Institute of Refractories Engineers

Material Properties & Thermal Shock Parameters

Training Day 2019

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- How does thermal shock occur?
- What properties affect the risk of thermal shock?
- Predicting thermal shock
- Thermal shock resistance testing
- Thermal shock resistant materials

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How Does Thermal Shock Occur?

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What is thermal shock?

- Thermal Shock occurs when a thermal gradient causes different parts of a structure/object to expand by different amounts
- Differential expansion causes stress; if the stress exceeds the 'strength' of the material then a crack will form
- If nothing prevents the crack from propagating through the material it will cause the object/structure to fail

THERMAL GRADIENT
⇩
DIFFERENTIAL EXPANSION
⇩
THERMAL STRESS
⇩
CRACK FORMATION
⇩
CRACK PROPAGATION
⇩
STRUCTURAL FAILURE

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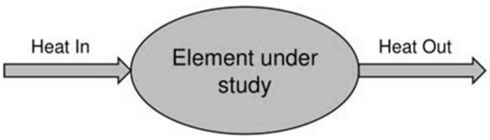
Thermal Gradient: Steady State

- Steady State: The system is in thermal equilibrium. The amount of heat entering any region of an object/structure is the same as the amount of heat leaving (i.e. the temperature of the system is constant).
  - The thermal gradient is linear (per material unit) and non-changing
  - In this condition the structure is normally stable unless the thermal gradient induces stress levels that cannot be accommodated by the material(s)



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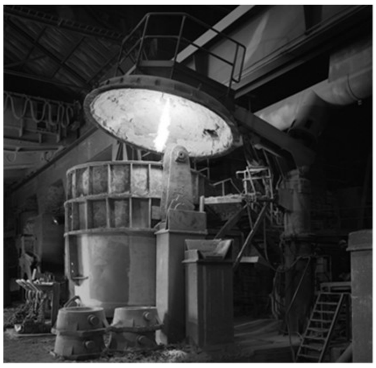
Thermal Gradient: Transient State

- Transient State: Non equilibrium. The system is in a state of rapid cooling or rapid heating.
  - The thermal gradient is non-linear (per material unit) and changing with time
  - Areas of the structure/object expand or contract rapidly leading to the development of regions of high levels of tensile stress which can be higher than the failure stress of the structure/object



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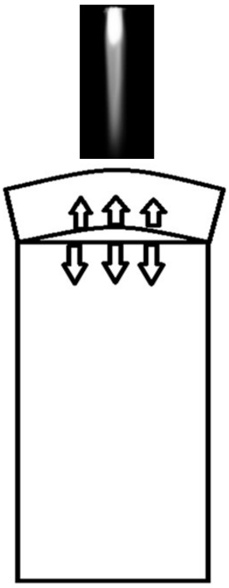
Thermal Stress Development in Transient State: Simple Shape (Unconstrained)



- Heat at front of shape sets up temperature differential
- Hot material at front of shape expands more than the cooler material further back
- The temperature gradient is non-linear as it is transient; this sets up tensile stresses at the front of the shape
- If the tensile stresses exceed the failure stress of the material cracking will occur leading to separation of the hot and cold material
- Rapid cooling of the hot face leads to the same effect (in reverse)

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Material Properties: Effects on Thermal Shock Resistance

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Which Material Properties Affect Thermal Shock Resistance?

- THERMAL PROPERTIES WHICH AFFECT THE DEVELOPMENT OF THERMAL STRESS IN RAPID HEATING/COOLING SITUATIONS:
  - Thermal expansion coefficient
  - Thermal conductivity/diffusivity
- PHYSICAL PROPERTIES WHICH AFFECT RESISTANCE TO THERMAL DISRUPTION
  - Tensile failure strength/strain
  - (Compressive failure strength/strain)
  - Elastic/V-Modulus
  - (Poissons ratio; the ratio of transverse to axial strain, for refractories this is typically between 0.15 – 0.3)
  - Work of fracture/resistance to crack propagation

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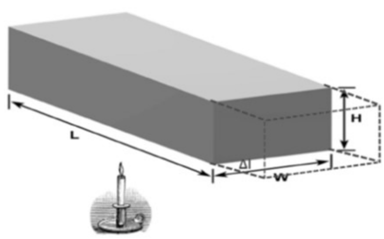
Thermal Expansion Coeffcient

Thermal expansion coefficient



$$\frac{\Delta l}{l} = \alpha \Delta T$$

The greater the thermal expansion coefficient, the greater the potential for high levels of thermally generated stresses to be built up in the shape or structure

The **coefficient of thermal expansion (cte)** describes how the size of an object changes with a change in temperature. Specifically, it measures the fractional change in size per degree change in temperature at a constant pressure.

