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DISTRIBUTION OF DISLOCATIONS IN NANOSTRUCTURED BAINITE

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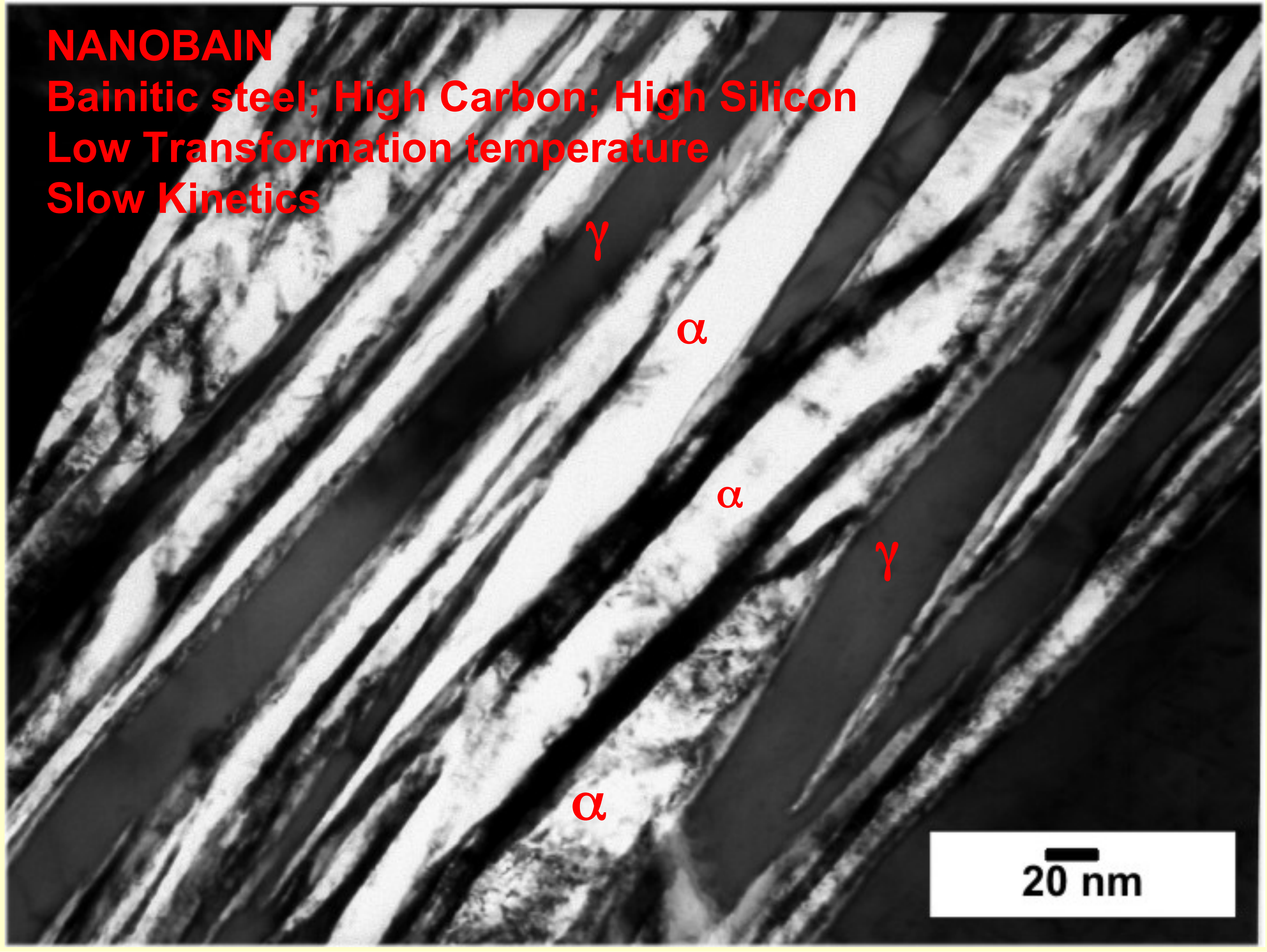
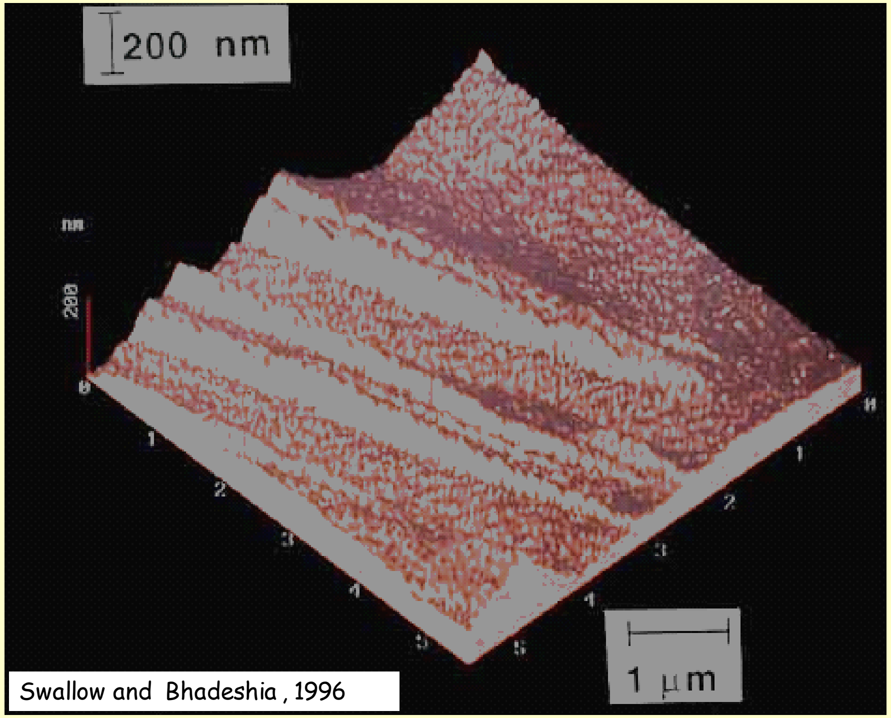
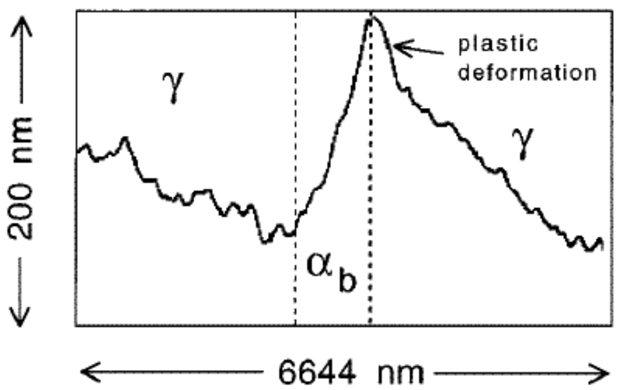

