6th IEA & JUPITER Joint Workshop on Vanadium Alloys for Fusion Applications
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Creep and Swelling

- Swelling -

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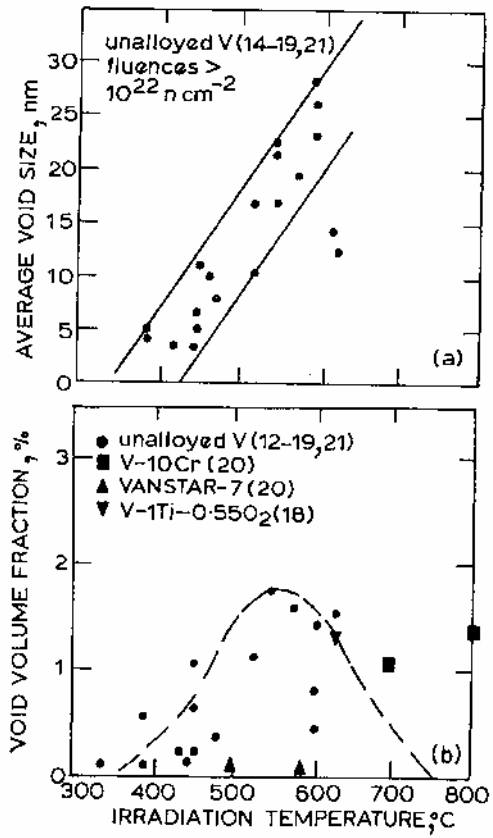
Initial study of swelling in vanadium alloys

~1980 R.E.Gold :Int.Mater.Rev, (1980) 232

Unalloyed vanadium, V-Ti binary alloys, V-Cr-Ti alloys and VANSTAR



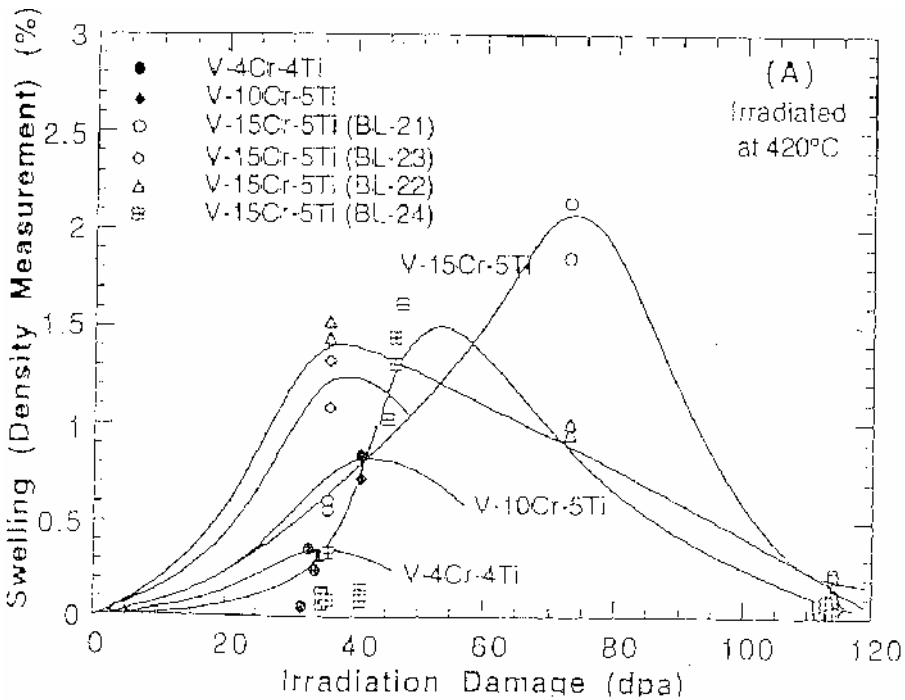
a average void size and *b* void volume fraction as function of irradiation temperature for unalloyed vanadium and selected vanadium alloys

The interests of the study

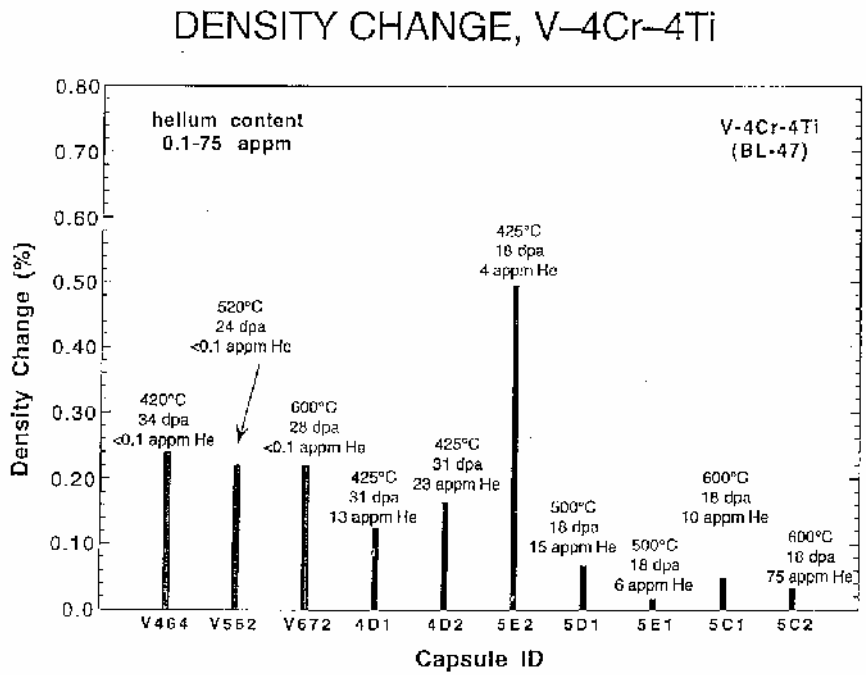
- Effects of oxygen on void swelling
- Precipitation in neutron irradiated V-alloys
  - Carbide in unalloyed vanadium
  - Ti-oxide in V-Ti binary alloys
- The swelling suppression in V-Ti binary alloys

The resistance to swelling of the V-Ti binary alloys containing greater than 3wt% Ti.

Study of void swelling in V-Cr-Ti alloys (~1990 ANL)



H.Chung, D.L.Smith, B.A.Loomis

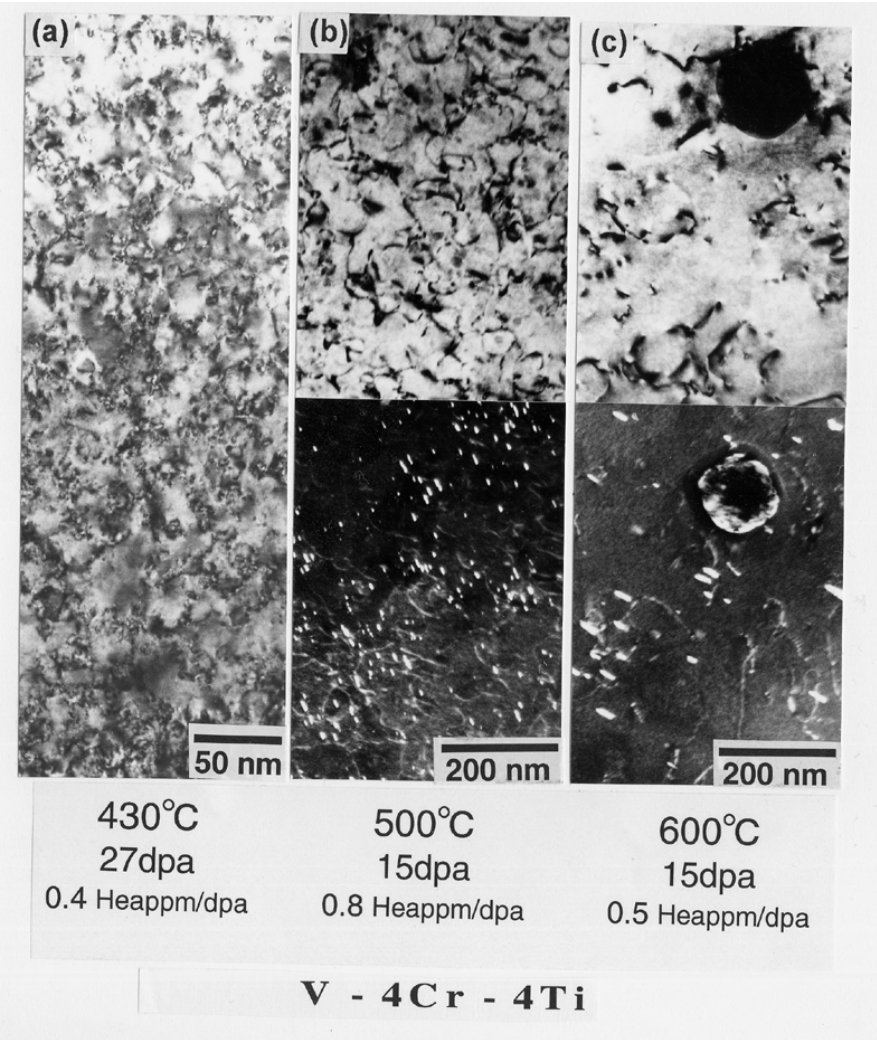


- Density change during irradiation with or without helium generation is not significant.

H.Chung, D.L.Smith

V-(3-5)Cr-(3-5)Ti alloys show good performance of the geometric stability under heavy neutron irradiation.

