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Creep Strength of Ferritic/Martensitic Steel P92 in Oxygen-Containing Lead at 650℃

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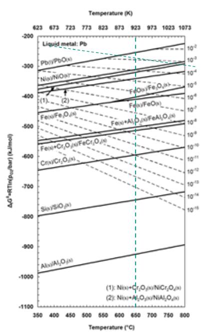
Motivation

The GEN-IV nuclear systems of different concepts are developed on the international level. E.g., lead-cooled fast reactor (LFR) concept is planned to be realized in Belgium and Russia with lead-bismuth eutectic (LBE) as a coolant. Increase of the nuclear reactor efficiency has to be done through increase of the service temperature up to 800℃. This requires development of new structural materials which have to possess high mechanical and physical properties at elevated temperatures.

Creep strength of the ferritic/martensitic steel P92 was investigated in oxygen-controlled lead (c_o=10^{-6} mass%) and air at 650℃ within the European Cross-Cutting Project GETMAT (Gen IV and Transmutation Materials).

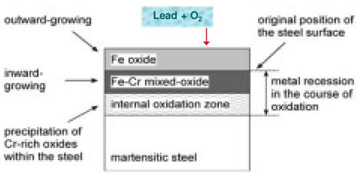
Oxygen Protection of Steel in HLM

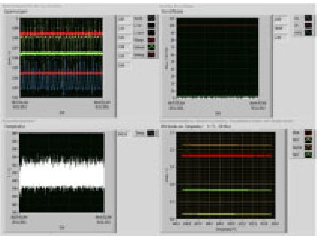


Ellingham diagram: formation of oxides of the main steel elements depending on T and c_o

Depending on O_2-activity in HLM the following prozesses can occur:
1) Metalls dissolve in HLM with a penetration of the latter into the steel;
2) Formation of oxide scale on the steel;
3) Precipitaion of HLM

Oxide scale formation on Cr-steels





Monitoring and control of the oxygen concentration in lead at 650℃

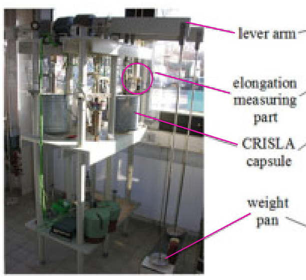
Redox gases used in the creep-rupture tests in Pb (c_o=10^{-6} wt%) at 650℃ for capsule with 900 ml:

(i) Ar (carrying gas): 80-100 ml/min
(ii) Ar/15vol% H_2: 3 ml/min
(iii) synthetic air: 1 ml/min (in automatic regime)

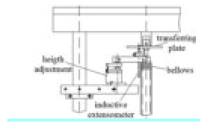
E*: 965±2.5 mV
corresponds

c_o : 9.29x10^{-7}<9.89x10^{-6}<1.05x10^{-6}

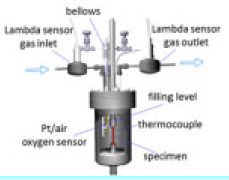
CRISLA (Creep-Rupture in Stagnant Lead Alloys) Facility



General view of the CRISLA stands

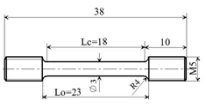


Elongation measuring system



CRISLA capsule with a specimen, an external loading and an oxygen-control systems

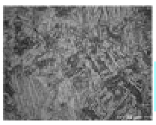
Five capsules with liquid lead (900 ml)
Three capsules with air (230 ml) for reference tests



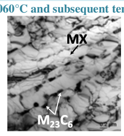
The ferritic/martensitic steel P92

Fe	C	Si	Mn	P	S	Cr	Mo
bal.	0.11	0.26	0.43	0.018	0.003	8.99	0.49
Ni	Al	Nb	V	W	B	N	
0.12	0.016	0.06	0.2	1.75	0.002	0.043	

Thermal heat treatment: normalization for 1 h at 1060°C and subsequent tempering for 2 h at 770°C.



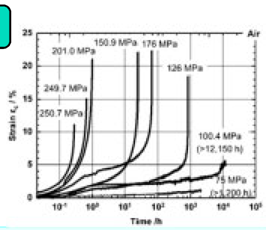
SEM micrograph of the as-received material obtained from perpendicular cross-section



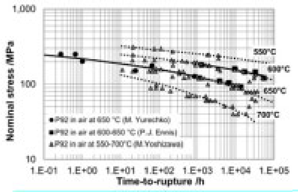
TEM micrograph of the as-received material obtained from perpendicular cross-section

