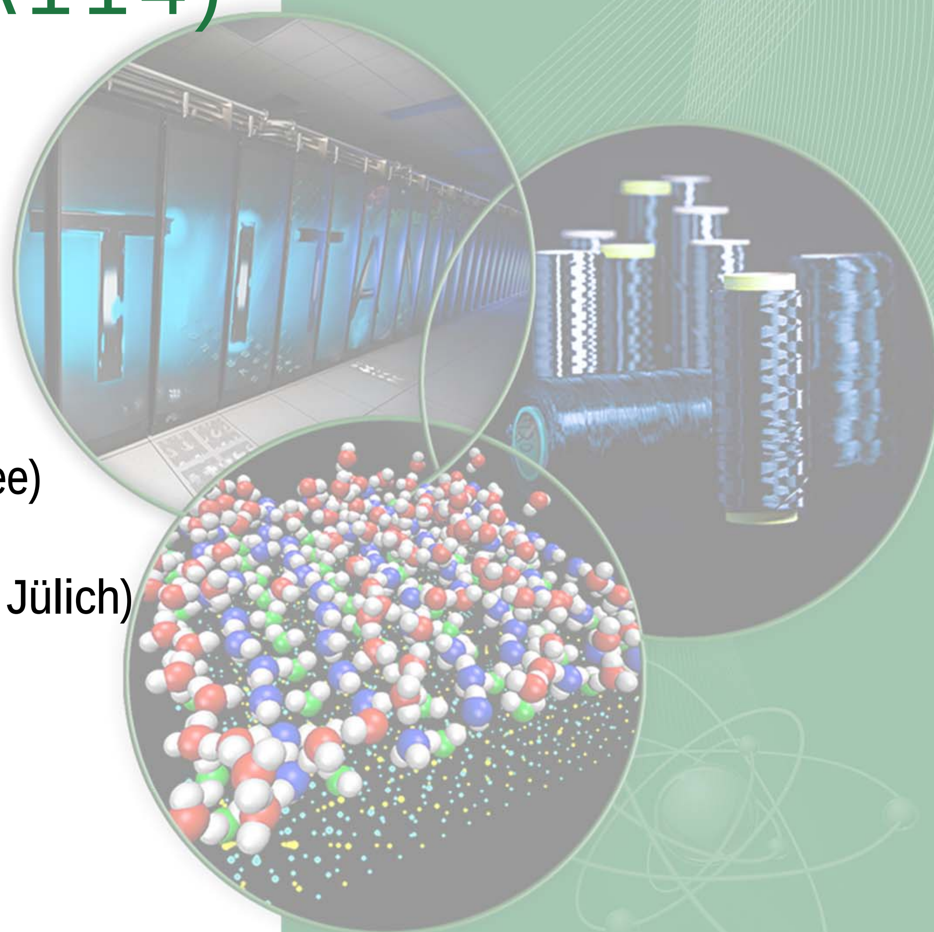
Advanced Alloy Design Concepts for High-Temperature Fossil Energy Applications (FEAA114)



PI: Yukinori Yamamoto

Oak Ridge National Laboratory
Oak Ridge, TN

Contributors:
Suresh Babu, Ben Shassere (Univ. of Tennessee)
Bruce Pint (ORNL)
Bernd Kuhn, Michal Talik (Forschungszentrum Jülich)

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Contents of This Talk

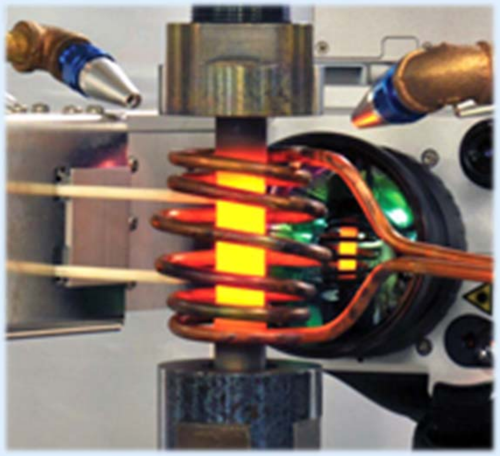
- Backgrounds/Motivation:
  - *High-Cr containing FeCrAl alloy development*
- Update on FY15/16
  - *Microstructure characterization of crept specimens*
  - *Oxidation update*
  - *Effect of alloying on Laves-phase solvus and size*
  - *Effect of alloying on yttrium effect*
  - *Trial weld results*
  - *Scale-up efforts*
- Summary
- Future Activities

Project objective

- To identify and apply breakthrough alloy design concepts and strategies for incorporating **improved creep strength, environmental resistance, and weldability** into three classes of alloys (ferritic, austenitic, and Ni-base) intended for use as heat exchanger tubes in fossil-fueled power generation systems at higher temperatures than possible with currently available alloys.

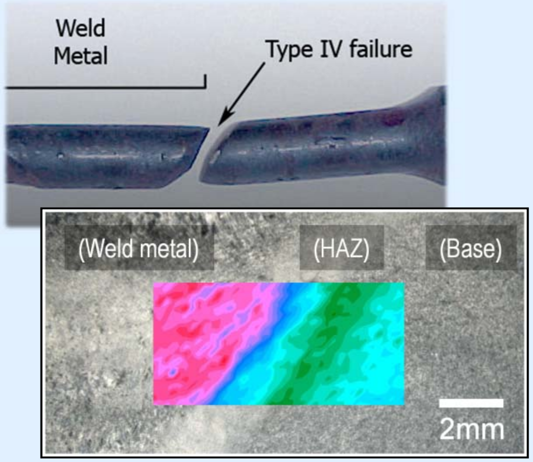
High-Cr containing FeCrAl ferritic alloy

High-temp. Strength



Oxidation/Corrosion

Weldments



https://mts.com/en/products/industry/materials-testing/index.htm
http://www.ccj-online.com/prioritization-of-issues-improves-hrsg-reliability-performance/

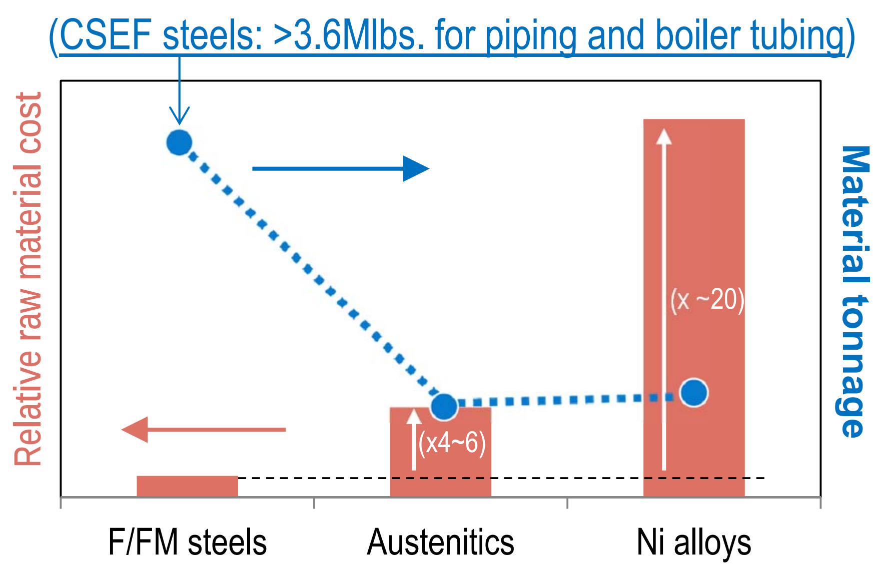
Target Materials/ Applications

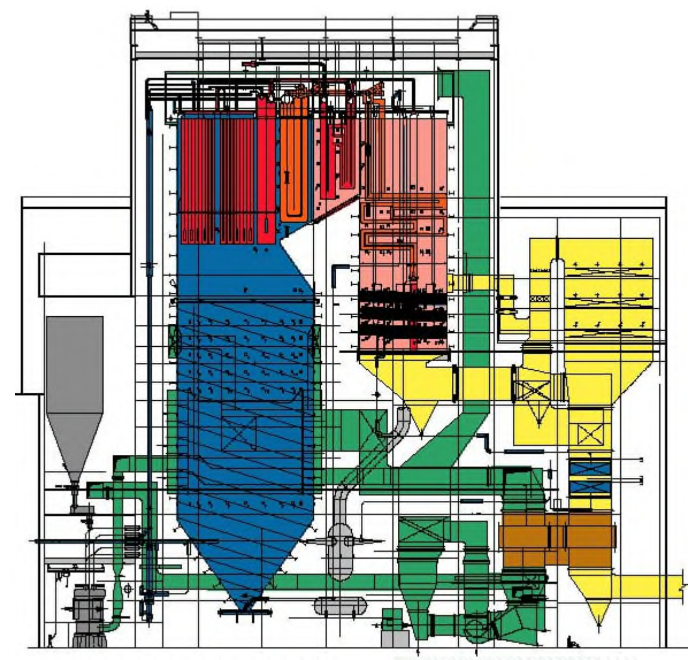
Three different grades of structural materials that are currently available for use by the US electric utility industry:

1) **Ferritic steels** for temperatures up to 600°C, with **ferritic-martensitic** versions (F-M steels) having increased strength up to 600-620°C;

2) **Austenitic stainless steels** with strength and environmental resistance up to 650°C; and

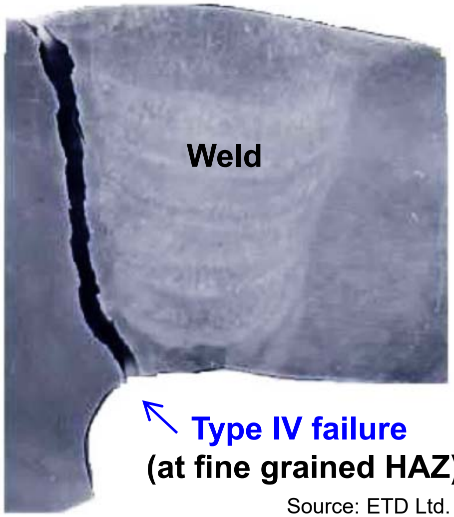
3) **Ni-base alloys** for temperatures > 700°C.





Alstom USC and AUSC Power Plants – J. Marion - NTPC/USAID Int. Conf. SC Plants - New Delhi, India, 22 Nov. 2013 – P 8

Type IV Issues of F-M Steels in Fossil Energy Applications



Source: ETD Ltd.

- **Life of weldments shorter than Base Metal**
  - Type IV failure shortens the material life, caused by weakened microstructure at the heat affected zone (HAZ)

⇩

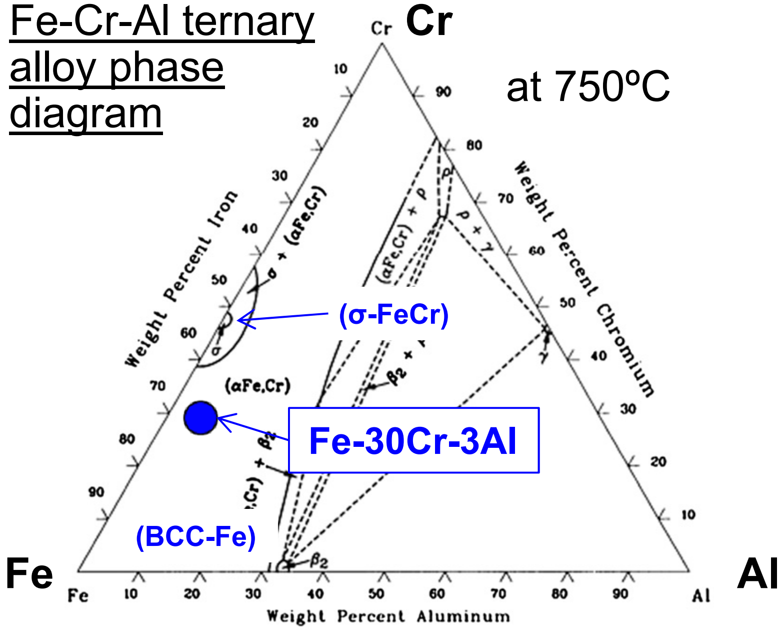
- **Type IV failure of traditional F-M steel weldments unavoidable**
  - To minimize: Optimization of heat treatment (FEAA107, ~FY13)
  - To eliminate: New alloy development (FEAA114, FY14~)
    - *No Type IV failure (= no phase transformation)* → Increase upper limit temperatures
    - *Improved mechanical properties AND oxidation/corrosion resistances in single alloy*
    - *Maintain competitiveness with existing structural materials (cost, fabricability, weldability)*

➔ Fe-30Cr-3Al with Nb addition

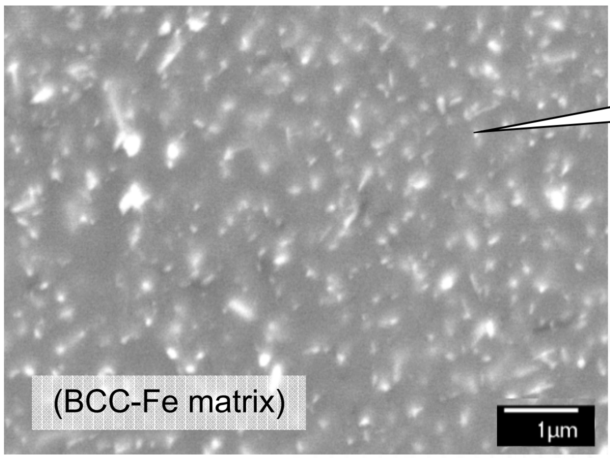
New Approach to Develop Heat-Resistant High-Cr FeCrAl +Nb Alloys

- **No phase transformation in Fe-Cr binary alloys with > ~13 wt.% Cr**
  - *The higher Cr addition the better oxidation/corrosion resistance (>25 wt.%)*
- **Improved steam oxidation resistance by Al addition**
  - *Also destabilize brittle σ-FeCr phase*
- **Require to strengthen the alloys at elevated temperatures**
  - *Nb addition to expect Fe_2Nb-Laves phase precipitation for HT strengthening*

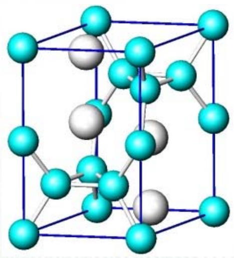
Fe-Cr-Al ternary alloy phase diagram



SEM-BSE
(Fe-30Cr-3Al + Nb, W, Si; aged at 700°C)



C14: Laves-Fe_2Nb



http://www.geocities.jp/ohba_lab_ob_page/structure5.html

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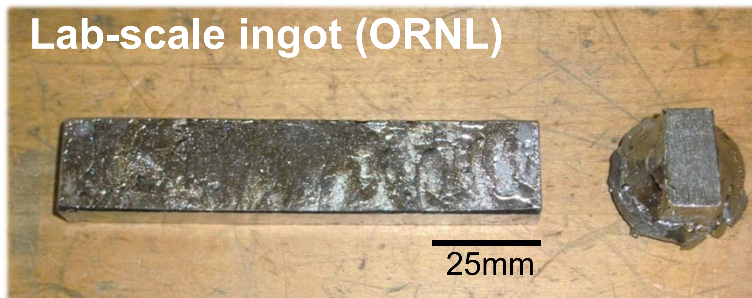
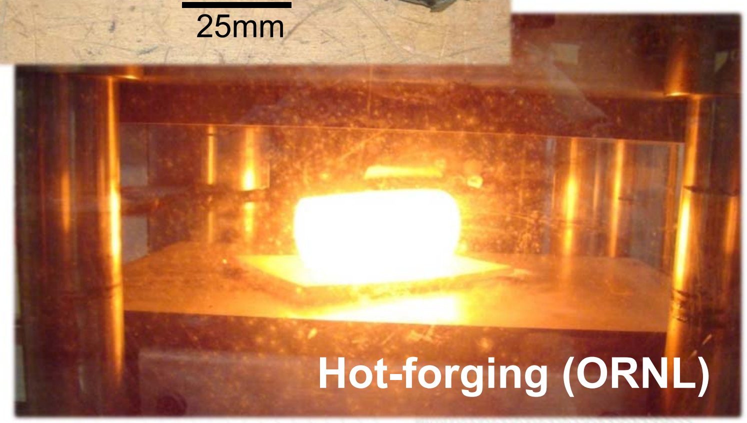
Properties Need To Be Evaluated

