NE 591: Advanced Reactor Materials

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Last Time

- Austenitic steels undergo excessive void swelling in fast reactor conditions
- F/M steels have good mechanical properties, are cheap, and their microstructure can be tailored through composition and fabrication
- M23C6 and monocarbide precipitate are prevalent both along grain boundaries and within the grains; M2X metallic precipitates form and can be converted to Laves phases
- F/M steels swell very little due to fundamental nature of defects in ferrite, C-vacancy bonding, and dislocation-solute interactions
- Tailoring of alloying elements has allowed for improved creep strength
- Stress induced preferential nucleation/absorption (SIPN – SIPA)
- Swelling interaction with creep

ADVANCED CLADDING

Irradiation Embrittlement

- Ferritic steels have these large monocarbides which aid in creep resistance
- The lath boundaries are decorated with Cr rich M23C6 precipitates which increase the thermal stability
- Embrittlement is caused by 1) segregation of elements to lath boundaries which make the grain boundaries decohesive, and 2) evolution of carbides and intermetallic phases
- For removable components such as clad, which are subjected to high temperature and pressure with a residence time of a few years, creep embrittlement is the issue which decides their design and performance
- For permanent support structures increase in hardening and loss in fracture toughness on irradiation are major issues

Irradiation Embrittlement

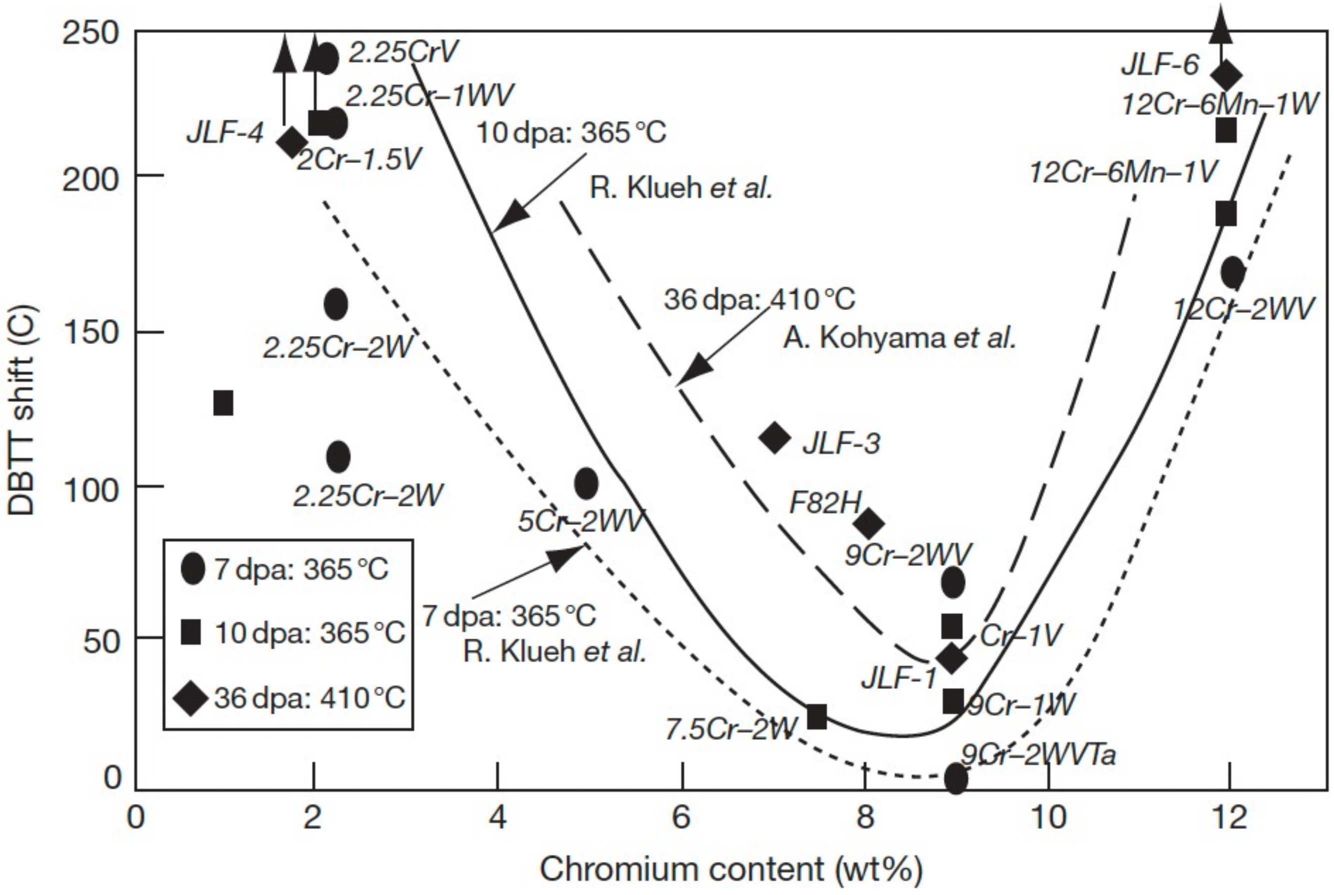
- The increase in the ductile to brittle transition temperature, DBTT, is known to be related to irradiation hardening, which is generally observed to saturate with fluence
- Evidence for a possible maximum in DBTT was observed for the 12Cr steel irradiated in the range of 35–100 dpa in the FFTF
- High fluence and/or high temperature are required before a maximum is observed
- Thus, these properties are a balance between the point defect production and irradiation-induced precipitation
- The precipitation during irradiation hardens the steel and irradiation accelerated recovery and aging soften the steel
- The high temperature recovery produces an observable saturation in hardening above ~720K