NANOBAIN
Bainitic steel; High Carbon; High Silicon
Low Transformation temperature
Slow Kinetics
γ
α
α
γ
α
20 nm

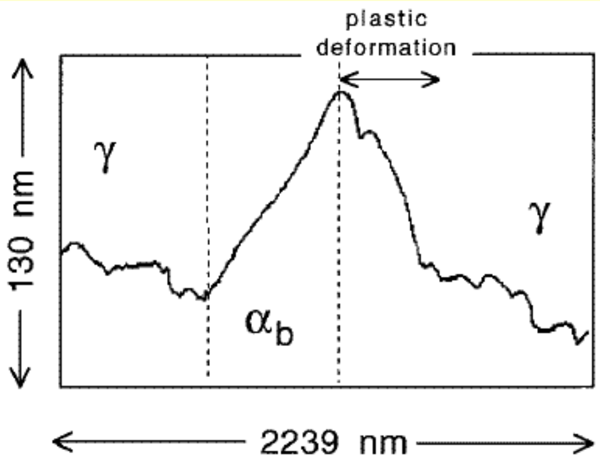
Plastic relaxation of the shape change

Relatively high dislocation density associated with bainitic ferrite (α) is attributed, at least partially, to the accommodation of the shape deformation accompanying the displacive transformation by plastic relaxation.

Then the resulting dislocation debris introduced into the austenite (γ) can be inherited by any bainite that forms subsequently.

