International Conference on Fast Reactors and Related Fuel Cycles (FR09)
7-11 December 2009, Kyoto, Japan

Microstructural effect of solute addition to Fe-15Cr-20Ni steels irradiated in Joyo

Ken-ichi Fukumoto[a], Hideki Matsui[b],
Ichiro Yamagata[c], and Naoaki Akasaka[c]

[a] *Research Institute for Nuclear Engineering, University of Fukui, Fukui, Japan*
[b] *Institute of Advanced Energy, Kyoto University, Kyoto, Japan*
[c] *O-arai Research and Development Center, Japan Atomic Energy Association (JAEA), Ibaraki, Japan*

Background

The second-generation advanced austenitic steel for near-term application for FBR

PNC1520 by JNC as Monju(FBR) core materials

Effects of solute atom addition

Cr, Ni	•••	well-known
C, Si, Ti, P, Nb, Mo, etc.	•••	not well-known

C, Si, P,Ti, Nb,Mo

Radiation -induced, enhanced, modified –Precipitation

affect the formation process of cavity → swelling behavior

Objectives

To classify the effect of minor solute addition for the microstructural evolution in Fe-15Cr-20Ni model alloys

Experimental procedure

<Specimens>

Fe-15Cr-20Ni austenitic stainless steel

1. Fe-15Cr-20Ni
2. -0.06C
3. -0.025P
4. -0.004B
5. -0.25Ti-0.06C
6. -0.1Nb-0.06C
7. -0.5Si
8. -2.5Mo
9. -0.24Ti-0.1Nb-0.06C
10. PNC1520

(Fe-15Cr-20Ni-1.5Mn-2.5Mo -0.03P-0.8Si-0.25Ti-0.1Nb-0.06C)