DBTT

- BCC materials can undergo significant increase in the DBTT at low T for even 1 dpa
- The minimum operating temperature to avoid embrittlement F/M steels is ~500 K
- Extensive evaluation of the embrittlement behavior of the ferritic steels for different chemistry has been performed
- Compositions around 9Cr show the least change in the DBTT
- Chemical variation affects on DBTT changes has been thoroughly studied
- Addition of phosphorous, copper, vanadium, aluminum, and silicon increase the DBTT

DBTT

- The 12Cr steels, HT9, show a larger shift in DBTT as compared to modified 9Cr–1Mo steel
- The balance is always between nearly nil swelling resistant 12Cr steels and 9Cr steel which is less prone to embrittlement than 12Cr steels



Features affecting Embrittlement

- There are a number of microstructural features that can impact the embrittlement of F/M steels
- Prior austenite grain size (PAGS)
- The size of martensitic lath and packet (which is sensitive to austenitization temperature)
- Tempering/annealing, which can increase carbide precipitate size
- The generation of helium through (n,alpha) reaction
- For low thickness components, the triaxial stress necessary for the embrittlement does not develop, which reduces the intensity of this otherwise serious problem of embrittlement in ferritic steels

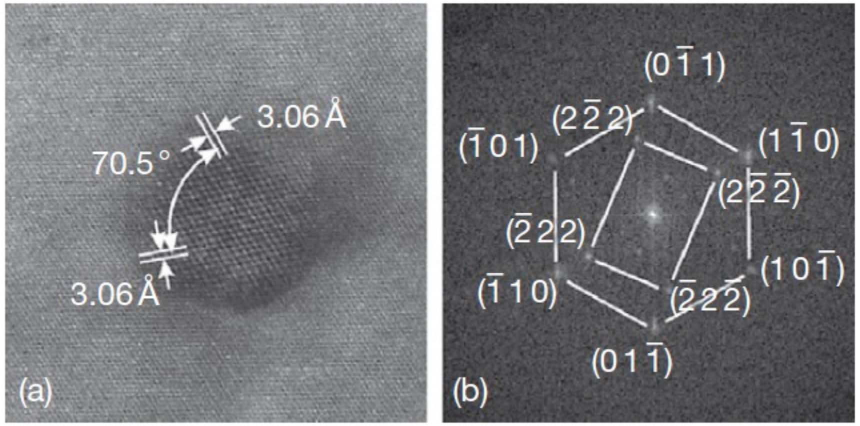
Ferritic/Martensitic Steels Summary

- Refer to “last time” slide…
- Embrittlement is caused by segregation of elements to lath boundaries and evolution of precipitates
- Maximum DBTT shift occurs in F/M steels for high T or fluence
- DBTT shift is minimized for 9Cr steels
- Microstructure can impact the embrittlement behavior
- In thin-walled materials, such as cladding, the stress state that leads to cladding embrittlement is typically not prevalent

ODS STEELS

Oxide Dispersion Strengthened

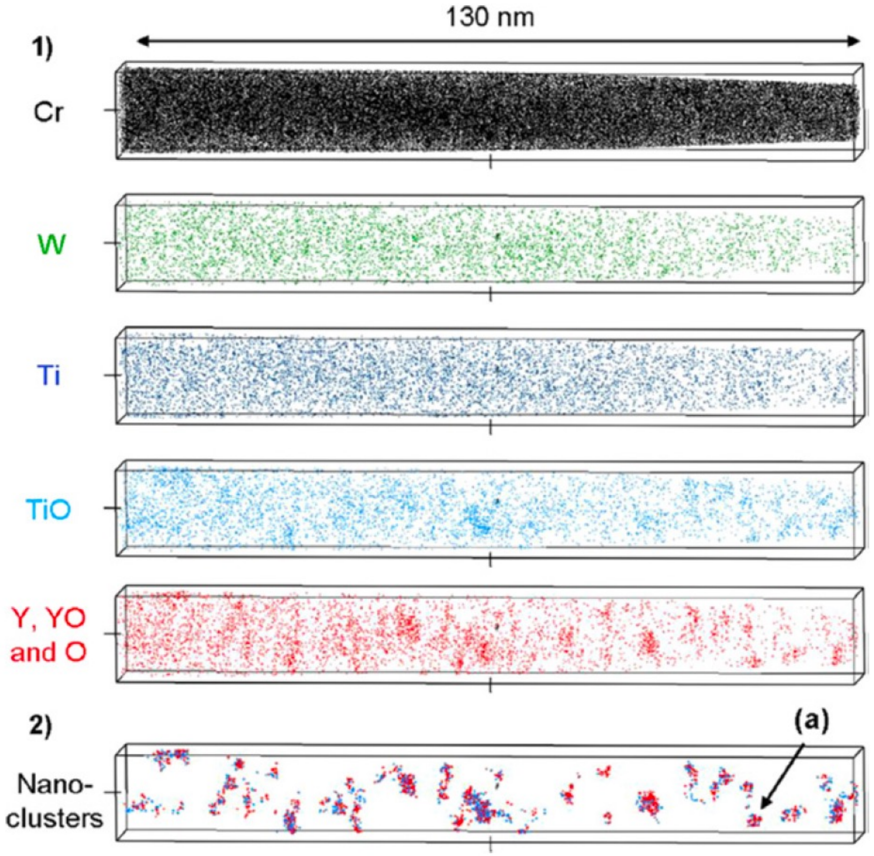
- Thermally stable oxide particles dispersed in the ferritic matrix improve the radiation resistance and creep resistance at high temperature
- ODS steels have a strong potential for high burnup (long-life) and high temperature applications typical for SFR fuels
- Typically, Y2O3 particles or Y2Ti2O7 particles



