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Effect of Friction Stir Welding on Microstructure Evolution on Self-Ion Irradiated MA956

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TMS 2018: Accelerated Materials Evaluation for Nuclear Application Utilizing Test Reactors, Ion Beam Facilities and Integrated Modeling

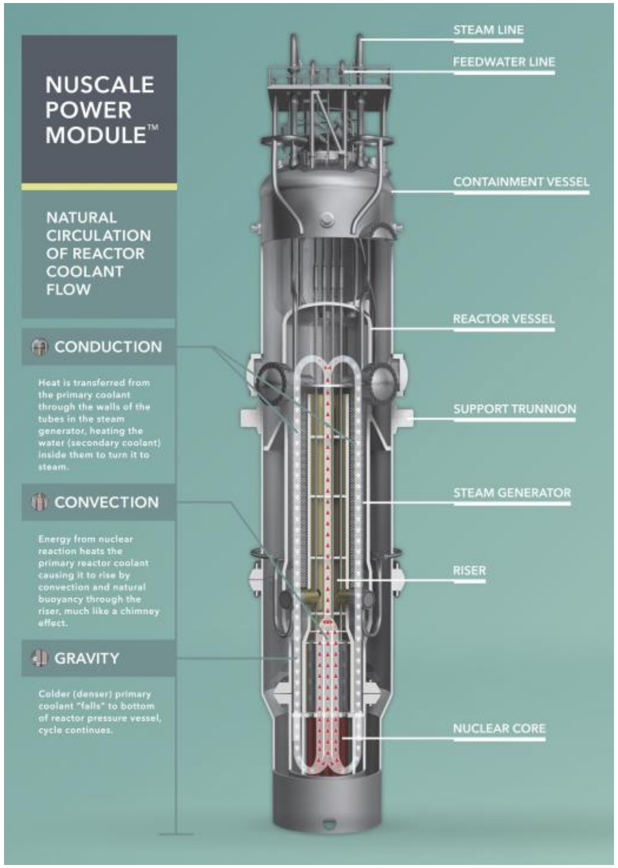
Motivation

Sodium Fast Reactors (SFR)

- Swelling of fuel cladding and duct at high dose
- Radiation-induced embrittlement by precipitation of brittle phases
- Corrosion from sodium
- Fuel-clad chemical interaction (FCCI)

Small Modular Reactors

- High damage due to non refuel design
- Stress corrosion cracking/Irradiation assisted SCC



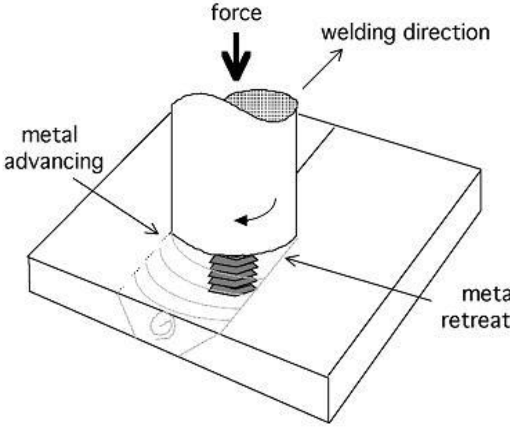
50 MWe modular reactor design

Courtesy of NuScale Power

Friction Stir Welding (FSW)

- Traditional fusion welding melt both pieces to be joined and fuse upon cooling
  - Has a large heat affected zone and cause heterogeneous dispersoid distribution
- Friction stir welding- a solid state joining technique that doesn't melt the workpiece and mechanically intermixes the joint
- A systematic comparison of effect of welding and irradiation is lacking in literature

FSW MA956



H. Bhadeshia, "Friction Stir Welding," University of Cambridge

Objective

To understand how welding and irradiation affect the microstructure of ODS steel MA956

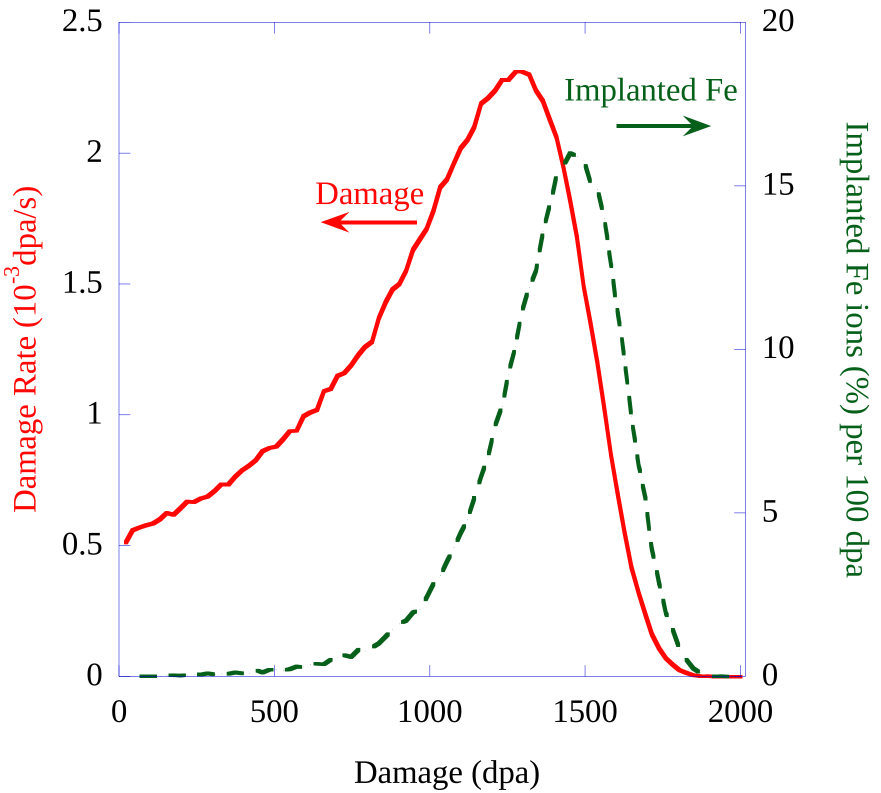
Approach

1. Comparison of FSW and base material (BM) as received
2. Systematic irradiation of FSW and BM at 450°C with increasing dose
3. TEM and APT characterization to determine changes in microstructure under ion irradiation

