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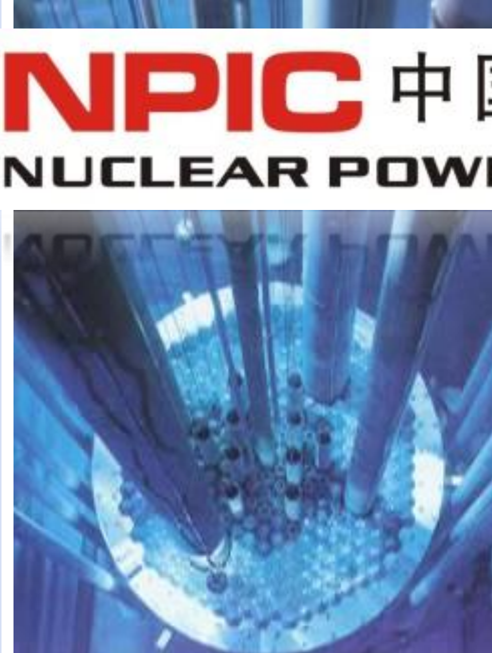

The microstructure of post-irradiated A508-3 steel and its effects on Charpy impact energy

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Contents

Introduction

Reactor Pressure Vessel

Key issues:

- ➢ Irradiation embrettlement

- ✓ One of the most important safety shield of the reactor
- ✓ Cannot change, determined the lifetime of the reactor

Severe conditions:

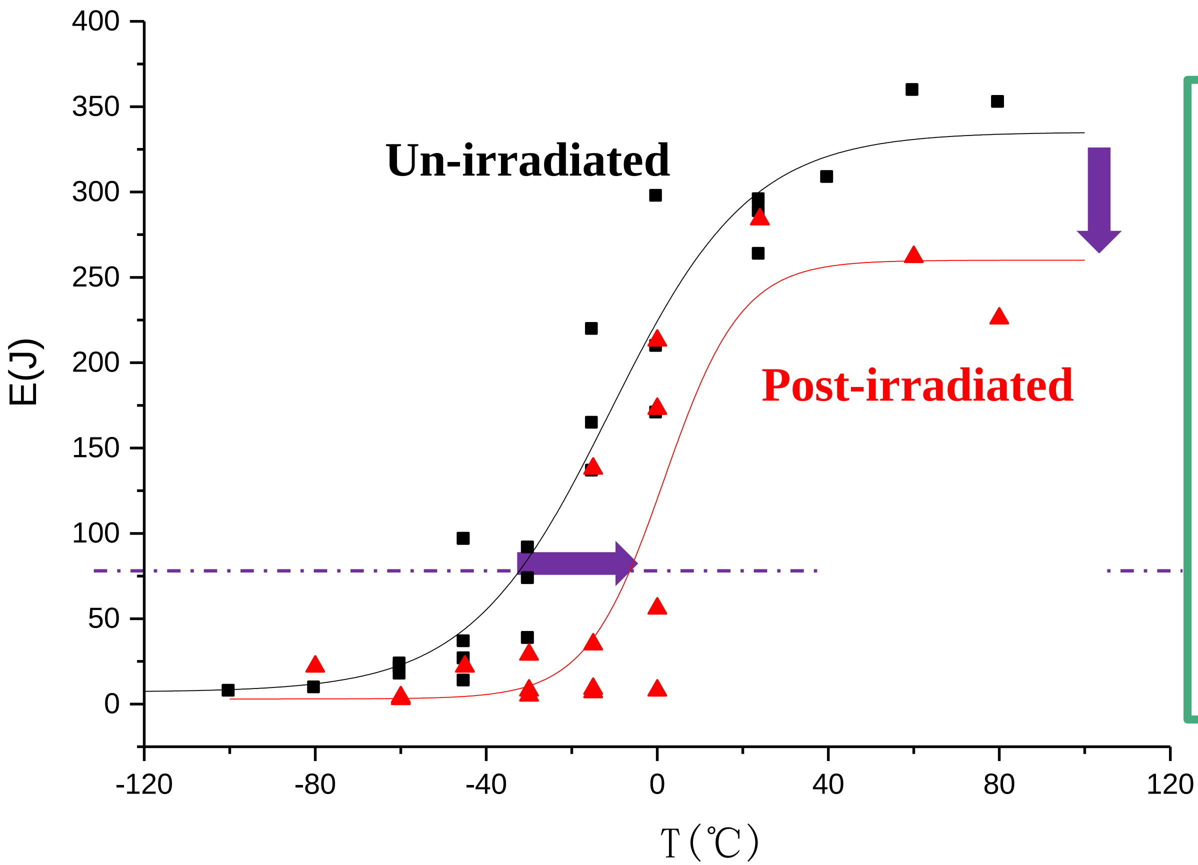
- ➢ Neutron irradiation
- ➢ Multi-stress situation
- ➢ High temperature and thermal shock
- ➢ Water/steam corrosion
- ➢ ……

Introduction

The chemical compositions of LWR RPV steels（wt.%）

Materials	C	Si	Mn	S	P	Cr	Ni	Cu	Mo	V
American A508-Ⅲ	≤0.25	0.15/0.40	1.20/1.50	≤0.020	≤0.020	＜0.25	0.40/1.0	-	0.45/0.60	≤0.05
French 16MND5	≤0.20	0.10/0.30	1.15/1.55	≤0.008	≤0.008	＜0.25	0.50/0.80	≤0.08	0.45/0.55	≤0.01
Japanese SQV2A	≤0.25	0.15/0.30	1.15/1.50	≤0.035	≤0.035	-	0.40/0.70	-	0.45/0.60	-
Russian 15×2HMΦA1	0.13/0.18	0.17/0.37	0.30/0.60	≤0.012	≤0.010	1.8/2.3	1.0/1.5	≤0.08	0.5/0.7	0.10/0.12
Chinese A508-Ⅲ	≤0.22	0.10/0.30	1.15/1.60	≤0.005	≤0.008	≤0.25	0.50/0.80	≤0.08	0.43/0.57	/

Introduction



Irradiation effects:

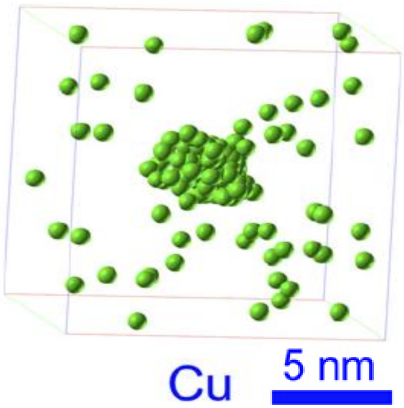
- **Ductile-to-brittle transition temperature (DBTT) increase**
- **Maximum absorb energy decrease**
- **……**

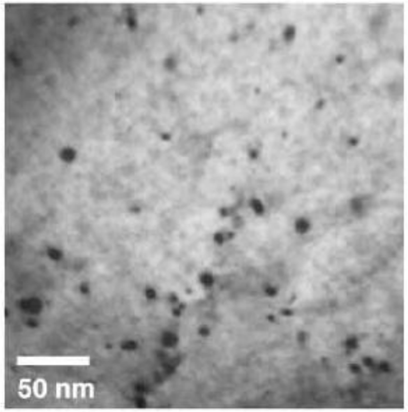
The Charpy V-notch impact energies of the A508-3 steel from the HFETR as a function of temperature for the un-irradiated and irradiated conditions at neutron fluence of 2.97×10^{19} n/cm^2

