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Effects of Mn, Si and N contents on VC Interphase Precipitation in Low Carbon Steels

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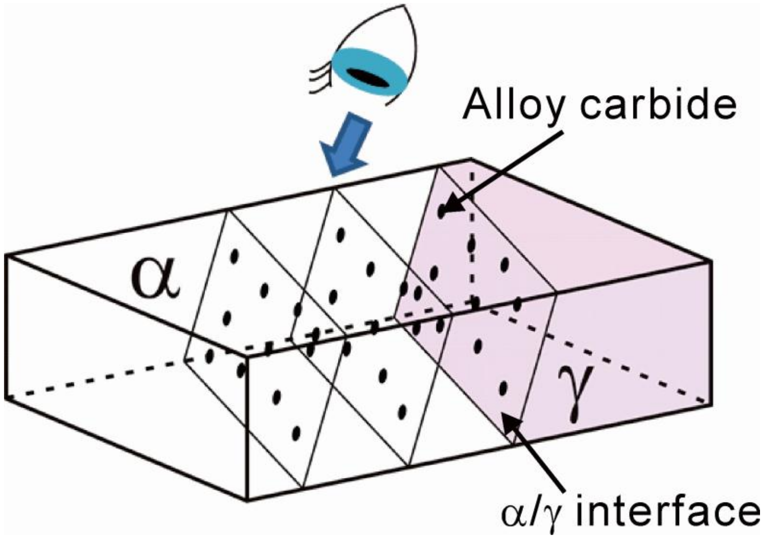
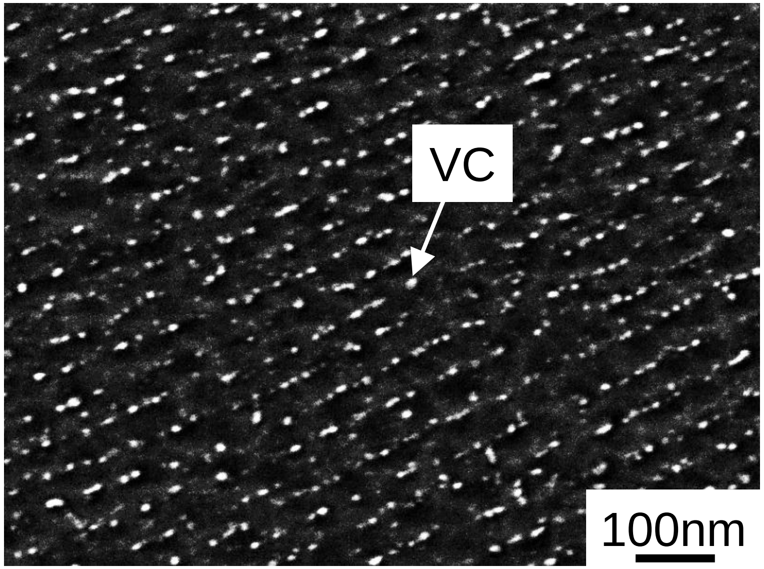
Interphase precipitation



Precipitation in parallel rows at migrating α/γ interface

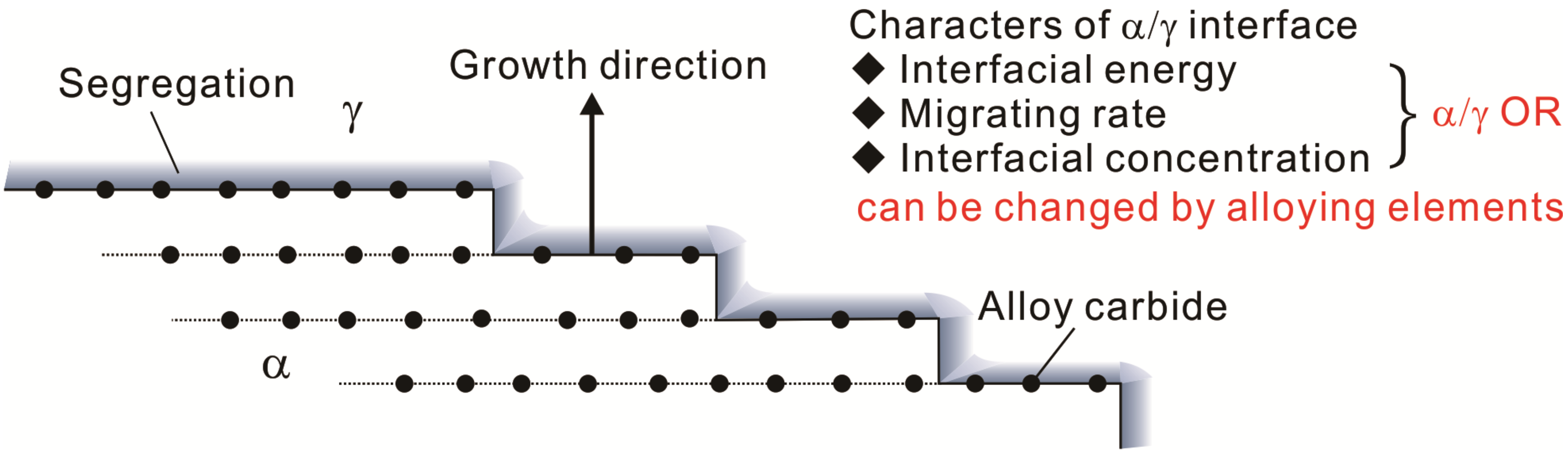
SEM image



V-added low carbon steel

Nano-sized carbides formed through interphase precipitation have been recently used to strengthen low carbon steels.

Various factors on interphase precipitation



Characters of α/γ interface
- ◆ Interfacial energy
- ◆ Migrating rate
- ◆ Interfacial concentration

} α/γ OR

can be changed by alloying elements

Objective:

The present study aimed to clarify the effects of alloying elements, i.e. Mn, Si and N on VC interphase precipitation in low carbon steels mainly by using three-dimensional atom probe (3DAP).