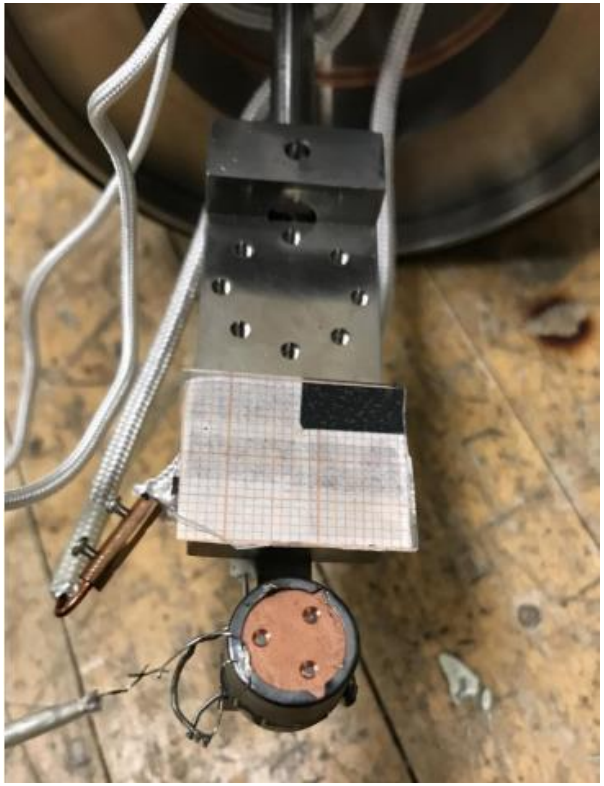
Ion Experiment Design

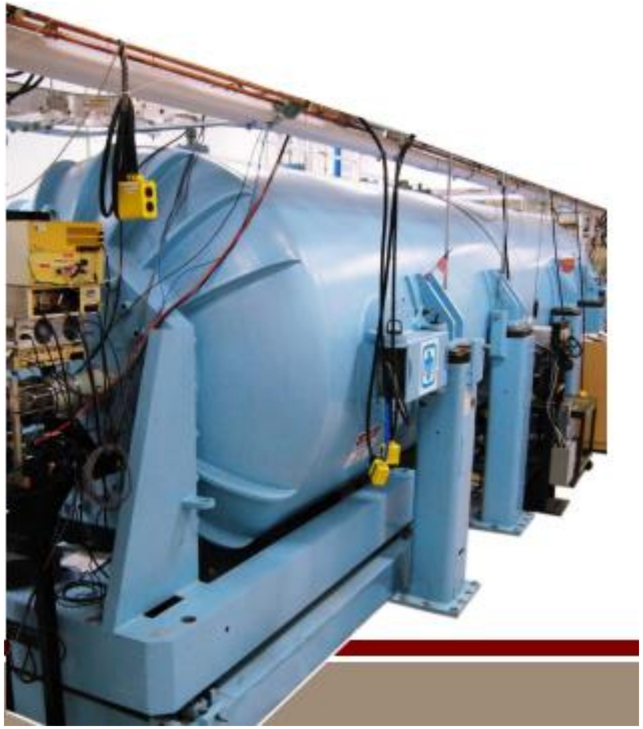
Alloy	Fe	Cr	Al	Y_2O_3	Ti	Mn	Si	Ni	C	Mo	S	P
MA956 (wt%)	Bal	19.93	4.75	0.51	0.39	0.09	0.08	0.04	0.023	0.02	0.008	0.006

- MA956
- Irradiation of tem bar samples and lamellas with 5 MeV Fe^{2+} ions performed with 6 MV Tandem at Sandia National Laboratory
  - Damage measured at 600 nm using Quick Kinchin-Pease with E_d=40 eV
  - Raster Scanning
- 1 and 25 dpa



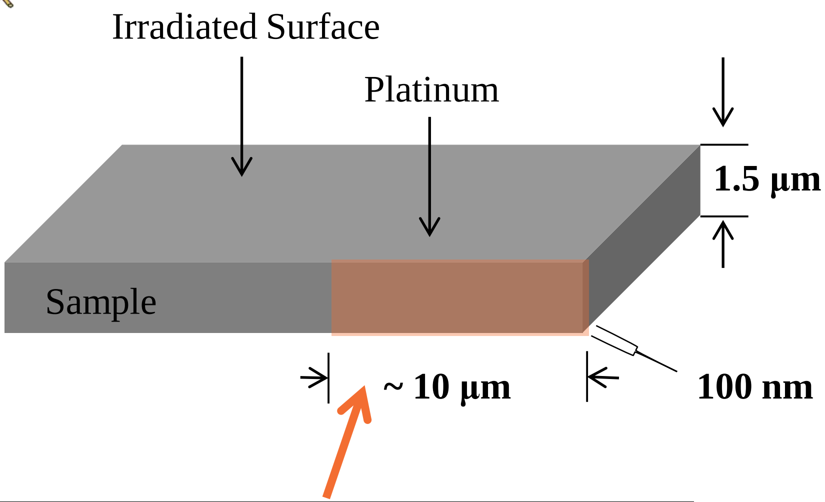
Ion Experiment Design (con't)

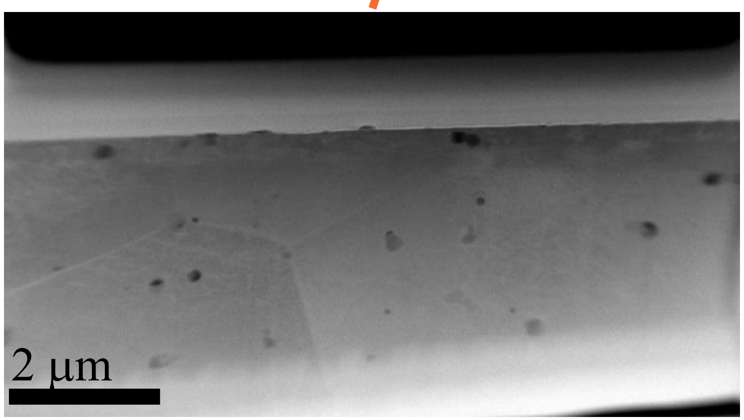




- Irradiations performed at SNL on the 6 MV Tandem
- LabView controlled button heater used to maintain temperature
- Ex situ irradiation of TEM lamellae attached with silver paste to button heater

Microstructure Analysis





MA956-Friction Stir Welded

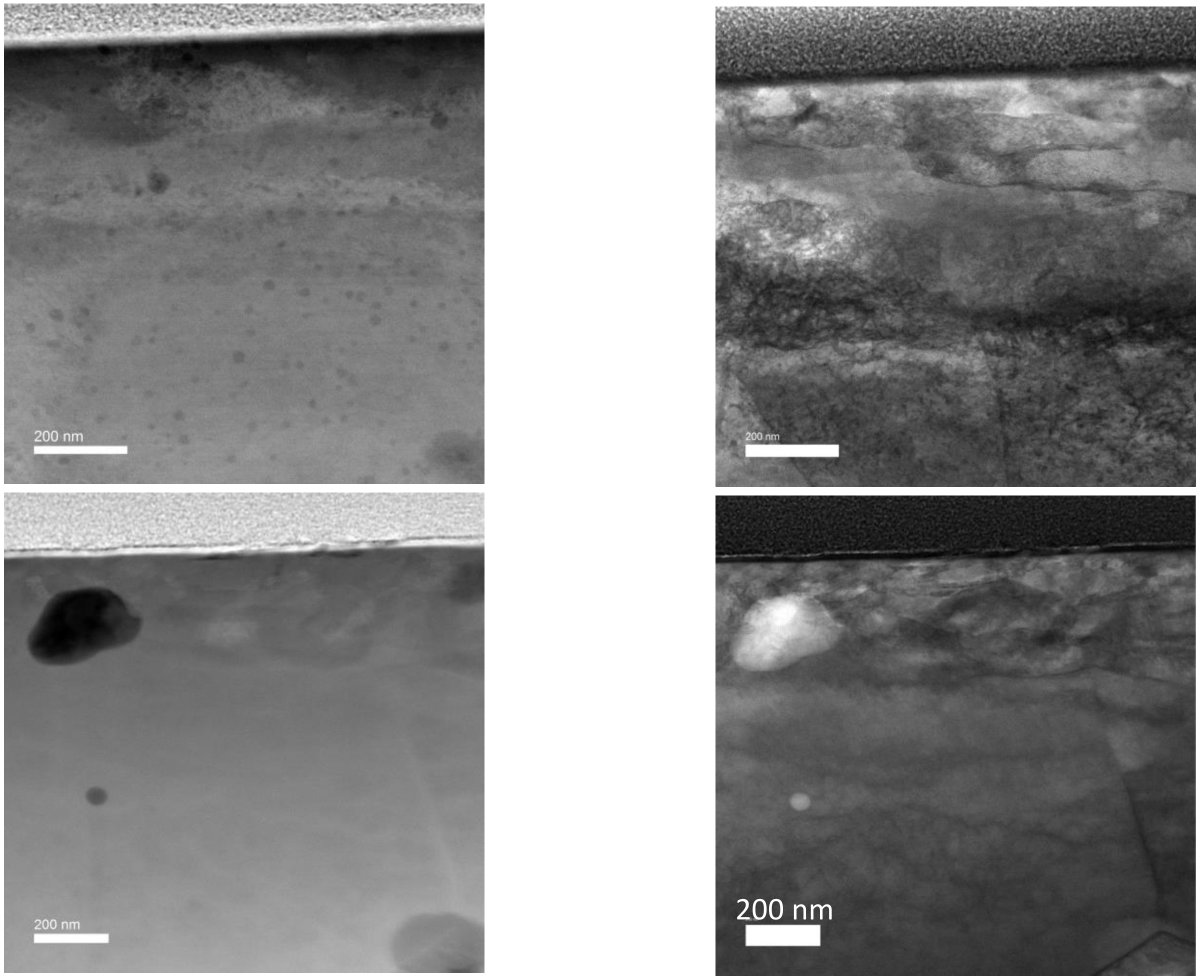
- Samples prepared via liftout method using Focused Ion Beam (FIB) at Naval Research Laboratory
- Cross section liftout maintains integrity of surface while allowing depth profiling of dispersoid distribution
- Dispersoids imaged in high angular annular dark field in STEM mode from 500-700 nm
- Dislocation loops and network imaged in STEM BF