Microstructure of V-4Cr-4Ti irradiated in DHCE irradiation



Swelling is less than 1% up to 30 dpa. The estimated He generation rate produced by DHCE is similar to the He generation rate in fusion reactor environment, 5Heappm/dpa.

Small radiation-induced precipitates are formed during neutron irradiation.

Usual type of RIP is
TiO (C and N atome are occupied in O-sublattice)
Fm3m. a_0=4.25A
V(001)//TiO(011),V<011>//TiO<022>

The void swelling of V-Cr-Ti-SiAlY

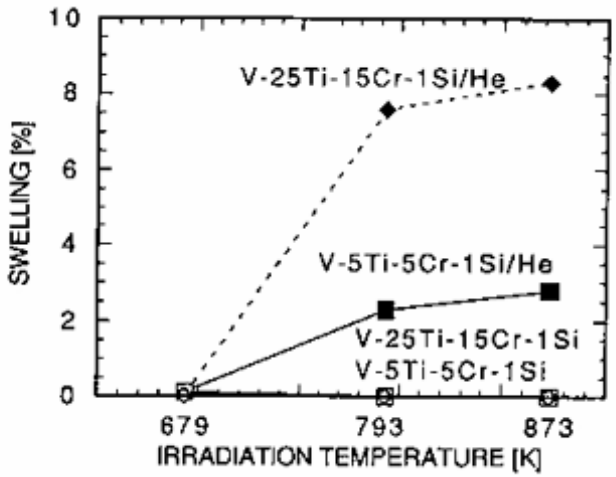


Fig. 4. Swelling of V–Ti–Cr–Si alloys with/without helium-charge after irradiation at 679, 793 and 873 K to ≈ 40 dpa. ◆: V–25Ti–15Cr–1Si with 2079 appm He; ◇: V–25Ti–15Cr–1Si without He; ■: V–5Ti–5Cr–1Si with 539 appm He; and □: V–5Ti–5Cr–1Si without He.

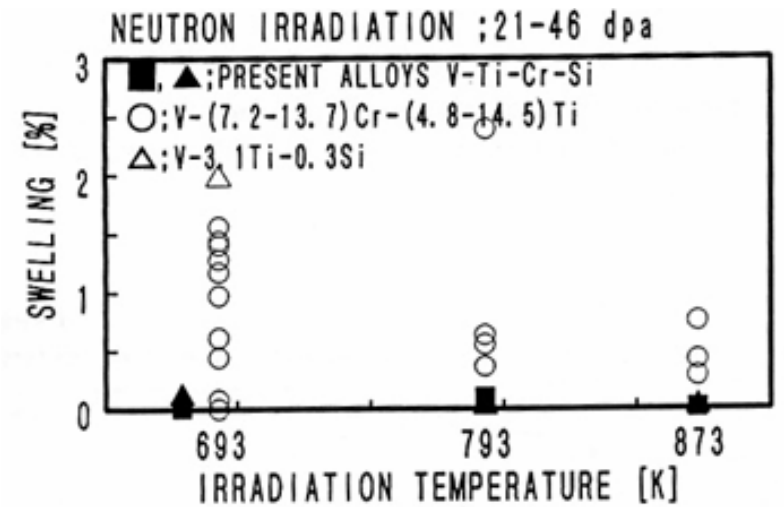


Fig. 7. Swelling versus irradiation temperatures for various vanadium alloys irradiated in the FFTF/MOTA. Previous data were quoted from refs. [6,7].

Satoh et al., J.Nucl.Mater. (1992, 1992)

The addition of minor solute element (SI, Al, Y etc…) is quite effective to suppress the swelling.

The addition of 1%Si in V-Cr-Ti alloys produces Ti_5Si_3 precipitates as well as TiO(OCN) during irradiation.

Void swelling in V-alloys at high temperature

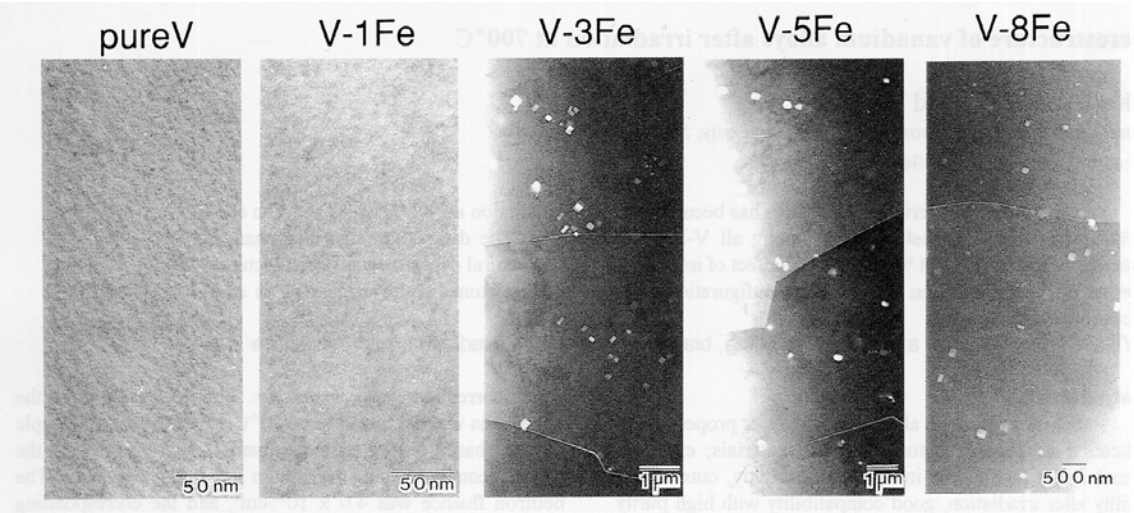
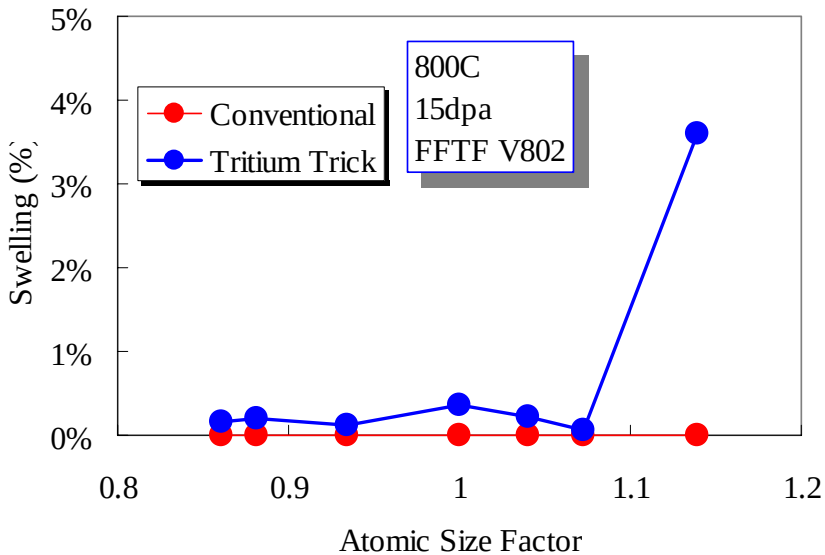


Figure 1. Cavity image of V-Fe alloys irradiated at 700°C



Above 700ºC, vacancy clusters in V-alloys are collapsed and dissipated in the matrix.

However, He-V complexes still remain the strong binding and nucleate the cavity, especially in V-5Nb, an oversized alloy.