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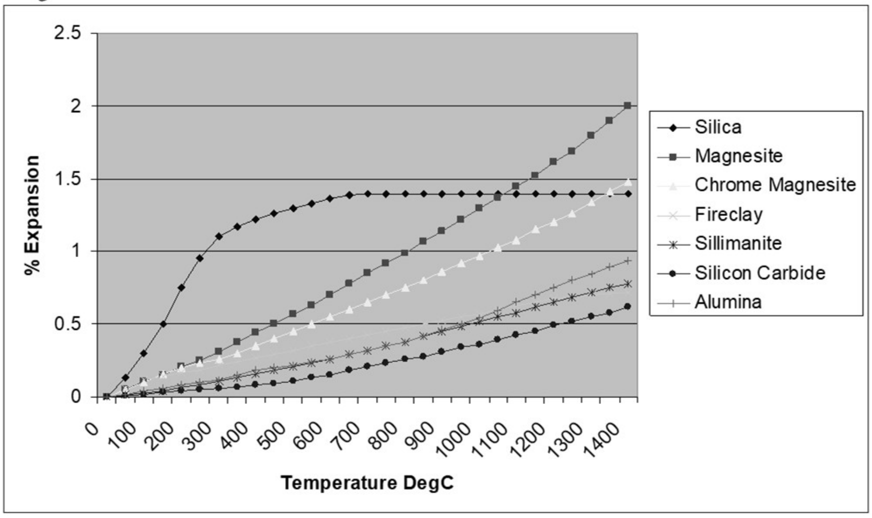
Thermal Expansion of Standard Refractory Materials



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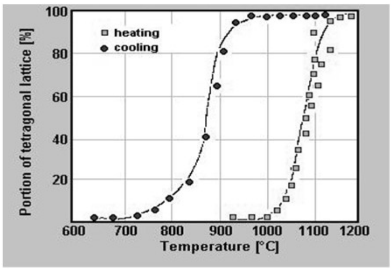
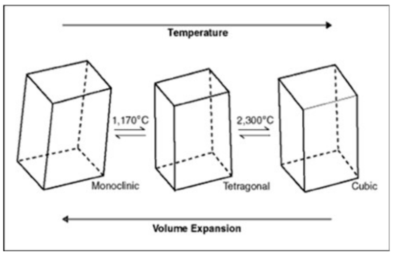
Thermal Expansion Refractory Materials: Non Linear Behaviour - Zirconia





- Zirconia undergoes phase transformations as the temperature increases.
- There is a significant volume change in moving from monoclinic to tetragonal form.
- This change can lead to significant stress development causing thermal shock cracking.
- There is a ‘lag’ on transformation on cooling – hysteresis.
- For technical ceramics the cubic form is ‘stabilised’ by adding Yttria, MgO or CaO or ‘partially stabilised’ to reduce thermal shock by creating of microcracks.

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Thermal Conductivity

- The thermal conductivity of a material is a measure of its ability to conduct heat.
- Heat transfer occurs at a lower rate in materials of low thermal conductivity than materials of high thermal conductivity.
- Relationship to thermal stress development:
  - Higher thermal conductivity materials more rapidly dissipate transient localised thermal differences and therefore mitigate differential thermal expansions and resultant thermal stress development.

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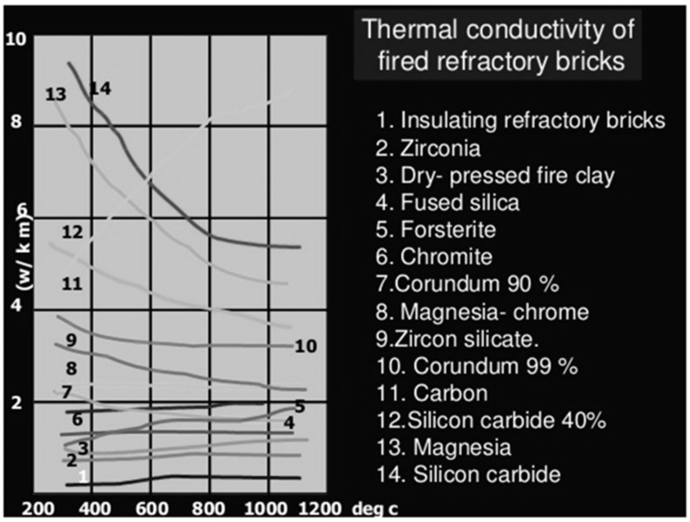
Thermal Conductivity – Refractory Materials