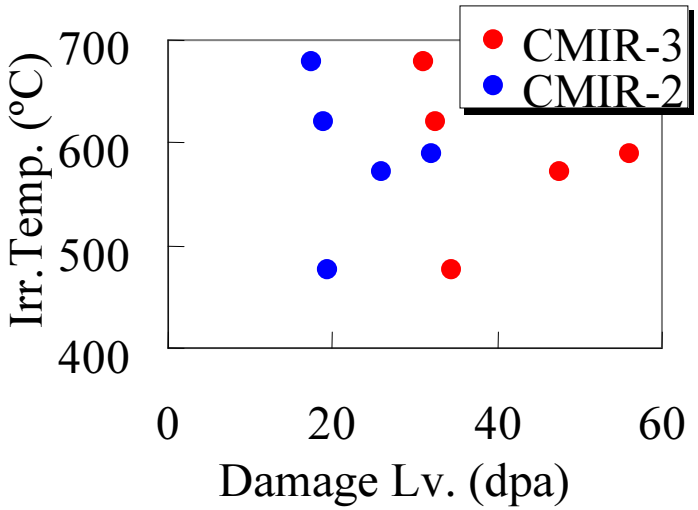
Heat treatment : SA

<Irradiation condition>

Reactor : JOYO

Irr. Temp. : 476ºC - 679ºC

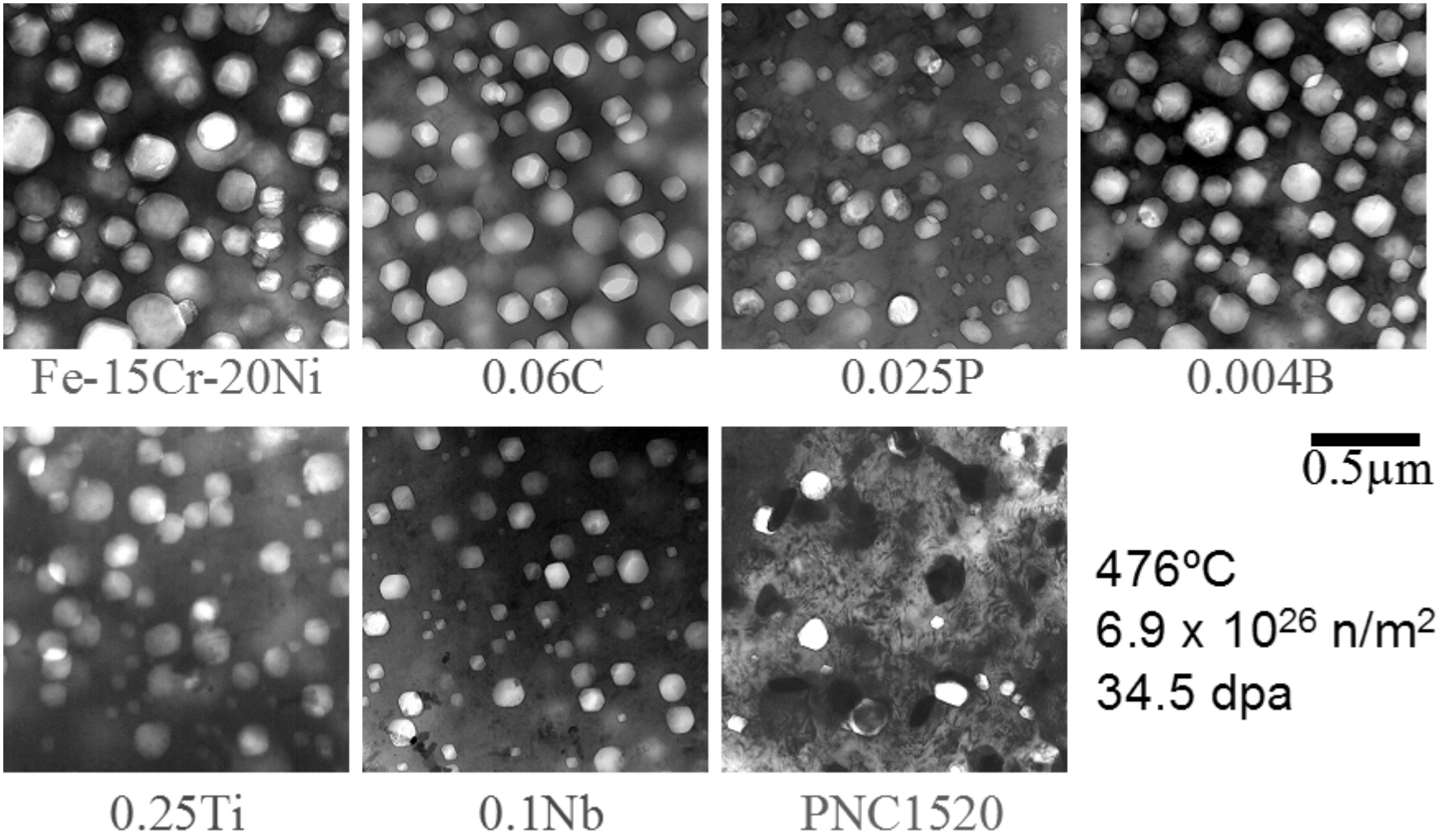