Void swelling in V-alloys at low temperature

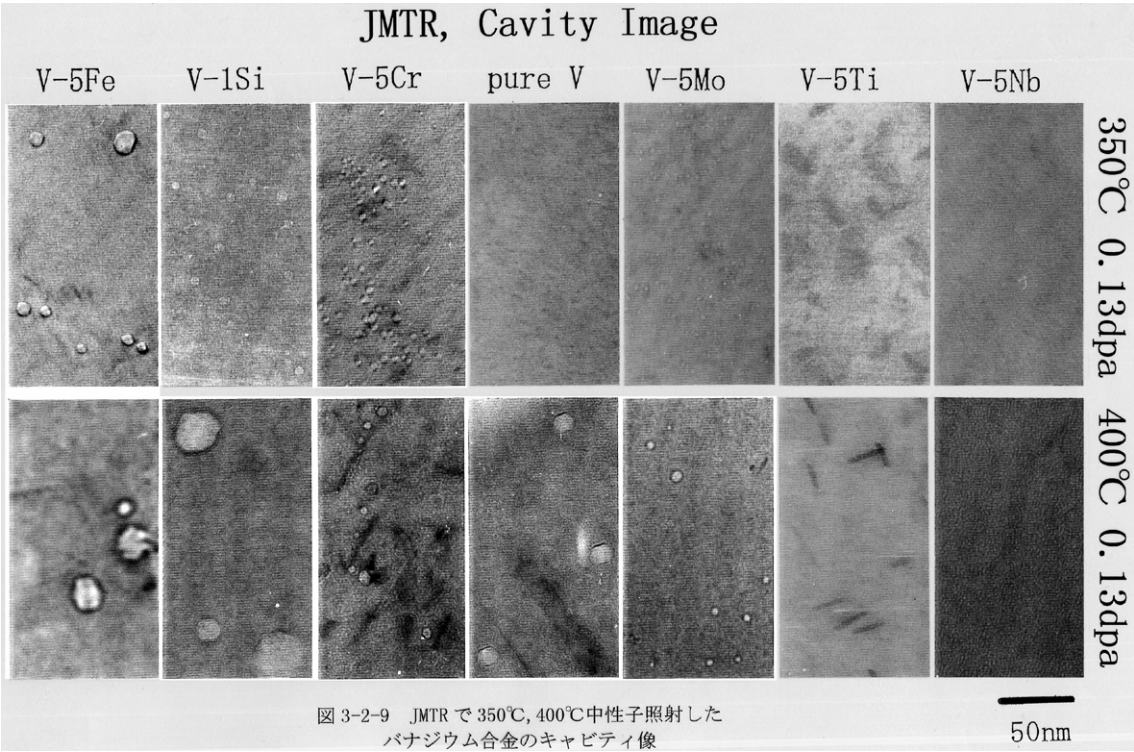
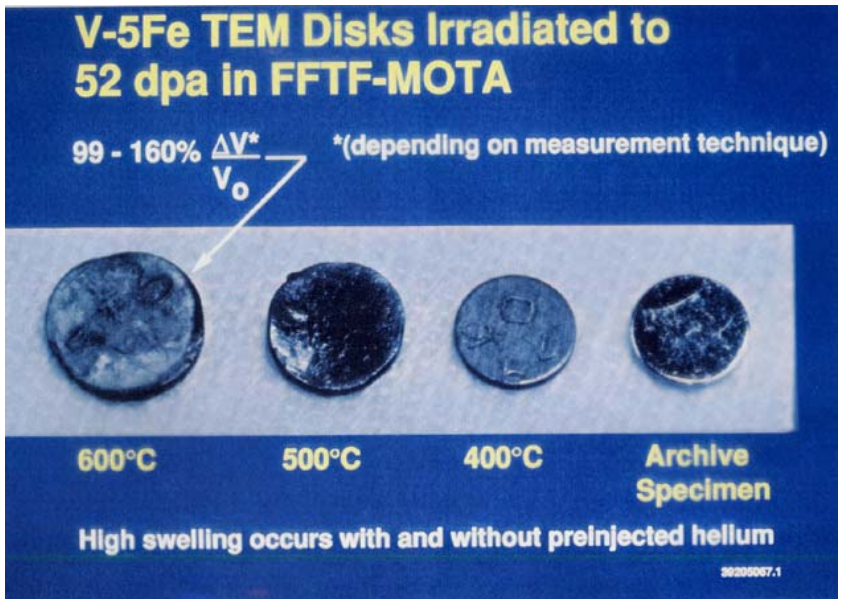


図 3-2-9 JMTR で 350℃, 400℃中性子照射した
バナジウム合金のキャビティ像

Y.Candra etal., J.Nucl.Mater., (1998)

A lower limit of irradiation temperature to produce visible cavities is 300ºC. No cavity can be seen in V-4Cr-4Ti alloys irradiated in ATR and HFIR with damage levels of 5dpa at 300ºC.

Discover of a Giant Swelling



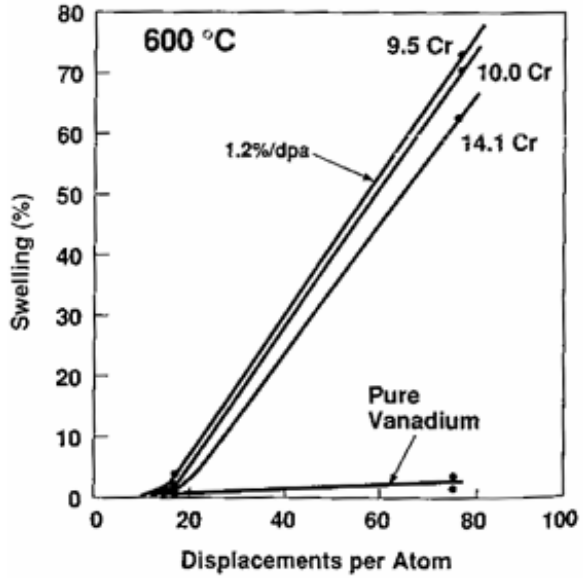
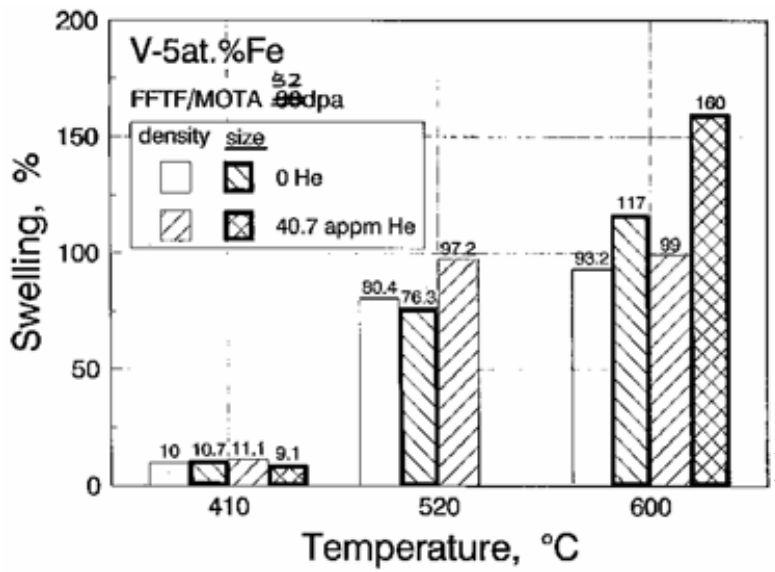


Fig. 1. Swelling observed in V–Cr alloys after irradiation to 17 and 77 dpa in FFTF cycles 7–9 at a target temperature of 600°C [5]. The actual temperature in the first half of the irradiation was rather complex, however.

Garner et al. J.Nucl.Mater.(1992)



Huge swelling beyond 100% was observed in V-Fe system alloys. 160%/50dpa is believed to be the world record for the swelling and swelling rate.

Matsui et al., ASTMSTP (1992)

Effect of under- or over- sized solute addition on the void swelling in V-binary alloys

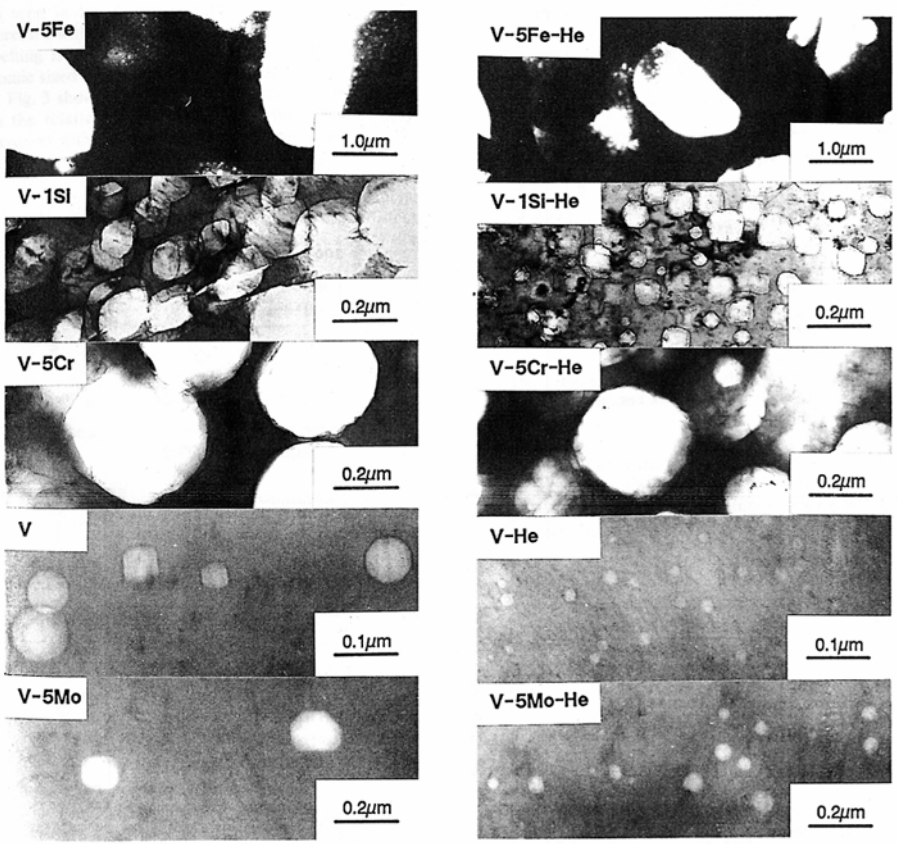
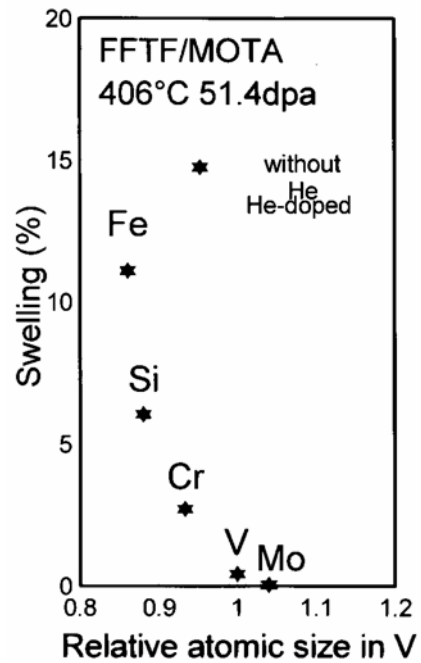


Fig. 1. (left) Cavity microstructure of vanadium, V–5at.%Fe, V–5at.%Cr, V–1at.%Si and V–5at.%Mo alloys without helium after irradiation in FFTF at 600°C. (right) Cavity microstructure of vanadium, V–5at.%Fe, V–5at.%Cr, V–1at.%Si and V–5at.%Mo alloys with helium doping after irradiation in FFTF at 600°C.



