Pulsed E-beams to improve corrosion barriers for lead alloy cooled reactors: overview and dedicated mechanical tests

Creep resistance of Al-surface alloyed T91 steel exposed to heavy liquid metals

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Introduction – why do we need corrosion barriers

Corrosion barrier concept

Mechanical tests - Creep to Rupture
- Influence of liquid lead alloy
- Behavior of corrosion barrier

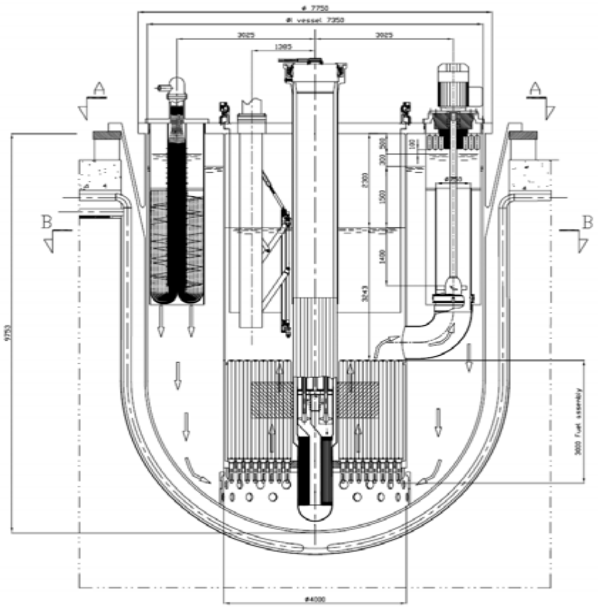
Summary

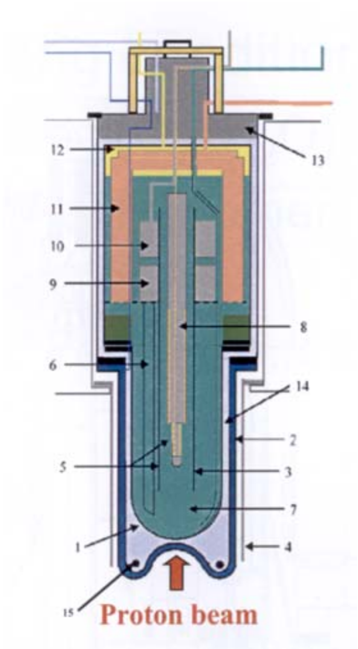
Actual and planned nuclear facilities cooled with liquid lead alloys

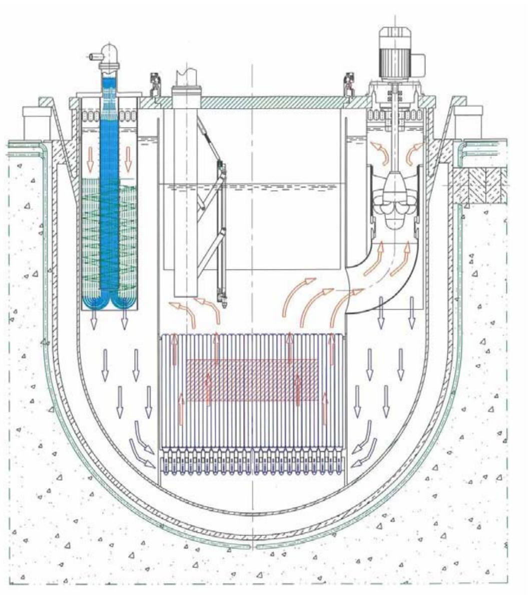
Subcritical systems for transmutation

Neutron source - spallation

Future GEN IV reactors







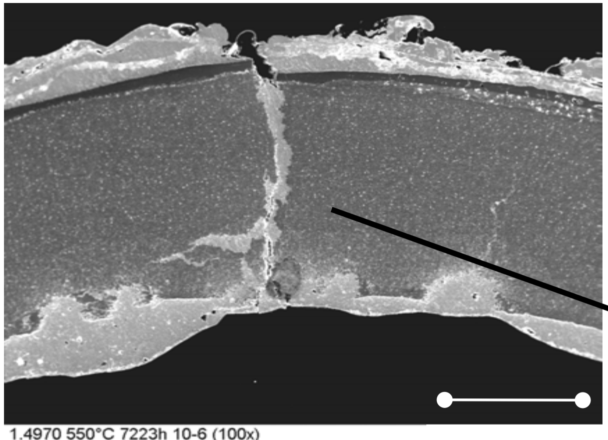
EFIT, XT-ADS, ***MYRRHA***
Coolant + target: Pb, PbBi

MEGAPIE
Coolant +Target: Pb, PbBi

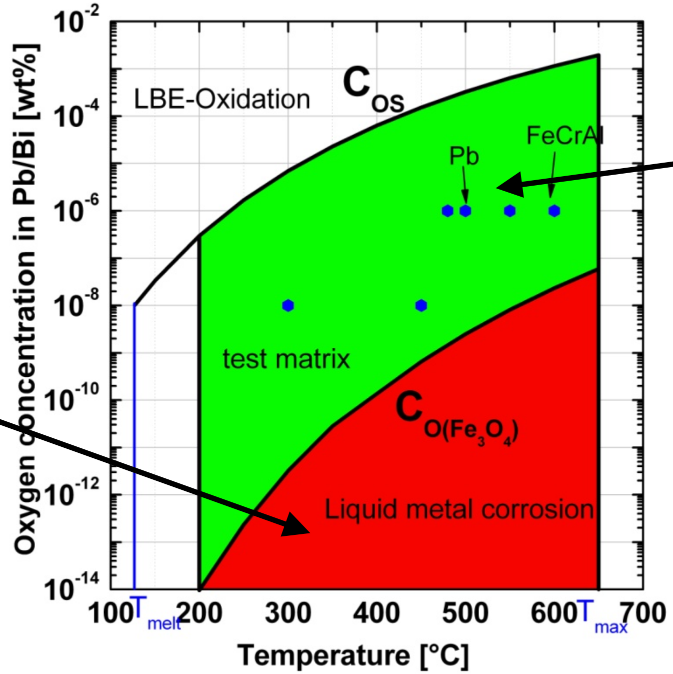
LEADER - Pb,
SVBR-100 – *PbBi*

Material compatibility of steels with lead alloys

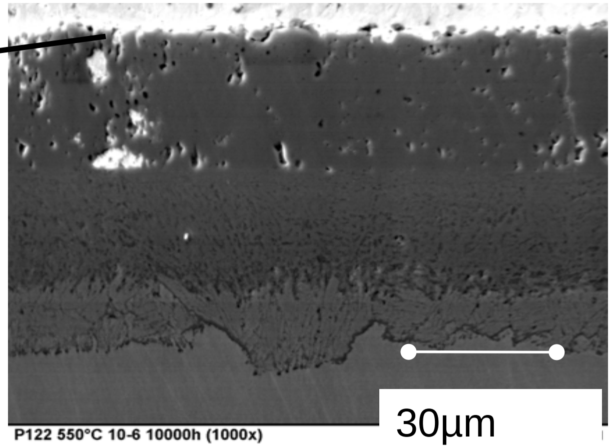
austenitic steel / 1.4970
550° C ~7000h's



200µm



f/m Stahl / T91
550 ° C ~10000h's



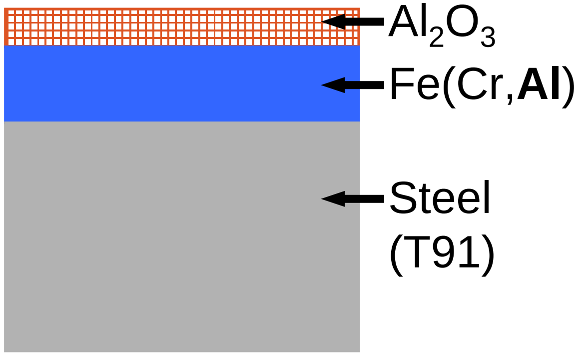
Dissolution of alloying elements
(solubility : Ni>>Cr>Fe).
Dissolution rate up to 1 µm/h

- strong oxide scale growth
  frequent spallation inter alia growth stresses
- reduced heat removal

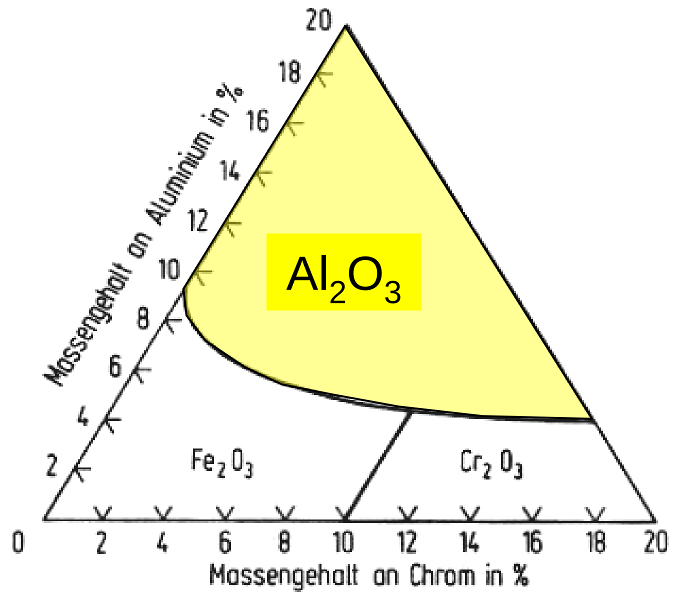
Two main effects of corrosion:
structural integrity – material loss of metal – dissolution attack, oxidation (Spinel + IOZ)
heat removal - : oxidation (magnetite + spinel)

> 500°C additional corrosion barriers are needed

Corrosion barrier concept against dissolution and strong oxidation: thin, protective, slow growing oxide scales