MA956: As received microstructure

HAADF | BF

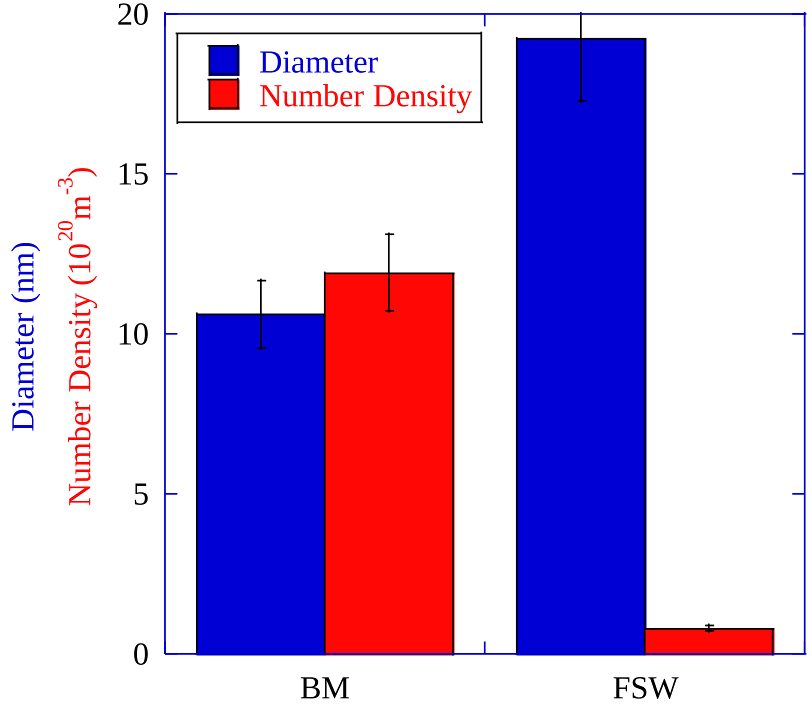
Base Material (BM)

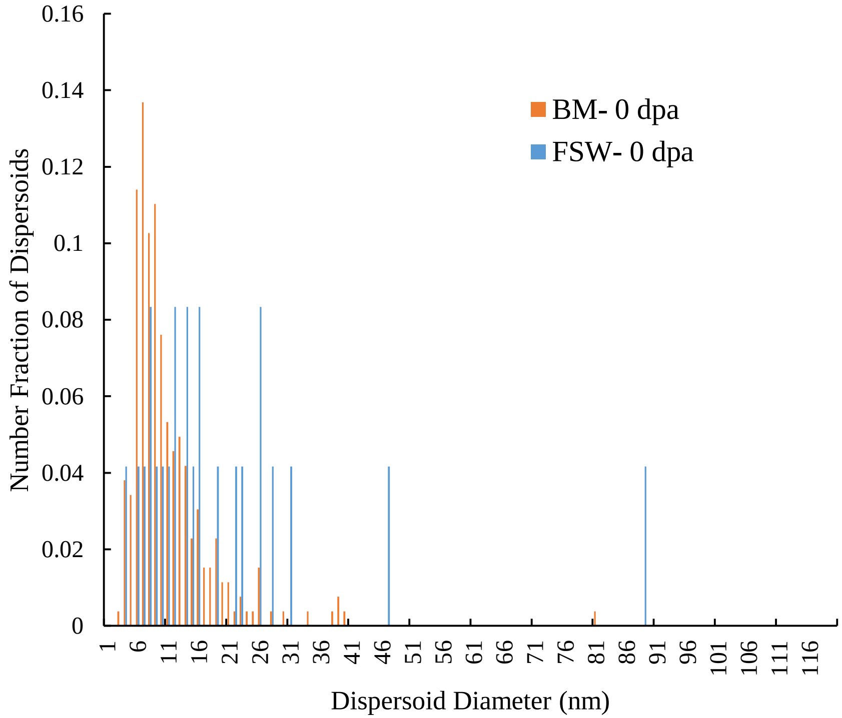
FSW



- Dispersoids much more visible with z contrast in HAADF images
- Qualitatively, fewer and larger dispersoids