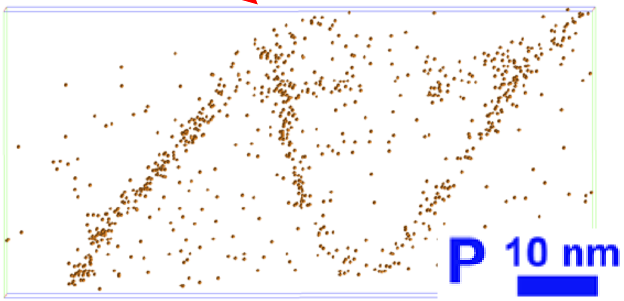
Introduction

The main reasons of the irradiation embrittlement of the RPV steel are：

- **The precipitation of nanoscale atomic clusters (Copper, Nickel, Manganese, etc.)**
- **The formation of dislocation loops inside matrix**
- **The segregation of Phosphorus atoms beyond boundary**







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[2]M.K. Miller, K.F. Russell, M.A. Sokolov, R.K. Nanstad. Journal of Nuclear Materials 361 (2007) 248–261
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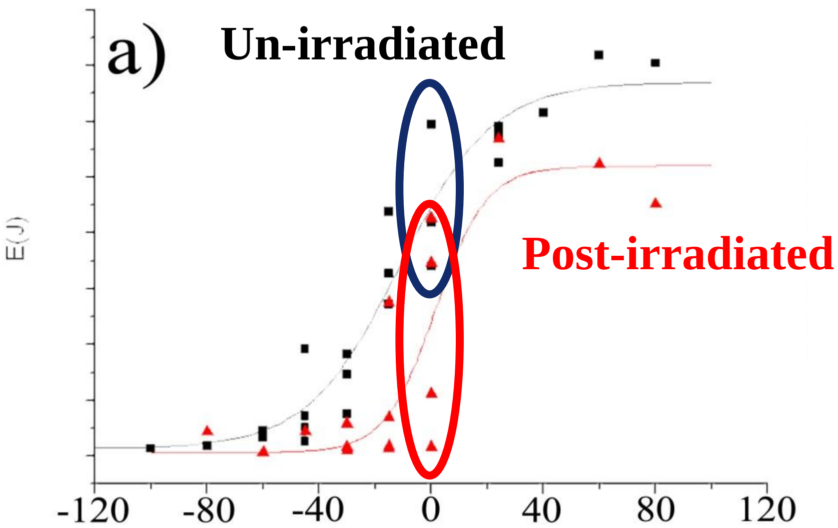
Introduction



Charpy V-notch impact energy curve of A508-3 steel

Besides the irradiation embrittlement, the impact energies of un-irradiated and post-irradiated A508-3 steel under the same testing environment are unstable.

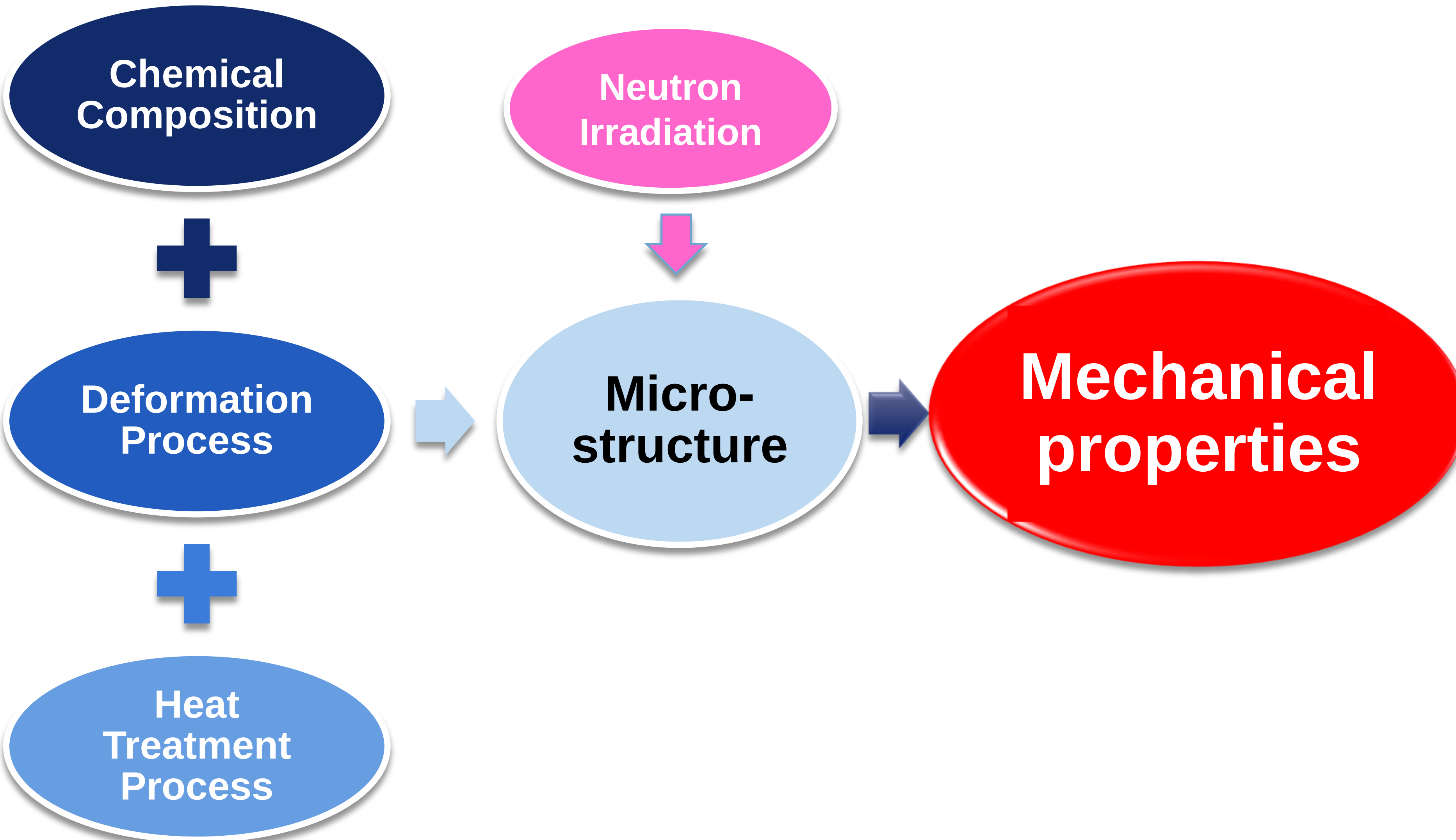
WHY?

Metallography?

