Advanced ODS FeCrAl Alloys As Accident Tolerant Fuel Cladding

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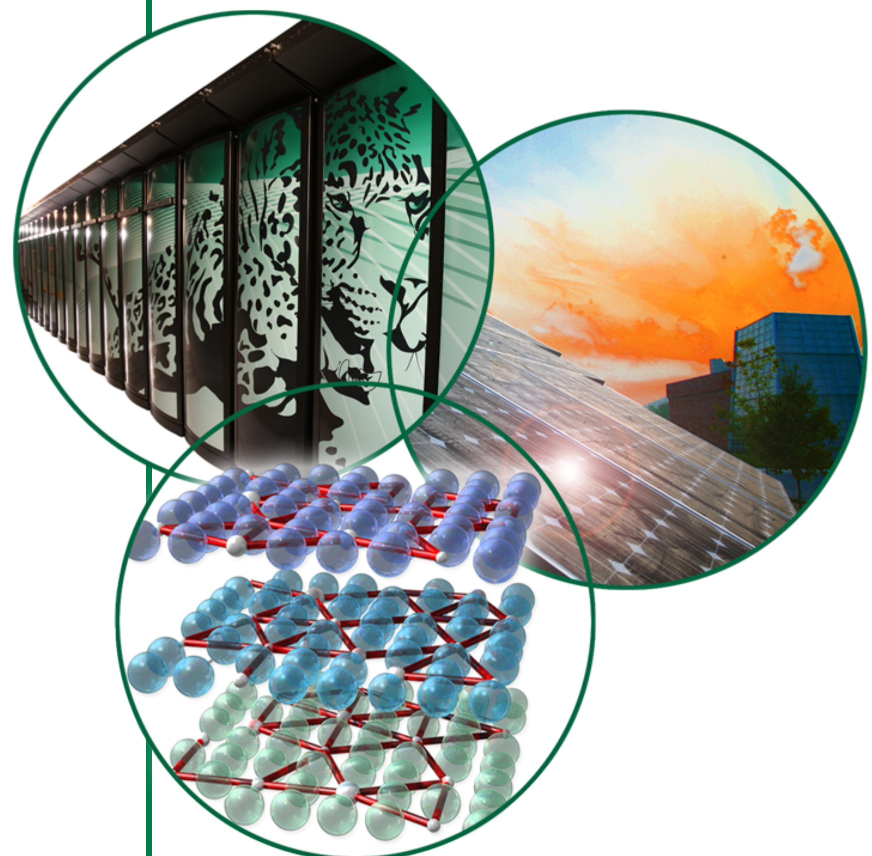

Fuel Cycle Research and Development Program

U.S. DEPARTMENT OF
ENERGY
Nuclear Energy

OAK RIDGE NATIONAL LABORATORY
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ODS FeCrAl Development Goals

- Excellent low temperature (~300ºC) mechanical properties:
  - potential reduction of cladding thickness to limit FeCrAl neutronic penalty
- Good high temperature mechanical properties (~800-900ºC)
  - higher burst temperature
- Excellent short-term high temperature (up to 1500ºC) oxidation resistance in steam
- Fabricability allowing industrial production of thin tubes
- Great irradiation resistance due to nano oxide particles

