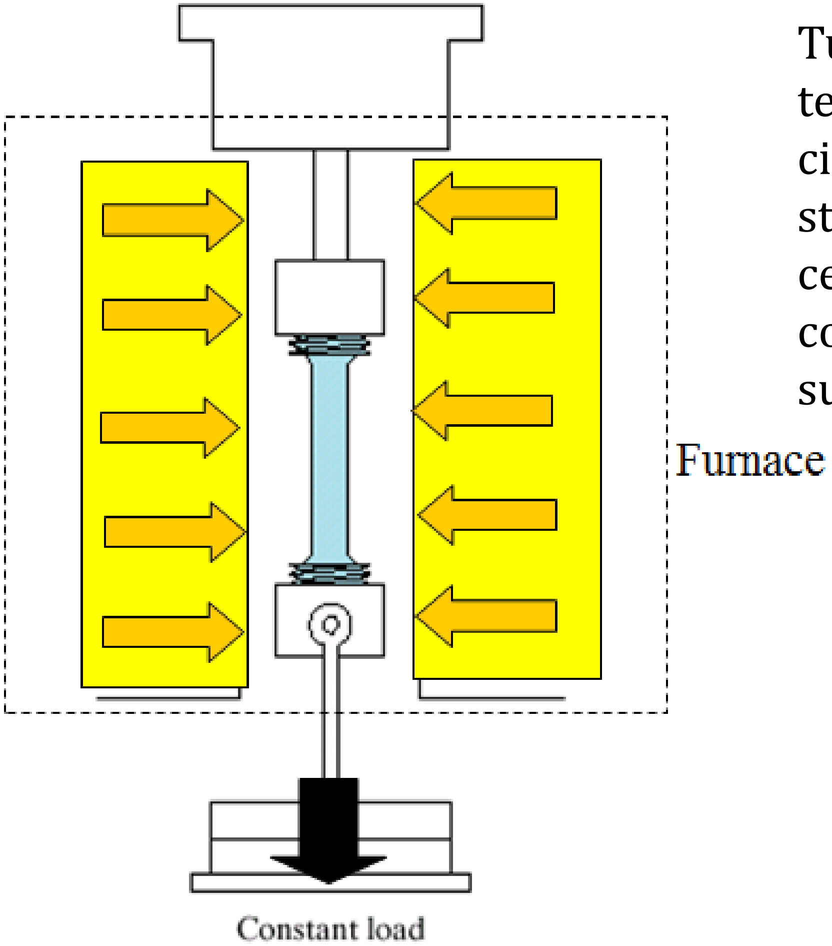
Properties of Ceramics

CREEP

Time-dependent deformation due to constant load at high temperature (> 0.5 T_m)

Examples: turbine blades, steam generators.

Creep test:



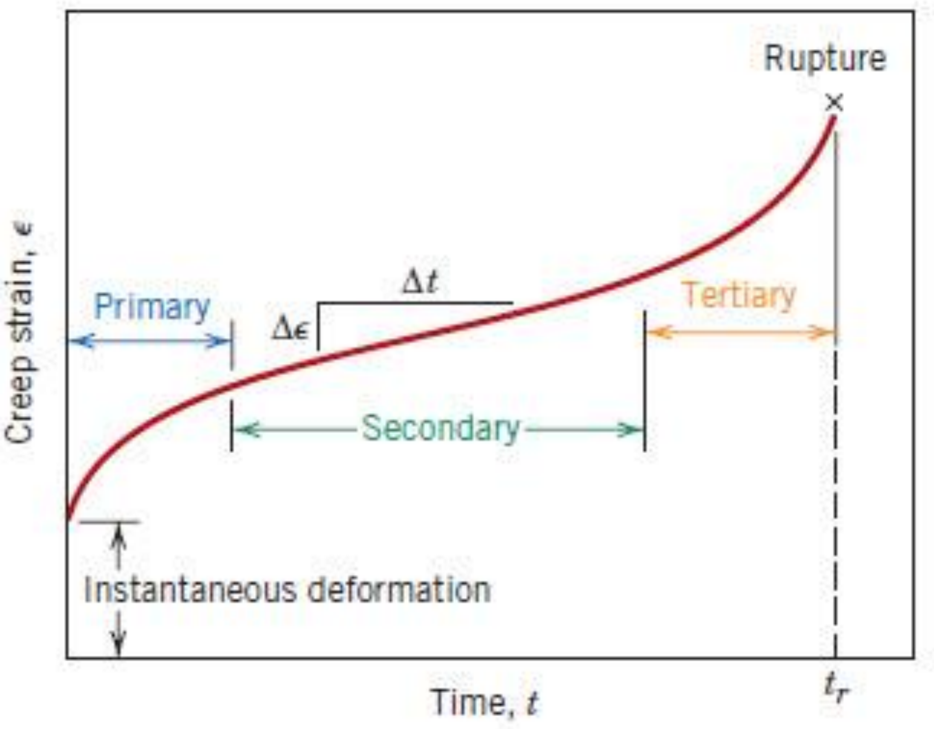
Turbine blade creep due to the inhospitable temperatures of a jet engine is an often cited example. High pressure boilers and steam lines, nuclear reactor fuel cladding, ceramic refractory brick in furnaces are components and systems that are also susceptible to creep effects.

Properties of Ceramics

Mechanical Properties

CREEP

The term creep is deformation at constant stress as a function of time and temperature. A typical creep curve has four distinct regions:
The secondary creep region (steady-state creep) is the most useful for predicting the life of the ceramic.



$$\boxed{\dot{\varepsilon}_{ss} = A\sigma^n e^{-(Q/\bar{R}T)}}$$

$\dot{\varepsilon}_{ss}$ – *steady state creep rate*

A – *creep constant*

n – *creep exponent*

Q – *activation energy for creep* $(\mathrm{J}mol^{-1})$

$\bar{R}$ – *universal gas constant* $(mol^{-1}K^{-1})$

Properties of Ceramics

Mechanical Properties

CREEP

Engineers perform two types of tests. The first aims to determine the steady state creep rate over a suitable matrix of stress and temperature. These tests are performed at the <u>same stress</u> but at different temperatures, as well as at the <u>same temperature</u> but different stresses, as shown in Fig.

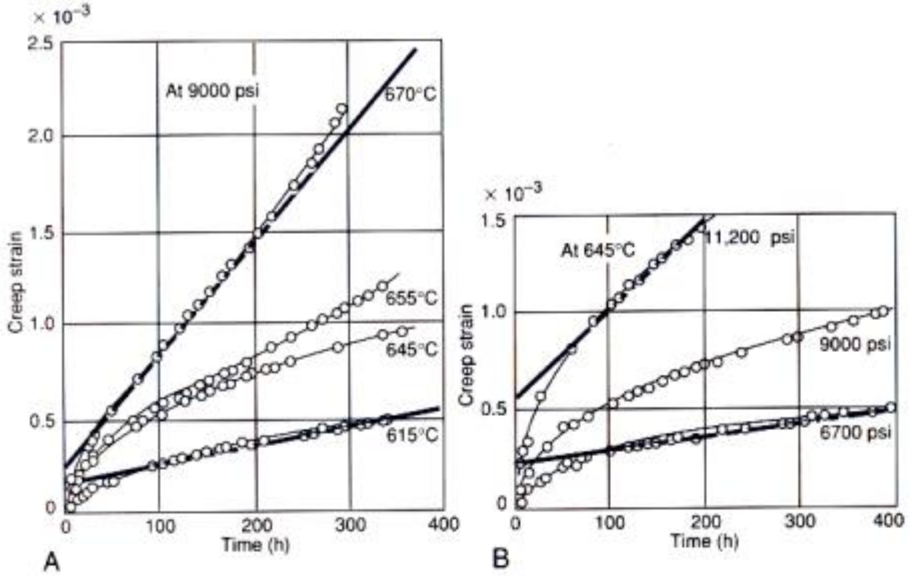


Figure 6. 15. Creep strain versus time in a 0.5 wt% o, 0.23 wt% steel. (A) Constant stress, variable temperature. (B) Constant temperature, variable stress. From A.J. Kennedy, *Processes of Creep and Fatigue in Metals.* Wiley, New York (1963)

Properties of Ceramics

Mechanical Properties

CREEP

Primary Creep or Transient Creep

This is the first stage of the creep which represents a region of decreasing creep rate. In this region the rate at which the material deforms decreases with time until it reaches a constant value.

In general, creep behavior of ceramics is similar to metals, however in ceramics creep happens at high temperatures ($>0.5\ T_m$)

In some ceramics, primary creep is the only creep region (SiC fibers)

$\varepsilon = \beta T^m$, where β is constant, m is a number btw 0.03 and 1.0 depending on the material, stress and temperature.

Properties of Ceramics

Mechanical Properties

CREEP

Steady-State or Secondary Creep

Strain increases linerly with time, the creep rate is constant, and deformation may continue for long time. This is the most important regime in creep. The equation is:

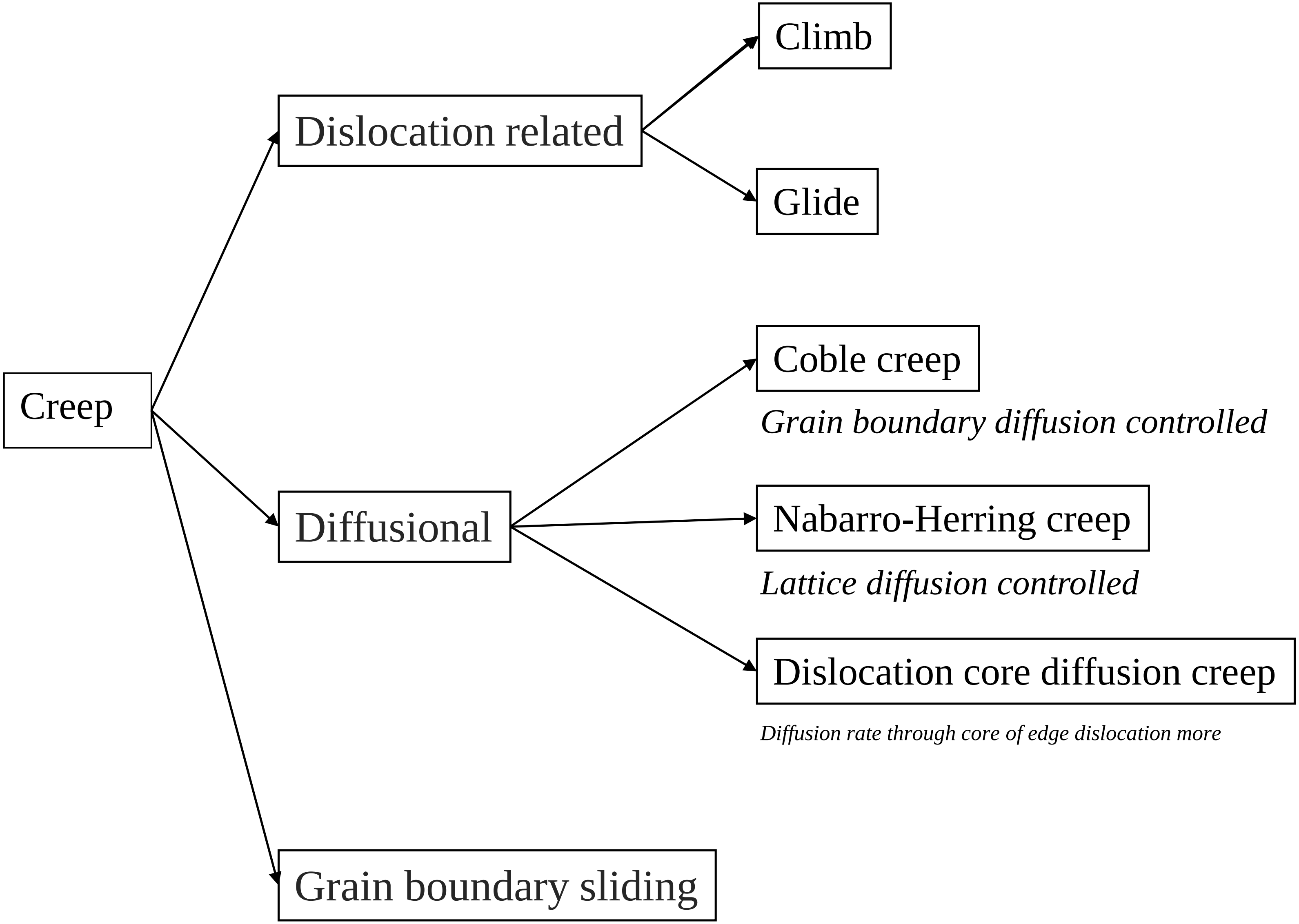
$$\varepsilon = Kt$$

where K is constant that depends on stress and temperature.

Tertiary Creep

A rapid increase in creep rate, just before failure. In ceramics, this stage is often missing.

Creep Mechanisms *of Ceramic Materials*



Creep

Dislocation related

Climb

Glide

Diffusional

Coble creep

Grain boundary diffusion controlled

Nabarro-Herring creep

Lattice diffusion controlled

Dislocation core diffusion creep

Diffusion rate through core of edge dislocation more

Grain boundary sliding

Properties of Ceramics

Mechanical Properties

CREEP

Dislocation Creep

Dislocation creep occurs by dislocation motion (climb, glide). For the climb controlled process, the creep rate can be expressed as:

$$\dot{\varepsilon} = \frac{\alpha D_L \mu b}{kT} \left(\frac{\sigma}{\mu}\right)^n$$

D_L is lattice diffusivity, μ is shear modulus, b is Burger’s vector, α is dimensionless constat. The eqn can be simplify by taking all the «constants» into a temperture-dependent constant Γ;

$$\dot{\varepsilon} = \Gamma \, \sigma^n$$

For climb, n is in the range of 4-5, for glide, n=3.

Properties of Ceramics

Mechanical Properties

CREEP

Diffusion Controlled Creep

Diffusion controlled creep is due to the atomic diffusion. There is no dislocation motion. There is a counterflow of atoms. The creep rate is given by:

$$\dot{\varepsilon} = \frac{\alpha D_L \sigma \Omega}{d^2\, kT} \qquad \text{Nabarro-Herring}$$

which can be simplify by taking all the «constants» into a temperture-dependent constant Γ;

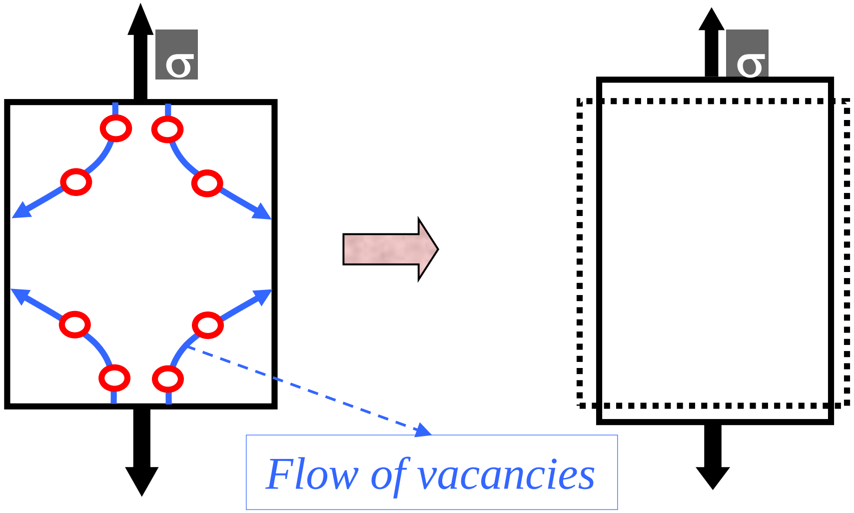
$$\dot{\varepsilon} = \Gamma\, \sigma^n$$

where α depends on the extent of grain boundary sliding (Herring)

Properties of Ceramics

Mechanical Properties

CREEP



Nabarro-Herring Creep

For simple tension measurements under steady state conditions α is 13.3.

It is assumed that;

- The main source and sink for vacancies are grain boundaries.
- We have equilibrium.
- There is no cavitation.

Properties of Ceramics

Mechanical Properties

CREEP

In response to the applied stress vacancies preferentially move from surfaces/interfaces (GB) of specimen transverse to the stress axis to surfaces/interfaces parallel to the stress axis→ thus causing elongation.

Diffusion of vacancies in one direction can be thought of as flow of matter in the opposite direction.

This process like dislocation creep (involving climb) is controlled by the diffusion of vacancies (but diffusional creep does not require dislocations to operate).

The diffusion could occur predominantly via the lattice (at high temperatures) or via grain boundaries (at low temperatures). The former is known as Nabarro-Herring creep, while the later is known as Coble creep.

Diffusion through edge dislocation cores (pipe diffusion) could play an important role in creep

Properties of Ceramics

Mechanical Properties

CREEP

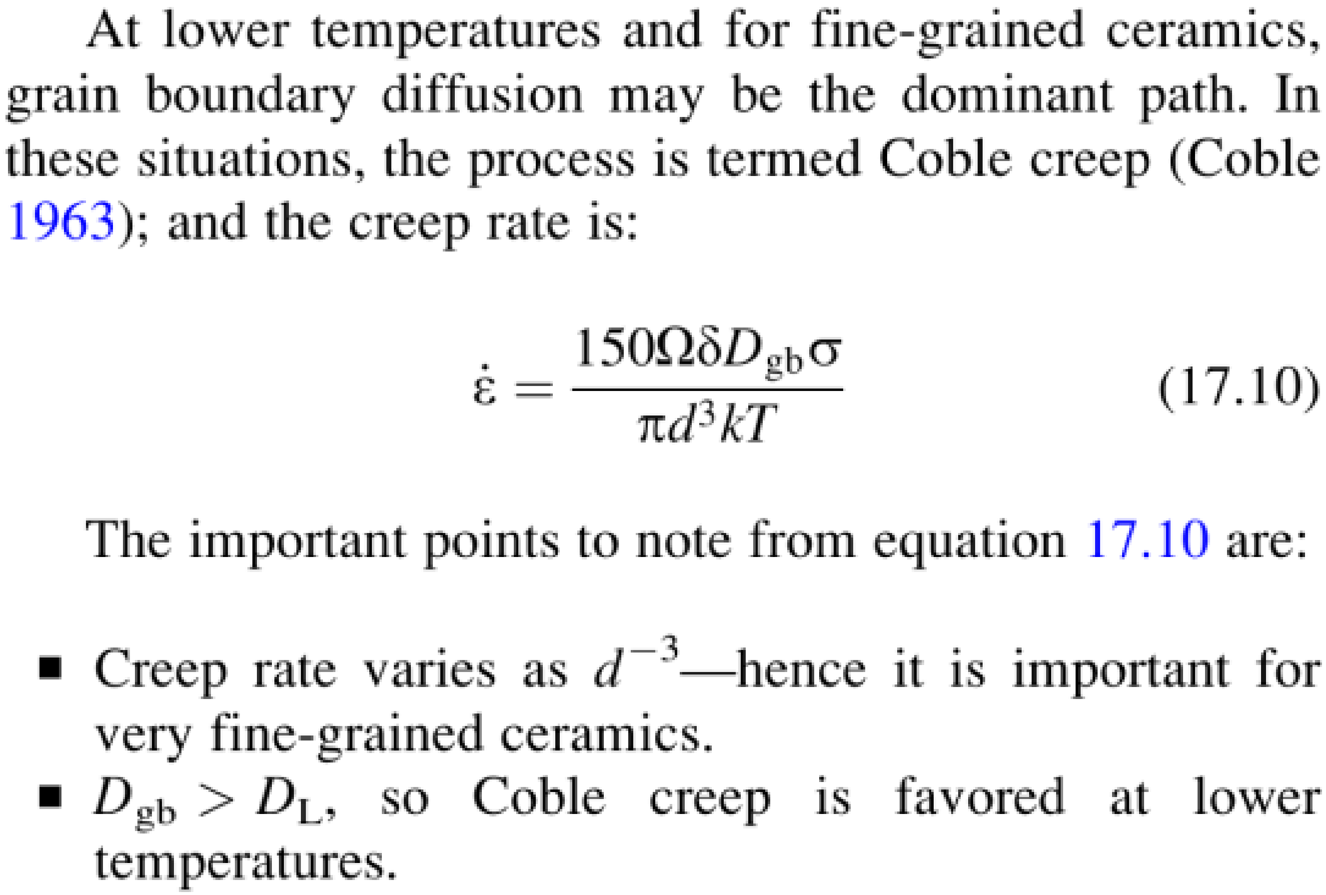
Important points about Nabarro-Herring Creep;

- T has to be high enough to allow vacancy diffusion
- Diffusion is considered to occur through the bulk
- Creep rate increases with decreasing grain size (d)
- Creep rate is proportional to the applied stress
- There is linear dependence between strain rate and stress

Properties of Ceramics

Mechanical Properties

CREEP



At lower temperatures and for fine-grained ceramics, grain boundary diffusion may be the dominant path. In these situations, the process is termed Coble creep (Coble 1963); and the creep rate is:

$$\dot{\varepsilon} = \frac{150\Omega\delta D_{\mathrm{gb}}\sigma}{\pi d^3 kT} \tag{17.10}$$

The important points to note from equation 17.10 are:

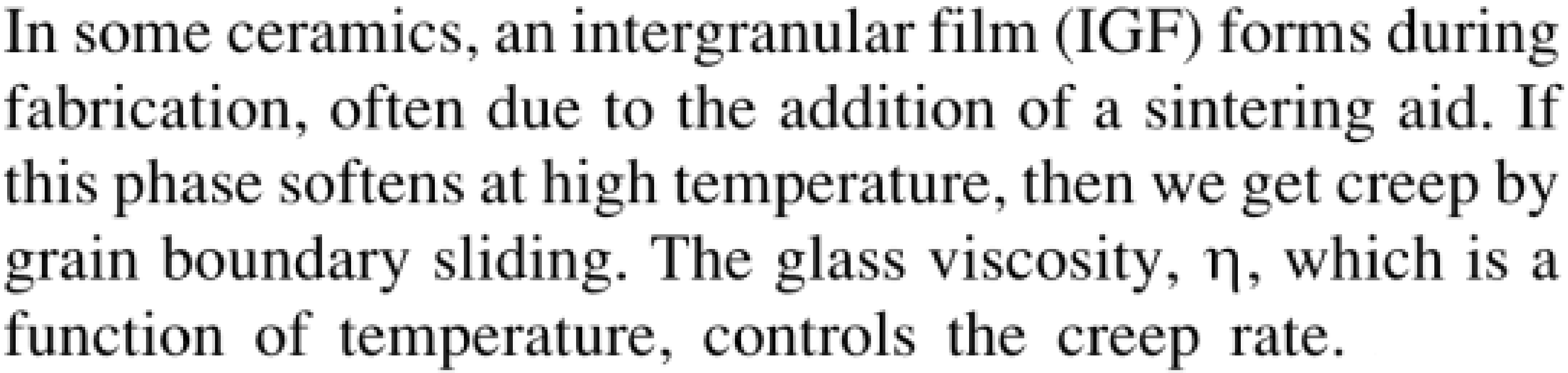
- Creep rate varies as d^{-3}—hence it is important for very fine-grained ceramics.
- $D_{\mathrm{gb}} > D_{\mathrm{L}}$, so Coble creep is favored at lower temperatures.

Properties of Ceramics

Mechanical Properties

CREEP

Grain Boundary Sliding



In some ceramics, an intergranular film (IGF) forms during fabrication, often due to the addition of a sintering aid. If this phase softens at high temperature, then we get creep by grain boundary sliding. The glass viscosity, η, which is a function of temperature, controls the creep rate.

At low temperatures the grain boundaries are '*stronger*' than the crystal interior and impede the motion of dislocations

Being a higher energy region, the grain boundaries *melt* before the crystal interior. At high temperatures grain boundaries are weaker than grain and slide past one another to cause plastic deformation

Properties of Ceramics

Mechanical Properties

CREEP

Dislocation Core Diffusion Creep

$$\dot{\varepsilon} = \frac{\alpha D_L \mu b}{kT}\left(\frac{\sigma}{\mu}\right)^n$$

The equation of dislocation creep is incapable of explaining certain experimental facts, notably an increase in the exponent *n* and a drop in the activation energy for creep at lower temperatures. To do so it is necessary to assume that the transport of matter via *dislocation core diffusion* contributes significantly to the overall diffusive transport of matter, and—under certain circumstances—becomes the dominant transport mechanism (Robinson and Sherby, 1969). The contribution of core diffusion is included by defining an effective diffusion coefficient (Hart, 1957 and Robinson and Sherby, 1969).

Robinson, S.L. and O.D. Sherby, *Mechanical behaviour of polycrystalline tungsten at elevated temperature.* Acta Met., 1969. **17**: p. 109.

Hart, E.W., *On the role of dislocations in bulk diffusion.* Acta Metallurgica (pre 1990), 1957. **5**: p. 597

Properties of Ceramics

Mechanical Properties

CREEP

Summary

Creep is the slow plastic deformation due to diffusion of atoms at high temperatures ($T > 0.5\ T_m$). Creep occurs at stresses **below the yield stress**. Note the difference: plastic deformation is not dependent on time; modern manufacturing uses the fact that metals can be shaped very rapidly. Creep is a viscous-like deformation and the stress rules the rate of deformation.

Thermal and Thermo-Mechanical Properties

Ceramics are widely used as insulators, primarily in various kinds of furnaces. The class of ceramics used for this purpose is called the refractories. Apart from heat resistance, these refractories should also possess a thermo-mechanical property called refractoriness under load

The thermal properties that are of important are **heat capacity, thermal expansion,** and **thermal conductivity.**

- **Heat capacity** is a measure of the heat required for changing the temperature. It is therefore important in the heat treatment and use of ceramics. The economy of running a furnace is decided by the amount of heat needed to reach a particular temperature.
- **Thermal expansion** becomes important in ceramic composites. The different constituents in a composite should have close thermal expansion coefficients in order to prevent accumulation of thermal stresses in the composite.
- **Thermal conductivity** is an undesirable property in the case of insulators. Generally, ceramics possess low thermal conductivity.

Heat Capacity

The heat given to a material is utilized for various processes:
a. For increasing the vibrational energy
b. For increasing the rotational energy
c. For increasing the energy level of electrons
d. For giving rise to defects and thereby for disordering
e. For changing magnetic orientation
f. For altering a structure

Atoms vibrate about their mean positions in solids. An increase in vibrational energy increases their amplitude and the frequency of their vibrations. Defects such as Schottky and Frenkel are produced by the movement of atoms from their original positions. All the aforementioned processes increase the internal energy of the material and the configurational entropy.

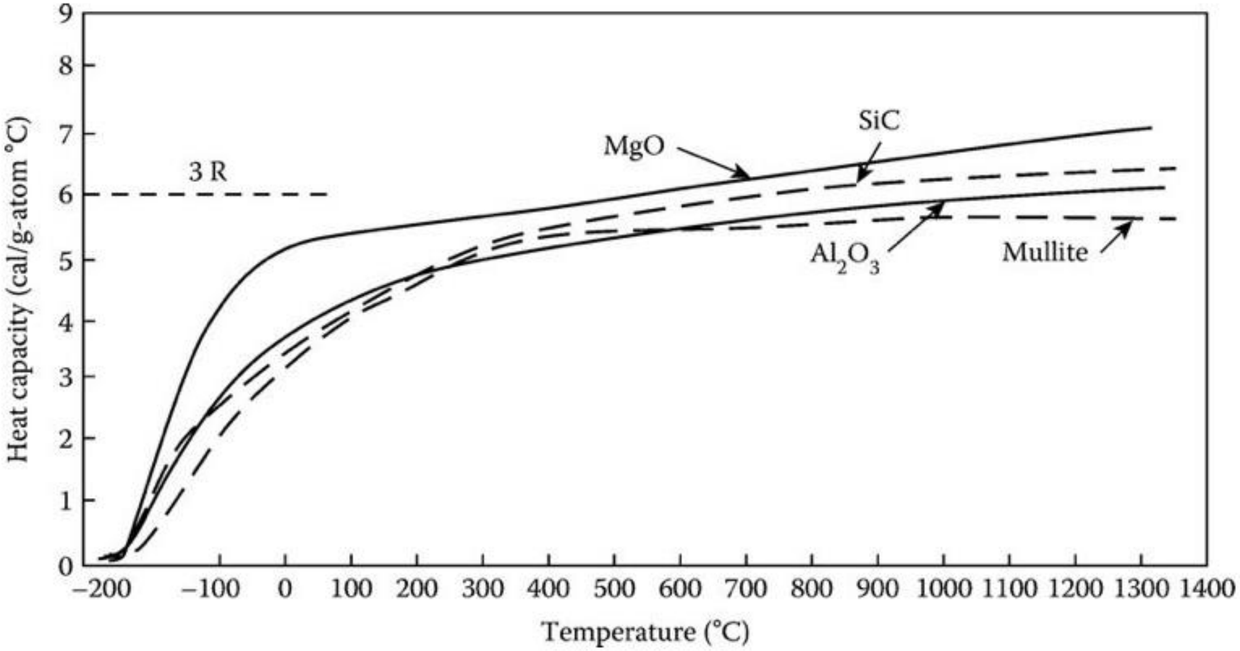
Heat Capacity

Each atom possesses an average energy of kT. Because there are three degrees of freedom along three axes, the total energy per atom becomes 3kT.

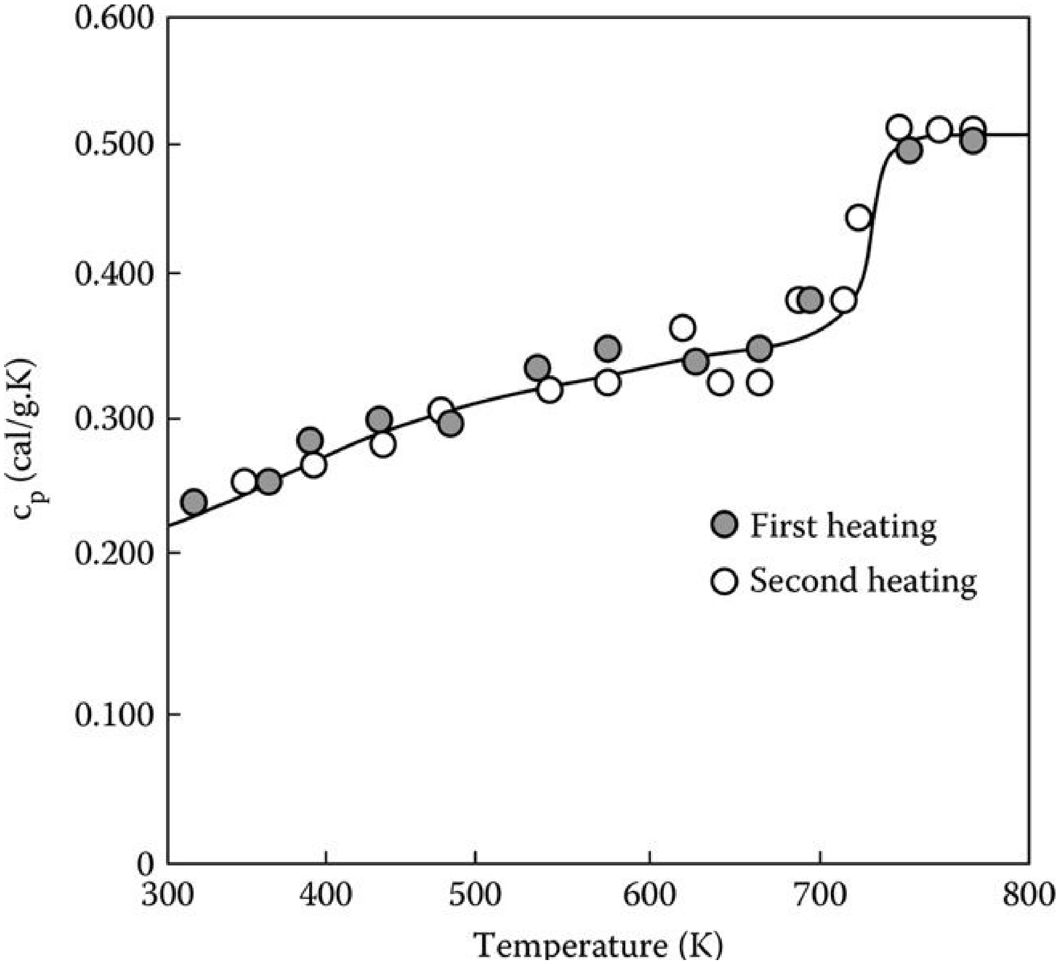
1 mole atom of the substance possesses 3NkT energy. The specific heat at constant volume per mole is given by:

$$c_v = (dE/dT)_v = [d(3NkT)/dT]_v = 3Nk$$

At higher temperatures, materials are found to acquire this constant value of heat capacity