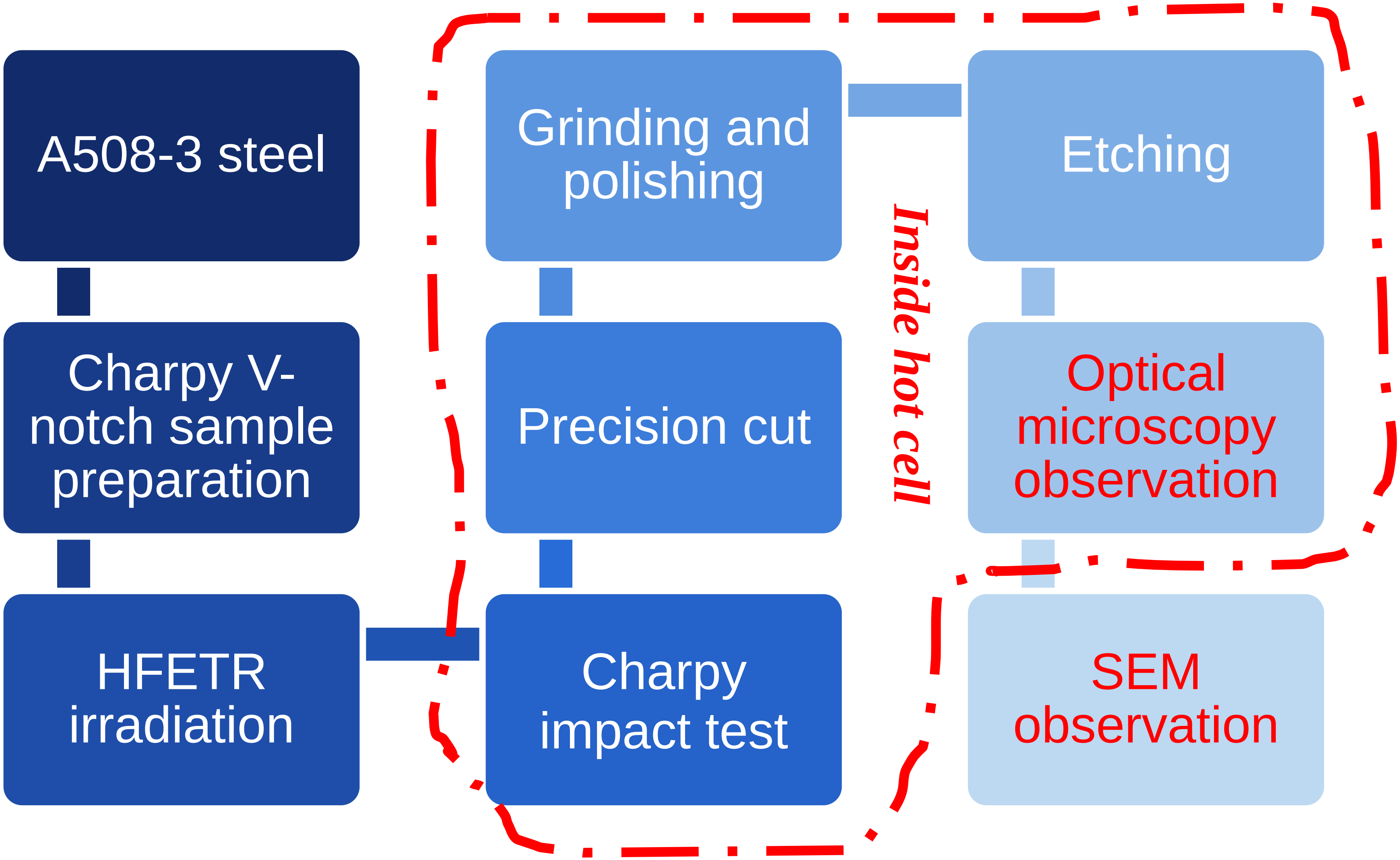
Grain Size?

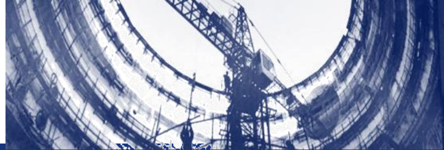
Defects?

Introduction



Experimental





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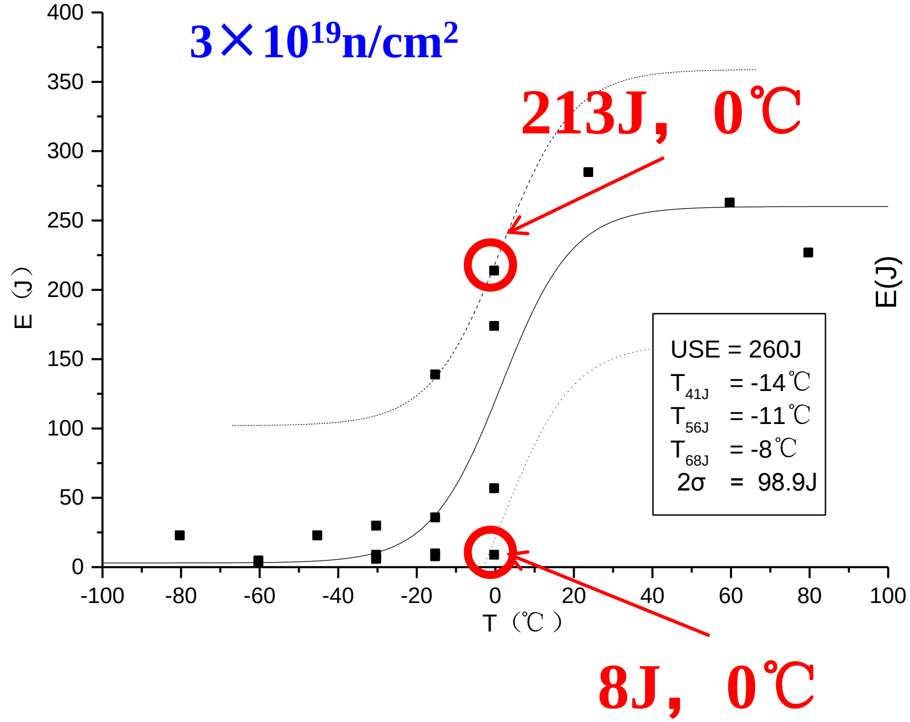
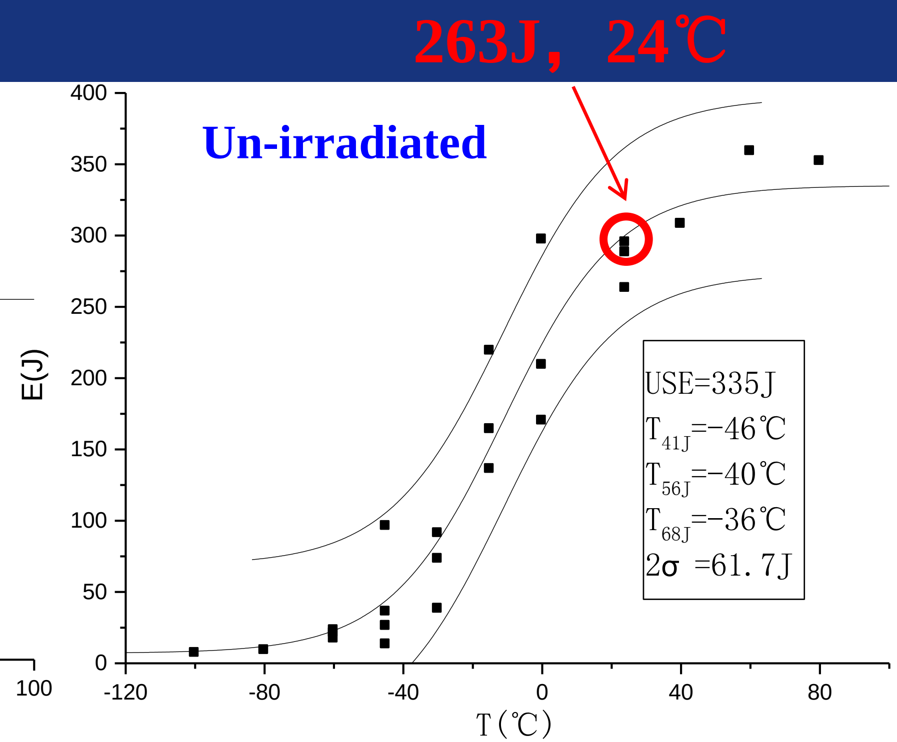
Experimental