Quantitative Comparison of Dispersoids, 0 dpa





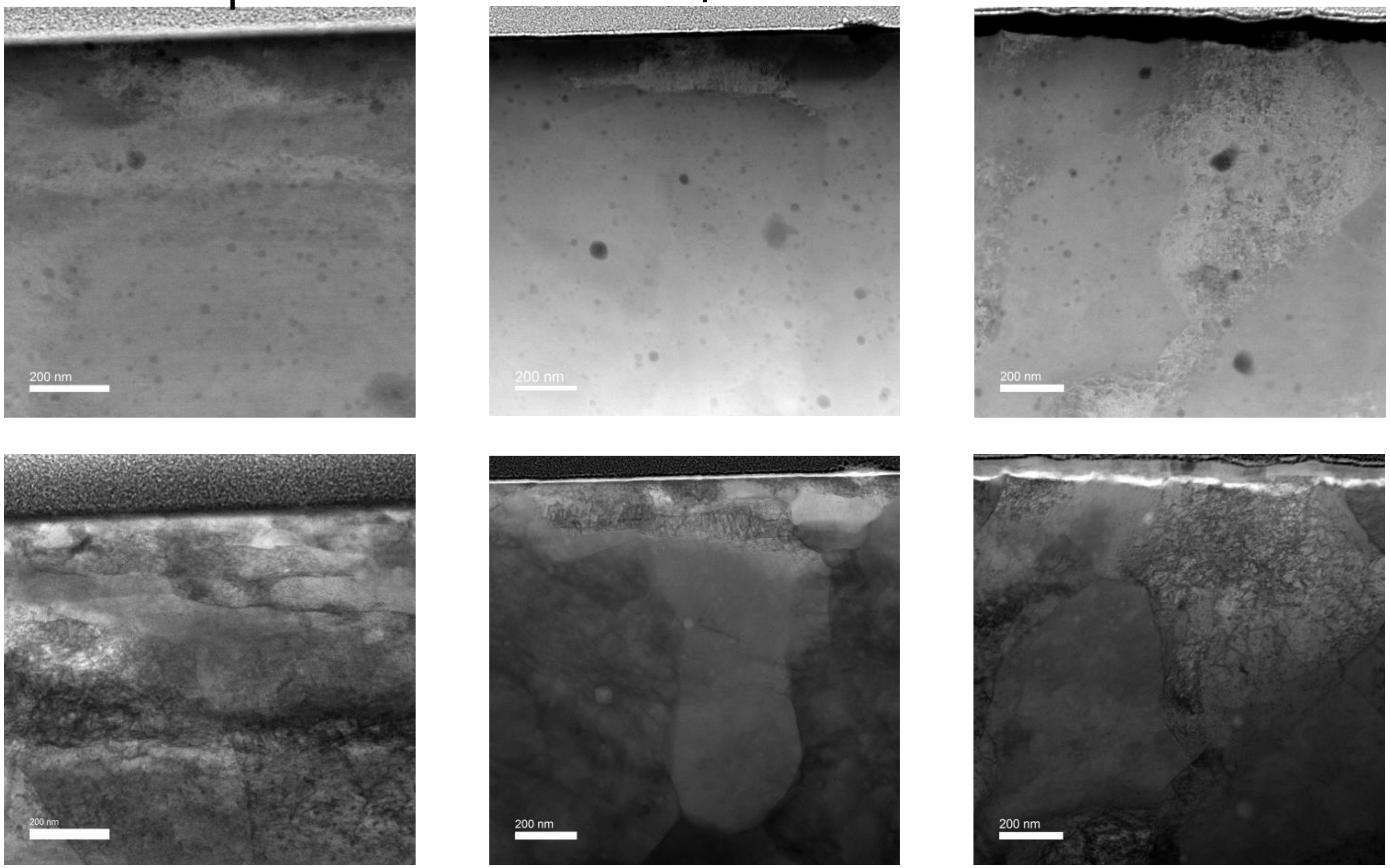
- Coarsening mechanisms (increased diameter, decreased number density and flatter distribution) consistent with previous results
- Size of dispersoids consistent with atom probe tomography (APT) results
  - BM Oxide Particles: 7.2 nm/0.74% volume fraction (APT)

Effect of irradiation on BM (0, 1 and 25 dpa)

0 dpa | 1 dpa | 25 dpa

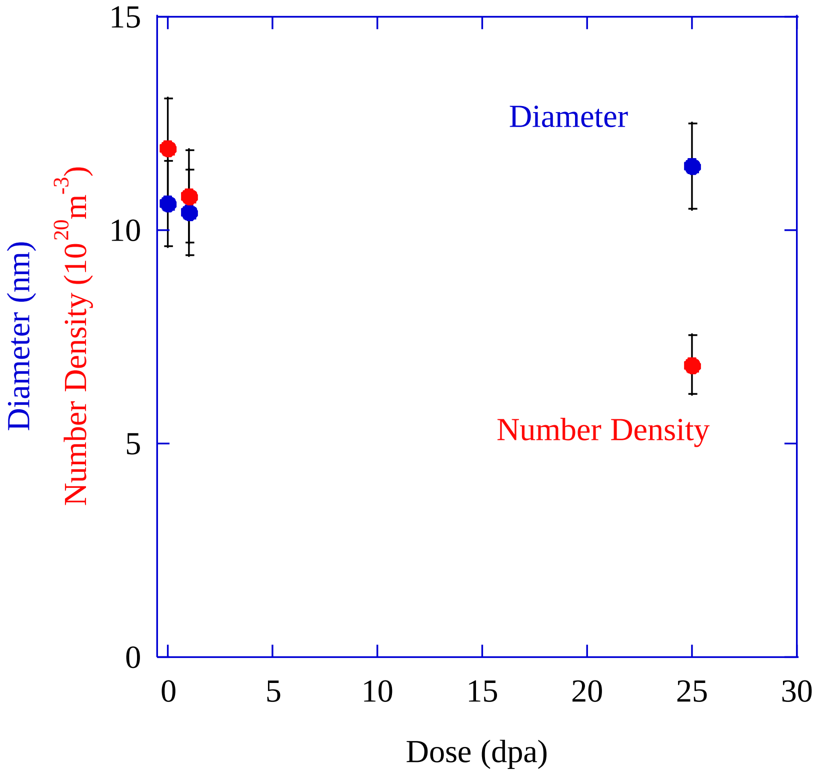
HAADF

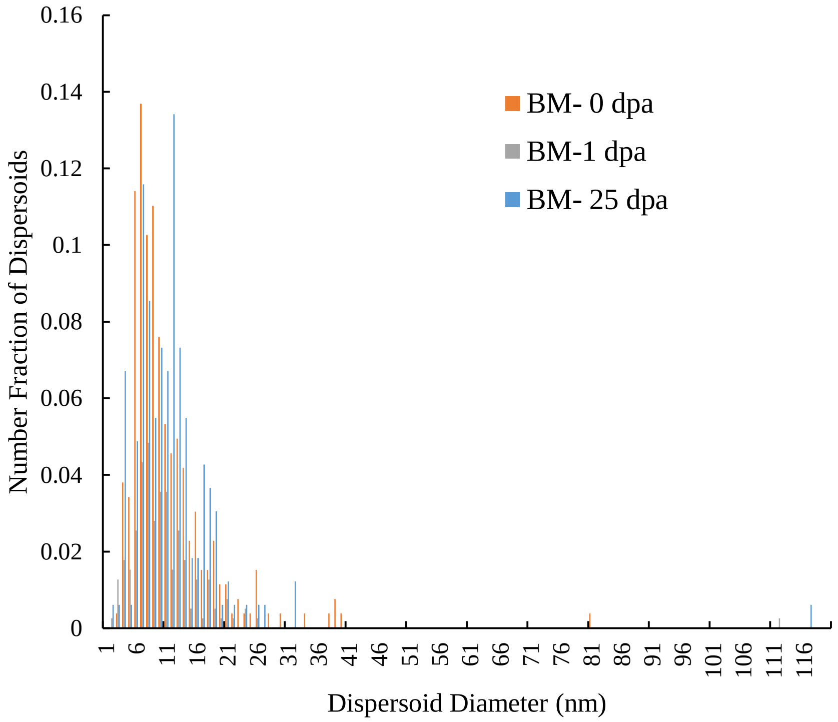
BF



- Heterogeneous distribution of dispersoids observed at 0, 1 and 25 dpa

Dispersoid Evolution with Increased dpa (BM)

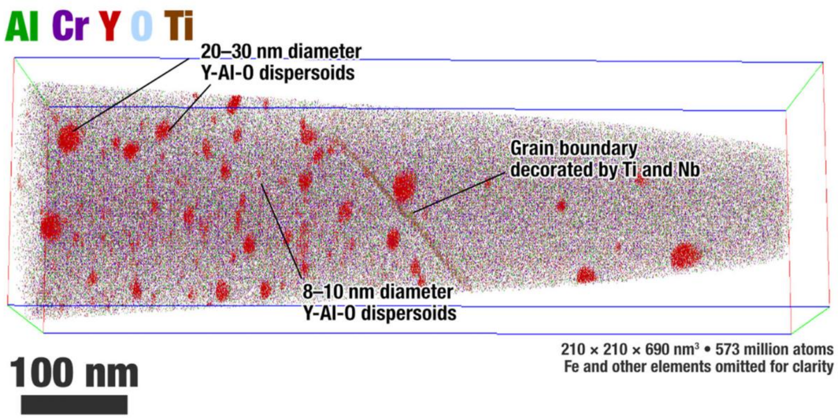




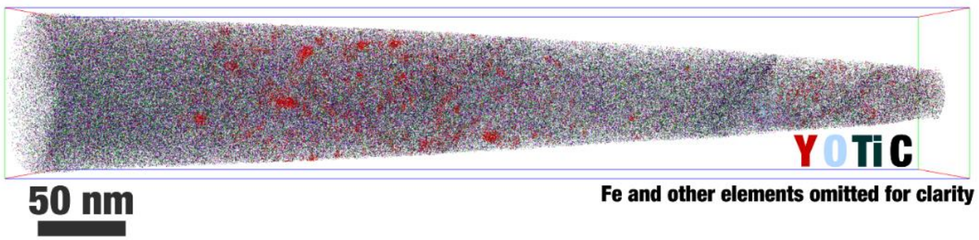
- Evidence of coarsening with irradiation
  - Increased diameter, decreased number density
- Shift of distribution to the right and flatter distribution

APT: Evidence of heterogeneous dispersoid distribution

0 dpa



25 dpa



B.W. Baker et al., Materials Science and Engineering A (2014) 217-227.