Damage Lv. : 20 – 56 dpa



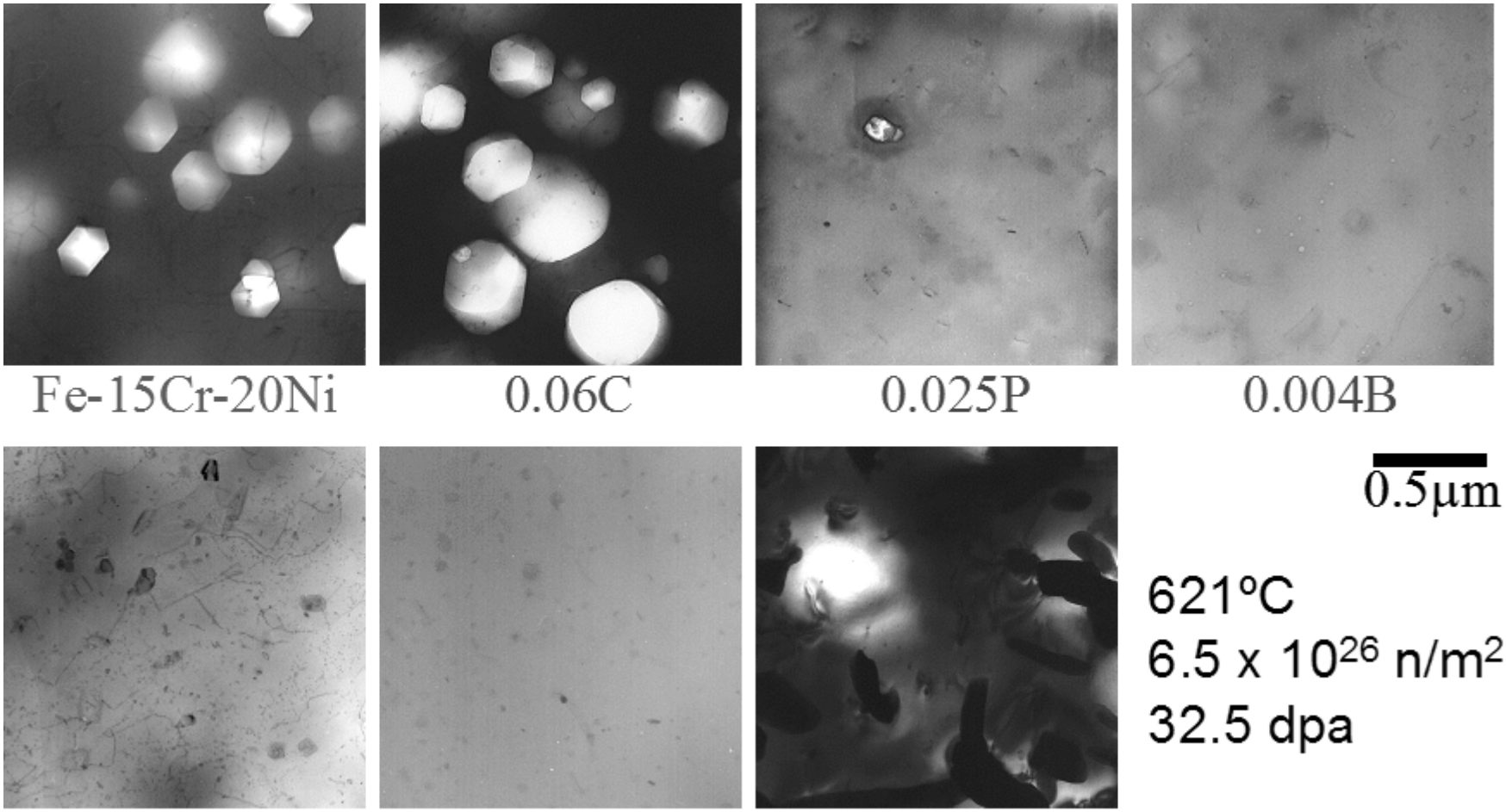
<PIE>

TEM observation (EDS-2Dmapping + Electron diffraction analysis)