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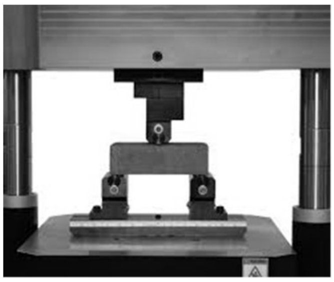
Failure Stress, Strain to Failure, Elastic Modulus

Physical properties important for thermal shock resistance:

- Failure Stress: Tensile failure stress determines the amount of stress the material can withstand before disruption. Normally measured via modulus/hot modulus of rupture testing. For thermal shock resistance high is good.
- Failure Strain: The level of deformation (extension in a tensile test) the material can accommodate before breakage. For thermal shock resistance high is good.
- Elastic modulus: V modulus, Youngs Modulus, essentially a measure of the flexibility of the material (Stress/Strain ratio). For thermal shock resistance low is good (high flexibility)



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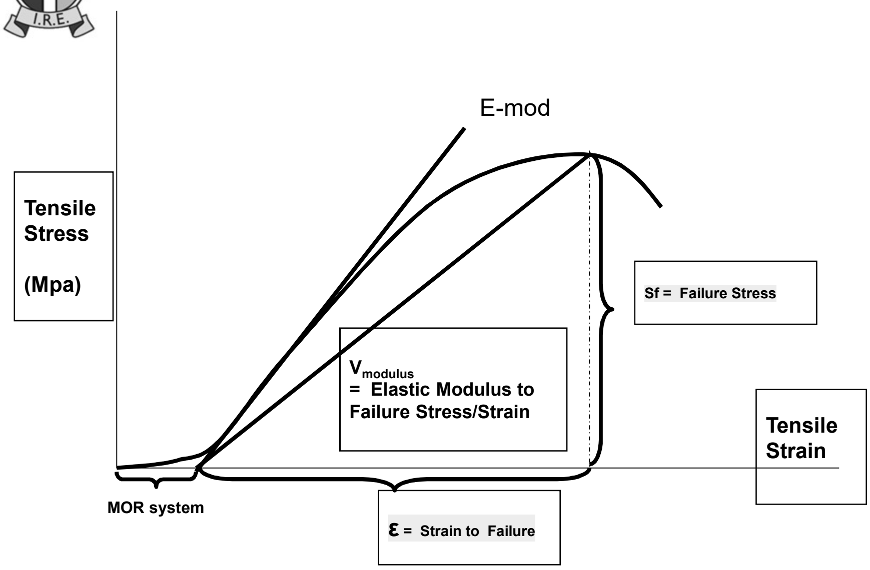
Failure Stress, Strain to Failure, Elastic Modulus



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Predicting Thermal Shock: Calculation Methods

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Calculating Thermal Shock Resistance – Hasselman Parameters

- Crack initiation parameters R, R', R''.

Parameter	Relation	Units	Physical Interpretation
R	$\frac{\sigma(1-\nu)}{E\alpha}$	°C	Maximum allowable temperature difference a material can withstand without fracture initiation.
R'	$\frac{\sigma(1-\nu)\,\lambda}{E\alpha}$	J/(m·s)	Maximum allowable heat flux into the material without fracture initiation.
R''	$\frac{\sigma(1-\nu)\,\kappa}{E\alpha}$	$m^2 \cdot °C/s$	Maximum allowable surface heating rate before fracture initiation occurs. (Incorporates density and specific heat)

- R is ratio between strength, σ, and stress due to temperature change, $E\alpha$.
- For R' and R'' the stress relieving effect of heat dissipation is added.
- R' is the most common parameter used for comparing refractory materials using standard material properties

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Comparison of 2 Materials A & B