- Heterogeneous dispersoid distribution at both 0 and 25 dpa
- Grain boundaries enriched with Ti/Nb at 0 dpa and Ti/C at 25 dpa

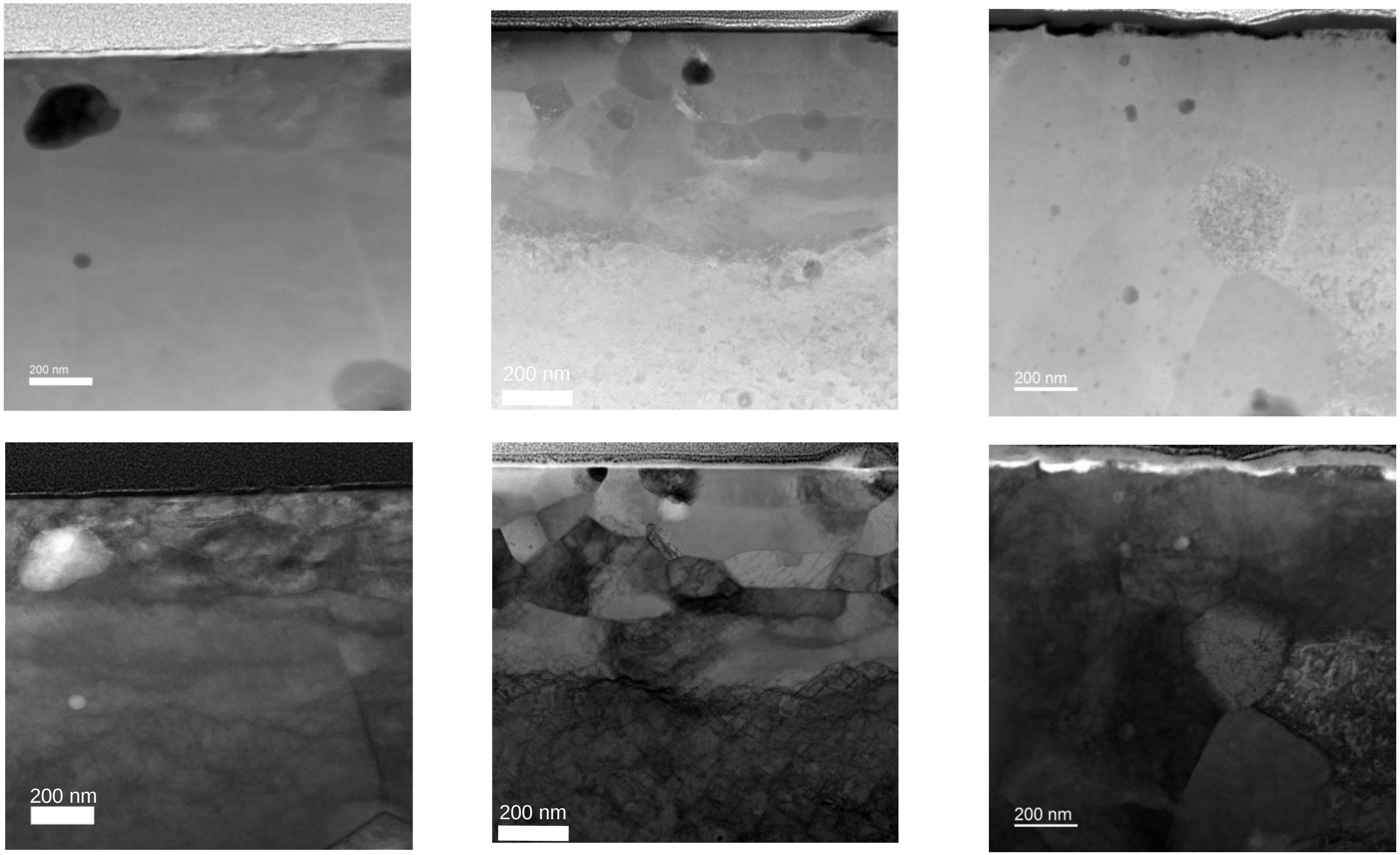
*APT data provided by K. Knipling at Naval Research Laboratory

Effect of irradiation on FSW (0, 1 and 25 dpa)

