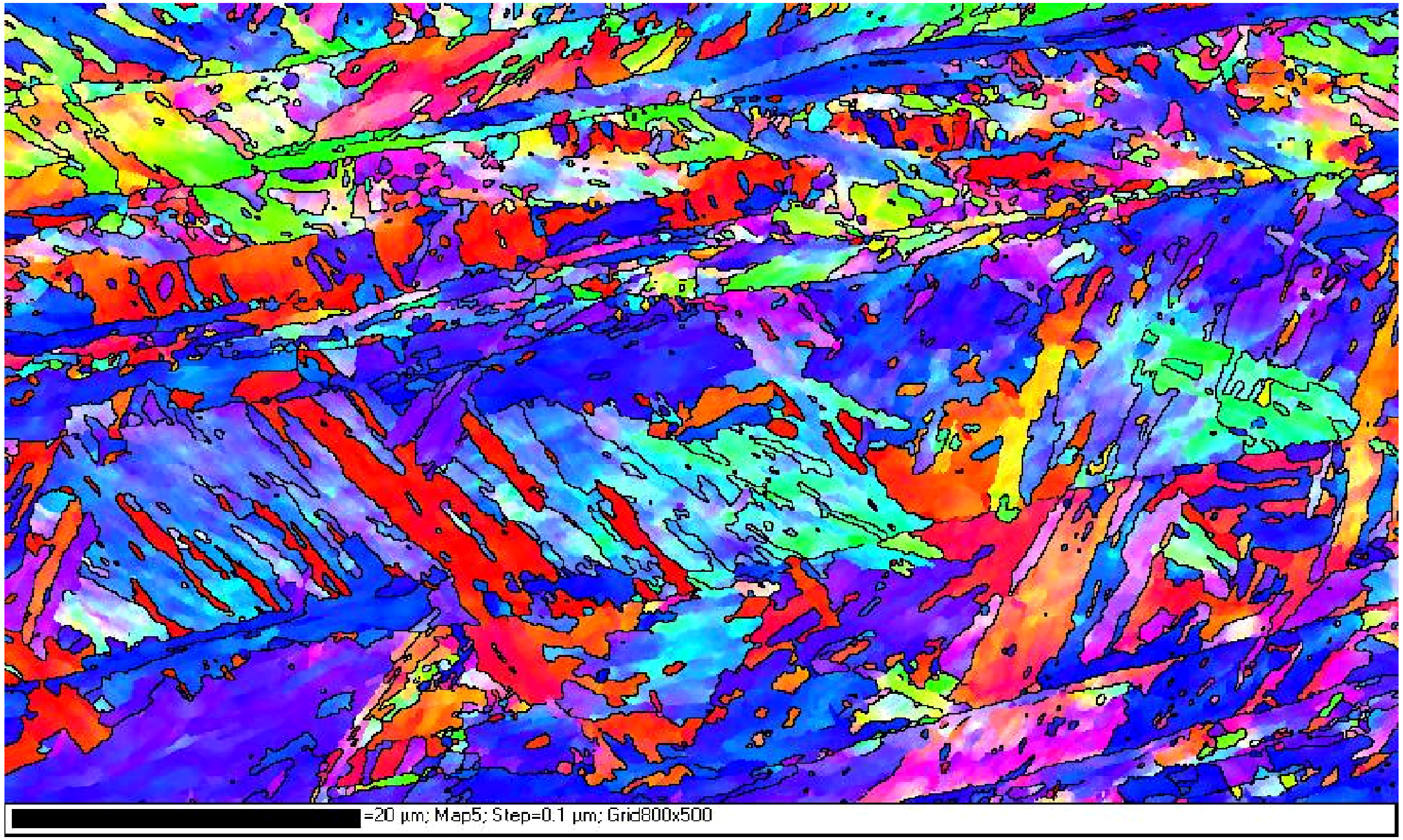

Role of interfaces in formation of bainitic structures

G. R. Purdy, R. Hadian, G. A. Botton

McMaster University

Outline:

- acknowledgements
- introduction; main issues
- materials
- morphologies
- kinetics
- TEM studies
- conclusions

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Acknowledgements:

Hatem Zurob
Igor Yakbutsov
Wenzheng Zhang
Zhang Wang
Stella Zhang
Audrey Debourg
Mani Subramanian
the ALEMI connection
NSERC

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Objectives:

To review the current state of the discussion.

To correlate *morphological, kinetic, crystallographic* data on carbide-free - and some carbidic - bainites. (Note that "carbide-free bainite" is, strictly, an oxymoron.)

To obtain a deeper understanding of the interrelations among these different aspects of bainite formation;

Perspectives on bainite formation:

These have been discussed at length, recently and notably in a viewpoint set edited by Mats Hillert (Scripta Mat. 2002;47:137), papers by Borgenstam, Ågren, Hillert et al) Acta Mat. 2009;57:3242, MMTA 2011;42A:1558), a book by Bhadeshia (Bainite in Steels, Transformations, Structures and Properties, 2nd edition, 2001, Inst. Of Materials).

The main difference concerns the role of carbon diffusion: before or after the initial growth of bainitic ferrite?
Other debates concern the structure and migration mode of the ferrite/austenite interface, the (related) origin of surface relief, the role(s) of alloying elements and of carbide precipitation, the three-dimensional morphologies, and even the definition of bainite.

(Full disclosure: I subscribe to the diffusional view.)

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Schools of thought:

Diffusionless initial growth: Zener, Ko&Cottrell, Oblak&Hehemann, Bhadeshia&Edmonds, Calballero et al, others.

Diffusional growth: Stockholm school (Hultgren, Hillert, Ågren, Borgenstam, colleagues); Aaronson and colleagues (Enomoto, Spanos, Reynolds Jr.), Quidort&Bréchet, others.

Both agree that nucleation is probably thermally activated.

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The diffusionless initial growth hypothesis due to Zener, (Ko&Cottrell), Oblak&Hehemann, Bhadeshia&Edmonds, Calballero et al, others.

A widely held view. Reasons?

- Low-carbon martensite and bainitic ferrite laths are similar in morphology; each is acicular, each is internally dislocated.
- Each can give rise to shear relief on a prepolished free surface.
- There is at least one report of similar dislocation structures in bainitic and martensitic α/γ interfaces.
- Bainitic ferrite is sometimes found to contain a measure of supersaturation with respect to carbon.

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Selected relevant developments:

JC Hell, Ph.D. thesis, University of Metz, 2011; carbide-free bainite formation above and below Ms. Synchrotron studies of carbon content evolution in ferrite and austenite; microstructures and properties of bainitic steels.

SMC van Bohemen, MJ Santofina, J Sietsma, Scripta Mat., 2008;58:488
Dilatometric studies of bainite formation above and below Ms;
Comparison of microstructures of autotempered martensite and bainite.

A Borgenstam, P Hedström, M Hillert, P Kolmskog, A Stormvinter, J Ågren, MMTA, 2011, 42A, 1558. Analysis of the symmetries of bainite and inverse bainite formation.

D Quidort, Y Bréchet, Acta Mat. 2001;**49**:4161, Scripta Mat. 2002;**47**:151.
Bainite grows from previously formed grain boundary ferrite allotriomorphs. This allowed the isolation of growth kinetics, and the evaluation of nucleation kinetics, from measurements of overall kinetics.

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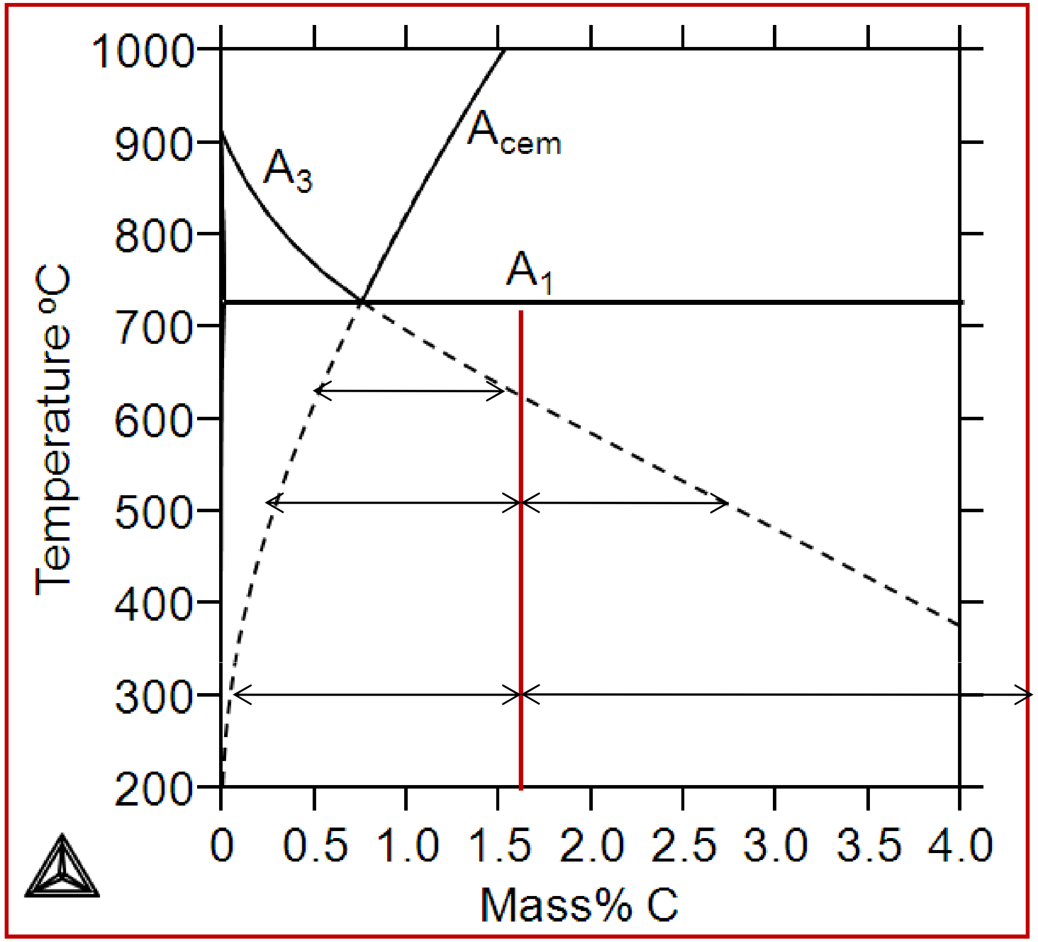
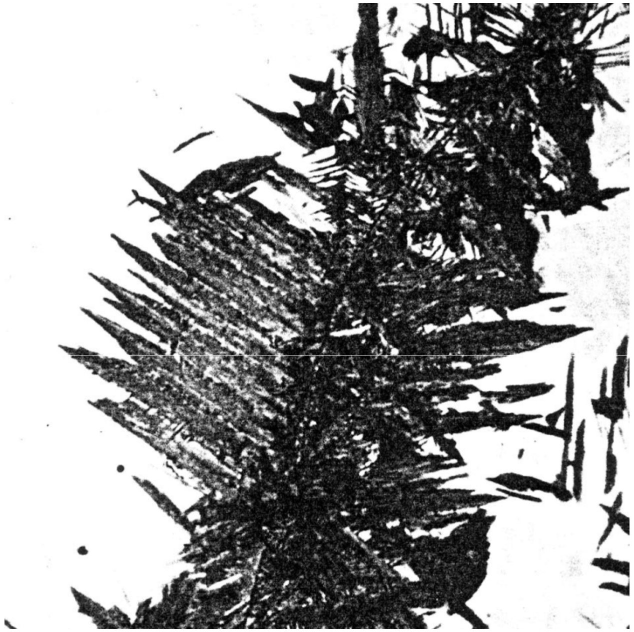


