



University of
South Australia

ENR116 Engineering Materials

Module 2 Material Properties

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Welcome to ENR116 Engineering Materials



University of
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ENR116 – Mod. 2- Slide No. 2

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Diffusion

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Diffusion (Chapter 5 in Callister)



Intended Learning Outcomes

At the end of this section, students will be able to:-

- Describe how **diffusion** occurs.
- Understand **how** diffusion is used in **materials processing**.
- Use expressions of **diffusion rate** to describe the influence of **structure** and **temperature**.

The intended learning outcomes from this presentation are:

Describe how diffusion occurs

Understand how diffusion is used in materials processing

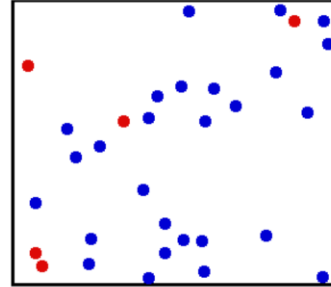
Use expressions of diffusion rate to describe the influence of structure and temperature



Diffusion

Diffusion: Mass transport by atomic motion

- Gases & Liquids – random (Brownian) motion



www.Wikipedia.com/Brownian_motion

- Solids – **Two mechanisms:**
Vacancy diffusion or Interstitial diffusion

Diffusion = mass transport by atomic motion

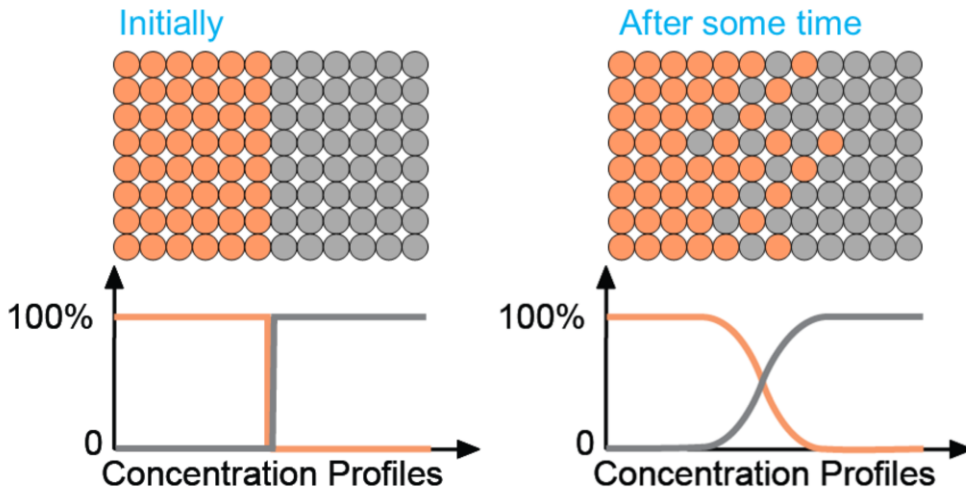
Diffusion mechanism depends on material type

Diffusion in solids is via vacancy or interstitial mechanisms



Diffusion

Interdiffusion: In an alloy, atoms tend to migrate from regions of high concentration to regions of low concentration



Adapted from Figs. 5.01 and 5.02, Callister & Rethwisch 8e.

Two metal bars placed in intimate contact

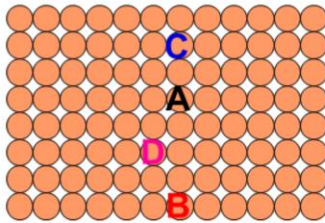
Metals diffuse across the interface into each other over time



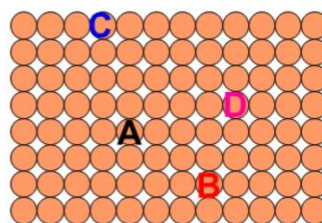
Diffusion

Self-diffusion: In an elemental solid, atoms also migrate.

Labelled atoms



After some time

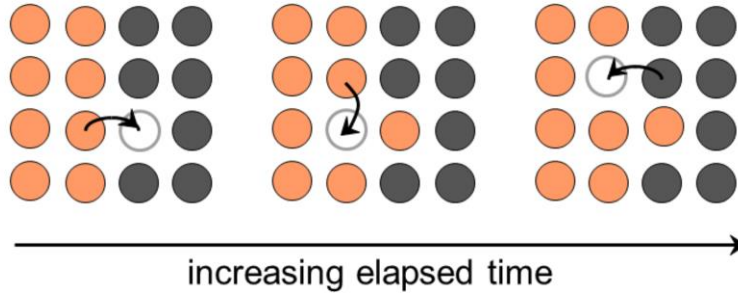


Atoms also migrate within pure metals



Diffusion mechanisms 1

Vacancy Diffusion: atoms exchange with vacancies



Applies to **substitution (impurity) atoms**

Rate of vacancy diffusion depends on:

- number of vacancies
- activation energy to exchange

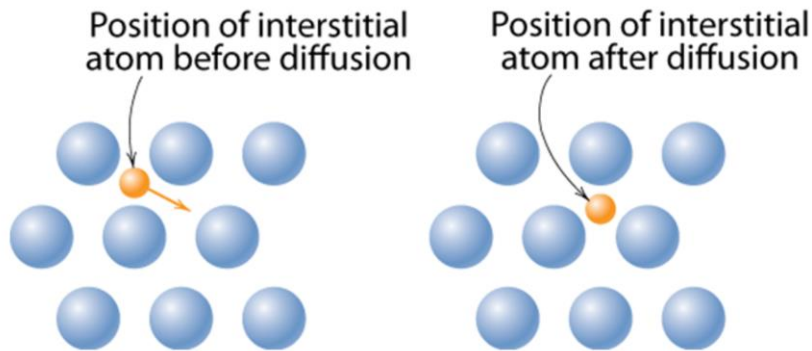
Vacancy diffusion = atoms exchange with vacancies

Rate depends on no. of vacancies, and activation energy



Diffusion mechanisms 2

Interstitial diffusion: smaller atoms can diffuse between atoms.



More rapid than vacancy diffusion

Adapted from Fig. 5.03,
Callister & Rethwisch 8e.

Interstitial diffusion = smaller atoms diffusing between atoms

For example Carbon into Iron

More rapid than vacancy diffusion due to the size of the diffusing atoms



Processing using diffusion

Case Hardening:

An example of interstitial diffusion is a **case hardened gear**.

Carbon atoms diffuse into the host iron atoms at the surface.

Result: The presence of C atoms makes iron (steel) harder



Fig. 05, pg 122a, Callister & Rethwisch 8e.
(Courtesy of
Surface Division, Midland-Ross.)

Carbon atoms in the surface of an iron gear can be used to make the surface harder and more resistant to wear.



Quantifying Diffusion

How do we quantify the amount or rate of diffusion?

Diffusion Flux, J

$$J \equiv \text{Flux} \equiv \frac{\text{moles (or mass) diffusing}}{(\text{surface area})(\text{time})} = \frac{\text{mol}}{\text{cm}^2\text{s}} \text{ or } \frac{\text{kg}}{\text{m}^2\text{s}}$$

Units of Diffusion:

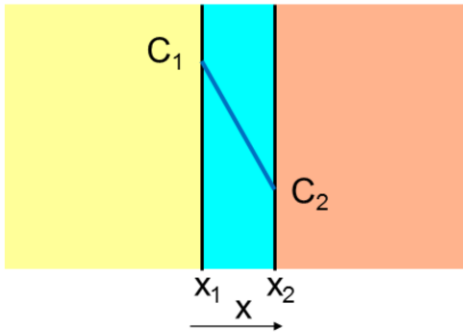
Diffusion Flux, J , is given in $\text{mol}/\text{cm}^2 \text{ s}$, or $\text{kg}/\text{m}^2 \text{ s}$.



Steady-state diffusion

Rate of diffusion **independent** of time

Flux proportional to concentration gradient = $\frac{dC}{dx}$



Fick's first law of diffusion:

$$J = -D \frac{dC}{dx}$$

if linear $\frac{dC}{dx} \cong \frac{\Delta C}{\Delta x} = \frac{C_2 - C_1}{x_2 - x_1}$ $D \equiv$ diffusion coefficient

Steady state diffusion described by Fick's First Law of Diffusion

$$J = -D (dC/dx)$$



Example: Chemical protective clothing (CPC)

Methylene chloride is a common ingredient of paint removers. Besides being an irritant, it also may be absorbed through skin. When using this paint remover, protective gloves should be worn.

If butyl rubber gloves (0.04 cm thick) are used, what **is the diffusive flux of methylene chloride** through the glove?