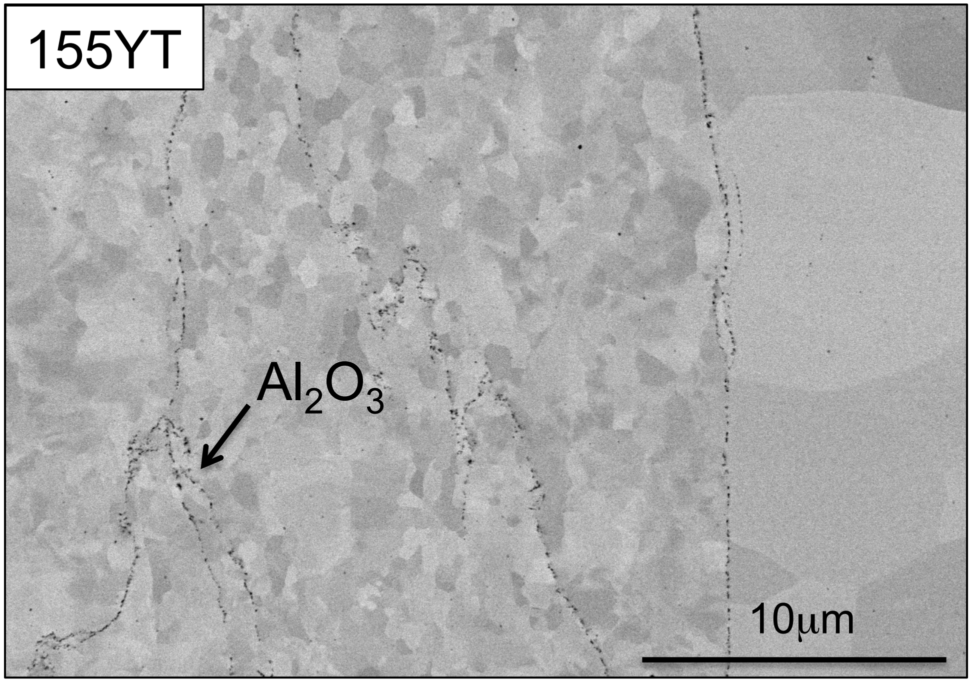
- ODS FeCrAl Development based on
  - Wrought FeCrAl candidates
  - Former commercial ODS-FeCrAls (PM2000, MA956…)
  - NE ODS FeCr alloys such as 14YWT
  - Collaboration with Fusion program

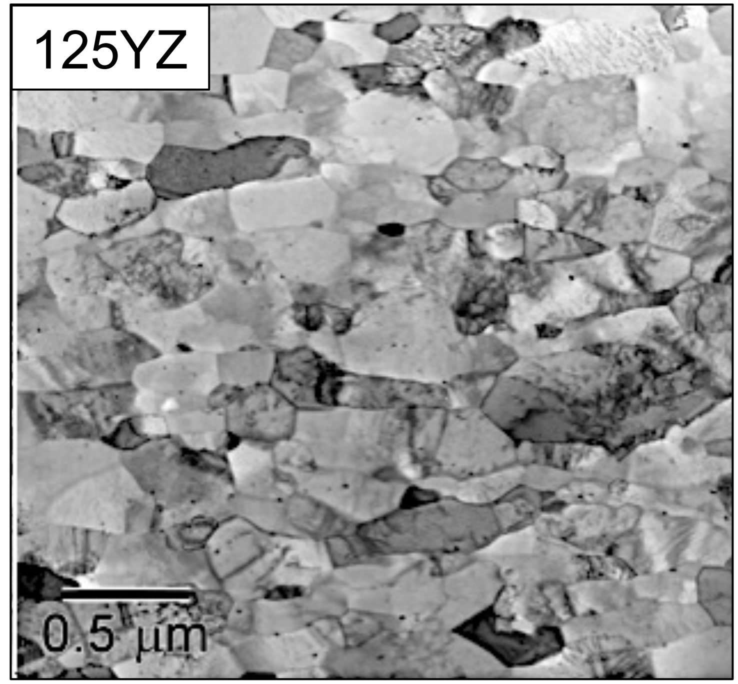
ODS FeCrAl Fabrication & Composition

- Purchased gas atomized powders: Fe-12Cr-5Al, Fe-13Cr-4Al, Fe-15Cr-5Al-0.4Ti, Fe-15Cr-5Al-1Mo-0.4Ti
- 40h ball milling in Ar with Y_2O_3 and addition of TiO_2, HfO_2 or ZrO_2 for the 12Cr-5Al alloys
- Extrusion can degassed at 300ºC for 24h, & extrusion at 950ºC
- Comparison with commercial APMT, PM2000 and PM2000 powder extruded at ORNL
- Recent focus on 125YZ and 125YT alloys

Wt %	Fe	Cr	Al	Ti	Y	Si	C (ppm)	N (ppm)	O (ppm)	S (ppm)	Other
125YZ	82.8	11.51	4.86	<0.01	0.18	0.01	250	161	1920	10	0.3Zr, 0.01Hf
125YT	82.4	12	4.9	0.2	0.16	0.01	350	140	2220	30	
125YH	82.3	11.68	4.82	<0.01	0.17	0.01	220	110	2280	10	0.68Hf, 0.01Zr
155YT	bal.	14.57	4.7	0.44	0.16	0.02	340	240	951	10	
PM2000	74.12	19.13	5.46	0.48	0.39	0.02	14	86	2480	8	
PM2000 ORNL	74.66	18.77	5.34	0.45	0.39	0.02	20	67	2440	7	
APMT	69.16	21.06	4.99	0.02	0.25	0.59	300	402	526	<10	2.82 Mo, 0.23Hf 0.1Zr