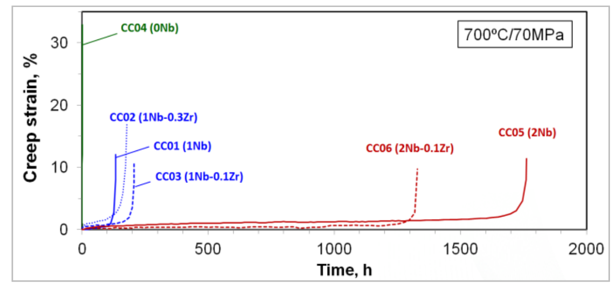
- **Thermo-mechanical Treatments:**
  - *Homogenization*
  - *Solution heat-treatment*
  - *Hot-forging/ -rolling*
  - *Annealing*
- **Microstructure characterization**:
  - *As hot-processed*
  - *Solution treated and Aged*
  - *Creep-ruptured*
  - *Cross-welded*
- **Mechanical properties**:
  - *RT/HT tensile properties*
  - *Creep-rupture properties*
  - *Hardness*
  - *Toughness*
- **Environmental compatibilities**:
  - *Oxidation test in Air + 10%* H_2O
  - *Ash-corrosion test*
- **Weldability**:
  - *E-beam weld*
  - *Gas Tungsten Arc Weld*

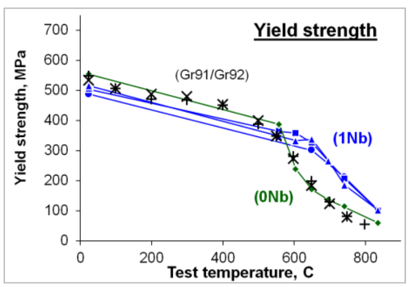


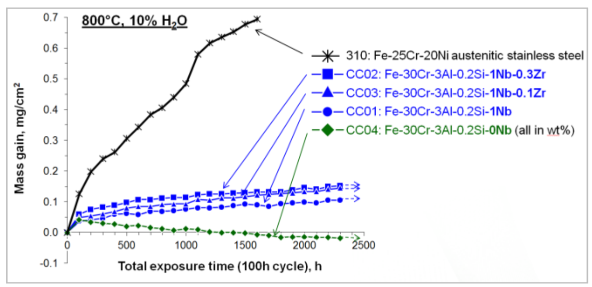


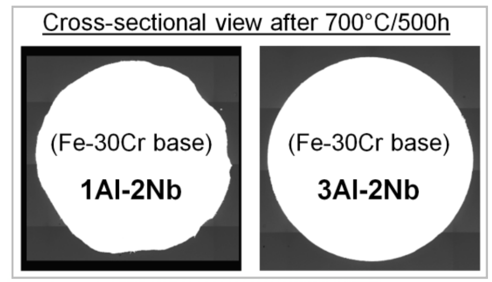
Alloy Development in Progress

- **<u>1st series</u>: Fe-30Cr-3Al with (0~2)Nb-(0~0.3)Zr (in wt.%)**
  - *Optimization of thermo-mechanical treatment*
  - *Tensile test (RT~800°C)*
  - *Oxidation test (800°C, in air + 10%H_2O)*
  - *Ash corrosion test (700°C, in ash + corrosive gas)*
  - *Creep-rupture test (650~700°C, 40~110MPa)*





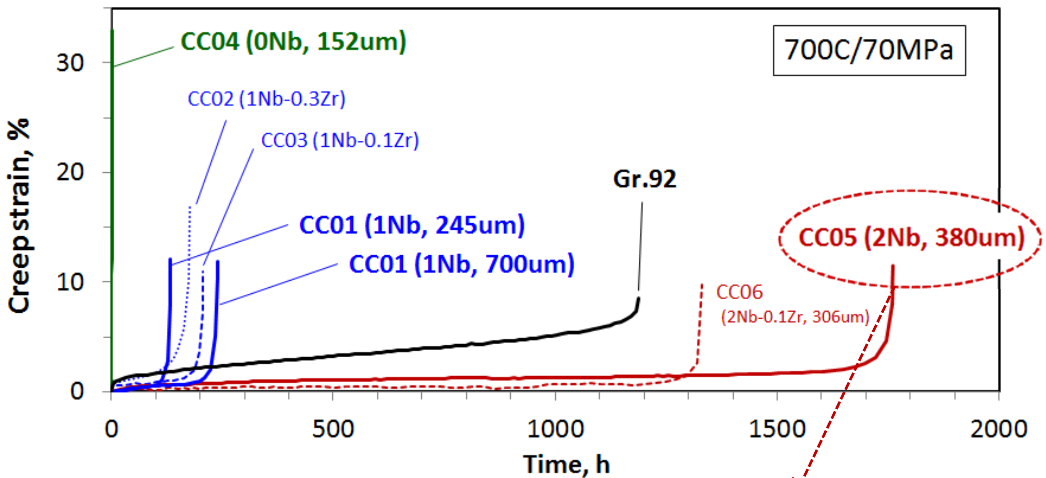




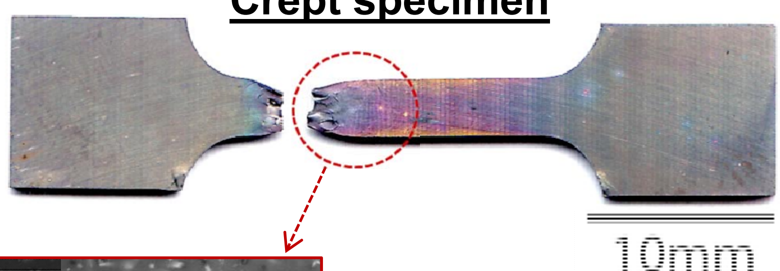
- **<u>2nd series</u>: Fe-30Cr-3Al with (0.5~2)Nb + W, Mo, Ti, or Y**
  - *Solvus temperature control*
  - *Size stability of Lave-phase particle at 700°C*
  - *Size stability of grain structure at 1200°C*
  - *Trial E-beam weld*
  - *Scale-up effort*

Improved Creep Properties in 2Nb Alloys

Creep-rupture curves



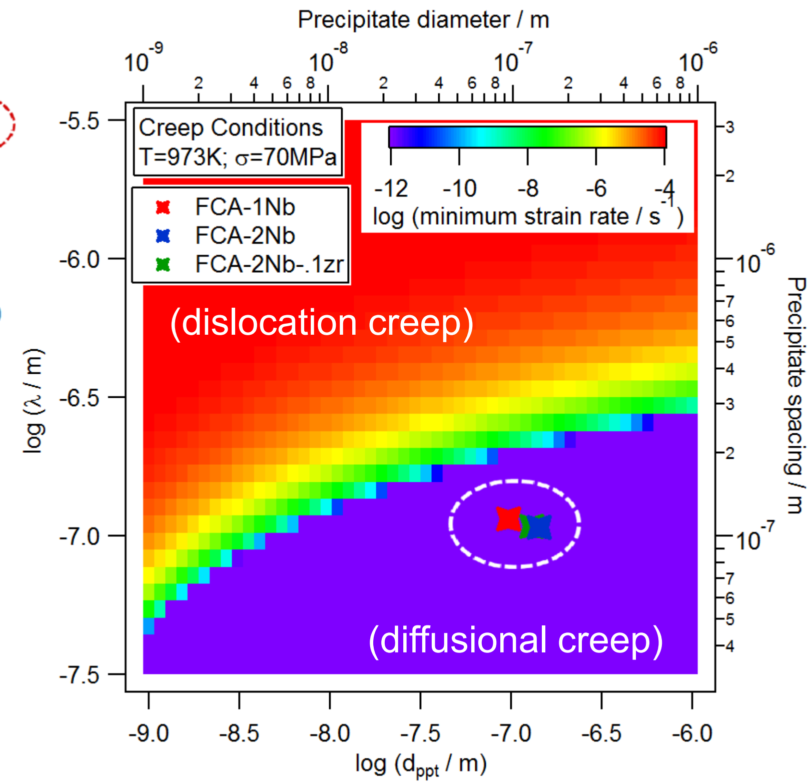
Crept specimen



Precipitate Free Zone

ε_{min}: 1.47 x10^{-7} s^{-1}
Particle size: 1.4 x 10^{-7} m
Particle spa.: 1.0 x 10^{-7} m

