

Morphology and crystallography of bainitic transformation

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Botton

Outline:

- Cementite precipitation crystallography in bainite and tempered martensite;
- Ferrite lath crystallography in Cementite free bainite;
- Possible crystallographic relationship between the three phases, austenite, ferrite and cementite;

Materials composition:

- Steel A: 0.5%C, 5% Ni(bainite with cementite precipitation)
- Steel B: 0.5%C, 5% Ni, 1.8% Si(bainite without cementite)
- Steel C: 0.5%C, 5% Mn, 2%Si(bainite without cementite)

Precipitation crystallography

Orientation relationship

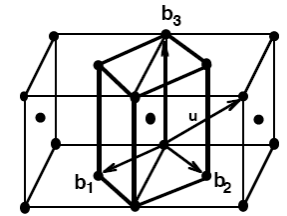
Habit plane

Interface structure

Bainite with cementite/without cementite microstructure

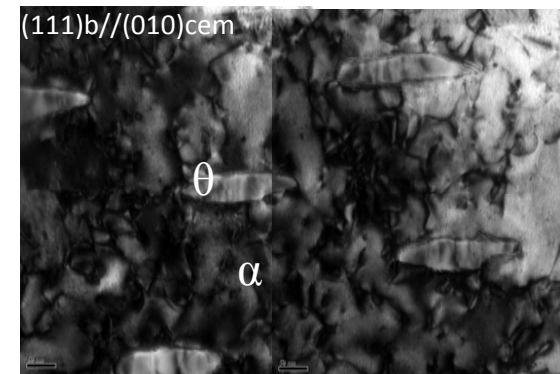
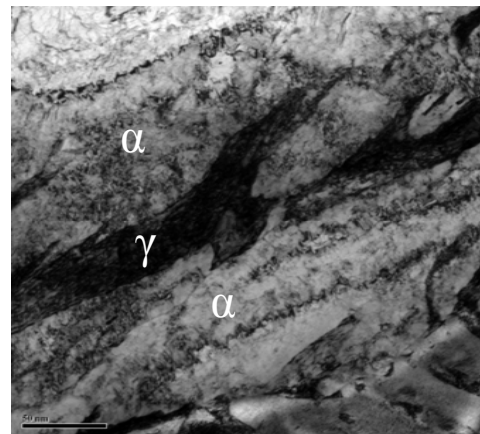
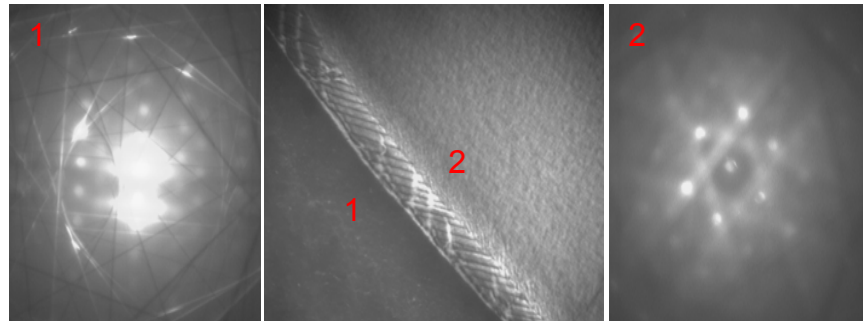
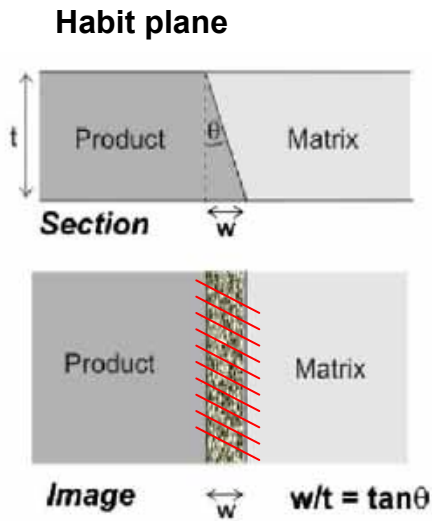
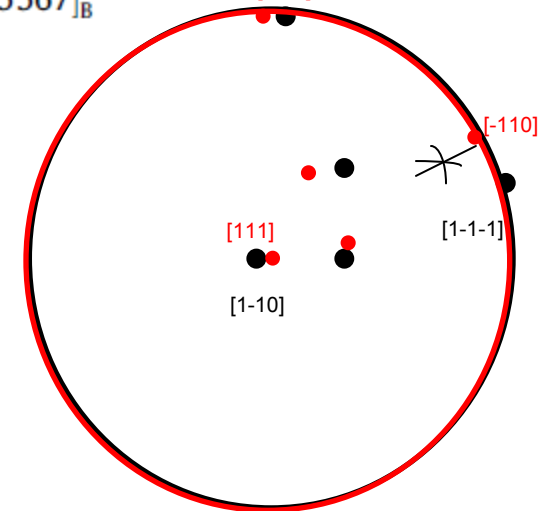
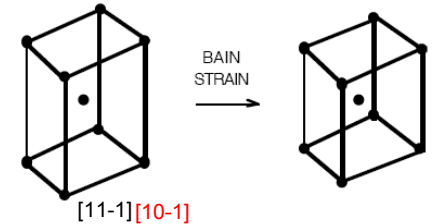
OR:

$(111)_f$ 0.5° from $(101)_b$
 $[1-10]_f$ 0.8° from $[11-1]_b$



OR matrix

$$\begin{aligned} [100]_F & \parallel [0.65712782, 0.73496730, 0.16735024]_B \\ [010]_F & \parallel [-0.15936876, -0.08152928, 0.98384682]_B \\ [001]_F & \parallel [0.98384682, -0.67318352, 0.06355567]_B \end{aligned}$$



M. Zhang, progress in mat.Sci.2009,p1101

Bainite/Cementite precipitation

Tempering Orientation relationship:

$$(103)_{cem} // (110)_{bcc}$$

$$[010]_{cem} \approx // [-111]_{bcc}$$

OR :

-0.10299	0.550205	-0.6532
-0.57735	0.57735	0.57735
0.915769	0.425871	0.489898

Cementite habit plane:

$$\approx (20-1)_{cem}$$

Bainite habit plane:

$$\approx (-1-65)_{bcc}$$

Stacking faults on:

$$(001)_{cem}$$

Previous works:

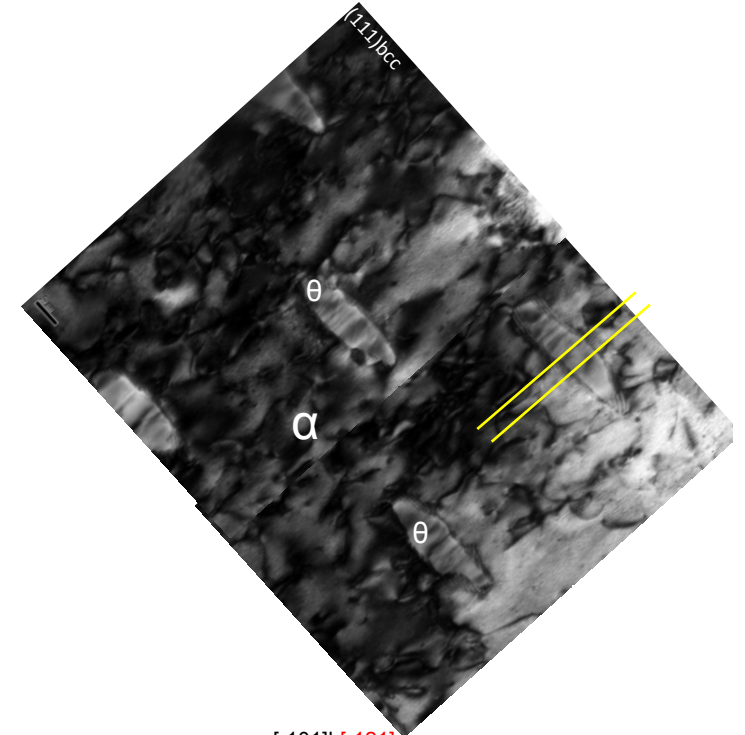
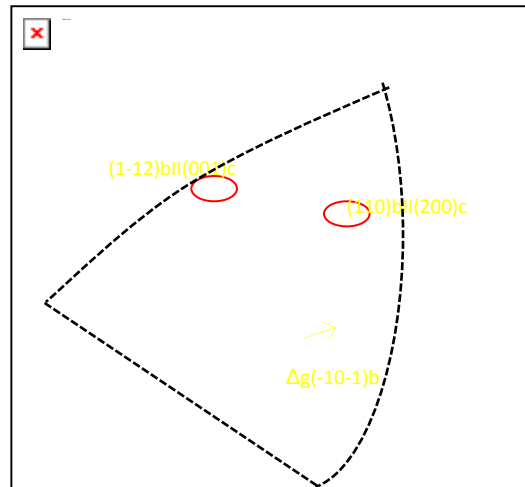
(Ohmori, Acta.Mater.2001.p3149.)