Nano-grains With Few Larger Grains

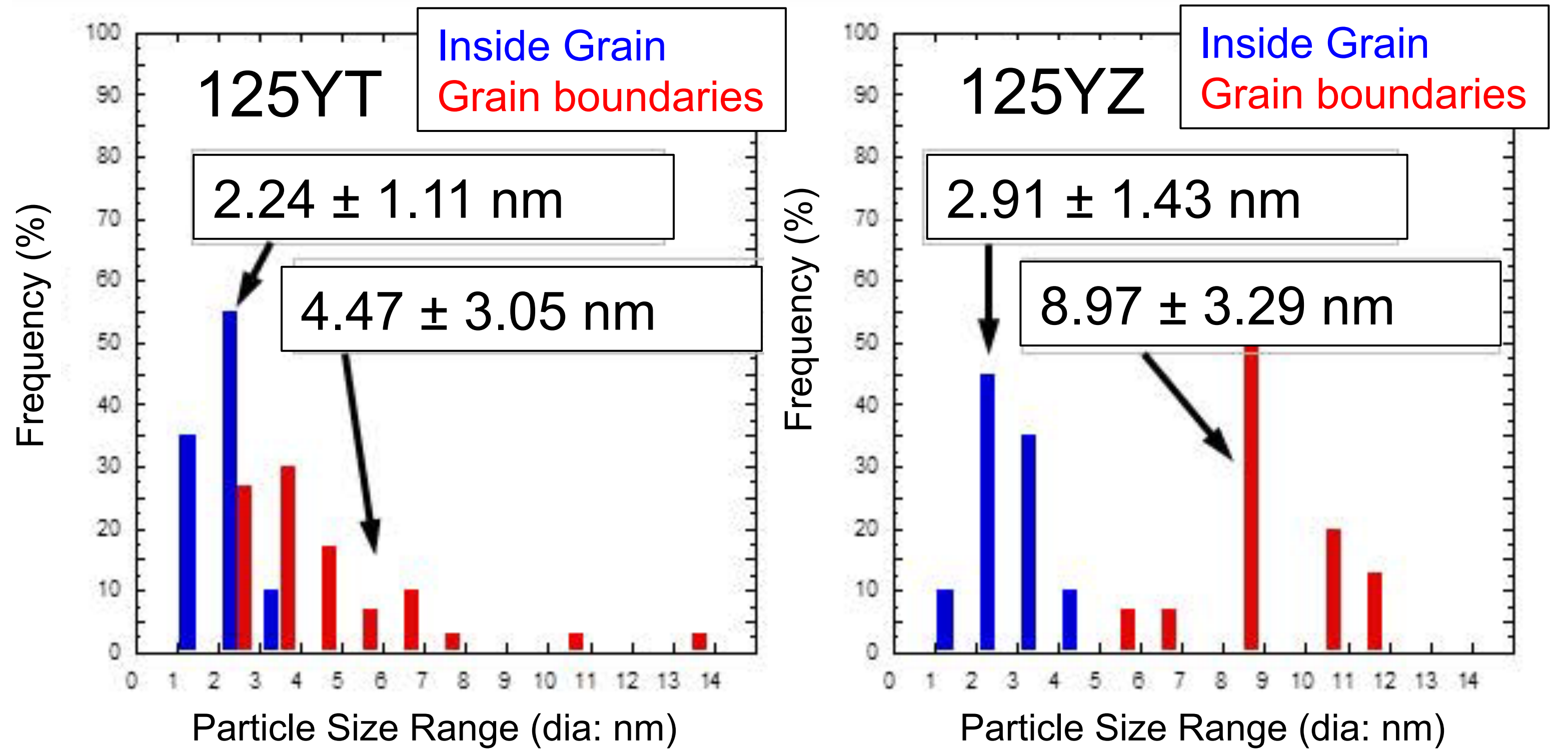




- Network of Al_2O_3 stringer
- Small grains, especially with TiO_2 and ZrO_2, most likely because of low extrusion T°C