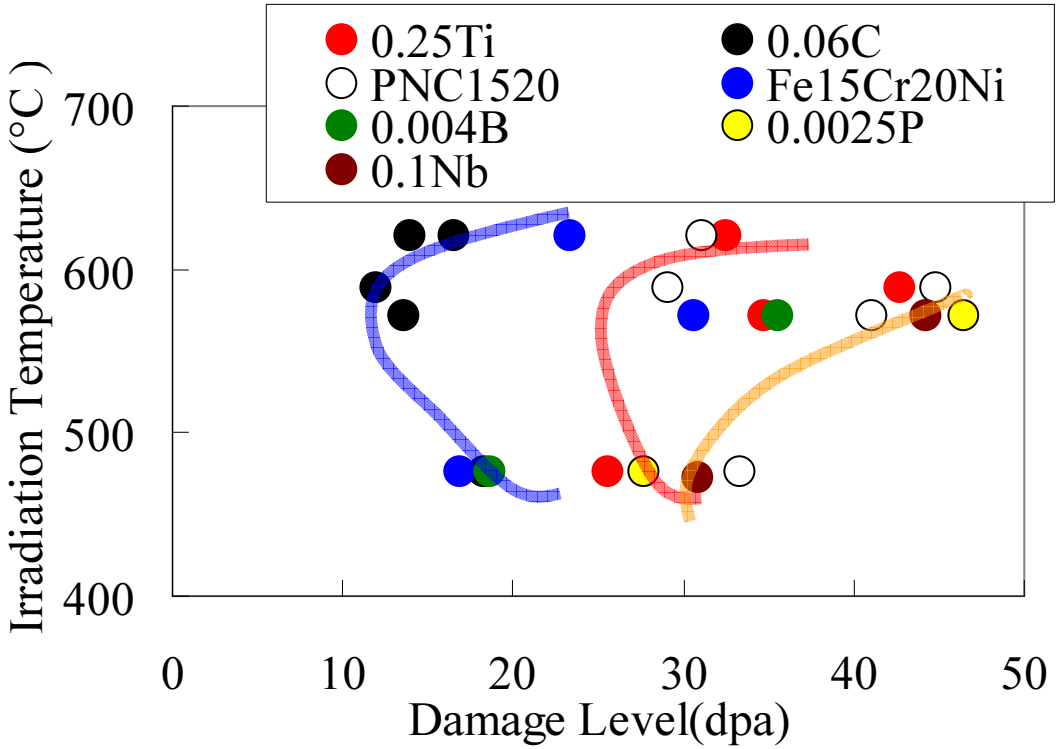
476° C 35dpa - Cavity image



621° C 33dpa - Cavity image



Incubation dose – damage level

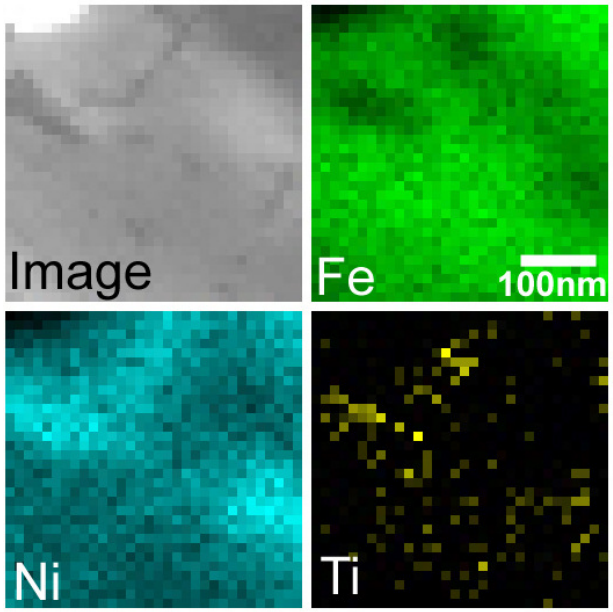


Incubation damage level
Estimation extrapolating with a 1%/dpa of swelling rate from swelling data

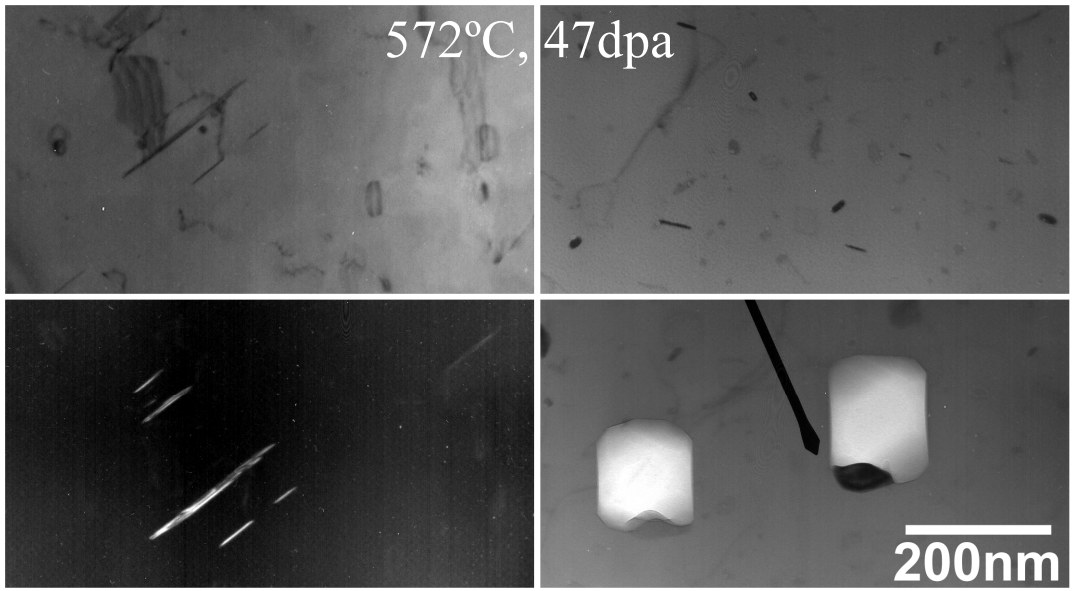
Three types of swelling behavior

- Fe-15Cr-20Ni, 0.06C : incubation damage level ≈ <20dpa
- PNC1520, 0.25Ti : incubation damage level ≈ 30dpa
- 0.04B, 0.0025P, 0.1Nb : strong suppression of swelling at higher T

Typical feature of precipitates in Fe-Cr-Ti modified alloys (Ti & Nb)



0.25Ti-0.06C



0.25Ti-0.06C 0.1Nb-0.06C

Only 0.25Ti addition alloys show the frank loop formation for the model alloys.

Ti atoms aggregate on the extra half plane of the Frank-loop.

✧Ti addition makes the stacking fault energy lower during irradiation.