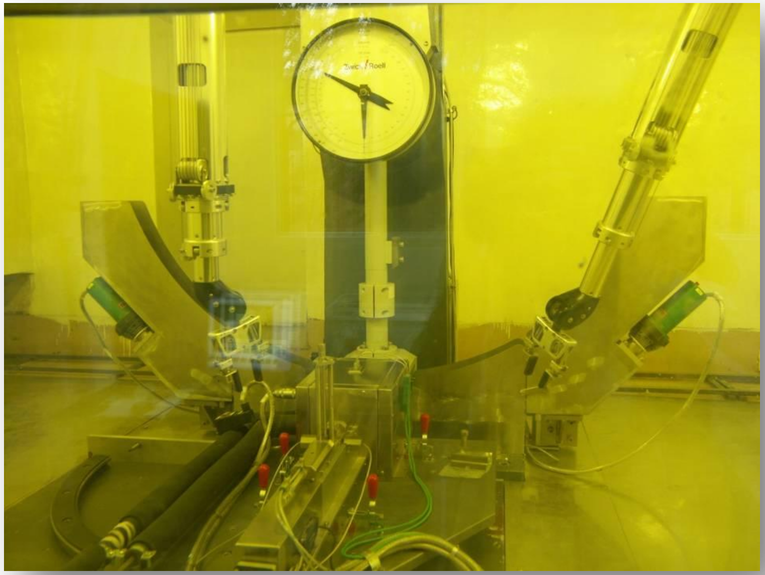




Charpy V-notch impact energy curves of A508-3 steel

Samples	Irradiation Temperature T（℃）	Neutron fluence（n/cm²）	Test temperature T（℃）	Charpy V-notch impact energy E（J）
1#	/	0	24	263
2#	290±15	2.97×10^{19}	0	213
3#	290±15	2.97×10^{19}	0	8

Experimental



Zwick RKP450 Charpy impact testing machine

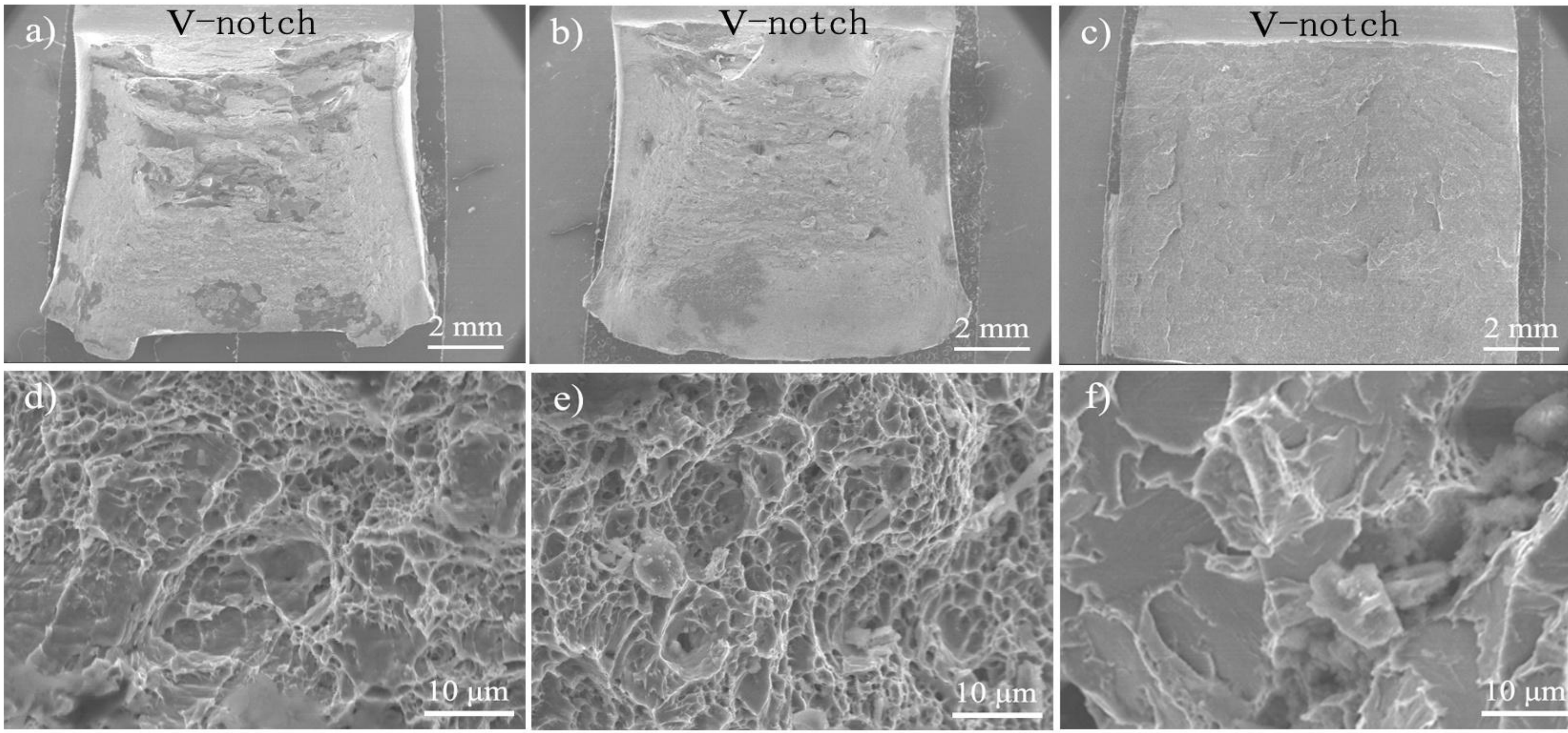
Leica MEF4A Optical microscopy inside hot cell

Experimental

FEI Quanta 450 FEG field emission scanning electron microscope with EDS inside a cast iron cell

