Present Status of Thermomechanical Lining Simulation

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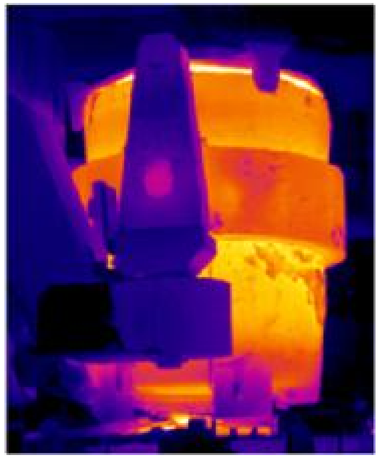


Service conditions of refractories

High temperature
Hot thermal shock
Cold thermal shock
Cyclic operation
Mechanical constraints
…..

A fact

The thermomechanical wear process cannot be observed directly in service or easily identified after service!

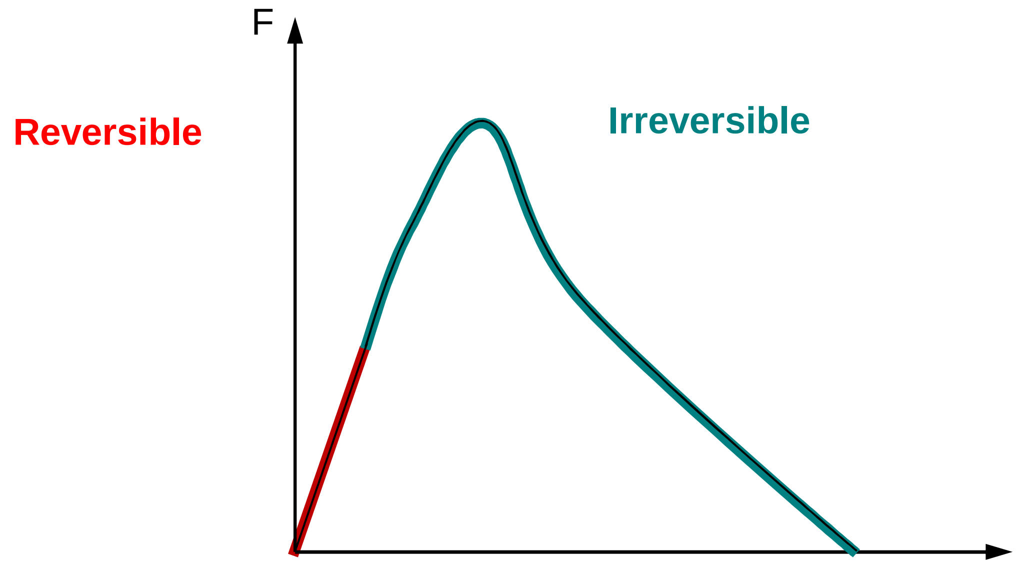
Finite element method

- is a useful tool to visualize the performance of refractory linings under complicated process conditions
- brings about an understanding of the thermomechanical wear mechanisms of industrial vessels and gives rise to an extended campaign life

The following knowledge will increase the understanding of advanced finite element thermomechanical modelling

- Types of refractory behavior
- Reasonable applications of material constitutive models
- Corresponding characterization measures for refractories at various temperatures

Refractory behavior



A load-displacement curve

Defining reversible behavior

Young's modulus *E*

Shear modulus *G*

Poisson's ratio n

Coefficient of thermal expansion a

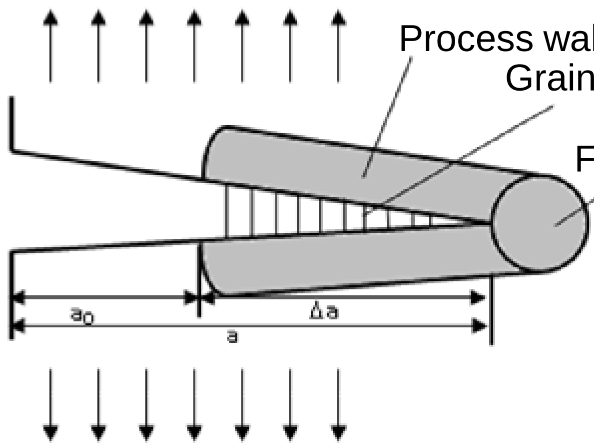
Causes of irreversible behavior

Tensile failure

Shear failure

Creep or/and shrinkage

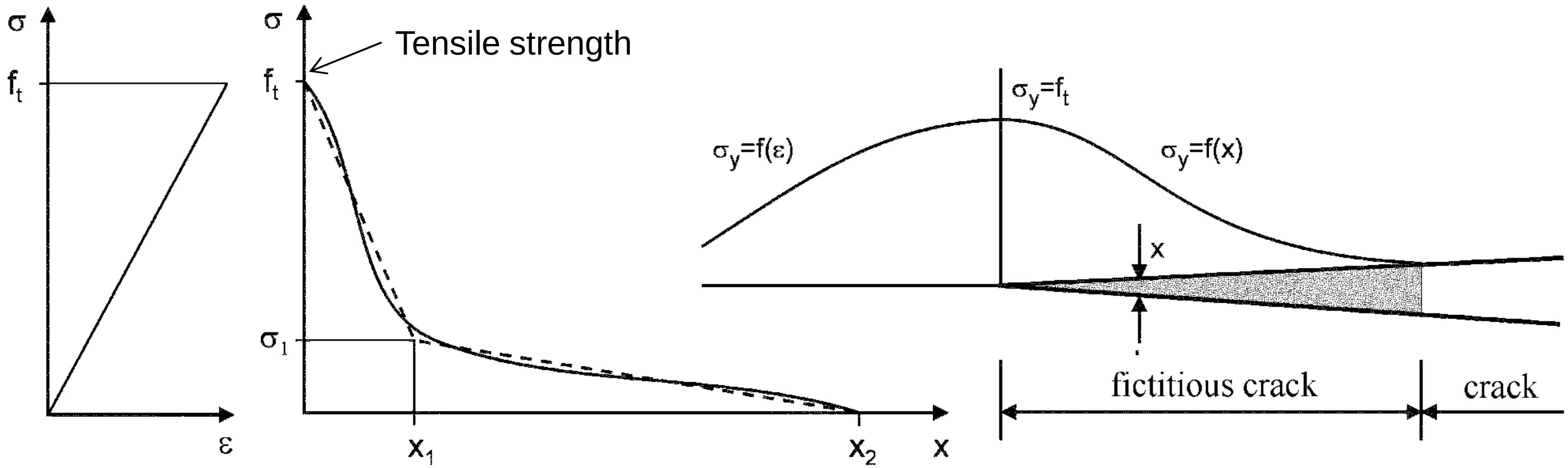
Material constitutive model accounting for tensile failure