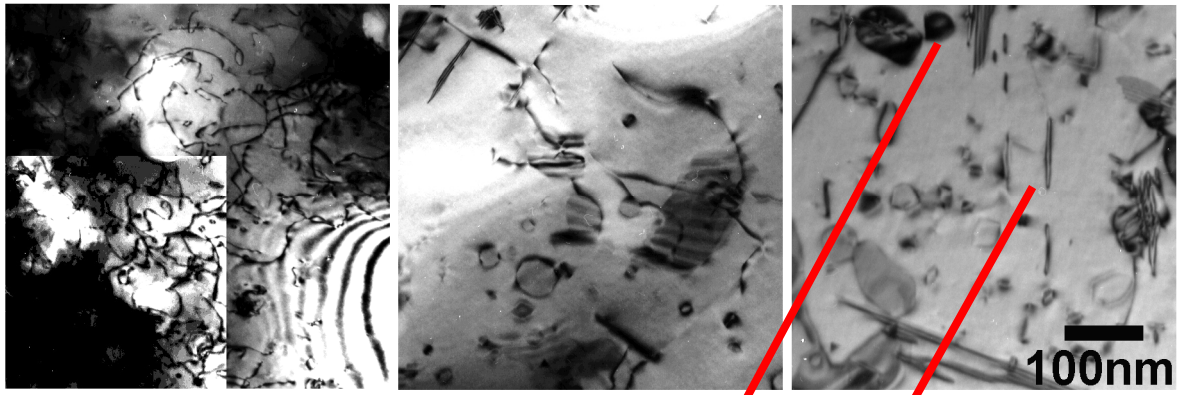
Comparison between Nb addition and Ti addition

Ti → inside of Frank-loops, Nb→ incoherent MC precipitates from low T

A Nb addition easily makes MC precipitates

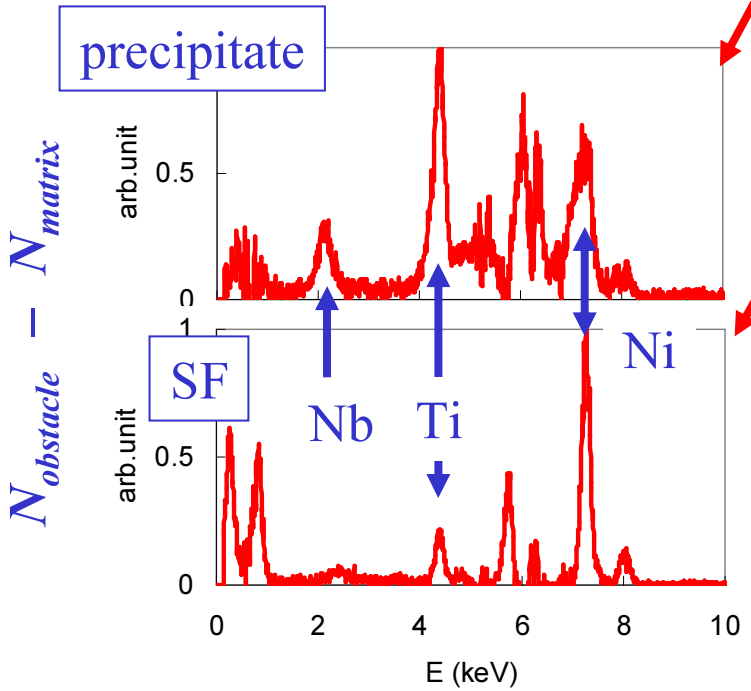
✧The contribution for swelling suppression : Nb addition > Ti addition

Synergistic effect of Ti and Nb addition



480ºC, 35dpa 570ºC, 48dpa 620ºC, 33dpa

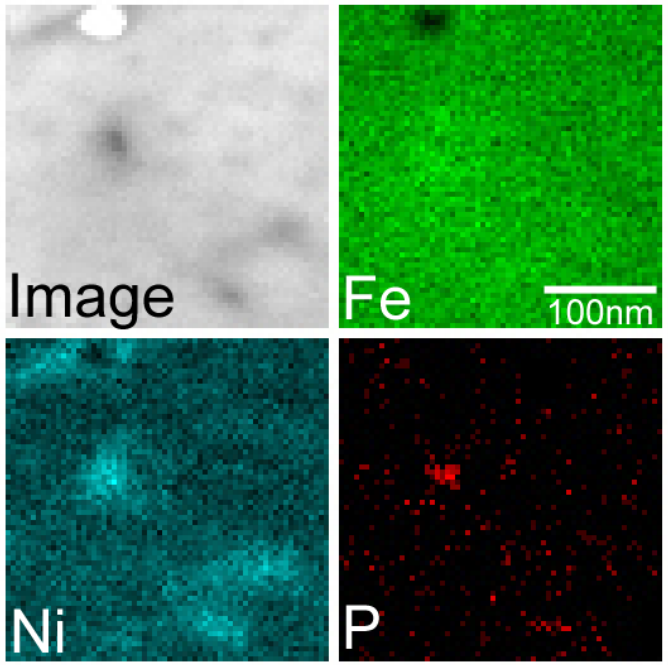
$M_{23}C_6$ on GB.
In 480-620ºC,
(Nb,Ti)C presipitate and
Ti segregation on
stacking fault