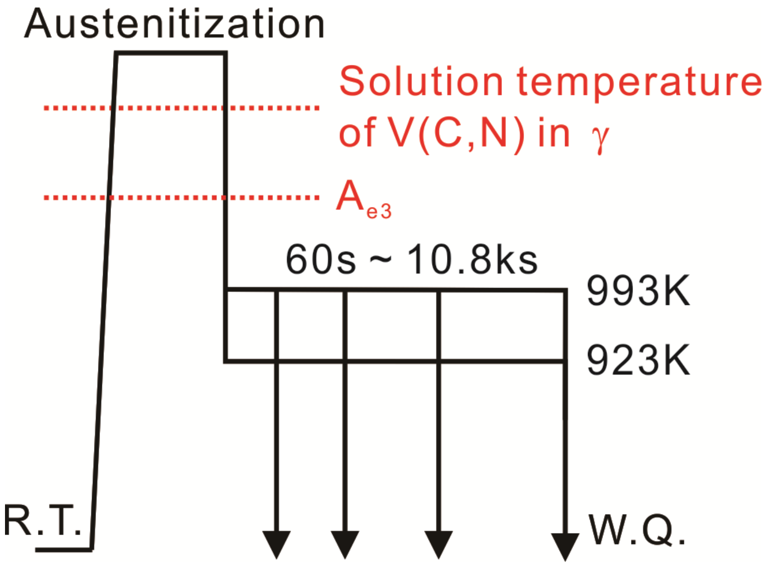
The effects α/γ orientation relationship (OR) should be investigated at first to eliminate its influence.

Experimental

- Alloys (mass%)

	C	V	Mn	Si	N (ppm)
Base	0.095	0.43	1.49	0.047	10
Low Mn	0.09	0.43	**0.69**	0.048	11
High Si	0.093	0.43	1.30	**0.41**	11
High N	0.092	0.42	1.52	0.05	**147**

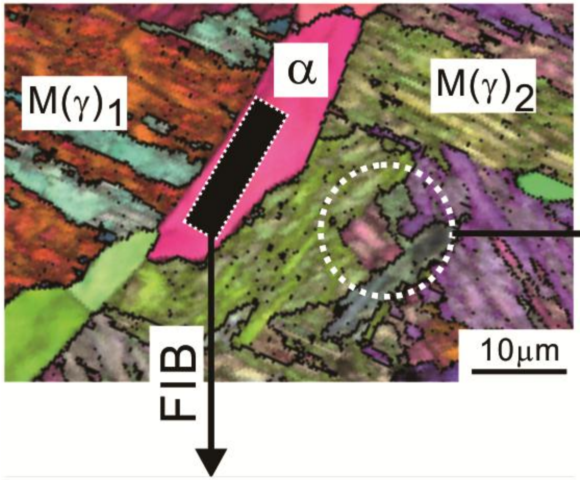
- Heat treatment



- Microstructural characterization
  - Optical microscopy (OM)
  - Electron backscattering diffraction (EBSD)
  - Focused ion beam (FIB)
  - Three-dimensional atom probe (3DAP)

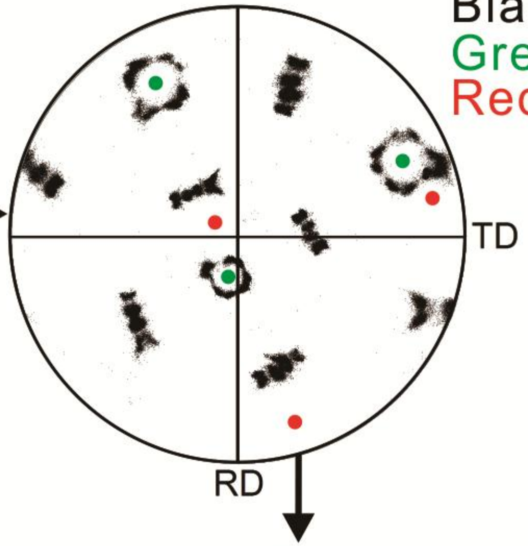
Combination of EBSD, 3DAP and nano-indentation

① EBSD: α-orientation map



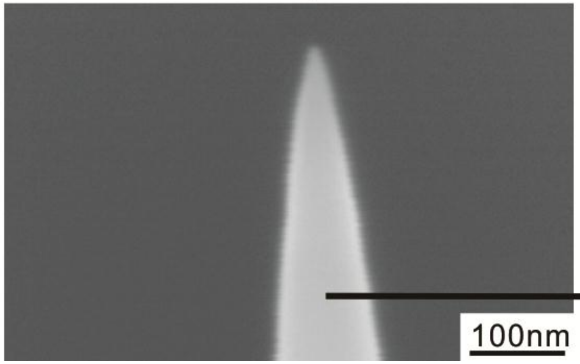
② α/γ OR analysis: 001_{bcc} pole figure

Black points $<001>_M$
Green points $<001>_\gamma$
Red points $<001>_\alpha$



Deviation angle from the exact K-S OR: $\Delta\theta$
Near K-S: $\Delta\theta < 5$deg.
Non K-S: $\Delta\theta > 5$deg.