	Average Grain Size (μm)		GAR
Alloy	Parallel to ED	Normal to ED	
125Y	0.83	0.56	1.48
12YT	0.14	0.12	1.17
125YZ	0.27	0.17	1.59
125YH	0.7	0.39	1.79
155YT	0.7	0.65	1.08
PM2000 Plansee	1	0.7	1.43

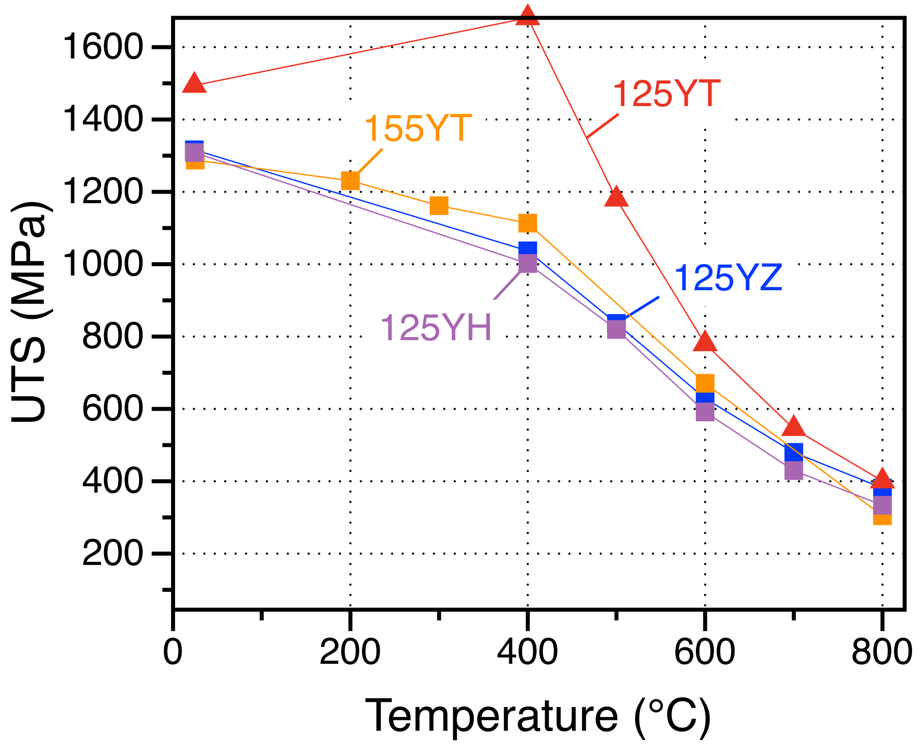
High Density of Small Nano-precipitates

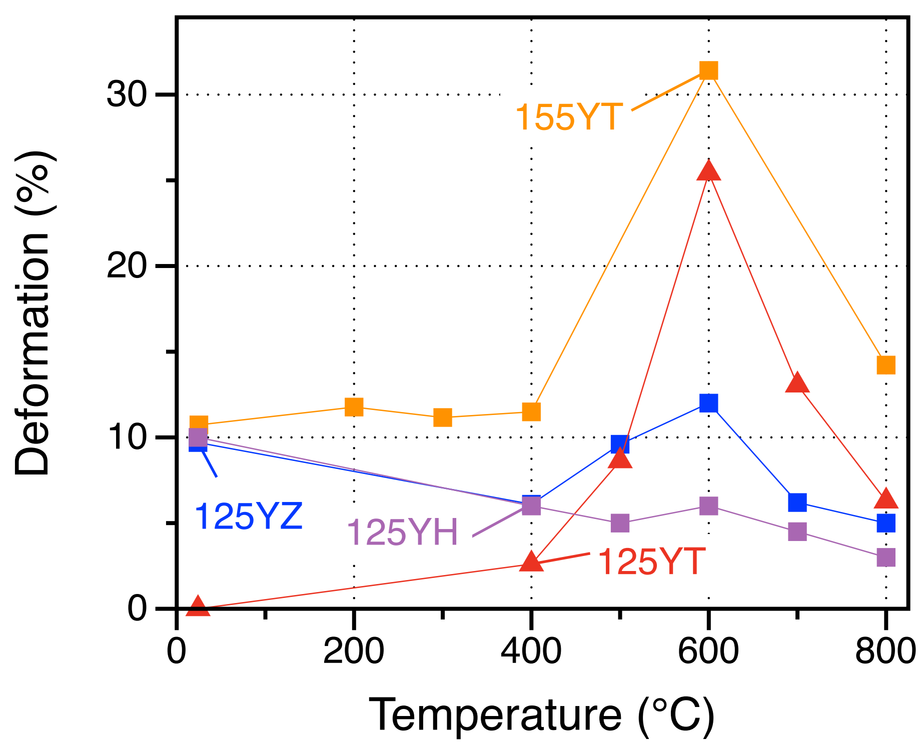


Alloy	Number Density