Oxide map FeCrAl – Oxide at 1000°C



Requirements

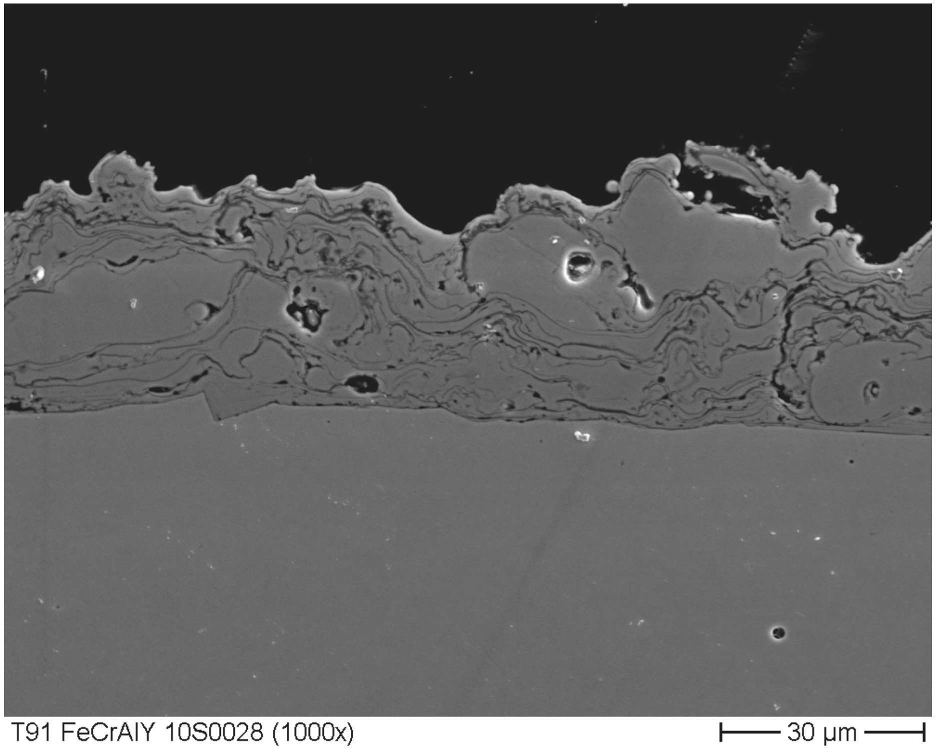
- Corrosion resistant in HLM up to ca. 650 °C
- Self healing of mechanically damaged layers
- No negative influence on mechanical properties
- Irradiation stability under relevant fluxes
- The coating / alloying process *must be of industrial relevance*

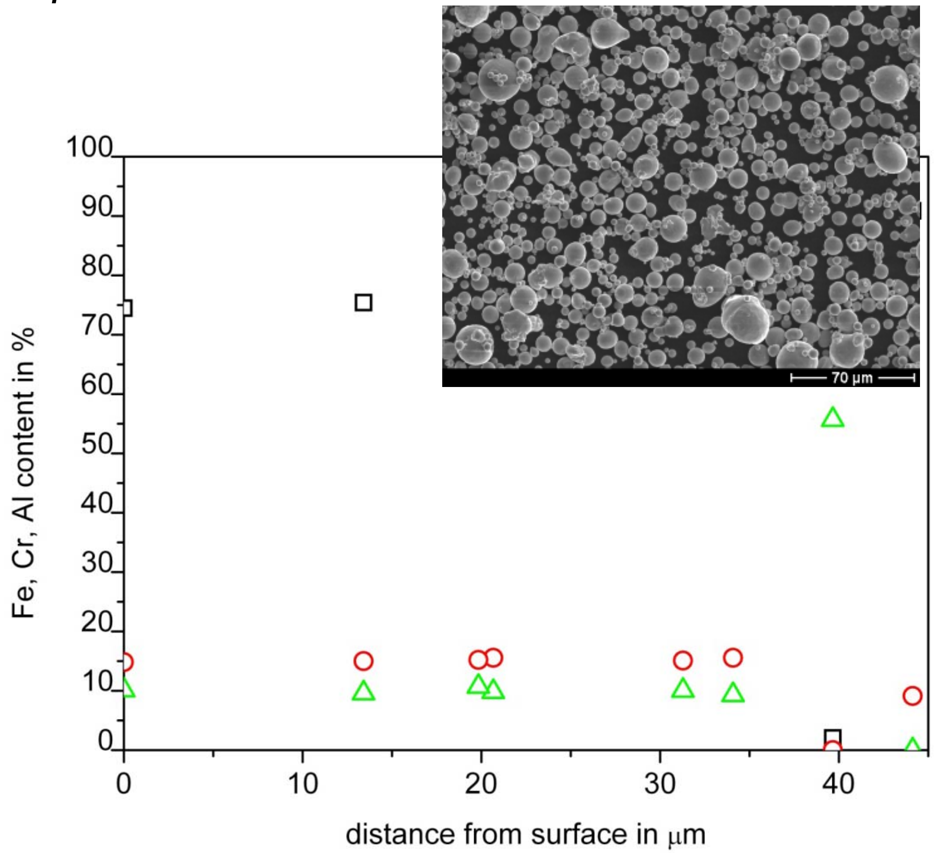
Thermal conductivity of Al_2O_3

(400°C) = 8 – 12 W/mK
(500°C) = 14 W/mK

LPPS sprayed FeCrAlY coating on T91 steel

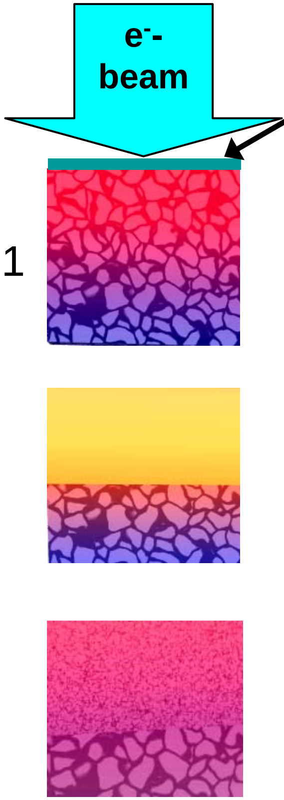
Al content of powder eg. around. 11 wt% Al – particle size ~ 30µm -
Al content still under investigation
specific LPPS process that allows spraying of 20 to 30µm thick scales
Substrate temperature during spraying < 600°C





Layer is porous, rough with significant variation in thickness, bonding to substrate only mechanical
➔ GESA – Re-Melting of deposed layer by pulsed electron beams – T91 has to stay < 650 °C

Surface modification using Pulsed Electron Beams (GESA)
(Process development in cooperation with NIIEFA, St. Petersburg)



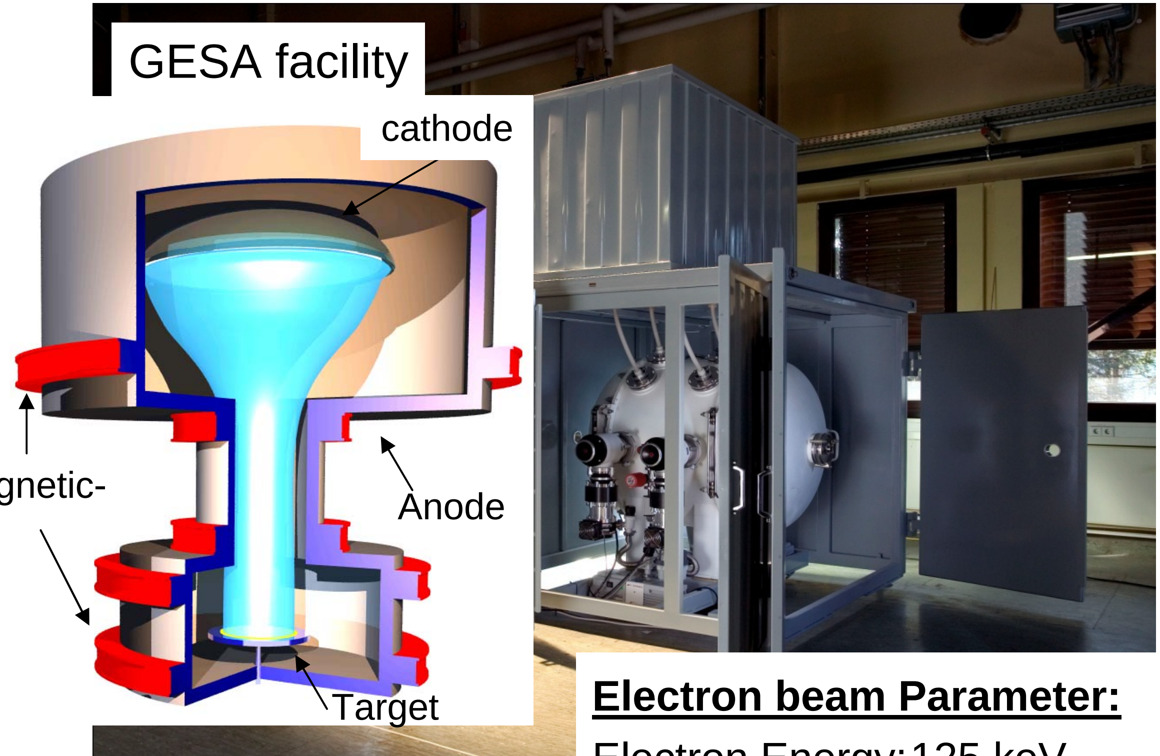
LPPS sprayed FeCrAl layer

T91

Volumetric Heating:
rate: < 10^9 K/s
time: < 40 µs

Melt layer:
depth: < 100 µm
cooling: < 10^7 K/s
(heat conduction)

Surface alloyed layer



Electron beam Parameter:

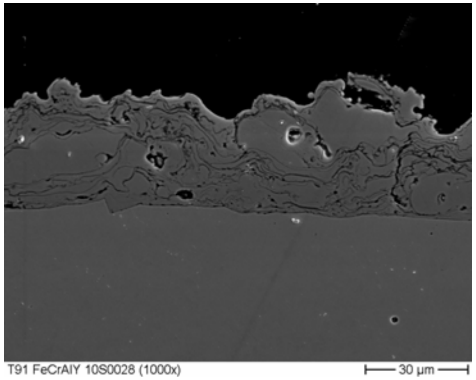
Electron Energy: 125 keV
Power density : ~ 2 MW/cm²
Pulse duration controllable: < 40 µs
Beam diameter: ~ 4cm GESA I
Treatable length ~ 30 cm GESA IV

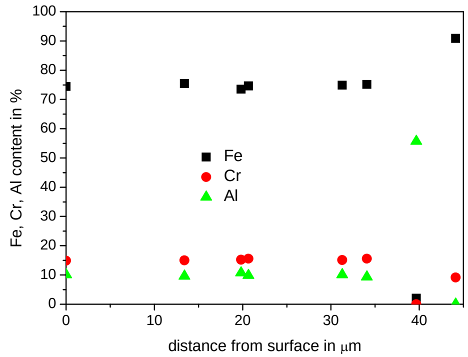
Substrate temperature remains relatively low – no micro-structural changes in T91 observed