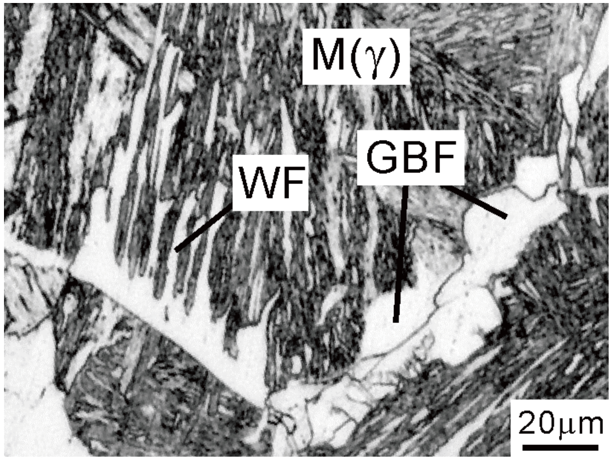
③ Needled specimen



④ 3DAP analysis on VC precipitates

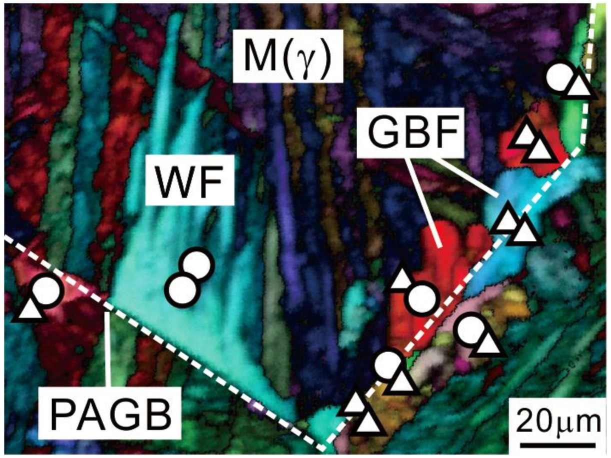
VC precipitation in the Base alloy transformed at 923K

Optical microstructure



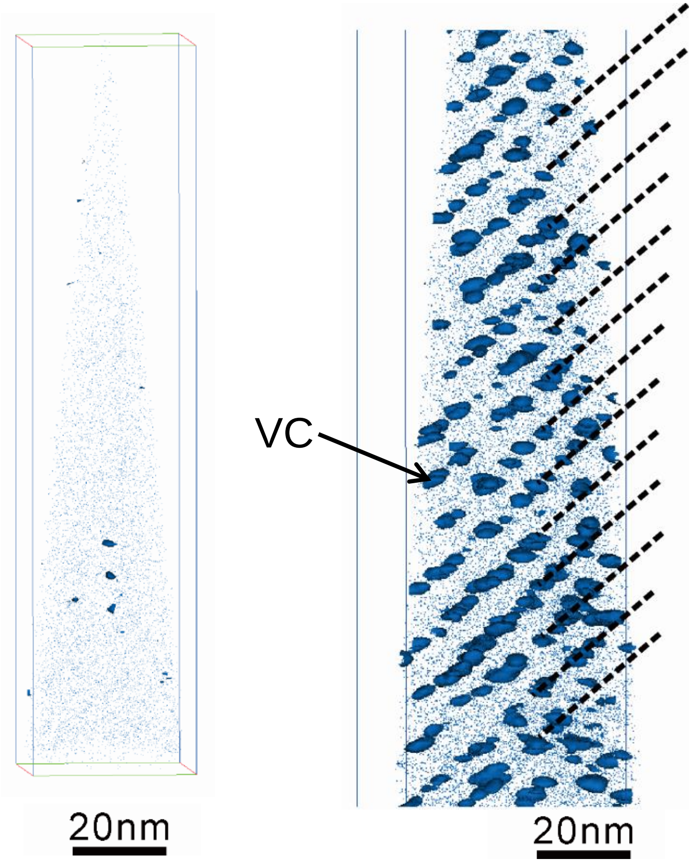
GBF: grain boundary α;
WF: Widmanstatten α;
M(γ): martensite

α–orientation map



○: Near K-S
△: Non K-S
PAGB: prior γ grain boundary

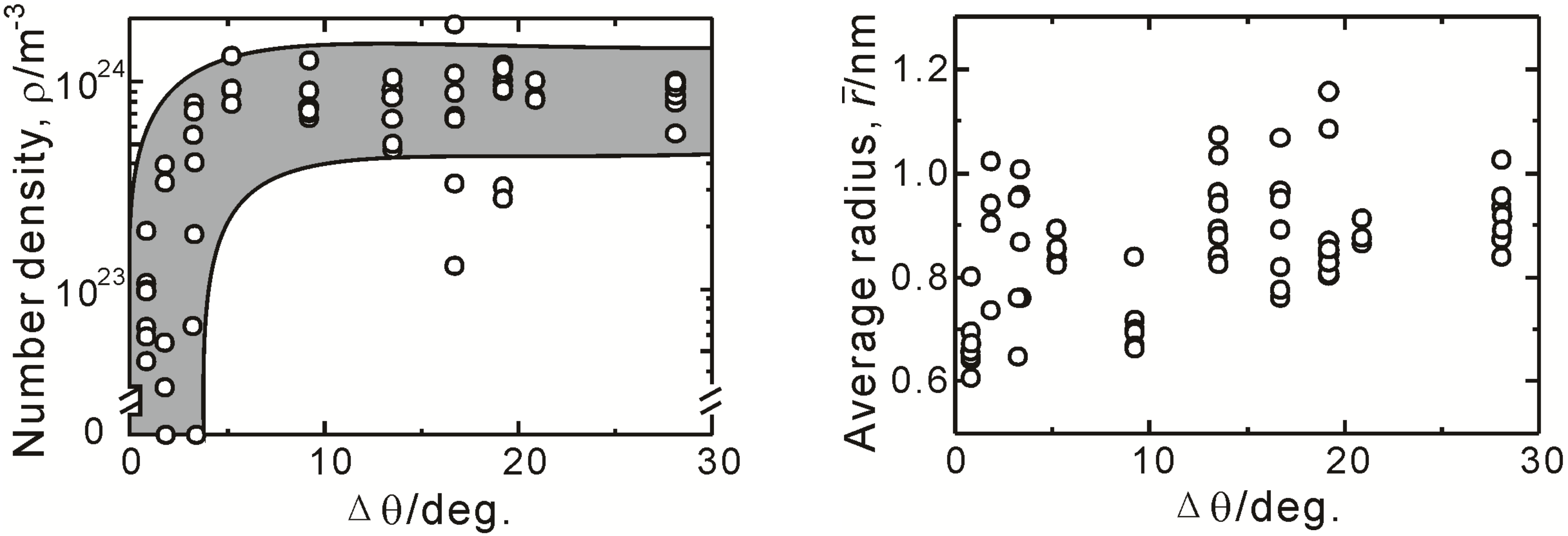
Three-dimensional V atom map


WF (Δθ = 0.8deg.)
GBF (Δθ = 19.2deg.)