Calc. minimum creep-rate map at given particle distribution



*Used Bird-Mukherjee-Dorn (BMD) model

$$\frac{\dot{\varepsilon}_m kT}{DEb} = A_{Dis}\left(\frac{\sigma_a - \sigma_{th}}{E}\right)^n$$

$$\sigma_{th} = \frac{Eb}{2\pi\lambda}\ln\frac{d_{ppt}}{b}$$

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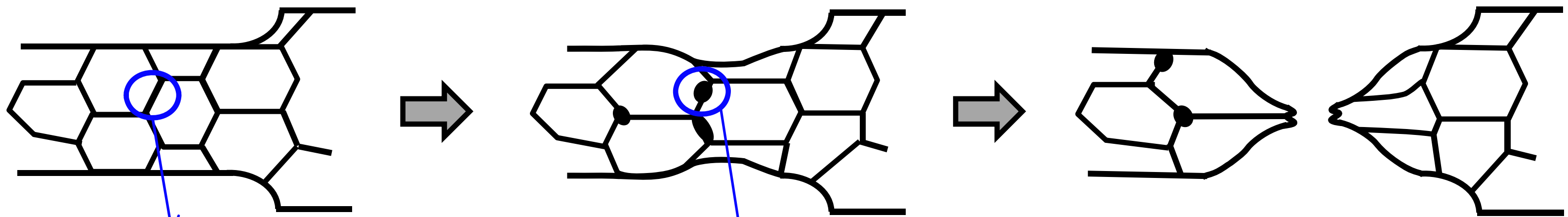
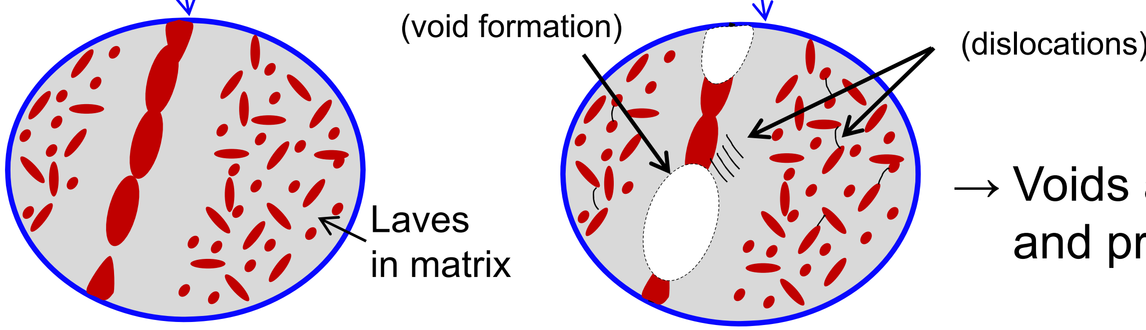
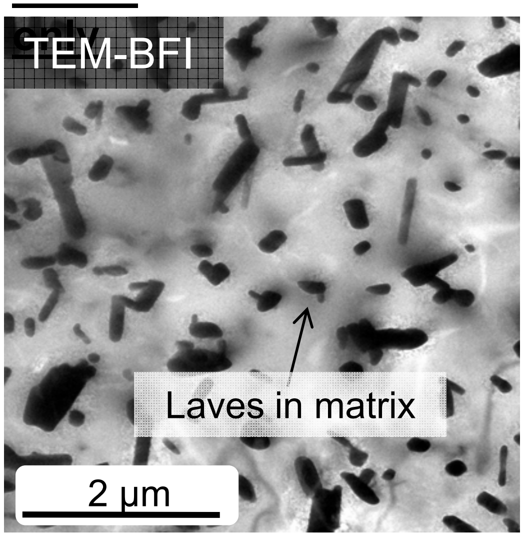
Creep-Failure Mechanisms Near GB



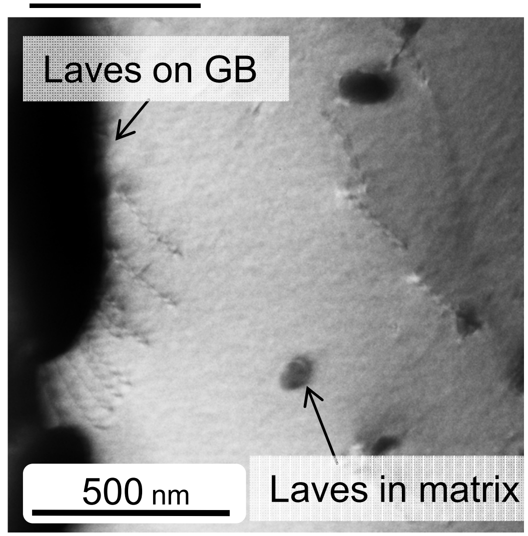


→ Voids accumulate along GB and produce ductile GB failure

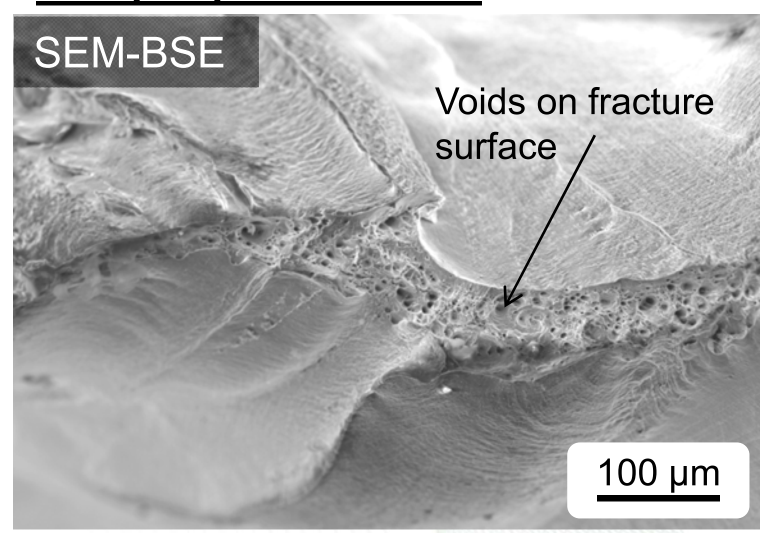
Matrix



Near GB

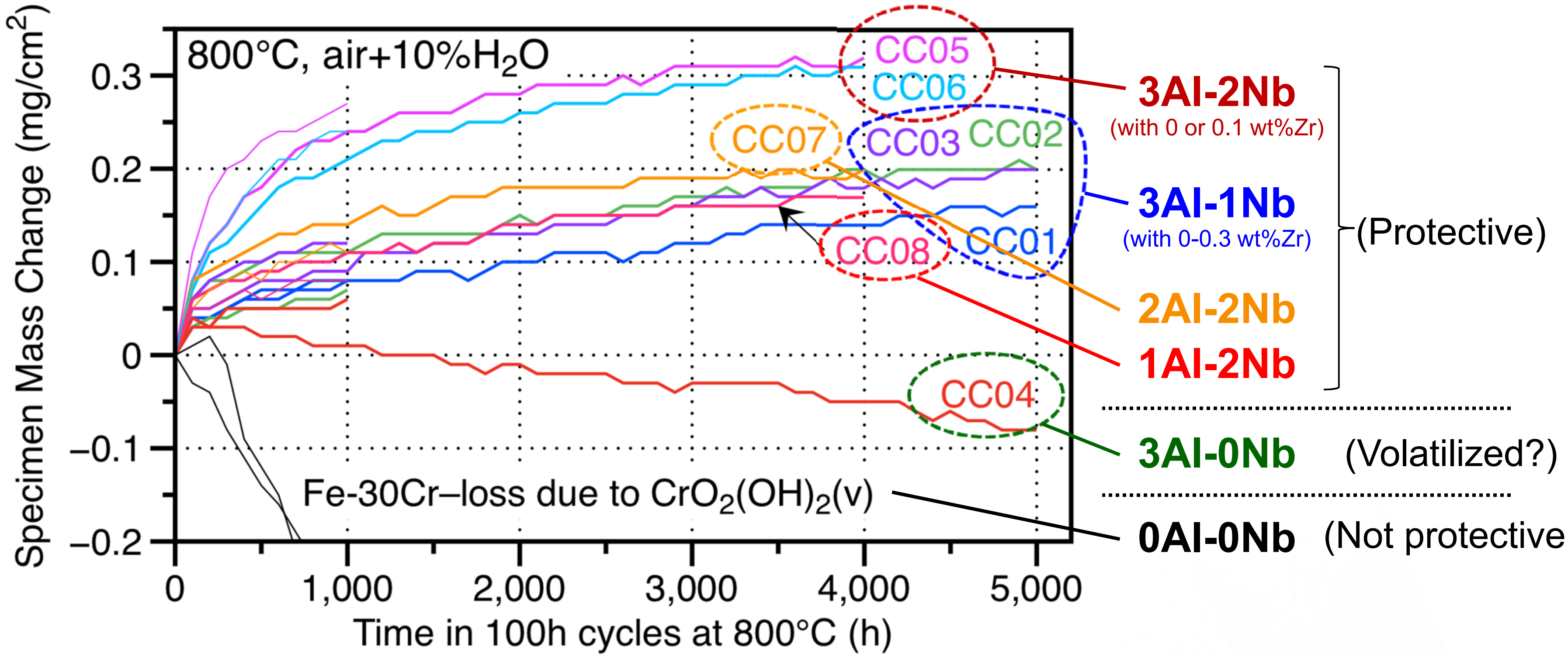


Creep rupture surface



(Creep ruptured specimen (2Nb alloy) tested at 700C and 70MPa)