Y2O3 particle with surrounding matrix

Y2O3 Decomposition

- The fine distribution of Y2O3 particles is attained by the dissociation of stable Y2O3 particles which are forced to decomposed into the ferritic steel matrix during the mechanical alloying process
- The lattice structure change of Y2O3 in the ODS steel during MA consists of three stages: (1) destruction of the lattice structure, (2) formation of a blurry lattice structure, (3) appearance of amorphous areas

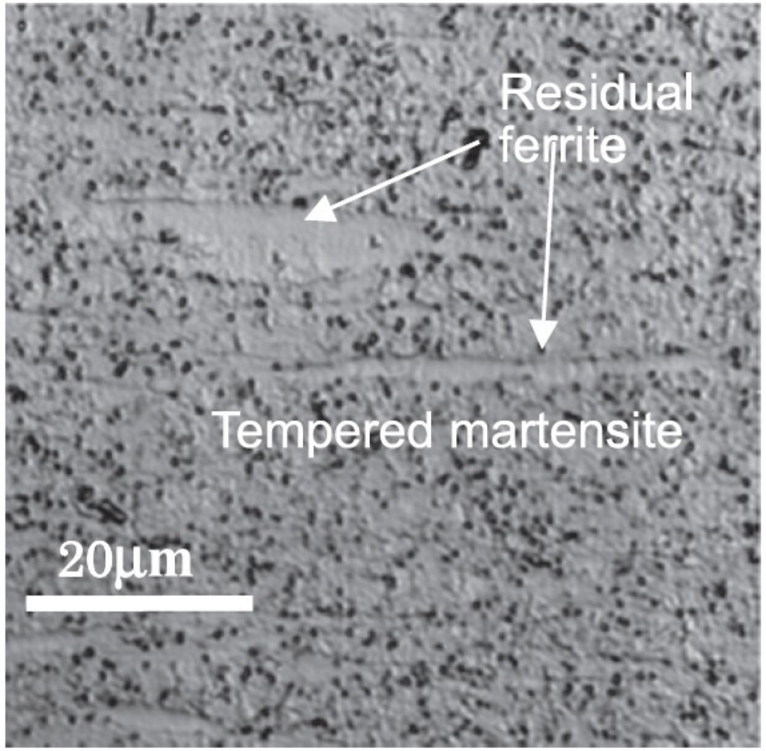


9Cr-ODS

- For nuclear applications, the choice of 9 wt% Cr with a tempered martensitic matrix is preferable to suppress the ductility loss by irradiation hardening and improve the microstructure stability and creep strength at high temperature
- The high-temperature strength of 9Cr-ODS is drastically improved by nano-scale oxide particles dispersion in the matrix
- The standard chemical composition of 9Cr-ODS being developed by the JAEA for SFR application is 9Cr–0.13C–0.2Ti–2W– 0.35Y2O3 (wt%)
- The addition of titanium produces the nanoscale dispersion of oxide particles
- Tungsten of 2 wt% is also added in order to improve high-temperature strength by means of solid solution hardening

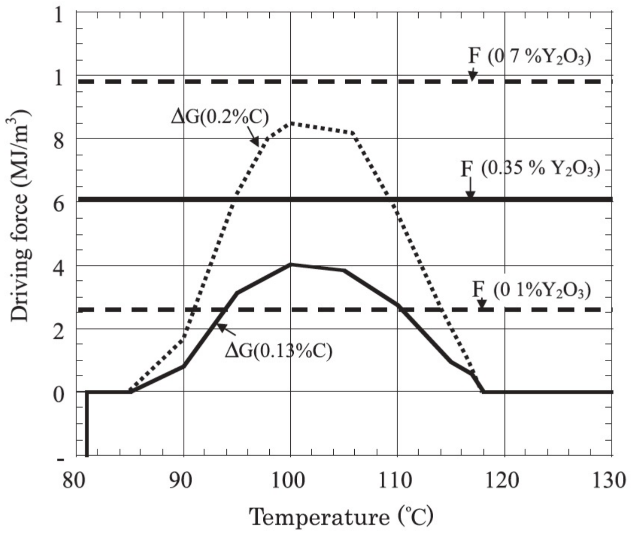
9Cr-ODS microstructure

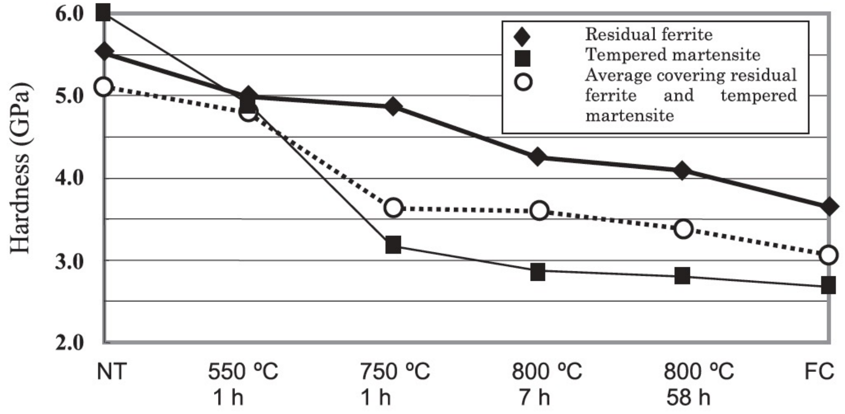
- The microstructure of 9Cr-ODS steel cladding is basically tempered martensite, but includes some residual ferrite phases
- Only the full martensite phase can be expected in 9Cr-ferritic steel without yttria under the same conditions
- The high temperature strength is greatly improved with the ferrite, and thus control of ferrite is key in ODS fabrication