- Almost no VC precipitate is formed at near K-S α/γ interface, while sheet-like VC interphase precipitation occurs at non K-S α/γ interface.

[1] Y.-J. Zhang, G. Miyamoto, K. Shinbo, T. Furuhara, Scripta Mater. 69 (2013) 17.

Effects of α/γ OR on VC interphase precipitation

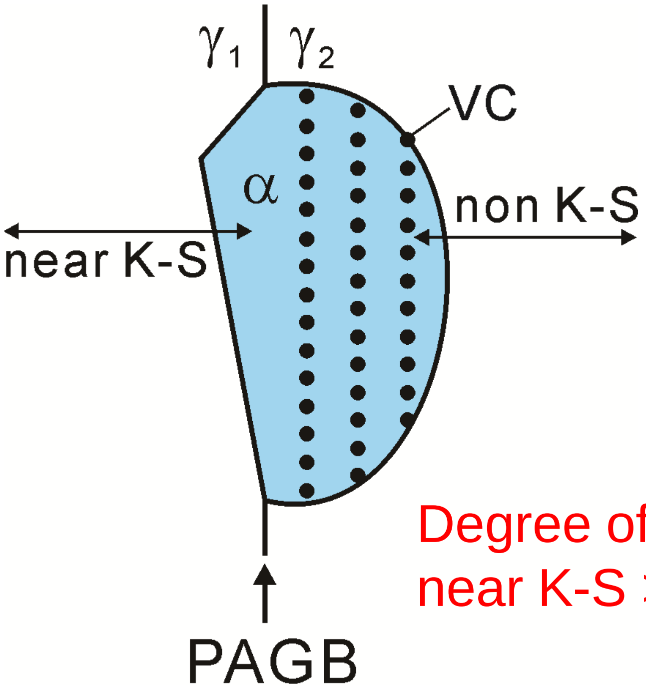


Parameters for cluster analysis:
d_{max} = 1.0nm, N_{min} = 15

- As α/γ OR deviates from the exact K-S, the number density of VC increases significantly at first and remains almost constant later.
- The effects of α/γ OR on the size of VC is relatively small.

[1] Y.-J. Zhang, G. Miyamoto, K. Shinbo, T. Furuhara, Scripta Mater. 69 (2013) 17.