The addition of undersized solute atoms in vanadium enhances the swelling.

- Good relationship between atomic size factor of solute atom in solution and swelling behavior

Effect of solute addition on swelling behavior

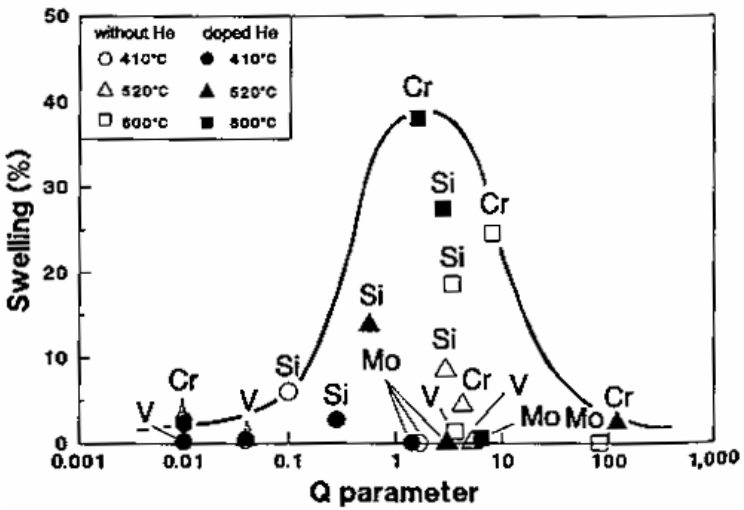
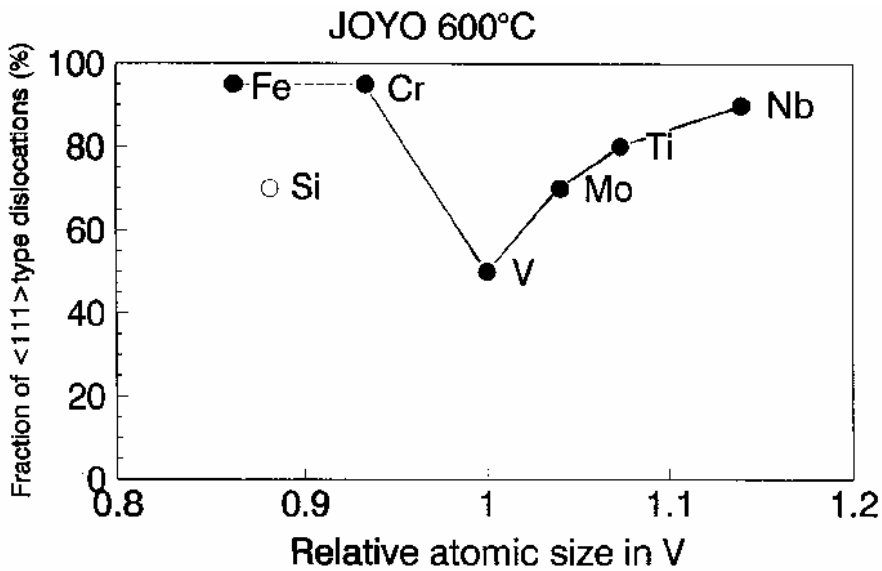


Fig. 4. Relation between swelling and Q values.

Nakajima, J.Nucl.Mater. 1992

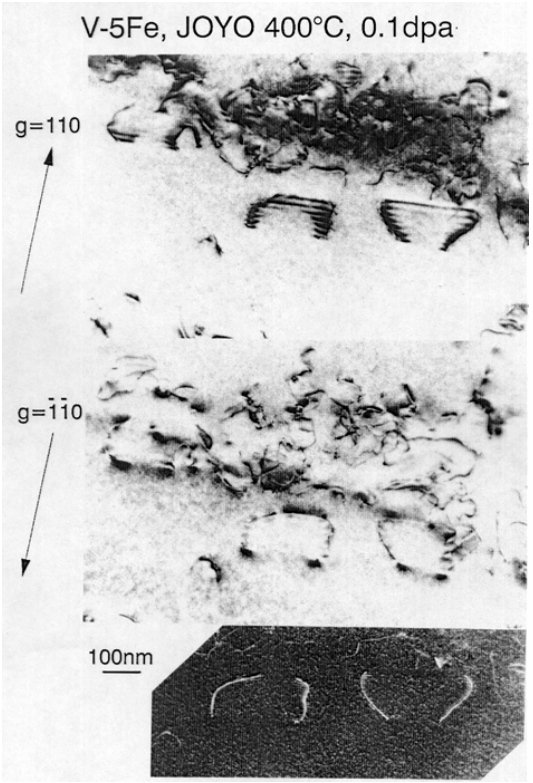


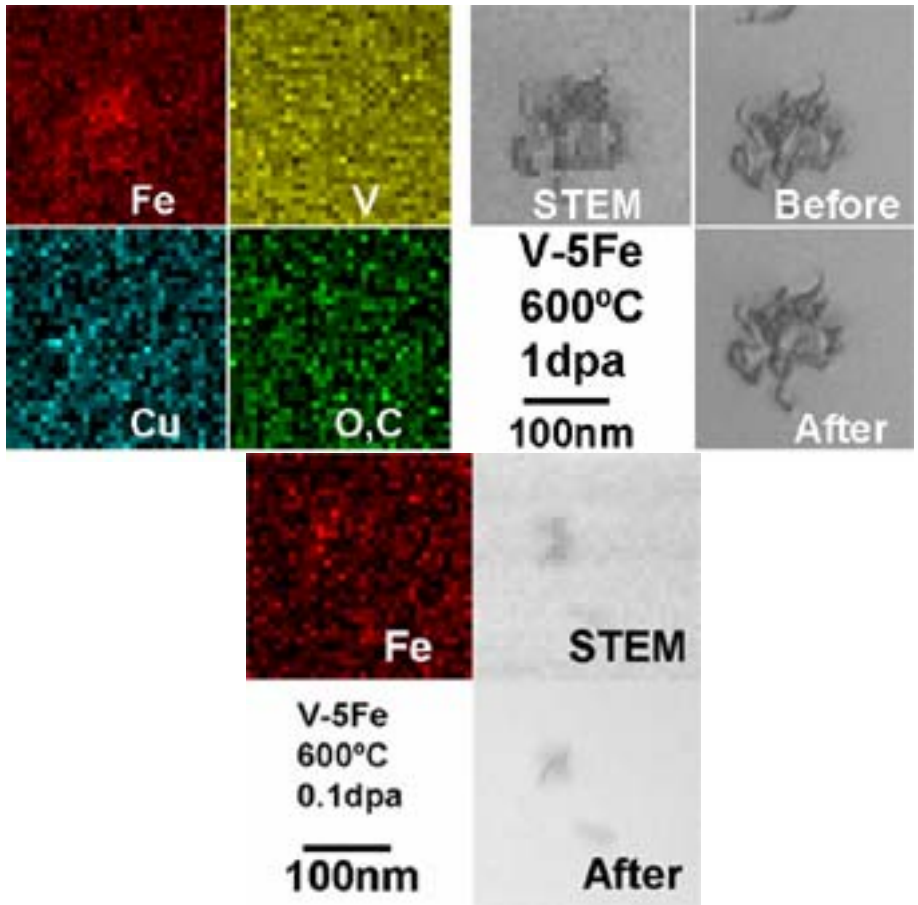
The Q-parameter can explain the relation between the swelling and atomic size factor for undersized vanadium alloys.

The character of dislocation loops depends on the atomic size factor.

a/2<111> dislocation has an important role to produce dislocation bias. The synergistic effects of both dislocation bias and atomic size factor, should be considered.

