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Creep Behavior of Austenitic Steel 316L in Low Oxygen-Containing Pb-Bi Eutectic at 450-550°C

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Austenitic 316L steel in nuclear power plants

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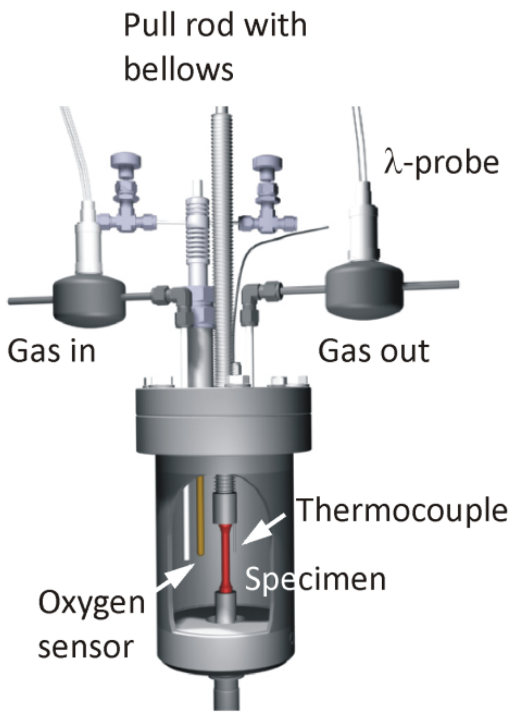
- Construct pipes, vessels and in-vessel components in lead-cooled fast reactor, MYRRHA ADS system (heat exchanger, vessel, diafragm, core barrel)
- Corrosion impact the wall thickness in LBE (load-bearing copability) and effect of elevated temperatures on mechanical properties
- No industrial experience of lead alloy-cooled technology (the lead-cooled fast reactor – LFR). But many concepts worlwide. Mechanical properties (incl. creep) were considerably studied in air, while information about effect of HLM (Pb, LBE) on creep is still limited.

- ***Goal of the current work***: To evaluate impact of lead alloys at 450-550°C on mechanical behaviour and to determine links between creep resistance and microstructural evolutions.

Creep-rupture tests in oxygen-controlled heavy liquid metal



CRISLA-capsule for HLM

Continuous control of oxygen concentration in HLM

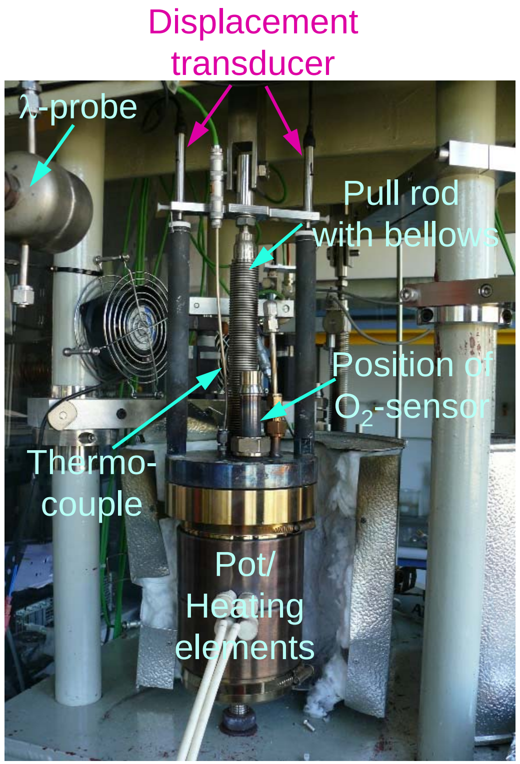
- Oxygen activity close to the specimen with air/Pt O_2-sensor
- λ-probes in gas -inlet and -outlet
- Automatic introducing of gas with variable p_{O_2} (Ar, Ar/H_2 and synthetic air)

Conditions:

- Stagnant Pb or LBE (900 ml)
- T_{max} = 650°C
- $c_O{}^{max} = c_{HLM}{}^{saturation}$
- $c_O{}^{min} = 10^{-13}$ mass%

CRISLA Facility:

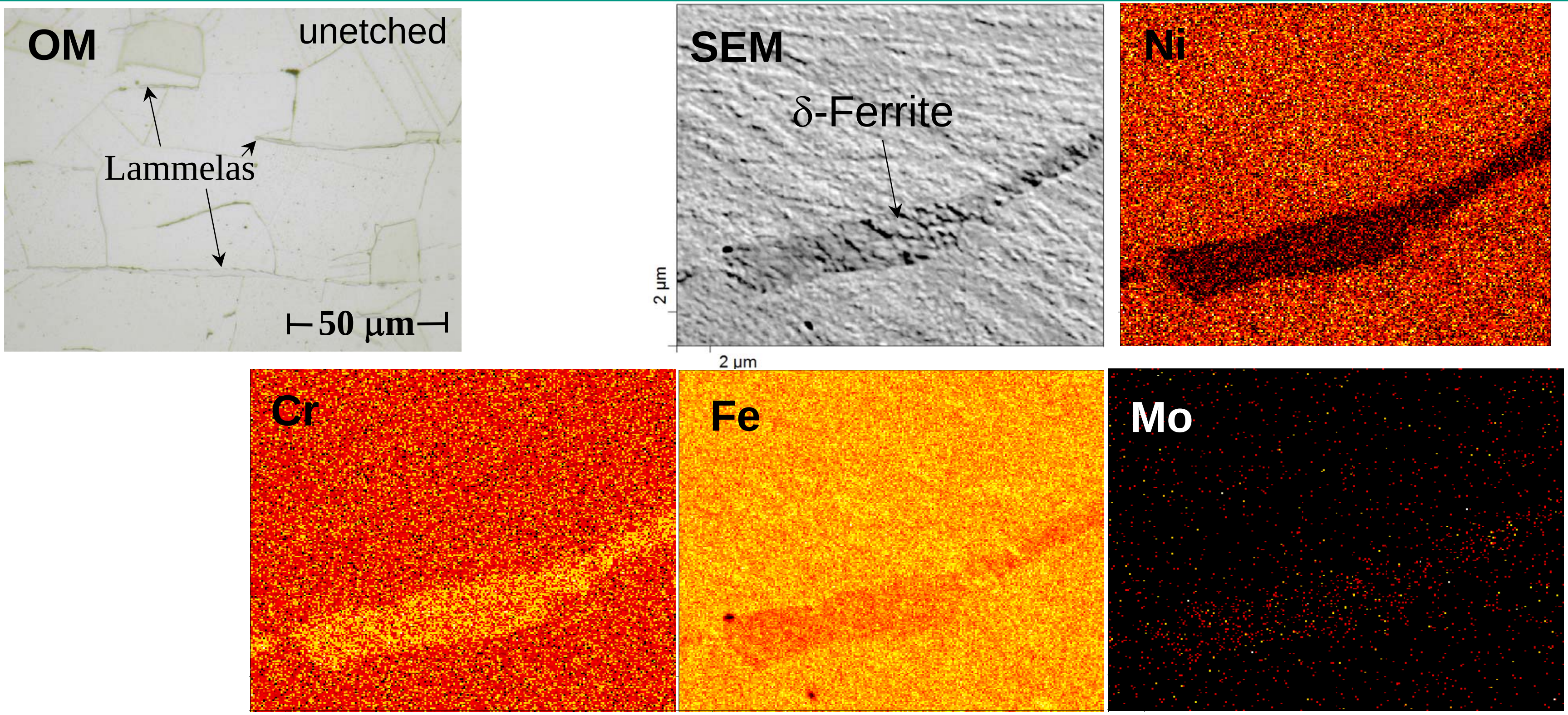
- 5 capsules for HLM
- 3 capsules for air (gas)



CRISLA-capsule for liquid metal

Tested material: austenitic 316L steel

316L														
Fe	Cr	Ni	Mo	Mn	Si	Cu	V	W	Al	Ti	C	N	P	S
bal	16.73	9.97	2.05	1.81	.67	.23	.07	.02	.0183	.0058	.019	.029	.032	.0035