Promotion of VC precipitation at non K-S interface

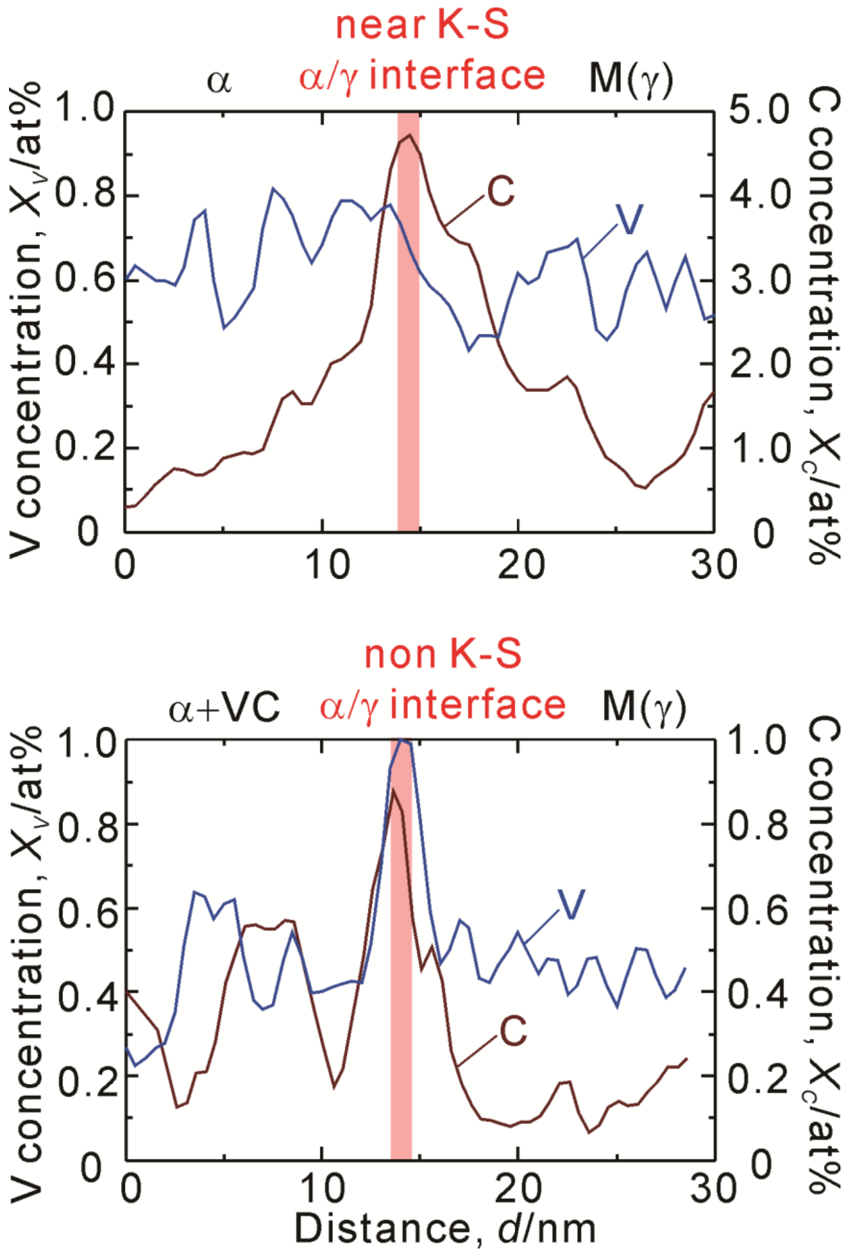


Degree of coherency:
near K-S > non K-S

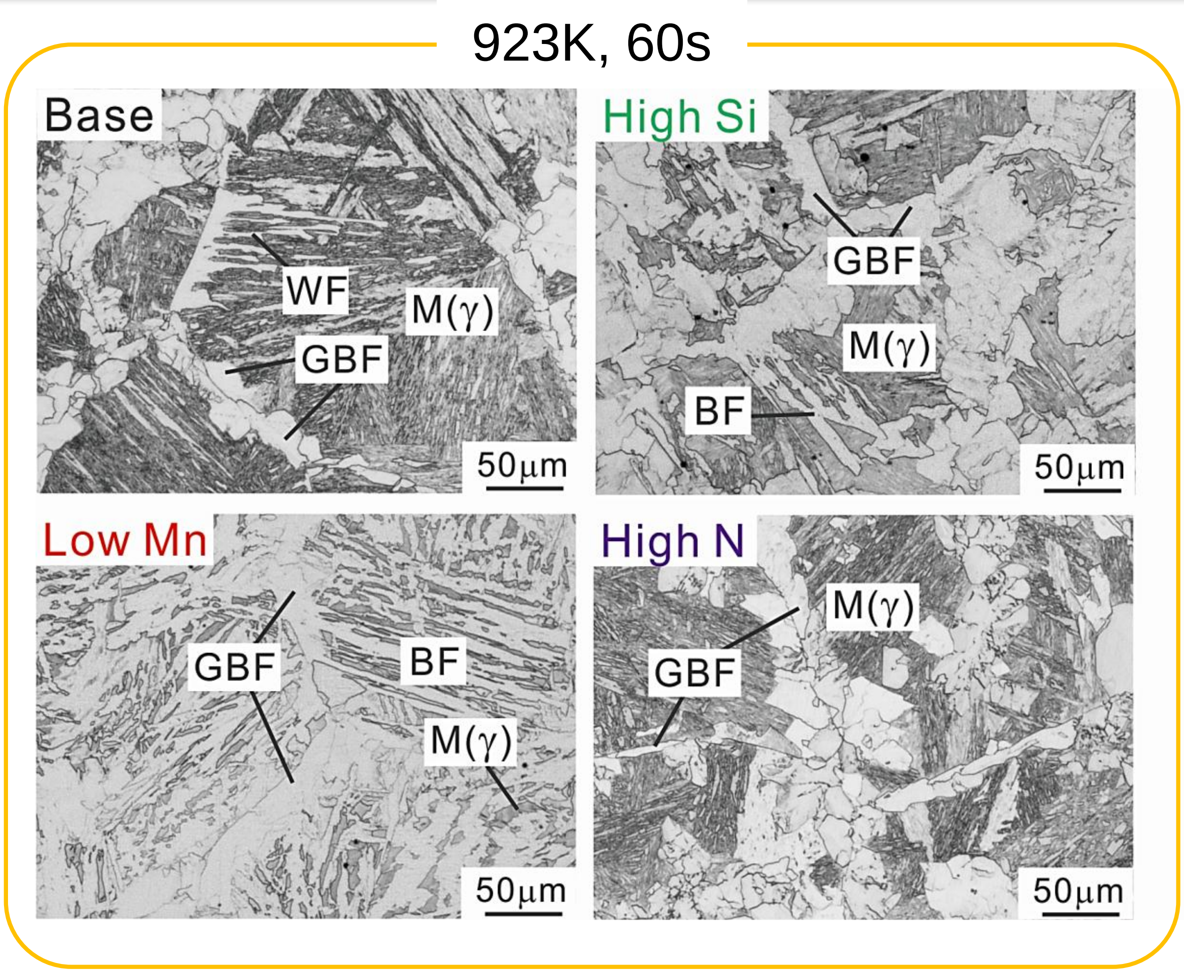
With deviation from the exact K-S OR

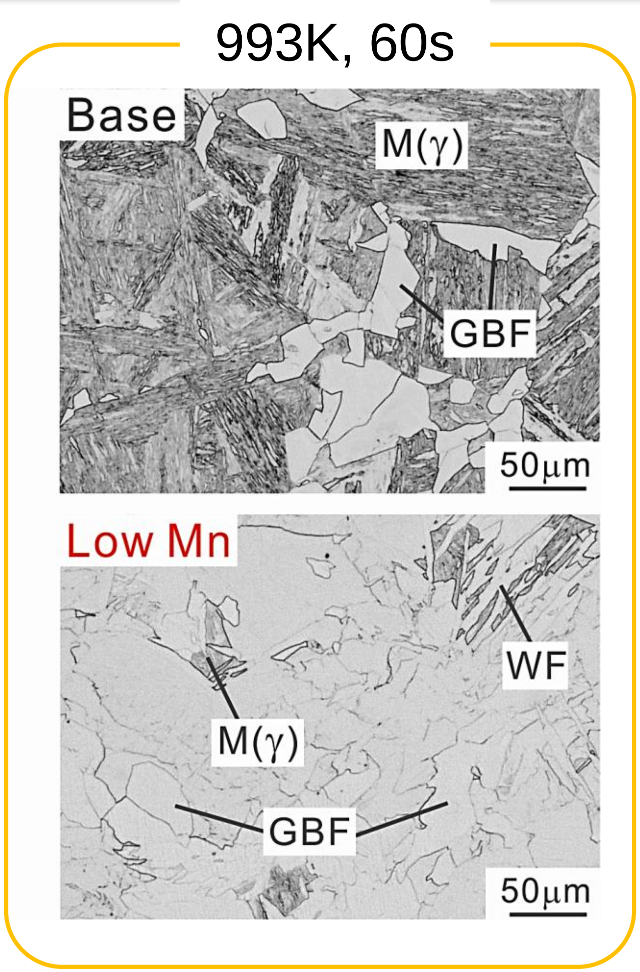
- Higher α/γ interfacial energy
- Higher interfacial diffusivity of V
- Severe segregation of V