Residual Ferrite

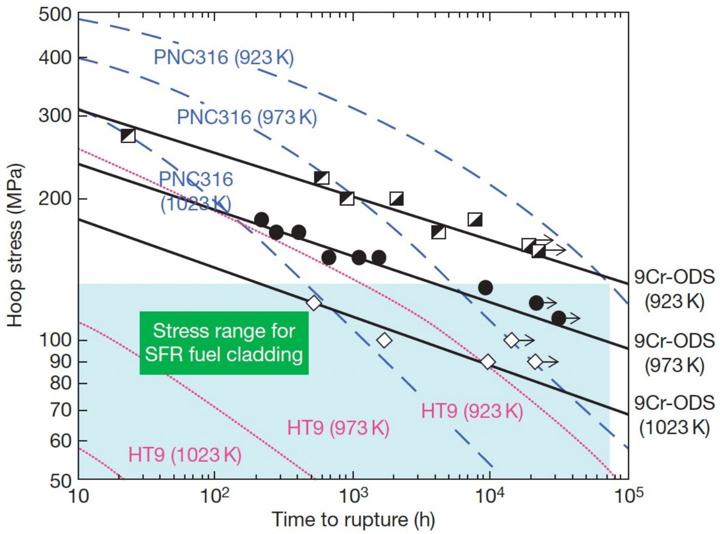
- Annealing results in the formation and precipitation of Y–Ti complex oxide particles at elevated temperatures of 700C or higher
- Since the reverse transformation of alpha (ferrite) to gamma (austenite) takes place at a temperature over 850C, alpha ferrite is attributed to the presence of the Y-Ti-O particles
- These particles block the motion of the alpha-gamma interface, there by partly suppressing the reverse transformation from alpha to gamma-phase

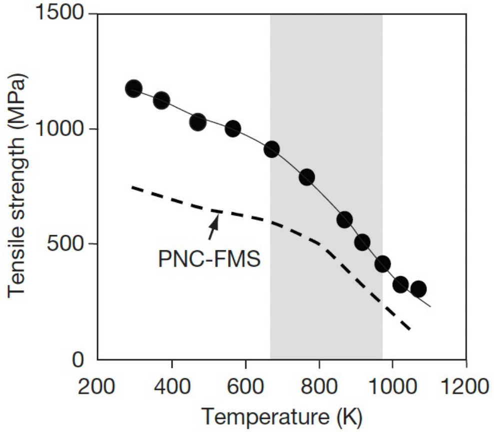


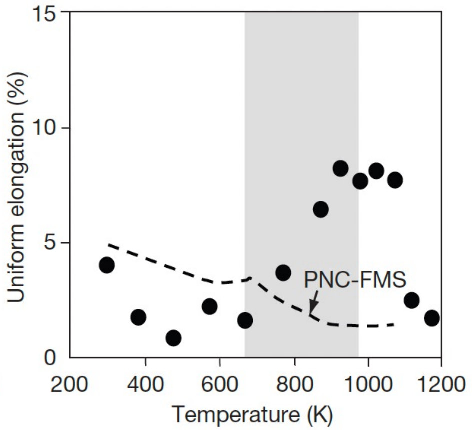


Mechanical Properties

- The lifetime of a SFR cladding is mostly determined by the internal creep rupture strength with the internal pressure of the fission gas at a temperature of ~700C
- PNC316 is austenitic steel used developed by JAEA for fast reactors
- PNC-FMS is a F/M steel
- 9Cr-ODS steels have superior creep resistance and higher tensile strength