T91 + FeCrAlY layer before and after surface modification

Al content ~ 10 wt%

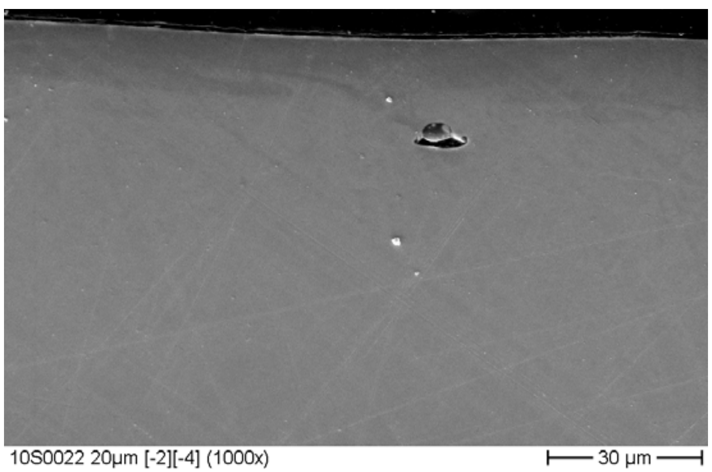
As sprayed

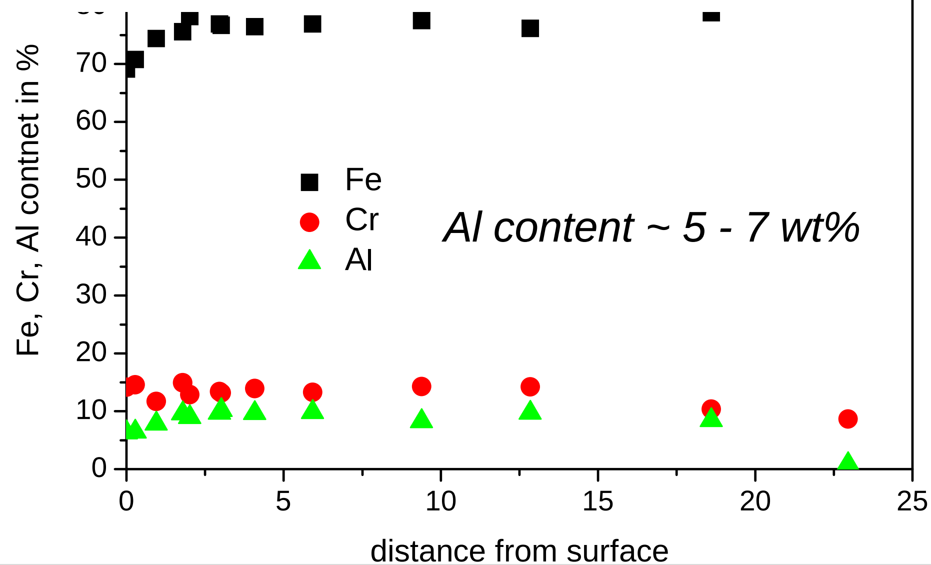




Surface smoothed, pores are removed, layer densified, metallic bonding to substrate ➔ surface alloyed material

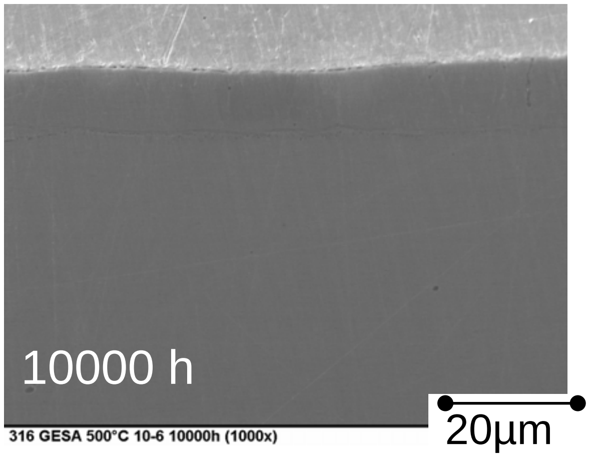
After GESA treatment



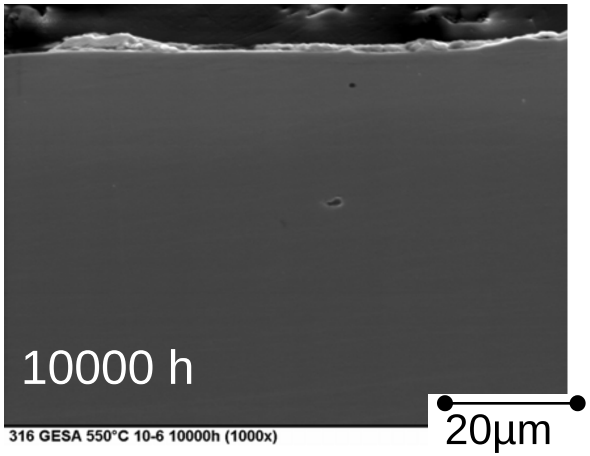


Influence of temperature – “perfect” Al surface alloyed steel at optimal oxygen concentration 10^{-6} wt%

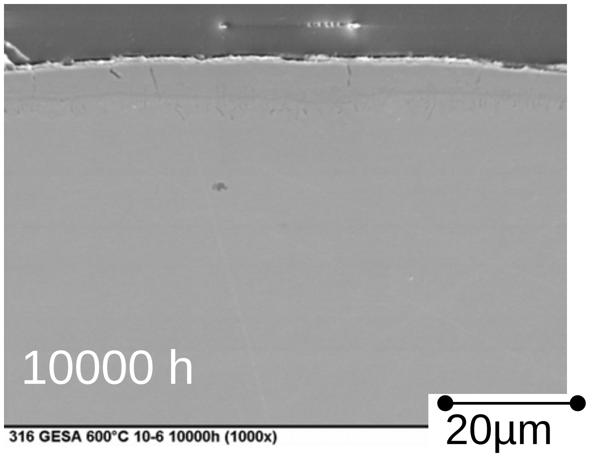
500° C



550 ° C



600° C



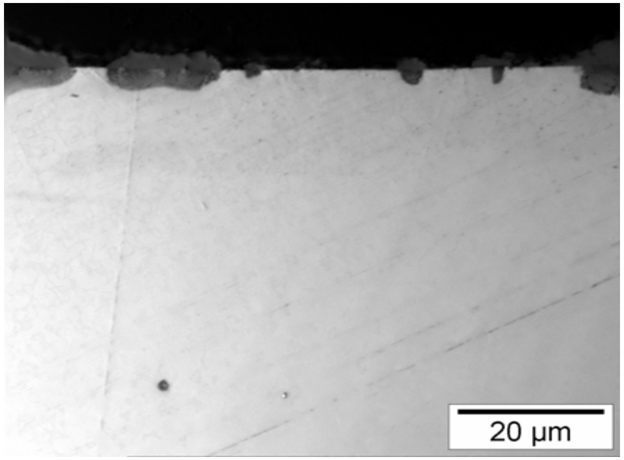
GESA treated FeCrAlY

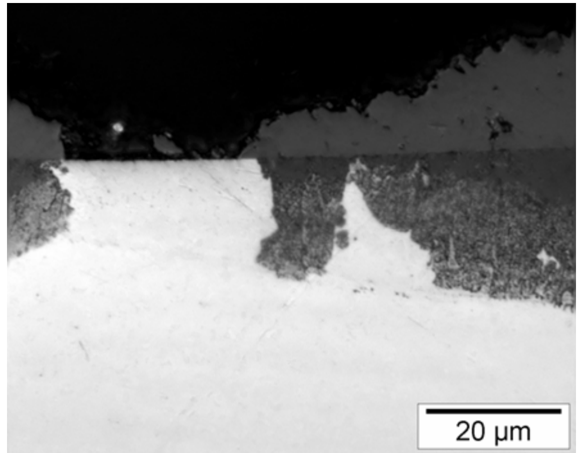
5000 h at 600 ° C in flowing LBE (10^{-6} wt%)

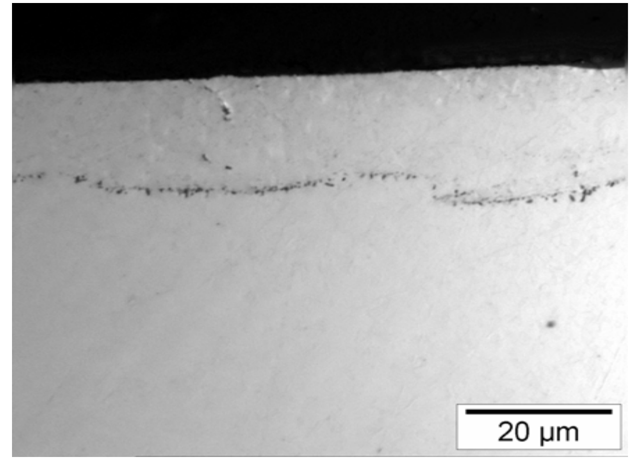
Up to 600°C and 10000 h no corrosion attack and no visible oxidation.

Thin alumina scales protect the surface alloyed steel.

Exposed to PbBi having 10^{-6} wt% oxygen 2000h at 10^{-6} wt
Oxide scale formation at different temperatures (Al_{powder}7wt%)







480 ° C

550 ° C

600 ° C

Large areas showed unexpected oxidation especially at 480 and 550°C

Al content (~4 wt%) before and after exposure

➔ Optimisation of coating and post treatment process to increase Al content

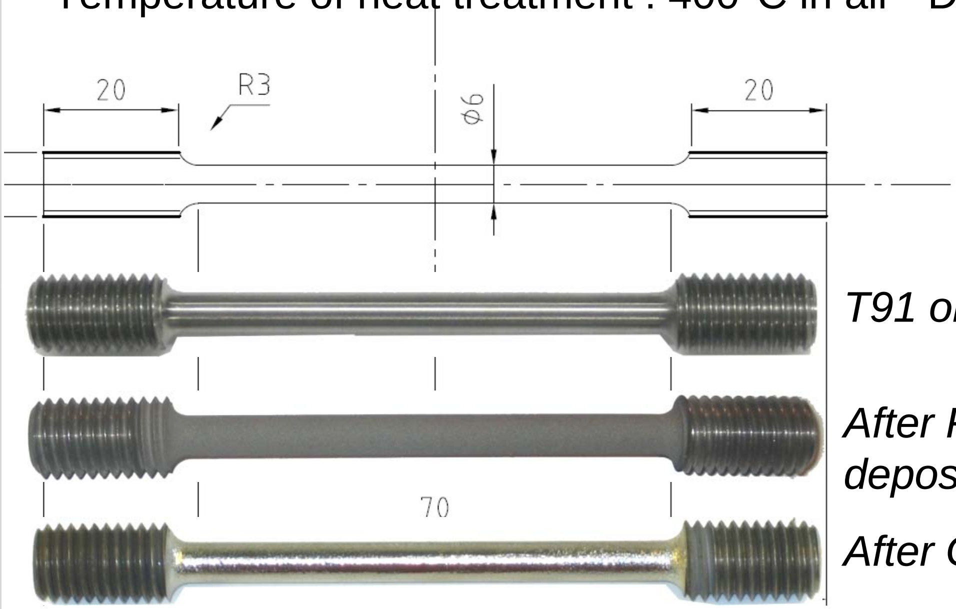
Al content required for selective Al-oxide formation –preliminary results
At 476°C Al > ~6.2 wt%
At 490°C Al > ~5.6 wt%
At 550°C Al > ~5.2 wt%