Bainite Pearlite Inverse Bainite

A Borgenstam et al, ALEMI, 2010, Avignon FR
MMTA 2011;42A:1558



H. Modin, S. Modin,
Fe-1.65%C, 25 s at 500C
2000

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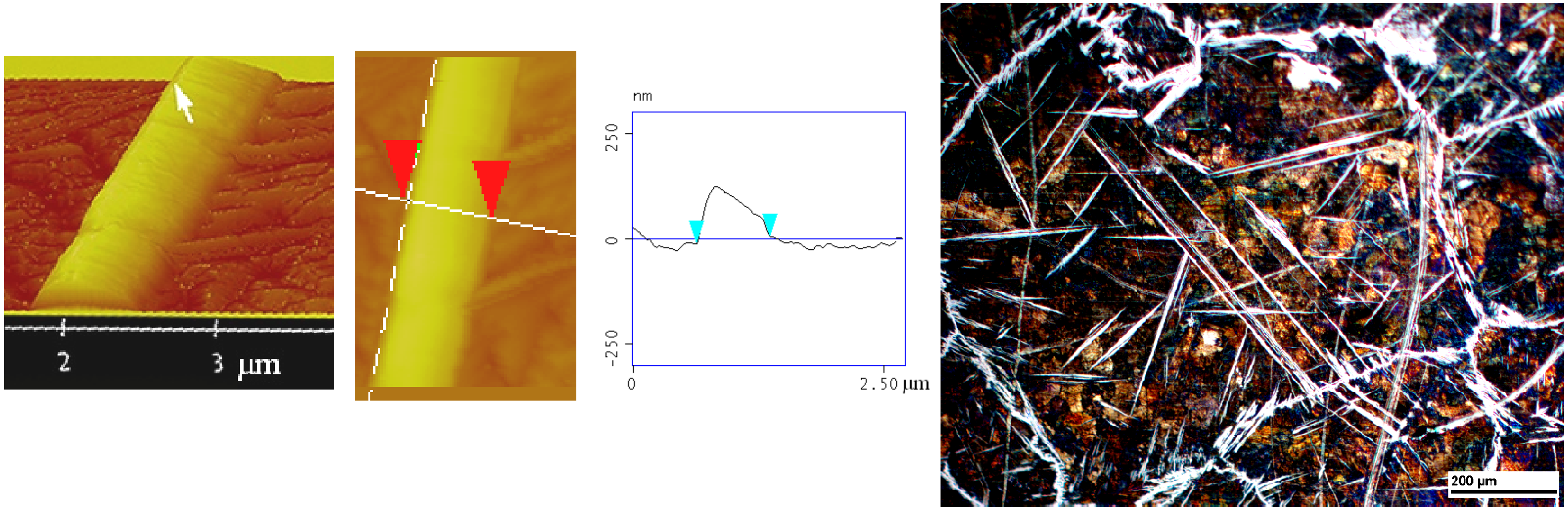


Fe-1.6C-0.24Si-0.56Cr-0.25Mn, 750 C
courtesy Wenzheng Zhang, 2010

Fundamental aspects to be clarified:

What are the true morphologies (three-dimensional)?

Bainite kinetics, microstructures above and below Ms

Distinctions between bainite, autotempered martensite.

Materials:

Fe-5%Ni-0.5%C

Fe-5%Ni-0.5%C-1.8%Si

(courtesy of Yves Bréchet)

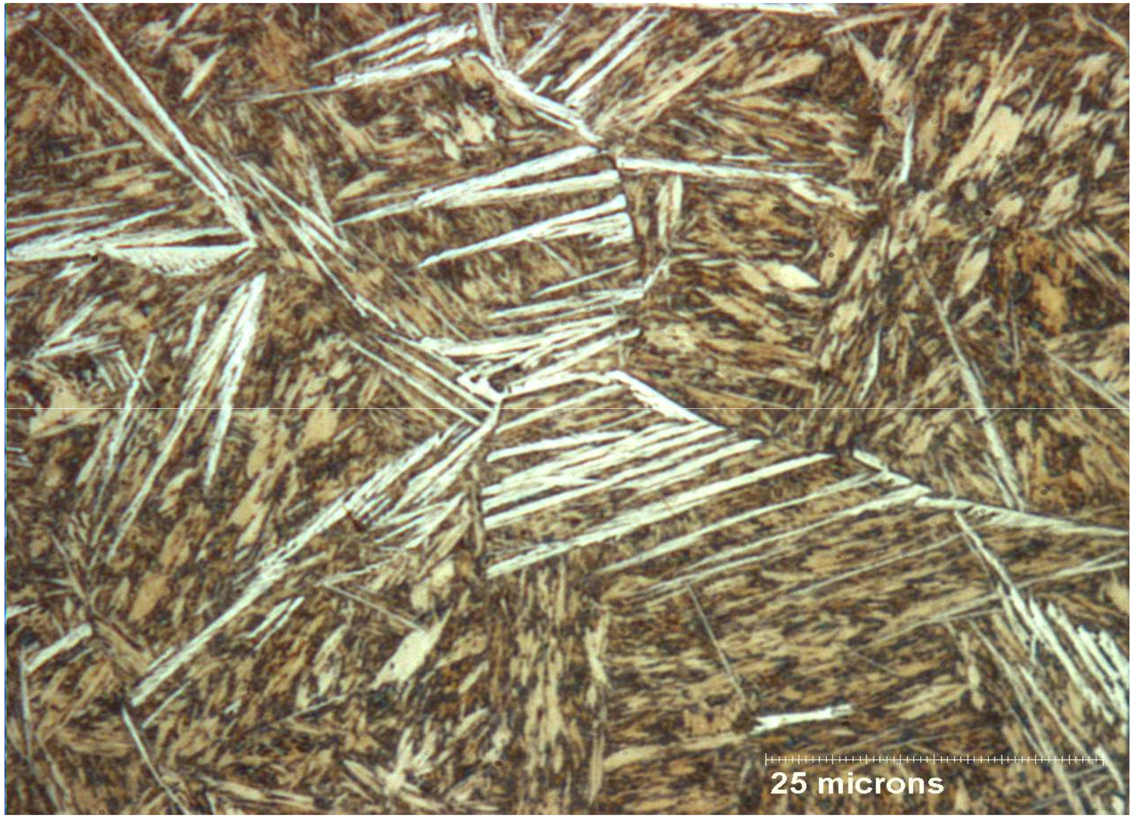
and

Fe-2.8%Mn-0.4%C-1.8%Si

BAINITE MORPHOLOGY;