Creep-to-Rupture Tests Under Stagnant Conditions

AIR



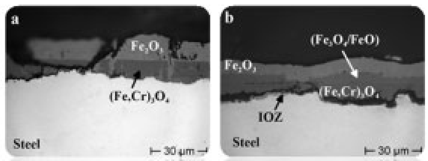
The strain-time curves in range of 75-325 MPa



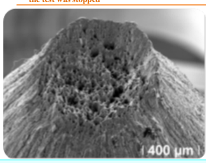
Experimental stress-rupture curves in comparison to literature

σ MPa	t_R h	$\varepsilon_{c;R}$ %	Z %	$\dot{\varepsilon}_{c,s}$ %/h	$t_{1,2}$ h	$t_{2,3}$ h
325.5	0	20	83	-	-	-
290.3	0.017	31	89	-	-	-
250.7	0.3	20	90	17.68	0.083	0.12
249.7	0.68	21	86	11.63	0.217	0.33
201.0	1.0	31	90	10.68	0.317	0.65
176.0	65.5	28	89	0.083	5.133	37.4
150.9	25.1	31	91	0.270	1.933	12.4
126.0	839.1	23	83	0.004	147.2	610
100.4*	>12,150	-	-	0.0002	337.8	-
75.5*	>1,104	-	-	(0.0004)	81.5	-

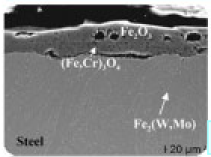
* the test was stopped



OM: Oxide scale formed at the beginning of the necking region (a) and far from fracture surface (b)

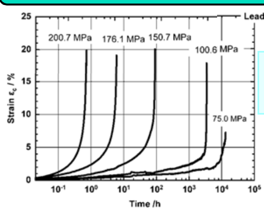


Ductile fracture of the specimens ruptured in stagnant air at >125 MPa with Z~85-90%

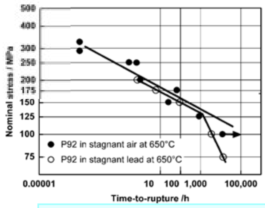


SEM: Oxide scale and steel microstructure after 839h in air at 126 MPa

OXYGEN-CONTROLLED LEAD (c_o=10^{-6} wt.%)

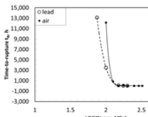


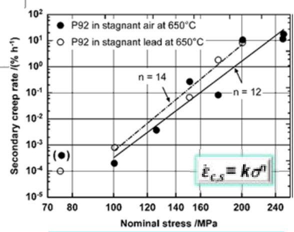
The ε_c-t curves in the range of 75-200 MPa



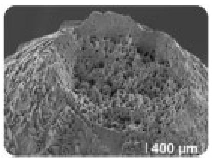
Comparison of the σ-t_R curves obtained in stagnant lead and air at 650℃

σ MPa	t_R h	$\varepsilon_{c;R}$ %	Z %	$\dot{\varepsilon}_{c,s}$ %/h	$t_{1,2}$ h	$t_{2,3}$ h
200.7	0.73	23	92	8.4034	0.183	0.23
176.1	5.97	16	89	1.8241	1.05	2.73
150.7	90.0	18	90	0.0670	18.67	46.78
100.6	3,442	27	94	0.0008	597.6	2477
75.0	13,090	13	23	0.0001	1276	6363

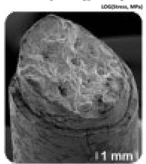




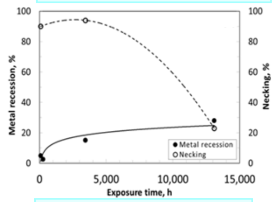
Comparison of $\dot{\varepsilon}_{c,s}$ for P92 tested in stagnant lead and air at 650℃



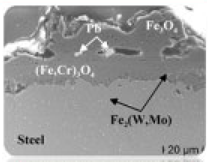
Typical ductile fracture of the specimens ruptured in stagnant Pb at σ>100 MPa with Z~90%



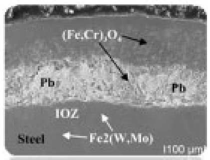
Fracture at 75 MPa Z=23% (t_R=13,090 h)



Exposure time effect on metal recession and necking



Pb in the outer oxide layer



Pb in the inner oxide layer

Conclusions

- Formation and coarsening of the Laves phase during the creep-rupture tests is a consequence of thermal aging and not the media.
- No difference in the creep mechanism in air and stagnant lead at >100 MPa and 650℃. Fracture appearance and creep characteristics ε_c and Z result in a change in creep mechanism at σ>75 MPa.
- Weak effect of liquid lead on the creep strength of P92 at 650℃ was found in comparison to air at >100 MPa. Increasing the exposure time, this effect becomes more pronounced due to advanced corrosion and lead penetration into the steel.

Acknowledgment

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