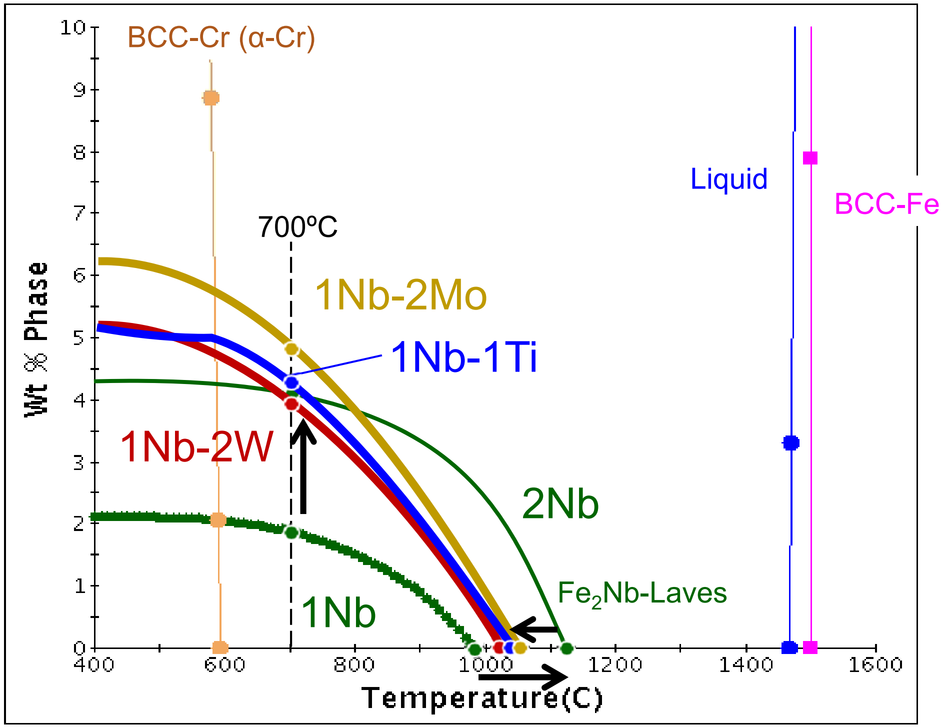
Strong Benefit of Al+Nb Additions on Slow Oxidation Kinetics in Air+10%H_2O



- *No significant impact from the Zr addition (0.1-0.3 wt.%)*
- *Ash-corrosion test at 700°C revealed improved protective characteristics by the combined additions of Al+Nb (FY15)*

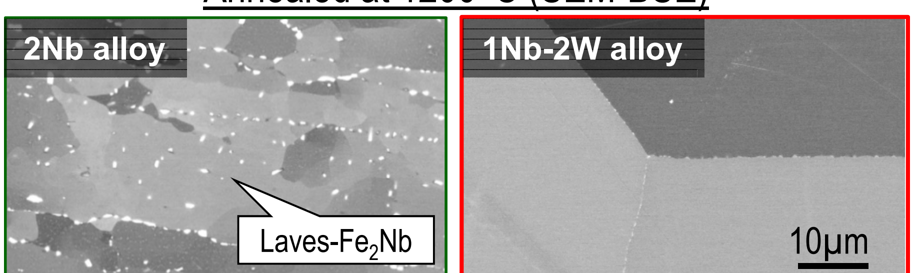
Impact of "Third Additional Elements" on Microstructure

Fe-30Cr-3Al-0.2Si base alloys*

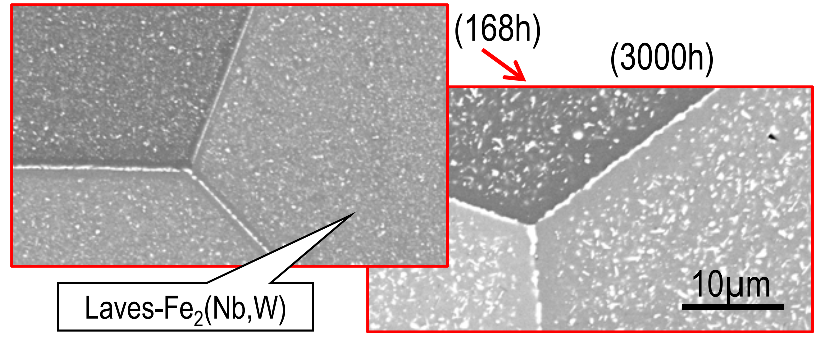


***calculated by JMatPro**

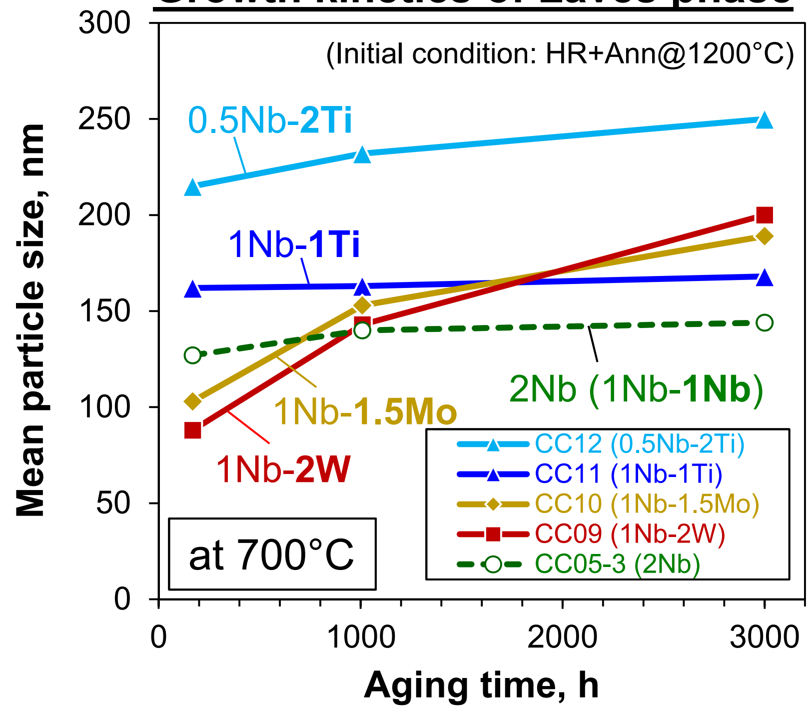
Annealed at 1200°C (SEM-BSE)



1Nb-2W alloy, aged at 700°C (SEM-BSE)