0 dpa | 1 dpa | 25 dpa

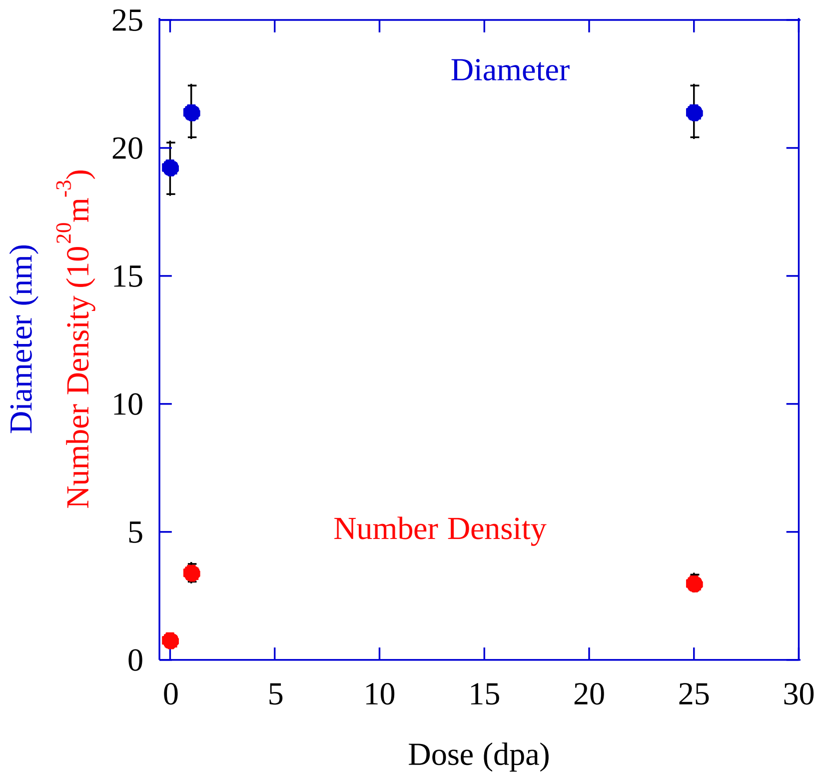
HAADF

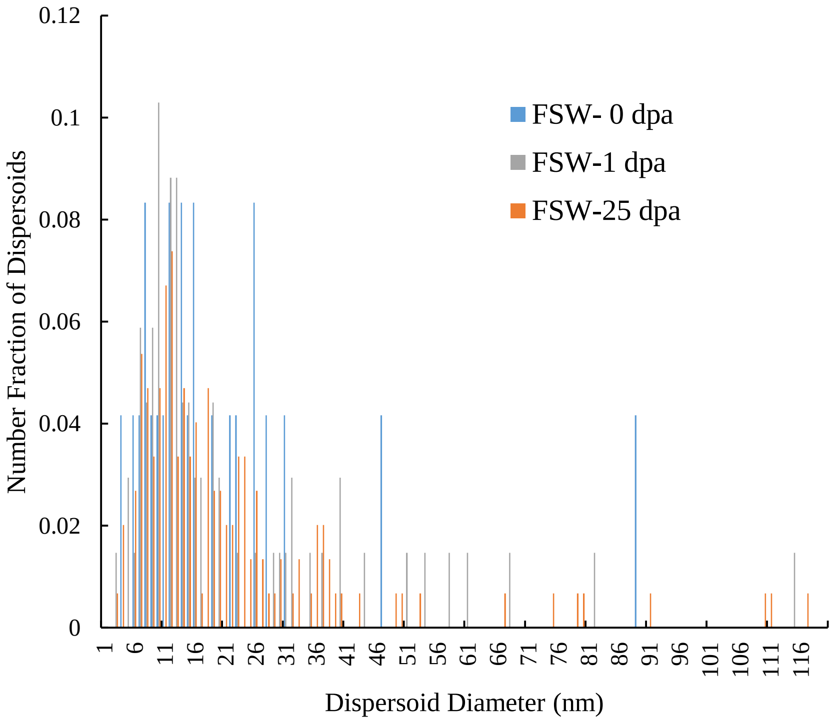
BF



- Formation of "new" dispersoids- evidence of reprecipitation?

Dispersoid Evolution with Increased dpa (FSW)

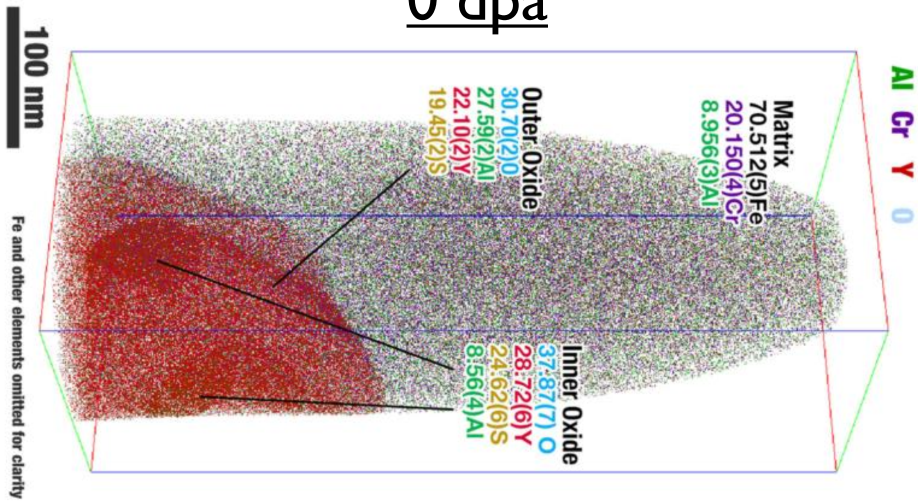




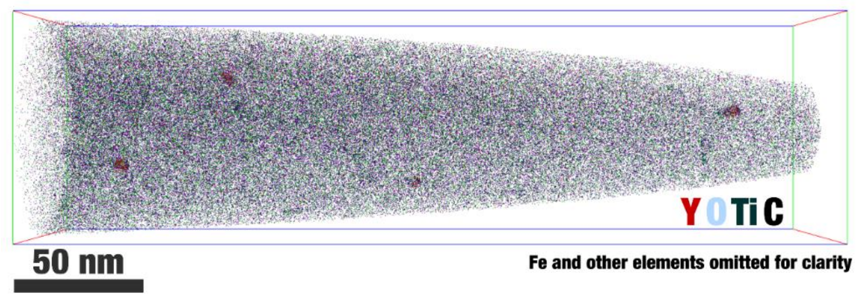
- Increase in number density due to small dispersoids re-precipitating post welding observed at 25 dpa but not 1 dpa
  - Again, low statistics for FSW as received

APT: Evidence of Re-precipitation?

0 dpa



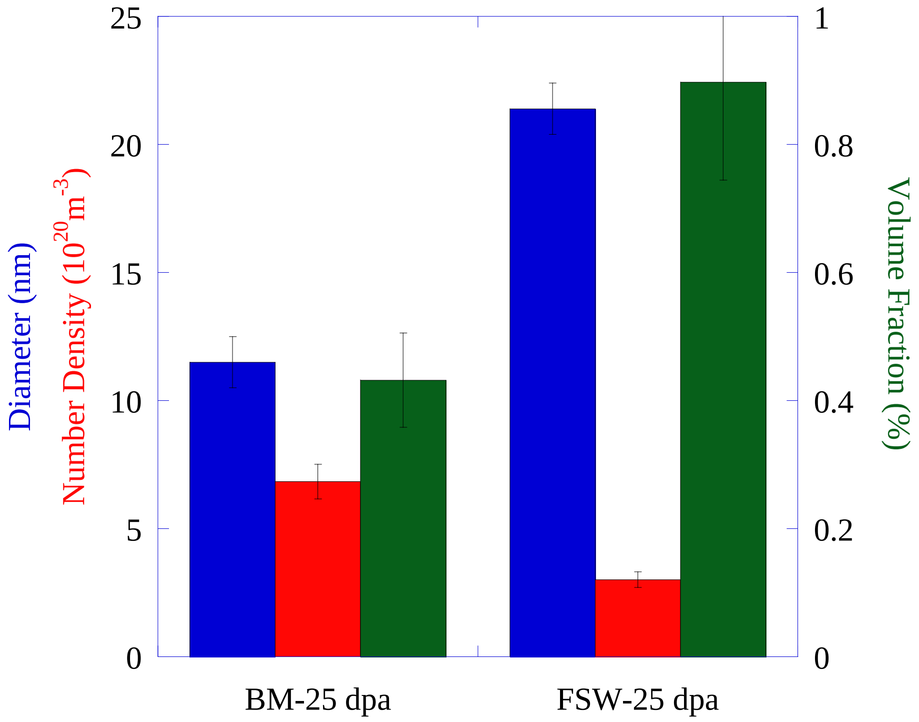
25 dpa

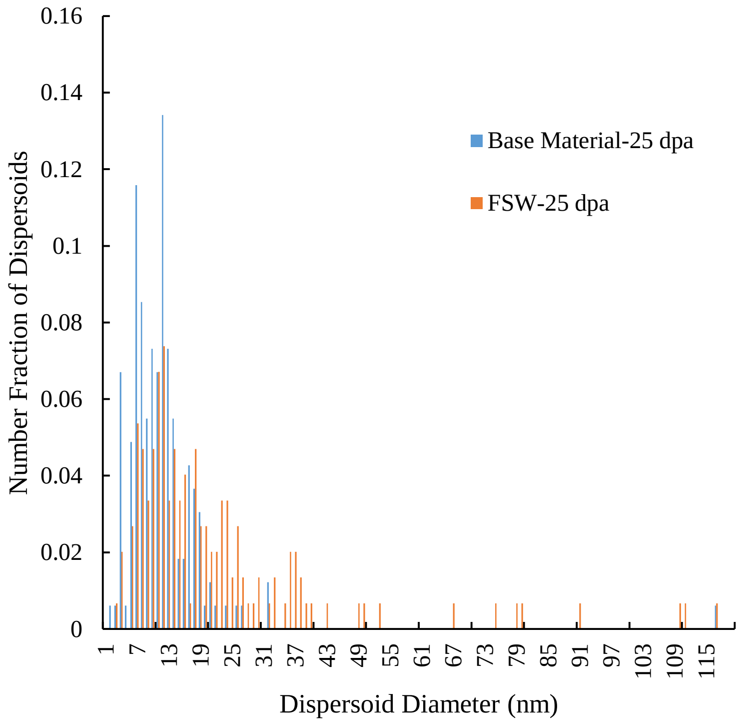


B.W. Baker et al., Materials Science and Engineering A (2014) 217-227.

