TEMPERING OF LOW-TEMPERATURE BAINITE

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ABSTRACT

- Tempering of low-temperature carbide free bainite, at 400^{0}C and 500^{0}C → Cementite observed nm scale
- Proximity histograms: slight partitioning of solutes (except Si).
- Core of carbide appears to be deeply depleted in Si
- Retained austenite observed as thin films after tempering at 400^{0}C
  - C content was less than in as transformed state, but there is known to be thickness relation.

INTRODUCTION

Nanostructured bainitic steels exist

- Tempering of interest –thermal stability – structure control.
- Previously shown that hardness is resilient to tempering.

Alloy A2 Fe–0.75C–1.63Si–1.95Mn–1.48Cr–0.28Mo–0.1V wt% transformed at 200^{0}C;

- Bainitic ferrite has 1.1$\pm$0.7 at% carbon (supersaturation wrt. cementite)
- Austenite has 8$\pm$1.6 at% carbon (double the T_0 limit)

Literature has defined stages of tempering, and processes expected

Alloy A2 Fe–0.75C–1.63Si–1.95Mn–1.48Cr–0.28Mo–0.1V wt% transformed at 200^{0}C tempered at 400 and 500 ^{0}C → APT characterisation

INTRODUCTION

Previous Atom Probe Studies

- Thompson and Miller – Martensite Fe-(0.15,0.4)C-2.25Cr-1Mo wt%
  - Cr Mn Mo did not partition after 40h at 350ºC
    - Paraequilibrium displacive transformation to cementite
  - 187h at 450ºC, cementite enriched in Cr Mn Mo. Cr partitioned more quickly
  - Si had partitioned into the matrix
  - → Diffusion into matrix possible rate limiting step in cementite growth
- Redistribution of carbon studied by Miller Fe-C and Fe-Ni-C alloys. Carbon segregated to coherent twin, lath and grain boundrys
- Barnard etal, Chang+Smith, Silicon diffusion controls 3rd stage of tempering
- Ghosh+Olson, Bhadeshia etal, Kozeschnik and Bhadesia calculations show silicon effect on cementite nucleation is large (paraequilibrium).

INTRODUCTION

Previous Atom Probe Studies

- Caballero and co-workers Alloy B, Fe-0.98C-1.46Si-1.89Mn-1.26Cr-0.26Mo-0.09V wt%
  - Higher carbon content → more austenite than the steel we studied