Deviations from pure linear elastic fracture mechanics

- Linear stress/strain laws may be applied as a reasonable approximation for refractory behaviour as long as failure does not occur
- In cases of failure usually irreversible displacement remains
- Fracture energy is dissipated within a process zone
- Due to a process zone, the definition and measurement of a crack length is not possible

Material constitutive model accounting for tensile failure



Fictitious crack model proposed by Hillerborg

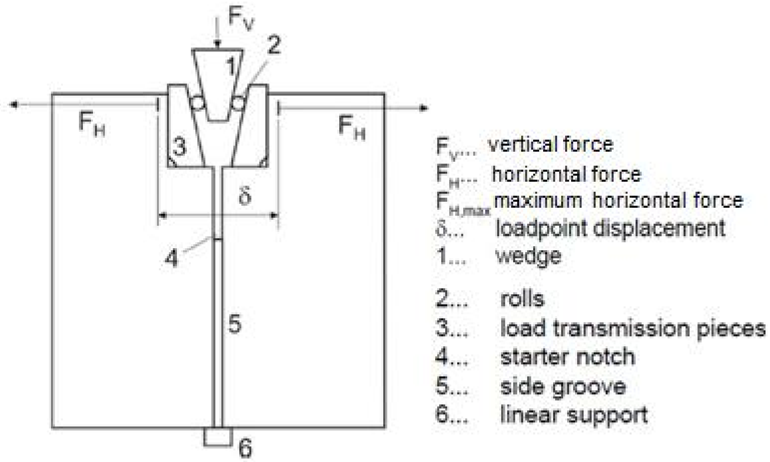
Fracture energy $$G_f = \int_0^{x_2} \sigma(x)\,dx$$

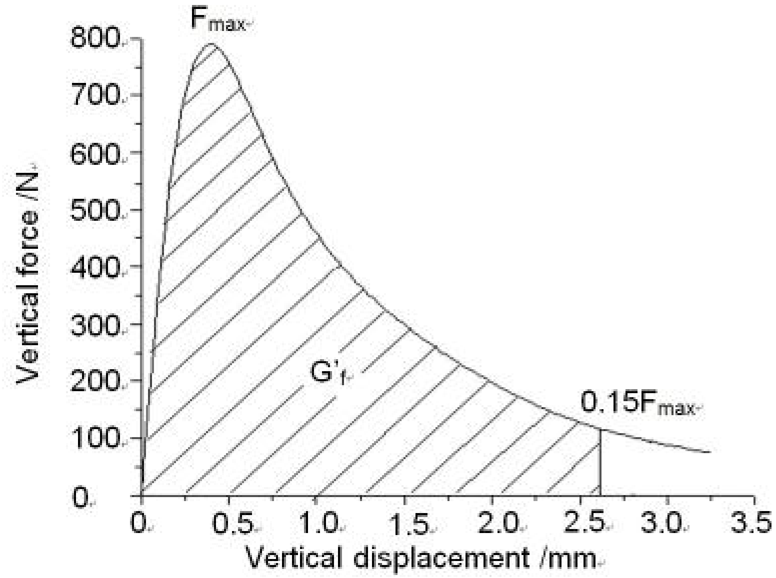
Characteristic length $$\lambda_{ch} = \frac{G_f E}{f_t^2}$$

λ_{ch} is proportional to *R*''''(thermal shock damage resistance parameter)

Characterization method for tensile failure

Wedge splitting test





$$F_H = \frac{F_V}{2\tan\frac{\alpha}{2}}$$

$$G_f = \frac{1}{A}\int_0^{\delta_{max}} F_H \, d\delta$$

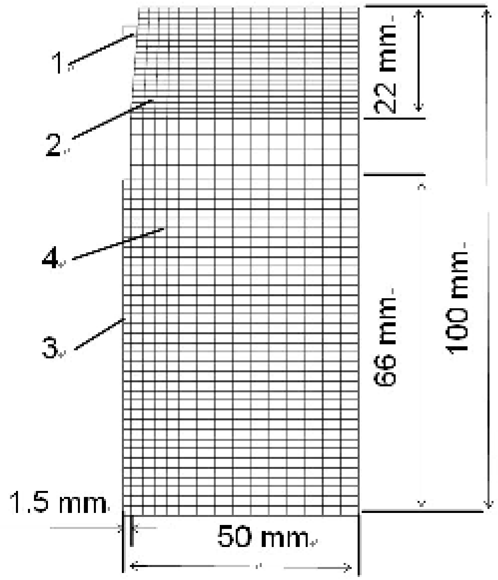
$$\sigma_{NT} = \frac{F_{H,max}}{bh}\left(1 + \frac{6y}{h}\right)$$