Cementite habit plane:

$$\approx (201)_{cem}$$

Bainite habit plane:

$$\approx (-143)_{bcc}$$

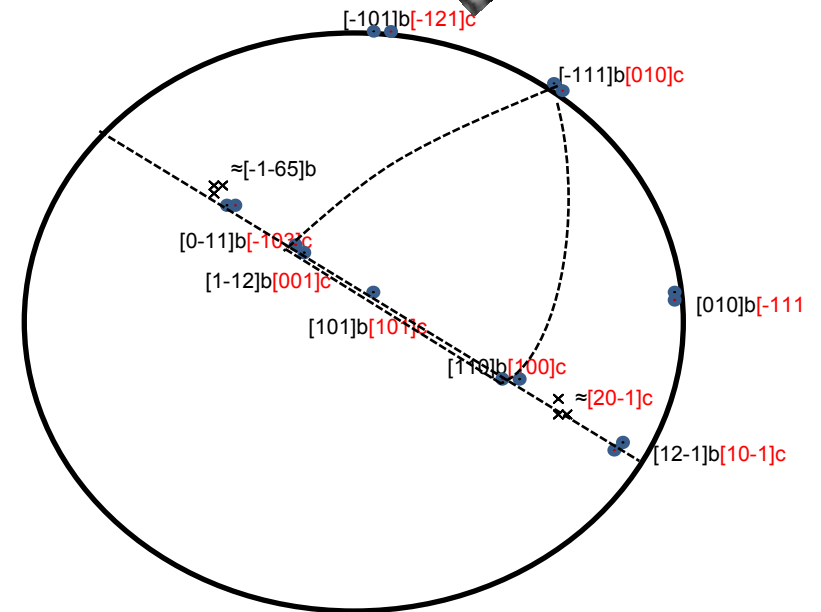
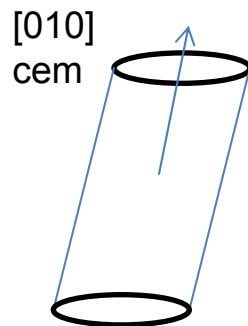
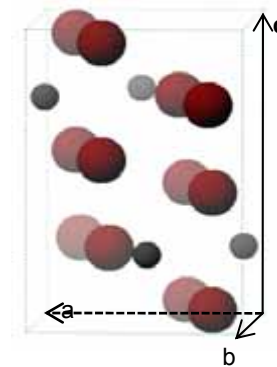


$$a = 4.512 \text{ \AA}$$

$$b = 5.082 \text{ \AA}$$

$$c = 6.733 \text{ \AA}$$

Fe₃C



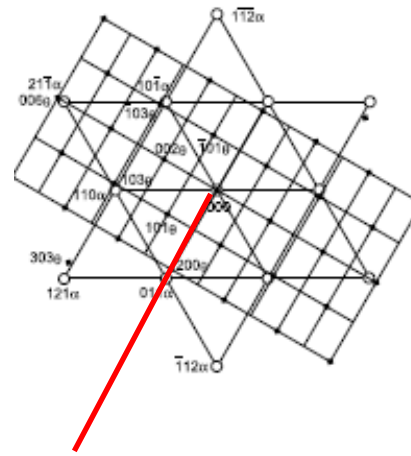
Cementite/ferrite orientation relationship

Fu.Wei, Acta.Mater.(2005), p.2419

$[111]_{bcc} // [010]_{cem}$
In tempered martensite

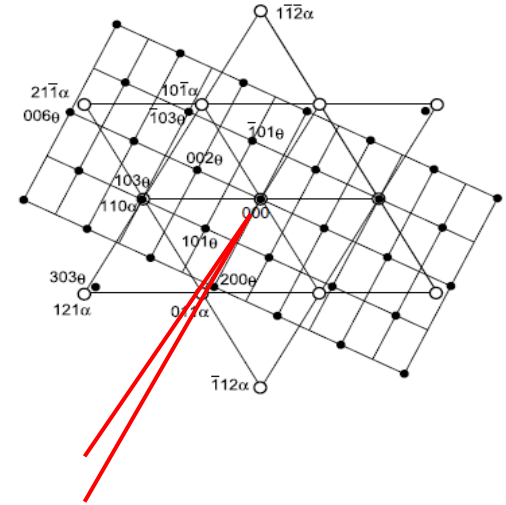


$[111]_{bcc} // [010]_{cem}$
In bainite



Bagaryatskii OR

Isaichev OR



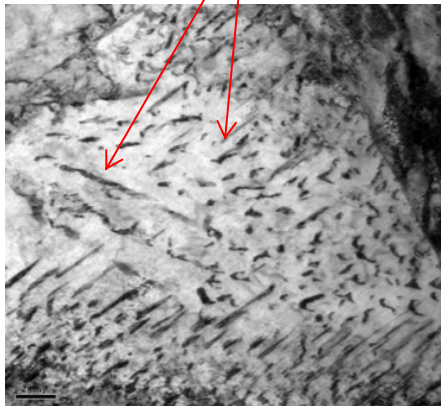
$(011)_{bcc} // (200)_{cem}$

0.5°

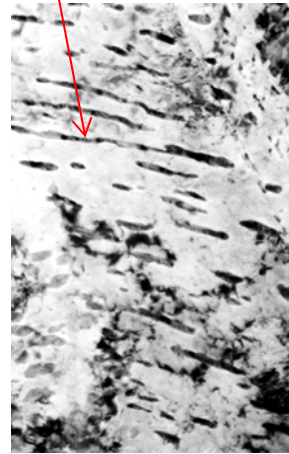
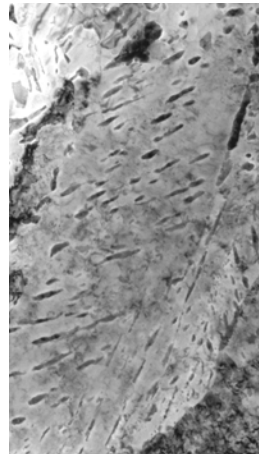
2.5°