125Y	1.41×10^{23} m^{-3}
125YT	6.78×10^{23} m^{-3}
125YZ	2.51×10^{23} m^{-3}
125YH	0.98×10^{23} m^{-3}

Phase Identification (on going):
125YT: Al_2TiO_5
125YZ: $Al_5Y_3O_{12}$, Zr(O,C,N), no clear evidence of $Y_4Zr_3O_{12}$

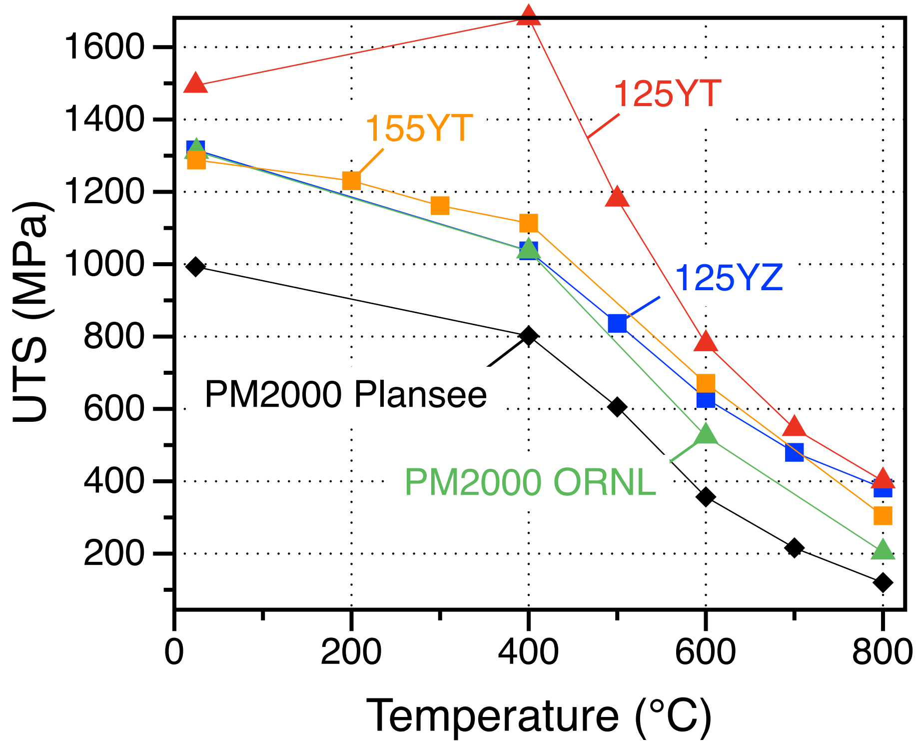
High Yield and Ultimate Stresses But Limited Ductility