α: Wedge angle
A: Fracture surface area
y: The vertical distance of the center of gravity of the fracture surface from the horizontal force
h: Height
b: Width

$G'_f < G_f$ due to termination of test at relatively low loads

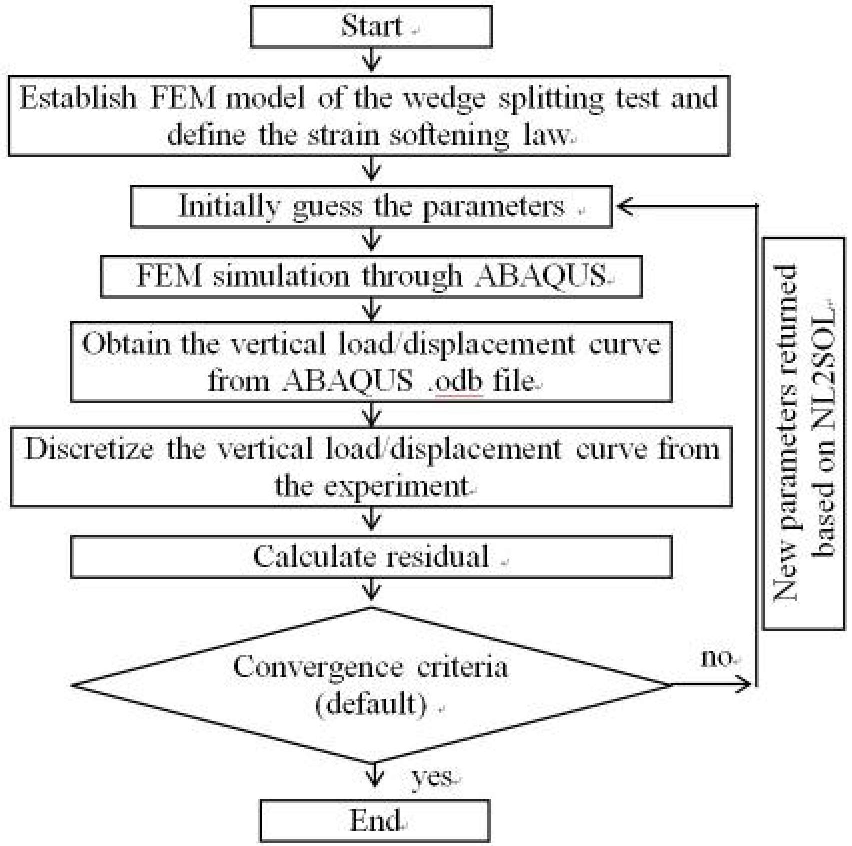
G_f f_t are anonymous

Characterization method for tensile failure



1-roller,
2-load transmission piece
3-ligament area,
4-linear elastic part of specimen

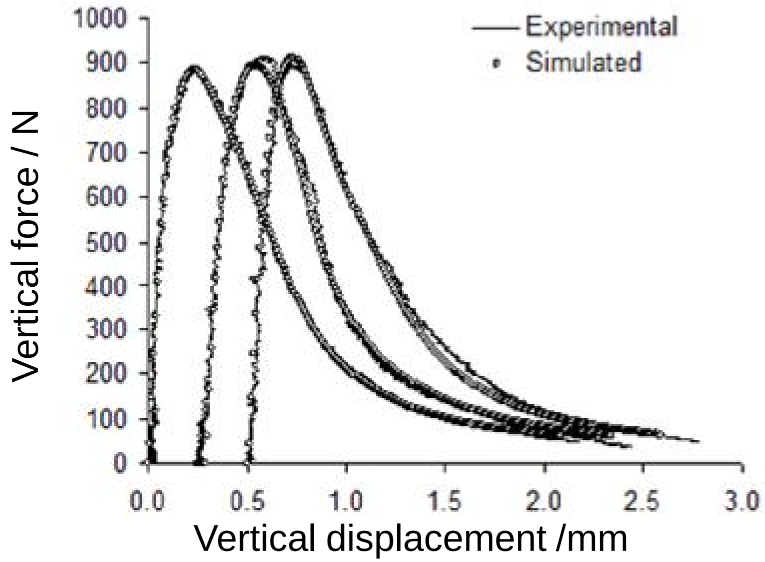
Two-dimensional and symmetrical model for the wedge splitting test



the flowchart of inverse estimation process

S. Jin, D. Gruber, H. Harmuth. Determination of Young's modulus, fracture energy and tensile strength of refractories by inverse estimation of a wedge splitting procedure. Engineering Fracture Mechanics, 2014, 116: 228-236.

Characterization method for tensile failure



Experimentally and simulated curves of a burnt magnesia-chromite material at room temperature

Experimentally obtained and inversely estimated parameters of a burnt magnesia-chromite material at room temperature

	Experiment	Inverse estimation
Fracture energy, / $N \cdot m^{-1}$	151	177
Strength, / MPa	8.9	5.5
l_{ch} / mm	156	475