3°

Tempered martensite, multiple variants



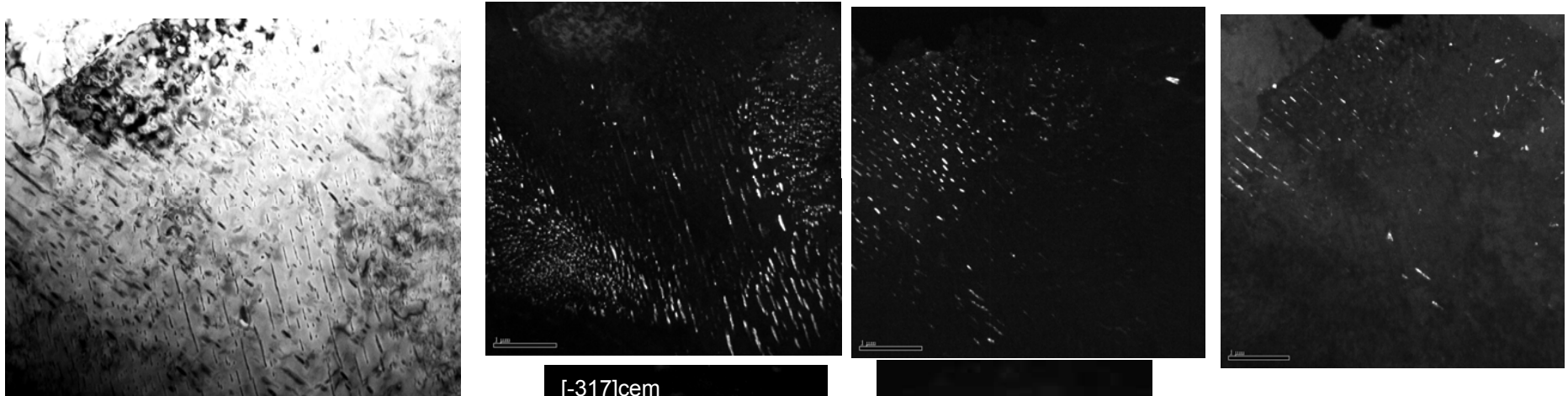
Bainitic ferrite, single variant



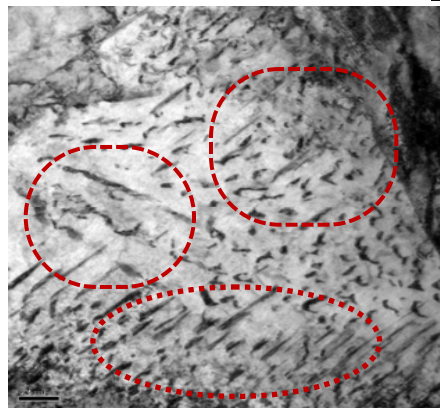
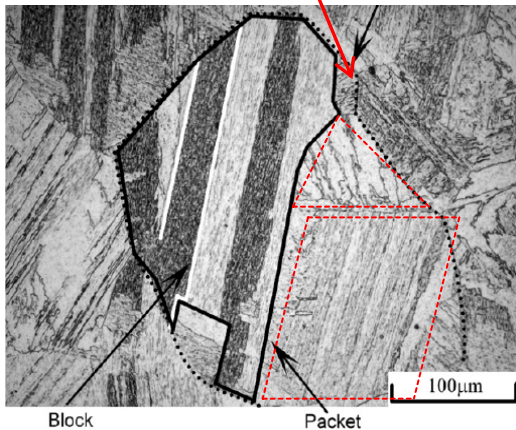
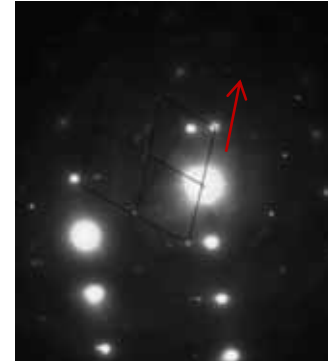
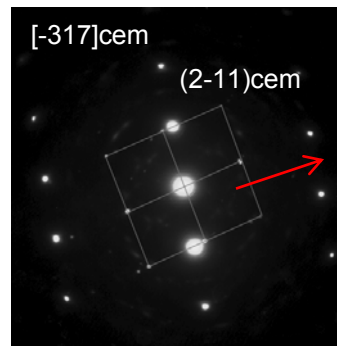
Bagaryatskii OR. Variants.

variant	Direction parallel	Plane parallel
V ₁	$[111]_b // [010]_c$	$(0-11)_b // (100)_c$
V ₂		$(-110)_b // (100)_c$
V ₃		$(10-1)_b // (100)_c$
V ₄	$[-111]_b // [010]_c$	$(110)_b // (100)_c$
V ₅		$(101)_b // (100)_c$
V ₆		$(01-1)_b // (100)_c$
V ₇	$[1-11]_b // [010]_c$	$(110)_b // (100)_c$
V ₈		$(011)_b // (100)_c$
V ₉		$(-101)_b // (100)_c$
V ₁₀	$[11-1] // [010]$	$(1-10)_b // (100)_c$
V ₁₁		$(101)_b // (100)_c$
V ₁₂		$(011)_b // (100)_c$

Cementite precipitation in tempered martensite (below MS)



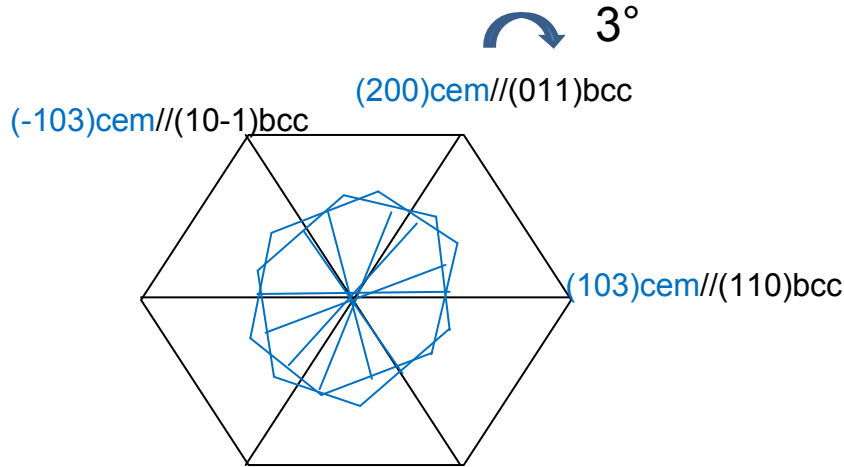
Original grain of austenite transformed to 4 packets of martensite



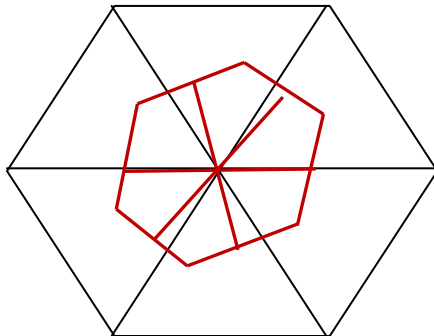
1-less than 12 possible B OR.
2-colonies of variants