Nucleation rate of VC increased at non K-S interface



Effects of alloying elements

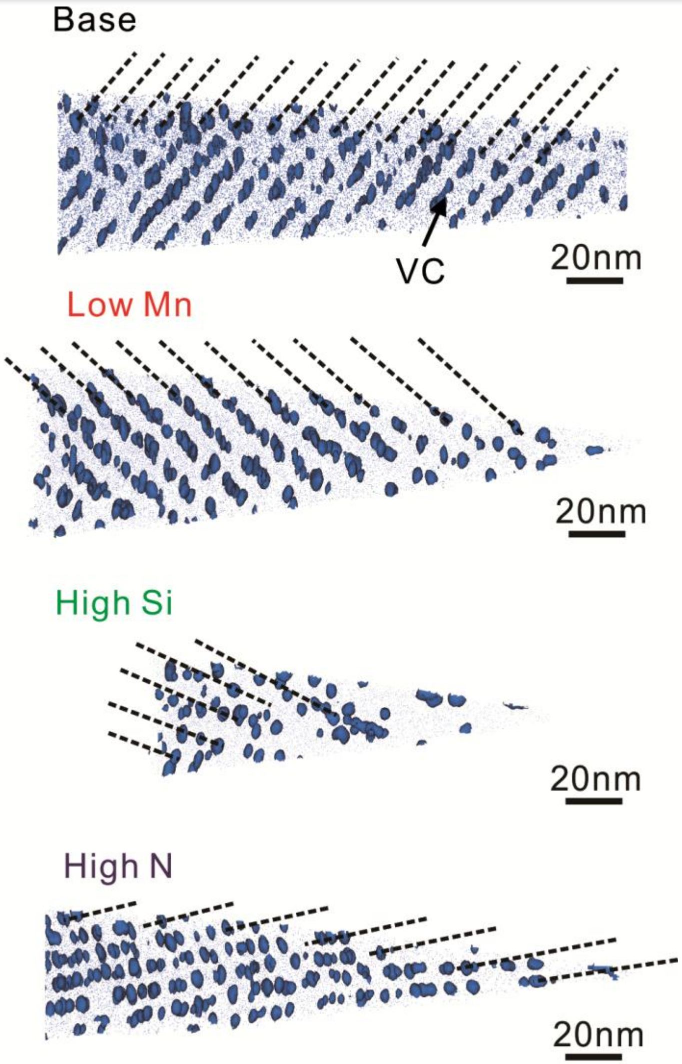

923K, 60s

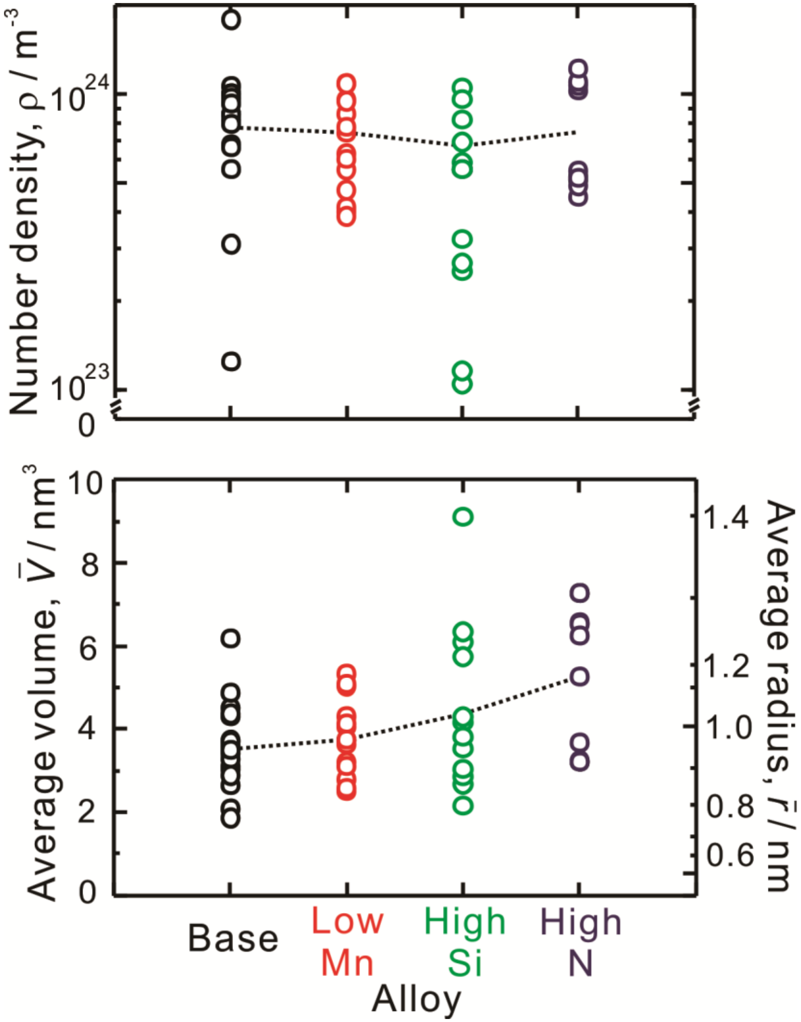

993K, 60s

GBF: grain boundary α, WF: Widmansttaten α, BF: bainitic α, M(γ): martensite

- GBF is formed along PAGBs with some WF in the Base alloy at 923K.
- WF or BF formation is promoted with lower Mn content, and suppressed with higher N content.
- α transformation is promoted by decreasing Mn content at 993K.