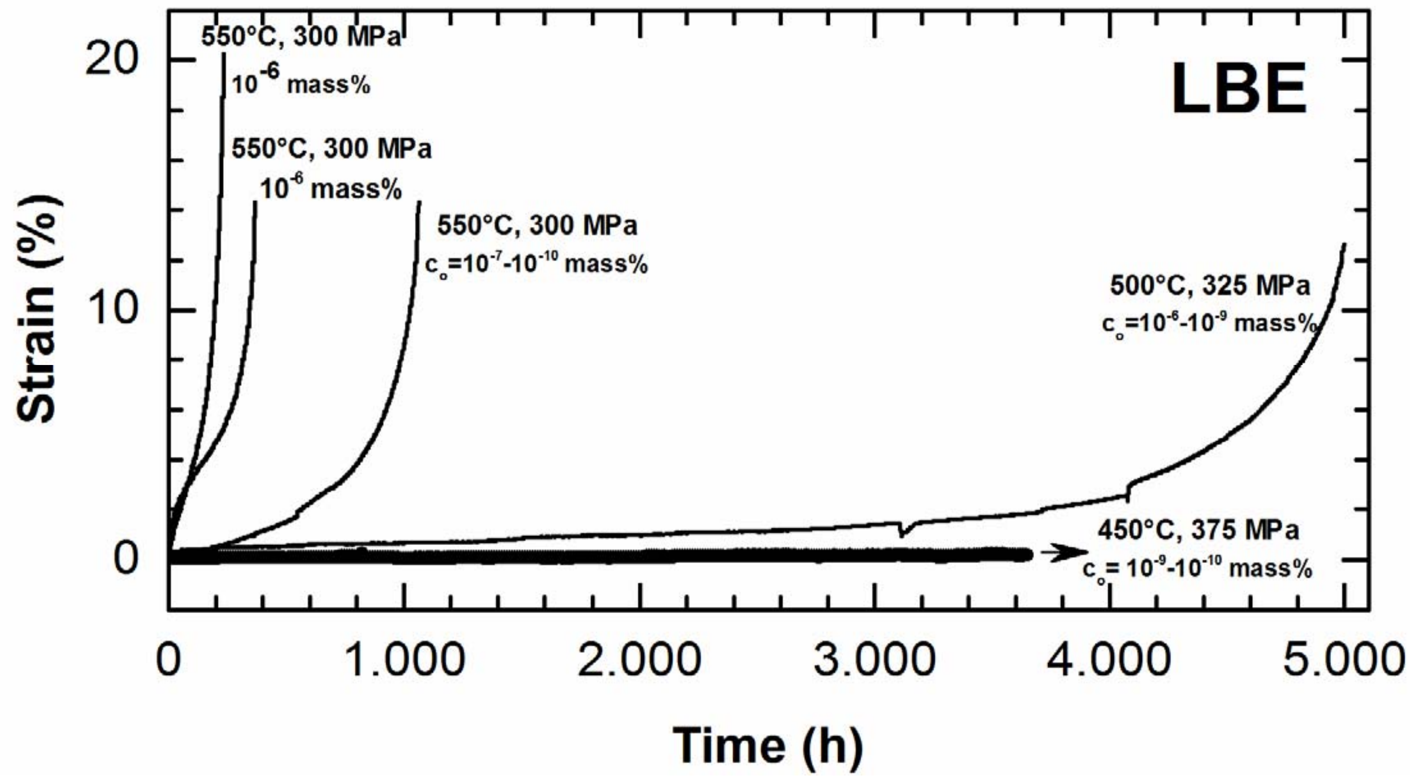


Lamellae texture enriched in Cr, sligtly in Mo and depleted in Fe, Ni in comparison with the average composition of 316L

Tests on 316L austenitic steel

Experiments	Status
LBE, $c_o = 10^{-7}$–10^{-10} mass%, 550 °C/ 300 MPa	t_R =1,060 h
LBE, $c_o = 10^{-6}$ mass%, 550 °C/ 300 MPa	t_R = 182 h, 231 h, 365 h
Air, 550 °C/ 300 MPa	Stopped before rupture, t_R > 1,150 h
LBE, $c_o = 10^{-8}$–10^{-9} mass%, 500 °C/ 325 MPa	t_R =5,025 h
Air: 500 °C / 325 MPa	Test still running, t_R > 9,015 h
LBE, $c_o = 10^{-8}$–10^{-9} mass%, 450 °C/ 375 MPa	Test still running, t_R > 3,795 h
Air, 450 °C/ 375 MPa	Test still running, t_R > 2,425 h