Creep to rupture of T91 in PbBi and air
T91 with and without GESA modified FeCrAl layer

Specimens: cylindrical test-length 70 mm – diameter 6 mm

Material:
T91 : normalized [1050° C (30 min)] – air quenched followed by tempering [770° C (1h)]

GESA surface modified specimens are heat treated to release possible residual stresses
Temperature of heat treatment : 400°C in air– Duration : 2 h



T91 original

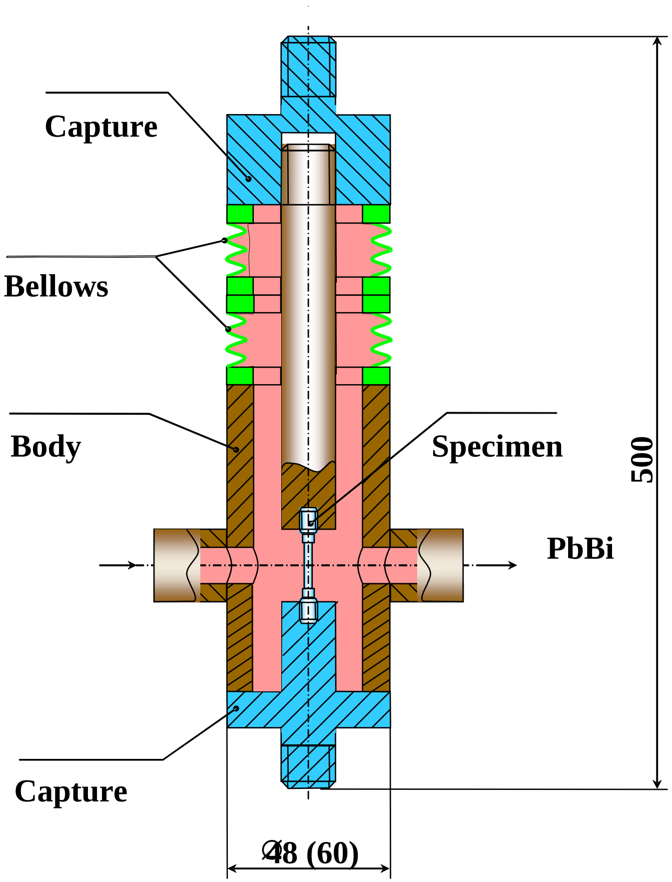
After FeCrAlY deposition

After GESA treatment

Test environment:
Air at 550 and 600°C
LBE at 500, 550°C and 600°C
LBE contains 10^{-6}wt% oxygen

Stress levels:
in air: 140 to 220 MPa
in LBE: 60 to 220 MPa

Test – setup of creep rupture experiments examined at Prometey St. Petersburg (gratitude A. D. Kasthanov, V. G. Markov)



PbBi:
10^{-6} wt% oxygen

Flow velocity :
0.5 m/s

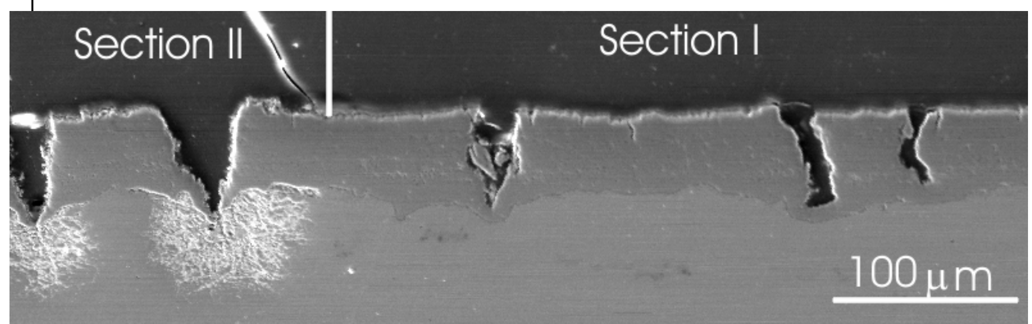
Specimens 100h in test section prior to stress initiation
Measurement of strain outside at capture
Using calibration curve from air experiments strain at specimen is calculated

Influence of PbBi on time to rupture of T91 orig at 550°C

Journal of Nuclear Materials 394 (2009) 102–108

Significant reduction in time to rupture of T91 due to contact with PbBi

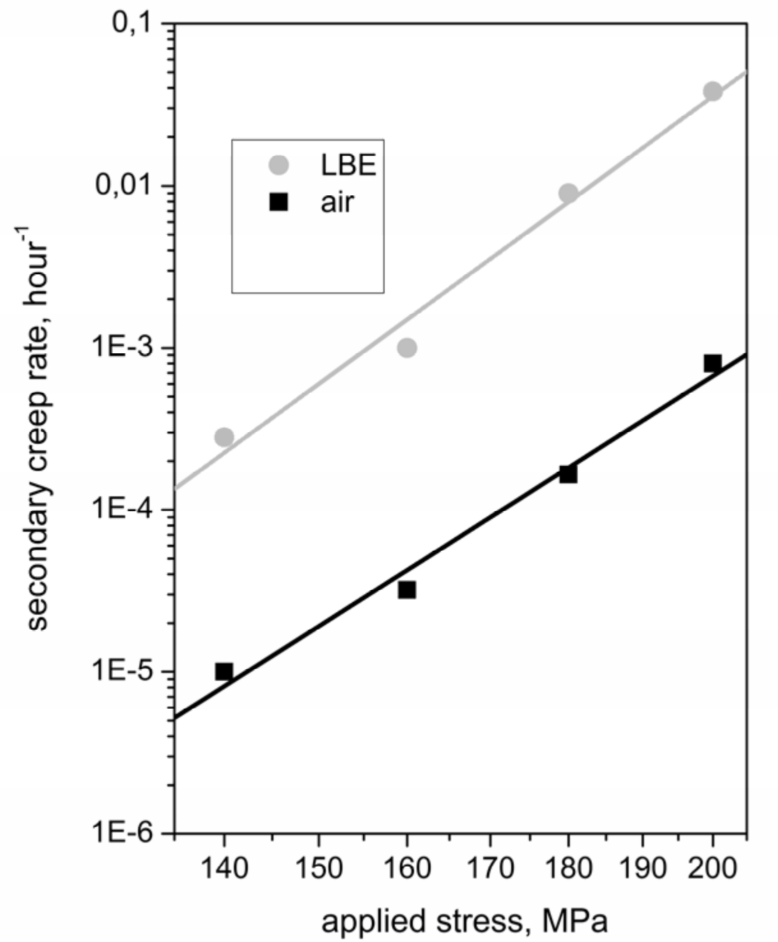
Oxide scale cracks ➔ PbBi penetrates and reduces the surface energy – Rebinder effect – stress corrosion cracking



Comparison of secondary creep rates of T91 in air and PbBi at 550 °C

Stress [MPa]	*Ratio of 2nd creep rates, LBE/air*
140	*27*
160	*35*
180	*44*
200	*53*

Influence of PbBi

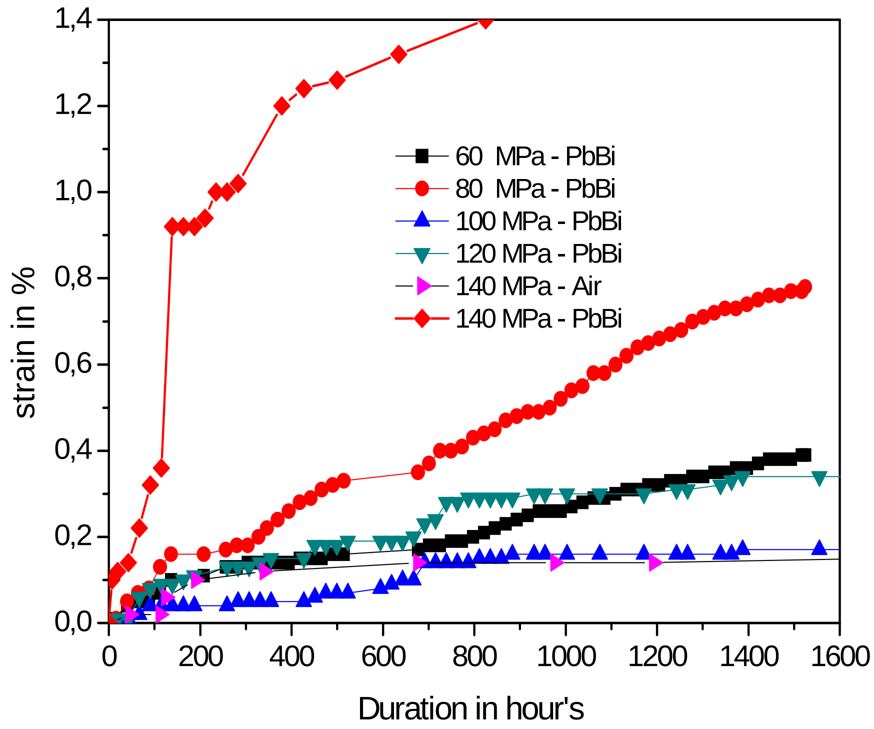


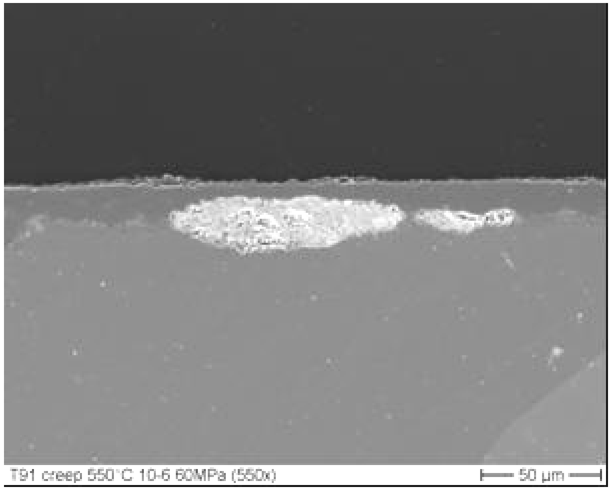
Creep rate in PbBi up to 50 times higher than in air

Ratio of creep rate in PbBi and air is stress dependant

At low stresses – no cracking of oxide scale ?? – no direct contact with PbBi – no influence on creep strength - threshold stress ??