Cementite orientation variants

$[111]_{bcc} // [010]_{cem}$

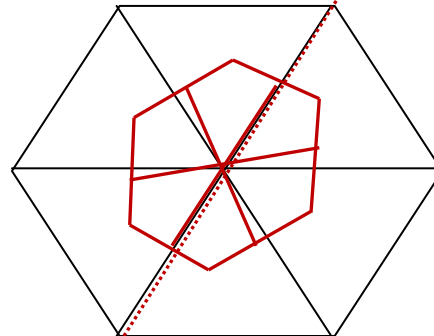


24 Isaichev



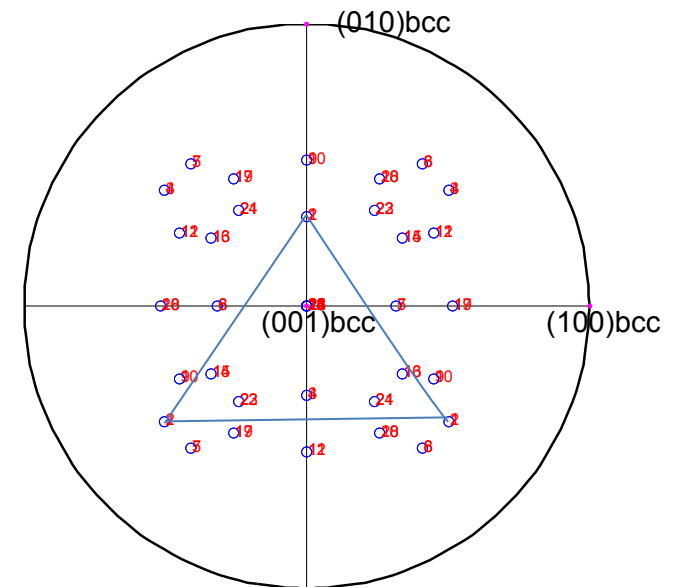
12 Bagaryatskii

Mirror plane



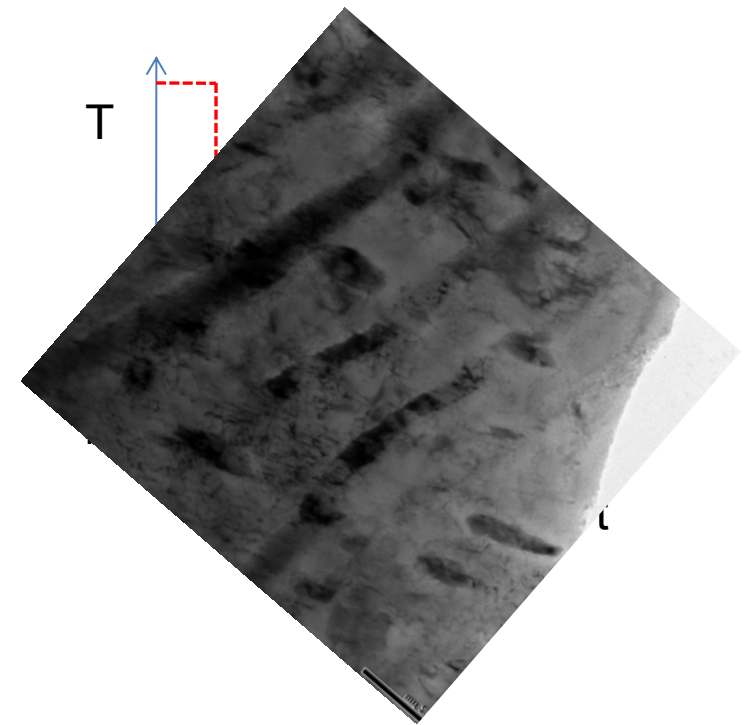
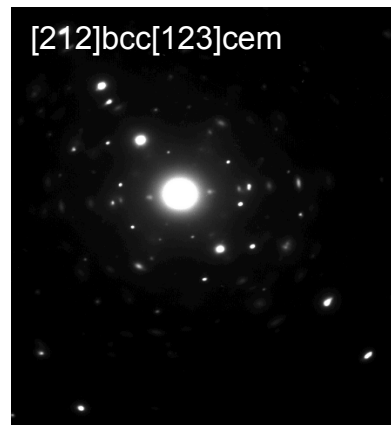
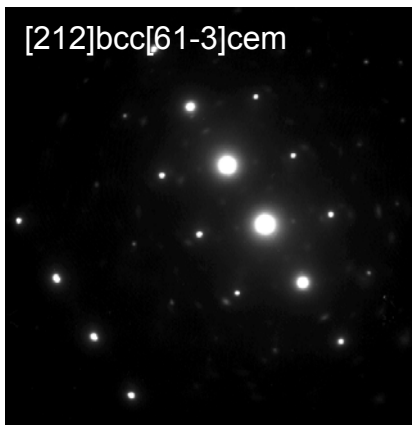
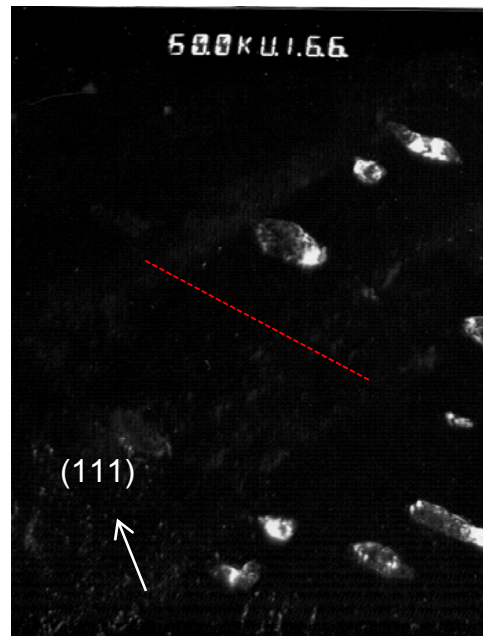
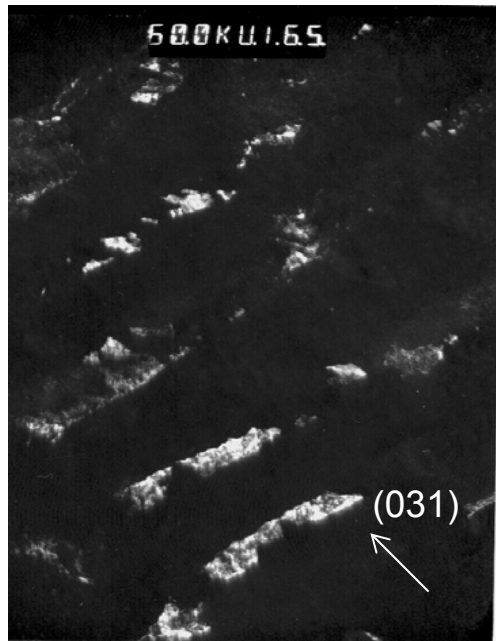
Bagaryatskii OR. Variants.

variant	Direction parallel	Plane parallel
V_1	$[111]_b // [010]_c$	$(0-11)_b // (100)_c$
V_2		$(-110)_b // (100)_c$
V_3		$(10-1)_b // (100)_c$
V_4	$[-111]_b // [010]_c$	$(110)_b // (100)_c$
V_5		$(101)_b // (100)_c$
V_6		$(01-1)_b // (100)_c$
V_7	$[1-11]_b // [010]_c$	$(110)_b // (100)_c$
V_8		$(011)_b // (100)_c$
V_9		$(-101)_b // (100)_c$
V_{10}	$[11-1] // [010]$	$(1-10)_b // (100)_c$
V_{11}		$(101)_b // (100)_c$
V_{12}		$(011)_b // (100)_c$

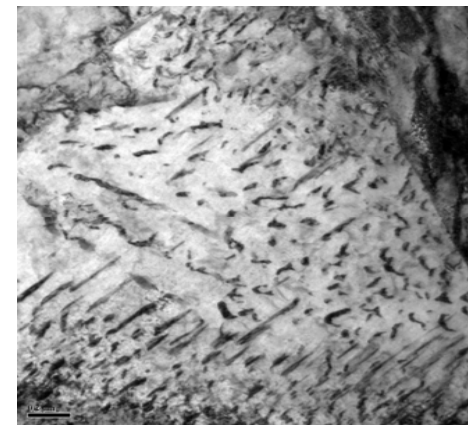


{001}Cementite variant on a standard bcc stereogram 7

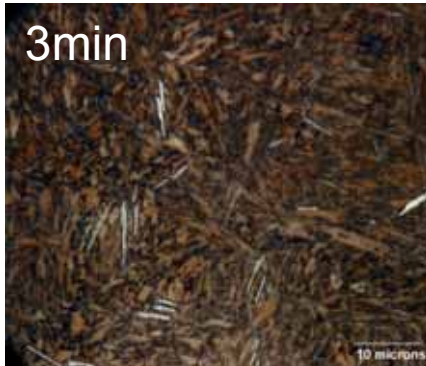
Microstructure below MS



Multiple variant tempered martensite

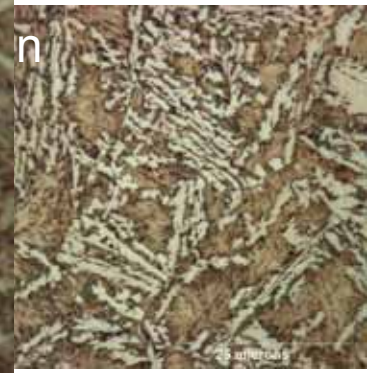
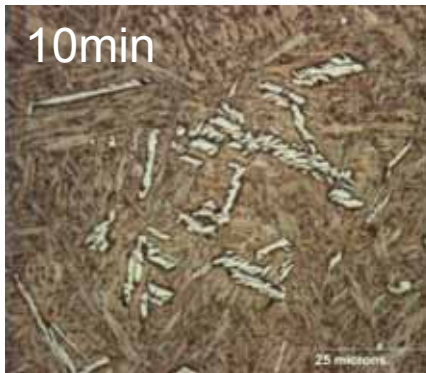