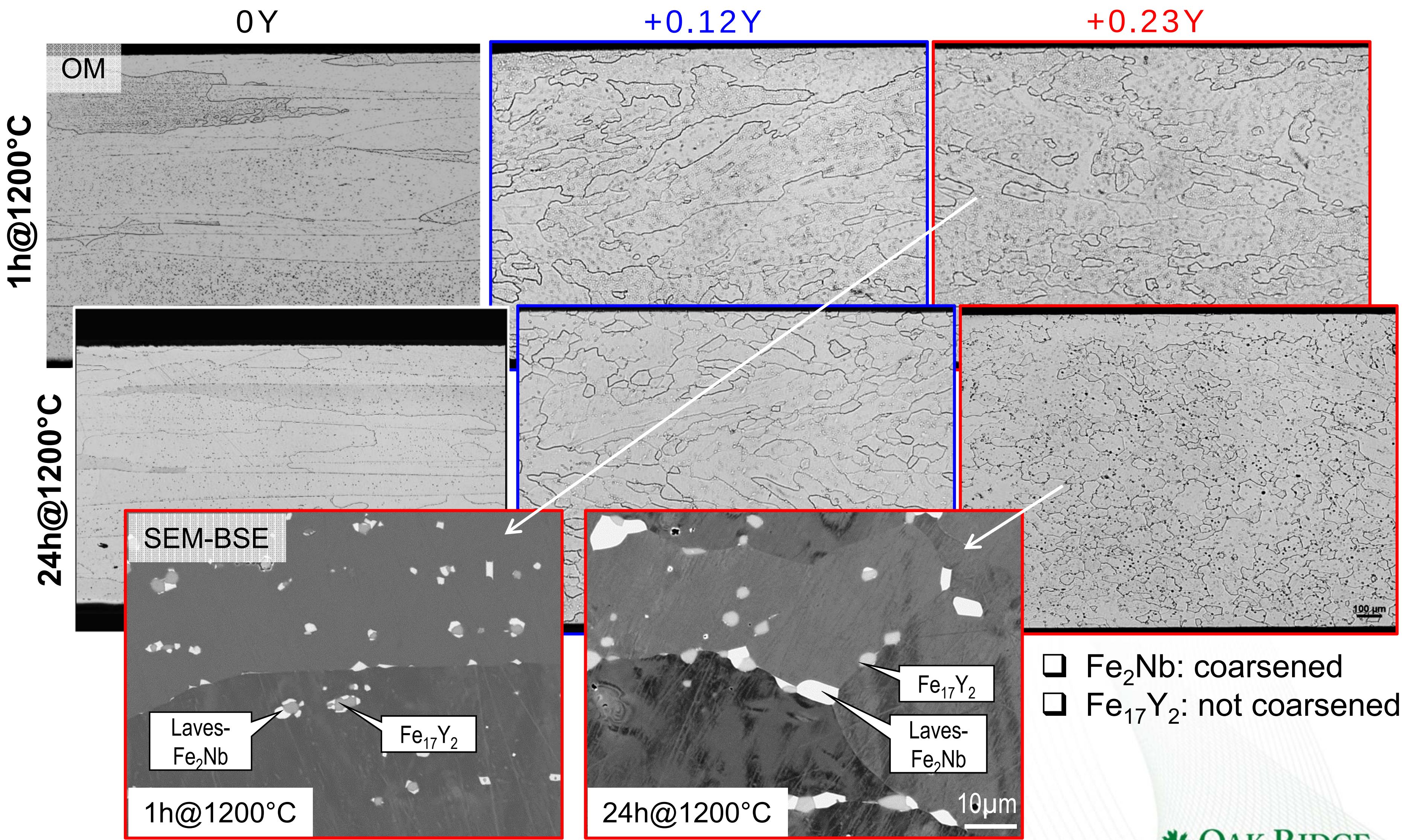


Growth kinetics of Laves phase



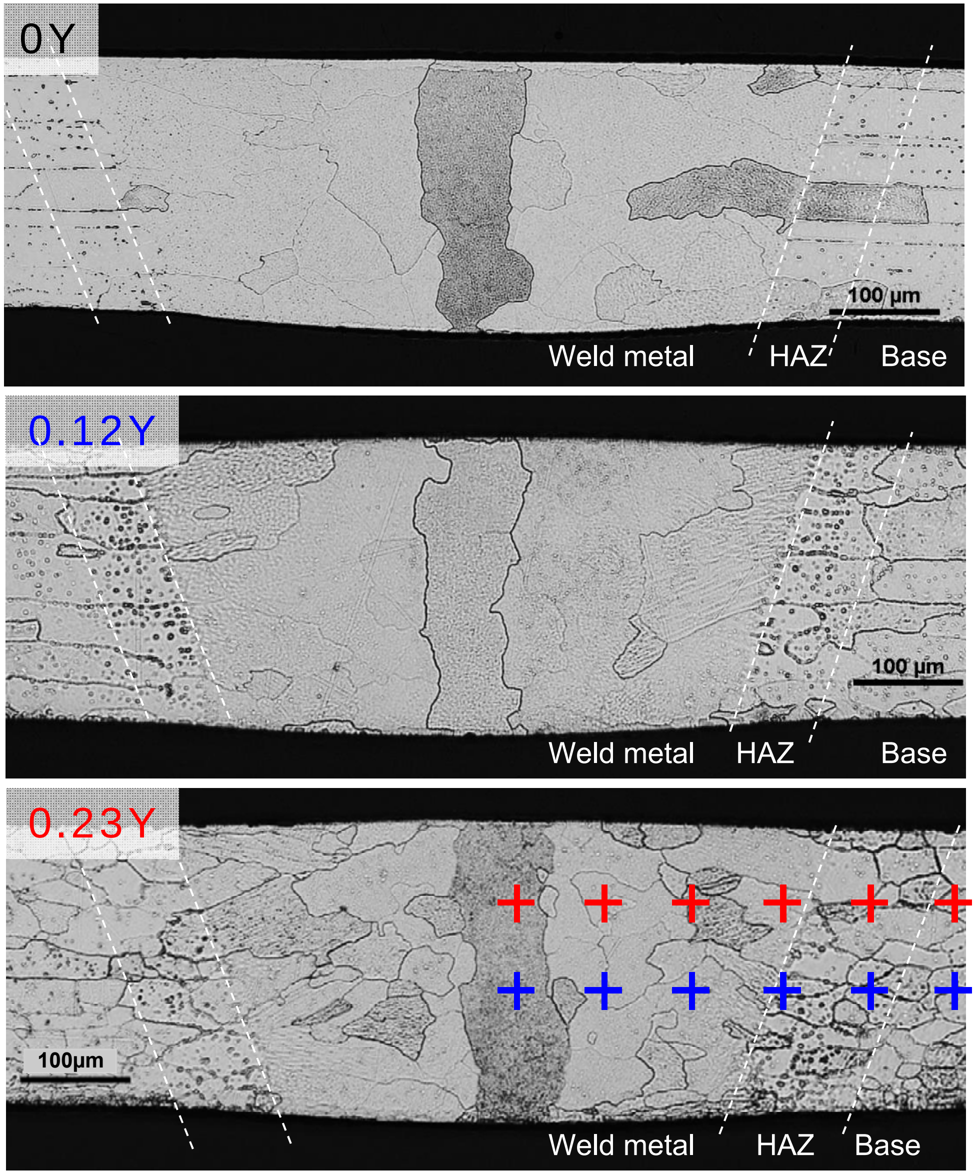
Stabilized Grain Size Through Y Addition

Fe-30Cr-3Al-2Nb + Y, Hot-rolled at 800°C + annealed at 1200°C

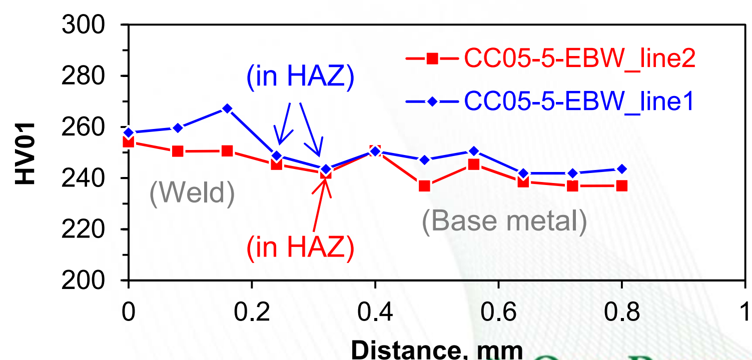


- Fe_2Nb: coarsened
- $Fe_{17}Y_2$: not coarsened

Y Addition Also Beneficial on Weld (EBW)

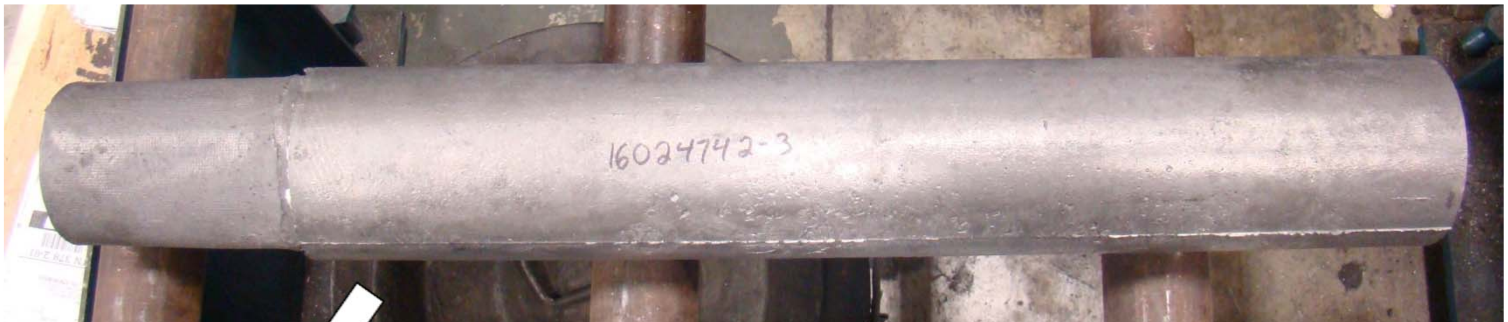


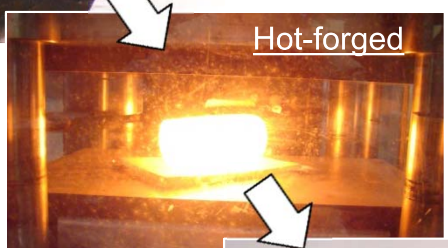
- High Y addition (0.23 wt.%) effectively refine the grain size inside weld metal
- No obvious grain coarsening nor hardness drop at HAZ
- Uniform hardness profile across the weld/HAZ/base metal