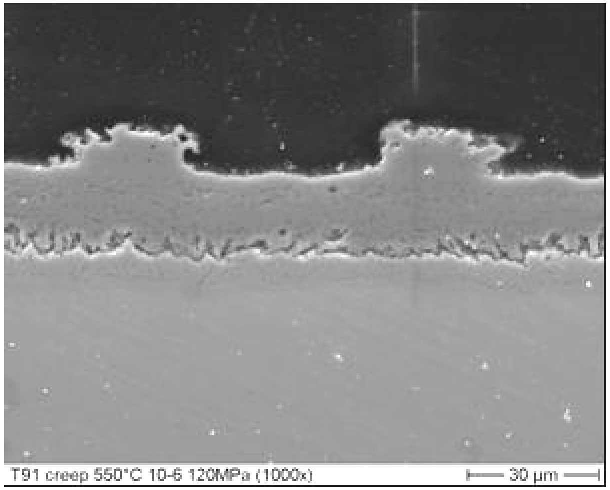
Creep tests at low stresses at 550°C – Threshold stress ??





60Mpa

Cracks PbBi can penetrate



120 MPa

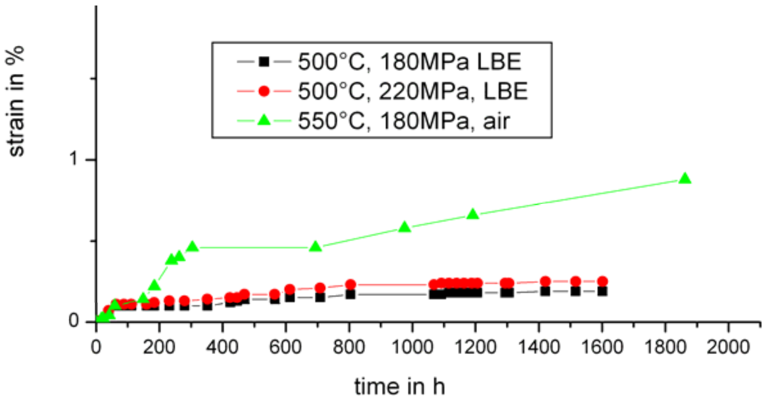
No cracks
No PbBi
No influence

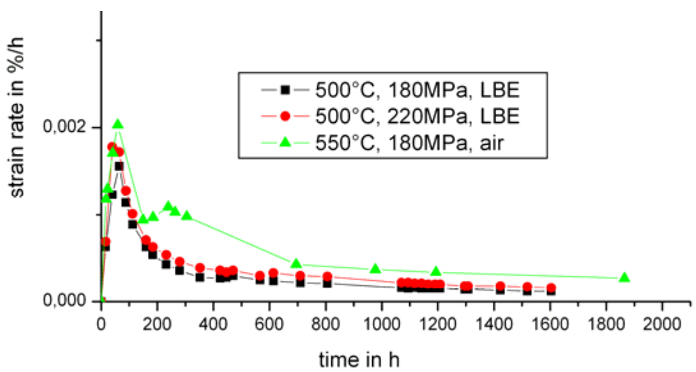
60 to 120 MPa no change - as long as oxide scale intact no influence ➔ cracks at 60 and 80 MPa ➔ reduction in strength

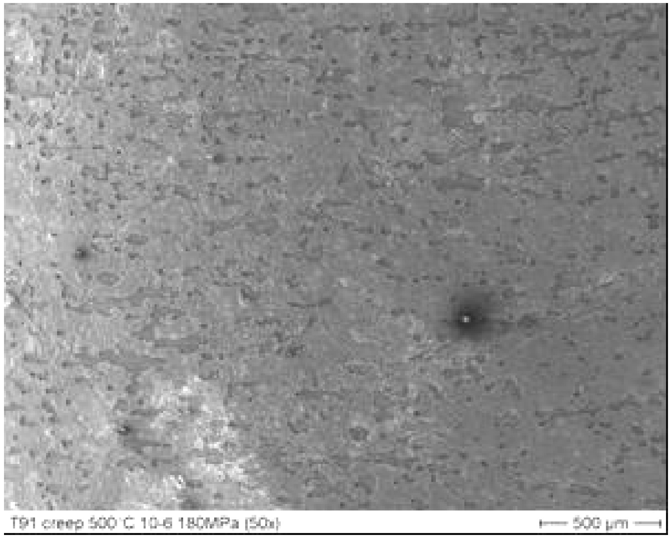
Any deterioration of the oxide scale results in reduced creep strength

Creep tests at lower Temperature of 500°C – reduced diffusion and sliding reduced strain

Reduction of temperature to 500°C lead to significant differences
➔ Reduced strain ➔ no cracks in oxide scale ➔ neglect able influence of PbBi