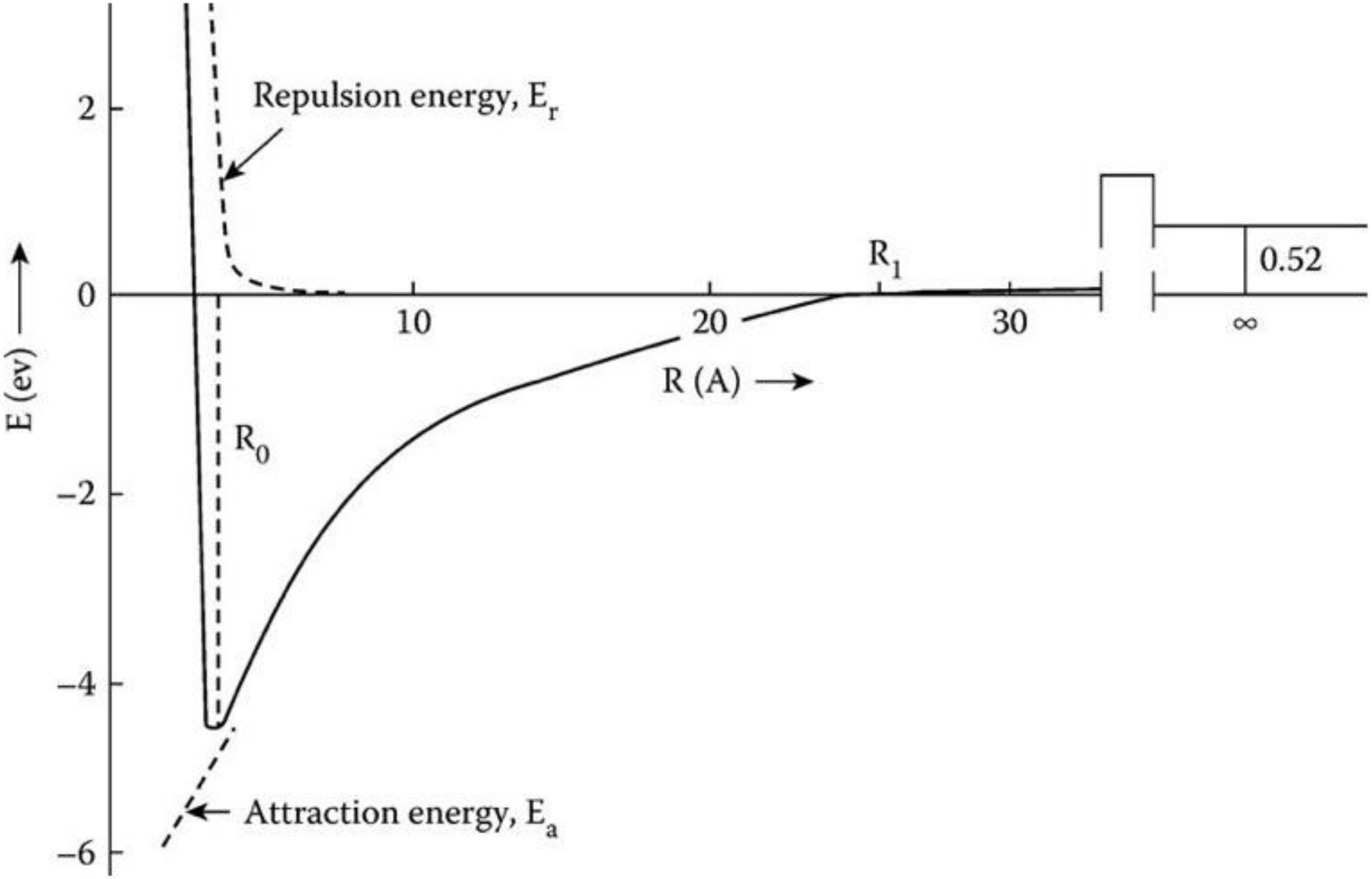


Heat Capacity



the variation of heat capacity (c_p) with temperature for $0.15Na_2O{-}0.85B_2O_3$ glass. The sudden increase in heat capacity marks the transition to the liquid state. In the liquid state, configurational entropy comes into play, which results in higher heat capacity

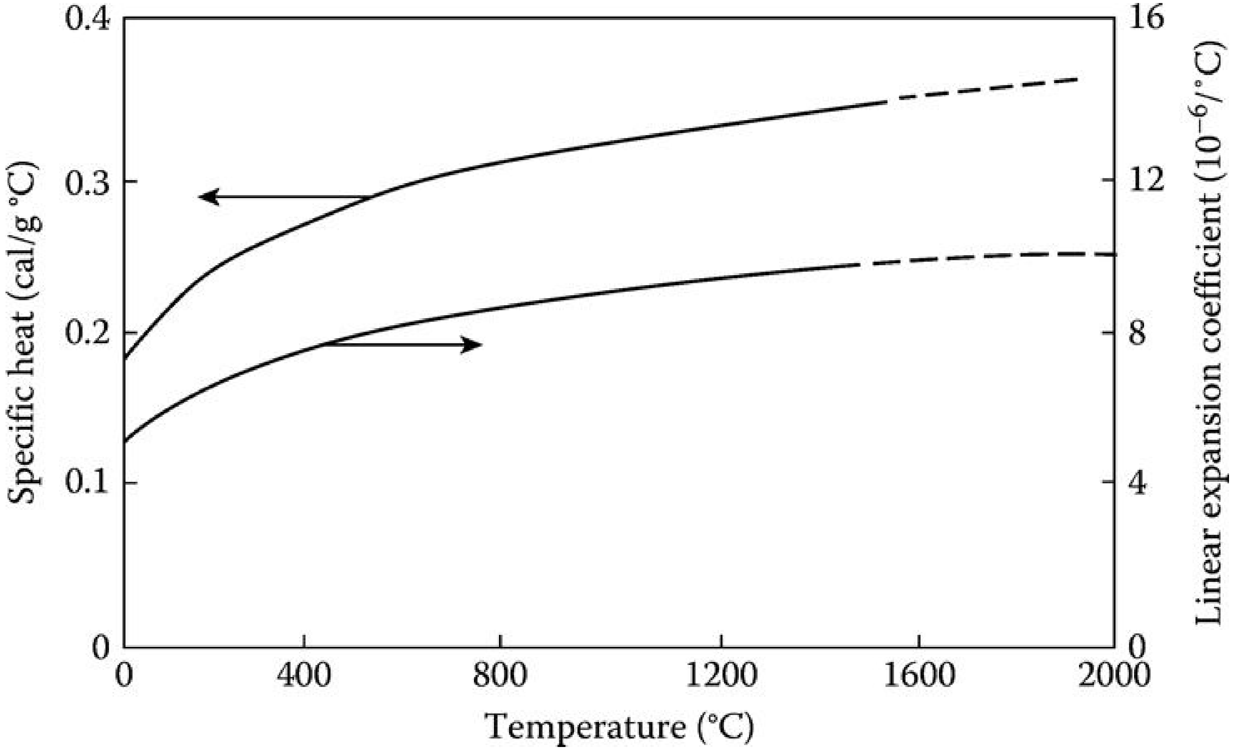
Thermal Expansion



Variation of lattice energy with interatomic separation

Thermal Expansion

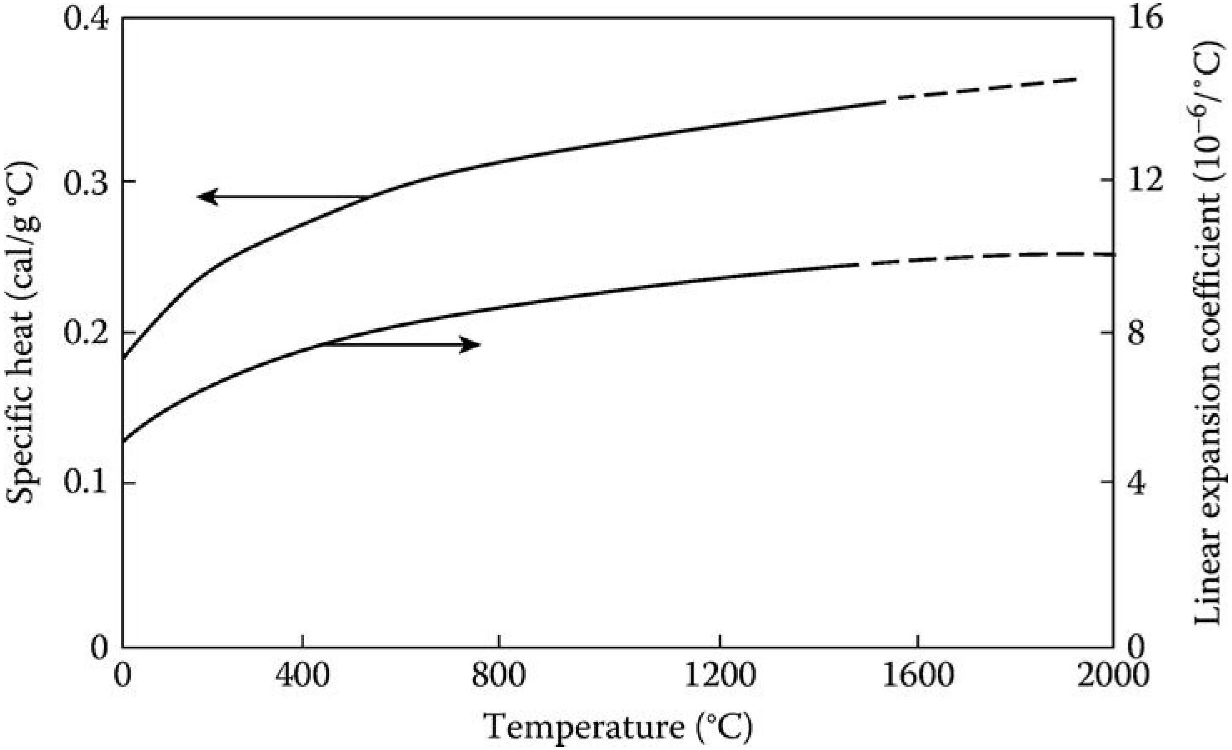
Temperature increases the equilibrium interionic separation. This is because the amplitude of vibration increases with temperature. But it brings about a more symmetrical arrangement. In other words, the entropy decreases as temperature is increased. The increase in thermal expansion and heat capacity is parallel with an increase in temperature, as shown in Figure. Both result from an increase in the internal energy of the material.