Optical, TEM metallography
FIB sectioning, imaging

Fe-0.4%C-2.78%Mn-1.81%Si,   R. Hadian



10 min. at 350 C

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20 min. at 350 C

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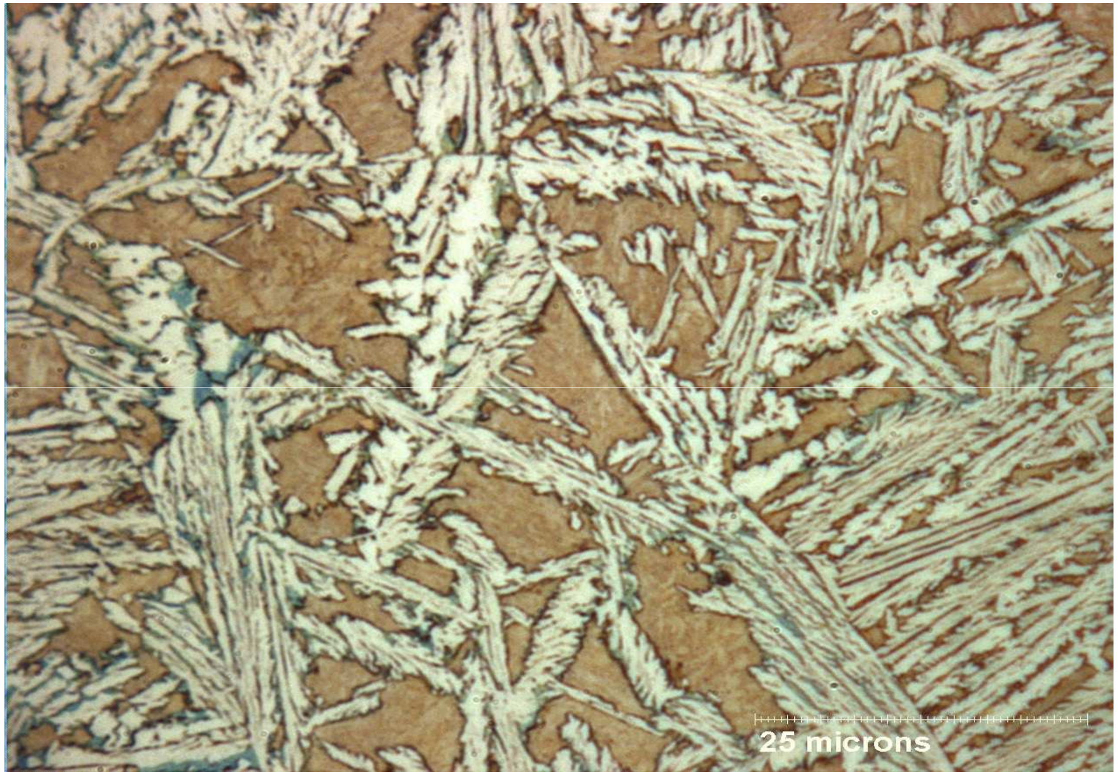
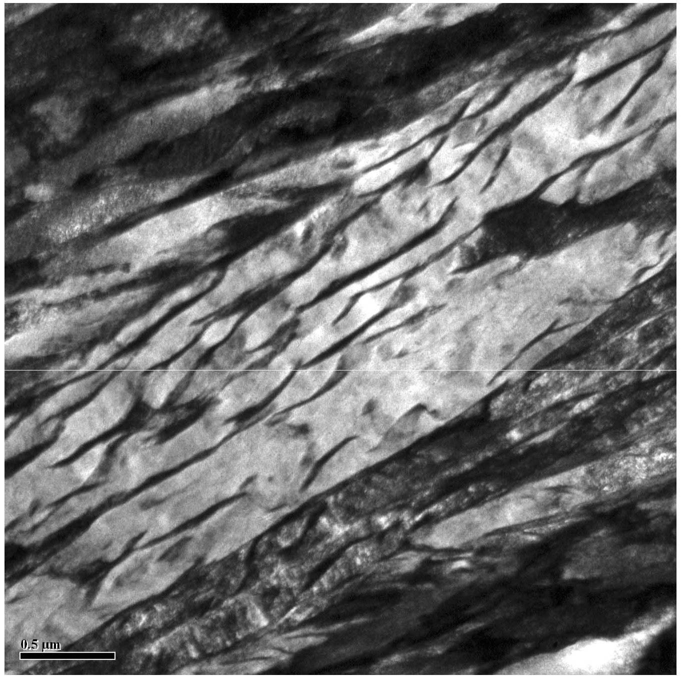


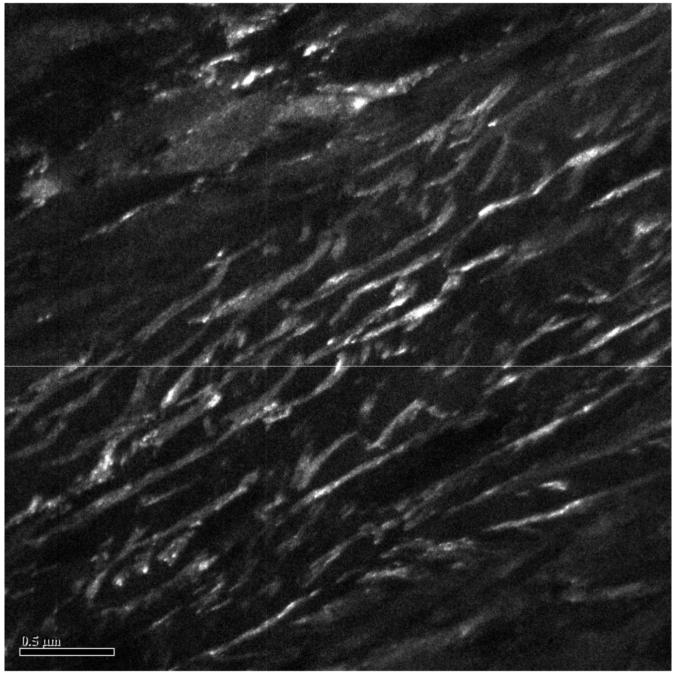
40 min. at 350 C

80 min. at 350 C

20 min. at 300°C

40 min. at 300^{o}C





Bainitic ferrite and retained austenite

Fe-0.4C-2.78Mn-1.81Si, 300^{o}C

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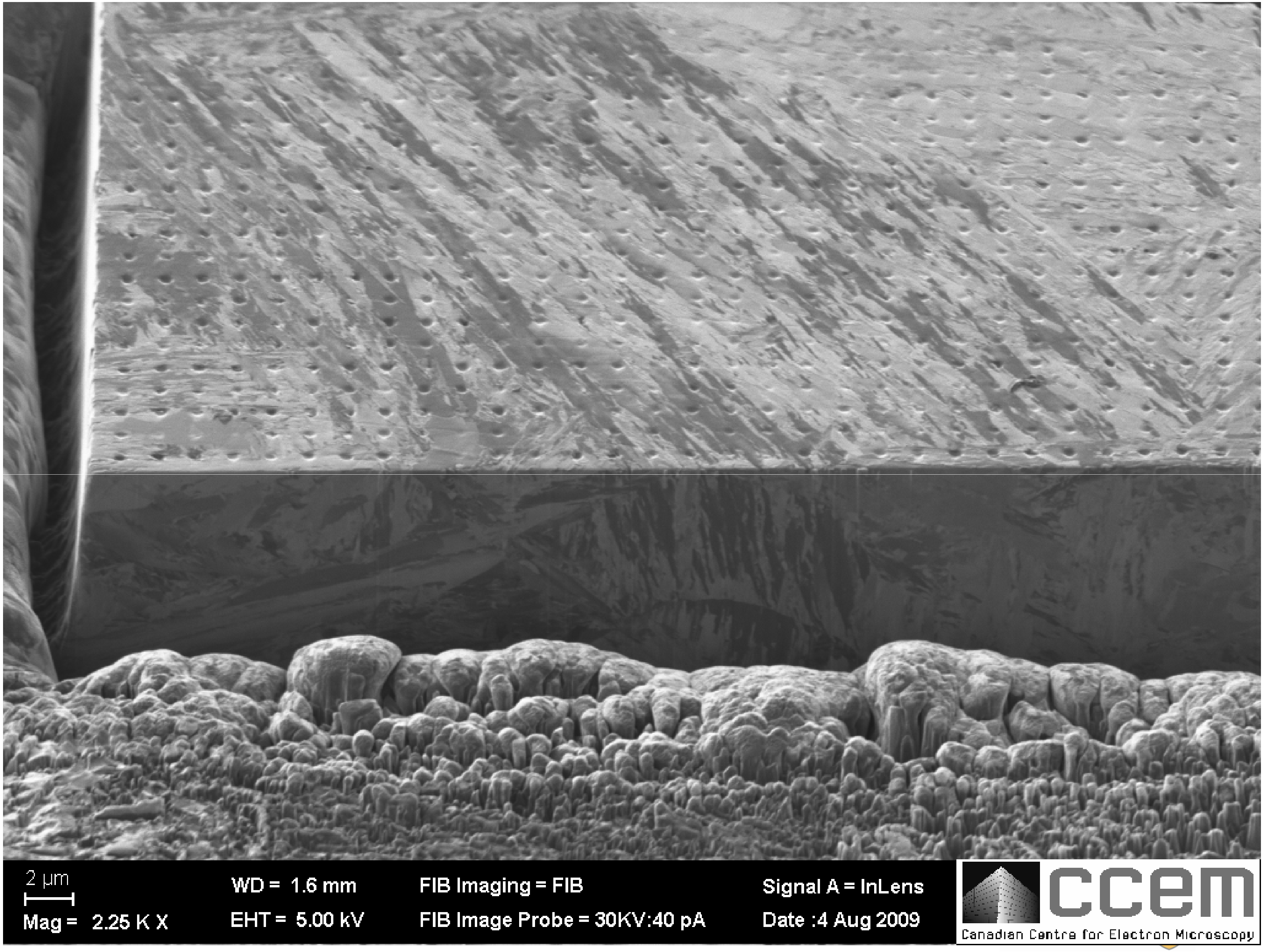
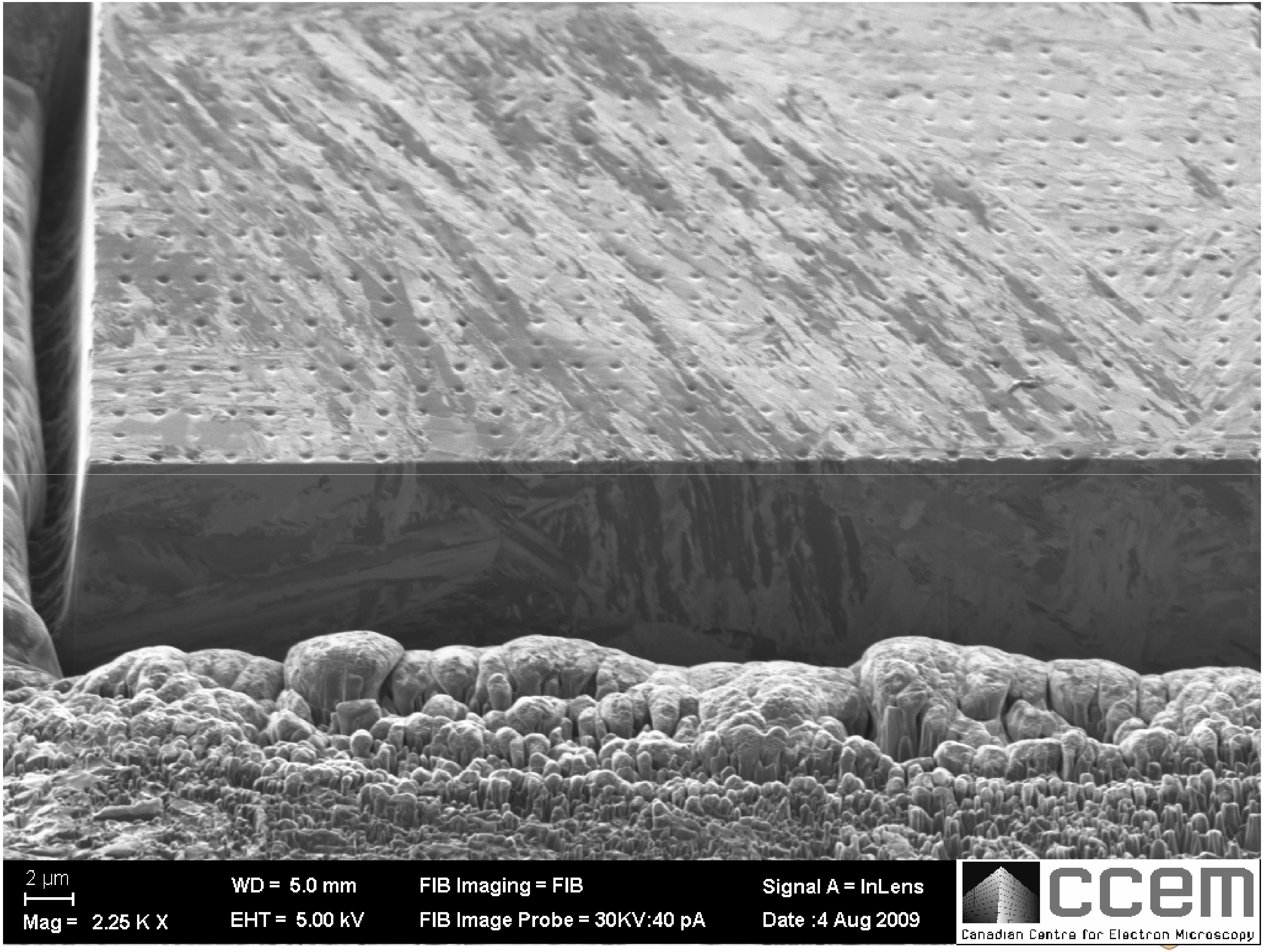