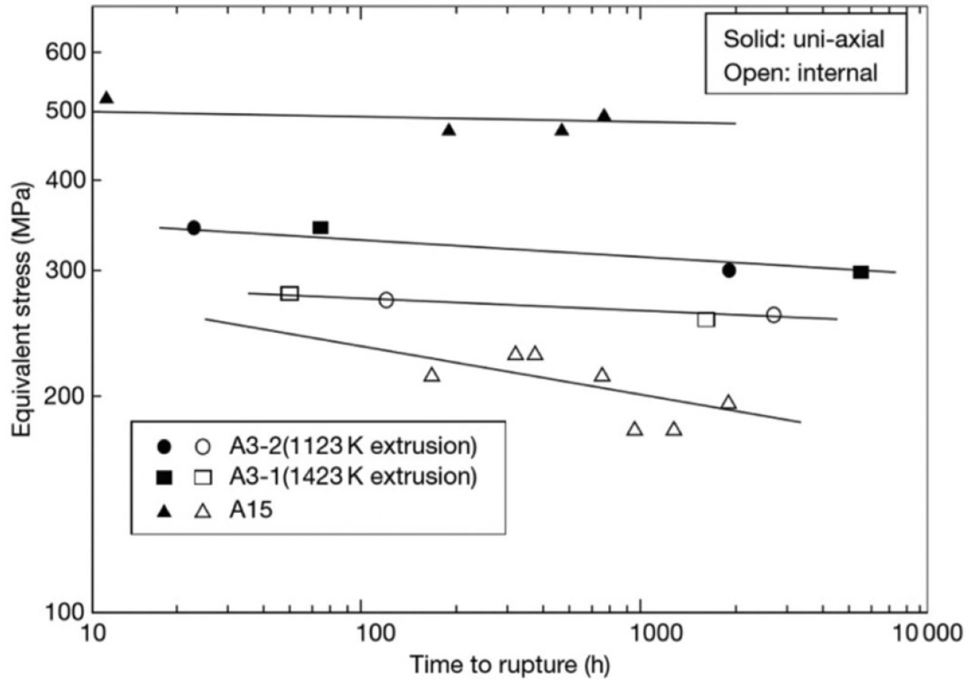






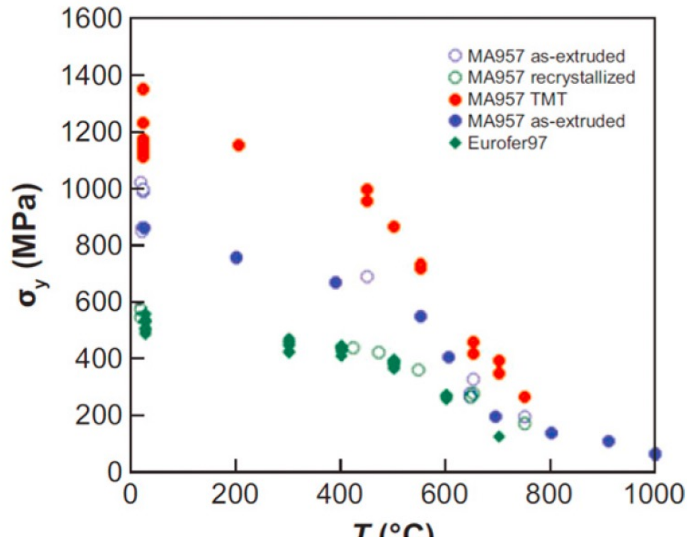
Ferritic 12Cr-ODS Steel

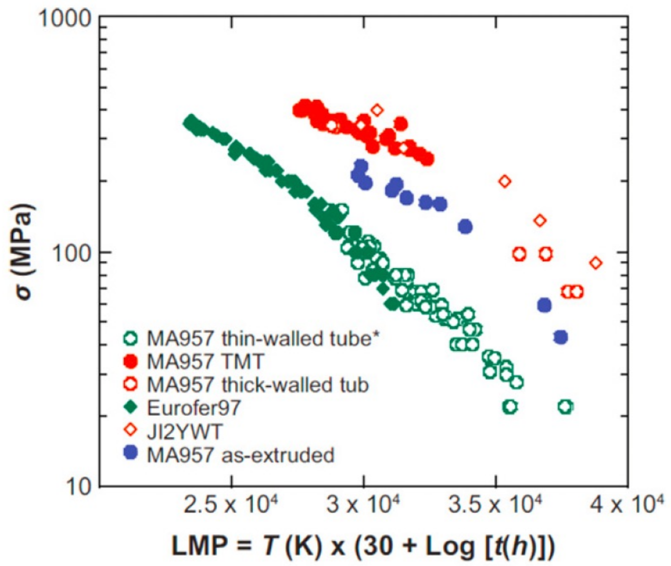
- Development of ODS steels began with purely ferritic types, similar to MA957
- While these types of steel exhibit excellent creep rupture resistance, there is anisotropy of the rupture strength
- If the Y2O3 content is kept sufficiently low, an equiaxed grain structure can be maintained, providing more isotropic mechanical properties



NFAs

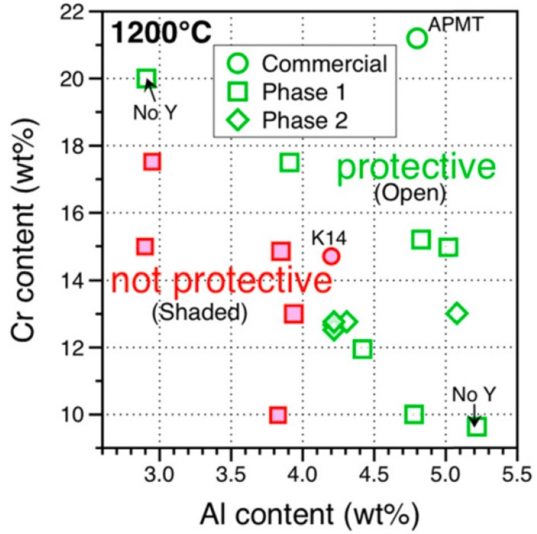
- Nanostructured ferritic alloys (NFAs) are 12%–20% Cr ferritic stainless steels that are dispersion strengthened by a very high density of ultrafine Y-Ti-O nanofeatures
- This high density can yield excellent strength and radiation resistance, but make fabrication processes very difficult
- MA957 and Eurofer are examples of NFAs