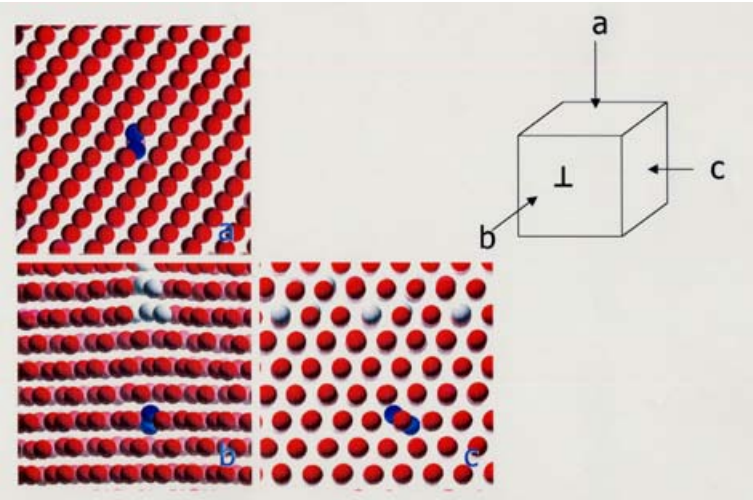
Dislocation bias to produce excess vacancy

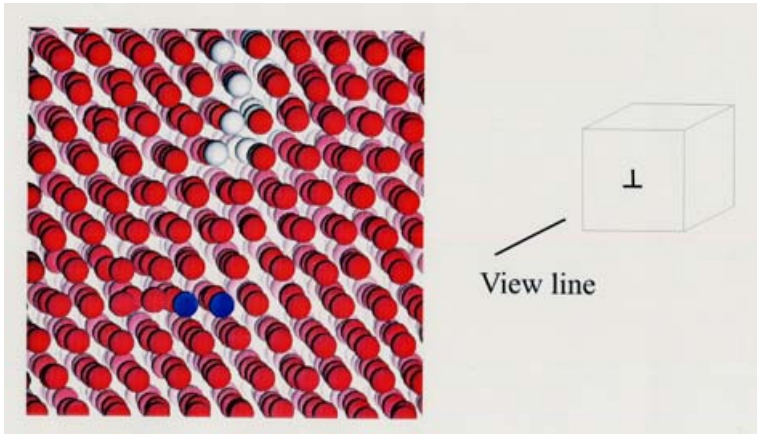




The irradiation-induced enrichment (segregation) of undersized solute atoms (Fe in V-Fe alloys) on the inside of dislocation loops can be seen. The cavity nucleation can be seen so often on the inside of the loop.

MD simulation : Crowdion formed below dislocation

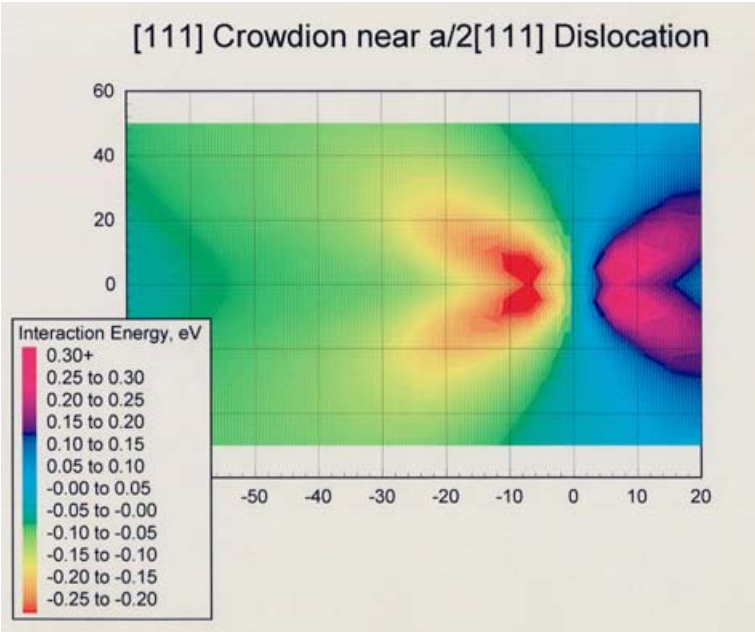


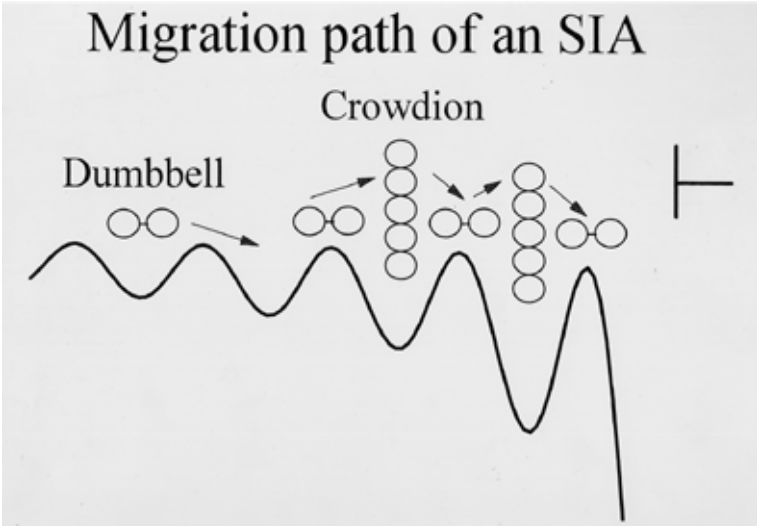


A [110] SIA dumbbell converts into a [111] crowdion around a a/2[111] dislocation in pure Fe and pure vanadium in MD simulation.

- A crowdion can not move in one-dimensional direction to [111]
- The movement for SIA to get close to dislocation is suppressed.

Model of “Conversion of SIA into crowdion”

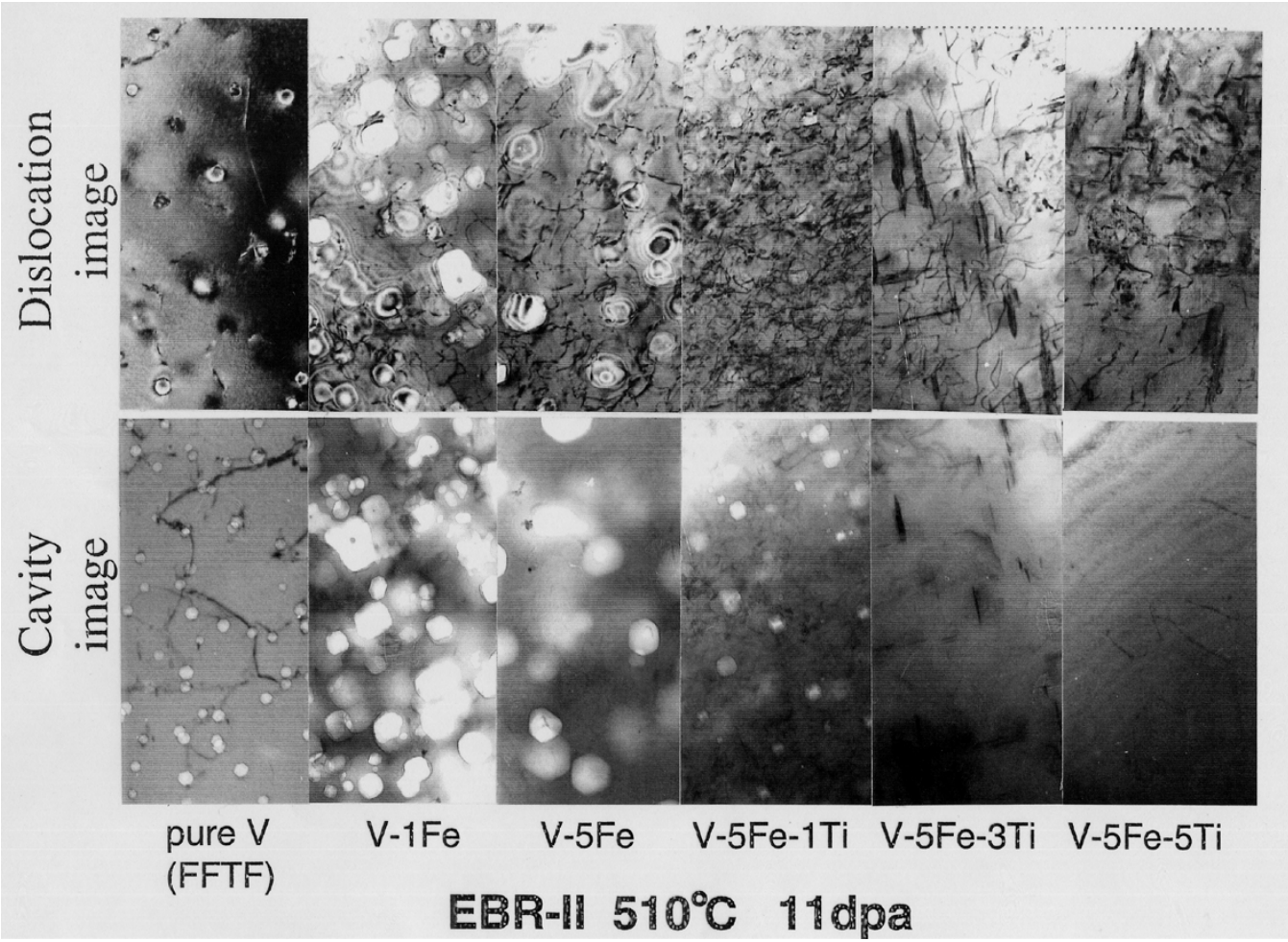




No conversion into [111] crowdion occurs in MD simulation when an iron atom for SIA in a vanadium lattice.