2 µm
Mag = 2.25 K X
WD = 1.6 mm
EHT = 5.00 kV
FIB Imaging = FIB
FIB Image Probe = 30KV:40 pA
Signal A = InLens
Date :4 Aug 2009
ccem
Canadian Centre for Electron Microscopy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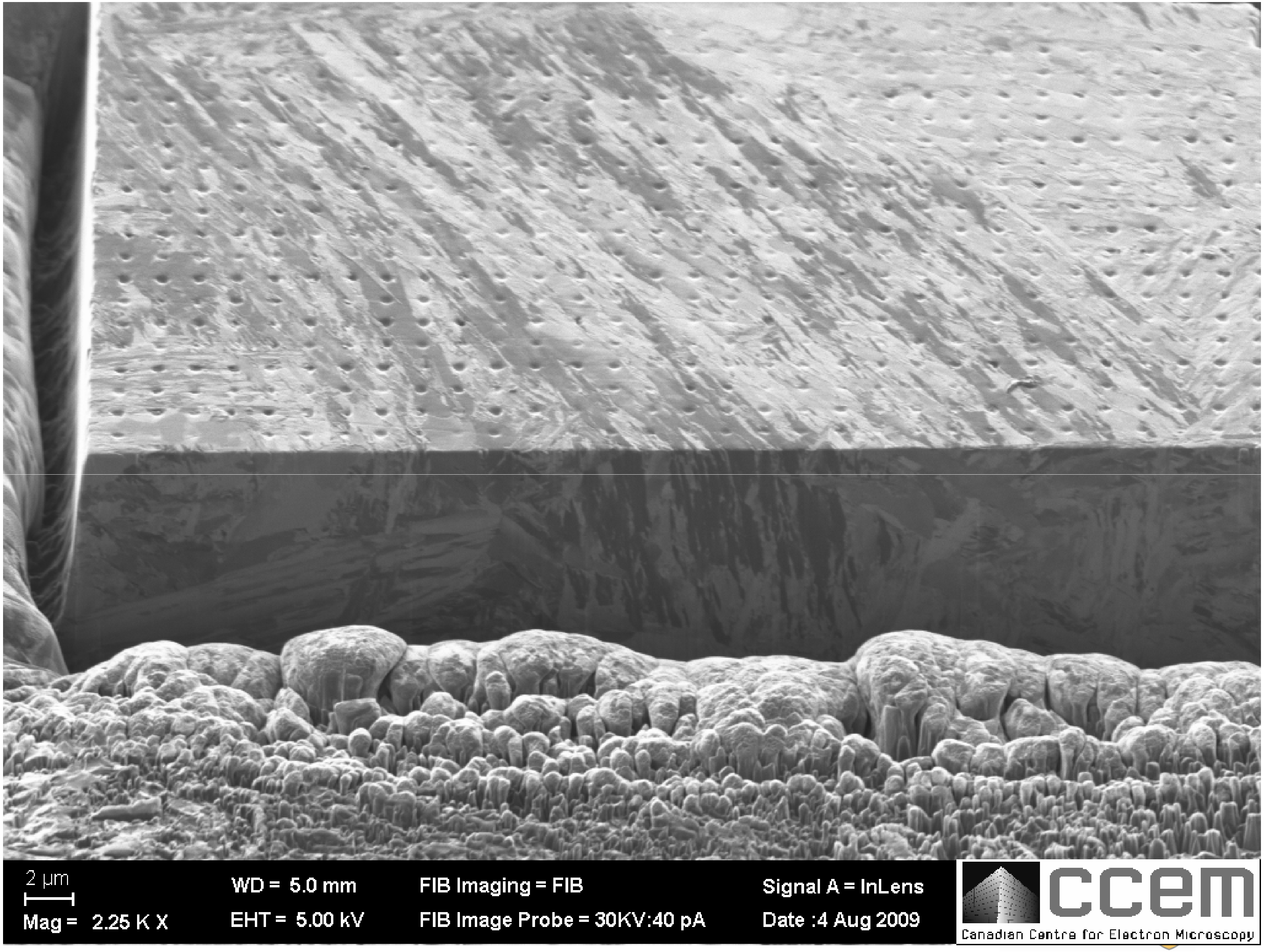
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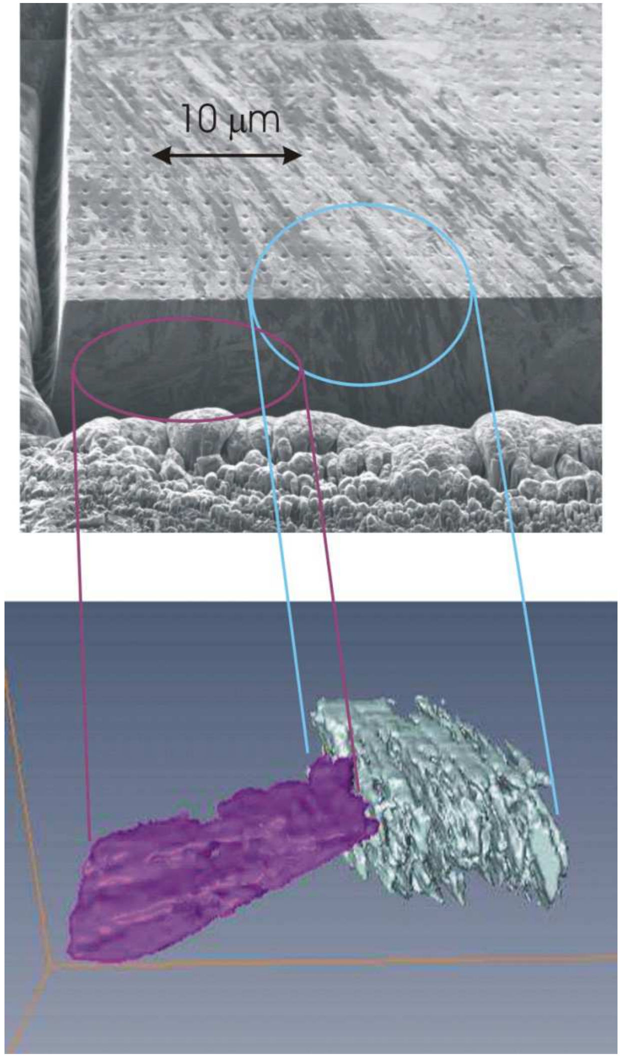

reconstruction

Focused ion beam imaging, sectioning of bainite laths;

Fe-0.4%C-2.8%Mn-1.8%Si, 30 min. at 300 C.