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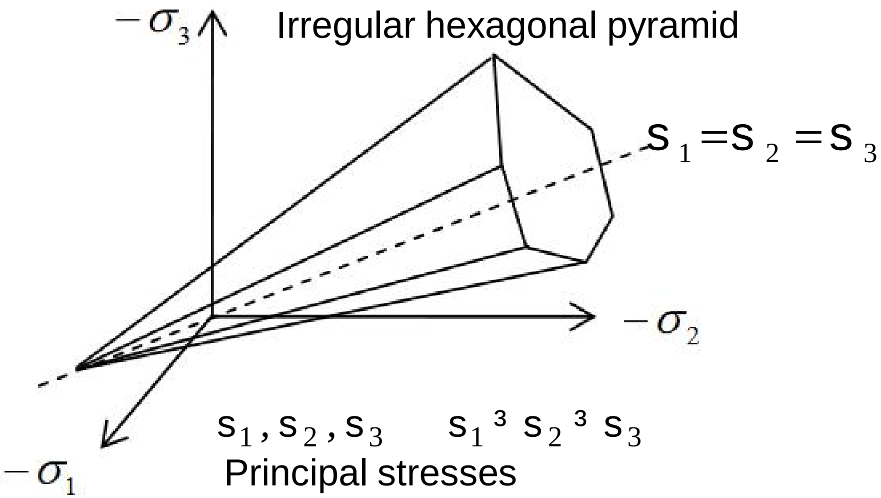
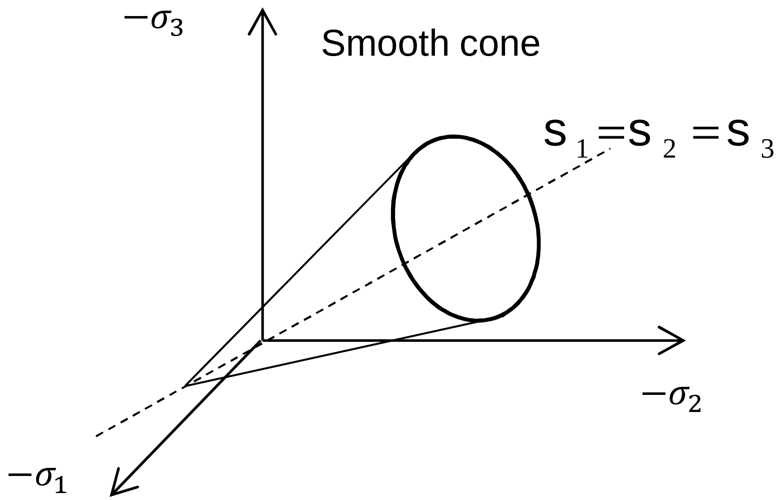
Material constitutive model accounting for shear failure

The capacity of geomaterials to resist shear failure is pressure dependent



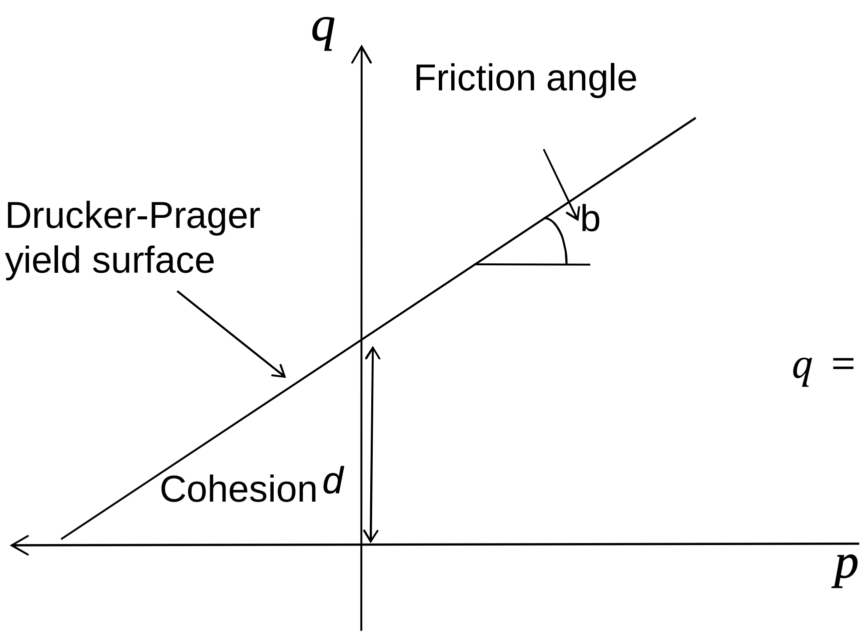
Mohr-Coulomb yield surface in principal stress coordinates



Drucker-Prager yield surface in principal stress coordinates

- The Mohr-Coulomb criterion does not account the contribution of the intermediate principal stress and disagreements with experimental results are often discovered
- The Drucker-Prager criterion is preferable

