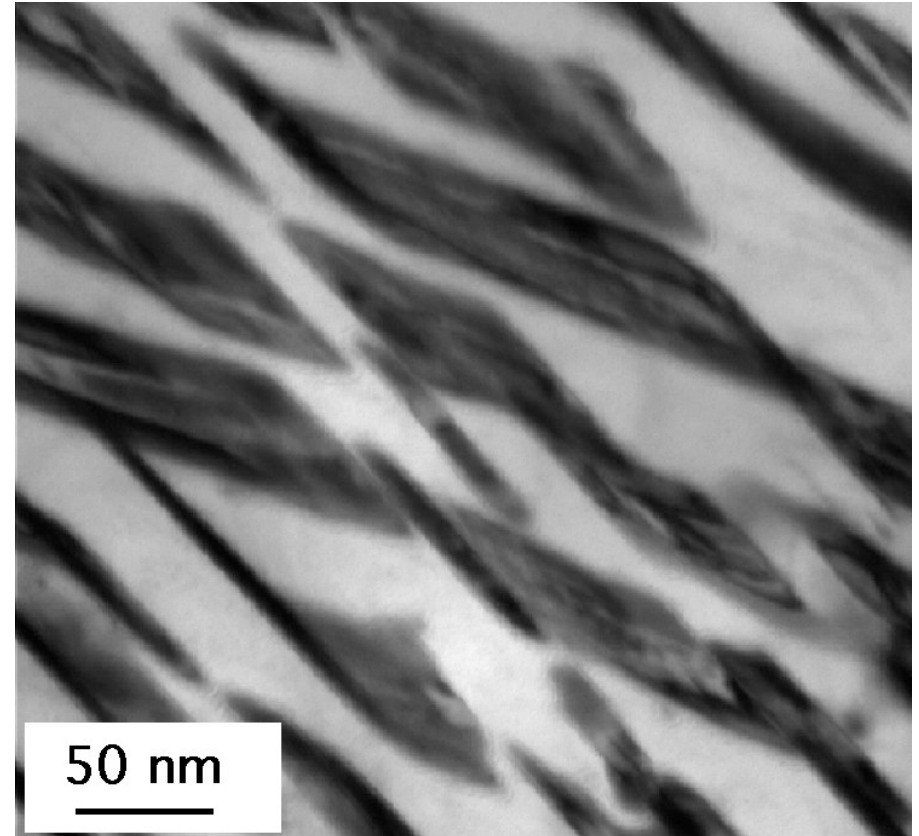
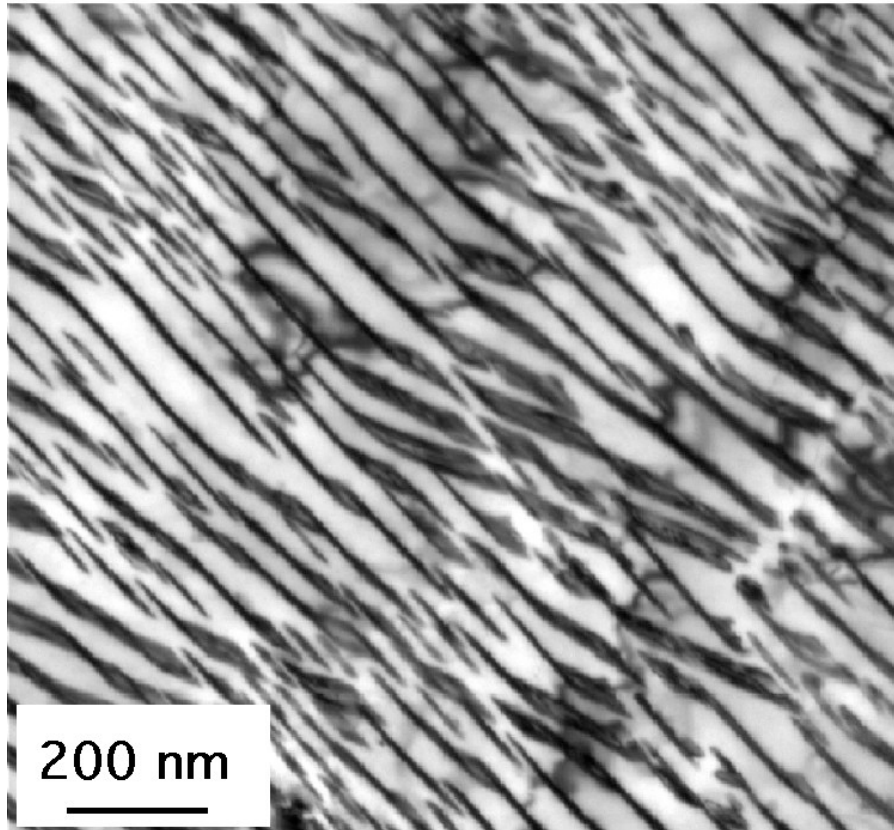
ballistic mass efficiency

consider unit area of armour

$$BME = \frac{\text{mass of ordinary armour to defeat given threat}}{\text{mass of test material to defeat same threat}}$$



30 Tesla field, 485 HV



R. A. Jaramillo, S. S. Babu, G. M. Ludtka, R. A. Kisner, J. B. Wilgen, G. Makiewicz-Ludtka, D. M. Nicholson, S. M. Kelly, M. Muruganath and H. K. D. H. Bhadeshia

Scripta Materialia, (2004) in press.



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www.msm.cam.ac.uk/phase-trans