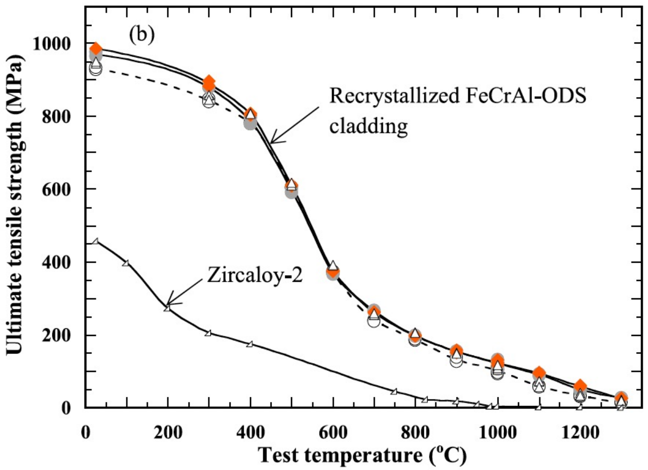




FeCrAl-ODS Steel

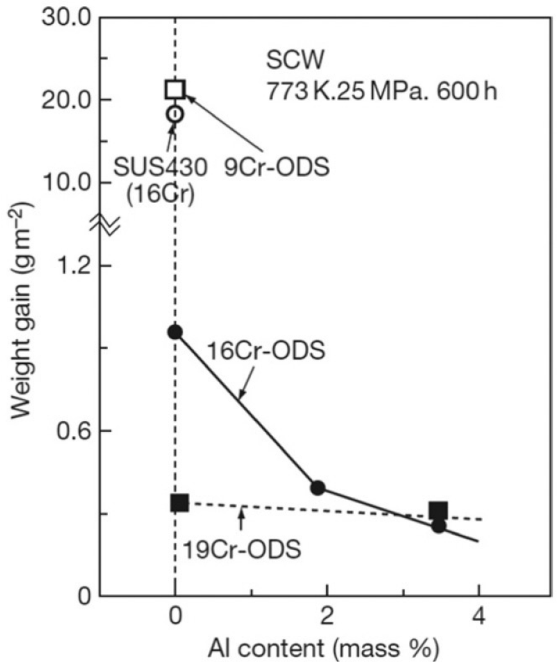
- FeCrAl steels, with and without ODS are of interest since Al-containing steels produce the stable alumina (Al2O3) scale to prevent direct reaction of Fe with steam
- A nominal composition of Fe-10Cr-6.1Al-0.3Zr (wt%) with 0.3wt% Y2O3 has been studied by ORNL
- Zr is added to prevent Y-Al oxide particle formation

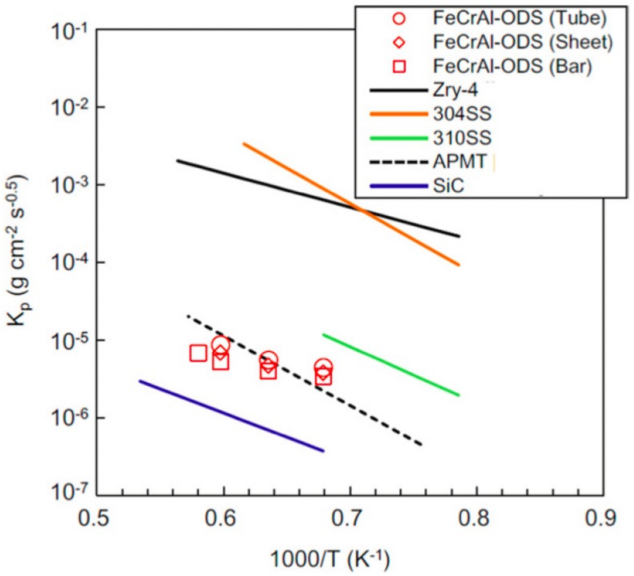




Corrosion

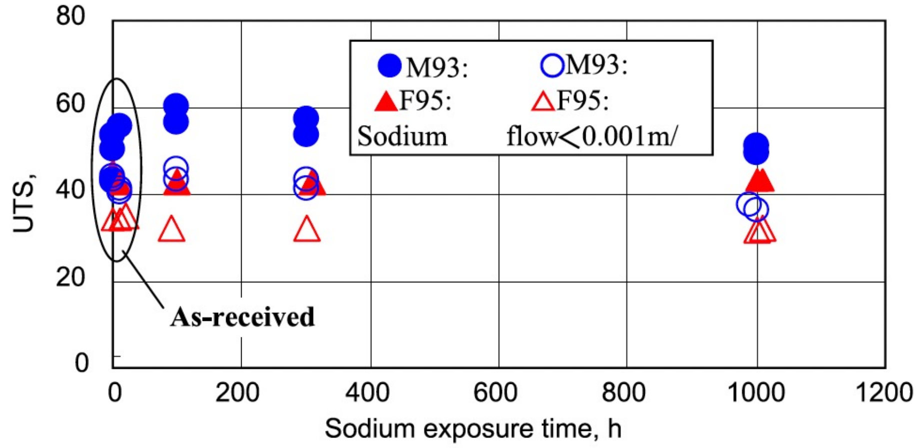
- Hot steam oxidation tests are fairly limited in ODS steels
- Additional Cr improves corrosion resistance, and Al content greater than 2 wt% provides a protective barrier
- Excess oxygen content in the alloys can serve to suppress corrosion
- In systems with high amounts of excess oxygen, Zr content can further aid in corrosion resistance