Data:

Diffusion coefficient in butyl rubber: $D = 110 \times 10^{-8} \text{ cm}^2/\text{s}$

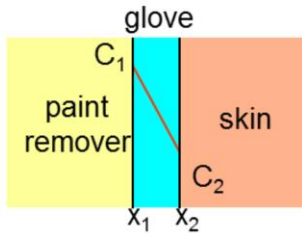
surface concentrations: $C_1 = 0.44 \text{ g/cm}^3$
 $C_2 = 0.02 \text{ g/cm}^3$

Common example of steady state diffusion



Example: Chemical protective clothing (CPC)

Solution: – assuming linear conc. gradient



$$J = -D \frac{dC}{dx} \cong -D \frac{C_2 - C_1}{x_2 - x_1}$$

Data:

$$D = 110 \times 10^{-8} \text{ cm}^2/\text{s}$$

$$C_1 = 0.44 \text{ g/cm}^3$$

$$C_2 = 0.02 \text{ g/cm}^3$$

$$x_2 - x_1 = 0.04 \text{ cm}$$

$$J = -(110 \times 10^{-8} \text{ cm}^2/\text{s}) \frac{(0.02 \text{ g/cm}^3 - 0.44 \text{ g/cm}^3)}{(0.04 \text{ cm})} = 1.16 \times 10^{-5} \frac{\text{g}}{\text{cm}^2\text{s}}$$

Assume steady state diffusion
Concentration gradient is linear
Fick's First Law can be applied

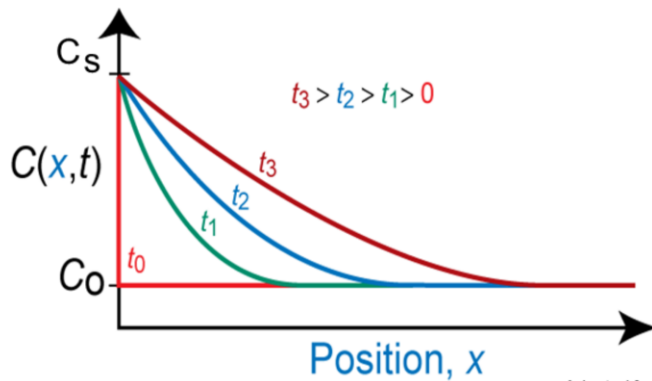


Non-steady state diffusion

The concentration of diffusing species is a function of both time and position $C = C(x, t)$

In this case Fick's Second Law is used

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2}$$



Adapted from Fig. 5.05, Callister & Rethwisch 8e.

In the non-steady state the concentration profile develops with time.

Fick's Second Law of Diffusion is used

Non-steady state diffusion must be understood to optimise the properties of materials



Diffusion and temperature

Diffusion coefficient **increases** with **increasing temperature**

$$D = D_0 \exp\left(-\frac{Q_d}{RT}\right)$$

- D = diffusion coefficient (m²/s)
- D₀ = a temperature-independent pre-exponential (m²/s)
- Q_d = activation energy (J/mol or eV/atom)
- R = gas constant (8.314 J/mol·K)
- T = temperature (K)

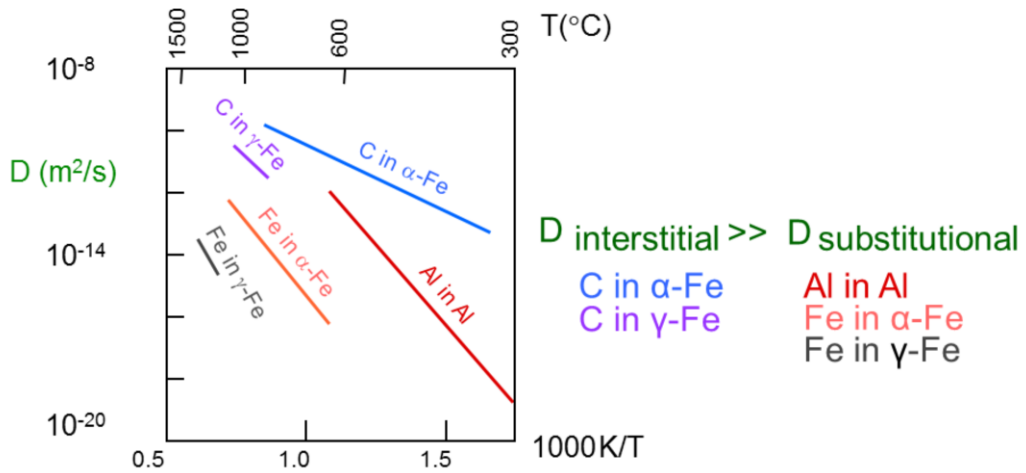
Diffusion coefficient depends on D₀, Q_d and T

D₀ and Q_d are fixed for a given system

T has a major effect on D



Diffusion in different systems



Adapted from Fig. 5.07, Callister & Rethwisch 8e.

D increases with T

D is also affected by crystal structure, and diffusion mechanism



Summary

- Solid-state diffusion is **mass transport** at the **atomic level**.
- Diffusion occurs using **imperfections** in solids i.e. **Vacancies** and **interstitials**.
- The **coefficient** of diffusion is a function of **temperature**.

Solid-state diffusion is mass transport at the atomic level.

Diffusion occurs in solids due to imperfections

Diffusion coefficient is a function of T



Thank you