Parallel changes in specific heat and thermal expansion coefficient of alumina

Thermal Expansion

Temperature increases the equilibrium interionic separation. This is because the amplitude of vibration increases with temperature. But it brings about a more symmetrical arrangement. In other words, the entropy decreases as temperature is increased. The increase in thermal expansion and heat capacity is parallel with an increase in temperature, as shown in Figure. Both result from an increase in the internal energy of the material.



Parallel changes in specific heat and thermal expansion coefficient of alumina

Thermal Expansion

In the case of isotropic materials, such as those having cubic crystal structure, the thermal expansion is given by

$$1 + \alpha\Delta T = 1 + 3a\Delta T + 3a^2 (\Delta T)^2 + a^3(\Delta T)^3$$

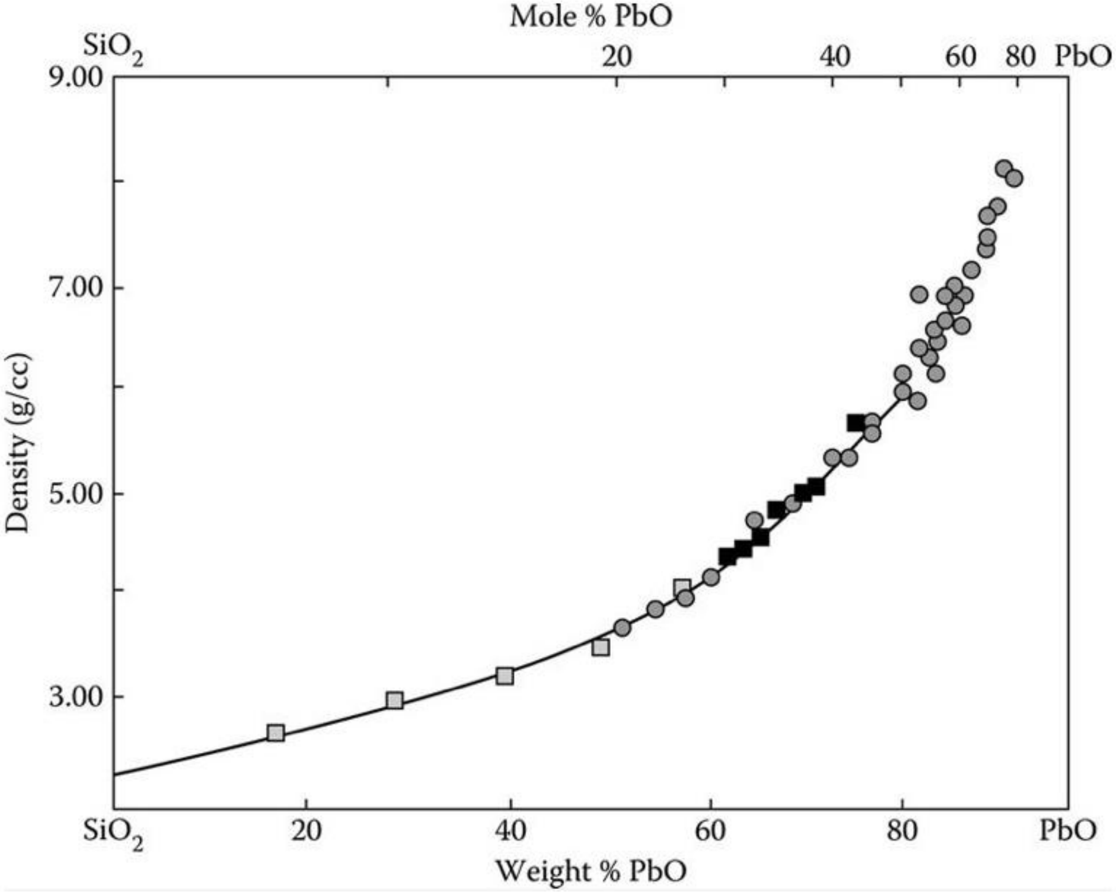
$$\alpha = 3a + 3a^2 (\Delta T) + a^3(\Delta T)^2$$

Here, $\overline{\alpha}$ is the average volume thermal expansion coefficient and a is the average linear expansion coefficient for a small temperature change ΔT. Because a is small for a small temperature change, higher orders of a than 1 can be neglected. Hence, the volume expansion coefficient for an isotropic material can be written as:

$$\overline{\alpha} = 3a$$

Thermal Expansion of Glasses

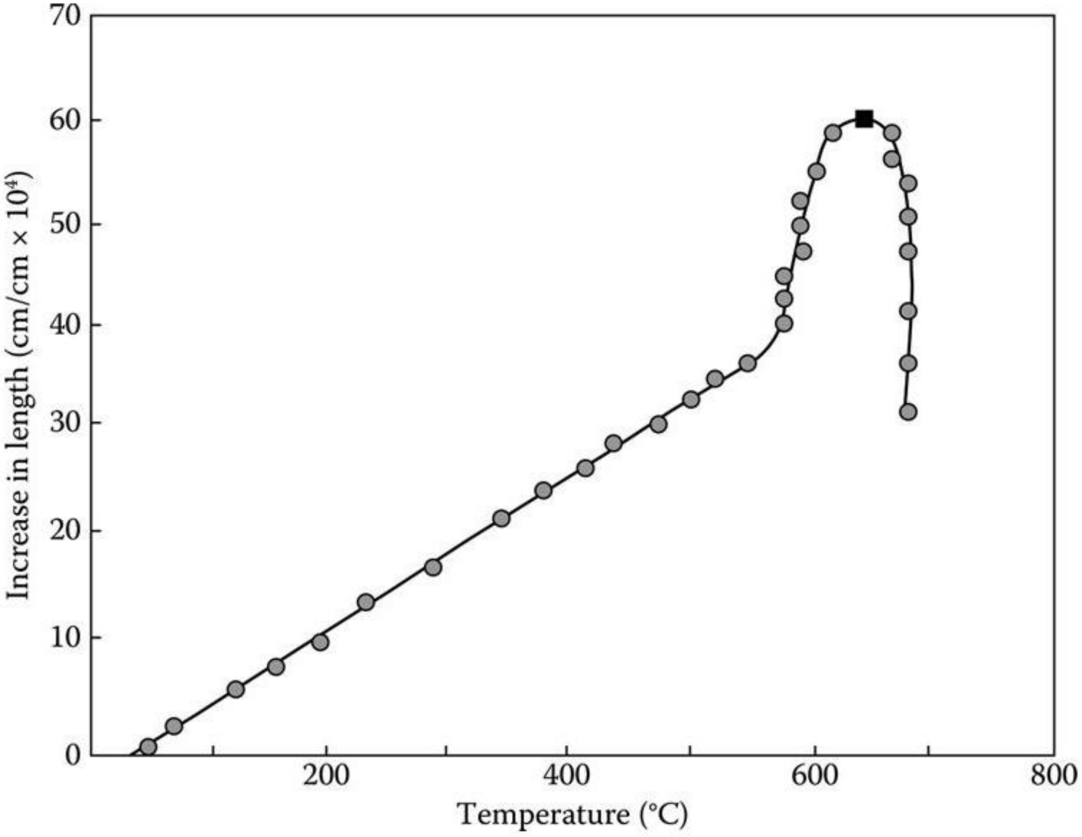
The network structure in glasses has a low density. When modifiers are added, their density increases, even though the structure is loosened. Figure shows the effect of adding lead dioxide to silica glass.



Thermal Expansion of Glasses

The density of a glass depends on the rate of cooling of a glass melt. As the rate of cooling increases, its density decreases. Its thermal expansion coefficient varies with temperature. This is shown in Figure. There is a sudden increase seen in the expansion coefficient in the temperature range of 550°C to 600°C. At this temperature range, a structural rearrangement takes place in which a glassy solid transforms to a supercooled liquid. Above this temperature range, viscous flow takes place, and the sample contracts.

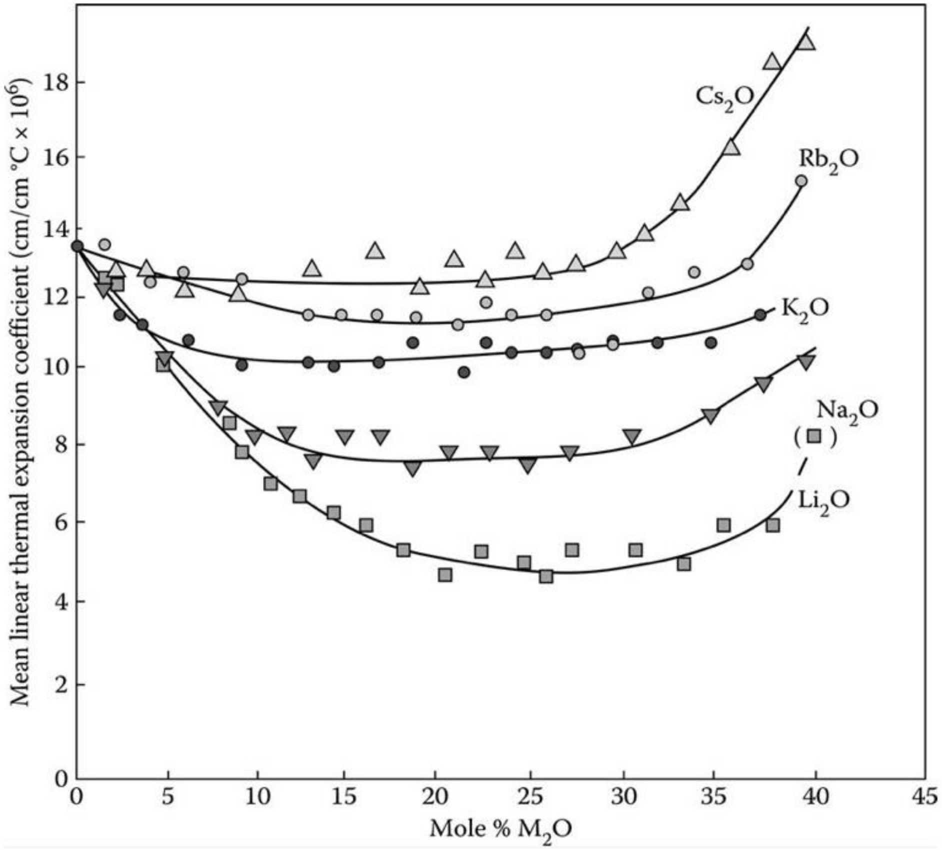
Variation of thermal expansion coefficient of a silicate glass



Thermal Expansion of Glasses

In the case of $Na_2O-B_2O_3$ systems, there is a minimum for the thermal expansion coefficient. This behavior is called the boric oxide anomaly. This happens because with low concentrations of the alkali oxide, the BO_3 triangles converts to BO_4 tetrahedra. This conversion reduces the expansion. For larger alkali concentrations, singly bonded oxygens are formed and the expansion increases.