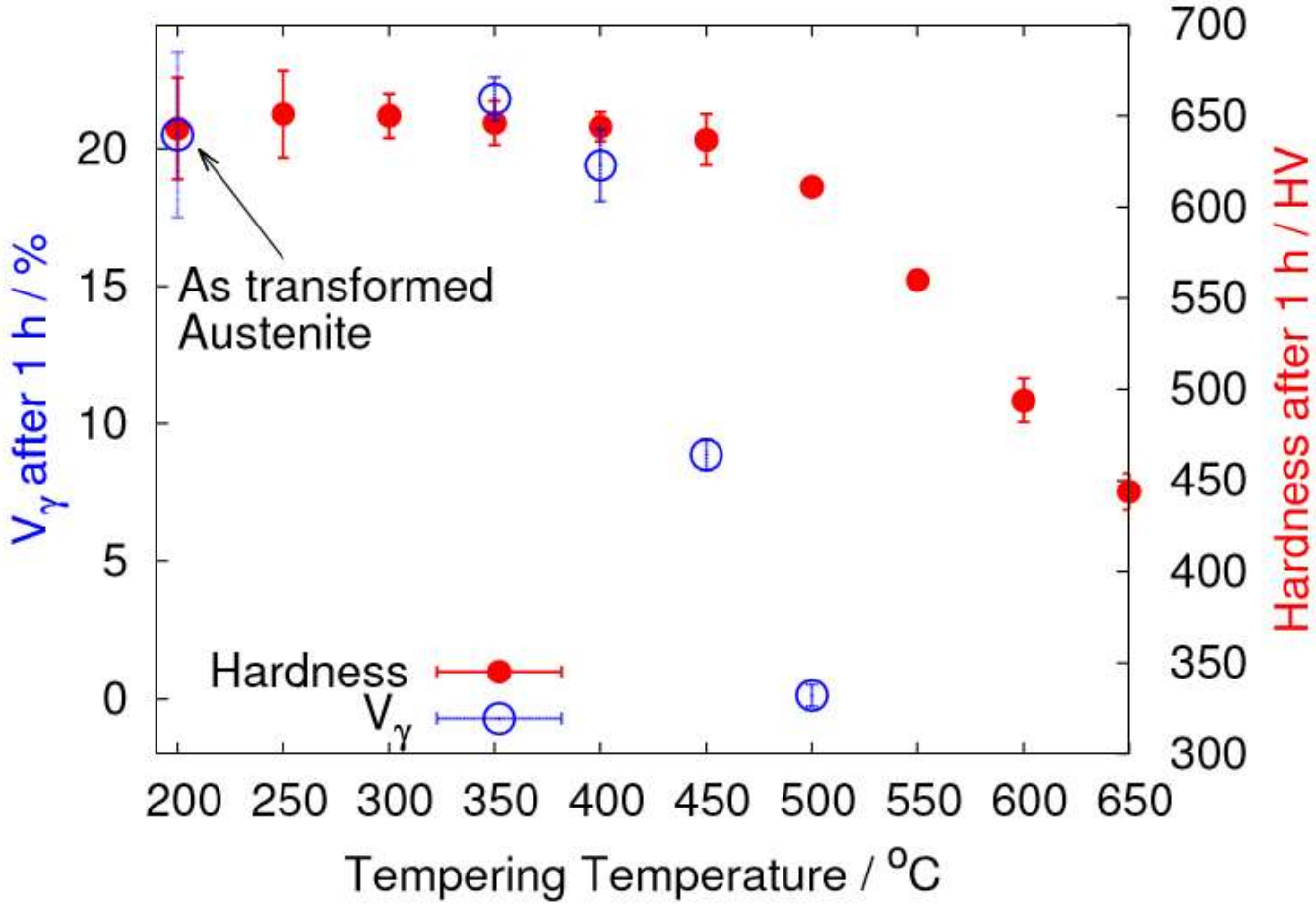
Temperature of tempering	Observations, Alloy B
400ºC	Lower-bainite θ-carbide ~25 at% carbon ϵ-carbide ~30 at% carbon
450ºC	Only ϵ-carbide
500ºC	Only θ-carbide

  - Caballero etal noted few studies on tempering on precipitation of cementite in carbide—free bainite, although expected to be similar to tempering in martensite

COMPARISON VS CABALLERO PAPER/ALLOY

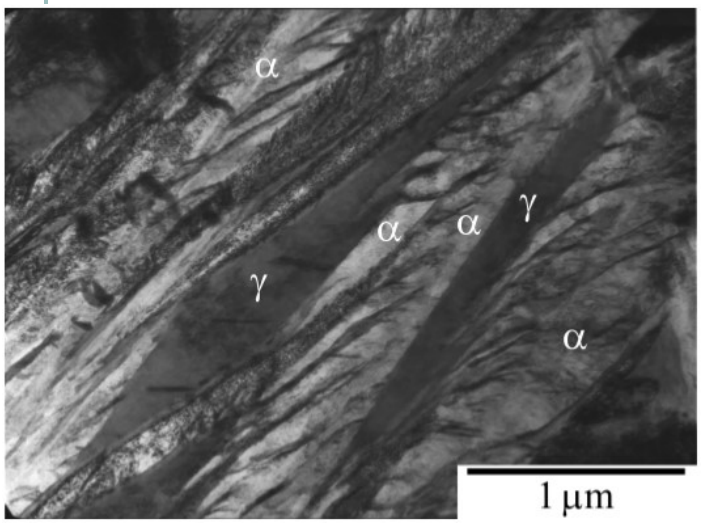
Caballero – Alloy B	Peet – Alloy A (A1/A2)
Fe-0.98C-nX	Fe-0.8C-nX
29±2 VFγ (peak fitting)	21.5 VFγ (Rietveld)
2.52±0.3 at.% C in ferrite (by X-ray or atom probe) (~0.7±0.1 wt% C)	1.19±0.3 wt% C in ferrite by X-ray, this is too high? Source? 1.1 ± 0.7 at.% C in ferrite by atomprobe (~0.25±0.2 wt%)
6.69±0.44 at.% C in austenite (by X-ray or atom probe?)	0.31±0.03 wt% C in austenite by X-ray, 8.0±1.6 at.% in atom probe (~2±0.4 wt%)
35±2 nm plate thickness	39±1 nm plate thickness (from thesis TEM/FEGSEM)
Cementite not observed in initial microstructure by TEM, but observed by atom probe.	Cementite not observed in initial microstructure by TEM or atom probe, although Carbide extraction and X-ray shows cementite is present.
617 HV	650 HV