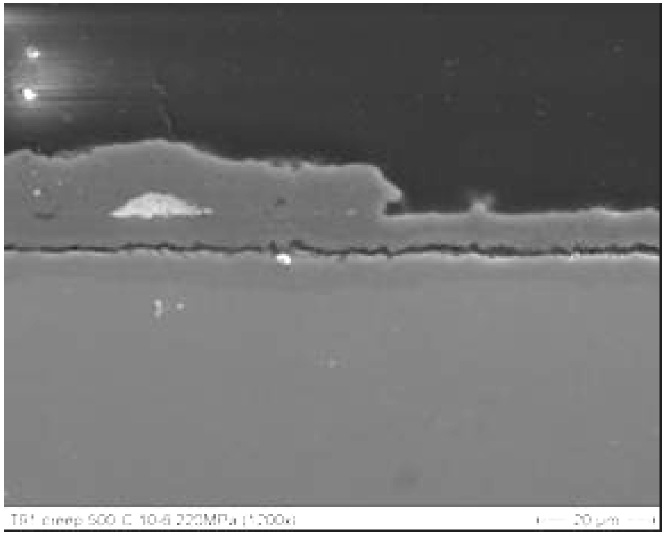




180 MPa

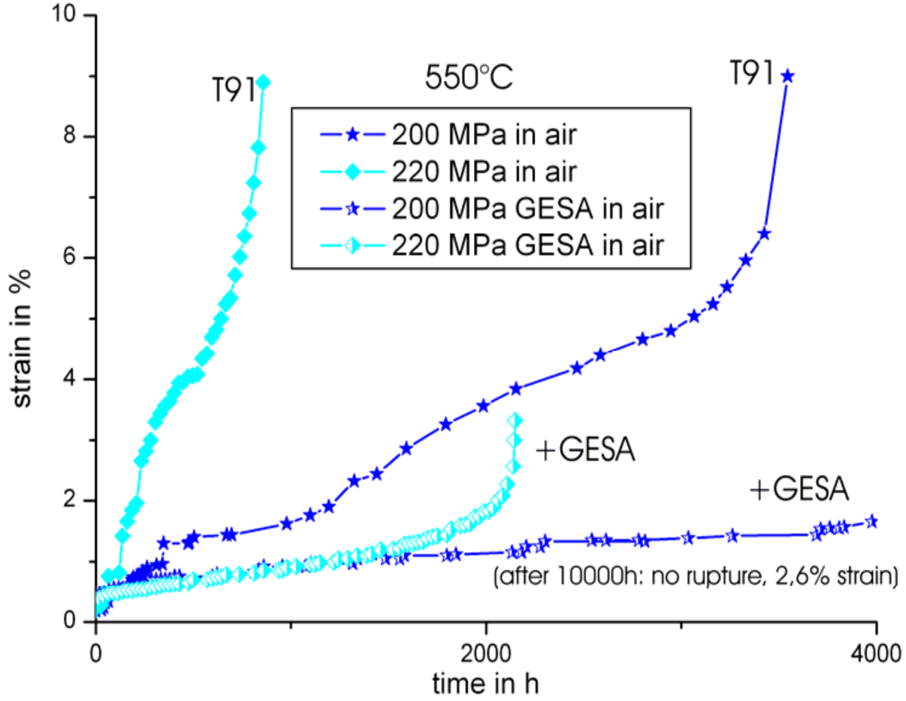
Slow strain <0.4%

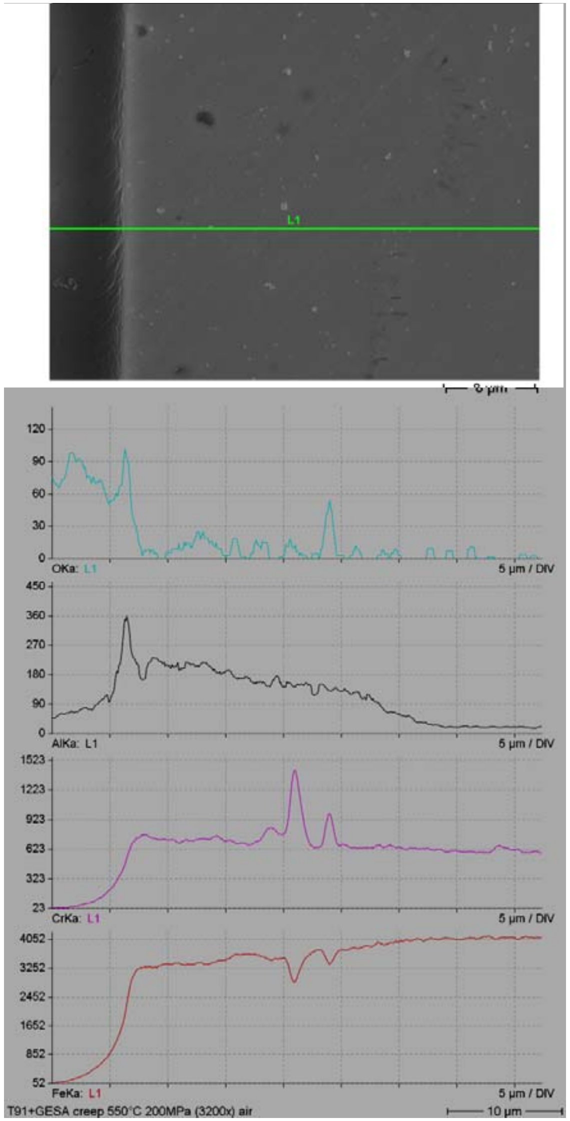
No cracks in oxide scale



220 MPa

Creep to rupture test of T91 orig. and GESA surface modified T91 in air at 550°C

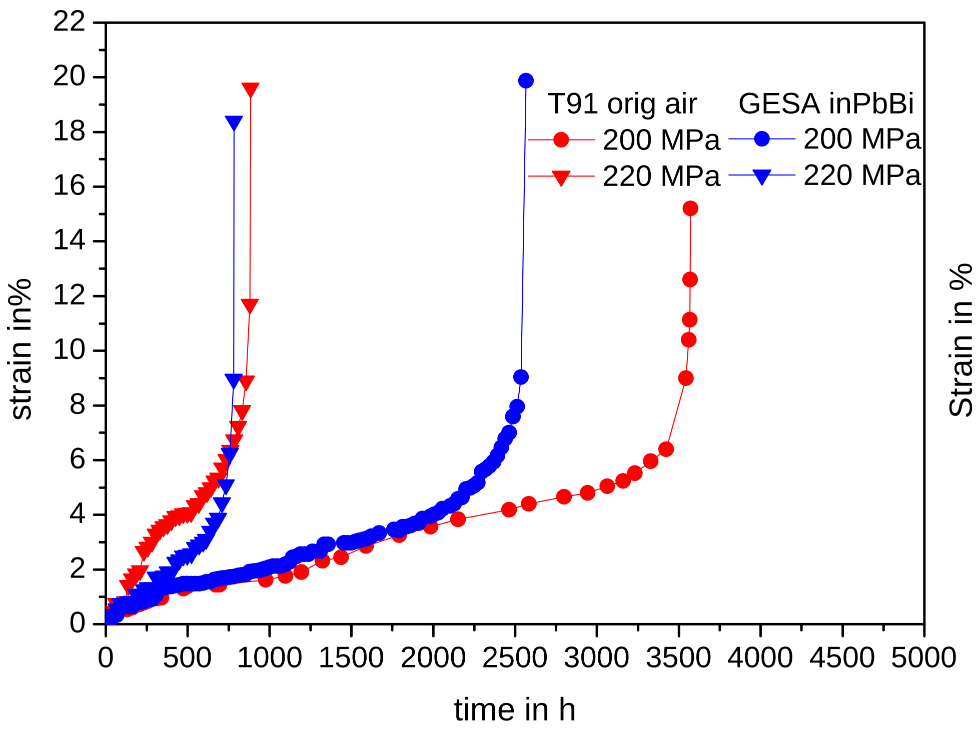




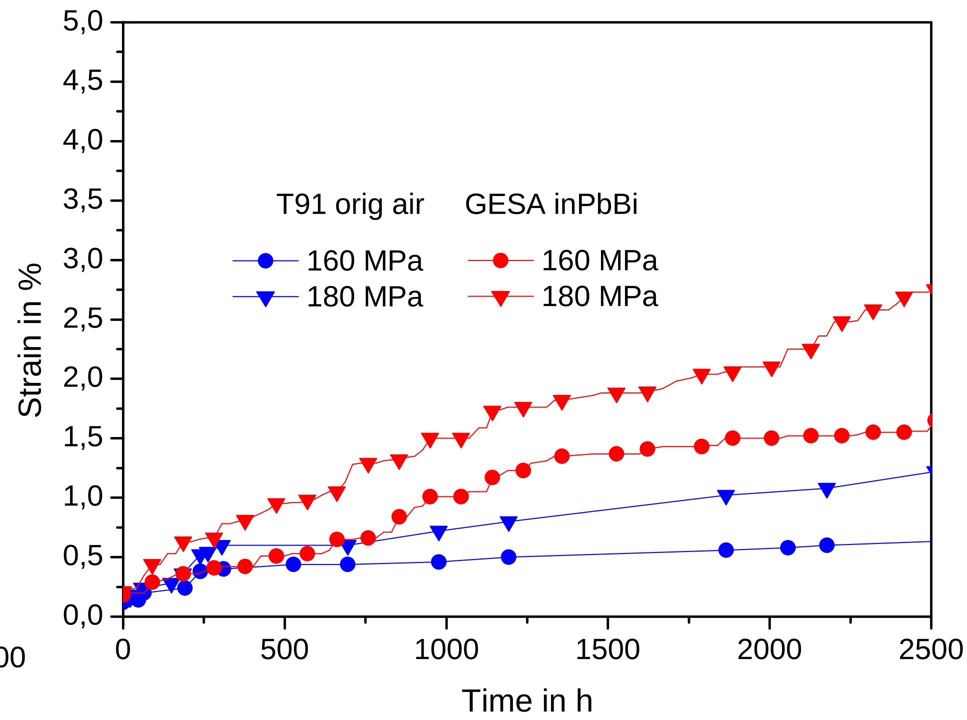
Significant longer rupture times of GESA modified T91
Surface alloyed layer improves creep strength
Thin Al_2O_3 scale formed at surface

Comparison of creep of GESA surface modified T91 in PbBi and T91 orig. in air at 550°C

Stress: 200 and 220 MPa

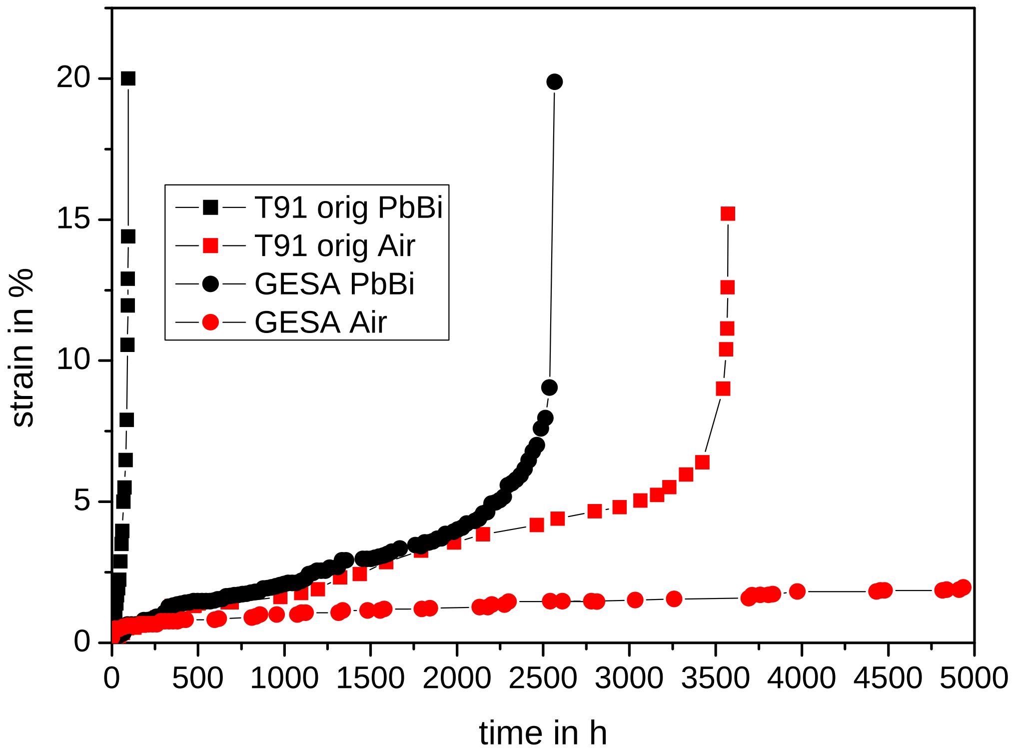


Stress 160 and 180 MPa



T91 with GESA modified FeCrAl layer also shows an influence of LBE. However, this deterioration is significantly reduced compared to the T91 original.
At 200MPa still a reduction in time to rupture from 3500 auf 2500h is observed. At a strain of about 3.5% influence of PbBi becomes visible.

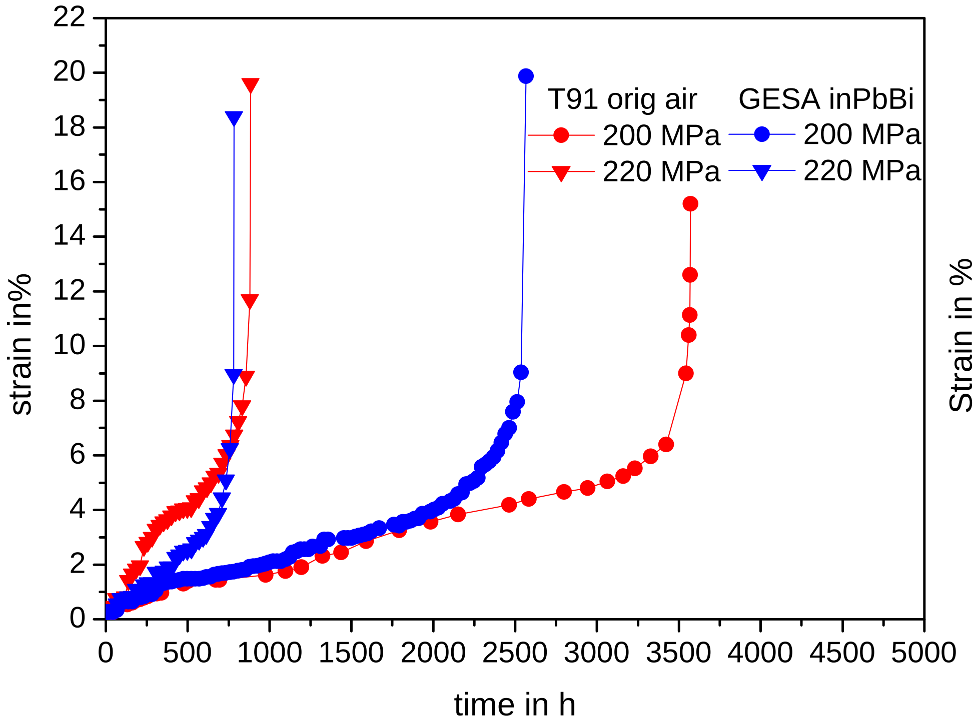
Comparison of creep to rupture (200 MPa) of GESA surface modified T91 and T91 orig. in air and PbBi at 550°C