Thermal expansion coefficients of alkali borate glasses as a function of composition



Thermal Expansion of Composites

In a composite, different phases have different expansion coefficients. But there will be restriction from neighboring grains for expansion and contraction. Because of this, microstresses are developed. The stresses on each grain are given by

$$\sigma_i = K(\alpha_r - \alpha_i)\Delta T$$

Here, σ_i and α_i are the stress and volume expansion coefficient, respectively, of the grain i; K is the bulk modulus, α_r is the average volume expansion coefficient of the composite, and ΔT is the temperature difference. The bulk modulus is given by

$$K = -P/(\Delta V/V) = E/3(1-2\mu)$$

Here, P is the isotropic pressure, V is the initial volume, ΔV is the change in volume due to the pressure P, E is the elastic modulus, and μ is the Poisson's ratio. The summation of stresses in a volume is zero. That is

$$K_1(\alpha_r - \alpha_i)V_1\Delta T + K_2(\alpha_r - \alpha_i)V_2\Delta T + \cdots\cdots\cdots = 0$$

Thermal Expansion of Composites

$$V_1 + V_2 + \cdots = V_r$$

$$V_i = F_i\rho_r V_r/\rho_i$$

where V_i is volume, F_i, weight fraction, ρ_i, density of the ith phase, and ρ_r and V_r are the average density and volume, respectively, of the composite

since $\Delta T \neq 0$

$$K_1(\alpha_r - \alpha_1)V_1 + K_2(\alpha_r - \alpha_2)V_2 + \cdots\cdots\cdots = 0$$

It is possible to make operations below

$$K_1(\alpha_r - \alpha_1)F_1\rho_r V_r/\rho_1 + K_2(\alpha_r - \alpha_2)F_2\rho_r V_r/\rho_2 = 0$$

$$K_1(\alpha_r - \alpha_1)F_1/\rho_1 + K_1(\alpha_r - \alpha_2)F_2/\rho_2 = 0$$

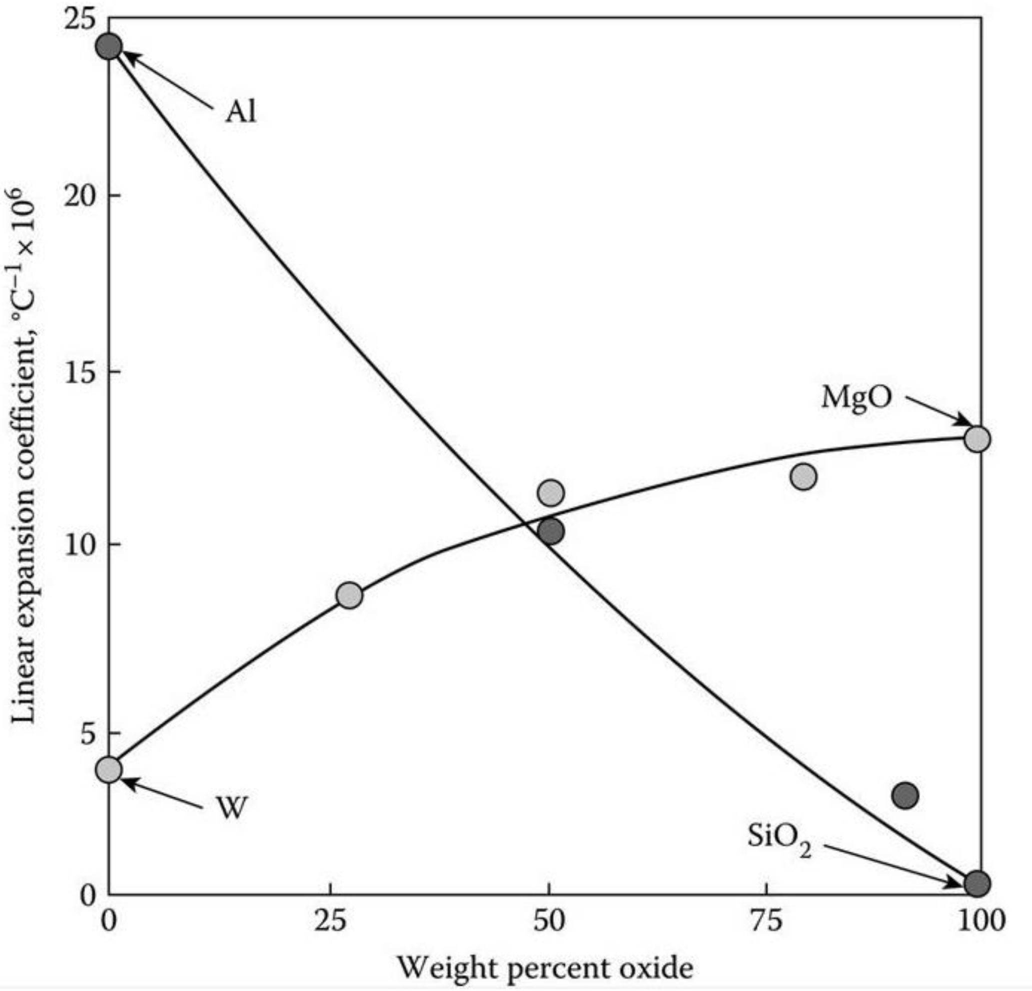
$$K_1\alpha_r F_1/\rho_1 - K_1\alpha_1 F_1/\rho_1 + K_2\alpha_r F_2/\rho_2 - K_2\alpha_2 F_2/\rho_2 = 0$$

$$\alpha_r(K_1F_1/\rho_1 + K_2\,F_2/\rho_2) = (K_1\alpha_1F_1/\rho_1 + K_2\alpha_2F_2/\rho_2)$$

$$\alpha_r = (K_1\alpha_1F_1/\rho_1 + K_2\alpha_2F_2/\rho_2)/(K_1F_1/\rho_1 + K_2\,F_2/\rho_2)$$

Thermal Expansion of Composites

This equation is plotted for two composites in Figure. It shows good agreement between predicted and experimental values.

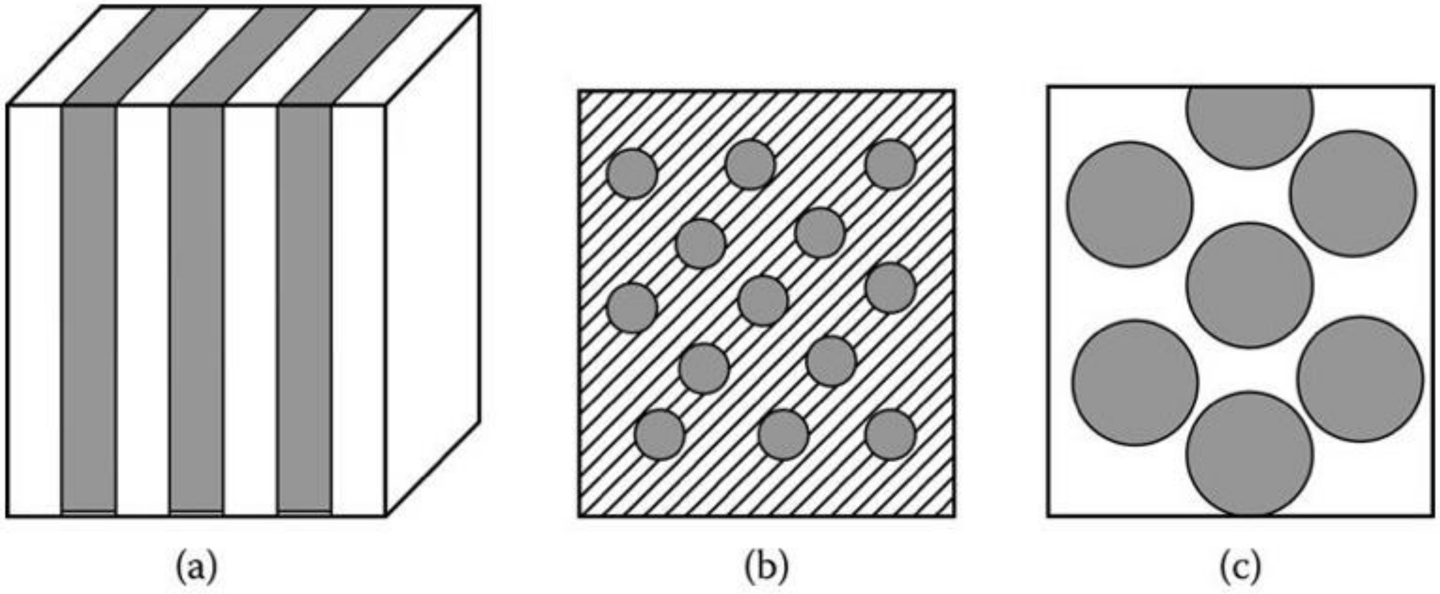


Conductivity of Polyphase Ceramics

Polyphase ceramics are more common than single-phase ones. They contain mixtures of one or more phases and pores. The conductivity of such ceramics depends on:

a. Amount of each phase
b. Arrangement of each phase
c. Conductivity of each phase

Three idealized microstructures are shown in Figure to represent the amount and arrangement phases in a two-phase structure. The structure shown in Figure(b) is that of a continuous major phase with a dispersed minor phase. This kind of structure is typical of many ceramics. Porosity is also commonly seen dispersed in a continuous matrix.



Conductivity of Polyphase Ceramics

In order to ascertain the effect of the amount of phases and their distribution on the conductivity of ceramics, let us consider Figure (a). When heat flows parallel to the slabs, it is like electricity passing through a parallel circuit. The thermal conductivity for such an arrangement is given by

$$k_m = v_1k_1 + v_2k_2$$

Here, all the slabs are assumed to have the same dimensions so that their volumes are proportional to their vertical and horizontal cross-sectional areas. In the case of $k_1 >> k_2$, the thermal conductivity for this structure is given by

$$k_m \approx v_1k_1$$

This means that the heat conduction is dominated by the better conductor. When the conduction takes place across the slabs, the relevant equation for the conductivity is given by

$$(1/k_m) = (v_1/k_1) + (v_2/k_2)$$

The heat flow in this case can be likened to electricity flow through a circuit connected in a series. Again, considering $k_1 >> k_2$, we get the conductivity of the system from

$$k_m \approx k_2/v_2$$

In this case, the conduction is dominated by the poorer conductor.