Results and Discussion

263J, 24℃ | 213J, 0℃ | 8J, 0℃

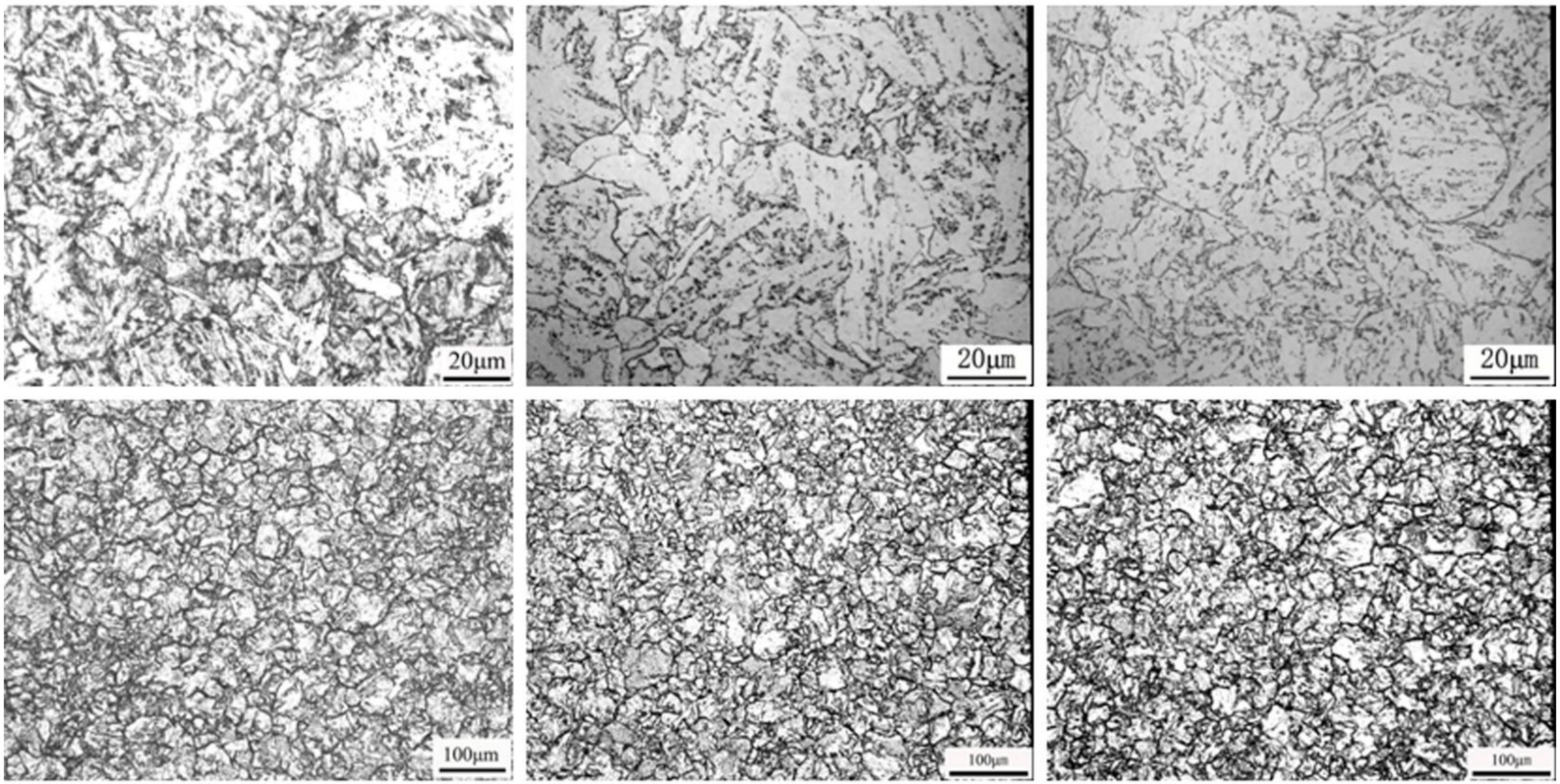


Unirradiated | $3 \times 10^{19} n/cm^2$ | $3 \times 10^{19} n/cm^2$

SEM image of the fracture. Both for un-irradiated and post-irradiated samples, high impact energy means big deformation of the fracture(good impact toughness).