Cementite free bainite Optical microscopy



steel

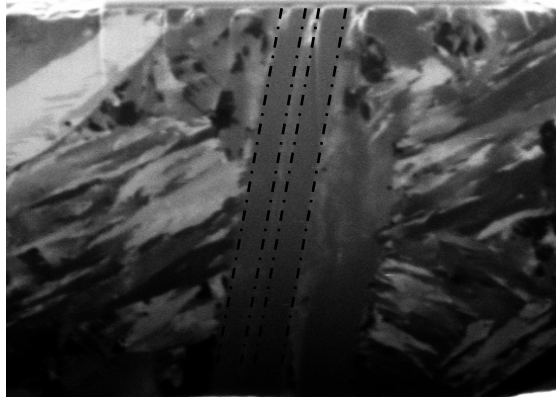
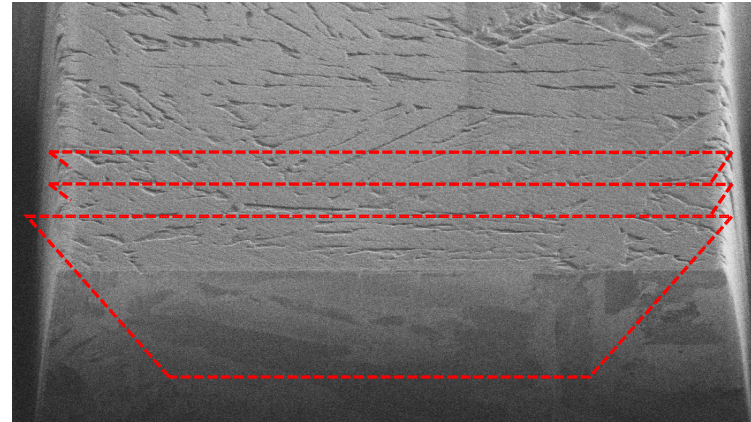
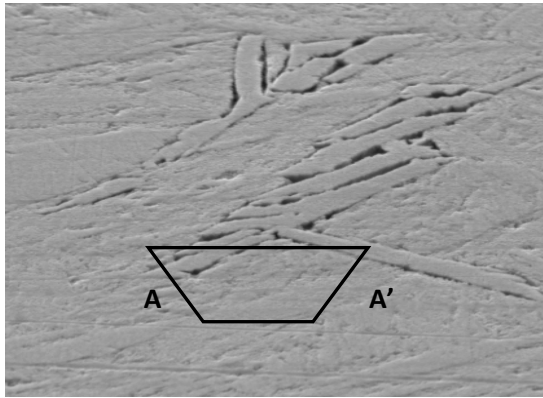
brown martensite



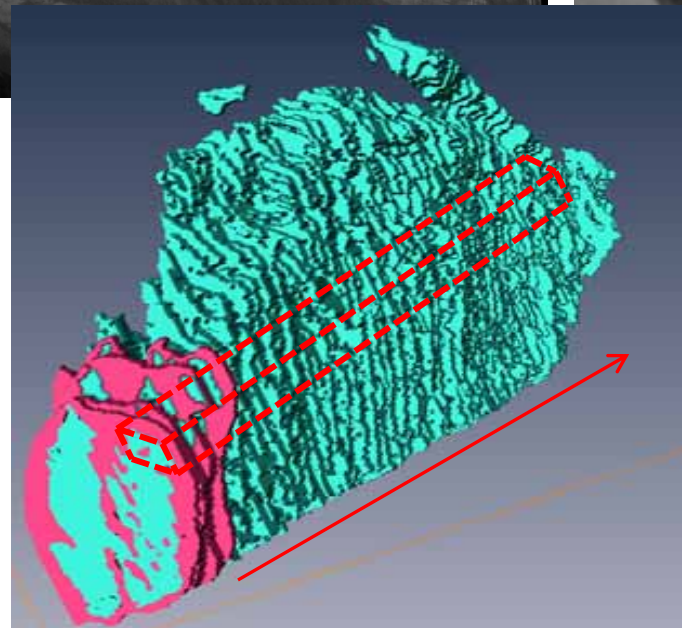
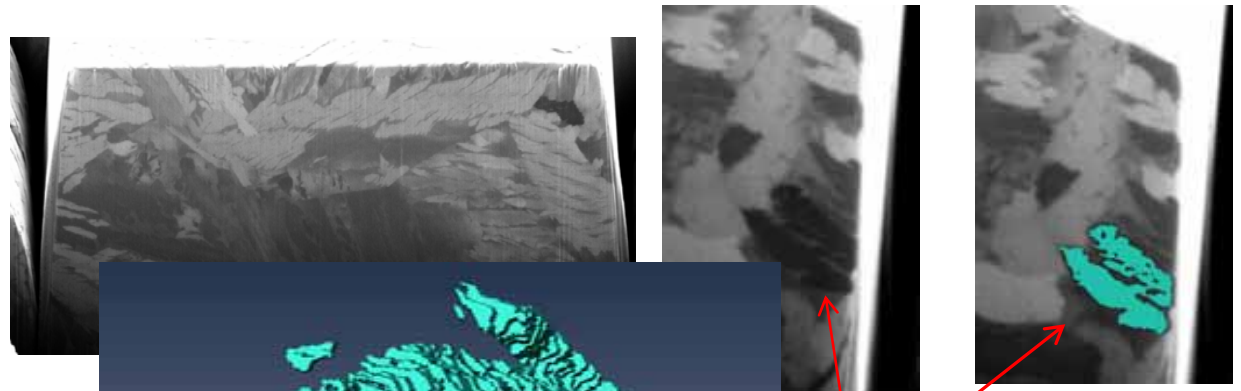
10min at 350°C

10min at 300°C

Bainite in 3 dimension

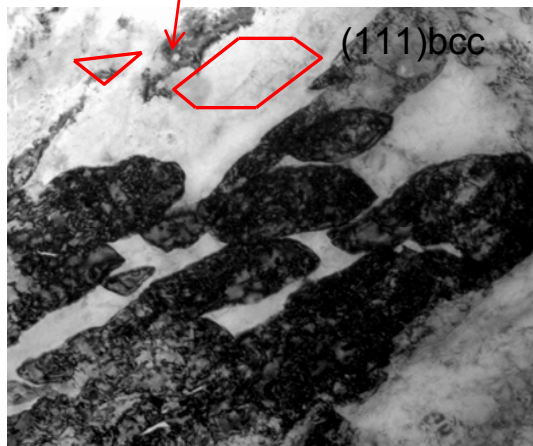
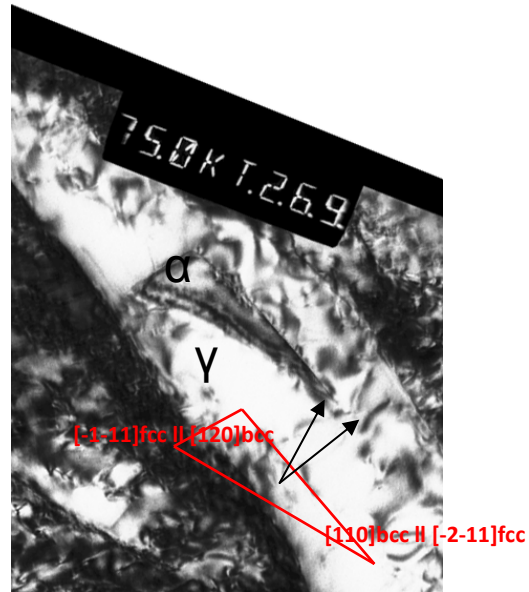
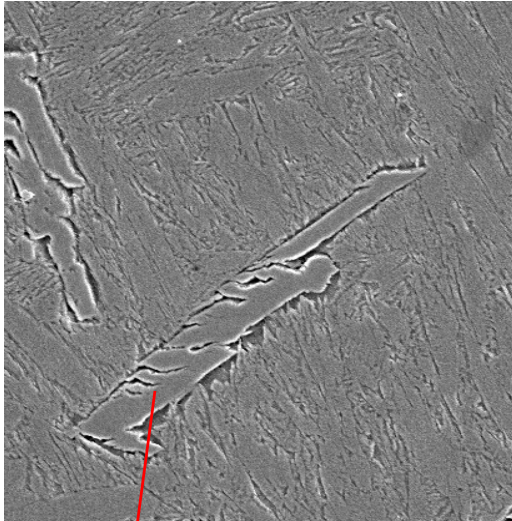