Material Properties		Materials A		Materials B
λ	J/(m·s·°C)	3.0	↑	2.5
C_p	J/(kg·°C)	1000	↓	1100
ρ	kg/m³	2500	↓	2750
α	10^{-6} °C^{-1}	5.0	↓	8.0
E	10^{9} Pa	5.5	↓	6.0
σ_t	10^{6} Pa	6.5	↑	6.0
ε_t	10^{-3}	1.2		1.0
σ_c	10^{6} Pa	35.0		30.0
ε_c	10^{-3}	6.4		5.0
ν	-	0.2		0.2

$\kappa = \lambda \, / \, (C_p \, \rho)$ ↑

Hasselman Parameters		Materials A	Materials B
R	°C	189	100
R'	J/(m·s)	567	250
R''	10^{-4} m²·°C/s	2.3	0.8

Material *A* is much more thermal shock resistant than material *B* ...
... says Hasselman

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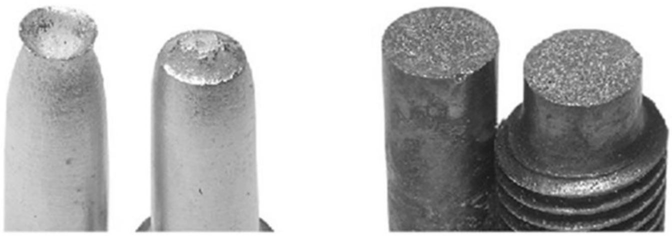
Fracture Mechanics:
Relationship to thermal shock resistance

Ductile vs. Brittle Failure



cup-and-cone fracture | brittle fracture

The previous analysis using the 3 Hasselman parameters only takes us to the stage where the fracture process is initiated.

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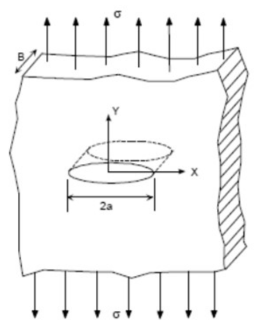
Fracture Mechanics: Relationship to thermal shock resistance

- The energy available during thermal shock may catastrophically shatter the material or may only produce surface 'crazing'.
- With surface crazing some strength is retained.
- This strength is related to the crack propagation distance which is related to Work of Fracture (WoF).
- For refractories, damage resistance is generally more important than crack initiation.

TS Damage Resistance = Difficulty for crack propagation / Energy available to be released

TS Damage Resistance = Work of fracture / Stored elastic strain energy



$$\mathbf{Rst = (WoF/a^2xE)^{0.5}}$$

Hasselman's Thermal Stress crack stability parameter

We'll come back to this when looking at TS resistant materials!

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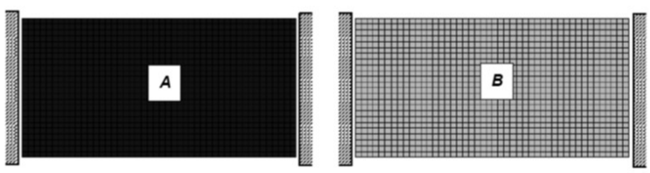
Caveat on Hasselman Parameters!

- Hasselman TSR parameters are not applicable for highly constrained systems.
- As such they are not always suitable to inform on materials selection and refractory lining design.
- A TSR analysis needs to take account for the construction and constraints or boundary conditions.
- *In other words, TSR is a system property, not a material property.*



2 bricks of materials A and B, expansion allowance 0.6mm

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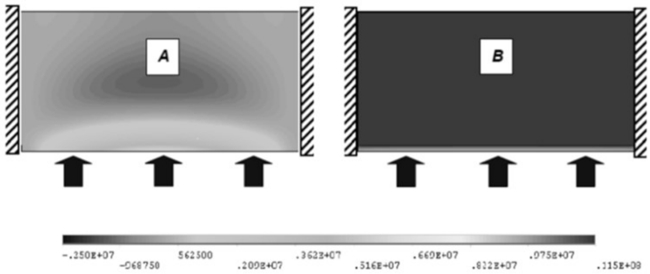
Tensile stress development in a constrained system. FE analysis



- Positive values equal tension, negative equal compression
- Limited amount of expansion allowance causes material B to experience higher level of compressive stress so tensile stress level stays below failure stress of material
- Material A, with lower Texp does not expand to constraint condition and so exhibits higher tensile stress.