Results and Discussion

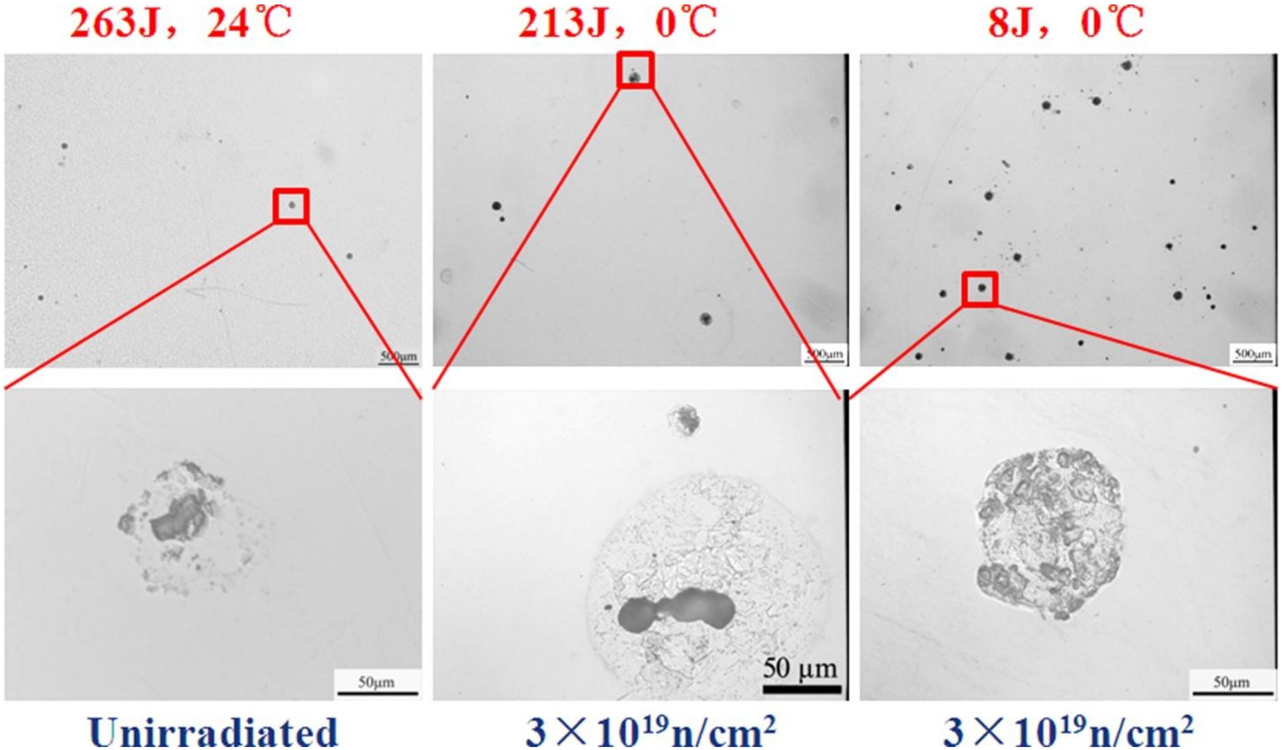
263J，24℃ 213J，0℃ 8J，0℃



Unirradiated 3×10^{19}n/cm^2 3×10^{19}n/cm^2

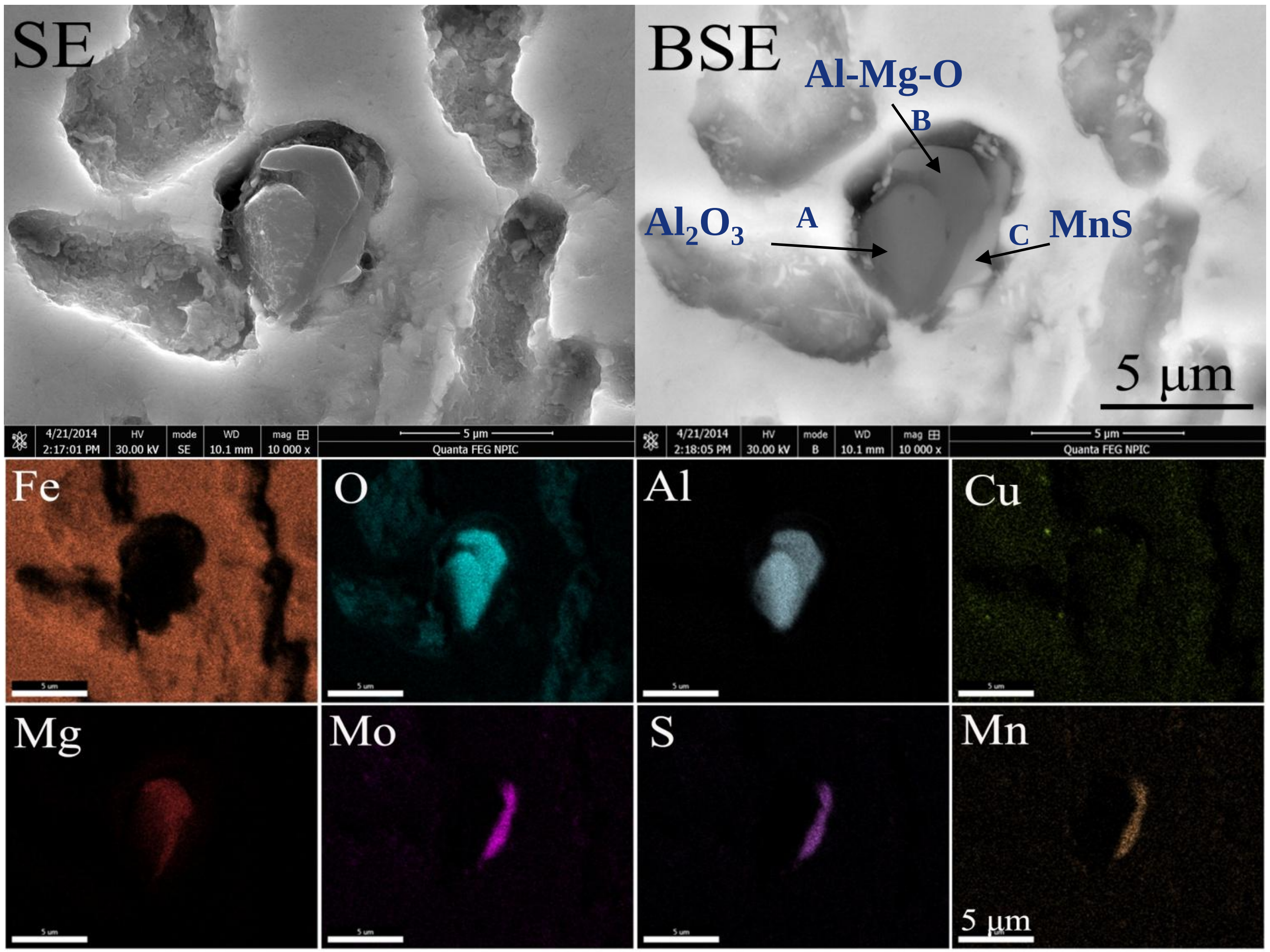
Optical metallography(upper) and grain size(lower) images – No big differences between un-irradiated and post-irradiated samples

Results and Discussion



- ***Observe after polishing directly(black points, defects). Optical images of morphology and distribution of defects/holes: Both for the un-irradiated and post-irradiated samples, the lower the absorb energy is, the higher the number densities of defects.***
- ***The holes in not formed during irradiation, but probably formed during solidification process. Need further investigation.***

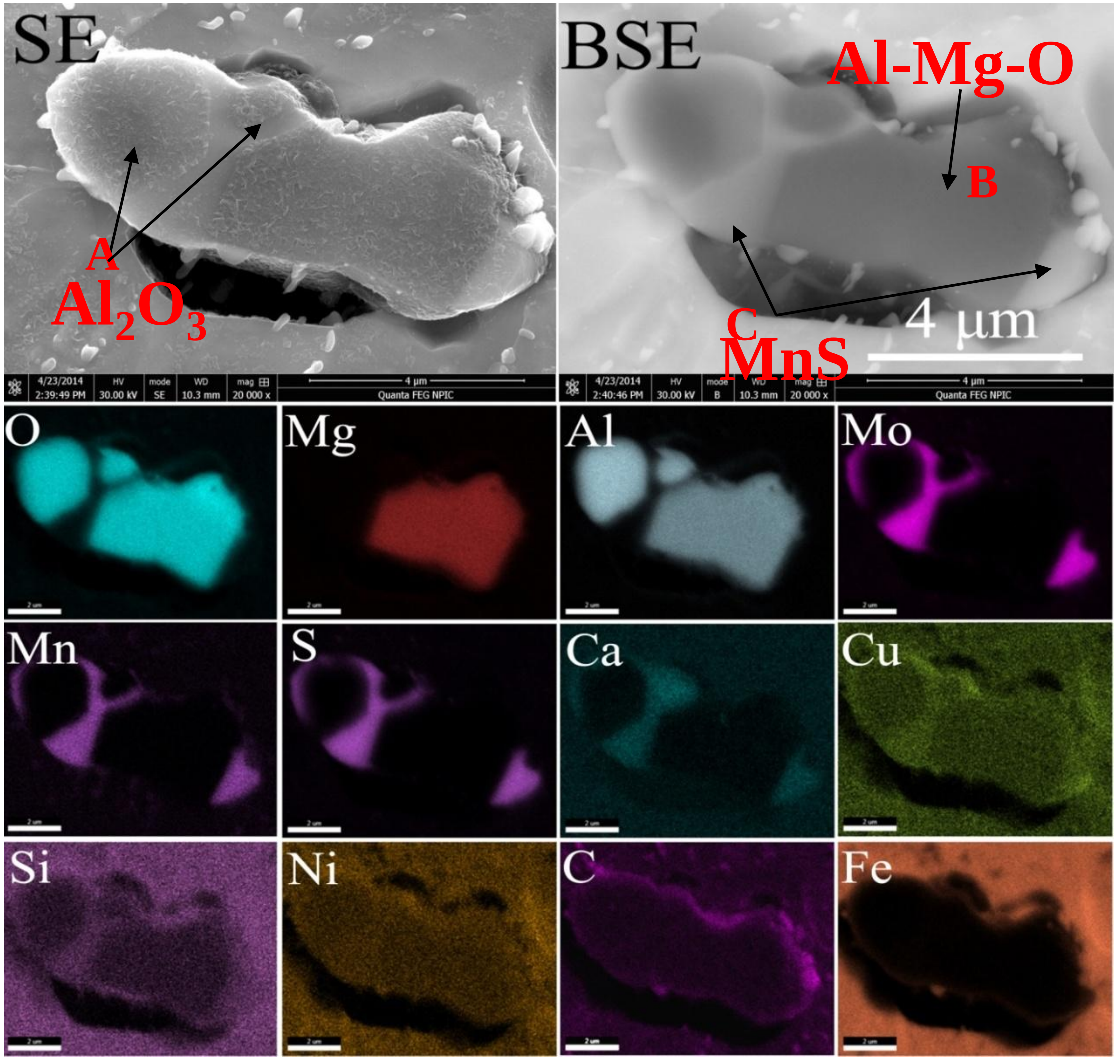
Results and Discussion



Positions		A	B	C
	Fe	0.08	-	3.00
	C	0.02	0.03	0.10
	O	55.42	56.56	-
	Al	44.34	29.89	0.27
	Mg	-	13.52	-
	Mo	-	-	1.38
	S	-	-	44.20
elements	Mn	-	-	42.74
	Ca	-	-	6.49
	Cr	-	-	0.25
	Ni	-	-	0.37
	Se	-	-	0.52
	Cu	-	-	0.68
	P	0.13	-	-
	总计	100	100	100