3min transformation



30 min transformation

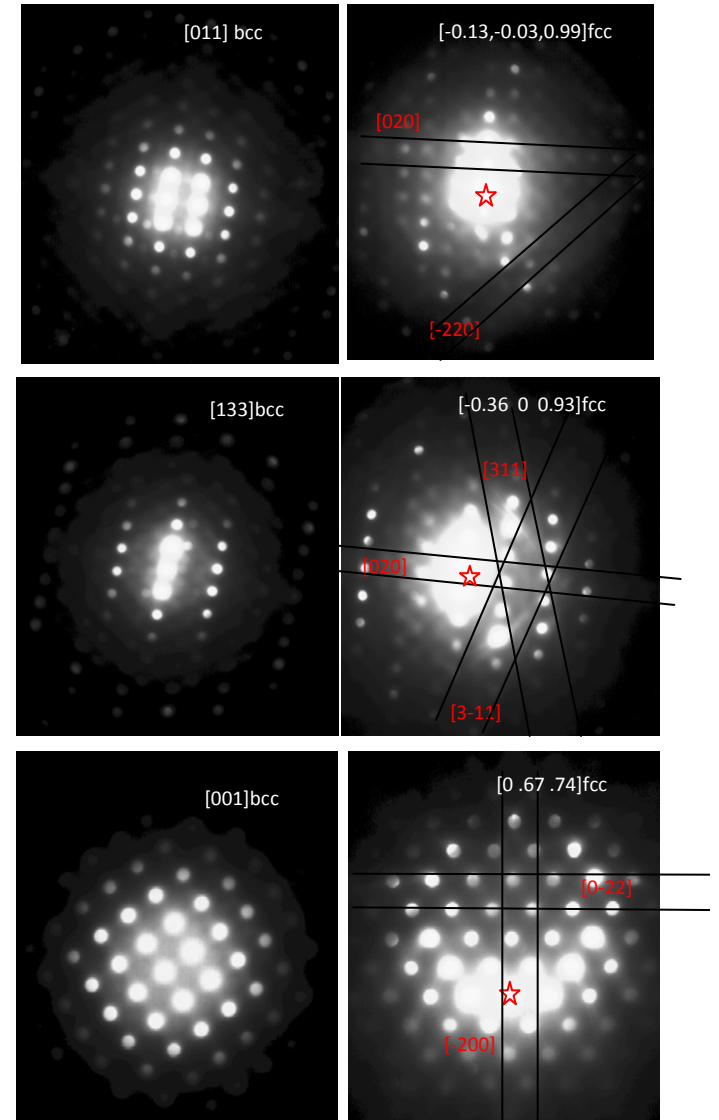
Crystallography of γ/α interfaces in bainite:



Near NW OR

Input:

OR matrix		
-0.95024	0.133092	-0.1205
-0.1794	-0.73671	0.66702
-0.01024	0.683895	0.732149



Crystallography of γ/α interfaces in bainite: agreement with O lattice calculation

Input:

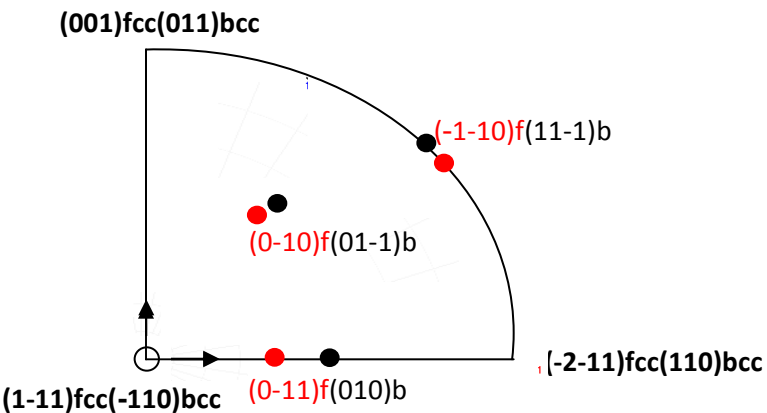
OR matrix		
-0.95024	0.133092	-0.1205
-0.1794	-0.73671	0.66702
-0.01024	0.683895	0.732149

$$\Delta g = (I - A^{-1})' g_{\alpha}$$

W.Zhang,phil.mag.A.(1993) p. 291

$$R = \sum_i \sum_j \sqrt{\frac{b_i b_j}{d_i d_j}}$$

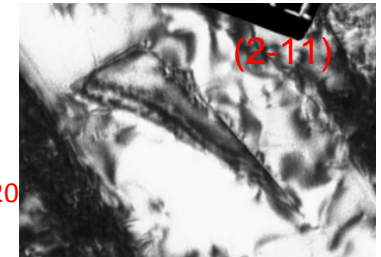
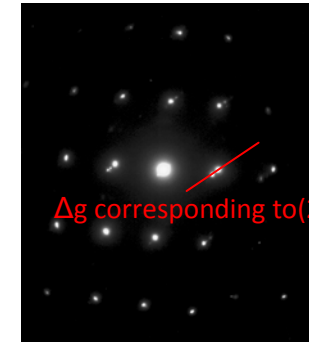
R.Ecob, Acta.Metall.(1981) p. 1037



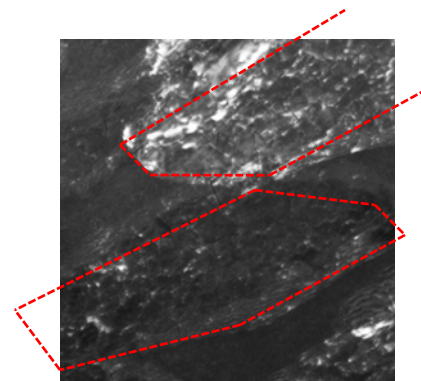
Coordinate system for O-Lattice calculations

Output:

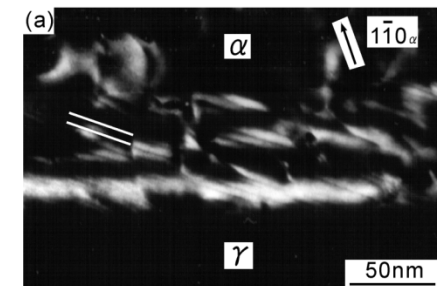
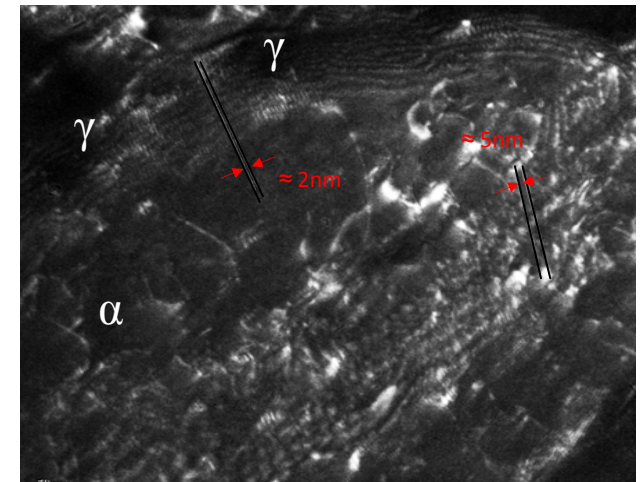
$\Delta g(200)$	$\Delta g(-1-11)$
2	-2
-0.92	0.901
0.91	-1.17