Creep-to-rupture in LBE at 450-550°C



- The higher T, the shorter secondary creep zone and t_R

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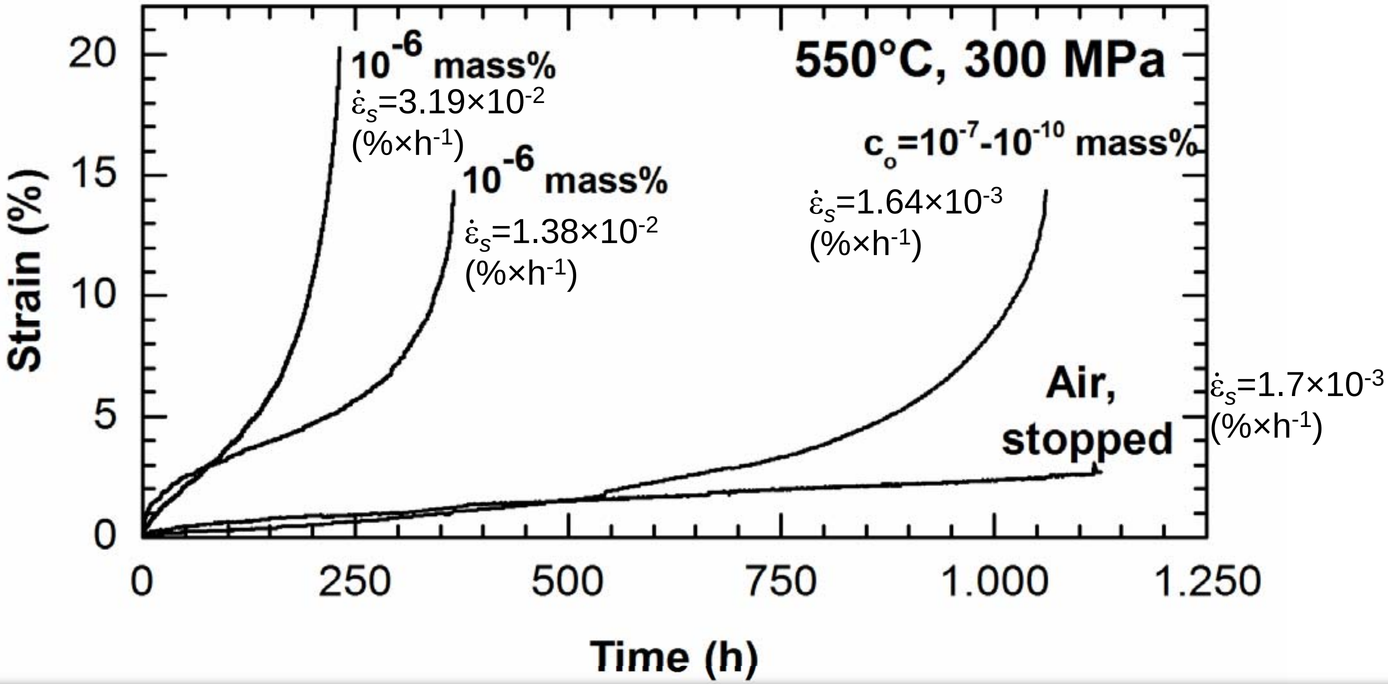
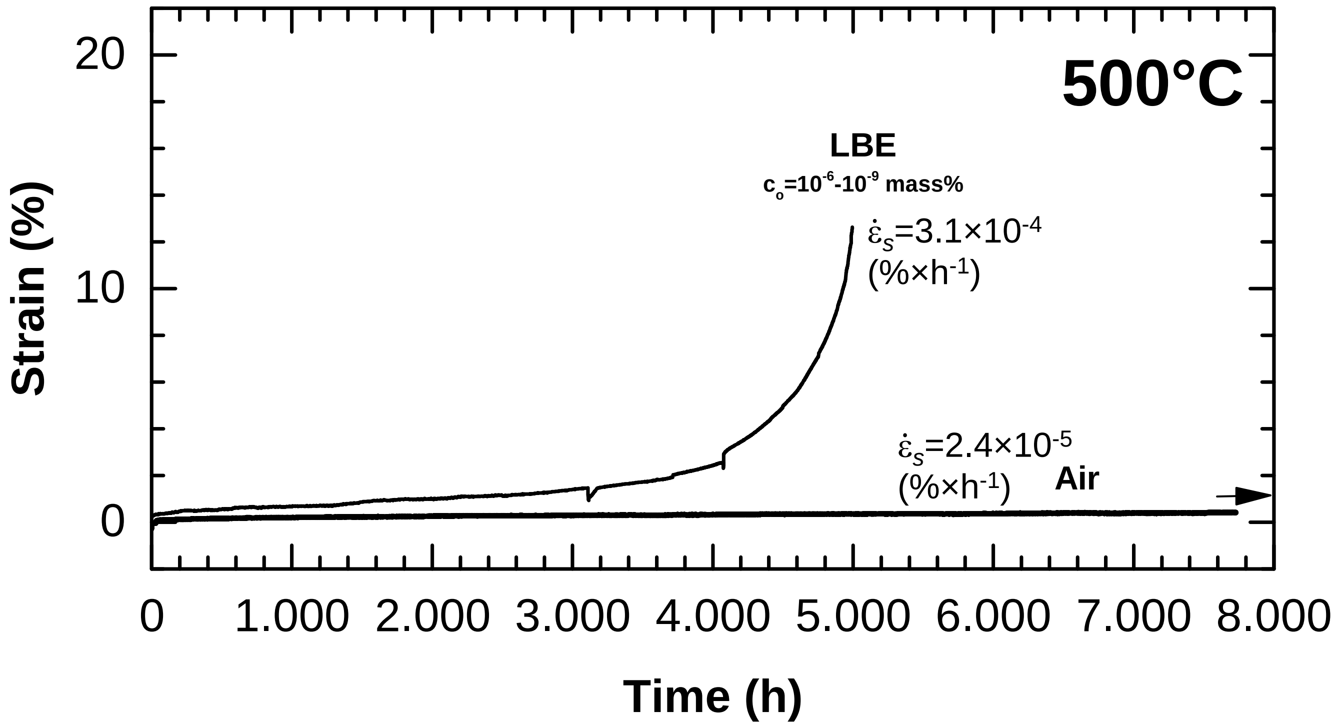
Creep-to-rupture at 550°C and 300 MPa



- $\dot{\varepsilon}_s$ up to one order higher in LBE than in air.
- The transition time from secondary to tertiary zone $t_{2,3}$ determines t_R: t_R is shorter in LBE than in air even if $\dot{\varepsilon}_s$ in LBE similar to that in air.
- c_o =10^{-6} mass% shows no improvement in comparison to lower c_o.

Creep-to-rupture at 500°C and 325 MPa



- $\dot{\varepsilon}_s$ is one order higher in LBE than in air
- $t_{2,3}$ is smaller in LBE than in air → shortage of t_R in LBE in comparison to air