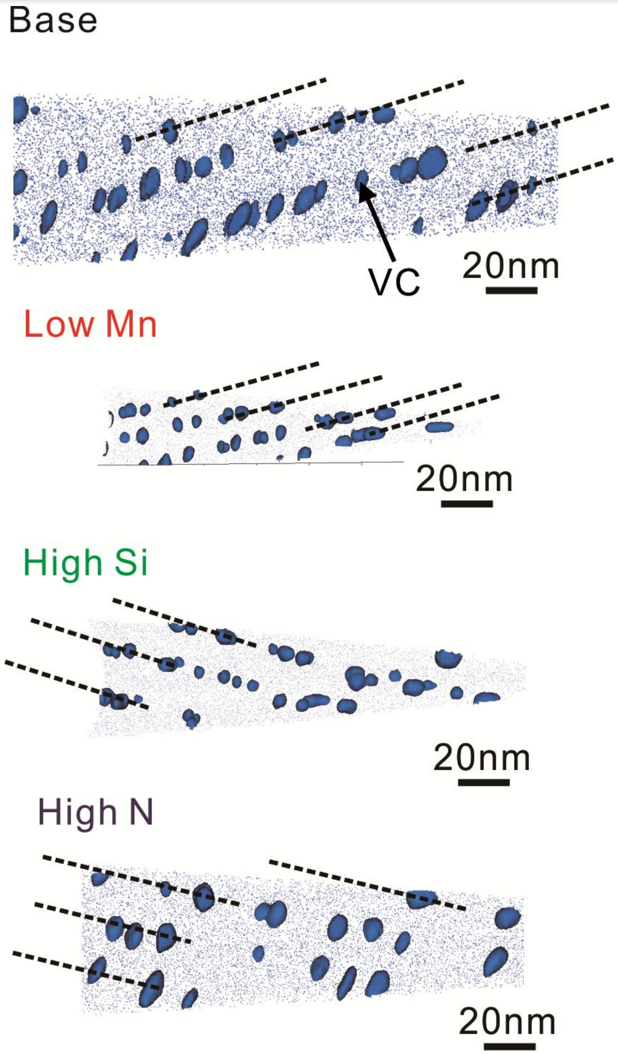
VC interphase precipitation at 923K

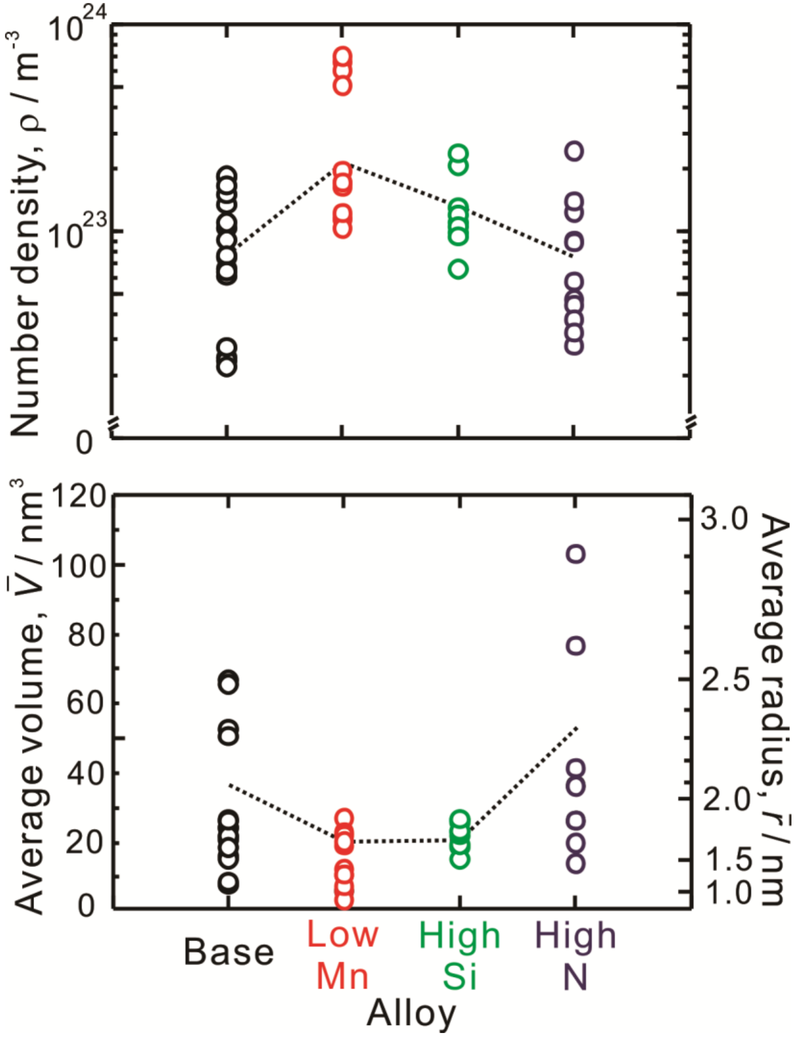




- No great change in VC number density is obtained by changing the alloying contents.

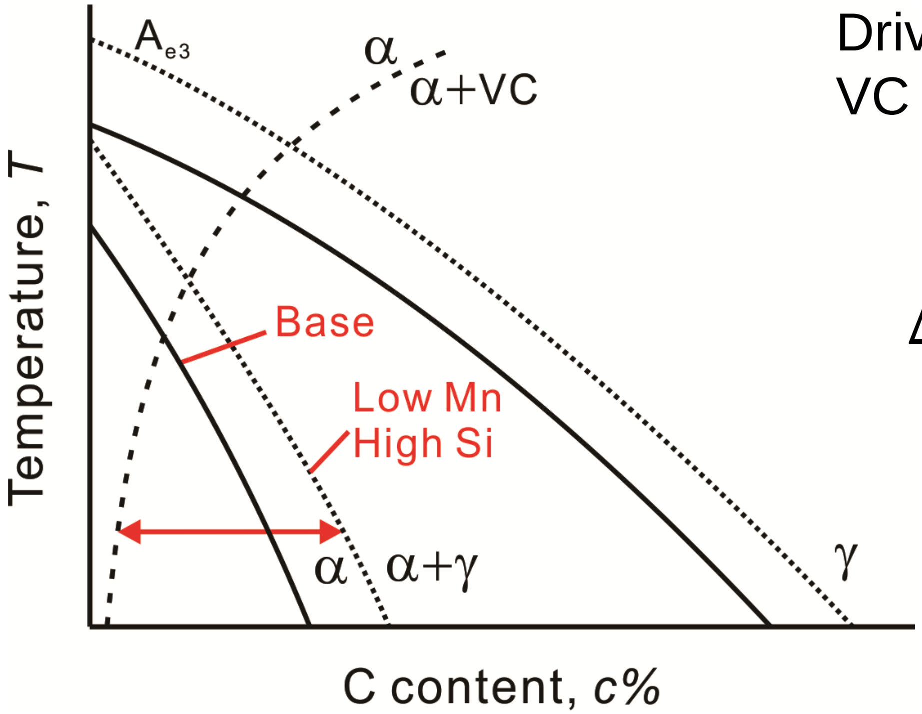
VC interphase precipitation at 993K





- By decreasing Mn or increasing Si content, the number density of VC increases, while the size of VC becomes refined.
- No great change is obtained by increasing the N content.