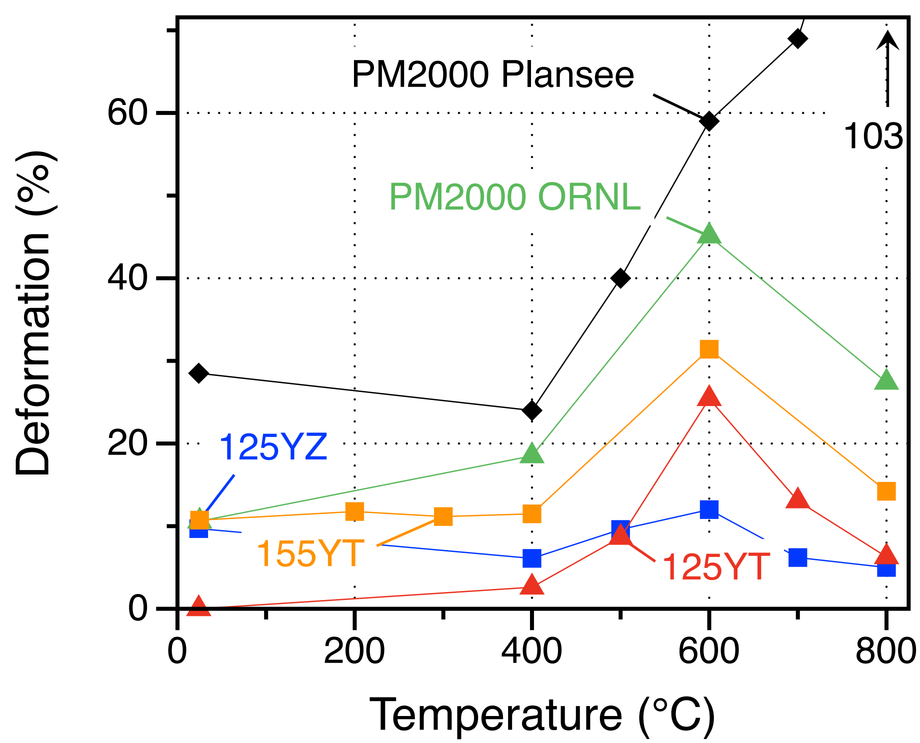




- Similar tensile properties for all new FeCrAl alloys except for 125YT with highest YS & UTS but no ductility
- Peak of ductility for most alloys at ~600ºC
- Lower O level in 155YT leads to better ductility

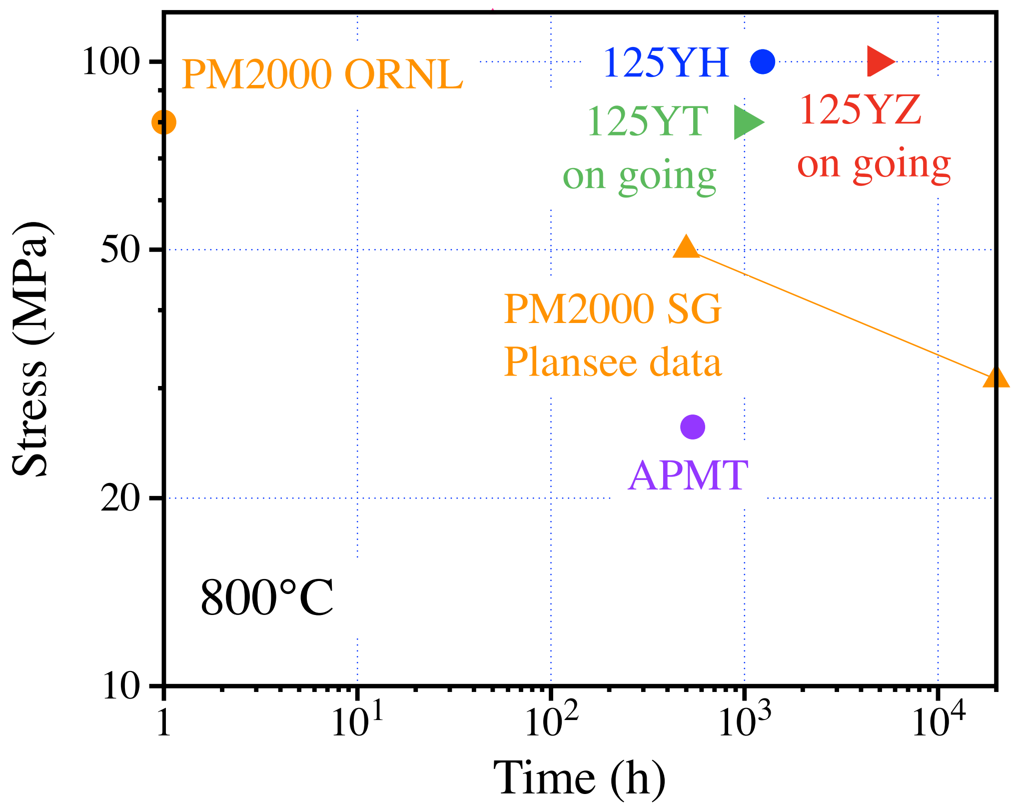
Effect of Fabrication Process on Tensile Properties