- Small precipitates seen in all tips of irradiated FSW
- No larger coarsened precipitates observed at 25 dpa
  - Likely due to the low density of very large precipitates

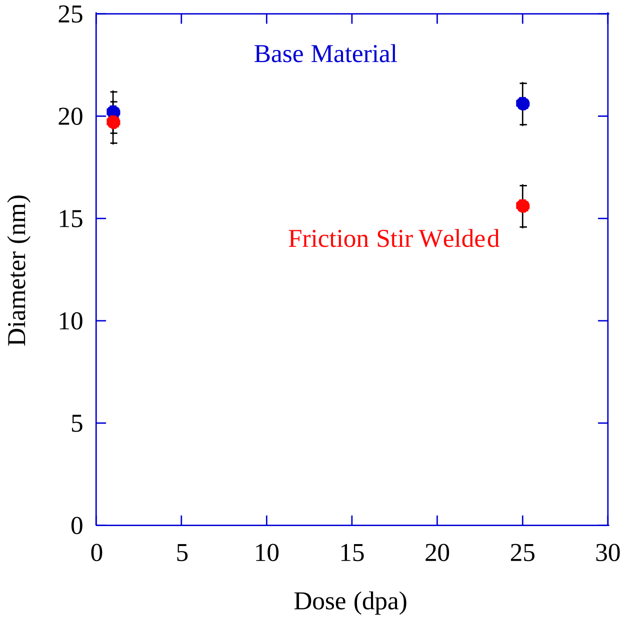
Comparison of BM and FSW at 25 dpa

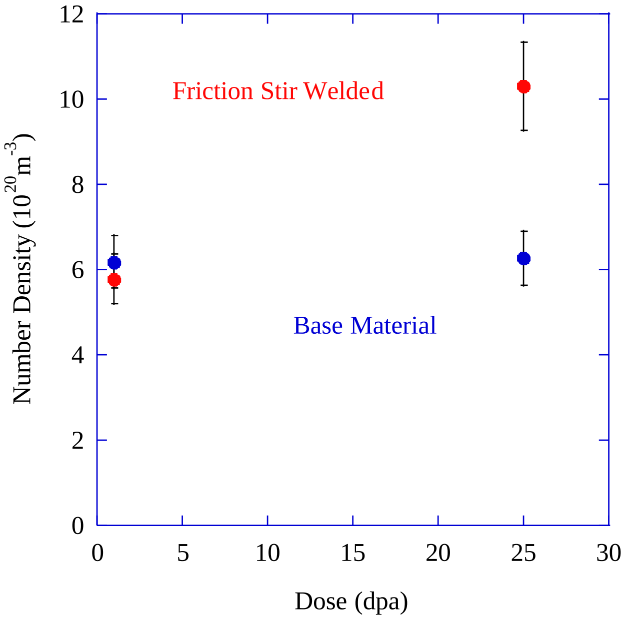




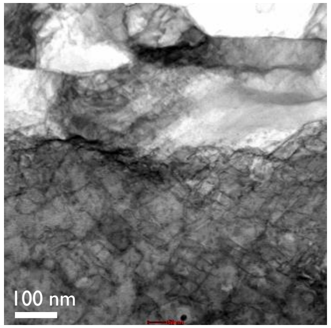
- Dispersoid number density increase regains some of the lost strength from welding
- Coarsening from FSW dominant feature

Evolution of Dislocation Loops

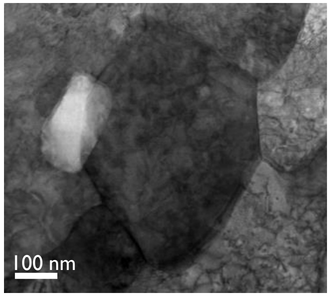




FSW, 450°C, 1 dpa

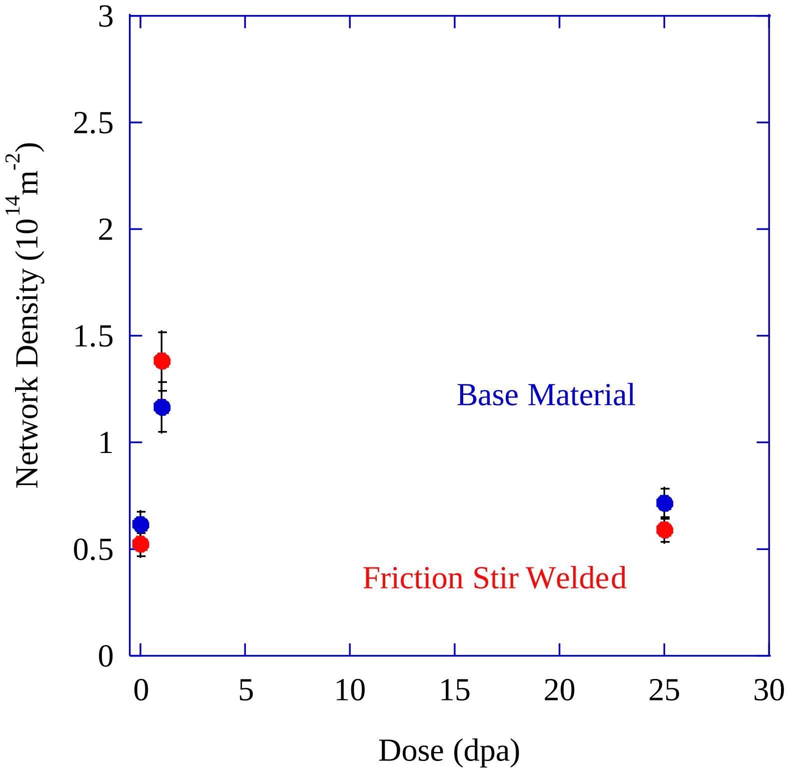


FSW, 450°C, 25 dpa

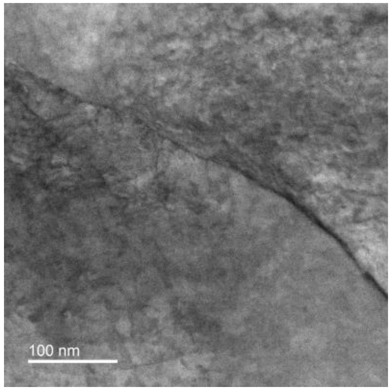


- Relatively large loops formed by 1 dpa also recovers lost strength from welding