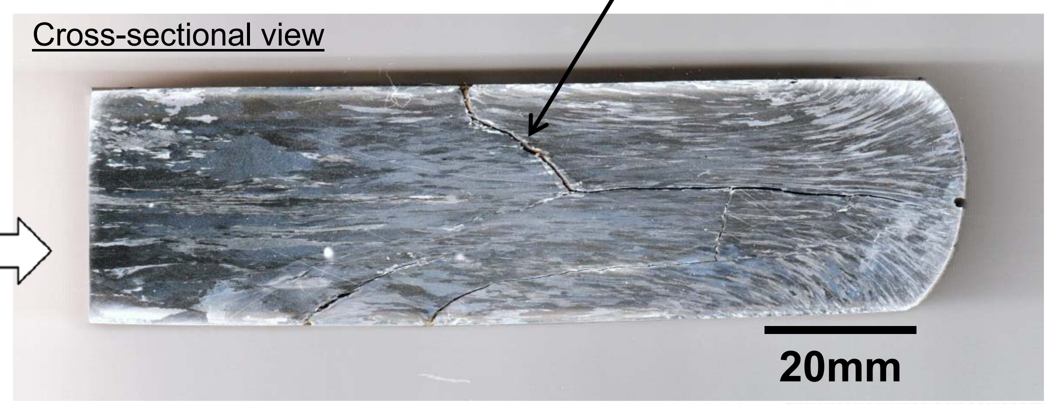
Scale-up Effort Initiated

VIM ingot: 4” diameter x 26” length (off-spec, Fe-30Cr-2.6Al-2Nb+Y)





- Cracks already exist in the as-cast ingot (not formed during hot-process)
- Hot-isostatic press has successfully eliminated the cracks



Summary

<u>Creep-resistant high-Cr FeCrAl alloy development in progress</u>

- **Microstructure characterization of crept specimens:**
  - *Creep-rupture specimens ➔ discussed creep-deformation mechanism*
- **Oxidation test up to 5,000h completed:**
  - *Found the benefit of Al + Nb combined additions*
  - *Corrosion test of the scale-up batches is planned*
- **Effect of third element additions on thermal stability:**
  - *Laves-phase formed elements (W, Mo, and Ti) ➔ further optimization would be suggested to balance the solvus temperature and particle stability*
  - *Y additions on high temperature grain size stability ➔ potential advantage of hot-workability and weldability*
- **Trial e-beam weld of Y containing alloys:**
  - *Potential advantage of Y addition to avoid unfavorable coarse grains*
- **Scale-up effort initiated:**
  - *Plan to have two 80lbs VIM ingots (on-spec. and off-spec.)*
  - *Process development in progress*

- **Communication with Forschungszentrum Jülich (FZJ) in progress:**
  - *For high-Cr fully ferritic steel development (Hiperfer, Fe-17Cr base)*
  - *ORNL supports process and weld development*

Future Activities

- **Complete thermo-mechanical treatment of the scale-up heat:**
  - *Screening basic properties (tensile, hardness, microstructure)*
  - *Intermediate/long-term creep-rupture test at or above 700ºC*
  - *Ash-corrosion resistance evaluation at 700ºC*
  - *GTAW screening*
- **Communicate with ASME Boiler and Pressure Vessel code committee for potential determination of code case:**
  - *Initiated to contact with the Section II committee members*

Thanks for your attention

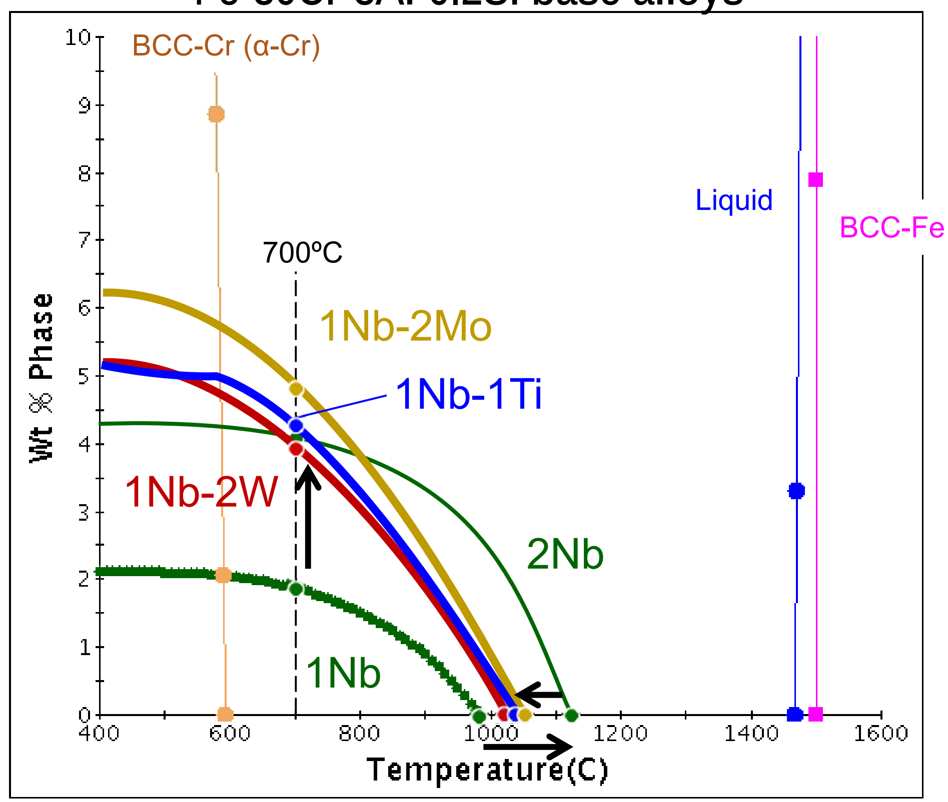
Preparation of Materials

- **Down-selected alloys to be evaluated**:
  - *12 alloys based on **Fe-30Cr-3Al + Nb, Zr, W, Mo, Ti, and Si***
  - *Expected Fe_2Nb type Laves-phase precipitates for strengthening*
  - *Used computational thermodynamic tools for downselect*

Table: Nominal composition of the alloys studied

wt%	Fe	Cr	Al	Nb	Zr	W	Mo	Ti	Si
CC01	Bal.	30	3	1	0				0.2
CC02	Bal.	30	3	1	0.3				0.2
CC03	Bal.	30	3	1	0.1				0.2
CC04	Bal.	30	3	0	0				0.2
CC05	Bal.	30	3	2	0				0.2
CC06	Bal.	30	3	2	0.1				0.2
CC07	Bal.	30	2	2	0.1				0.2
CC08	Bal.	30	1	2	0.1				0.2
CC09	Bal.	30	3	1		2			0.2
CC10	Bal.	30	3	1			1.5		0.2
CC11	Bal.	30	3	1				1	0.2
CC12	Bal.	30	3	0.5				2	0.2