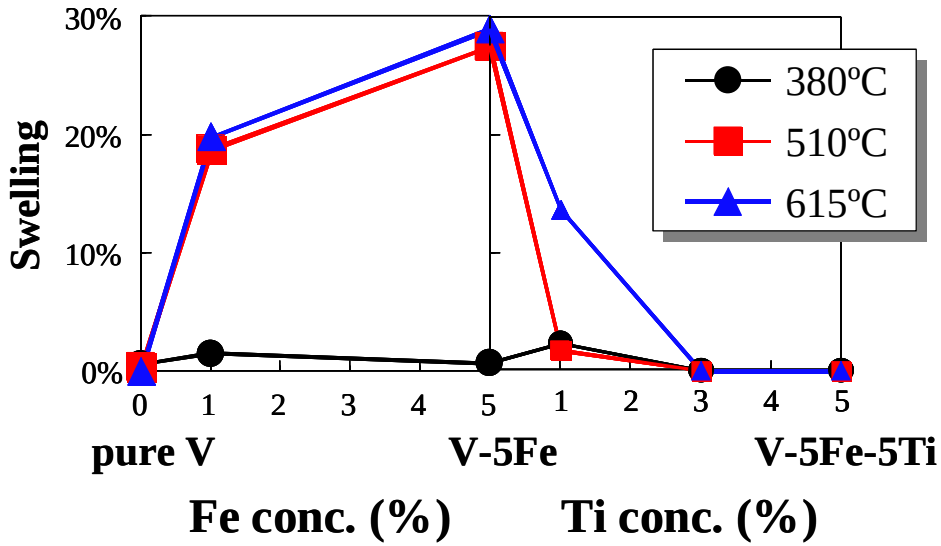
- The movement of SIA into dislocation is not restricted.
- It is possible to explain the appearance of swelling in undersized BCC alloys.

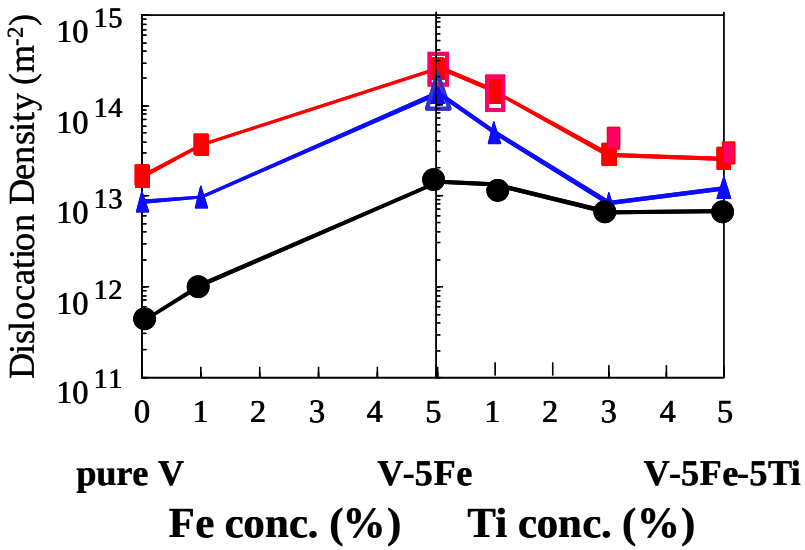
Effect of Ti addition on void swelling in V-Fe alloys



The Ti addition is one of answer to what factor is effective for the swelling suppression.

Effect of Ti addition on void swelling in V-Fe alloys (cont.)

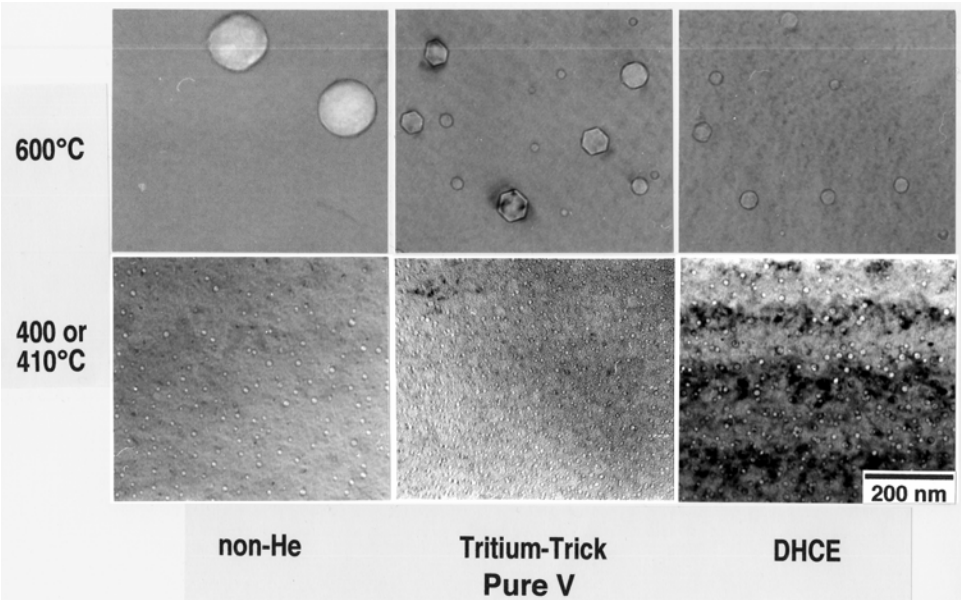


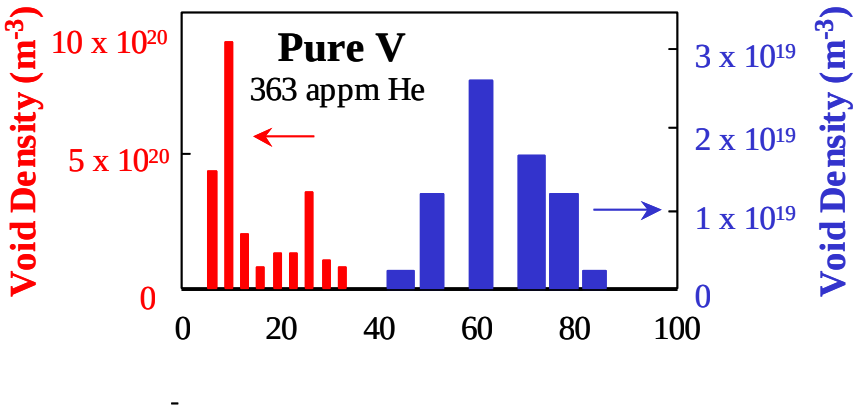


Ti shows strong effect for suppress the swelling even in heavily-irradiated V-Fe alloys.

Not only the precipitates of TiO(OCN) but also Ti atoms in solution works for suppression of swelling in V-alloys.