Material constitutive model accounting for shear failure



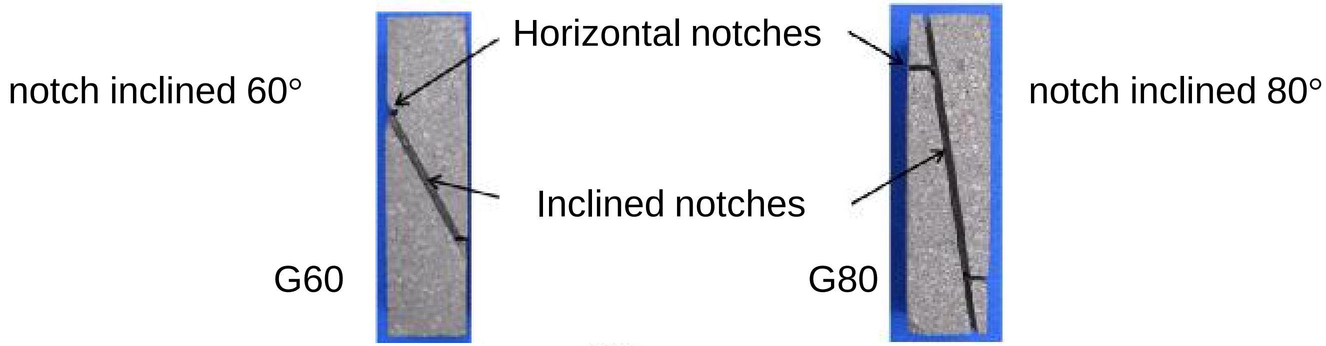
Drucker-Prager model in p-q diagram

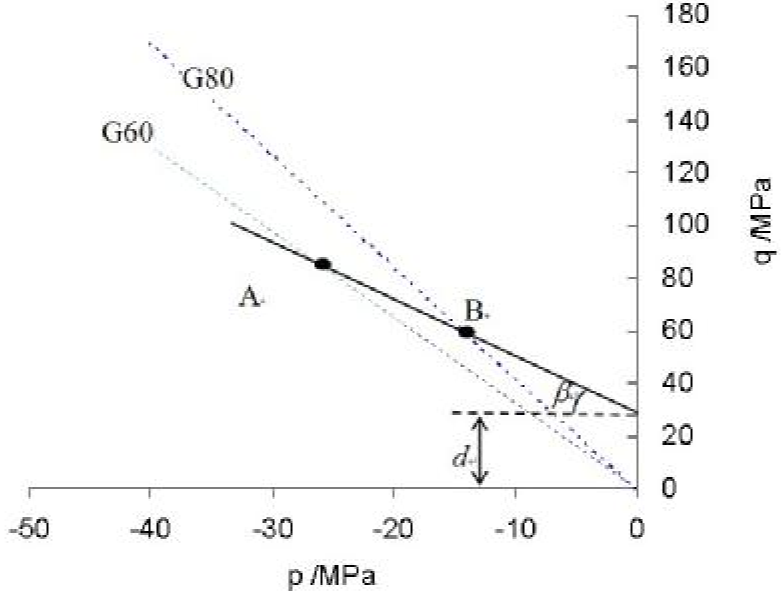
$$p = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$

$$q = \sqrt{\frac{1}{2}\left((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2\right)}$$

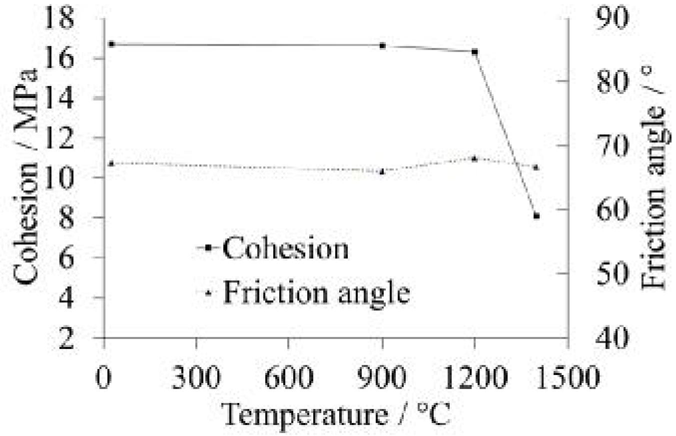
- Determination of friction angle and cohesion is necessary

Characterization method for shear failure





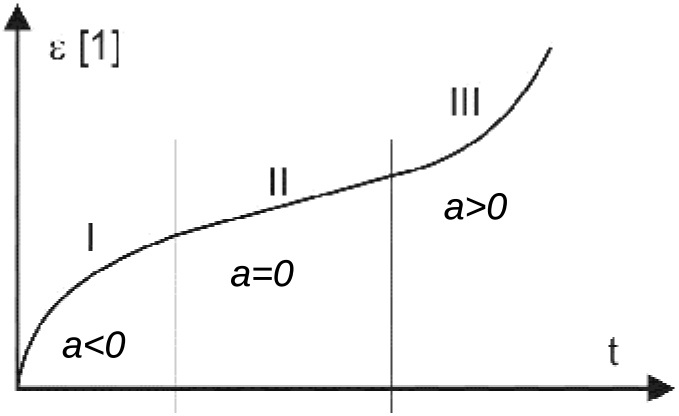
Stress path analysis of notch ligaments in the p-q diagram



Cohesions and friction angles of a burnt magnesia chromite material

S. Jin, D. Gruber, H. Harmuth, R. Roessler. Thermomechanical failure modeling and investigation into lining optimization for a Ruhrstahl Heraeus snorkel. Engineering Failure Analysis, 2016, 62: 254-262.

Material constitutive model accounting for creep



I: primary stage
II: secondary stage
III: tertiary stage

Norton-Bailey strain hardening/softening creep formulation

$$\dot{\varepsilon}_{cr} = K(T)\cdot\sigma^{n}\cdot\varepsilon_{cr}^{a}$$

K : a temperature function
n : the stress exponent
a: the creep strain exponent

Comments on creep in compression (CIC, European standard EN 993-9)

1) Ambiguous onset of creep due to a heating up under load (0.2MPa)

2) Rather low load level (maximum load up to 0.2MPa) will not allow for the determination of Norton-Bailey creep rate equation in a wide load range