Diffraction pattern showing a Δg normal to the habit plane in b

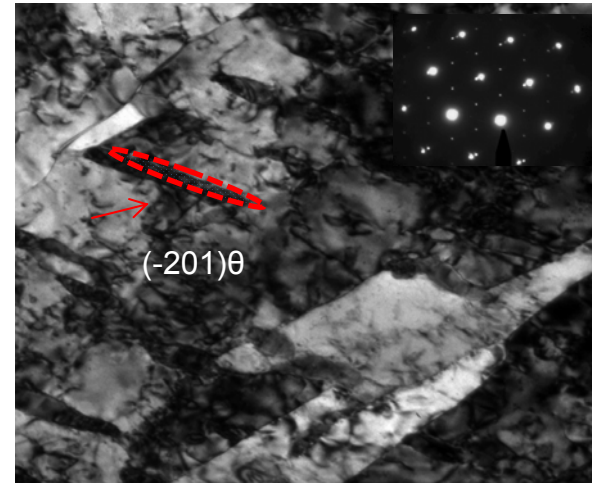
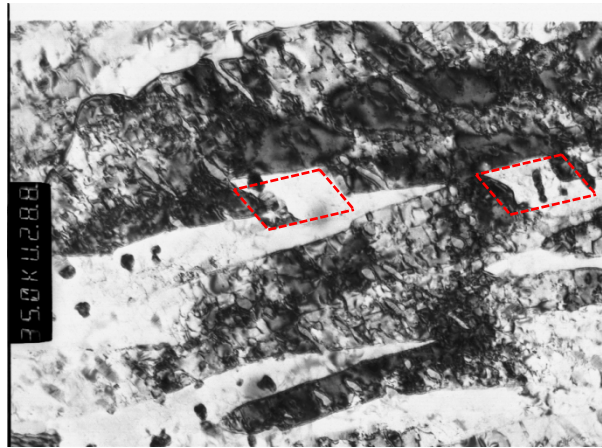


WBDF of ferrite



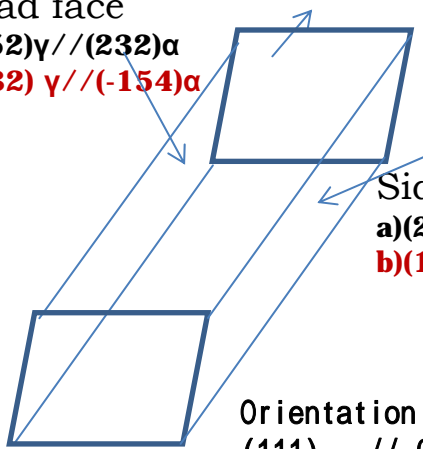
Furuha et.al. Scripta Mater., (2002), p193

3 phase crystallography: austenite, ferrite and cementite



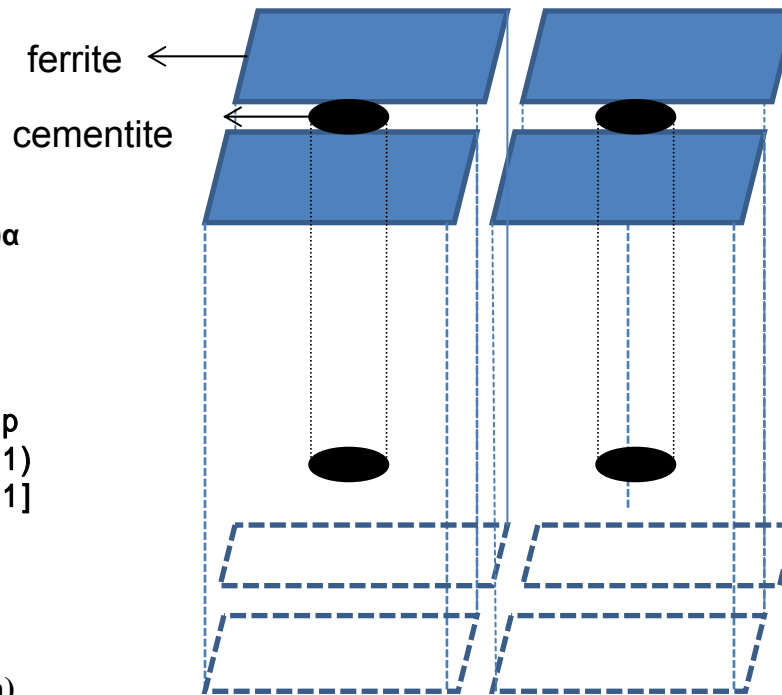
Long direction
a) and b) $[-101]_{\gamma} // [-1-11]_{\alpha}$

Broad face
a) $(252)_{\gamma} // (232)_{\alpha}$
b) $(232)_{\gamma} // (-154)_{\alpha}$



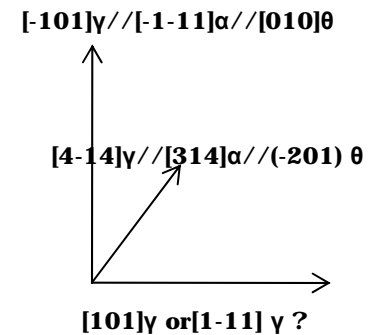
Side face
a) $(212)_{\gamma} // (101)_{\alpha}$
b) (101)

Orientation relationship
 $(111) // 0^{\circ} \sim 3^{\circ} (011)$
 $[101] // 0^{\circ} \sim 5^{\circ} [111]$



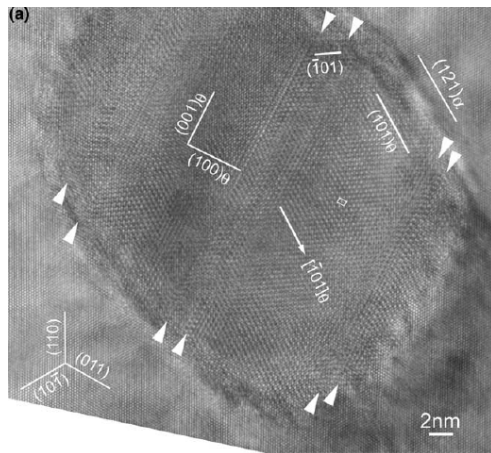
Cementite/austenite
 pitsch OR.

$(\bar{5}4\bar{5})_{\gamma} // (100)_{\theta}$
 $(\bar{1}01)_{\gamma} // (010)_{\theta}$
 $(252)_{\gamma} // (001)_{\theta}$