He effect on void swelling in pureV

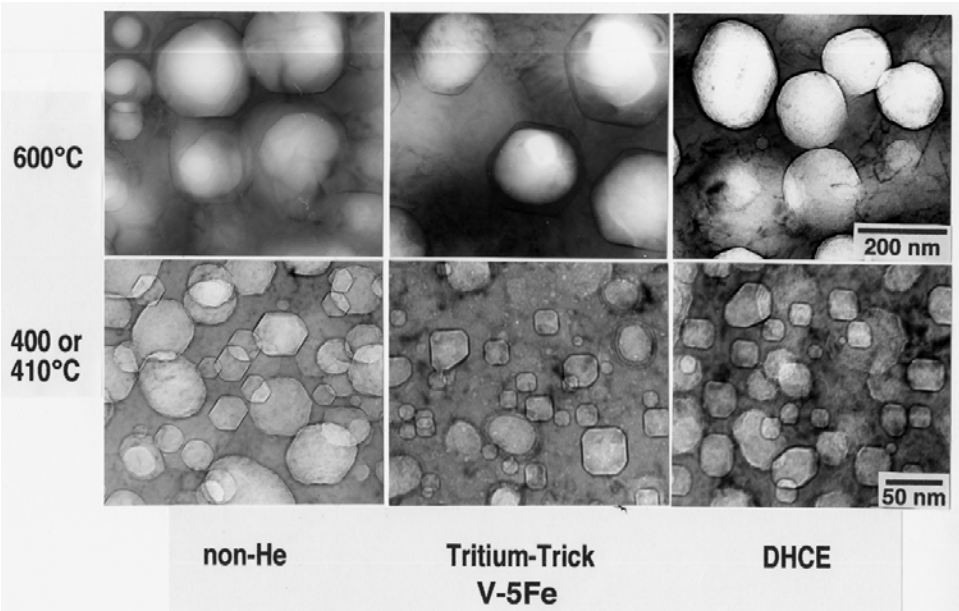


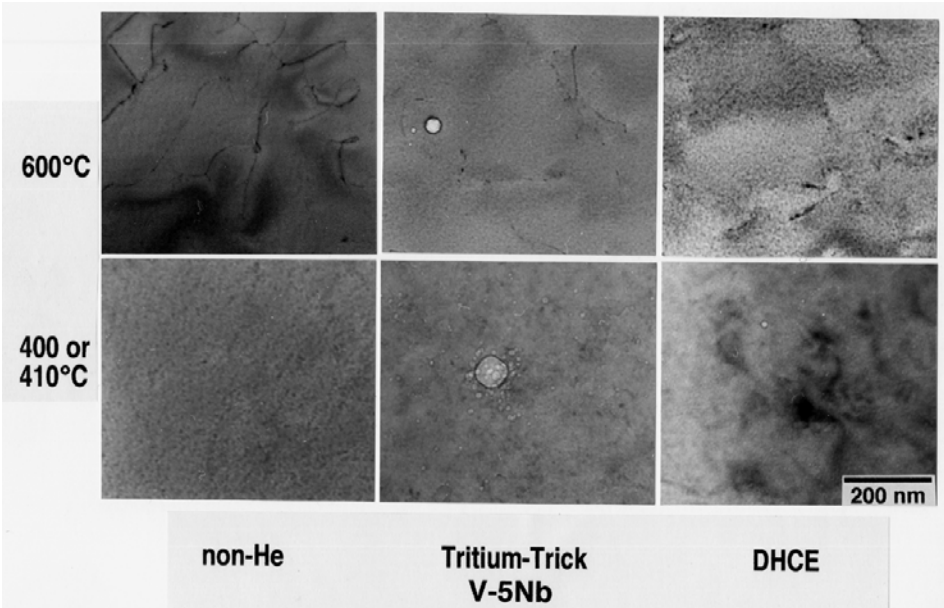


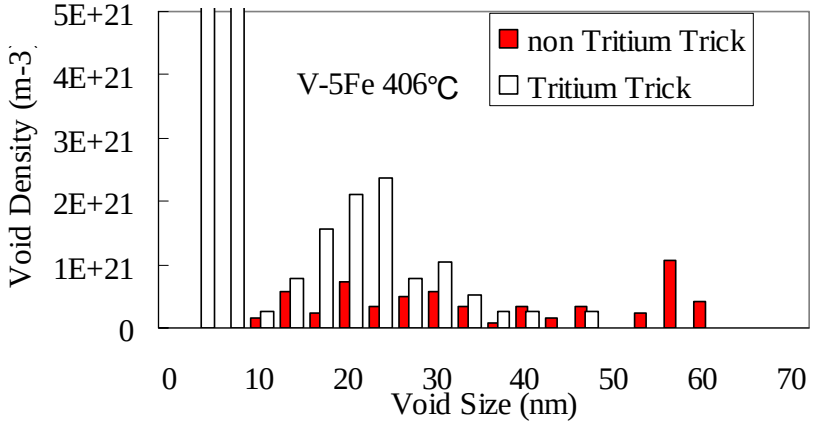
The difference of microstructural evolution from He implantation technique

- Bimodal distribution of cavities in FFTF neutron-irradiated pure vanadium with tritium-trick → the saturation of bubble formation in initial stage of irradiation.
- The size distribution of cavity with DHCE irradiation : Unimodal distribution but shift to smaller mean size from that of conventional irradiation → the nucleation and stable growth of He-V complexes.

He effect on void swelling in over- and under-sized V alloys



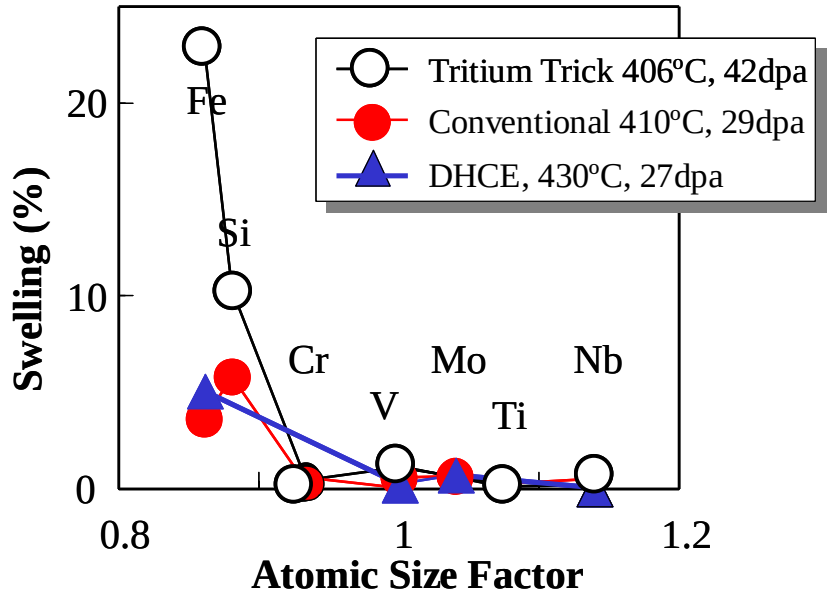




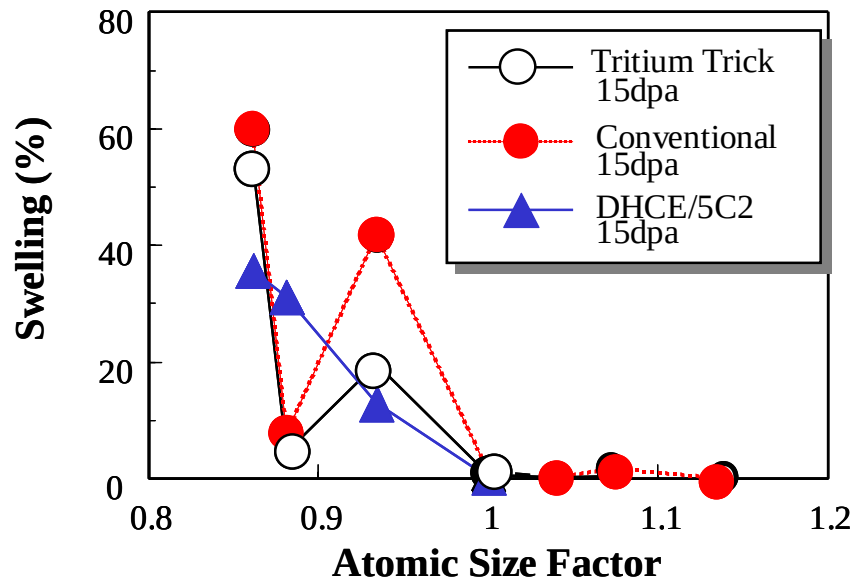
The bimodal distribution of cavity in neutron irradiated V-alloys with tritium trick technique is so often seen in undersized vanadium alloys.

The bubble formation in grain boundary is observed in oversized vanadium alloys before neutron irradiation.

Comparison of the void swelling between various He implanting technique



430ºC FFTF irradiation



600ºC FFTF irradiation

- The contribution for the swelling is apparent in undersized alloys with He implantation by tritium trick at 400° C.
- According to the DHCE results, the effect of He generation is not effective for the swelling behavior with same helium generation rate as fusion reactor environment.
- The relationship between He effects for swelling and atomic size factor is complicated at 600C.

B-generated helium on the swelling of neutron irradiated V alloys

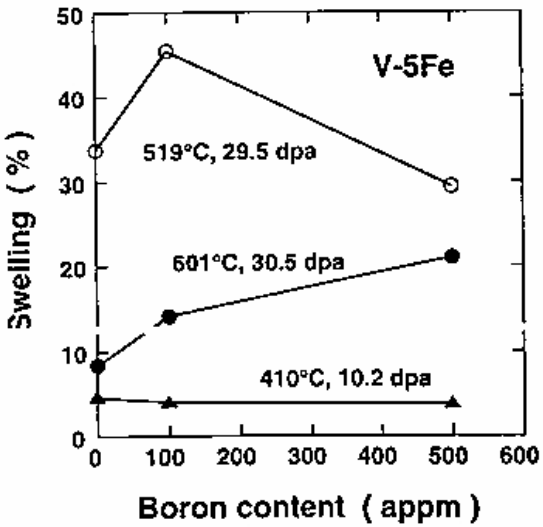


Fig. 6. Effects of boron concentration on swelling in V–5Fe–B alloys irradiated to 30 dpa at 520 and 600°C and to 10 dpa at 410°C.

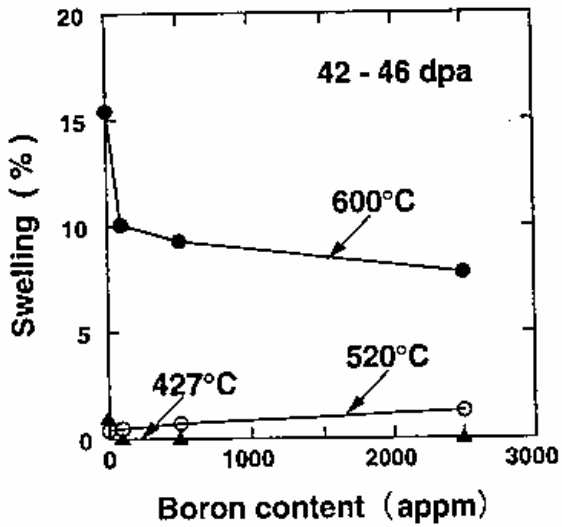


Fig. 5. Effects of boron concentration on swelling in V–5Cr–B alloys irradiated to 42–26 dpa at 427, 520 and 600°C.

Sekimura, Iwai, Garner, J.Nucl.Mater. (1996,1996,1998)

The He generated by B-10 technique enhances the swelling in V-5Fe. However, it suppresses the swelling in V-5Cr.

There is a quite possibility that the chemical interactions with B atoms are so strong that the helium effect are concealed.

Synergistic effects of H and He on the swelling behavior in V-alloys

pureV

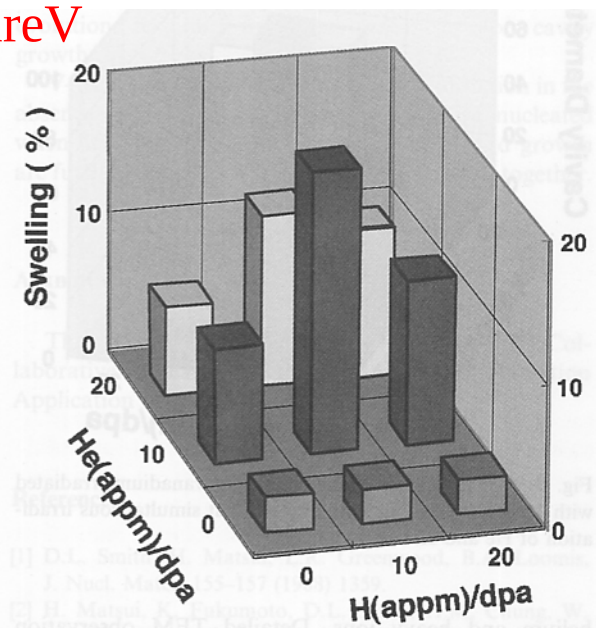


Fig. 1. Cavity volume fraction in pure vanadium irradiated with 12 MeV Ni^{3+} ions to 30 dpa at 873 K with and without simultaneous irradiation of He and H.