- PM2000 ORNL alloy shows similar low-temperature high UTS but properties decreased significantly for T>400ºC
- PM2000 bar from Plansee exhibited lower YS and UTS but excellent ductility at all temperatures

Excellent Creep Properties at 800ºC



On going 125YZ test at 700ºC 140MPa has reached 3800h

- Creep properties of 125YT, YH and YZ significantly better than PM2000 (ORNL & Plansee)
- Next test : 125YT, 100MPa to compare YZ and YT

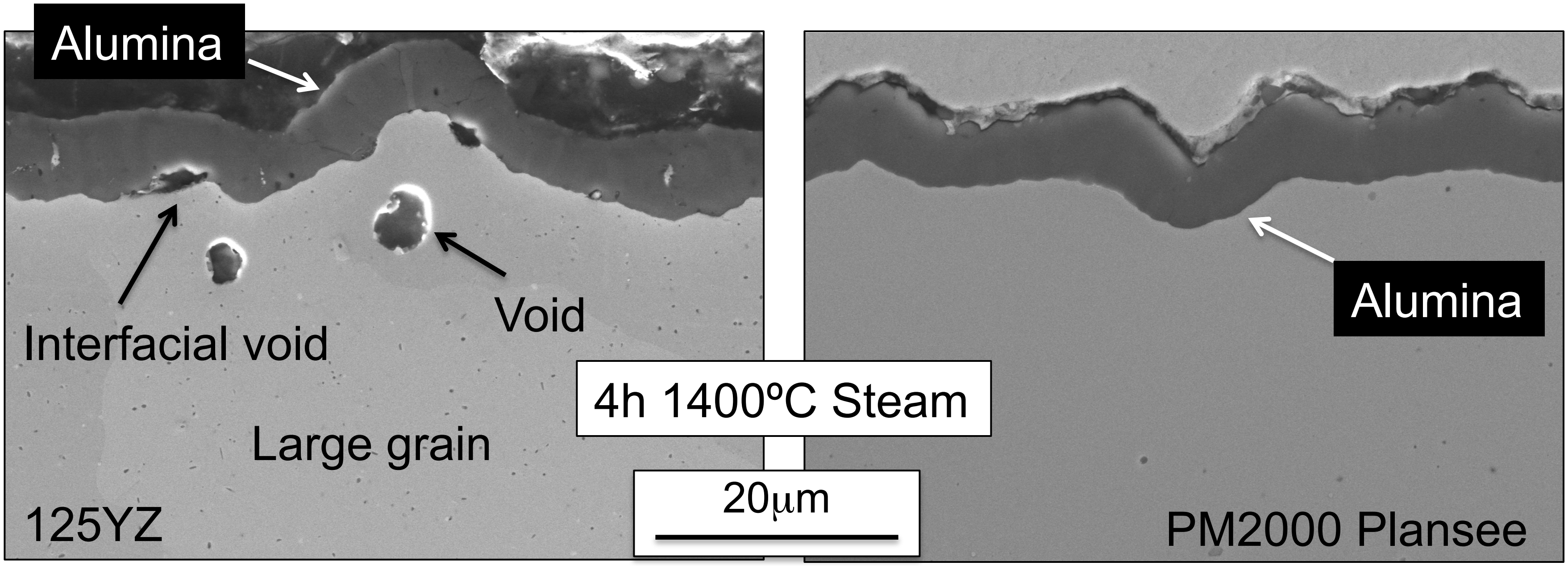
Failure of 125YT, YH and YZ Coupons After 5 min to 1h at 1450ºC in Steam

	1400°C, 4hr	1450°C, 5min	1450°C, 1hr	1450°C, 4hr
125YT	✗	✗	✗	
125YZ	✓	✗	✗	
125YH	✓	✓	✓, ✗	✗
MA956	✗			
PM2000 Plansee	✓	✓	✓	✓
PM2000 ORNL	✓	✗		
APMT	✓			✓