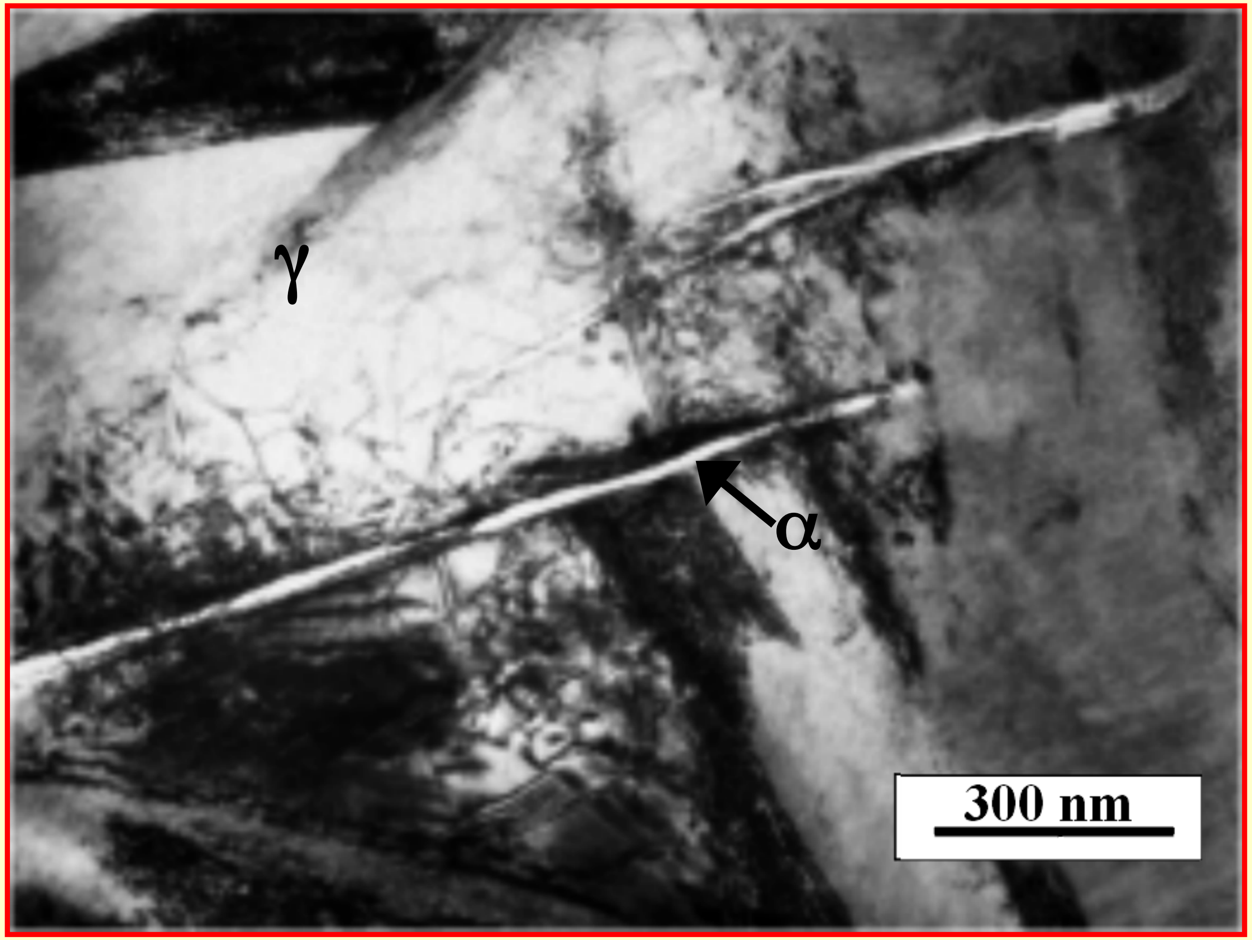






Plastic relaxation may also follow in the bainite itself, as the yield stresses of both ferrite and austenite decrease with increasing transformation temperature.

Dislocations close to Austenite/Ferrite interface

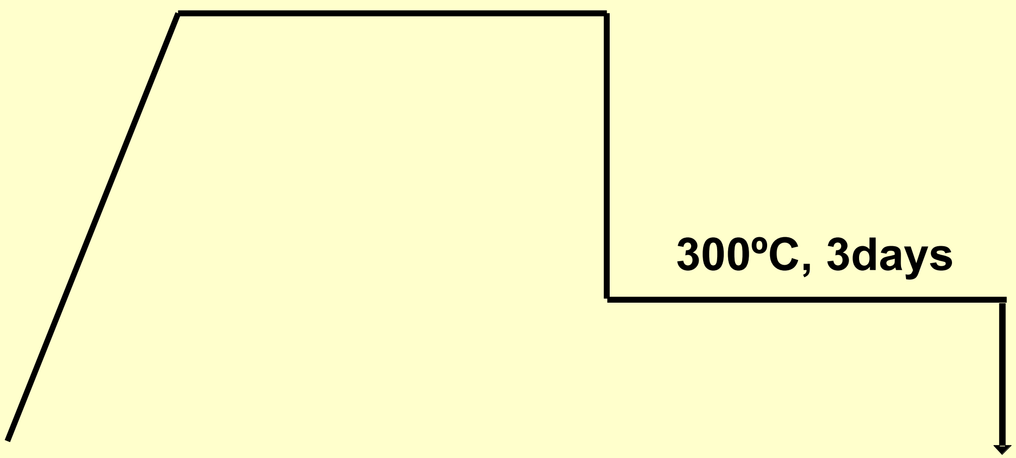


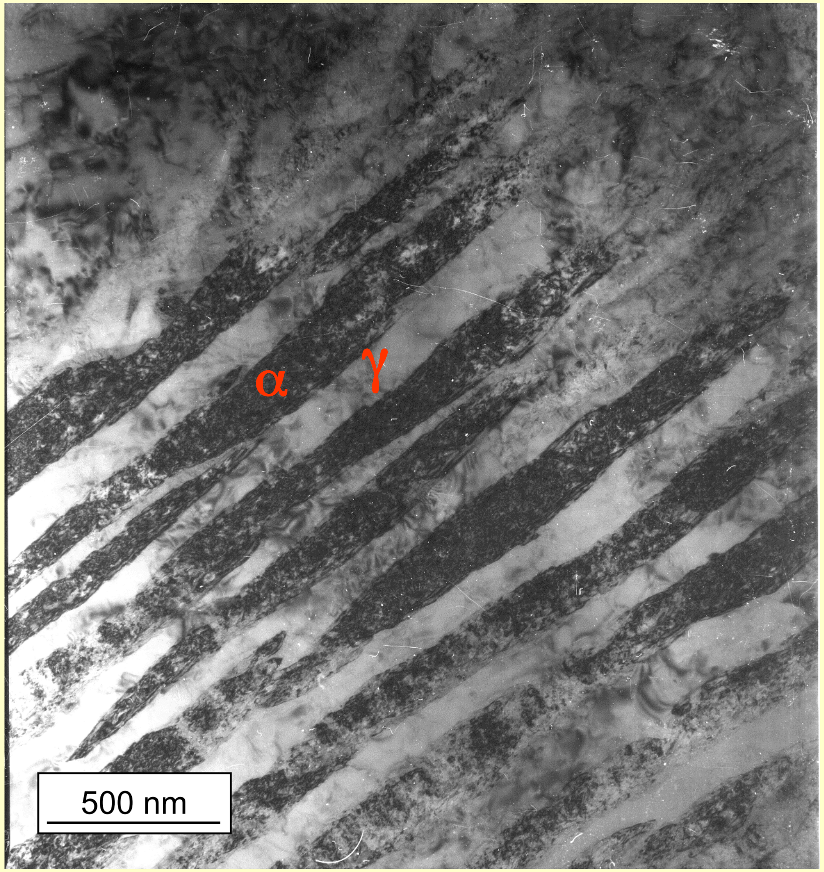
200 ºC 2 days

Material and heat treatment

Steel	C	Si	Mn	Mo	Cr	V
NANOBAIN	0.98	1.46	1.89	0.26	1.26	0.09

M_S/°C	125
B_S/°C	335
$\bar{L}_\gamma$/μm, 1000°C 15 min	49 ± 2





Lath size: (124 ± 4) nm

XRD

- **VF_γ_{Ret}**: 47 ± 3 %
- **Xγ %C**: 1.33 ± 0.12 wt.%
- **Xα %C**: 0.16 ± 0.04 wt.%