1#，un-irradiated

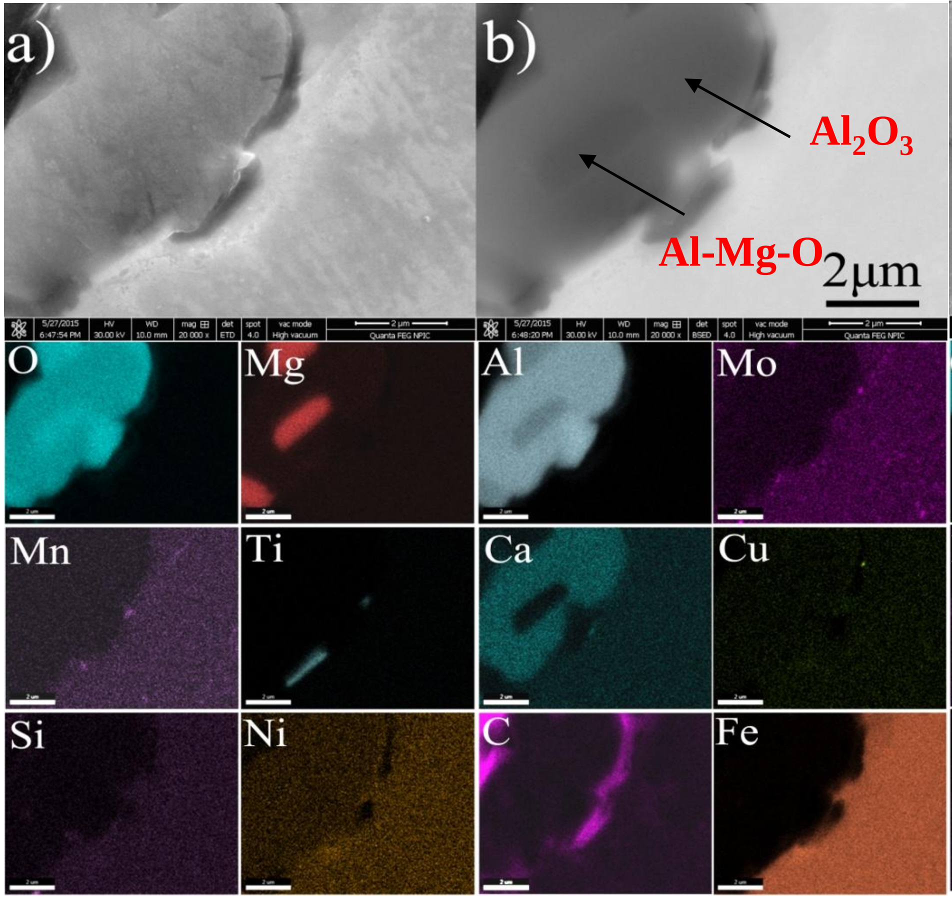
Results and Discussion



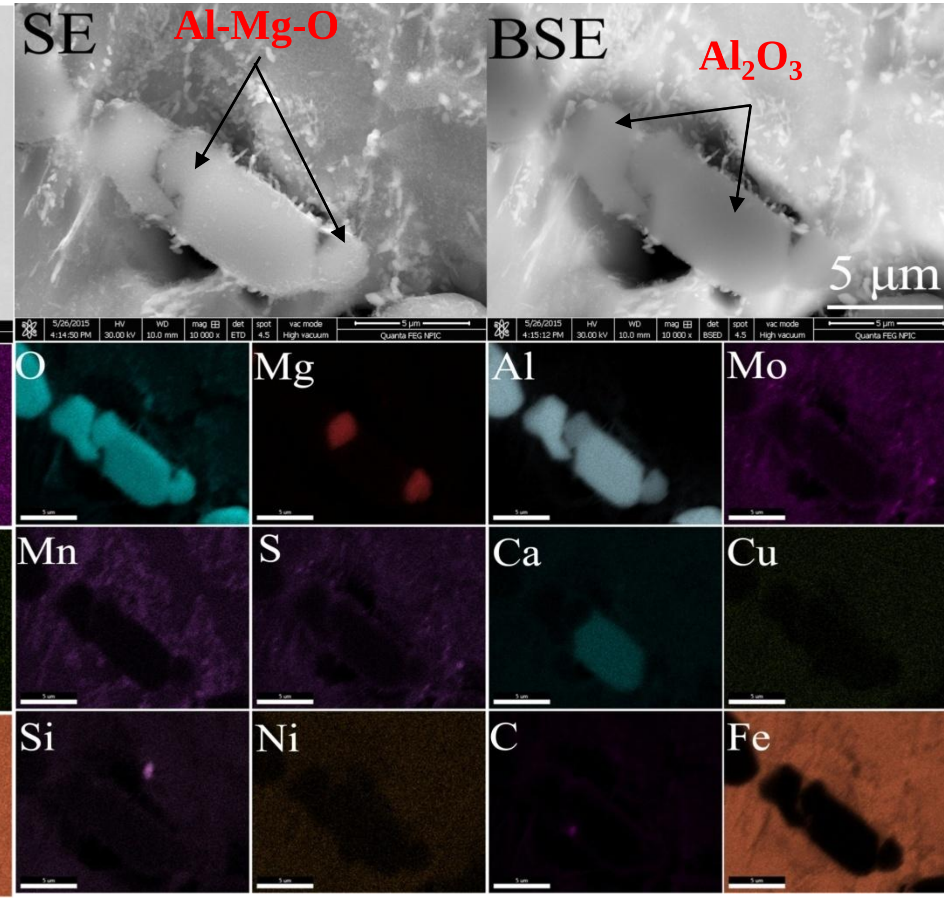
1#, un-irradiated

- ✓ The type of non-metallic inclusions can be easily distinguished by EDS. 3 kinds of non-metallic inclusions inside un-irradiated specimen: Al_2O_3, MnS, and Al-Mg-O ternary phase ($MgAl_2O_4$,Spinel)
- ✓ The boundary between non-metallic inclusions and the matrix is quite loose