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Predicting Thermal Shock: Test Methods

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Thermal Shock Resistance Tests

- TSR of refractories is normally measured by quenching a hot test piece in either water or air.
- For high TSR materials, more severe tests may need to be considered.
- Tests:
  - Water quench test (e.g. DIN 51068)
  - Air quench test (e.g. BS1902:5.11)
  - Ribbon spalling test (e.g. ASTM C1100-88)
  - (Thermite Test)

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Water Quench Test: DIN 51068

- Cylindrical sample pieces, h50mm x dia50mm
- Samples preheated to 100C
- Samples placed in furnace at 950C for 15min
- Plunged into cold running water (10 to 20C) and left for 3 minutes
- Returned to 100C before repeating cycle
- Number of quenchings withstood before disruption of sample is used as measure of TSR.

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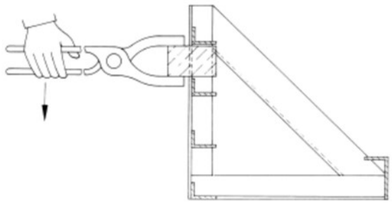
Air Quench Test: BS1902 5.11

- 75mm x 50mm x 50mm prism samples
- Samples dried at 110C
- Samples heated at unified rate to 1000C or 1200C (450C for silica)
- Samples held at temperature for 30minutes then placed on a cold firebrick for 10 minutes
- Samples examined for cracks and subjected to a bend test (20N) using a special frame
- Samples which fracture in the bend test are recorded.
- Remaining samples placed back at test temperature for 10 minutes and cycle repeated.
- Test repeated to 30 cycles or until all samples fail.



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Ribbon Thermal Shock Test

- Sample size 228 x 64 x 38mm (MOE/Sonic velocity measured beforehand)
- Test samples heated on one face by linear burner (typically from 800 to 1100C) and test temperature reached within 5 minutes
- Each heating cycle lasts 15 minutes. At end of cycle sample blown with cool air for 15 minutes.
- Test progressed for 5 cycles and MOE/SV measured to assess damage due to TSR

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Thermal Shock Resistant Materials

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Thermal Shock Resistant Materials

Desired Properties: Recap
- Low thermal expansion coefficient
- High thermal conductivity
- High flexibility
- Resistance to crack initiation
- Resistance to crack propagation

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Thermal Shock Resistant Materials

Low Thermal Expansion:
Example – Mullite

- Expansion typically 0.5% to 1000C compared to bauxite brick (0.65%) and corundum based bricks (0.7 – 0.8%)
- Widely used in BF and Hot blast stove due to excellent TSR in combination with high temperature resistance and good thermal conductivity.

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Thermal Shock Resistant Materials

High Thermal Conuctivity:
Example – SiC

- Tc typically 14-18W/MK at 800C compared to corundum based bricks, 4W/MK
- Widely used in BF (e.g. Tuyere band) and Incineration due to excellent TSR good heat removal potential, abrasion resistance and potential to operate in high temperature conditions.

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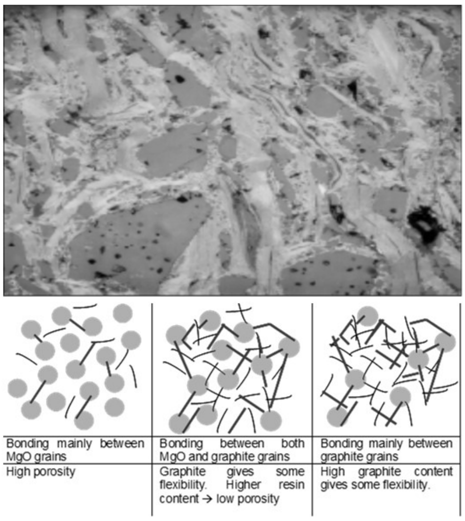
Thermal Shock Resistant Materials

Crack Resistance: Example Magnesia Carbon Brick

- Composite, carbon bonded material.
- Magnesia grains (low TSR) embedded in a high thermal conductivity, crack resistant flake graphite matrix
- Graphite matrix allows a level of plastic deformation (energy absorption) and limits grain-grain contact which would allow easy crack propagation
- Level of graphite affects TSR



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Thank you for your attention

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