3) Measurement of the displacement at the end faces of the specimen

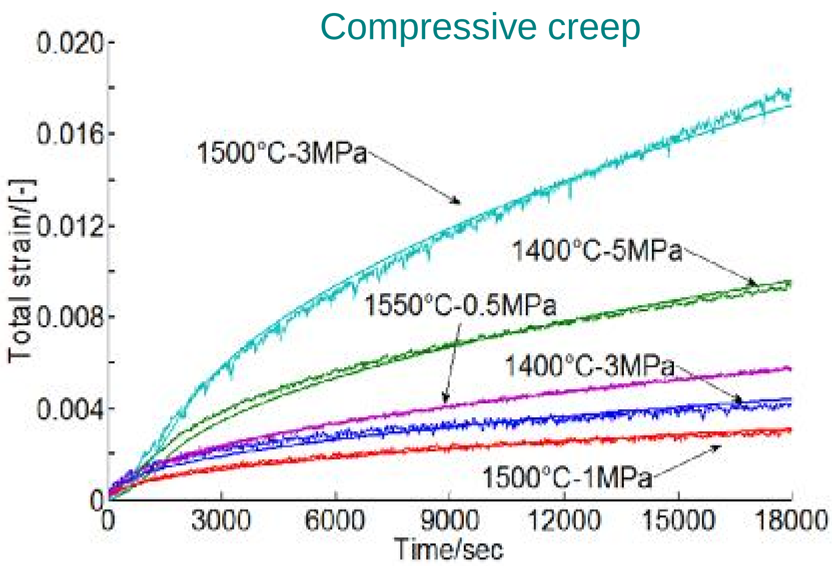
Characterization method for creep

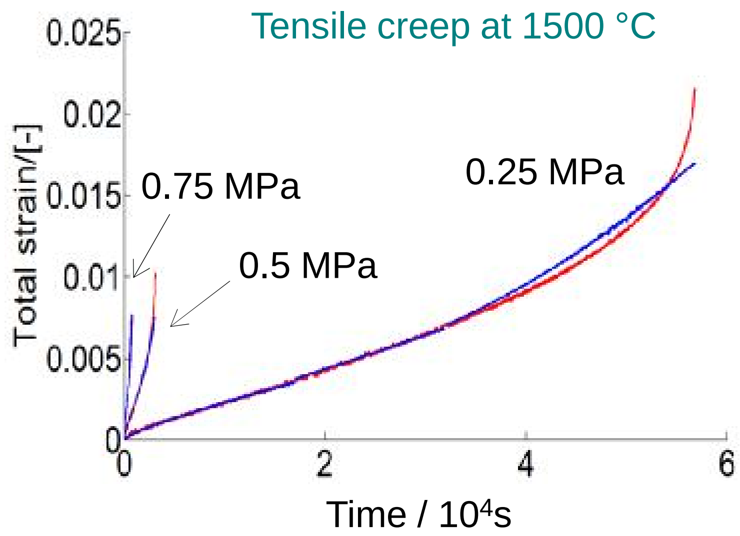
Setup of the high temperature creep measurements (left: compressive; right: tensile)

- Loads up to 20KN
- Uneven loading is avoided
- Deformation measurements on cylindrical surface of specimen with extensometers
- The height/diameter ratio of 2 allows the deformation measurements without influence from the end face friction in the case of compressive loading
- Creep origin is well defined

S. Jin, D. Gruber, H. Harmuth. Compressive creep testing of refractories at elevated loads-Device, material law and evaluation techniques. Journal of the European Ceramic Society, 2014, 34(15): 4037-4042.
Sidi Mammar A, Gruber D, Harmuth H, Jin S. Tensile creep measurements of refractories at service related loads including setup, creep law, testing and evaluation procedures. Ceramics International, 2016, 42(6) : 6791-6799.

Characterization method for creep

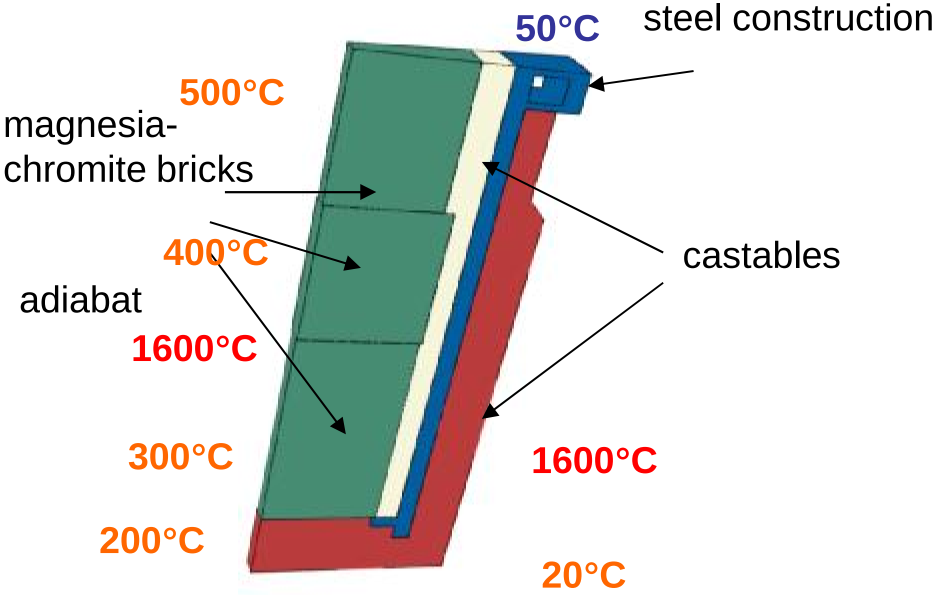


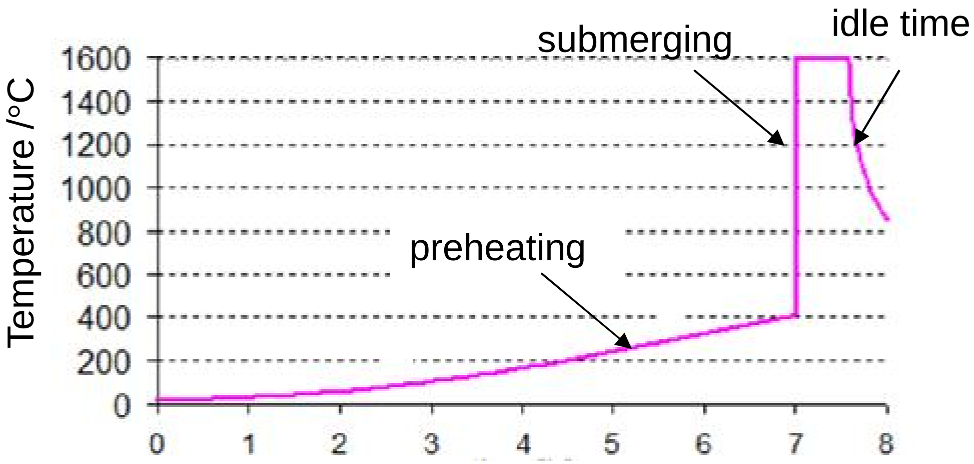


Primary creep parameters n, a and K [$MPa^{-n}s^{-1}$] of the magnesia chromite material at 1400 °C and 1500 °C in tension and compression