DISLOCATION DENSITY MESUREMENTS

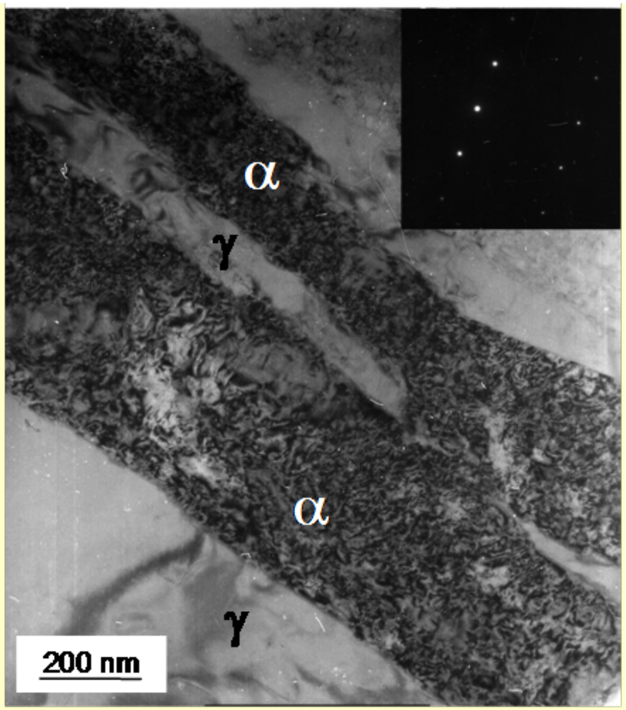
$$\rho = \frac{2N}{Lt} \longrightarrow \text{CBDE}$$

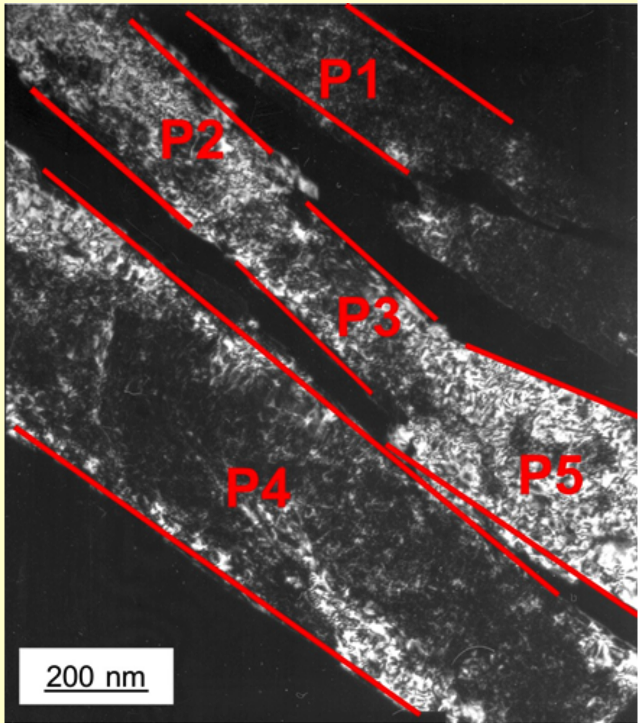
g =(002)$_\alpha$ or **g =(004)$_\alpha$** makes all the perfect dislocations in the bcc structure visible.

g = (220γ, -220γ, 200γ ,020γ) were used to observe all of the perfect dislocations in bcc

$$\frac{\sum \rho_i}{3} \leq \rho_{Real} \leq \frac{\sum \rho_i}{4}$$

Screw component Edge component





Calculation of error values (dρ)

$$\rho = \frac{2N}{Lt}$$

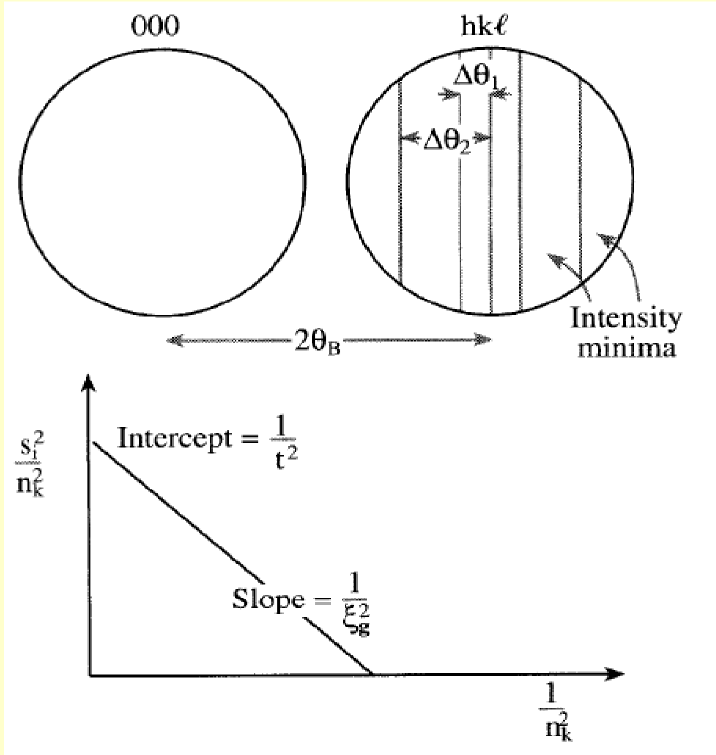
$$d\rho = \left(\frac{\partial \rho}{\partial L}\right) dL + \left(\frac{\partial \rho}{\partial t}\right) dt$$