FIG1



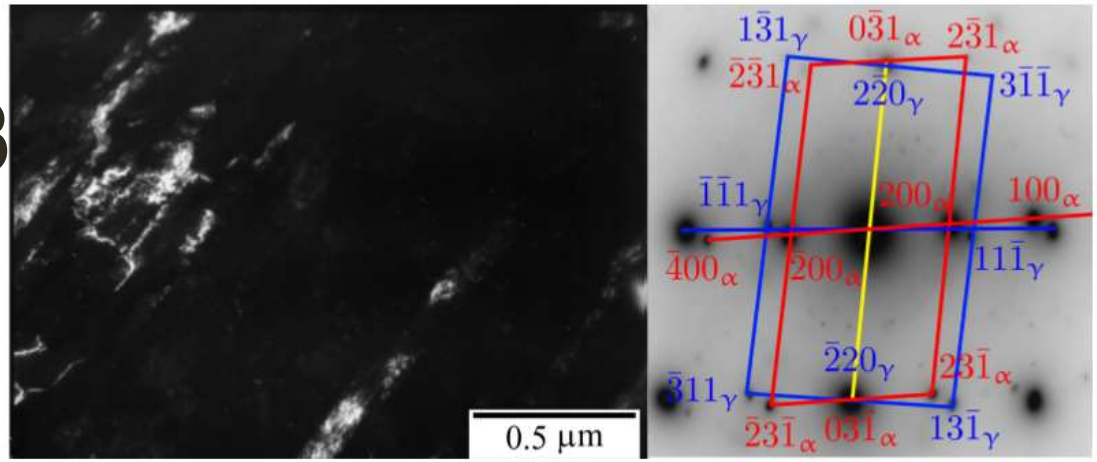
Changes in hardness and volume fraction of austenite due to tempering 1h in alloy A1.

Fig2



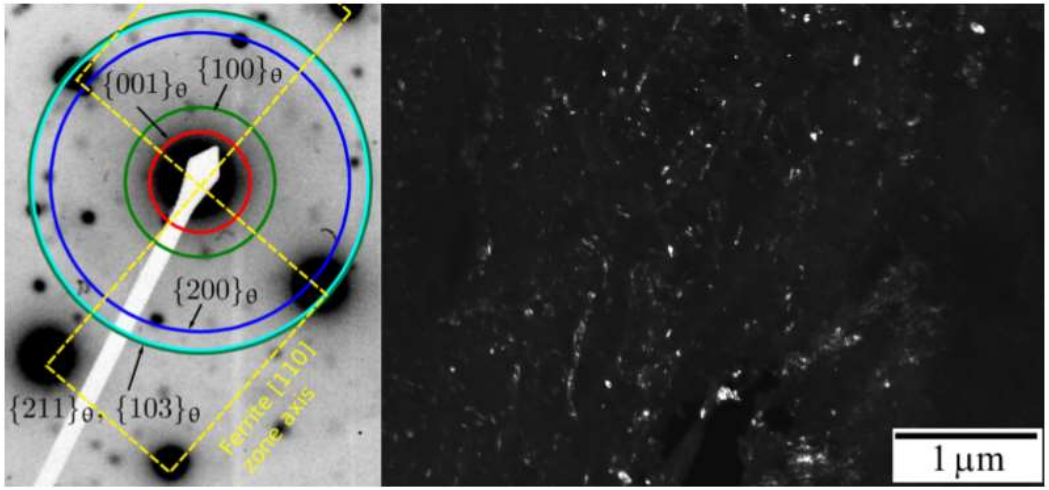
Alloy A1 completely transformed at 200'C and tempered at 400ºC for 30 min. Typical microstructure observed by TEM, showing bainite plates separated by austenite films.