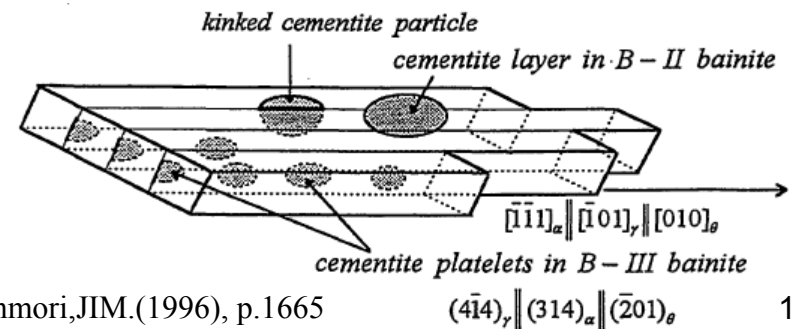
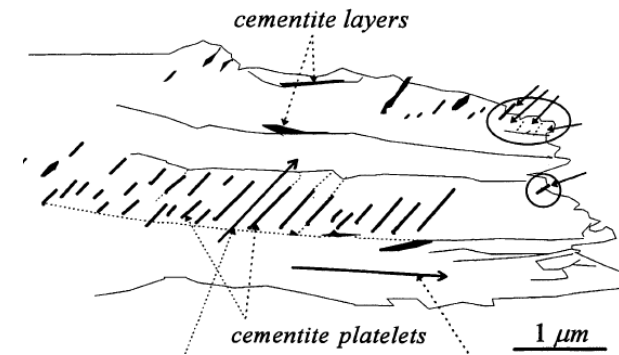
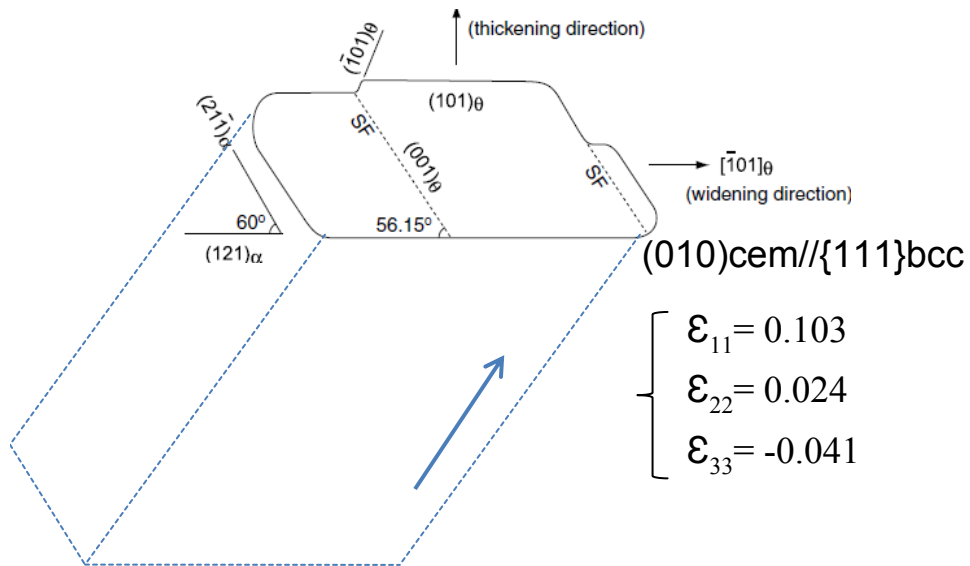
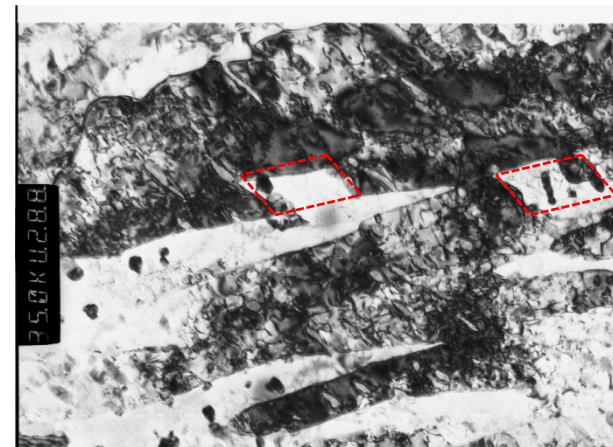
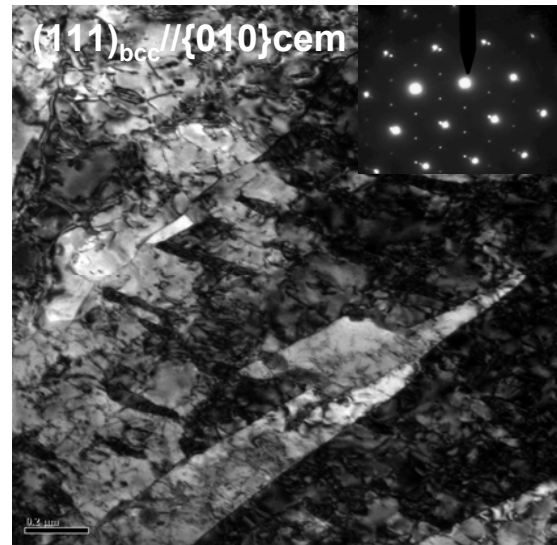


a) Furuhashi et al. presentation,
 Crystallography of bainitic ferrite (Fe-0.6C-2Si-1Mn)
 b) Bhadeshia, Metall.Mat.Trans.1990,p.767

3 phase crystallography: austenite, ferrite and cementite



Fu, Wei, Acta.Mater.(2005), p.2419



Ohmori, JIM.(1996), p.1665

summary and future work:

1-cementite precipitation

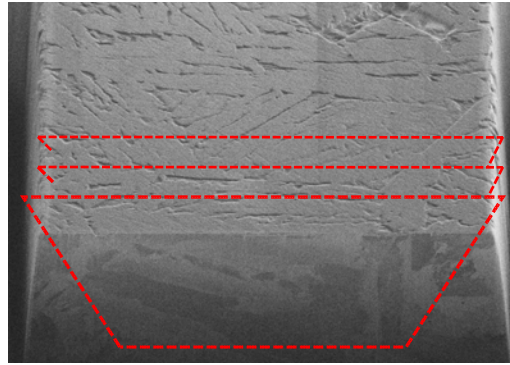
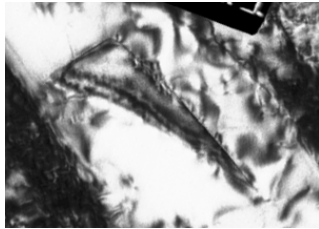
- single variant of orientation of cementite in bainite and multiple variants in tempered martensite were studied.
- Full characterization of the variants is a future task.

2- α/γ boundaries

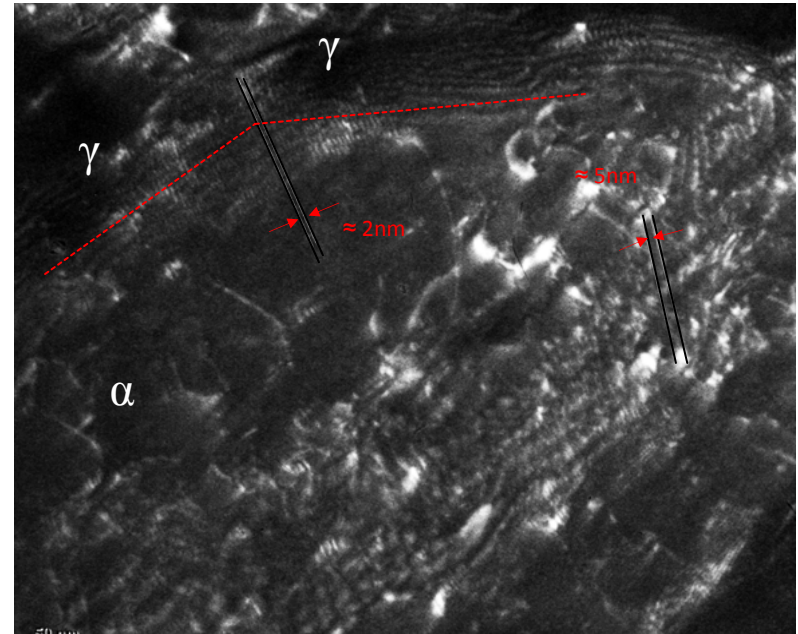
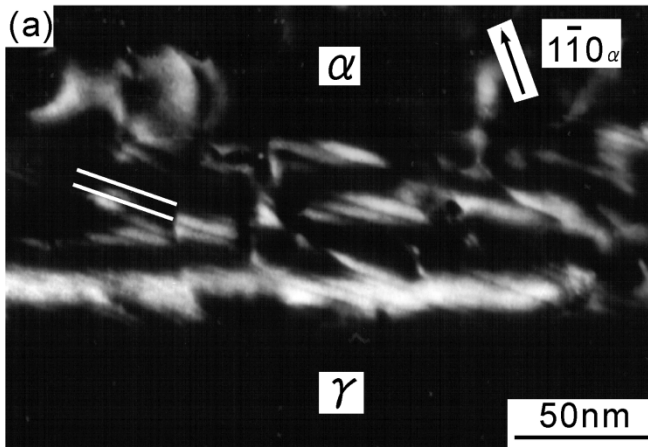
- Basic crystallography of α lath was done.
- Dislocation structure(?) and the long direction of the growth can be determined.

3- further study on the nucleation of cementite on side facets of α is required.

- Questions?



Crystallography of γ/α interfaces in bainite:



Scripta Mater., (2002), p193
Pure screw dislocations

Disl. spacing on $\Delta g(200)$ nm		
2.24417	5.92575	8.802