$$\frac{1}{t^2} = \frac{s_i^2}{n_k^2} + \frac{1}{\xi_g^2 n_k^2}$$

$$dt = \left(\frac{\partial t}{\partial s_i}\right) ds_i$$

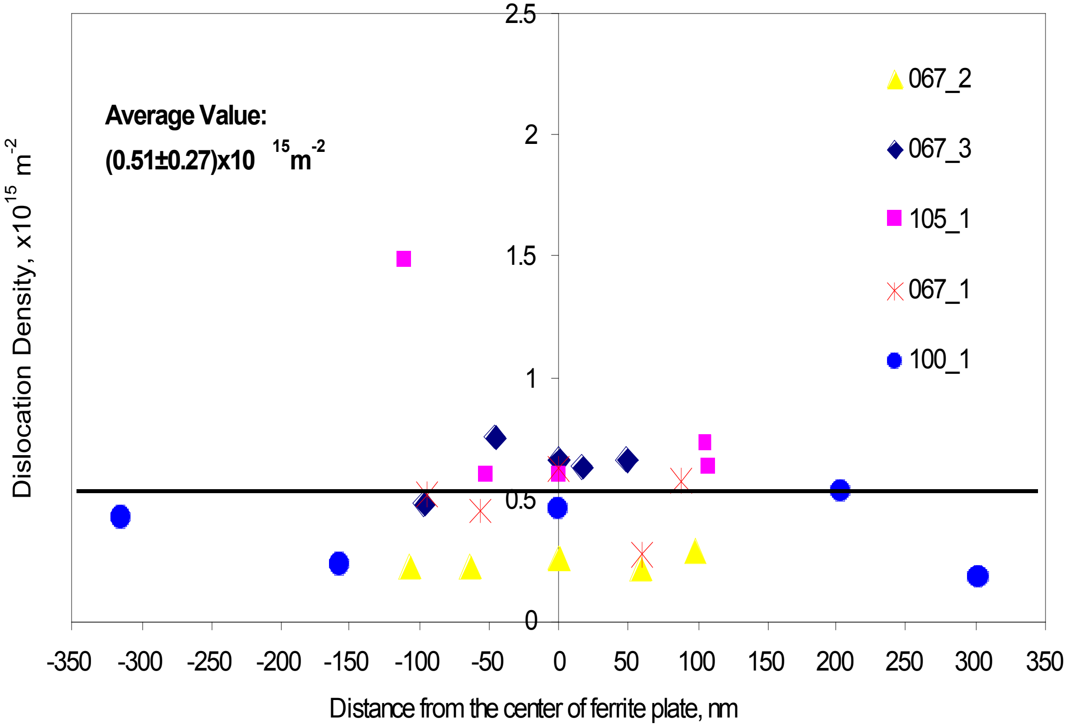
$$s_i = \lambda \frac{\Delta\theta_i}{2\theta_B d^2}$$

$$ds_i = \left(\frac{\partial s_i}{\partial 2\theta_B}\right) d2\theta_B + \left(\frac{\partial s_i}{\partial \Delta\theta_i}\right) d\Delta\theta_i$$



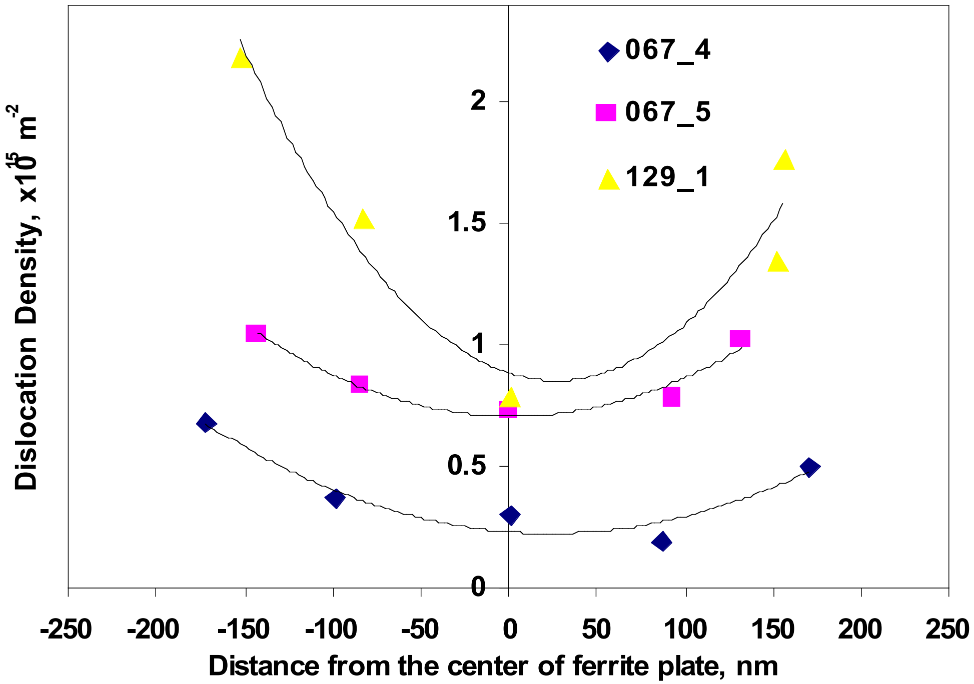
Williams, D.B. y Carter, C.B.: “*Transmission Electron Microscopy”,* Ed. Penum Publishing, 1996.