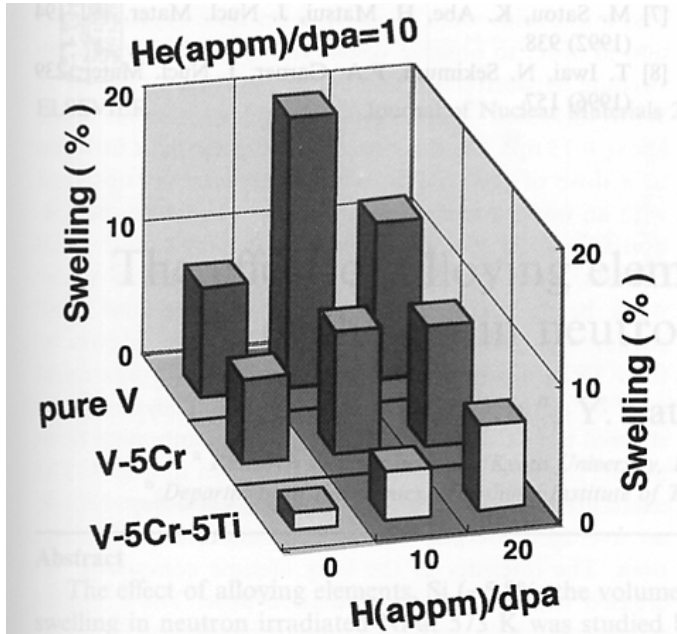


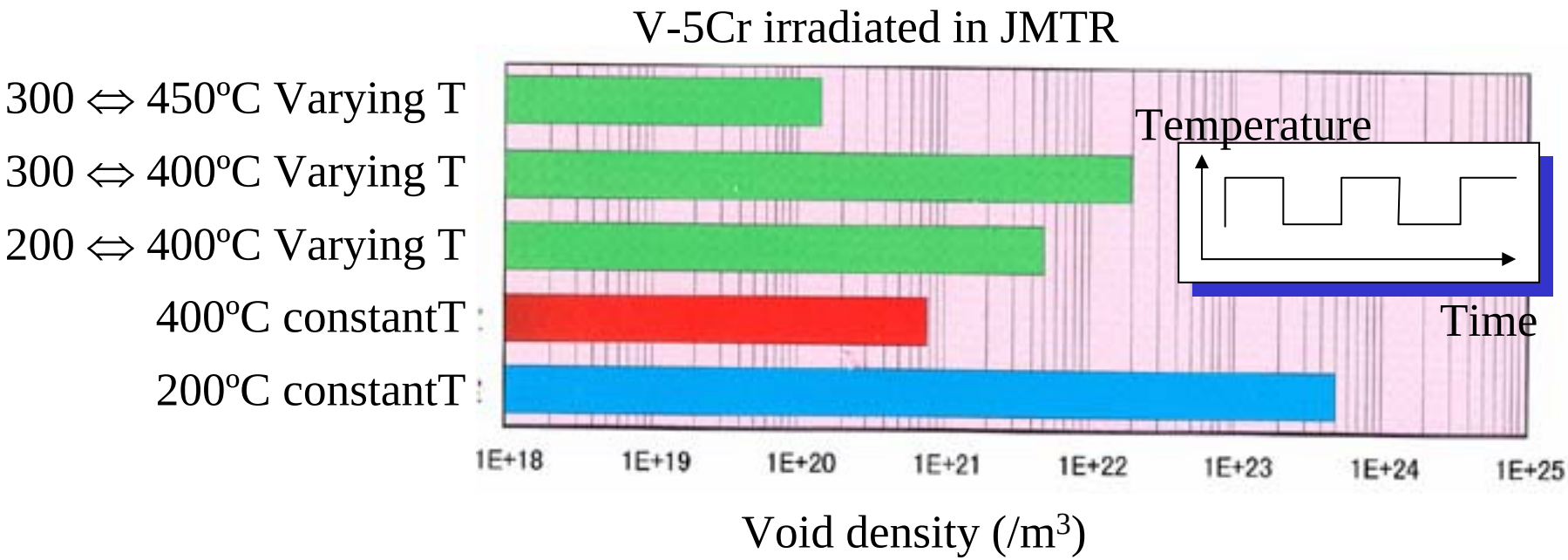
Fig. 5. Cavity volume fraction in pure vanadium, V–5Cr and V–5Cr–5Ti irradiated with 12 MeV Ni^{3+} ions to 30 dpa at 873 K at He(appm)/dpa ratio of 10 with and without simultaneous irradiation of H.

Sekimura, J.Nucl.Mater. (1999)

Triple ion beam irradiation (H, He and Ni) in V-alloys

Both He and H assist the generation of swelling during heavy ion irradiation. Especially, V-Cr-Ti affects synergistic effect of both He and H for swelling behavior.

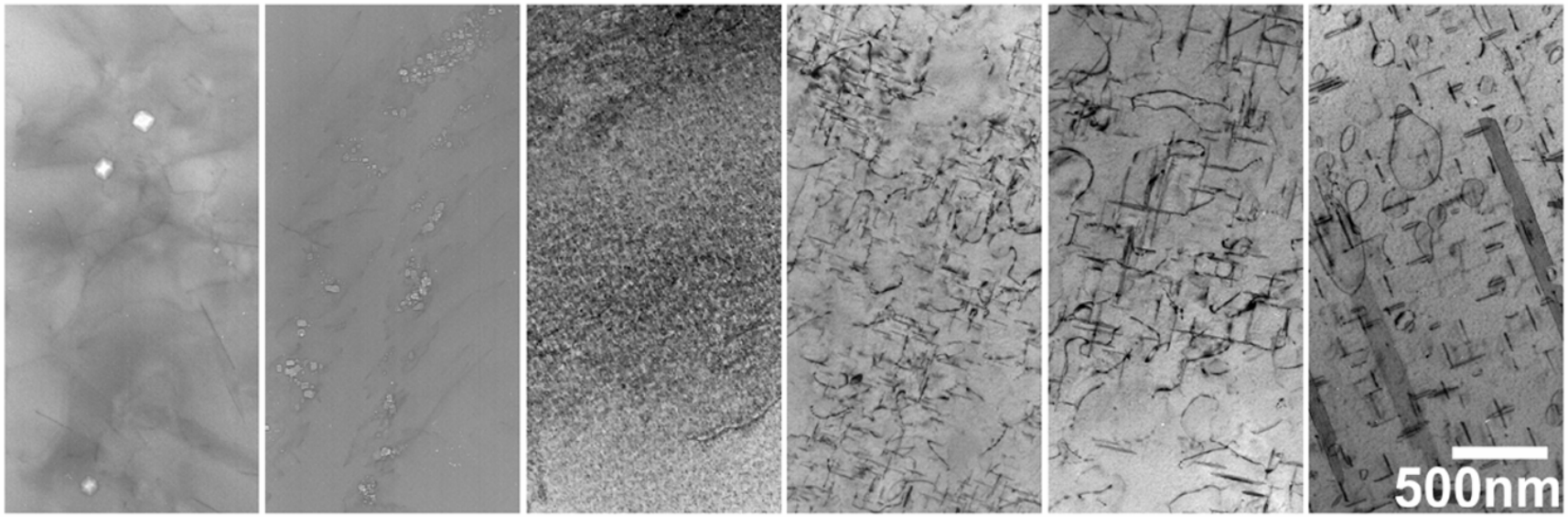
Varying temperature effects on microstructural evolution in V-alloys



The effect of non-steady-state temperature condition becomes an important problem for microstructural evolution during irradiation.

Cyclic-T irradiation generates more cavity formation than constant-T irradiation if the temperature regime of cyclic-T operation traverse between the temperature regime for high nucleation rate and the temperature regime for high growth rate of cavity.

The effects of Ti addition on microstructural evolution in V-Cr alloys



1 2 3 4 5 6

JMTR 520ºC irradiation

1. **V-1Cr** **1dpa**
2. **V-5Cr** **0.1dpa**
3. **V-4Cr-0.1Ti** **1dpa**
4. **V-4Cr-1Ti** **1dpa**
5. **V-4Cr-3Ti** **1dpa**
6. **V-4Cr-4Nb** **1dpa**

The addition of tiny fraction of Ti (0.1%Ti) retain capability to suppress the cavity formation, and have the dense precipitation of TiO in the matrix.

Summary

The swelling behavior of V-4Cr-4Ti alloys shows quite good performance up to 50 dpa of neutron damage levels.

- The increase of Cr addition makes swelling larger at high irradiation dose.
- The addition of Ti is most effective to suppress the swelling.

From the previous study, the swelling behaviors in V-Cr-Ti systems are independent of impurity levels.

The effects of helium vary depending on the techniques of helium implantation. The comprehensive understandings of helium and/or hydrogen effects on swelling behavior are still unknown.

More DHCE irradiations are strongly required to demonstrate the effect of He.