Results and Discussion



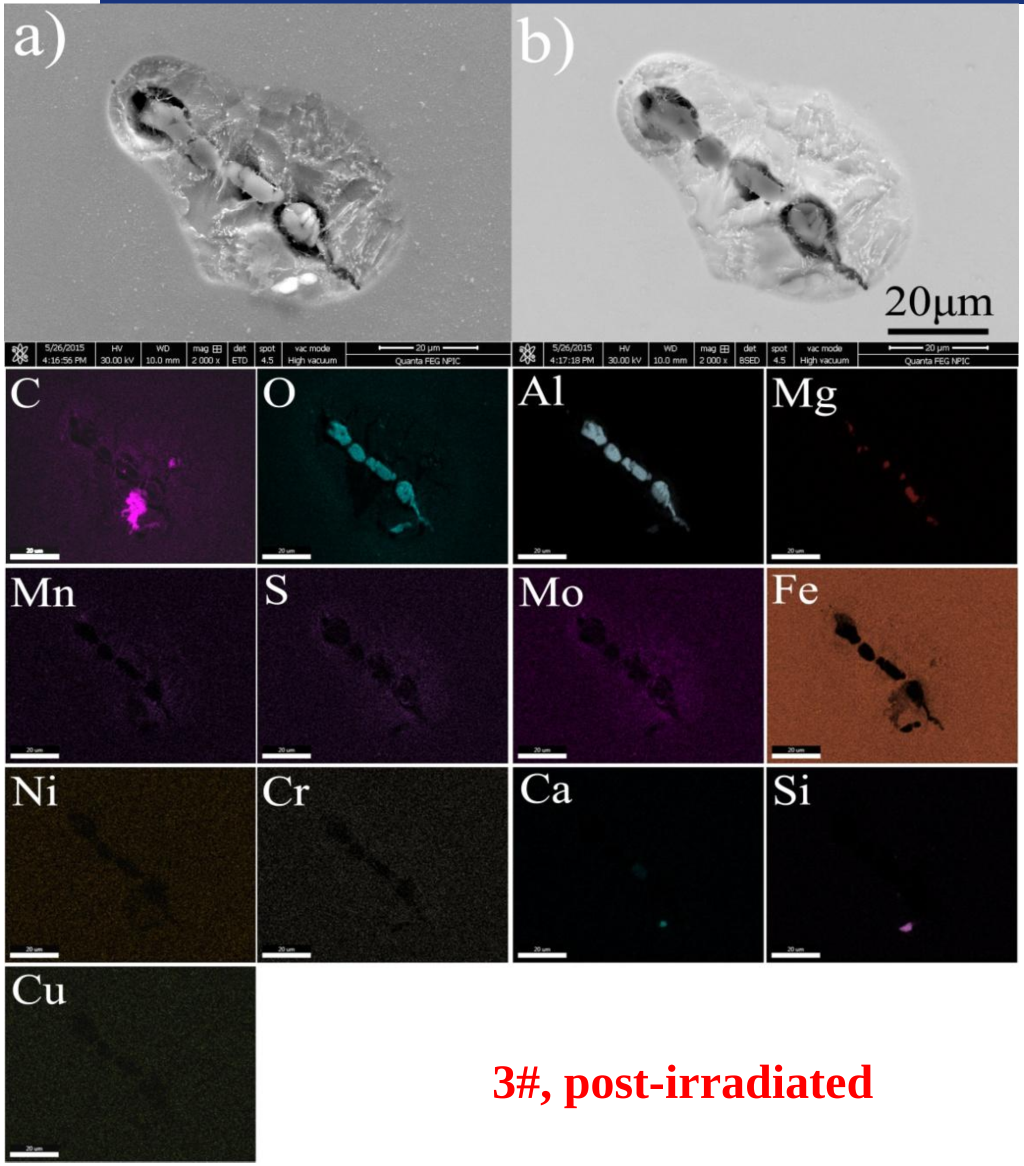
2#，post-irradiated



3#，post-irradiated

Only 2 kinds of non-metallic inclusions existed in post-irradiated samples: Al_2O_3 and Al-Mg-O ternary phase ($MgAl_2O_4$)

Results and Discussion



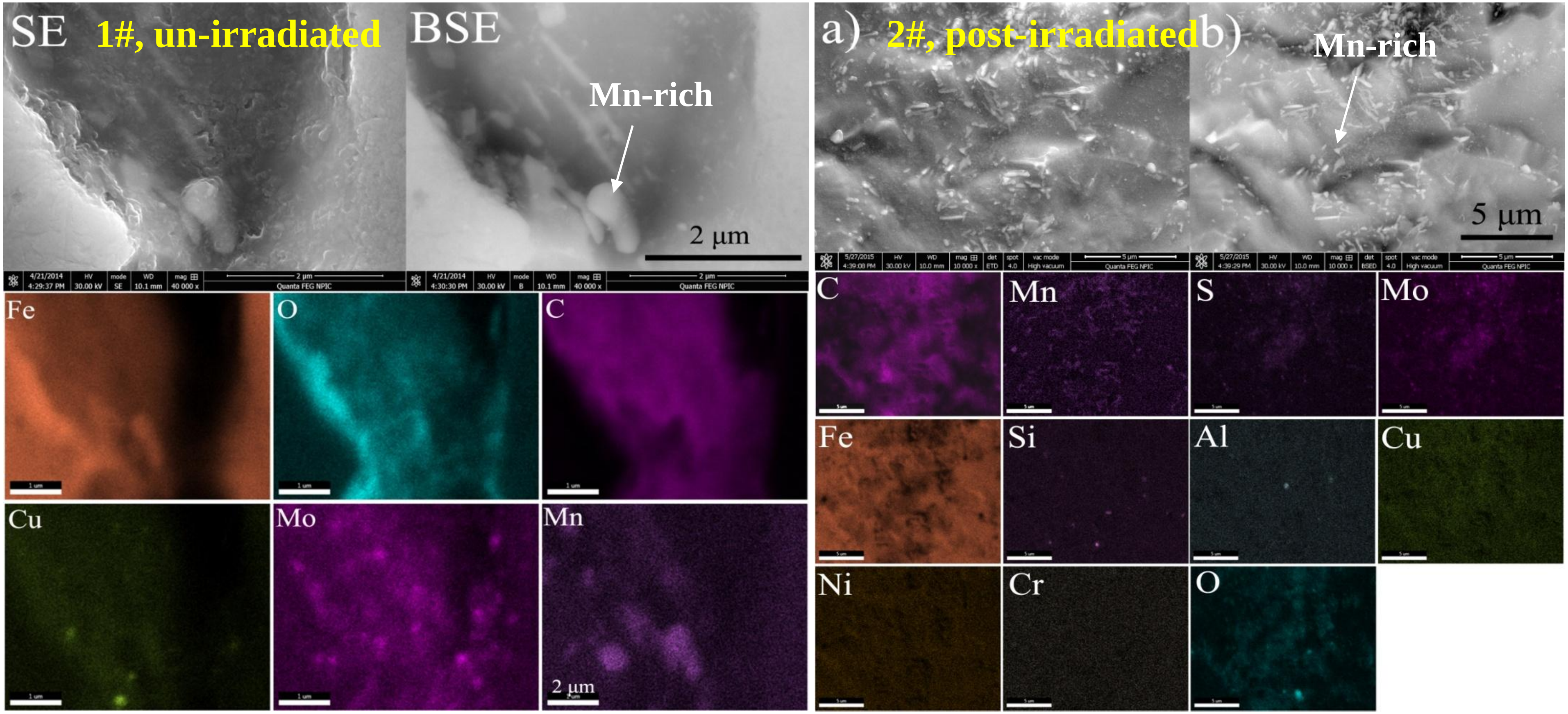
3#, post-irradiated

The evidence of MnS disappearred in post-irradiated samples: the enrichment of Mn and S element among the edge of holes.

Reasons:

- ✓ **Compare with Al_2O_3 and $MgAl_2O_4$, the melting temperature of MnS is quite lower. MnS is easier to decompose under the hot peak during cascade. In addition, combine with the effect of irradiation enhanced diffusion, S and Mn atoms move to boundaries.**
- ✓ **In the other hand, Mn atoms transmutation into Fe atoms by nuclear reaction, MnS decompose .**

Results and Discussion



- ✓ Because of low Copper concentration（0.08 wt.%）, very limited Copper clusters could be observed both in un-irradiated and post-irradiated samples
- ✓ Manganese and Molybdenum clusters exist after irradiation

Conclusions

- ***No obviously change** in the bainite structure and grain size of the A508-3 steel could be observed by OM under this irradiate conditions (fluence of neutron is 2.97×10^{19} n/cm^2, and irradiation temperature is 290℃±15℃), which could not causing impact energy abnormally.*
- ***The direct reason probably is the differences in fraction volume of the defects(holes) in the matrix, which formed during solidification process.***
- ***The defects could be divided into two types, one is filled with layer-like Al_2O_3, MnS, and Al-Mg-O ternary non-metallic inclusions combining together, and the other is holes.***
- ***Boundary between these non-metallic inclusions and matrix is quite loose, which is easily to decrease the impact toughness.***
- ***Except MnS phase, the morphology and composition of the Al_2O_3 and Al-Mg-O ternary non-metallic inclusions in defects were not modified by neutron irradiation significantly under this irradiate conditions.***

Conclusions

Next steps:

- ✓ EPMA observation, micro-composition analysis
- ✓FIB +TEM observation, microstructure analysis
- ✓Semi in-situ observation

Thank you for your attention!