Creep(-to-rupture) at 450°C and 375 MPa

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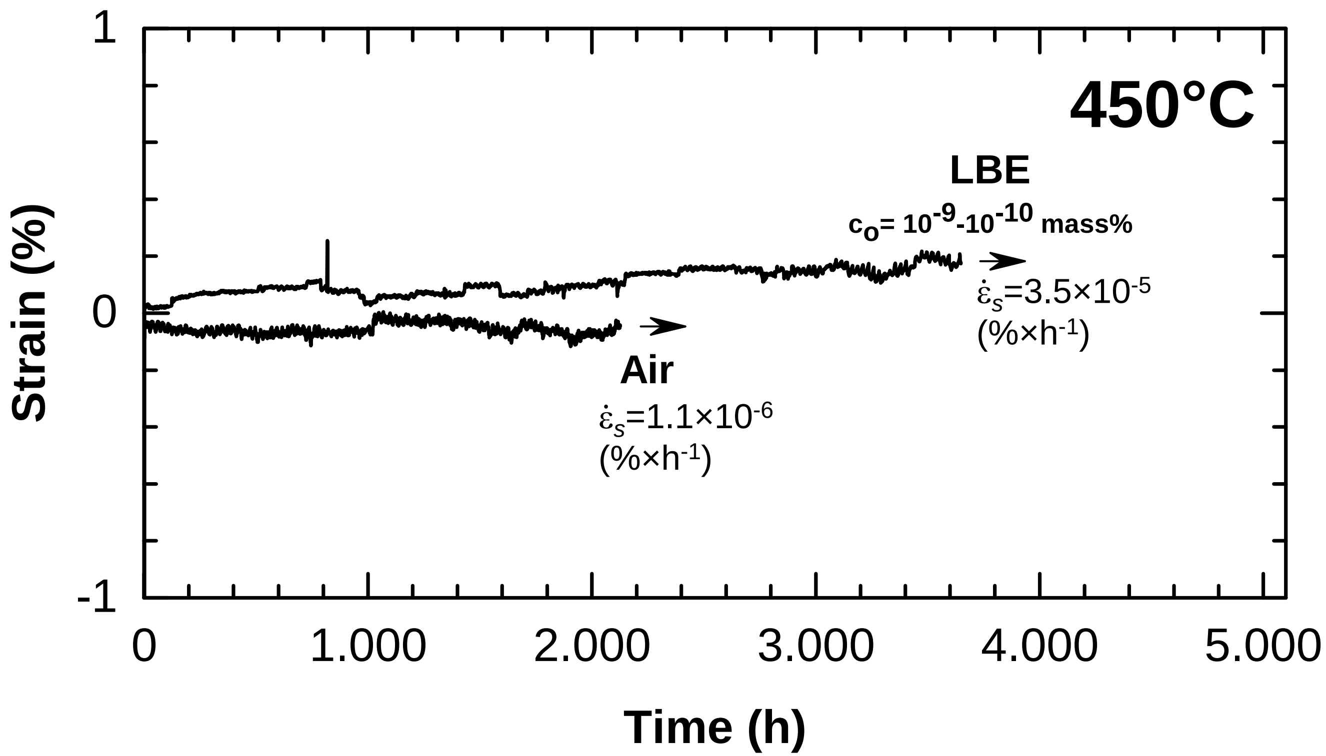
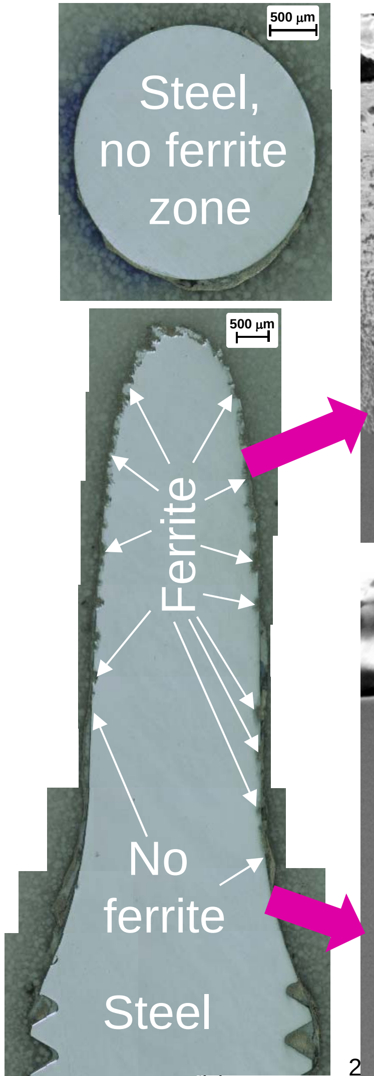
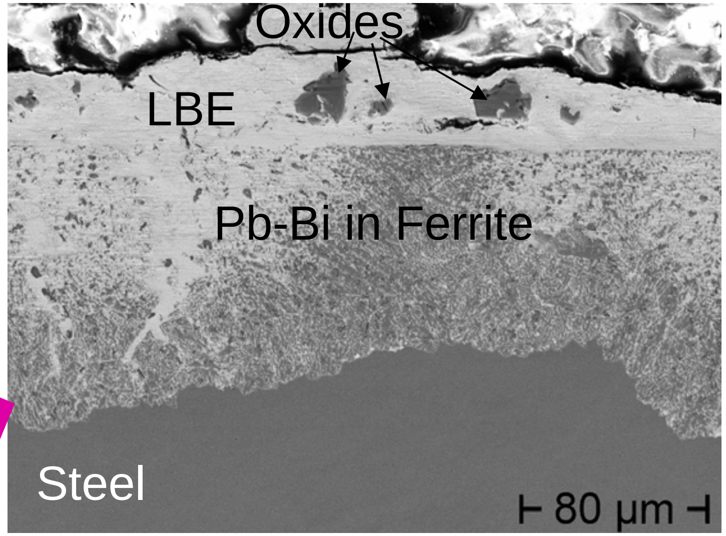