Fig3



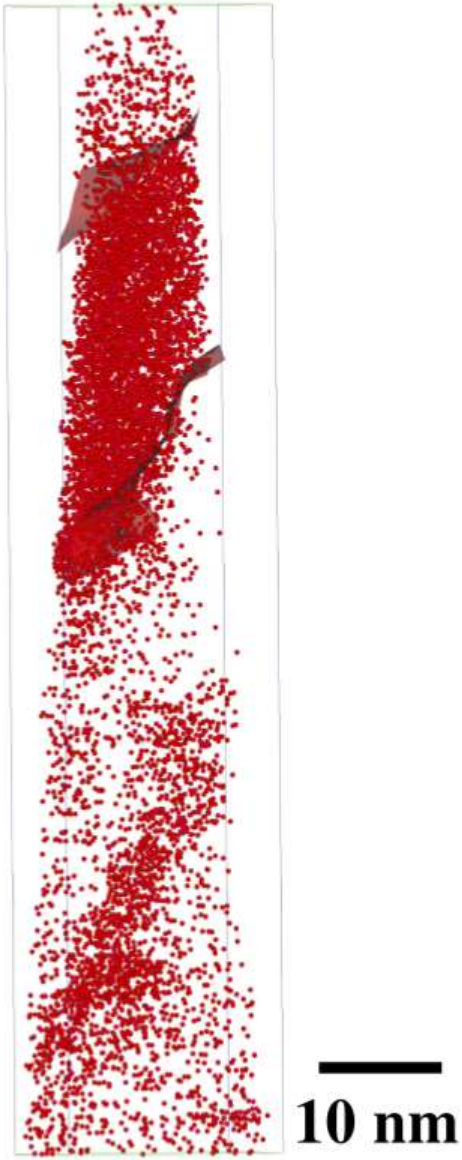
450'C for 30 min

Fig4



500'C for 30 min

FIG5/6


10 nm

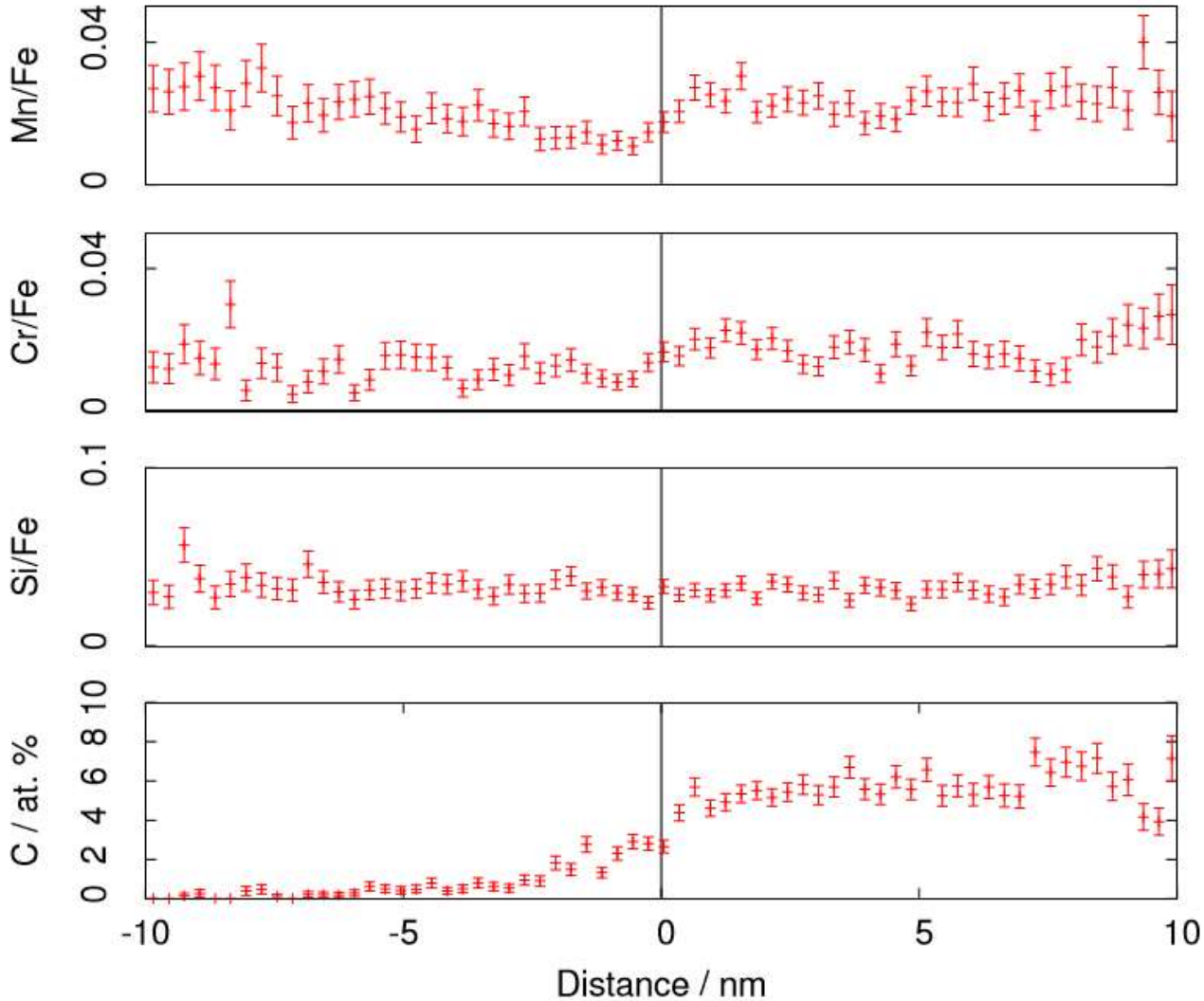