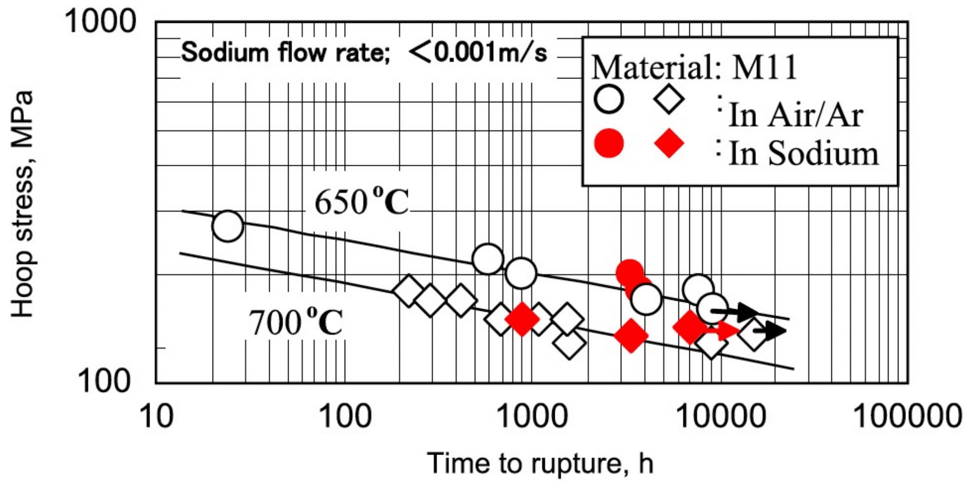




Liquid Na Compatibility

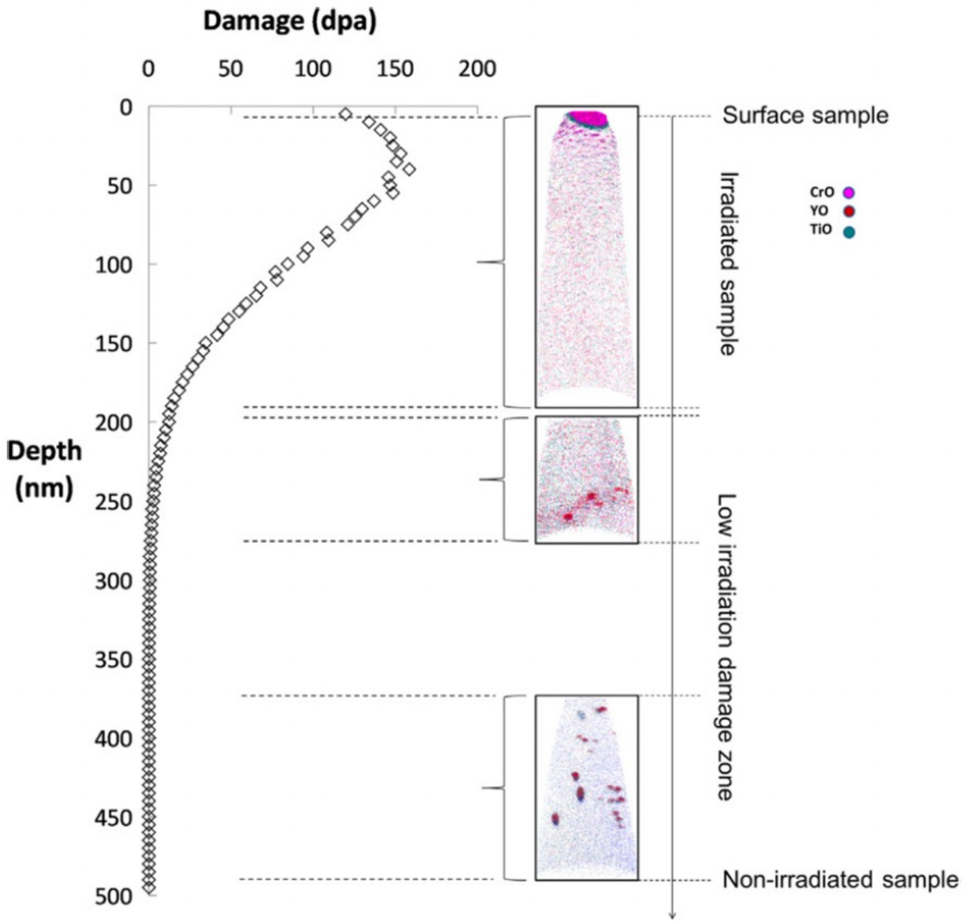
- OSD-steels display excellent compatibility with liquid sodium
- Both 9Cr and 12Cr ODS steels show no degradation in UTS after prolonged exposure to Na
- Creep rupture behavior of ODS steels in air is identical to that in liquid Na
- Under irradiation, this corrosion behavior may change, but has not been thoroughly studied





Irradiation Effects

- The stability of the oxide particles under irradiation is the key factor in these alloys maintaining their advantageous mechanical properties under operation
- Ballistic dissolution is the ejection of atoms from oxide particles due to high energy PKAs and the disordering of the particles