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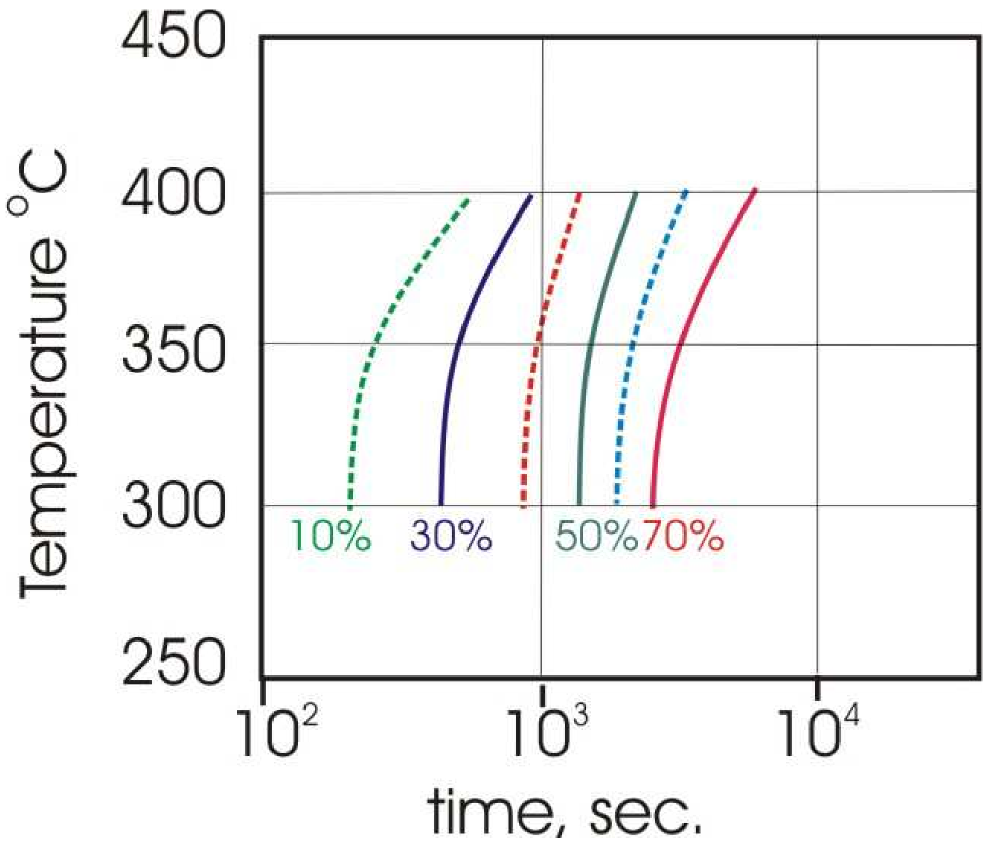
KINETICS:

From metallography, previous studies

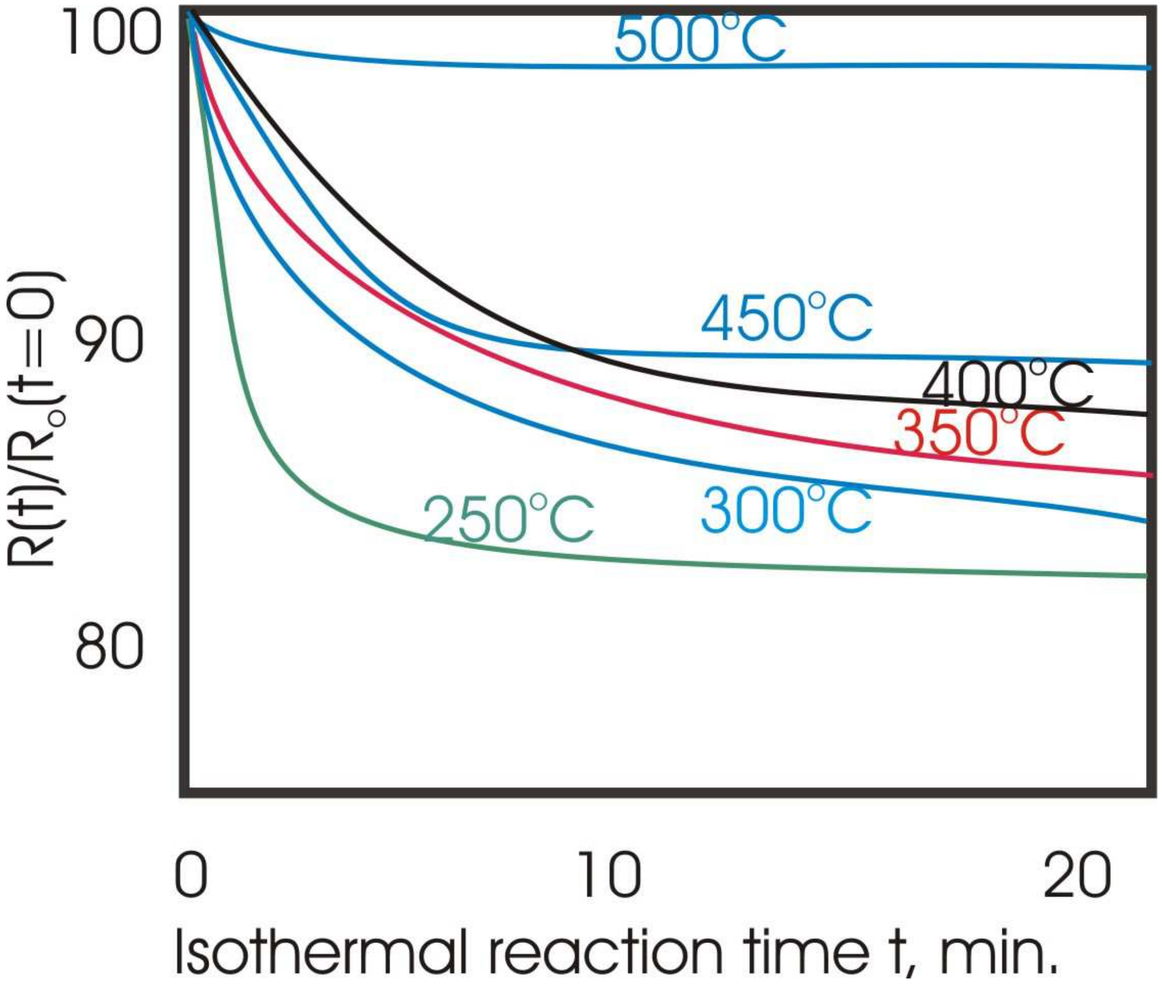
and

Resistivity studies of Fe-0.4C-2.8Mn-1.8Si

TTT diagram for Fe-0.4C-2.8Mn-1.8Si (determined by optical metallography):



Resistivity response through Ms (Ms=275^{o}C)