Failed specimen completely oxidized

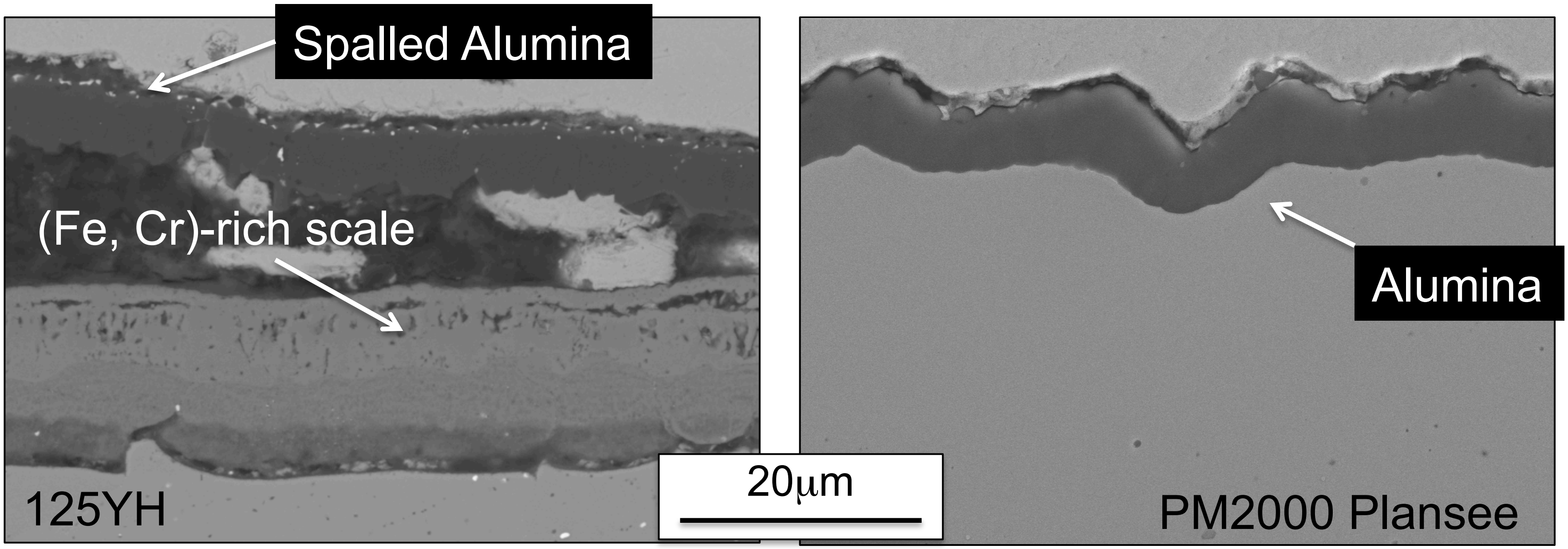
- PM2000 Plansee (recrystallized, large grain) and APMT showed only low mass gains after 4h at 1450ºC
- MA956 and 125YT exhibited the worse behavior and failed at 1400ºC
- PM2000 ORNL small grain failed after 5 min at 1450ºC like 125YZ and 125YH alloys

Microstructure Evolution Affects Scale Growth at T>1200ºC in Steam



- Similar thin convoluted alumina scale for 125YZ & PM2000 Plansee after 4h at 1400ºC in steam
- Grain growth & void formation (bulk and interface) during steam exposure of 125Y alloys

Scale spallation at T>1400ºC might explain 125Y alloys breakaway oxidation



- Evidence of alumina scale spallation at 1400 and 1450ºC for 125YH and formation of an (Fe,Cr)-rich scale
- Scale adhesion is likely affected by interfacial voids and oxide scale deformation

Conclusion

- Fe-12Cr-5Al ODS alloys show excellent tensile and creep strength up to 800ºC and good steam oxidation resistance up to 1400ºC
- Low ductility likely due to high oxygen content and low extrusion temperature
- Microstructure instability above ~1200ºC affects

the steam oxidation performance above 1400ºC

- Need to optimize the alloy processing conditions to improve the alloy fabricability

Future Work

- New FeCrAlZr atomized powders will be ball-milled with Y_2O_3 powder
  - lowering O content could improve alloy ductility
- Assess the effect of extrusion temperature on ODS FeCrAlYZr microstructure and properties
- Conduct warm and hot rolling trials (to simulate tube drawing)
- Assess the impact of radiation on the alloy microstructure and properties

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