Conductivity of Polyphase Ceramics

For the more realistic picture, the resultant thermal conductivity has been derived by Maxwell

$$k_m = k_c[1 + 2v_d(1 - k_c/k_d)/(2k_c/k_d + 1)]/[1 - v_d(1 - k_c/k_d)/(k_c/k_d + 1)]$$

Here, k_c is the conductivity of the continuous phase and k_d is that of the dispersed one. When k_c is greater than k_d, the resultant conductivity is given by

$$k_m \approx k_c\,[(1 - v_d)/(1 + v_d)]$$

In case, $k_d > k_c$, then the resultant conductivity is:

$$k_m \approx k_c\,[(1 + 2v_d)/(1 - v_d)]$$

Alumina porcelains contain corundum and glass phases. Both phases are continuous at a composition corresponding to about 9 vol% glass. In such a case, the thermal conductivity value will be in between that of the two phases.

Generally, the glass is continuous in vitreous ceramics. Therefore, the conductivity of these materials is closer to that of the glass phase

Thermo-Mechanical Properties

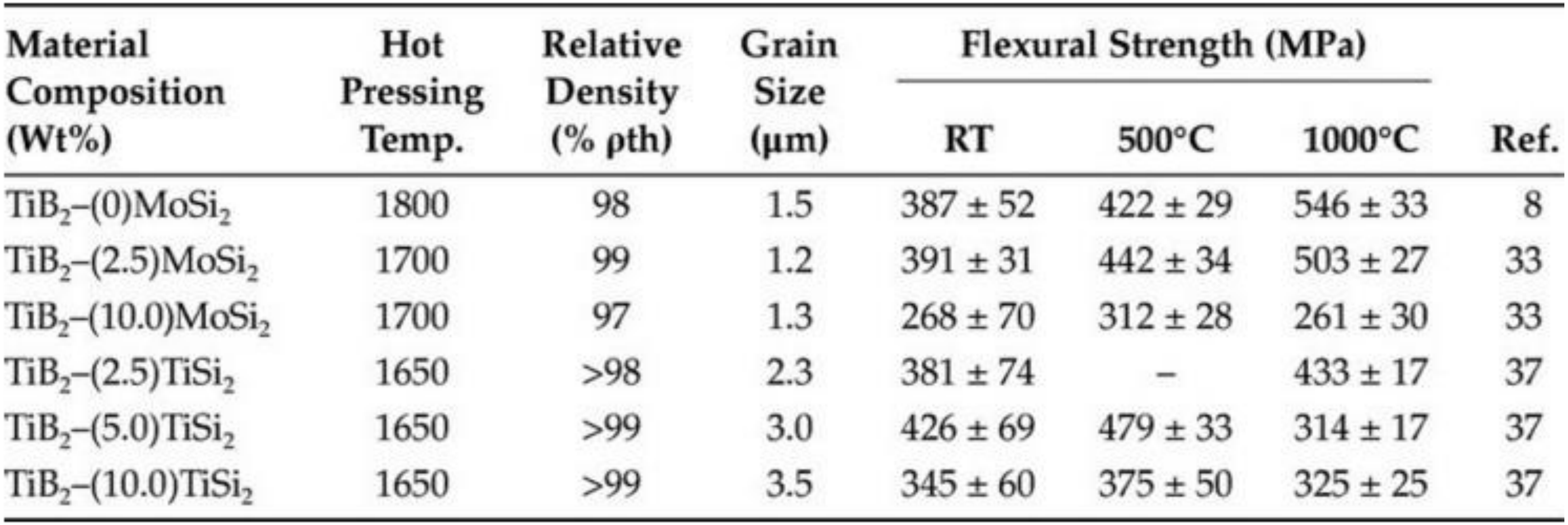
Thermo-mechanical properties are required for high-temperature materials. The last few decades have witnessed the development of various boride-based materials. This development has occurred due to their combination of properties, which include high hardness, elastic modulus, abrasion resistance, and superior thermal and electrical conductivity. The targeted applications include high-temperature structural materials, cutting tools, armor material, electrode materials in metal smelting, and wear-resistant parts

High-Temperature Flexural Strength

In order to demonstrate the high-temperature flexural strength of ceramics, TiB_2 was taken as an example. It was hot pressed (HP) TiB_2 with and without the help of sintering aids. The sintering aids used were $MoSi_2$ and $TiSi_2$. $MoSi_2$ was used in two weight percentages, 2.5 and 10, whereas $TiSi_2$ was used in three weight percentages, 2.5, 5, and 10. The samples were hot pressed for 60 min at 30 MPa. The sample size was $3 \times 4 \times 40$ mm^3. After hot pressing, they were tested in air with a four-point flexural configuration. The results are shown in Table

High-Temperature Flexural Strength

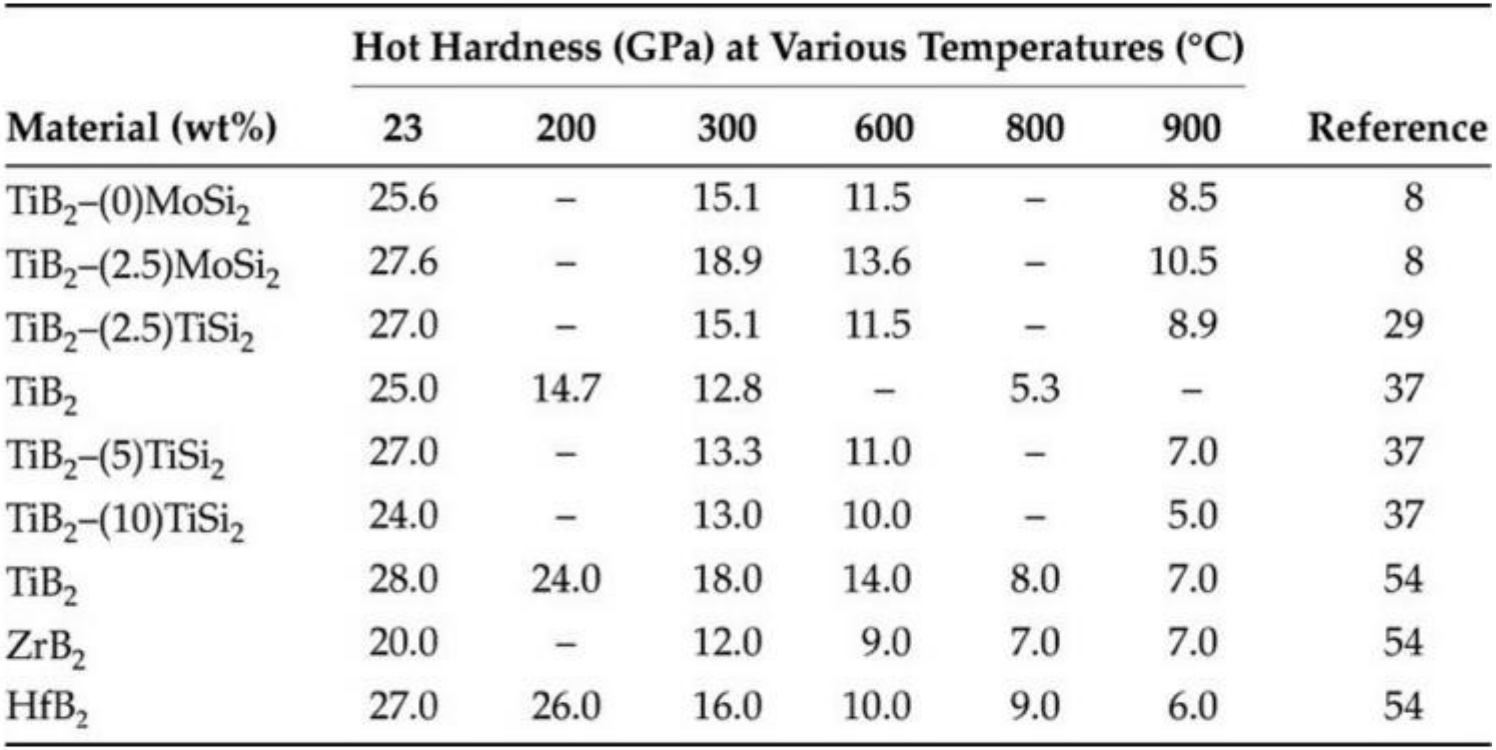
Effect of Temperature on Flexural Strength of $TiB_2$and $TiSi_2$/$MoSi_2$ Ceramics



Material Composition (Wt%)	Hot Pressing Temp.	Relative Density (% ρth)	Grain Size (μm)	Flexural Strength (MPa)			Ref.
				RT	500°C	1000°C	
TiB_2–(0)$MoSi_2$	1800	98	1.5	387 ± 52	422 ± 29	546 ± 33	8
TiB_2–(2.5)$MoSi_2$	1700	99	1.2	391 ± 31	442 ± 34	503 ± 27	33
TiB_2–(10.0)$MoSi_2$	1700	97	1.3	268 ± 70	312 ± 28	261 ± 30	33
TiB_2–(2.5)$TiSi_2$	1650	>98	2.3	381 ± 74	–	433 ± 17	37
TiB_2–(5.0)$TiSi_2$	1650	>99	3.0	426 ± 69	479 ± 33	314 ± 17	37
TiB_2–(10.0)$TiSi_2$	1650	>99	3.5	345 ± 60	375 ± 50	325 ± 25	37