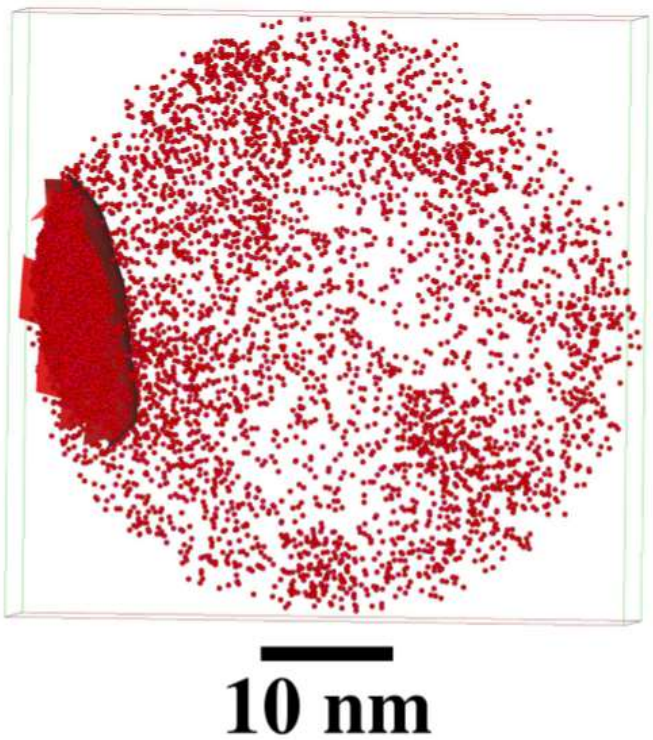

Mn/Fe
0.04
0
Cr/Fe
0.04
0
Si/Fe
0.1
0
C / at. %
0 2 4 6 8 10
-10
-5
0
5
10
Distance / nm