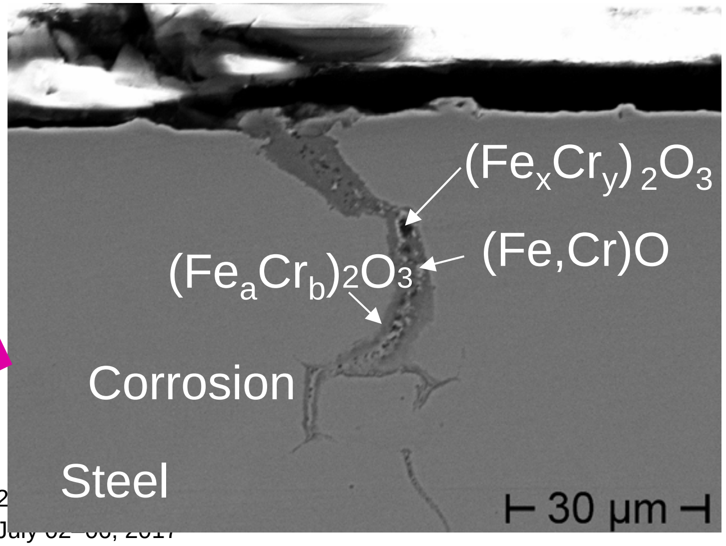
- $\dot{\varepsilon}_s$ is one order higher in LBE than in air

Structural study of 316L tested in LBE

- 316L after LBE for 365h at 550°C, c_o=10^{-6} mass% and 300 MPa as a sample







Typical image of the surface with a ferrite zone

- Steel feature of 316L in LBE under stress: The closer to rupture surface, the thicker the ferrite zone
- (Almost) No ferrite close to screw thread

Corrosion extending inwardly the steel without ferrite zone (exception)

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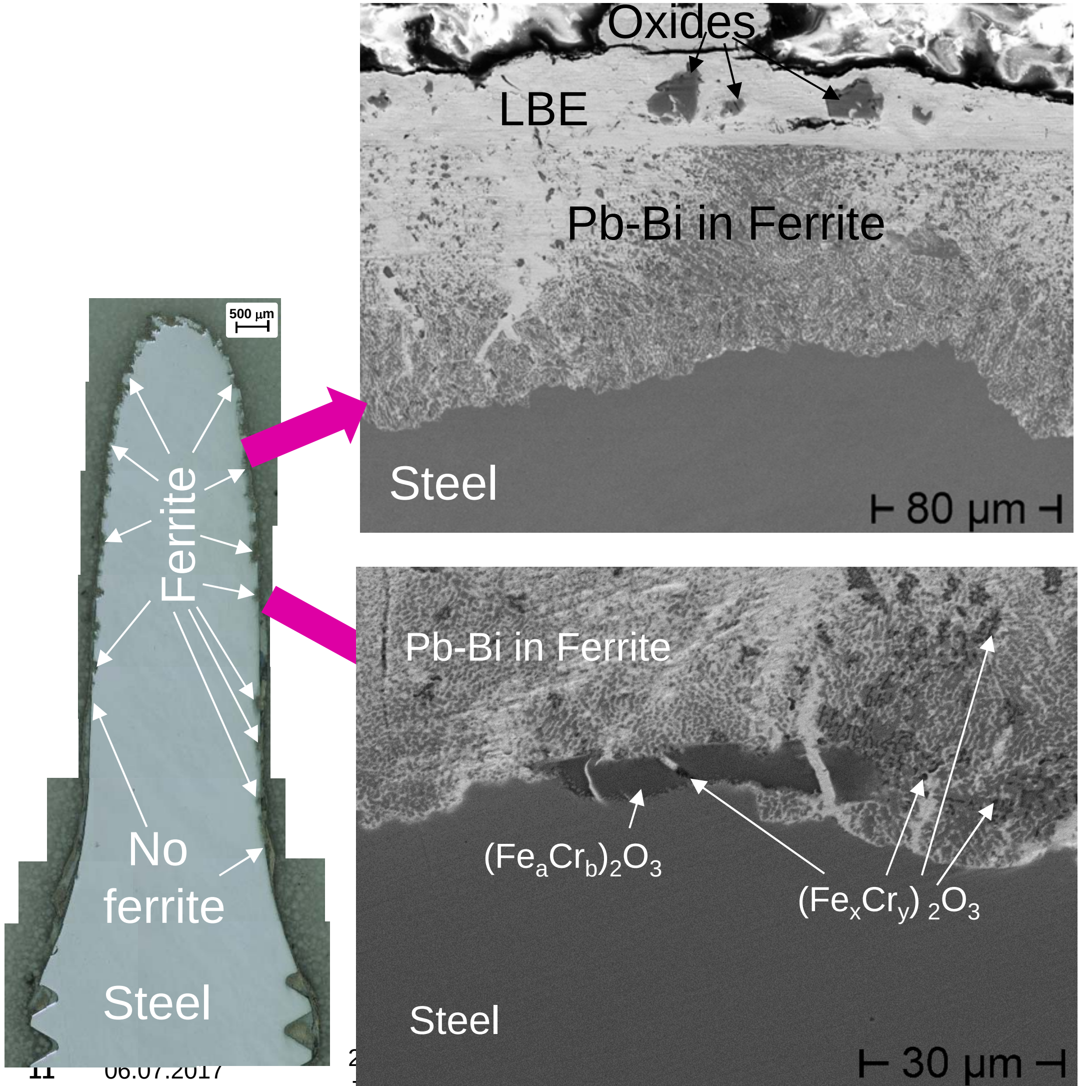
Structural study of 316L tested in LBE