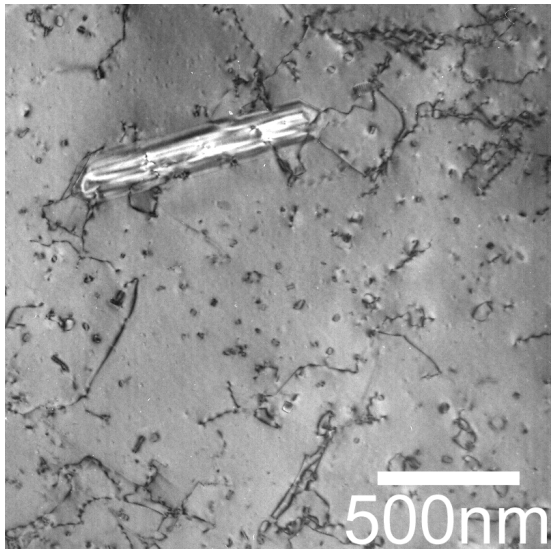
- No segregation of Nb on stacking fault.
- segregation element on stacking fault is only Ti.
- Stable formation of stacking fault at high temperature (620ºC).

No synergistic effect of Ti and Nb addition
The contribution for swelling suppression :
Nb addition > Ti addition

Typical feature of precipitates in Fe-Cr-Ti modified alloys (P & B)



0.025P



0.004B

P addition :

Low density of MP at high temperature (Ni concentrate around MP precipitates)

Phosphor in solution is important for the suppression of the swelling

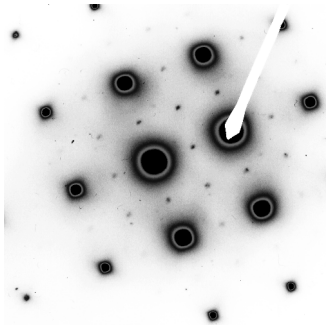
B addition :

No precipitates in the matrix, and some traces of boron precipitates were observed.

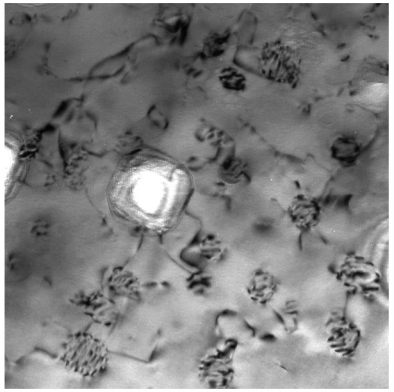
Most of boron precipitates are burn up during irradiation → He release

No bubble were observed → it is unclear problem to explain the suppression of swelling

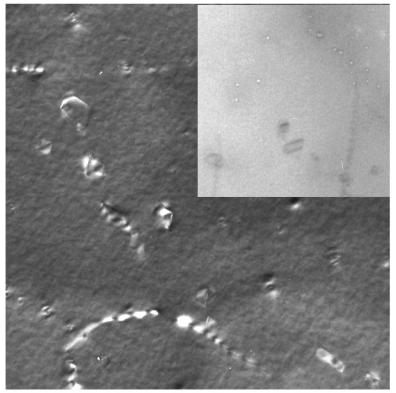
Typical feature of precipitates in Fe-Cr-Ti modified alloys (Si)