FIG8


10 nm

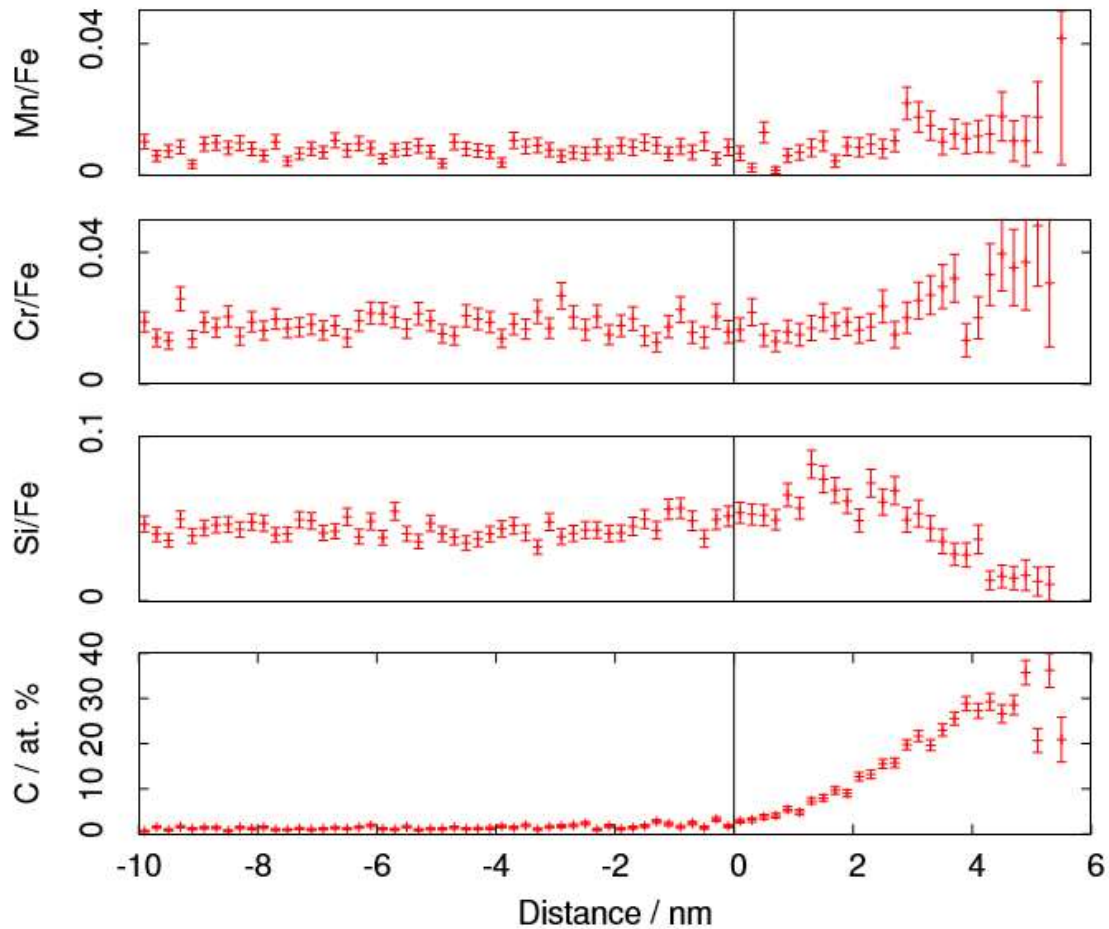
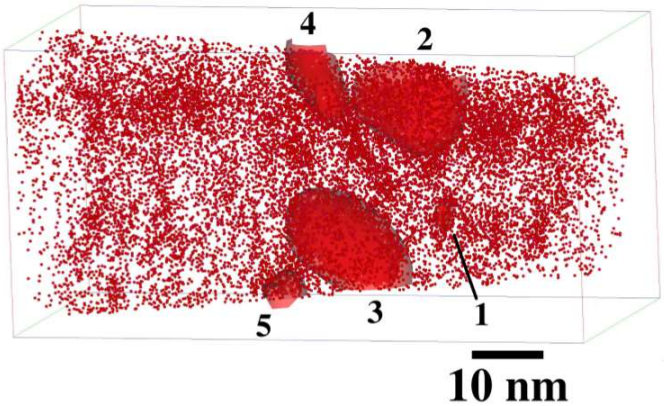
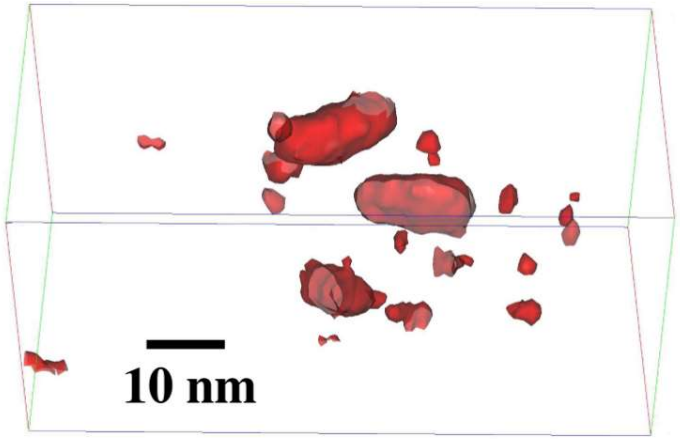
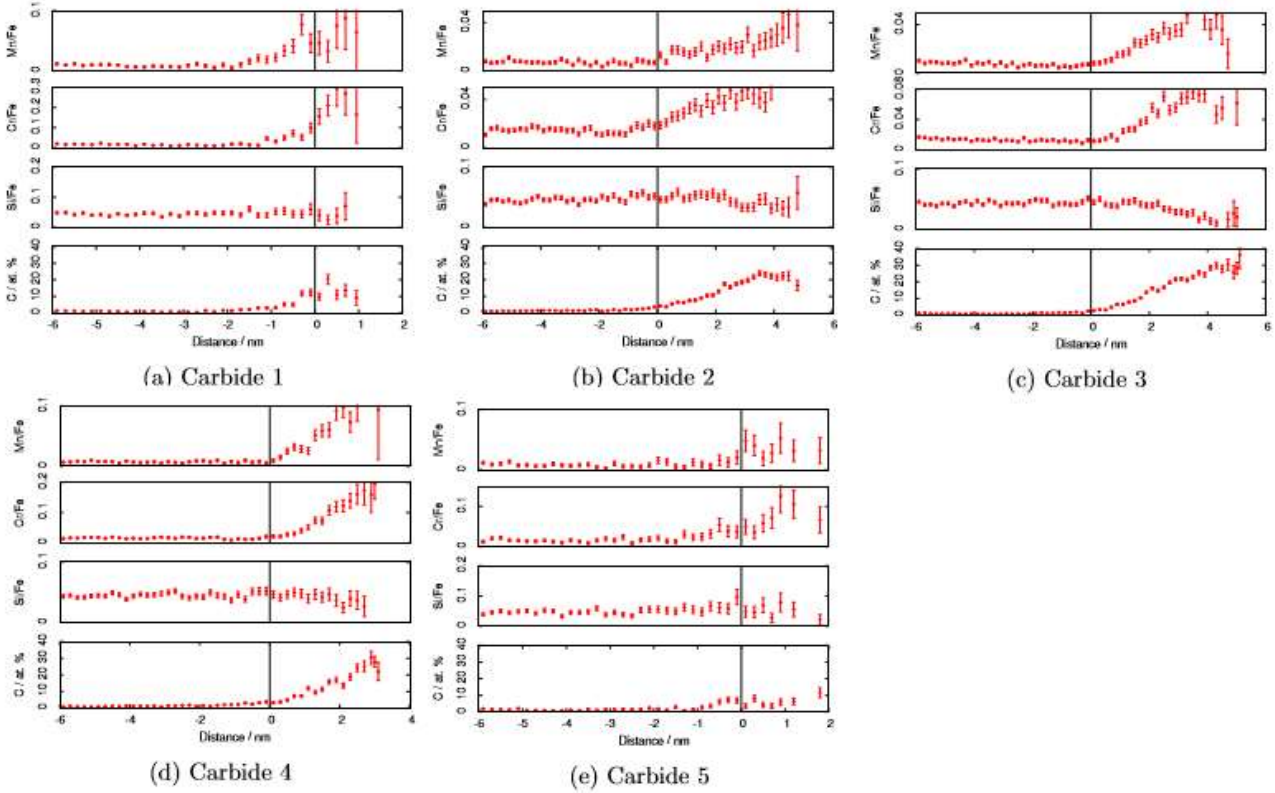

Mn/Fe
0.04
0
Cr/Fe
0.04
0
Si/Fe
0.1
0
C / at. %
0 10 20 30 40
-10 -8 -6 -4 -2 0 2 4 6
Distance / nm

FIG10







(a) Carbide 1 (b) Carbide 2 (c) Carbide 3

(d) Carbide 4 (e) Carbide 5

CONCLUSIONS

Carbon in ferrite decreased from 1.1at.% to 1.0at.% after 400^{0}C tempering and 0.8at.% after 500^{0}C.

After tempering at 400^{0}C possible decrease to ~6at.% carbon observed in a single thin-film of austenite, but film thickness may have a role to play too.

Carbide particles were observed after tempering at both temperatures. With core rich in C and low in Si.

On increase in tempering temperature the carbides are enriched in Cr, Mn, and reject Si.

Extremely small carbide particles ~5 nm observed after tempering at 400^{0}C