BAINITIC FERRITE

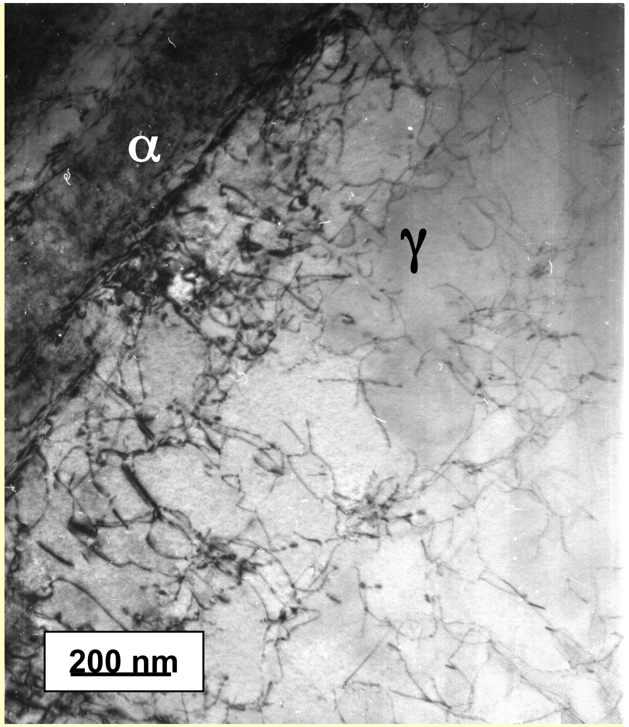


Homogeneous dislocation density distribution

Non homogeneous dislocation density distribution

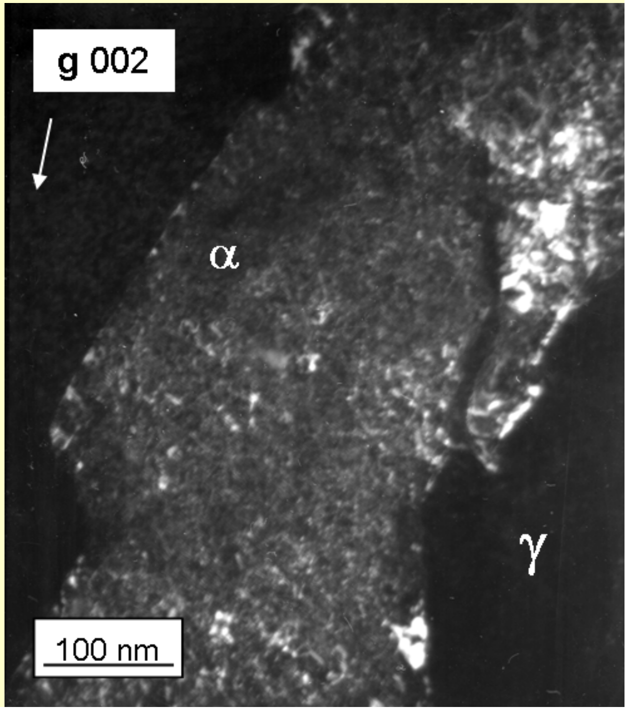


SUBSTRUCTURED BAINITIC FERRITE



- **Central region :**

Dislocations that may result from lattice-invariant deformation at the earlier stage of bainite growth by a co-ordinated movement of atoms.



- **Close to the ferrite/austenite interface region :**

Higher dislocation density at the vicinity of the austenite/ferrite interface is related to the plastic deformation occurring in the surrounding austenite to accommodate the transformation strain as growth progresses and the following inheritance of those dislocations by the expansion of the growing bainitic ferrite plate.