- 316L after LBE for 365h at 550°C, $c_o=10^{-6}$ mass% and 300 MPa as a sample



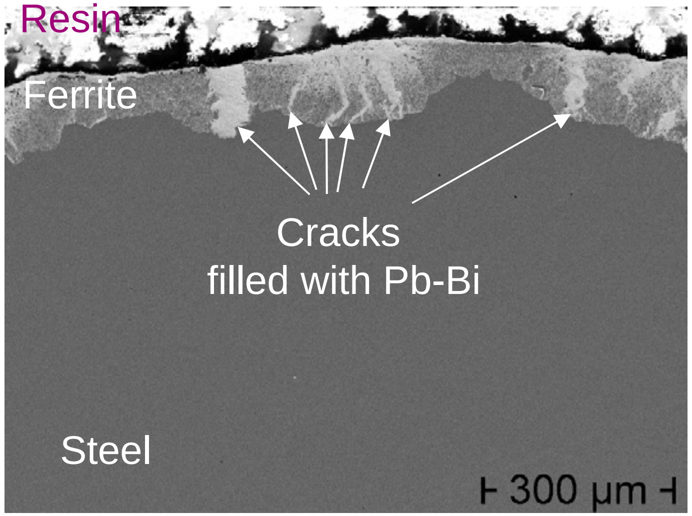
Typical image of the surface with a ferrite zone

- Oxides can form in LBE close to the steel surface and in the ferrite zone filled with Pb-Bi

Oxides at steel/ferrite interface (exception) and in the ferrite zone

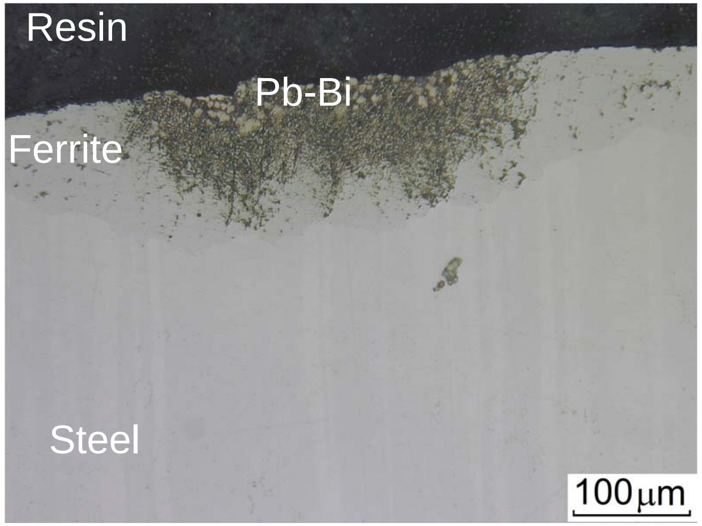
Structural study of 316L tested in LBE at 550°C

Stagnant LBE, $c_o = 10^{-6}$ mass%, 365 h and 300 MPa



Cracks in ferrite zone filled with Pb-Bi

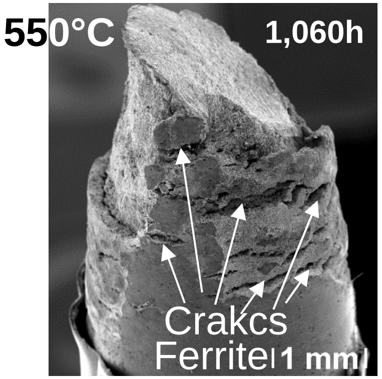
Flowing LBE, $c_o = 10^{-7}$ mass%; 2,011 h and 0 MPa (CORRIDA)