Alloying effects on VC driving force



Driving force of VC precipitation

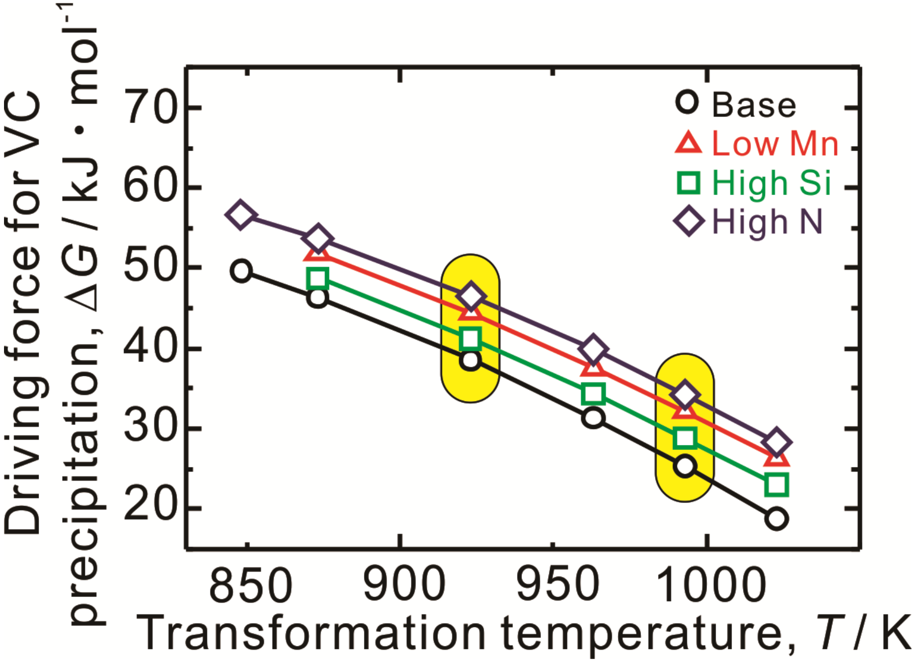
Interfacial Concentration (α/γ)

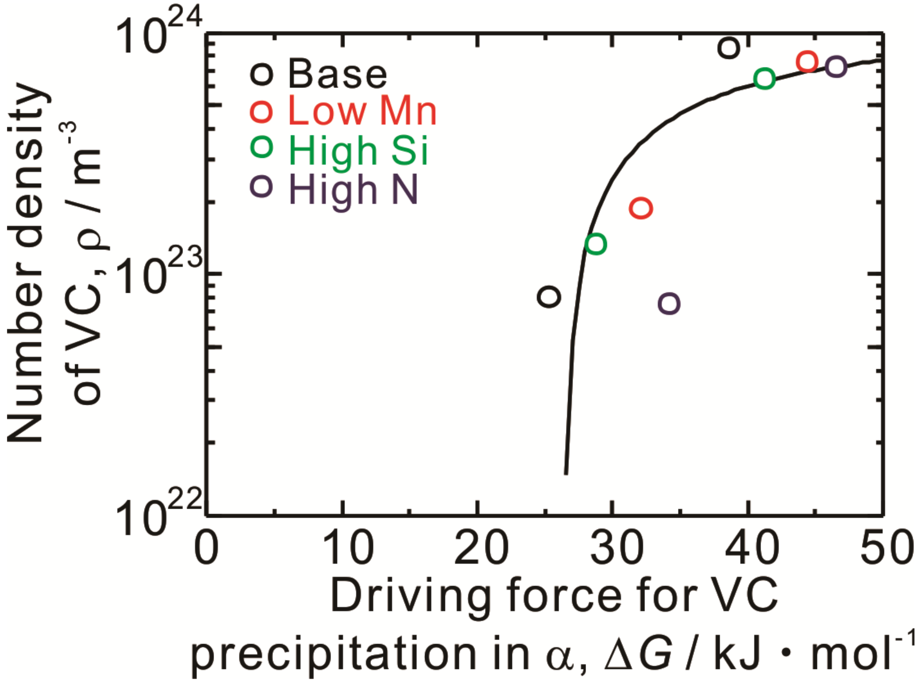
$$\Delta G^{VC} = RT \ln \frac{X_C^I \cdot X_V^I}{X_C^S \cdot X_V^S} \qquad (X_V^I = X_V^S)$$

Solubility (α/VC)

- Lower Mn or higher Si content tends to increase the interfacial C concentration, and thus increase the driving force for VC precipitation.
- V(C, N) tends to be more thermodynamically stable than VC in α.

Alloying effects on VC interphase precipitation





- The driving force for VC precipitation increases at lower temperature.
- At the same temperature, higher N, lower Mn or higher Si content increases the driving force for VC precipitation.
- The number density of VC appears to be strongly dependent on the driving force of its precipitation.

Conclusions

The effects of Mn, Si and N contents on VC interphase precipitation in low carbon steels were investigated in the present study.
The conclusions are summarized as follows:

1. VC interphase precipitation does not occur at near K-S α/γ interface, while large deviation from the exact K-S OR is necessary for it to take place in low carbon steels partly caused by the severe segregation of V at non K-S α/γ interface.

2. At 923K, almost no change in the number density of VC precipitates can be obtained by decreasing Mn or increasing Si, N contents; while at 993K, lower Mn or higher Si causes VC interphase precipitation to be finer.

3. The alloying effects on the number density of VC interphase precipitation can be well explained in terms of the driving force for its precipitation.