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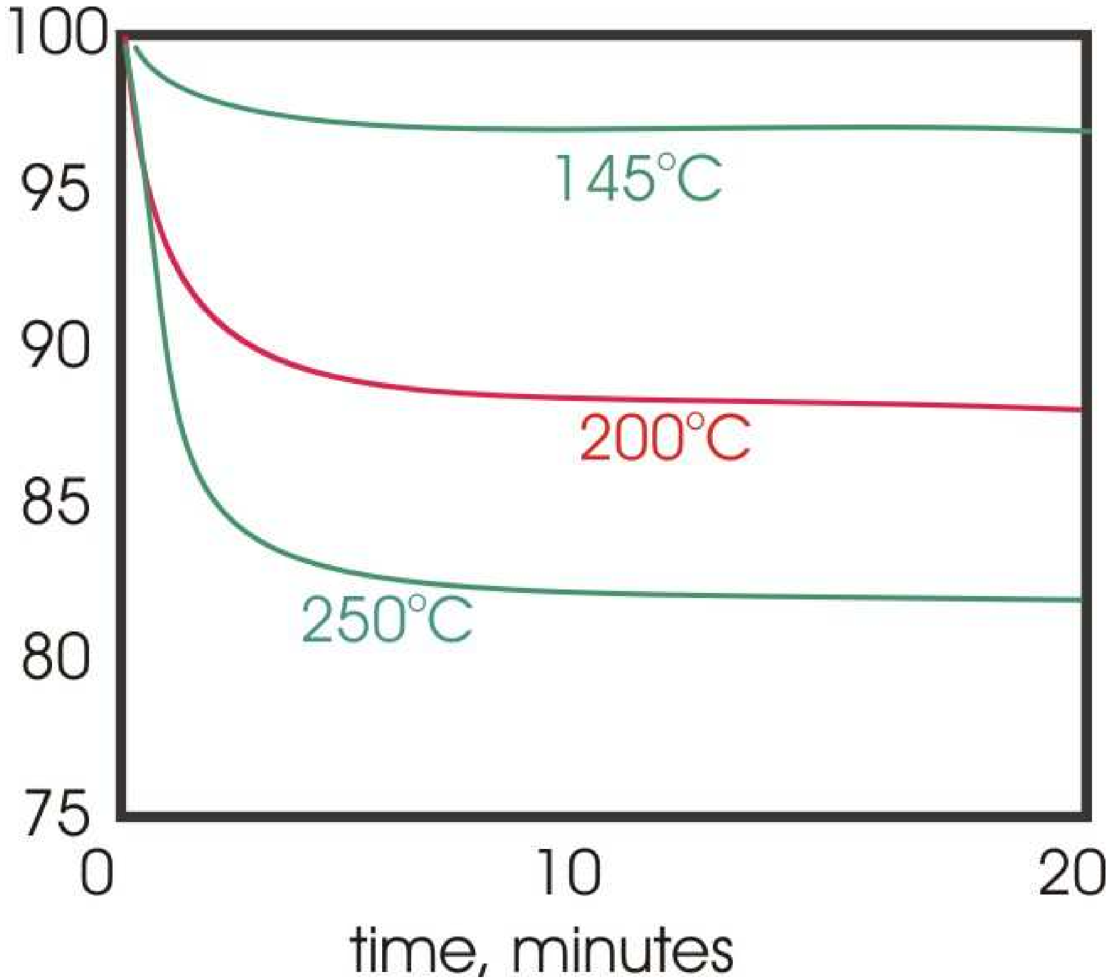
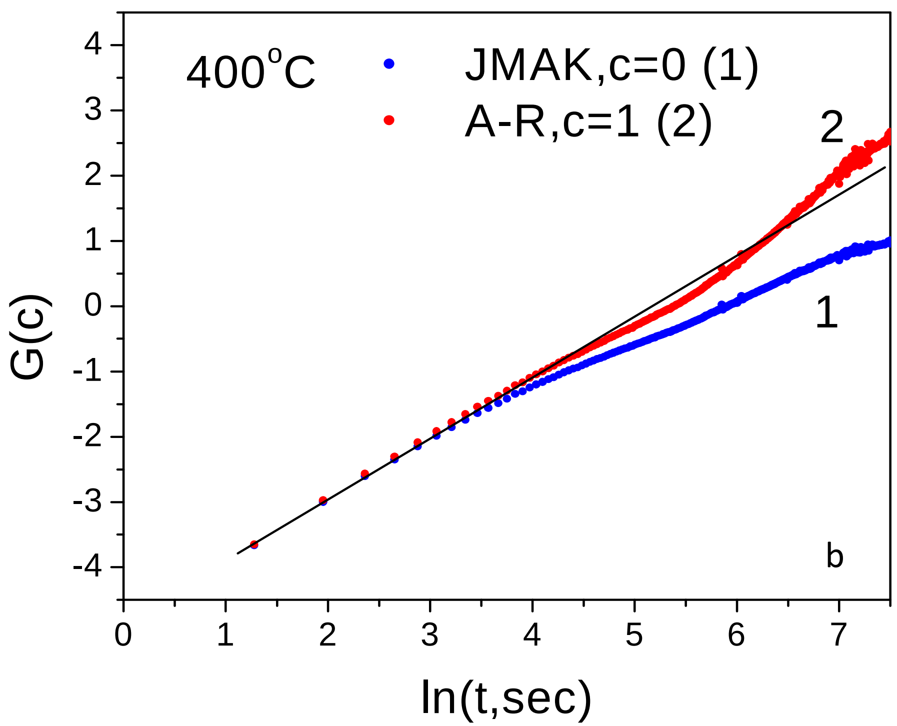
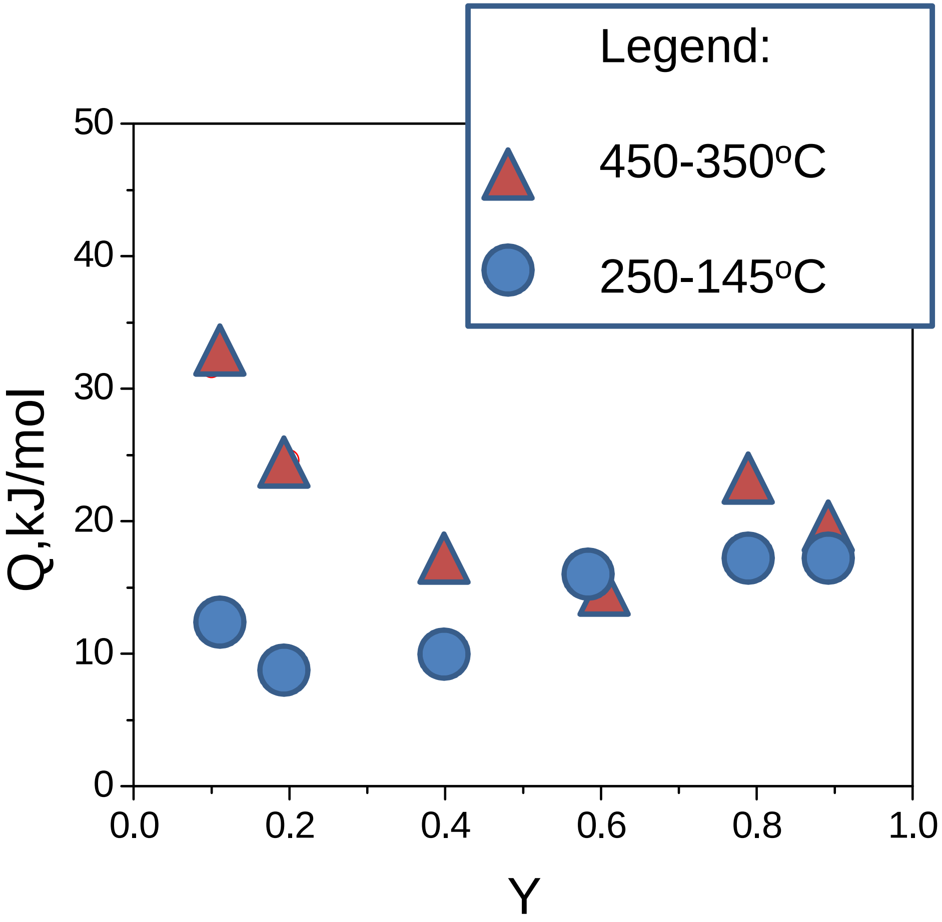
Response below Ms ($Ms=275^oC$)

100 $R(t)/R_o(t=0)$





$$G(c) = \ln\left[\frac{(1-Y)^{-c}-1)}{c}\right] = n\ln t + n\ln k$$



Apparent activation energy Q vs. fraction transformed Y

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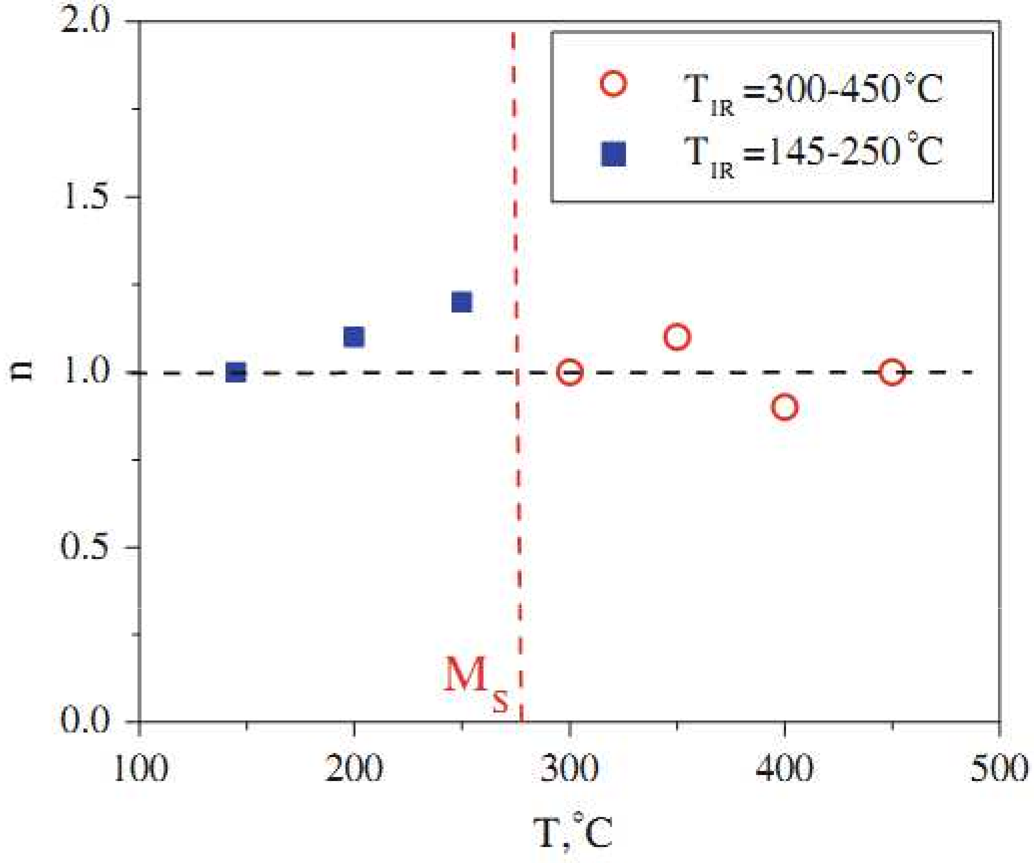

Reaction constant n vs. isothermal reaction temperature.

$$G(c) = \ln\left[\frac{(1 - Y)^{-c} - 1)}{c}\right] = n \ln t + n \ln k$$

Conclusions from the kinetic studies:

The kinetic observations are consistent with a limited number of initial precipitates that lengthen rapidly, and thicken much more slowly.

Bainites formed above and below Ms form continua in both microstructural and kinetic senses.

Bainite and athermal martensite are distinct and perhaps able to catalyze one another.