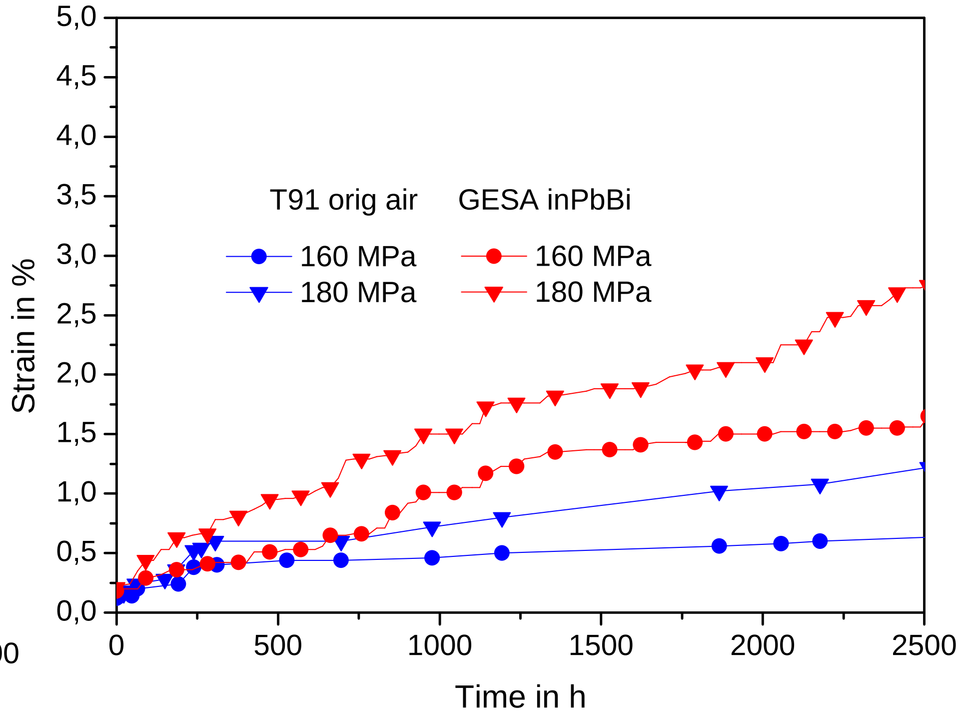
Negative influence of LBE on creep strength of T91 is strongly reduced by the surface alloyed layer

Comparison of creep of GESA surface modified T91 in PbBi and T91 orig. in air at 550°C

Stress: 200 and 220 MPa



Stress 160 and 180 MPa



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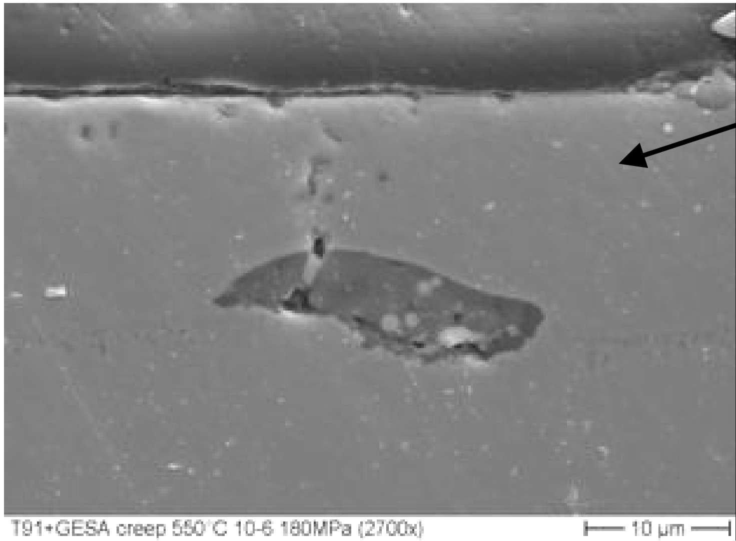
GESA Specimens after creep to rupture experiments in PbBi 180 and 220 MPa 550°C

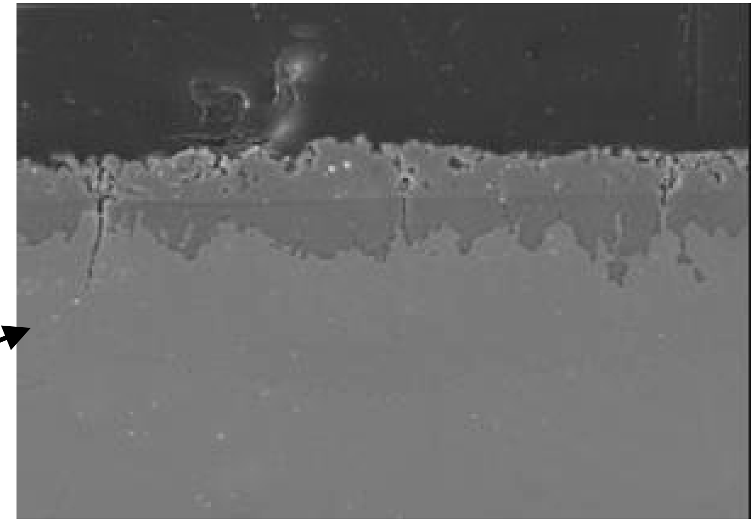
Al-content sufficiently high ➔ Alumina

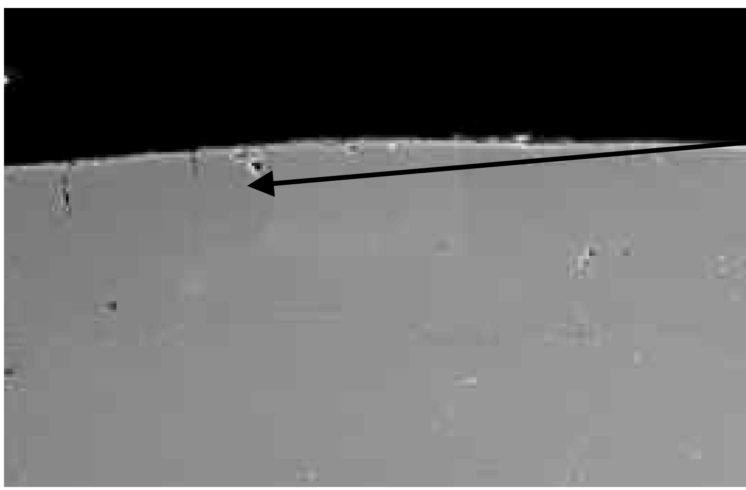
Al-content < 4wt% ➔ Spinel und Magnetite



180 MPa 2.2% strain
➔ only minor cracks

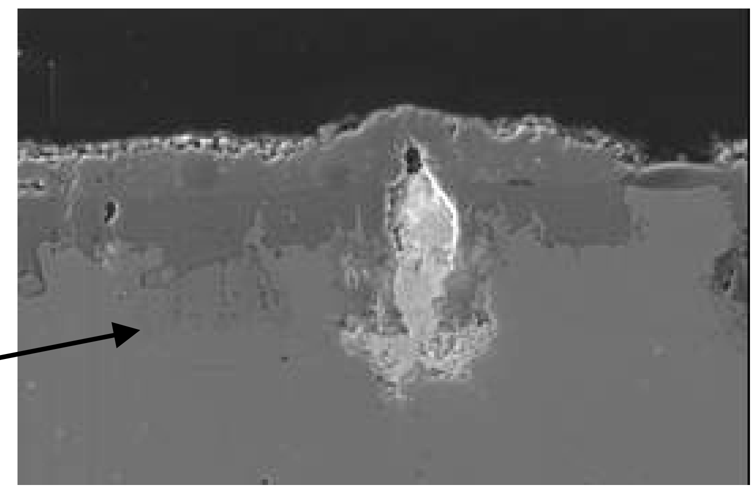
Cracks in magnetite and spinel
Up to now no PbBi penetrated





At the border to the necking region cracks but no PbBi

Cracks in magnetite und spinel
PbBi penetrated



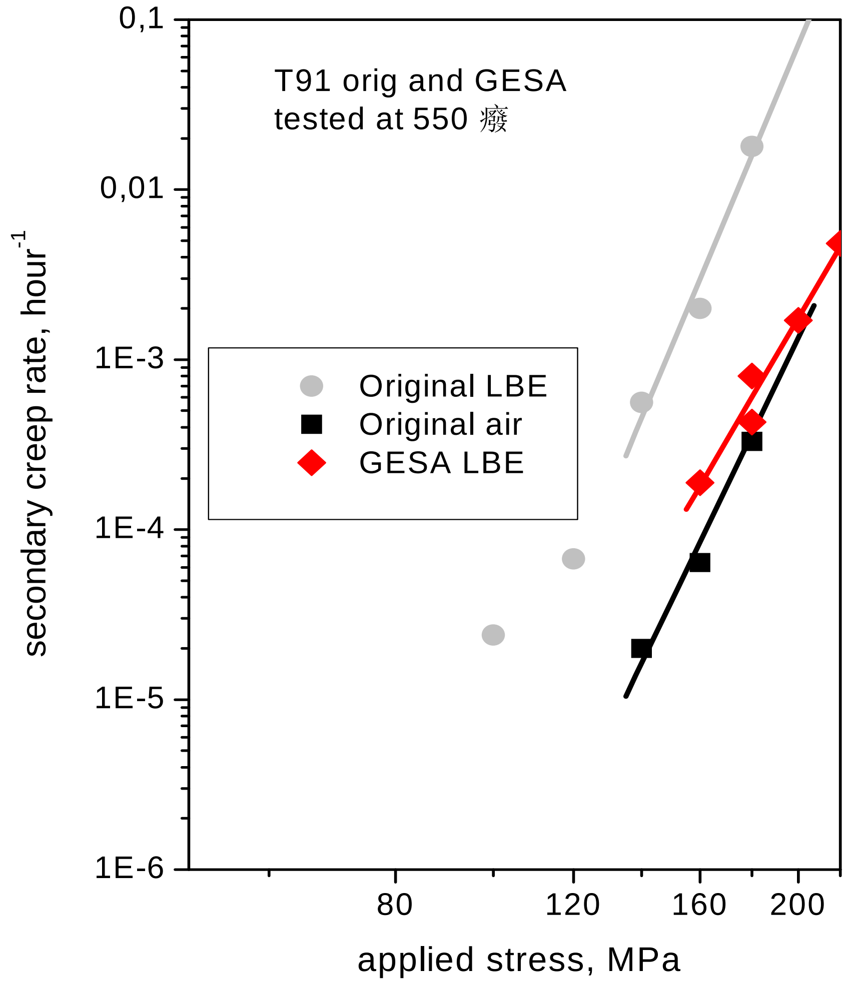
Comparing 2nd creep rate of T91 original at 550 °C in air and PbBi and T91 GESA in PbBi

T91 GESA:

•2nd creep rate in PbBi similar that of T91 original in air

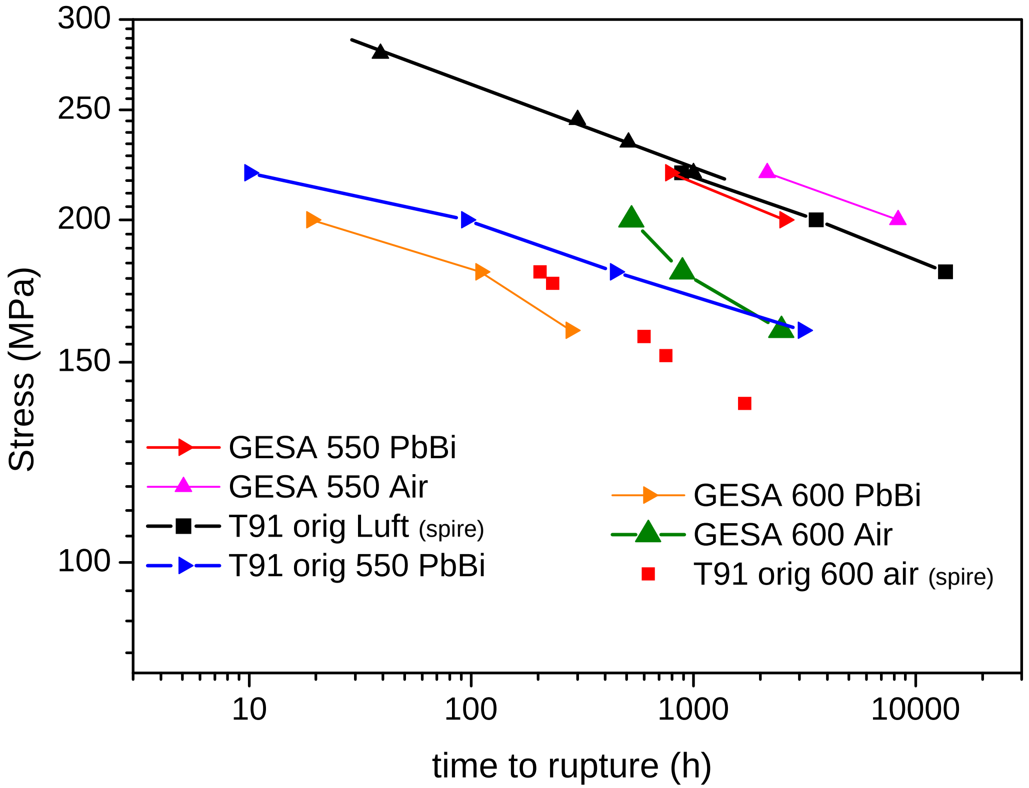
GESA modified FeCrAlY reduces the negative influence of PbBi at 550°C

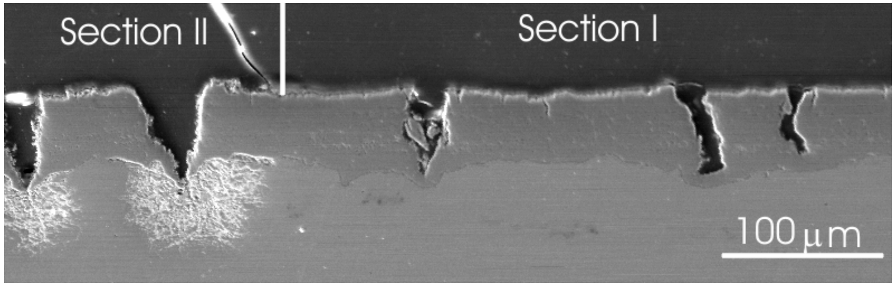
Specimens not entirely protected by thin alumina scale ➔ with optimized specimens an even better result to be expected



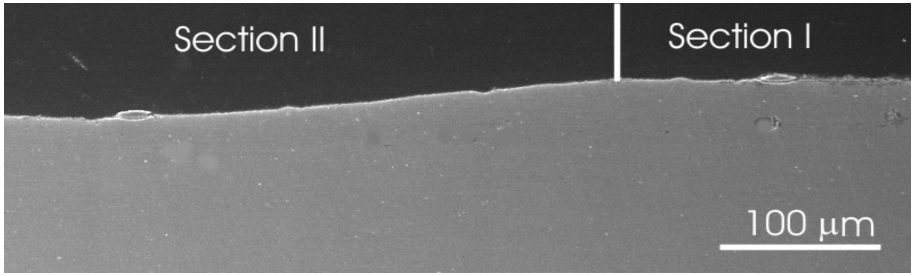
Creep to rupture of T91 with and without GESA in PbBi and air at 550°C

Stress over time to rupture of T91 original and T91 GESA





Oxide scale cracks ➔ PbBi penetrates the crack ➔PbBi reduces surface energy of steel ➔ dissolute steel elements and penetrates the grain boundaries ➔crack propagation



GESA modified FeCrAlY layer reduces the negative influence of PbBi
No cracking of oxide scale ➔ no influence of PbBi

Summary

Concept of strong oxide formers improves significantly the compatibility between steel and PbBi

Al content has to be high enough to ensure the formation of slow growing thin and stable scales

Process optimization towards Al-content, homogeneity and reproducibility is ongoing

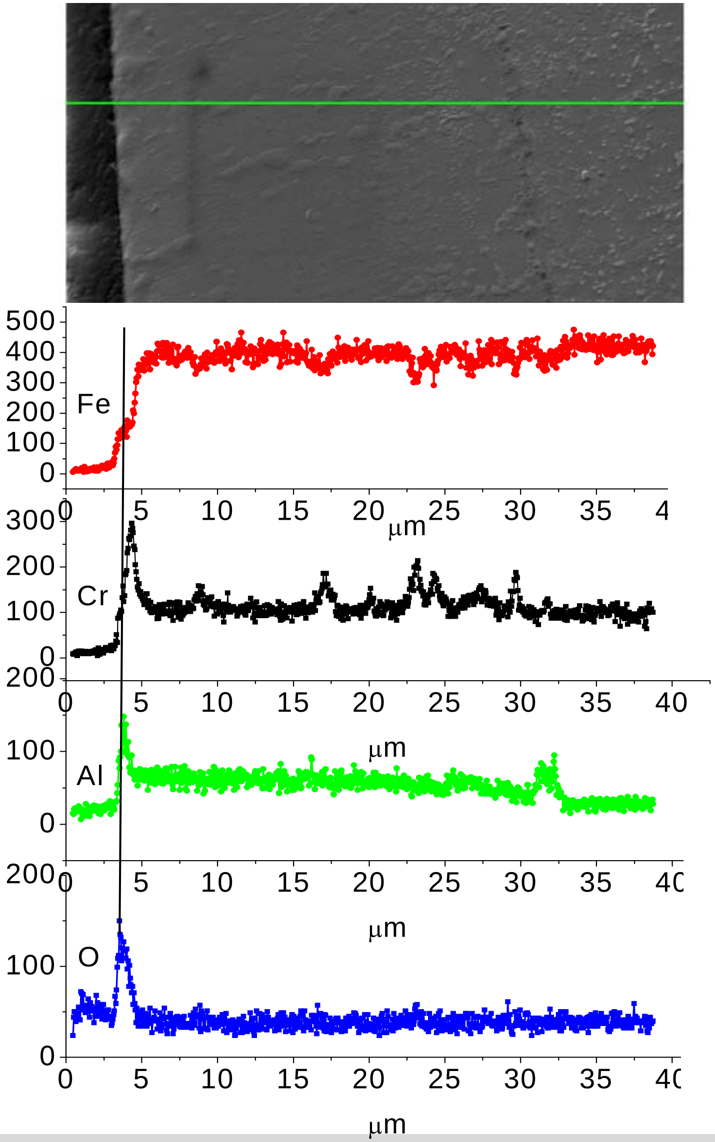
Negative influence of PbBi on creep strength of T91 f/m steel tested at high stress at 550°C

At 550°C low stress and at 500 °C significant reduced influence – Oxide scale stays intact – no cracks – no direct contact

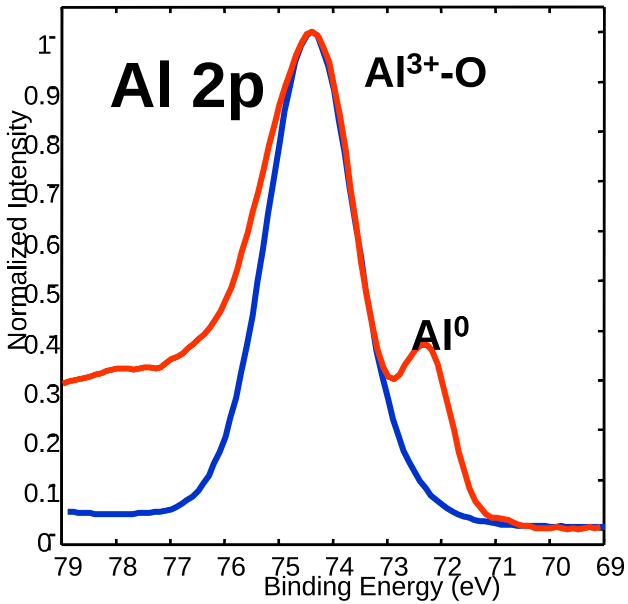
Surface alloyed layers improve significantly the creep behaviour in liquid PbBi
At 550°C very similar to T91 orig. in air

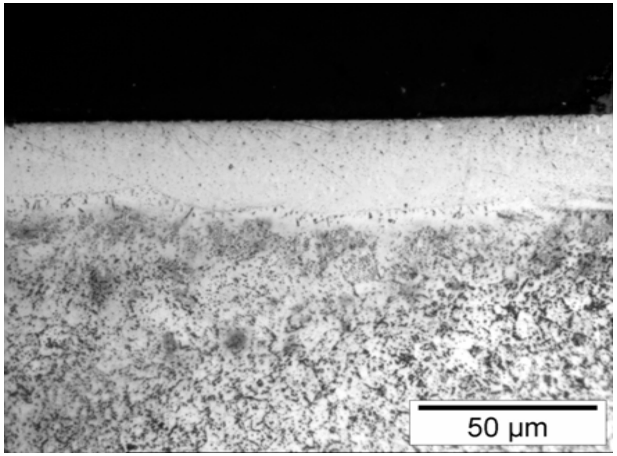
Acknowledgement:
V.G. Markov, A.D. Kashtanov Central Research Institute of Structural Materials – ‘‘Prometey”, 49 Shpalernaja, St. Petersburg, 191015, Russia

T91 surface modified specimens after 2000h of exposure 600 °C



XPS Measurement





Outer scale of Al oxide followed by chromium

Al precipitations at boundary layer (Fe_3Al)

No diffusion of Al into the bulk

Thin stable oxide layer protects the T91 cladding