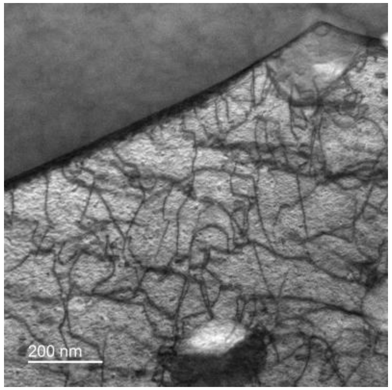
Network Density



BM, as received



FSW, as received

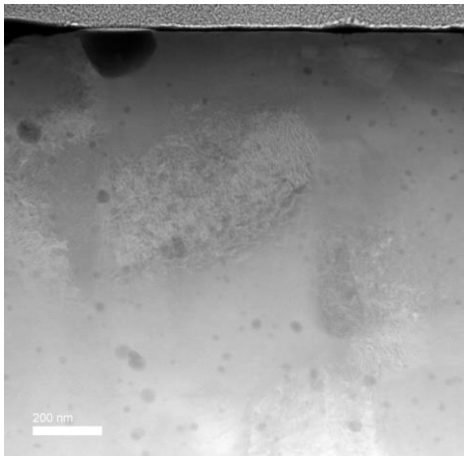


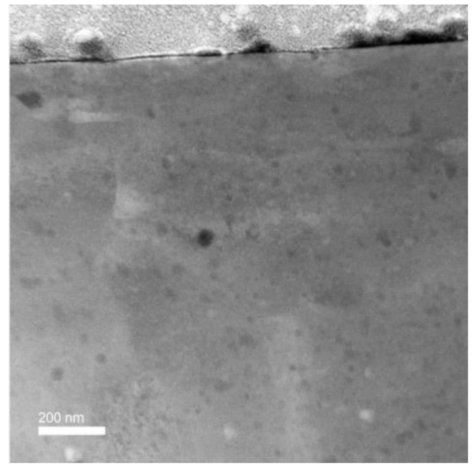
- Network density correlated to strength and typically increases with irradiation according to literature
  - Small decrease in network line density with welding likely due to annealing

Ex situ bulk versus lamella irradiation (1 dpa)

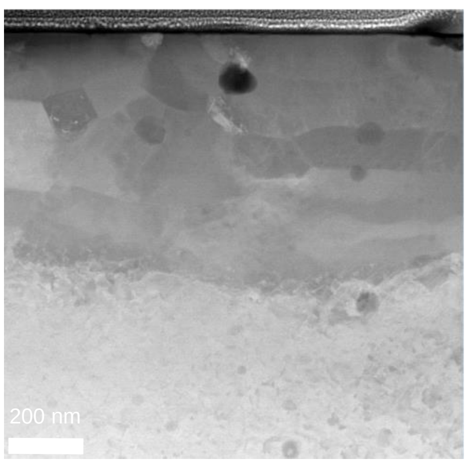
Bulk | Lamella

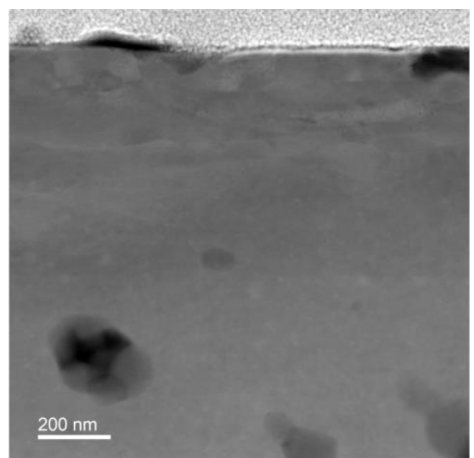
BM





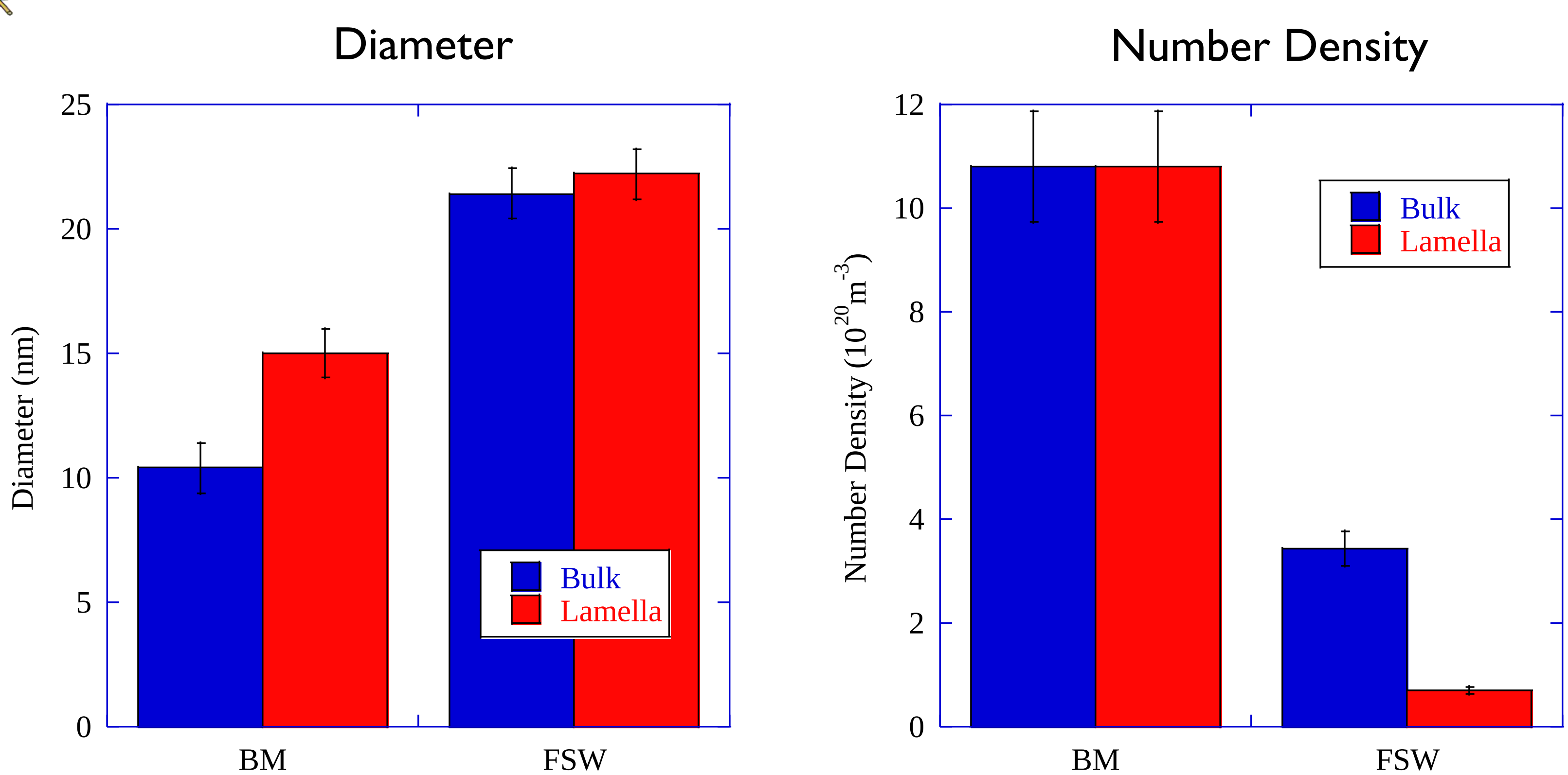
FSW





- White precipitates formed in lamella irradiations- may be surface contamination
- No other obvious differences in microstructure

Ex situ bulk versus lamella irradiation



- Variation in number density likely due to poor statistics of FSW (1 analyzed lamella sample per condition)

Significant Findings

- With irradiation, coarsening was observed in the base material. The FSW MA956 dispersoids exhibited both coarsening as well as potential re-precipitation of dispersoids lost during the welding process suggesting that strength lost due to welding process may be recovered via irradiation
- Differences between ex situ irradiations of bulk or lamella type samples were minimal for the features discussed
  - *In situ* irradiations are scheduled so a three way comparison can be made

Questions?