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TEM studies of carbide-free and carbidic alloys

R (Sherri) Hadian

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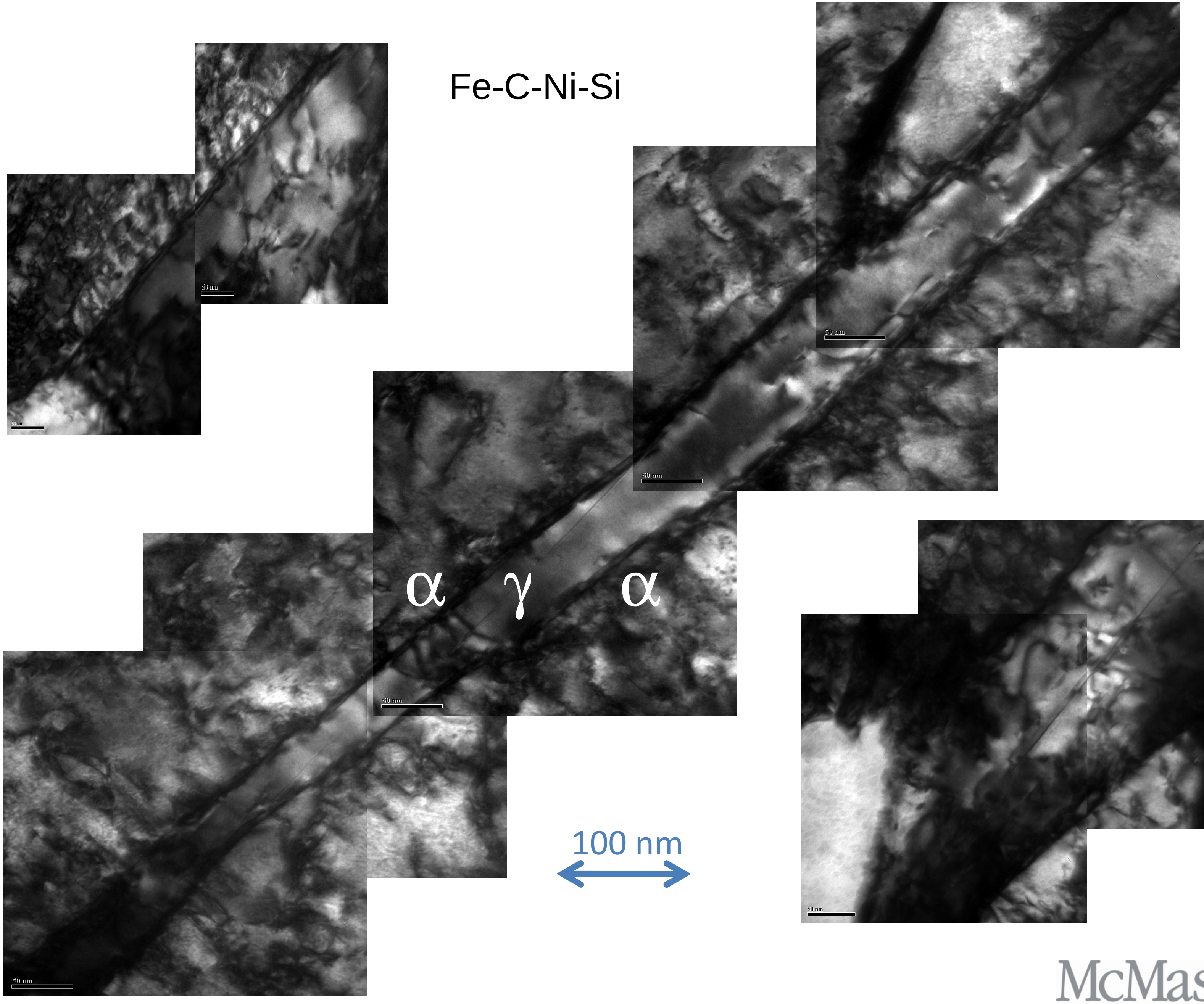
Fe-C-Ni-Si



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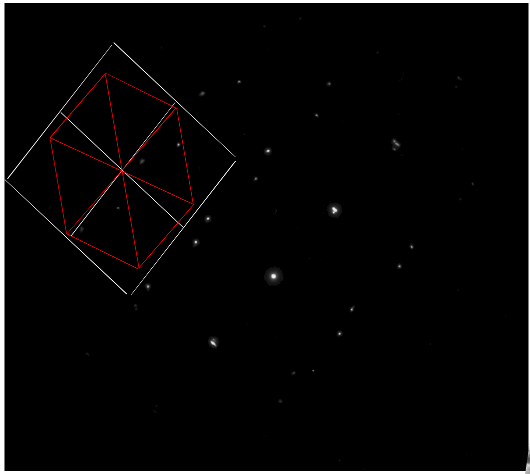
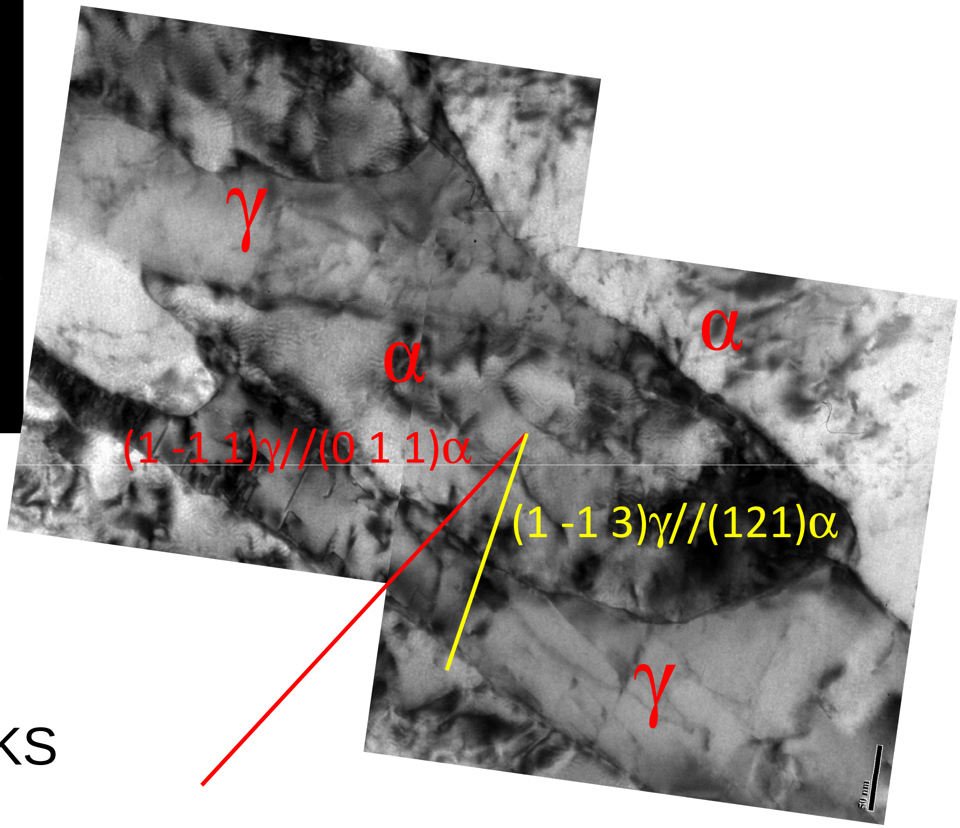
:

Ferrite/austenite orientation relationship; Fe-C-Ni-Si bainite 10 min. at 350^{o}C





OR between NW and KS
(1-11)γ ≈ 1° from(011) α
[110]γ ≈ 2.6° from[1-11] α

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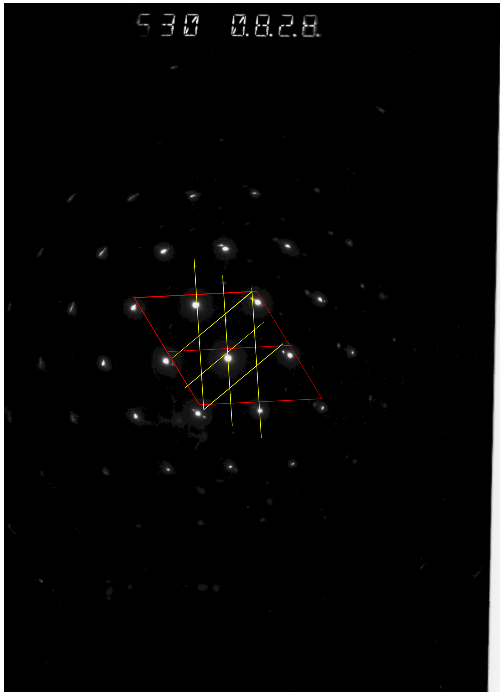
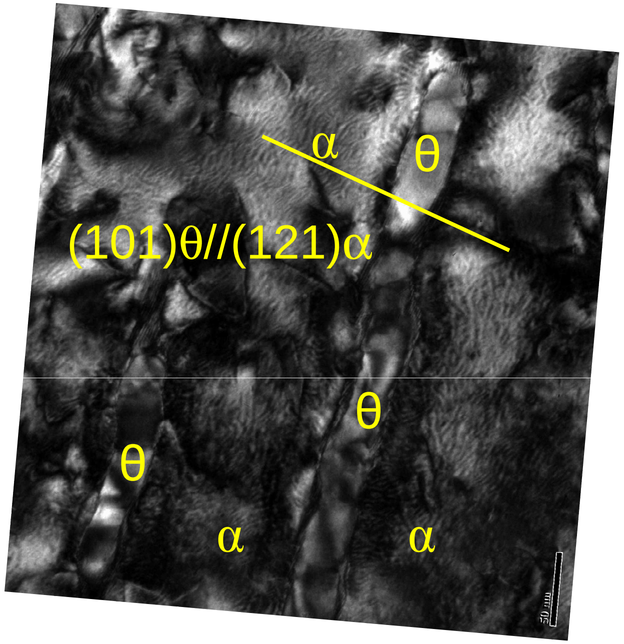
Ferrite/cementite orientation relationship;