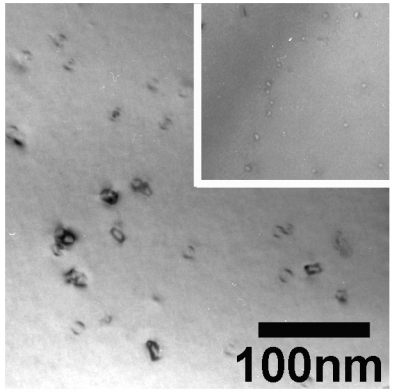
Ni_3Si - γ'phase



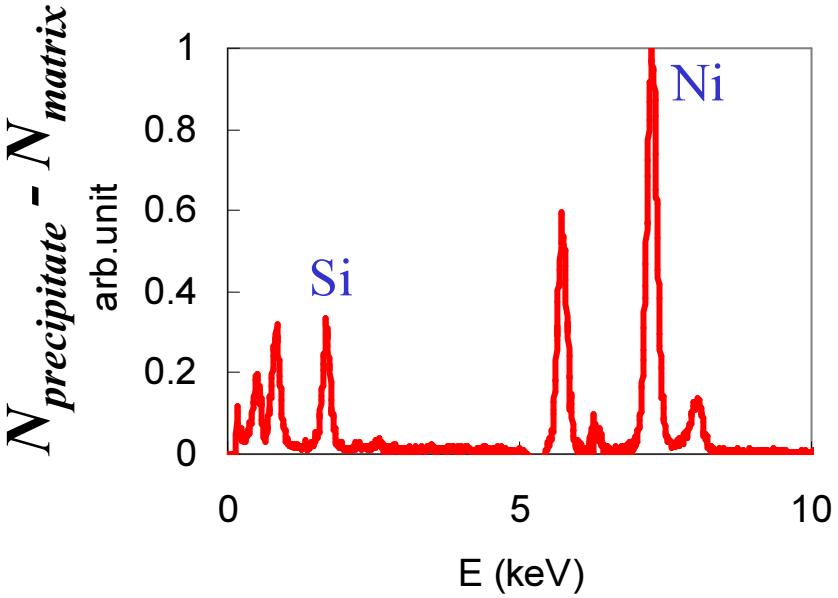
480ºC, 35dpa



570ºC, 48dpa



620ºC, 33dpa



EDS spectrum from dislocation at 570ºC

Si addition :

Ni_3Si - γ'phase formation below 500ºC with cavity formation

Above 500ºC, no typical precipitation.
Si segregation at the dislocation core.

Summary of solute addition effect for swelling behavior

C : Only C addition does not affect the precipitation and swelling behavior.
Synergistic effect with metallic minor elements (Ti, Nb…)

Mo : No effect of Mo addition on swelling behavior

Ti : Ti addition makes lower the stacking fault energy during irradiation.

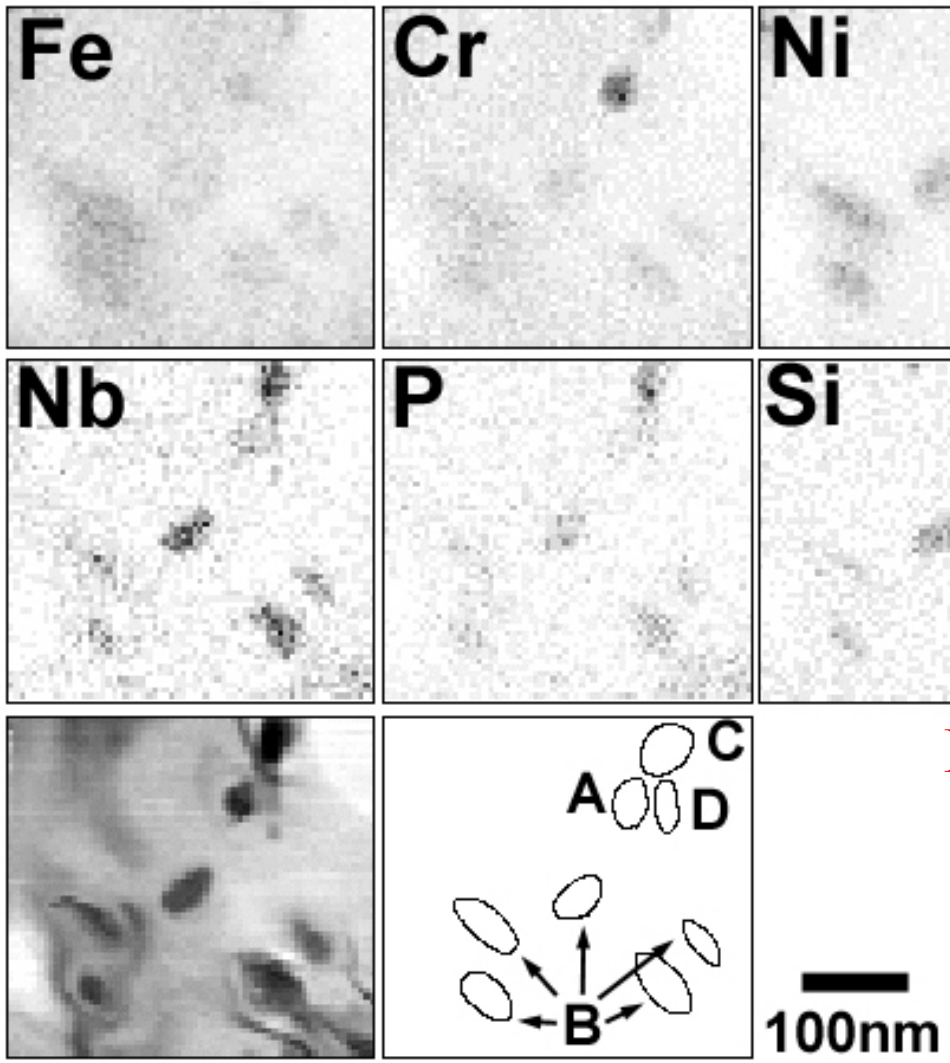
Nb: The incoherent MC precipitates are formed from 480ºC.
MC precipitates suppress the swelling at higher temperature (>550ºC)

P: MP precipitates and phosphors in solution suppress the swelling strongly.