Hot Hardness

Hot Hardness Values of TiB_2–$MoSi_2$/$TiSi_2$ Ceramics

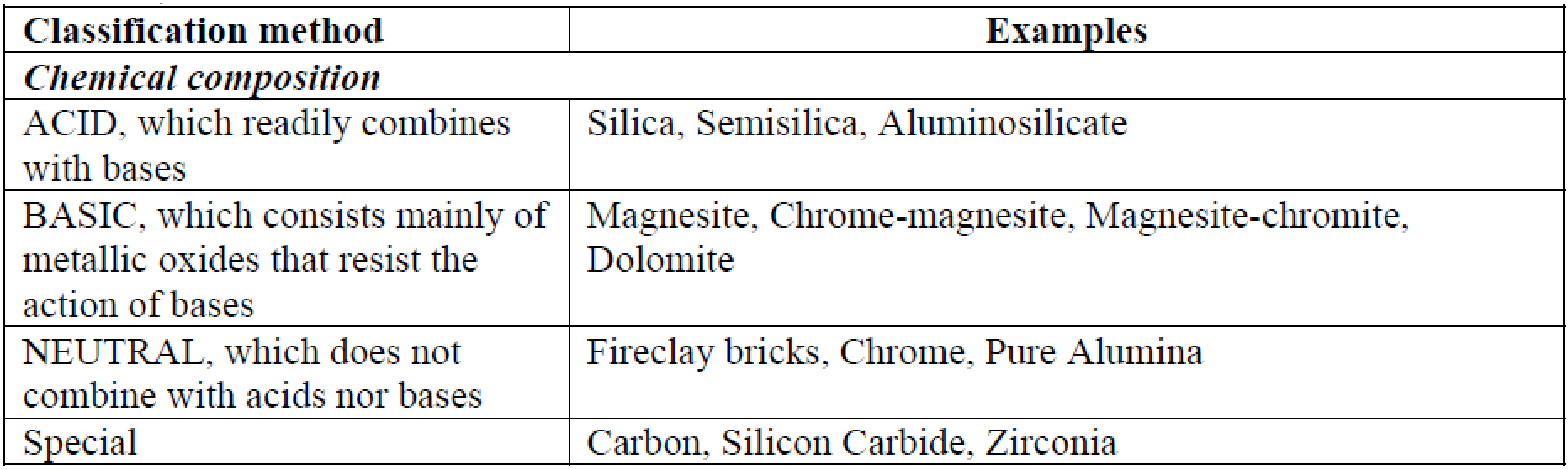


	Hot Hardness (GPa) at Various Temperatures (°C)						
Material (wt%)	23	200	300	600	800	900	Reference
TiB_2–(0)$MoSi_2$	25.6	–	15.1	11.5	–	8.5	8
TiB_2–(2.5)$MoSi_2$	27.6	–	18.9	13.6	–	10.5	8
TiB_2–(2.5)$TiSi_2$	27.0	–	15.1	11.5	–	8.9	29
TiB_2	25.0	14.7	12.8	–	5.3	–	37
TiB_2–(5)$TiSi_2$	27.0	–	13.3	11.0	–	7.0	37
TiB_2–(10)$TiSi_2$	24.0	–	13.0	10.0	–	5.0	37
TiB_2	28.0	24.0	18.0	14.0	8.0	7.0	54
ZrB_2	20.0	–	12.0	9.0	7.0	7.0	54
HfB_2	27.0	26.0	16.0	10.0	9.0	6.0	54

CLASSIFICATION of REFRACTORIES

Most refractories are ceramics. Carbon, which is the basis of organic materials, is also considered a refractory material. Among metallic materials, tungsten and molybdenum are refractories. All refractory materials possess a high melting point on the order of 2000°C and higher. They have the ability to retain their physical shape and chemical identity when subjected to high temperatures.

Refractories can be classified as acidic, basic, and neutral refractories. This classification is based on the behavior of refractories toward slags. Following is a brief discussion of each of these classes



Classification method	**Examples**
Chemical composition	
ACID, which readily combines with bases	Silica, Semisilica, Aluminosilicate
BASIC, which consists mainly of metallic oxides that resist the action of bases	Magnesite, Chrome-magnesite, Magnesite-chromite, Dolomite
NEUTRAL, which does not combine with acids nor bases	Fireclay bricks, Chrome, Pure Alumina
Special	Carbon, Silicon Carbide, Zirconia

CLASSIFICATION of REFRACTORIES

Acid Refractories

Acid refractories react with basic slags. Therefore, they are not useful in basic conditions but are used under acidic conditions. In these refractories, SiO_2 is the basic constituent. Examples are silica, fireclay series with 30%–42% Al_2O_3, sillimanite, and andalusite with about 60% Al_2O_3

Basic Refractories

Basic refractories react with acidic slags. Therefore, they are not useful in acidic environments. They are used under basic conditions and are based on MgO. Examples are magnesite, dolomite, chrome-magnesite, magnesite-chrome, alumina, and mullite

Neutral Refractories

Neutral refractories do not react with either acidic or basic slags. Hence, they are useful in acidic and basic conditions. Examples are carbon, chromite ($FeO.Cr_2O_3$), and fosterite ($2MgO.SiO_2$).

Certain refractories are grouped under *special refractories*. Examples are zirconia, thoria, and beryllia. They possess special properties that make them useful in special applications.

Bricks are commonly produced by refractories and come in standard and nonstandard shapes. Nonstandard shapes are costlier. Standard shapes include rectangular prisms, bricks, and tubular arms.

Running repairs are made from *castables*. These are plastic preparations that can be made in any shape; they are dried and fired in situ.

Another class of refractories is called *insulating refractories*. These are designed to have very low thermal conductivity. This is achieved mostly by incorporating a high proportion of air into the structure. Bricks made in this way are called porous bricks. Another example of an insulating refractory is the mineral wool. This is not self-supporting. Hence, it should be contained for use.

REFRACTORIES

Any material can be described as a ‘refractory,’ if it can withstand the action of abrasive or corrosive solids, liquids or gases at high temperatures. Refractory materials are made in varying combinations and shapes depending on their applications. General requirements of a refractory material are:

- Withstand high temperatures
- Withstand sudden changes of temperatures
- Withstand action of molten metal slag, glass, hot gases, etc
- Withstand load at service conditions
- Withstand load and abrasive forces
- Conserve heat
- Have low coefficient of thermal expansion
- Should not contaminate the material with which it comes into contact

REFRACTORIES

Table compares the thermal properties of typical high density and low density refractory materials.

Property	High Thermal Mass (High density refractories)	Low Thermal Mass (Ceramic fiber)
Thermal conductivity (W/m K)	1.2	0.3
Specific heat (J/kg K)	1000	1000
Density (kg/m3)	2300	130

Depending on the area of application such as boilers, furnaces, kilns, ovens etc, temperatures and atmospheres encountered different types of refractories are used. Typical installations of refractories are shown in Figure

Refractory lining of a furnace arch

Refractory walls of a furnace interior with burner blocks

REFRACTORIES

Some of the important properties of refractories are:

Melting point: Pure substances melt instantly at a specific temperature. Most refractory materials consist of particles bonded together that have high melting temperatures. At high temperatures, these particles melt and form slag. The melting point of the refractory is the temperature at which a test pyramid (cone) fails to support its own weight

Size: The size and shape of the refractories is a part of the design of the furnace, since it affects the stability of the furnace structure. Accurate size is extremely important to properly fit the refractory shape inside the furnace and to minimize space between construction joints

REFRACTORIES

Bulk density: The bulk density is useful property of refractories, which is the amount of refractory material within a volume (kg/m^3). An increase in bulk density of a given refractory increases its volume stability, heat capacity and resistance to slag penetration

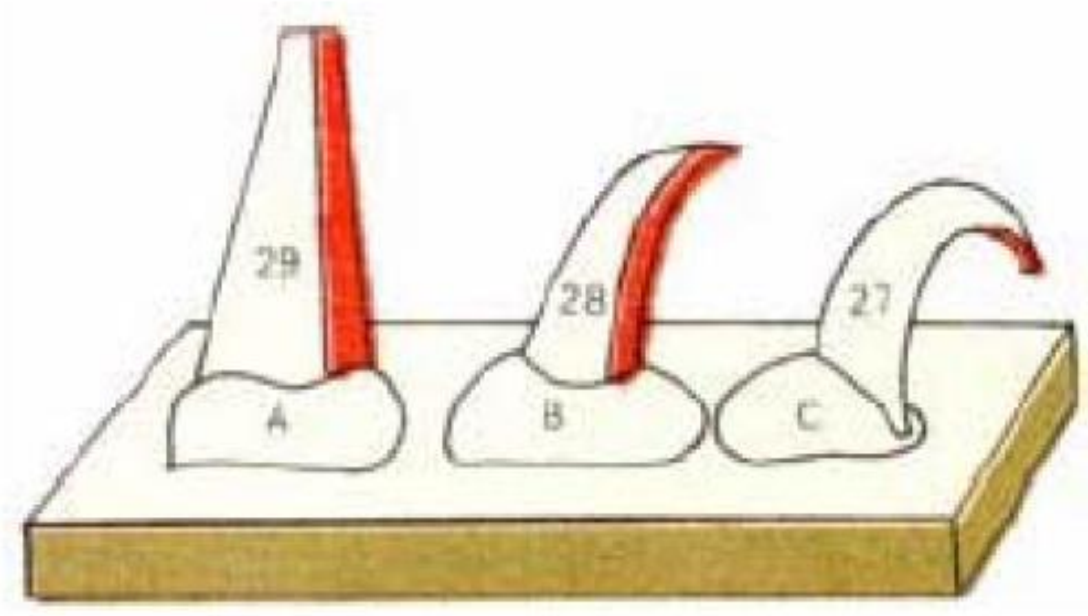
Porosity: The apparent porosity is the volume of the open pores, into which a liquid can penetrate, as a percentage of the total volume of the refractory. This property is important when the refractory is in contact with molten charge and slag. A low apparent porosity prevents molten material from penetrating into the refractory. A large number of small pores is generally preferred to a small number of large pores.

Cold crushing strength: The cold crushing strength is the resistance of the refractory to crushing, which mostly happens during transport. It only has an indirect relevance to refractory performance, and is used as one of the indicators of abrasion resistance. Other indicators used are bulk density and porosity.

REFRACTORIES

Pyrometric cones and Pyrometric cones equivalent (PCE)**:** The ‘refractoriness’ of (refractory) bricks is the temperature at which the refractory bends because it can no longer support its own weight. Pyrometric cones are used in ceramic industries to test the refractoriness of the (refractory) bricks. They consist of a mixture of oxides that are known to melt at a specific narrow temperature range. Cones with different oxide composition are placed in sequence of their melting temperature alongside a row of refractory bricks in a furnace. The furnace is fired and the temperature rises. One cone will bends together with the refractory brick. This is the temperature range in ^{o}C above which the refractory cannot be used. This is known as Pyrometric Cone Equivalent temperatures.

REFRACTORIES



Pyrometric Cones

Reversible thermal expansion: Any material expands when heated, and contracts when cooled. The reversible thermal expansion is a reflection on the phase transformations that occur during heating and cooling.

REFRACTORIES

Creep at high temperature: Creep is a time dependent property, which determines the deformation in a given time and at a given temperature by a refractory material under stress.

Volume stability, expansion, and shrinkage at high temperatures: The contraction or expansion of the refractories can take place during service life. Such permanent changes in dimensions may be due to:

- The changes in the allotropic forms
- A chemical reaction, which produces a new material of altered specific gravity
- The formation of liquid phase
- Sintering reactions
- Fusion dust and slag or by the action of alkalies on fireclay refractories, to form alkali-alumina silicates. This is generally observed in blast furnaces.

REFRACTORIES

Thermal conductivity: Thermal conductivity depends on the chemical composition and silica content of the refractory. The conductivity usually changes with rising temperature. Low thermal conductivity is desirable for conservation of heat, as the refractory acts as an insulator. Additional insulation conserves heat but at the same time increases the hot face temperature and hence a better quality refractory is required. Because of this, the outside roofs of open-hearth furnaces are normally not insulated, as this could cause the roof to collapse. Lightweight refractories of low thermal conductivity find wider applications in low temperature heat treatment furnaces. Insulating refractories have very low thermal conductivity. This is usually achieved by trapping a higher proportion of air into the structure. Some examples are:

- Naturally occurring materials like asbestos are good insulators but are not particularly good refractories
- Mineral wools are available which combine good insulating properties with good resistance to heat but these are not rigid
- Porous bricks are rigid at high temperatures and have a reasonably low thermal conductivity