Fe-C-Ni bainite formed at 350°C





OR near Isaichev:

(303) θ // (121) α

[010] θ ≈ // [1-11] α

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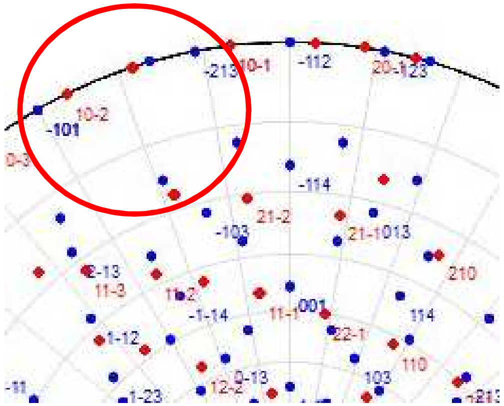
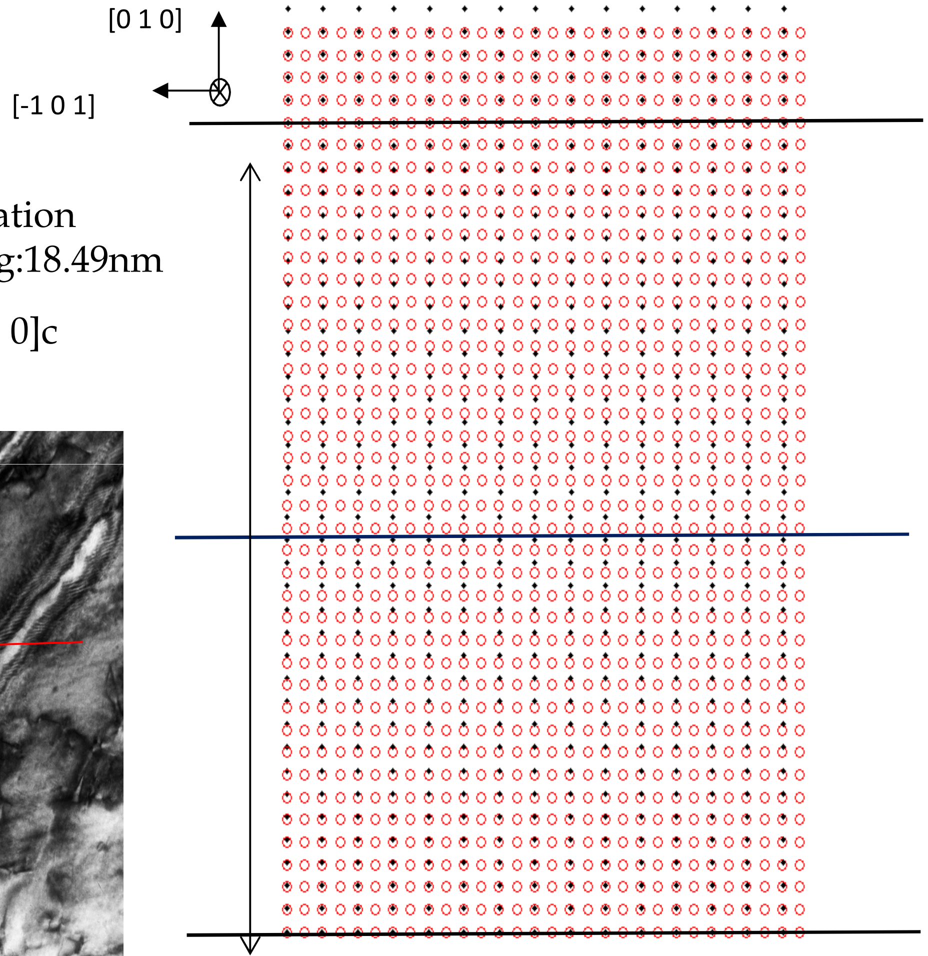
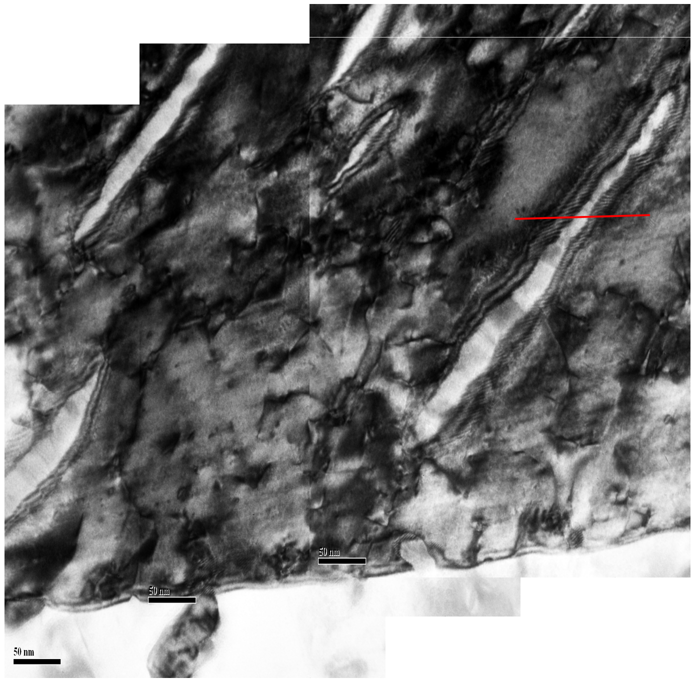
Modeling the cementite-ferrite interface:
R. Hadian



Dislocation
spacing:18.49nm

B= [0 1 0]c

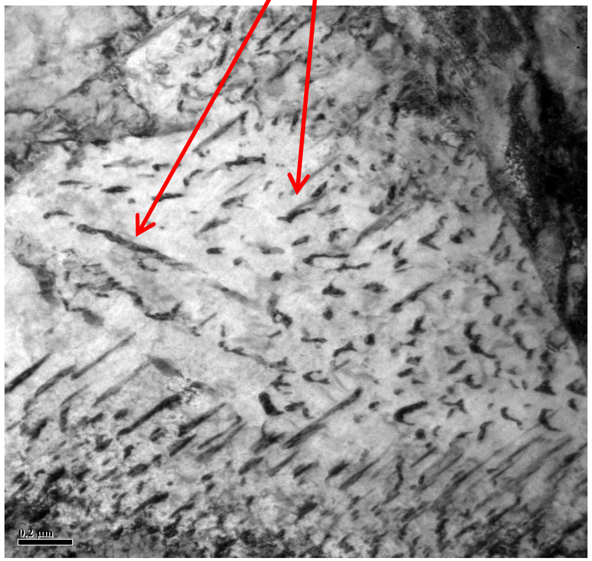




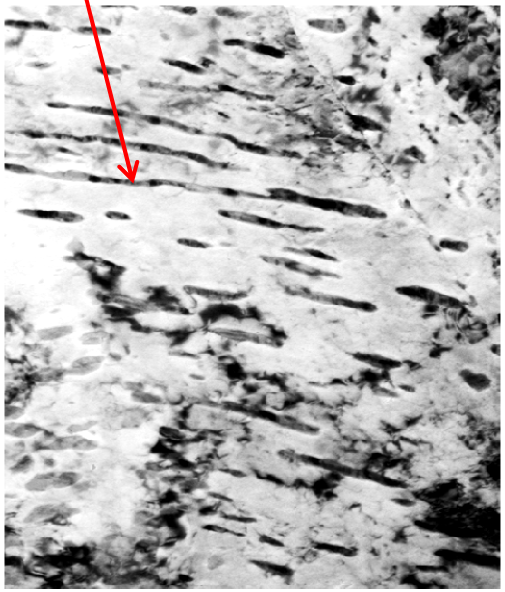
Comparison of autotempered martensite and bainite, specimen isothermally transformed below M_s

Multiple variants of cementite

Single variant



Martensite



Bainite

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RE: “CARBIDE-FREE BAINITES”:

a) The study of these structures permits the elucidation of ferrite/austenite kinetics, OR and habit. Our kinetic studies indicate that the ferrite forms first by rapid diffusional lengthening of a limited number of precipitates. Growth then continues by a slow thickening process.

b) There is no well-defined habit plane in the aged alloys studied; the complex morphologies developed at later stages are suggestive of weak anisotropy of interfacial properties (a/g).

c) The α/γ orientation relationship is between K-S and N-W. More precisely, $(1\text{-}11)\gamma \approx 1°$ from $(011)\alpha$; $[110]\gamma \approx 2.6°$ from $[1\text{-}11]\alpha$;

d) The residual austenite in Si-containing alloys (after, say, 90 min. at 300°C) contains > 2 % C. It is therefore remarkably stable.

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RE: CARBIDIC STRUCTURES IN FE-C-NI:

a) The orientation relationship in these bainites is close to Isaichev, that is:
(303) θ // (121) α; [010] θ ≈ **//** [1-11] α

b) For specimens transformed below Ms, bainites and autotempered martensites are found to coexist.

c) Autotempered martensites possess multiple variants of the cementite precipitates, while bainitic ferrites in the same specimens contain only one variant

Some General Conclusions:

Lengthening of bainite plates is completely consistent with control by carbon diffusion.

Bainitic ferrite formation is kinetically continuous through Ms; it is possible that athermal martensite and bainite catalyze one another but the two products are quite distinct.

In carbidic specimens reacted below Ms, carbide precipitation offers a way of distinguishing between autotempered martensite and bainite.

Surface relief (shear) is an indication of a displacive migration process which may involve site correspondence; motion of disconnections. In no way does it necessarily imply a diffusionless process.