Loading \ Temperature		1400 °C	1500 °C
Tension	K	2.31E-07	3.91E-06
	a	- 0.15	- 0.22
	n	2.82	3.13
Compression	K	1.24E-11	2.20E-10
	a	-1.04	-1.04
	n	3.20	3.20

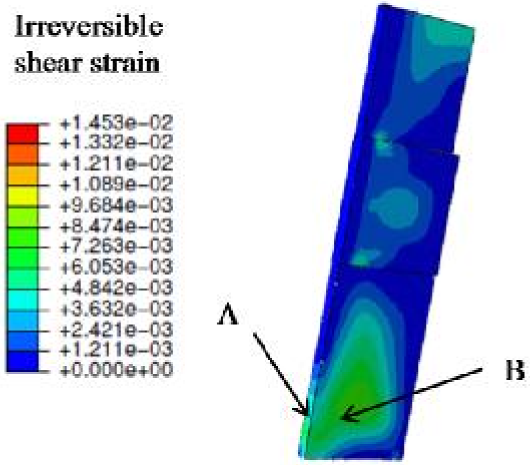
Ruhrstahl Heraeus (RH) snorkel

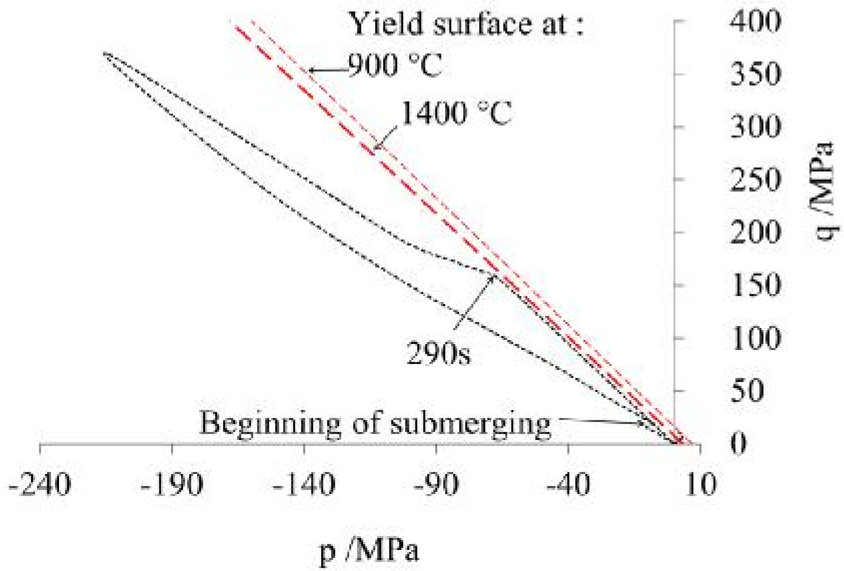




A process of a RH snorkel

- Shear failure and creep were considered for the magnesia chromite bricks in the working lining





Stress path of point A in the p-q diagram

- The hot face experienced shear failure and creep after 290s submerging
- Tensile failure occurred during the idle time

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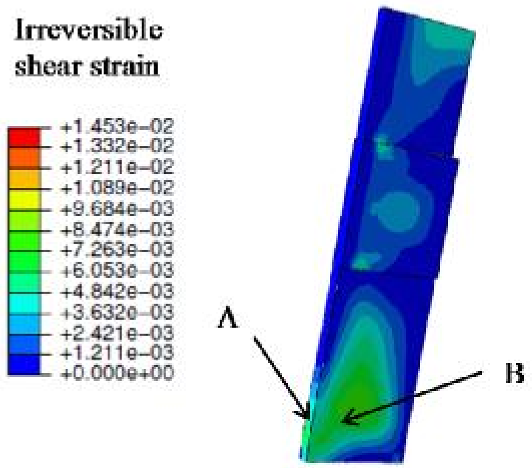

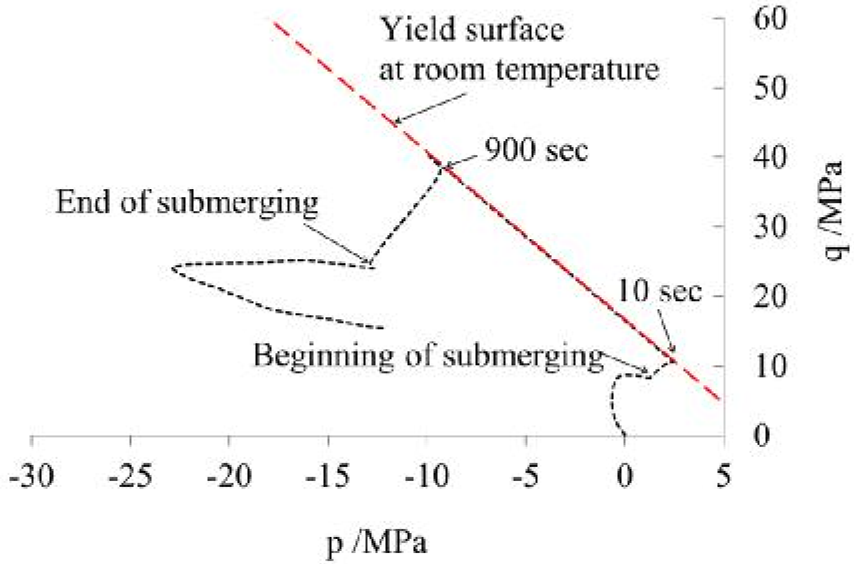

Stress path of point B in the p-q diagram

- The area close to the hot face experienced tensile failure at the beginning of submerging