DATA FORMERLY REPORTED IN LITERATURE

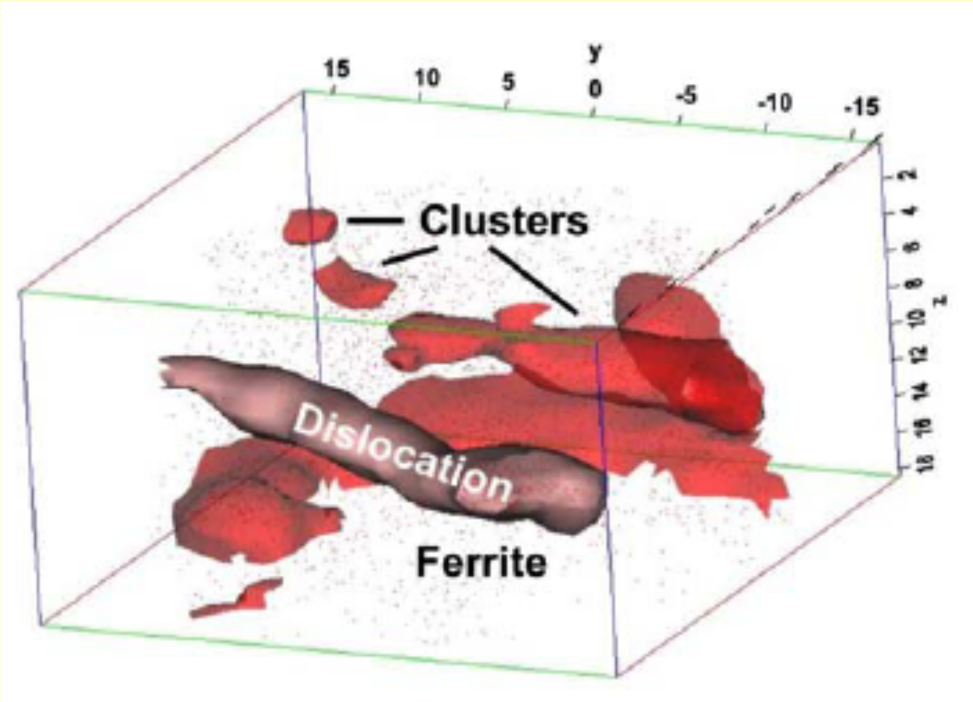
Phase/Microstructure	Dislocation density [m^{-2}]	Temperature	Technique	Reference
Retained Austenite	$(0.18 \pm 0.02) \times 10^{15}$	300 °C	TEM	Present work
Bainitic Ferrite	$(0.51 \pm 0.27) \times 10^{15}$	300 °C	TEM	Present work
Bainite	$(4.50 \pm 1.71) \times 10^{15}$	200 °C	XRD	Ref [16]
	$(3.97 \pm 1.63) \times 10^{15}$	200 °C		Ref [16]
	$(3.24 \pm 1.49) \times 10^{15}$	250 °C		Ref [16]
	$(3.24 \pm 1.49) \times 10^{15}$	250 °C		Ref [16]
	$(2.15 \pm 1.22) \times 10^{15}$	300 °C		Ref [16]
	$(1.55 \pm 1.03) \times 10^{15}$	300 °C		Ref [16]
	$(1.07 \pm 0.15) \times 10^{16}$	250 °C		Ref [17]
	$(7.43 \pm 1.12) \times 10^{15}$	300 °C		Ref [17]
	$(4.11 \pm 0.71) \times 10^{15}$	350 °C		Ref [17]
	$(3.29 \pm 0.58) \times 10^{15}$	375 °C		Ref [17]
Martensite	3.01×10^{15}	300 °C	TEM	Ref [13]
	4.11×10^{15}	357 °C		
Bainite+Martensite	7.46×10^{15}	200 °C	Empirical Model	Ref [18]
	7.40×10^{15}	300 °C		
	3.77×10^{15}	400 °C		

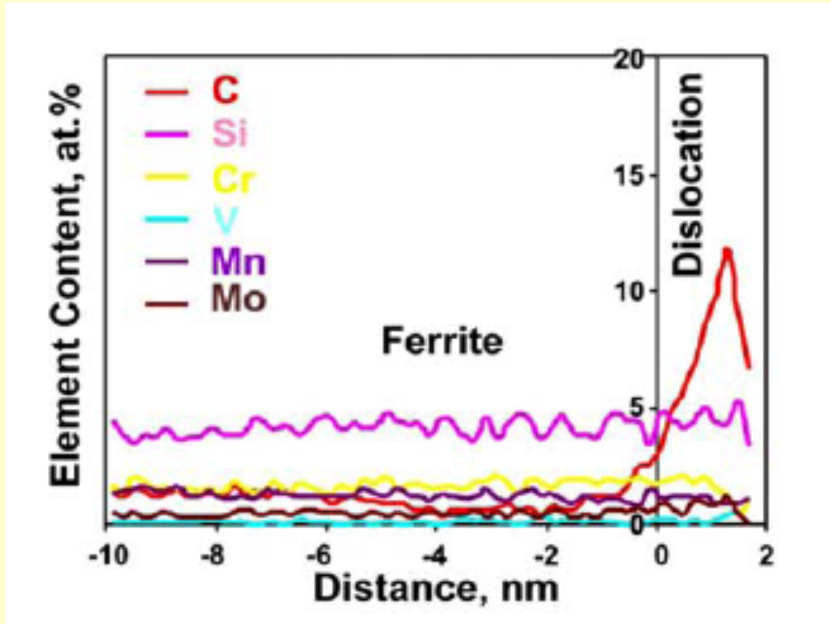
Ref [13]: S. Morito, J. Nishikawa and T. Maki: ISIJ Int. Vol. 43 (2003)
Ref [16]: C. Garcia-Mateo and F.G. Caballero: ISIJ Int. Vol. 45 (2005)
Ref [17]: C. Garcia-Mateo, F.G. Caballero, C. Capdevila and C. Garcia de Andres: Scripta Mater. Vol. 61 (2009)
Ref [18]: M. Takahashi and H.K.D.H. Bhadeshia: Mater. Sci. Technol. Vol. 6 (1990)