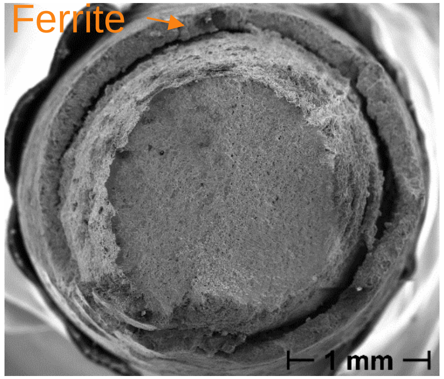


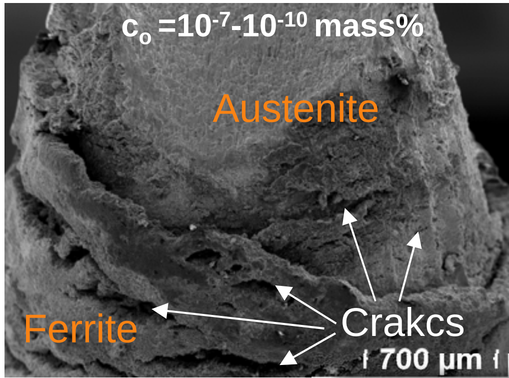
Pit-type corrosion damages as a result of selective leaching of the steel elements [V.Tsisar, C.Schroer, KIT]

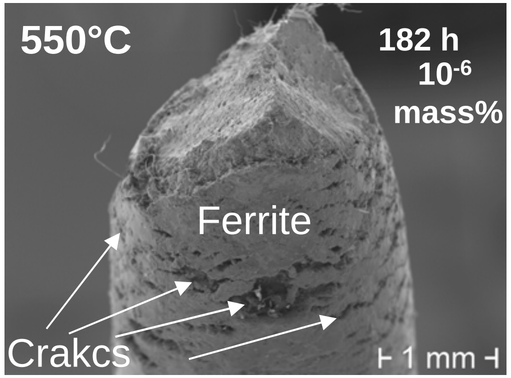
- Diverged cracks propagated in ferrite zone towards the steel and filled with Pb-Bi is a feature of 316L under stress in LBE

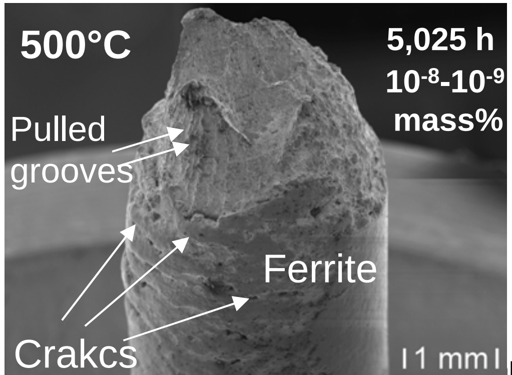
Structural study of 316L tested in LBE

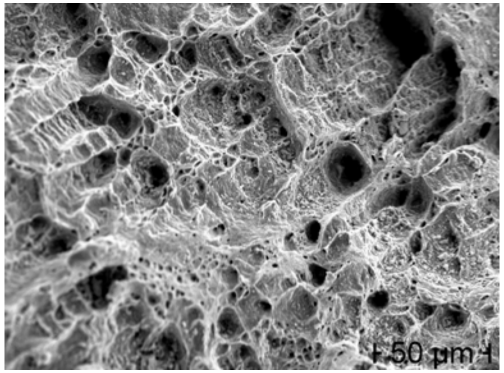












Ductile-dimple rupture mode at RT in air [Structural Alloys for Power Plants, ed. by A. Shirzadi & S. Jackson, 2014]

- Ductile rupture mode
- Transformation of austenite into ferrite due to selective-leaching steel elements into LBE at 500-550°C independing on c_o (≤10^{-6} mass%)
- The austenite-to-ferrite transformation is characterised with a shortage of t_R in comparison to air.
- Cracks found not only in ferrite but also in the steel. Therefore rupture topography can contain from one up to multiple rupture planes.

Structural study of 316L tested in LBE

T / °C	Enviroment	*Co*, mass% / t_R, h	Strain / %	Reduction of area / %	Thickness of ferrite / µm
550	LBE	10^{-6} / 231	14-22	32	0-86
		10^{-6} / 365			0-37
		10^{-7}-10^{-10} / 1,059			0-326
	air[1]	1,025	3	10	-
500	LBE	10^{-8}-10^{-9} / 5,025	12	43	93-200
	air[2]	after 7,729	0.4	-	-
RT	**air**		**50-70**	**Comprehensive Nuclear Materials, ed. by J. Konings, 2012**	

[1] - stopped; [2] - running

- Strain at rupture at 500-550°C in LBE is significantly less than at RT. Reduction of area increases in LBE with lowering of T. But ductile-dimple rupture mode of austenitic 316L steel is remains in LBE at 500-550°C.
- Ferrite zone at lower T, c_o and longer t_R is more regular distributed and it is thicker than at $c_o=10^{-6}$ mass% (at 550°C)

316L tested in LBE

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Conclusion:

- 316L austenitic steel degrades stronger in LBE than in air at 500 and 550°C due to selective leaching of the steel elements leading to :

(i) austenite-to-ferrite transformation at steel/liquid metal interface and

(ii) penetration of liquid metal into ferrite and cracks formed into the ferrite and propagated further into the steel

- $c_o=10^{-6}$ mass% (at 550°C) does not decrease LBE effect in comparison to lower c_o.

Acknowledgment:

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Functionality check of Pt/O-sensor