B: All boron precipitates are burn away during irradiation.
The mechanism of swelling suppression at higher temperature due to B addition is unclear.

Si: Unstable γ' phase above 500ºC, but effect of swelling suppression is little.

Characteristics of precipitates in PNC1520 steels by using EDS-2Dmapping



PNC1520 589ºC 32dpa

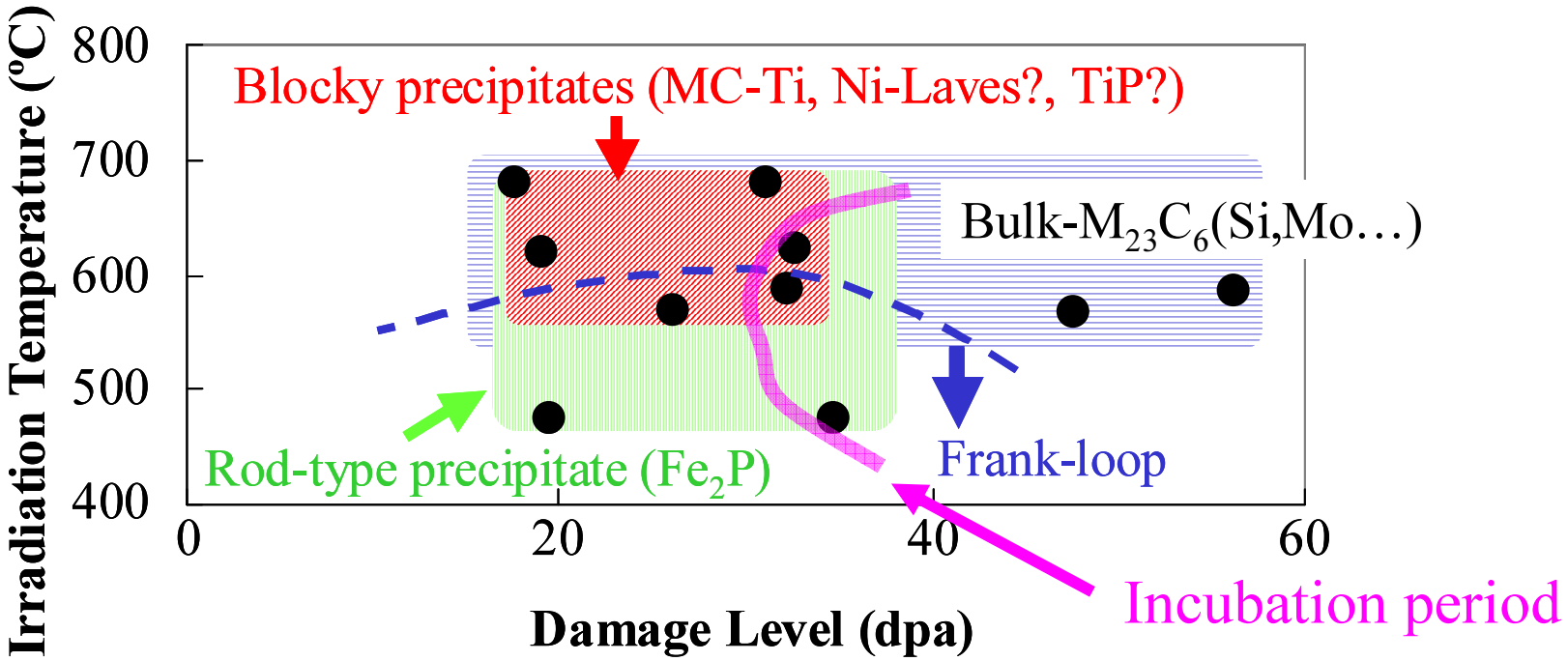
A: $M_{23}C_6$

B: MC

C: Laves

D: ? Si-rich Precipitate

Temperature – dose dependence of character of precipitates



Typical features

Fe_2P : strong effect for the suppression of swelling

Ti aggregate on Frank- loops in the temperature regime below 550ºC

Dissipation of the MP and other precipitates at high dose levels

→ coarsening of the large $M_{23}C_6$ RMP

Summary

Swelling behavior of PNC1520

- Incubation damage levels is about 30 dpa for a PNC1520-SA steel
- Phosphor precipitates are effective for swelling suppression in PNC1520.

The effect of minor solute element for the swelling behavior

- Nb addition is stronger for the swelling suppression than Ti addition
- Ti addition makes stacking fault energy lower in a Fe-15Cr-20Ni alloy.
- P, Nb and B additions are effective for swelling suppression.
- Both Phosphor precipitates and P in solution is effective for swelling suppression.