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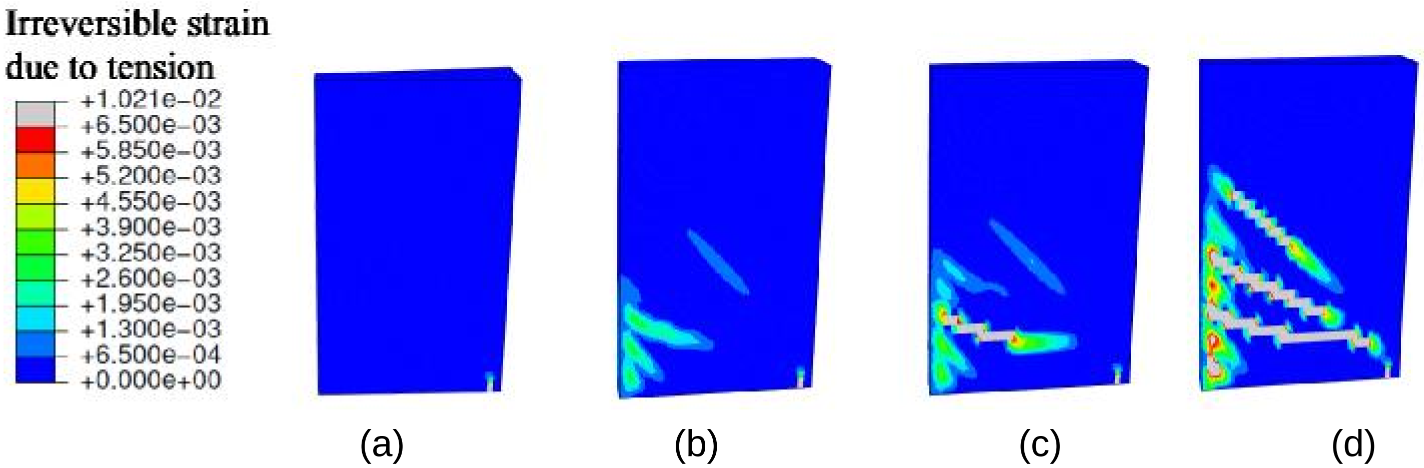

Distribution of irreversible equivalent tensile strains due to tension at the lowest section at a) the end of preheating, b) 1 s of submerging, c) 2 s of submerging, d) 7.6 s of submerging

- Fictitious crack model was applied to account for tensile failure caused by thermal shock
- Cracks occurred close to the hot face in 1s
- Cracks propagated inclined to the bottom of the lowest section

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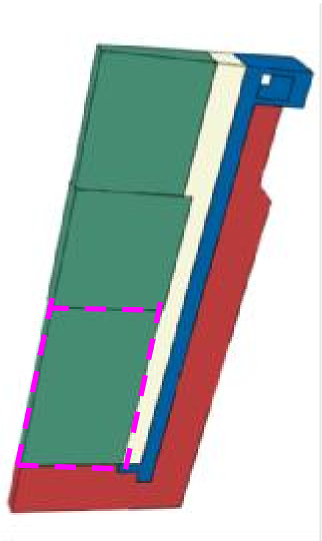

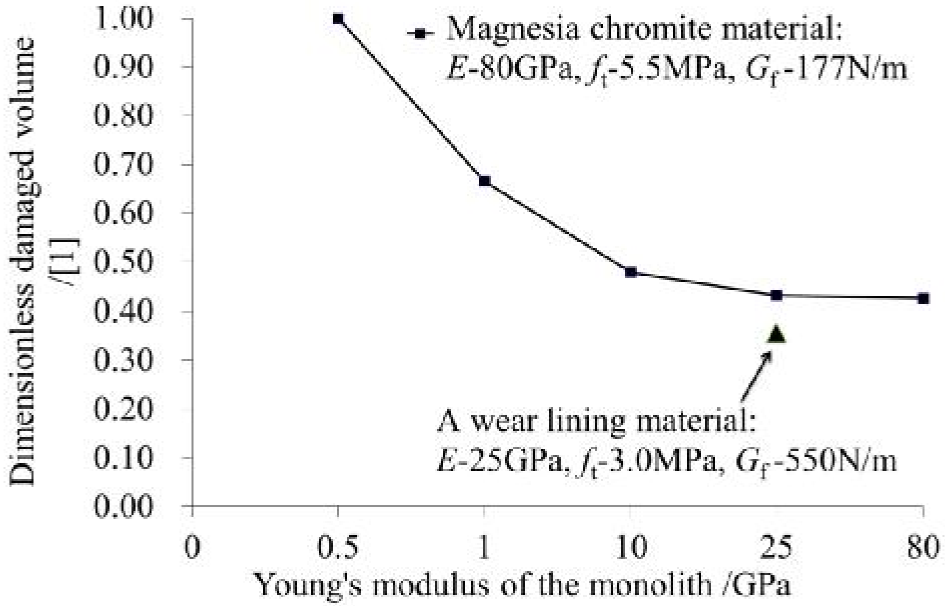

Dimensionless damaged volume of the lowest wear lining section based on various lining concepts

- Tensile failure were allowed in the monolith for the case study
- A well elaboration of lining concept can mitigate the damage volume with understanding of thermomechanical wear mechanisms

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- The wedge splitting test, modified shear test, and uniaxial tensile and compressive creep tests were applied for refractories;
- These advanced testing procedures provide quantitative definitions of refractory mechanical behavior at high temperatures;
- The understanding of thermomechanical wear mechanisms of refractories in service, and lining optimization were enhanced accordingly.

Vielen Dank für Ihre Aufmerksamkeit