APT results

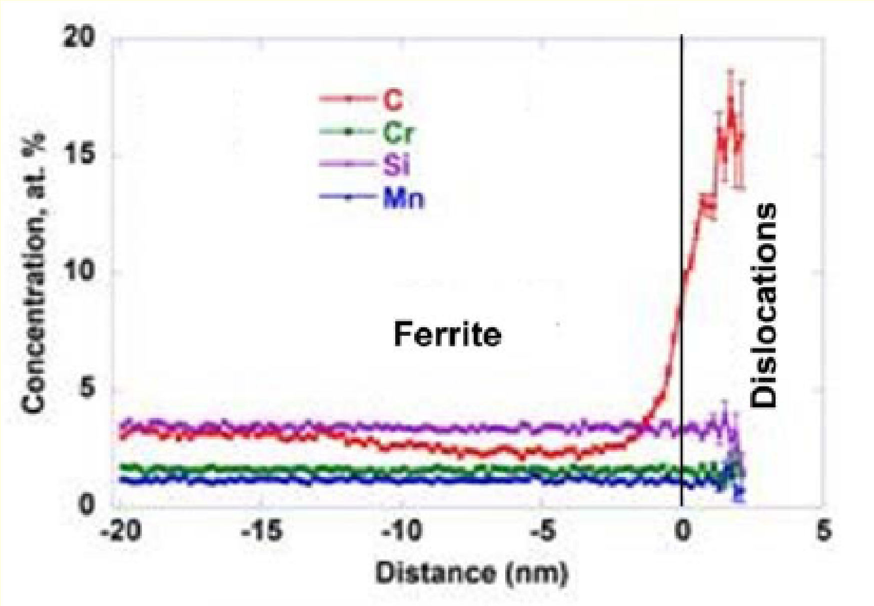
APT specimens were electropolished using the standard double layer and micropolishing methods. Atom probe analyses were performed in the voltage-pulse mode in an Imago Scientific Instruments local electrode atom probe (LEAP® 2017) operated with a specimen temperature of 60 K, a pulse repetition rate of 200 kHz, and a pulse fraction of 0.2

APT reveal the presence of carbon-enriched regions randomly dispersed throughout the ferrite matrix.

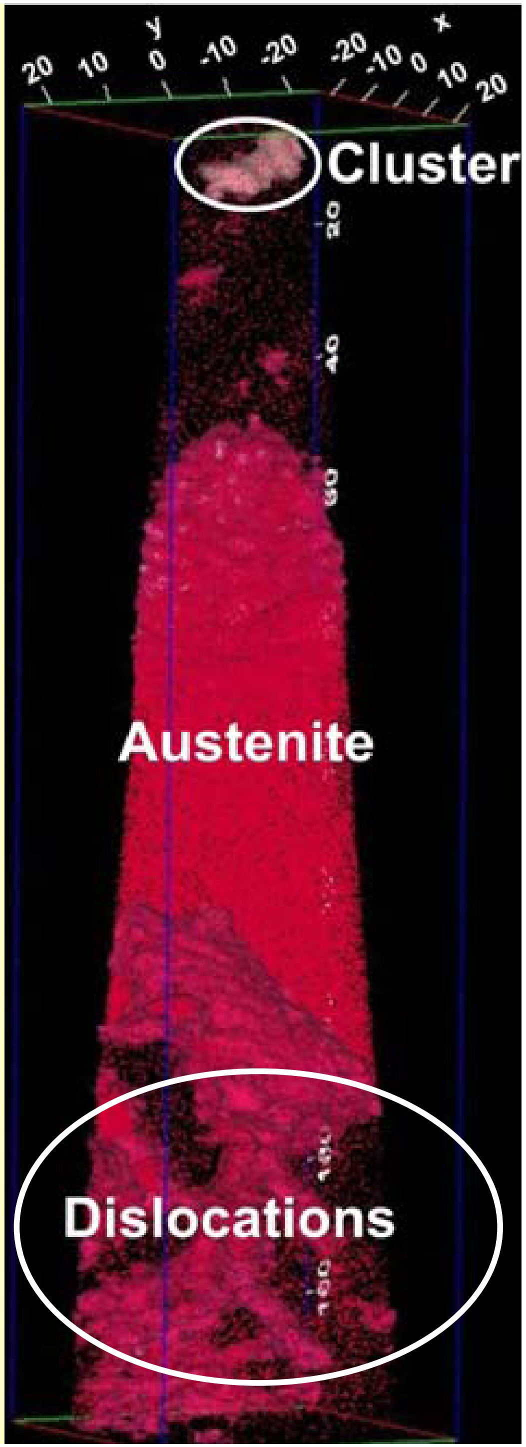




Central carbon-enriched (10.4 ± 0.6 at. % C) austenite film.
Bainitic ferrite plates (<3 at. % C) and dislocation tangles in the vicinity of a ferrite–austenite interface at the bottom of the volume Carbon-enriched cluster at the top of the volume.(~15 at.% C).
Average carbon level of the Cottrell atmosphere was estimated to be 13.4 ± 0.8 at. % C.



APT results suggested that dislocation tangles observed in the vicinity of the ferrite/austenite interface might trap higher amount of carbon than single dislocations inside the baintic ferrite plate.



CONCLUSIONS

• Experimental results on the distribution of dislocation density in the bainitic ferrite plate as a function of the distance to the closest austenite/ferrite interface revealed a progressive increase in the dislocation density as the interface is approached.

•Dislocations in the central region of the ferrite plate result from the lattice-invariant deformation at the earlier stage of bainite growth, whereas the higher dislocation density at the vicinity of the austenite/ferrite interface is related to the plastic deformation occurring in the surrounding austenite to accommodate the transformation strain as growth progresses.

•Atom-probe tomography suggested that dislocation tangles observed in the vicinity of the ferrite/austenite interface might trap higher amount of carbon than single dislocations inside the baintic ferrite plate.

ACKNOWLEDGES

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Thank you for your kind attention