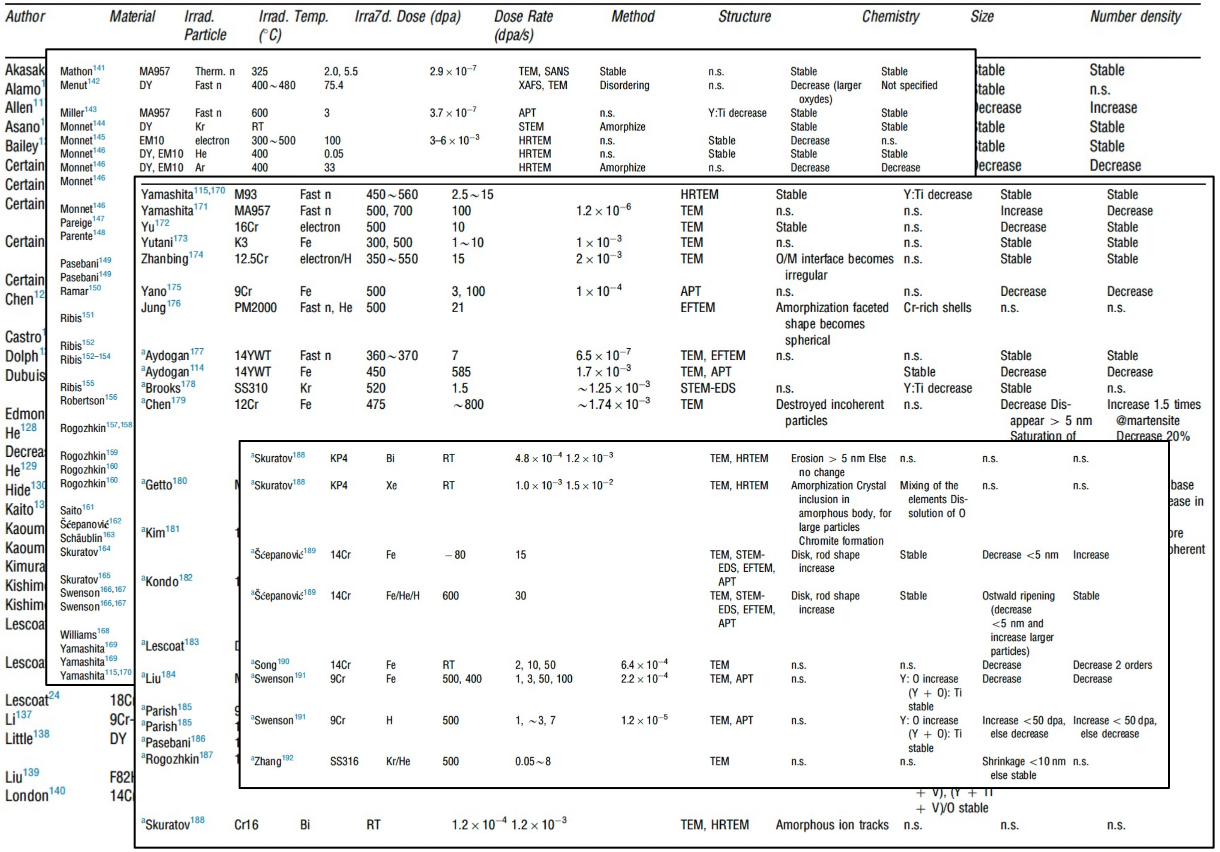


Irradiation Effects

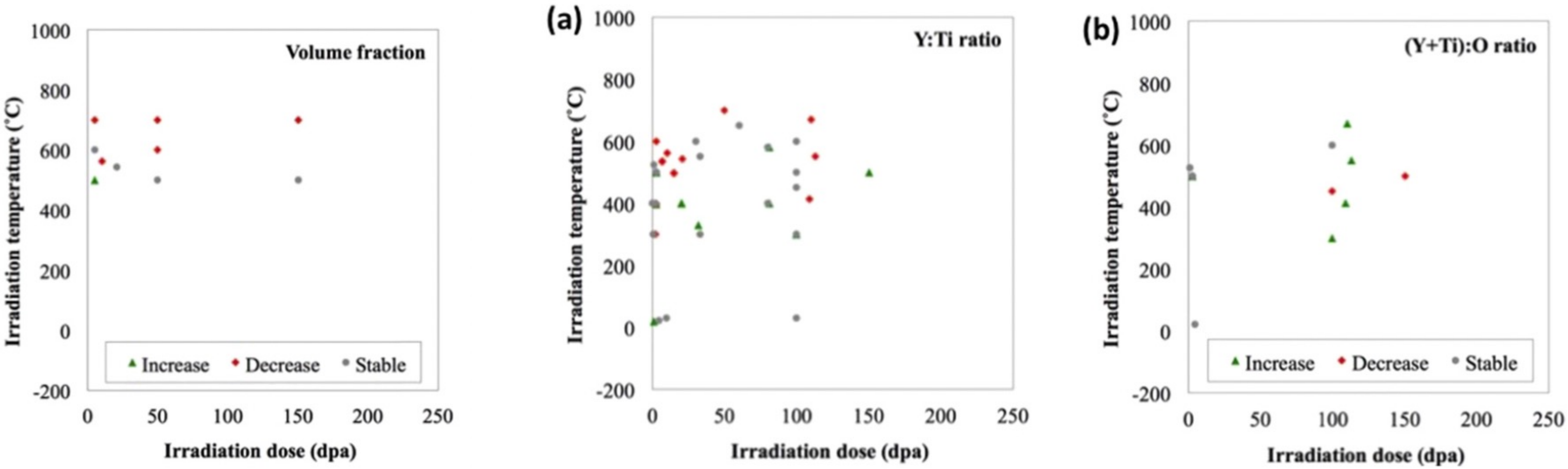
- At higher temperatures where vacancy diffusion is possible, ballistic dissolution works in conjunction with irradiation-assisted diffusion and changes the dispersion of oxide particles
- The atoms ejected from oxide particles can diffuse back to the original oxide particles, stay in the matrix, or reach other oxide particles
- Most research groups have reported that the size and number density of the oxide particles hardly change compared to how they were before irradiation
- The predominant mechanism of these results are the recovery arising from back diffusion to the original oxide particles or re-join to other existing oxide particles

Irradiation Effects

- A large number of irradiation experiments have been performed and analyzed to study the evolution of oxide particles
- It appears that there is no correlation between irradiation dose, irradiation temperature, and the trend of change in size or number density of oxide particles



Irradiation Effects



Irradiation Effects

- Swelling:
  - ODS steels are very swelling resistant, as the oxide particles trap vacancies and gas atoms, resulting in very small and homogeneously dispersed voids/bubbles
- Hardening:
  - hardness increases due to irradiation in ODS steels are smaller than in non-ODS steels
  - Oxide particles dominate hardness, and act as sinks for generated point defects

Summary

- ODS is fabricated through mechanical alloying and subsequent annealing
- 9Cr-ODS steel has a unique structure consisting of tempered martensite and residual ferrite that induces superior strength through finely dispersed oxide particles
- NFAs have a very high density of oxide particles, producing very high strength and creep resistance, at the cost of workability
- FeCrAl-ODS can provide superior corrosion resistance while retaining the ODS influenced mechanical properties
- Further in-reactor studies on ODS steels need to be performed
- While performance of ODS steels is widely studied, current production is limited to laboratory scale, with prohibitive costs for large scale production