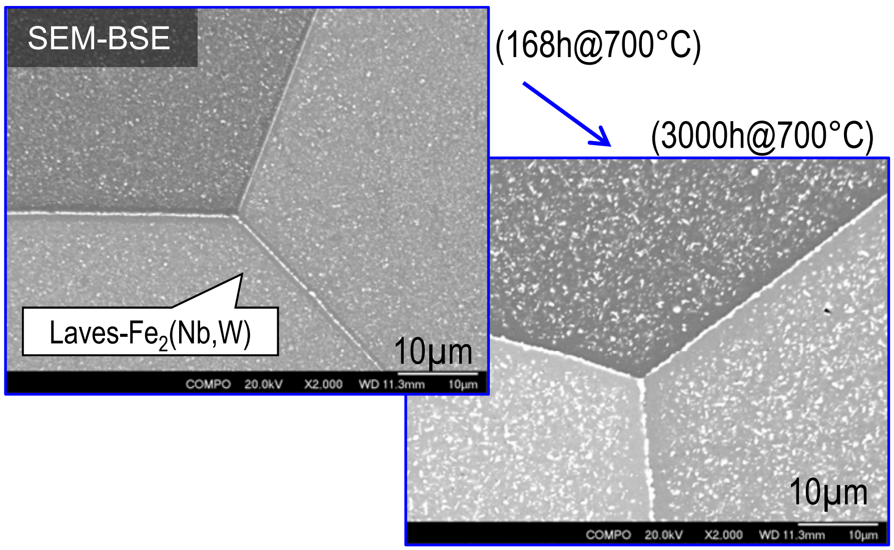
Fe-30Cr-3Al-0.2Si base alloys*



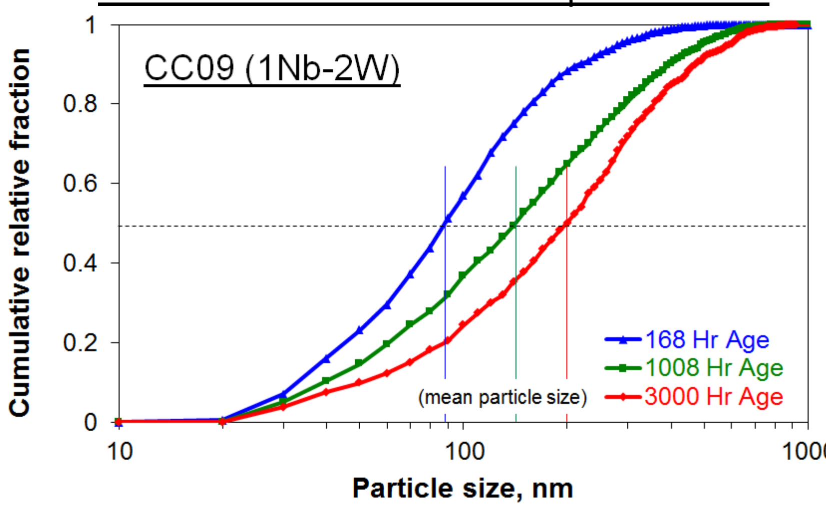
*calculated by JMatPro

Negative Impact of "Third Element Additions" on Precipitate Size Stability

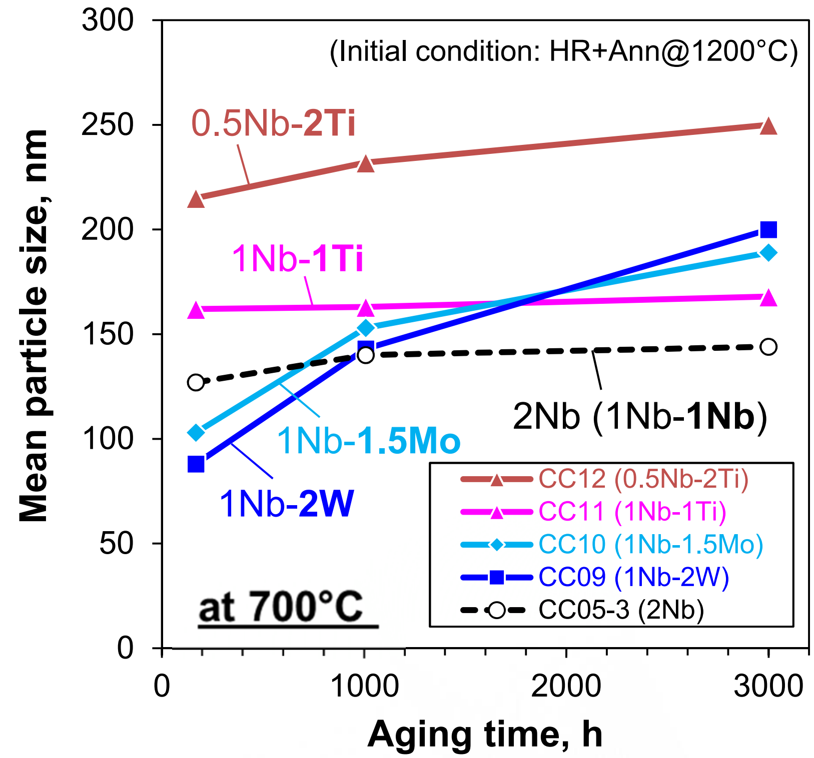
1Nb-2W alloy, aged at 700°C



Cumulative relative fraction of particle sizes



Growth kinetics of Laves phase



Third element effects:

- *Solvus of Fe_2Nb in BCC successfully lowered (not shown)*
- *Less positive effect on size stability during aging at 700°C*

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Bird-Mukherjee-Dorn (BMD) Model

$$\sigma_{th} = \frac{Eb}{2\pi\lambda}\ln\frac{d_{part}}{b}$$

$$\frac{\dot{\varepsilon}_m kT}{DEb} = A_{Dis}\left(\frac{\sigma_a-\sigma_{th}}{E}\right)^n$$

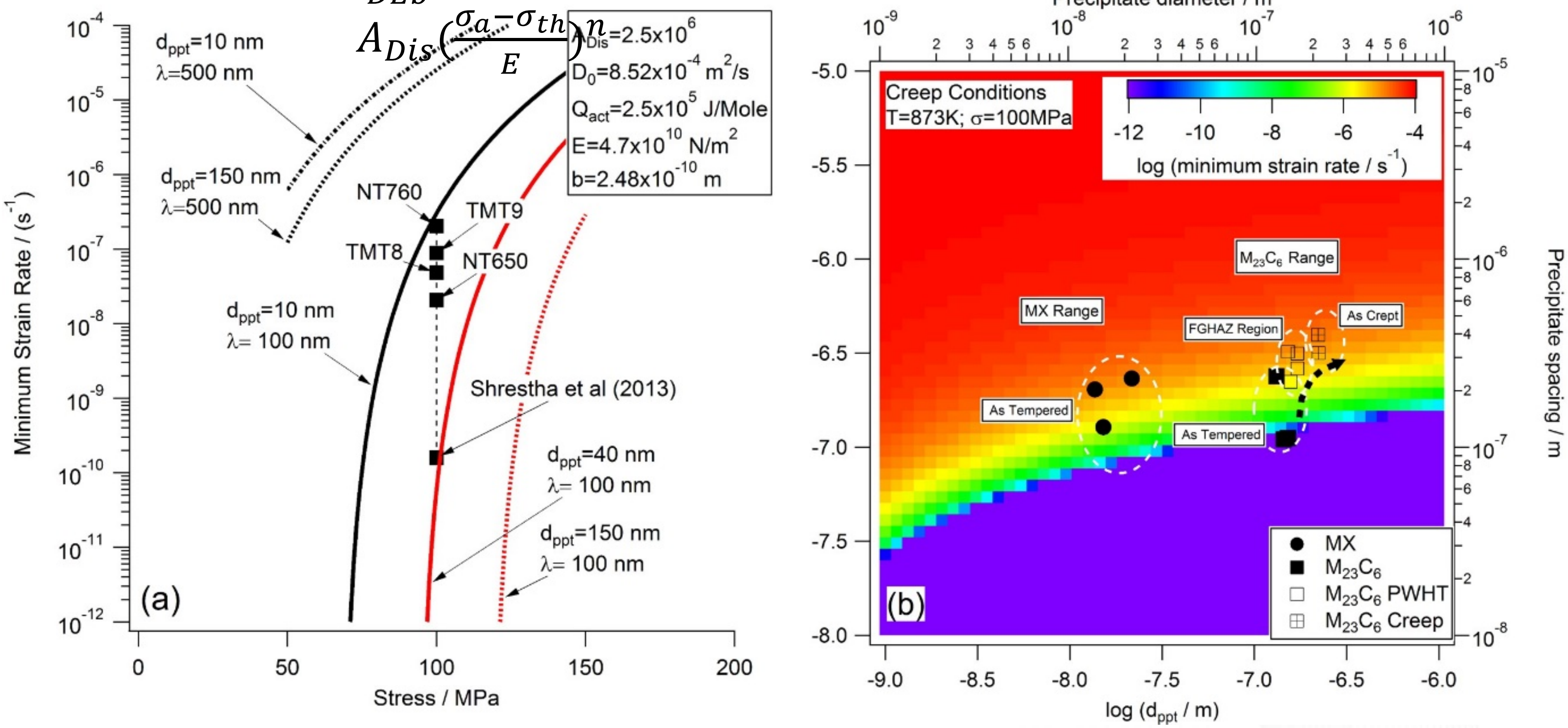

Figure: Results from parametric calculations of minimum creep rate using BMD phenomenological model as a function of (a) stress and (b) precipitate characteristics. (B. Shassere, et al. MMTA, 2016)