Subjects of interest

- Introduction/Objectives
- Grain boundary strengthening
- Yield-point phenomenon
- Strain ageing
- Solid-solution strengthening
- Strengthening from second phase particles
- Martensitic strengthening
- Strain hardening or cold working
- Bauschinger effect
- Preferred orientation (texture)
Objectives

• Different types of strengthening mechanisms in metals which improve mechanical properties will be highlighted in this chapter.

• This also includes the nature of grain boundaries and their effects on the strengthening mechanisms, the influences of solute atoms, second phase particles, and fibre on the strengthening mechanisms.

• Other strengthening mechanisms such as strain hardening, martensitic hardening and cold working on the mechanical properties of the materials will also be discussed.
Introduction

The ability of a metal to plastically deform depends on the ability of dislocations to move.

Strengthening techniques rely on restricting dislocation motion to render a material harder and stronger.

To obtain material strength

Sometimes ductility or toughness are sacrificed.

Strengthening mechanisms

- Cold working
- Martensitic strengthening
- Grain boundary strengthening
- Strain hardening
- Fibre strengthening
- Fine-particle strengthening
- Solid-solution strengthening
- Strain ageing
Grain boundary strengthening

Grain boundaries

Grain boundary separates two grains having **different** **crystallographic orientations**.

Grain boundary structure contains **grain boundary dislocations**, which are not mobile and produce extensive slip.

Schematic atomic model of a grain boundary

Dislocation model of grain boundary
High and low angle grain boundaries

**High - angle grain boundary** ➔ high surface energy

**Low - angle grain boundary** ➔ low surface energy

High energy grain boundary serves as *preferential sites* for solid state reactions:
1) Diffusion
2) Phase transformation
3) Precipitation

Schematic diagram showing low- and high-angle grain boundaries.

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Low angle grain boundaries

- Along the boundary the *atoms adjust their position* by localised deformation to produce a smooth transition from one grain to the other.
- Where the atom planes end on the grain boundaries, it is therefore considered to have *an array of dislocations*.
- The *angular difference* in orientation between the grain is \( \theta \).

Diagram of low-angle grain boundary
Subgrain boundaries

Subgrain boundaries are low-angle boundaries, with lower-energy boundaries than the grain boundaries. Therefore etch less readily than grain boundaries.

If the angle $\theta$ is small the distance between dislocation is large. It is often possible to observe pits (corresponding to sites for edge dislocations) along the boundaries, see fig.

Subgrain boundary network in Fe-3% alloy.

Etch-pit structures along low-angle grain boundaries in Fe-Si alloy.
Polygonization

- **Polygonization** occurs when a single crystal is bent to a relatively small curvature and then annealed.

- Bending results in an excess number of dislocations of similar sign distributing along the bend-glide plane.

- After heating, dislocations group themselves into the lower-energy configuration of a low-angle boundary, forming a *polygonlike network*.

*Movement of dislocations to produce polygonization.*
Deformation of grain boundaries.

- Discontinuity due to grain boundaries leads to *more complex deformation mode* in polycrystals than in single crystals.
- Individual grain is constrained since mechanical integrity and coherency are maintained along the grain boundaries, causing different deformation between neighbouring grains.
- A polycrystal macroscopically deforms as the stress is applied. Slips operate in each grains which produces *overlaps* and *voids* at boundaries, *fig (a),(b)*.
- These overlaps and voids can be corrected by introducing *geometrically necessary dislocations* at (c),(d).

*Ashby’s model of deformation of a polycrystal.*
Plastic deformation of polycrystalline metals

• Due to random crystallographic orientations of the numerous grains, the direction of slip varies from one gain to another.

• Fig. shows two slip systems operate in each grain and variation in grain orientation is indicated by the different alignment of slip lines.

Note: More slip systems are usually operate near the grain boundary, the material is usually harder near the boundary than the grain interior.
**Grain boundary sliding**

At $T > 0.5T_m$, deformation can occur by sliding along the grain boundaries.

**Equicohesive temperature**

Above the *equicohesive temperature*, the grain boundary region is weaker than the grain interior. Strength increases with increasing grain size.
There are two important roles of the grain boundary which acts as a barrier to dislocation motion:

1) Difficulty for a dislocation to pass through two different grain orientations (need to change direction).

2) The atomic disorder within a grain boundary region contributes to a discontinuity of slip planes from one grain to another.

The motion of a dislocation as it encounters a grain boundary.
Hall-Petch relation

A fine-grained material is harder and stronger than one that is coarse grained since greater amounts of grain boundaries in the fine-grained material impede dislocation motion.

The general relationship between the yield stress (tensile strength) and grain size was proposed by Hall and Petch.

\[ \sigma_o = \sigma_i + kD^{-1/2} \]  

...Eq. 1

Where \( \sigma_o \) = the yield stress  
\( \sigma_i \) = the ‘friction stress’ or resistance to dislocation movement  
\( k \) = the ‘locking parameter’ or hardening contribution from grain boundary.  
\( D \) = grain diameter
**Hall - Petch relation and dislocation pile-up model**

- The *dislocation model* for the *Hall-Petch equation* was originally based on the idea that grain boundaries act as *barriers* to dislocation motion.

- Dislocations will be sent out from the source at the centre of a grain of \( D \) diameter to *pile up* at grain boundary.

- The number of dislocations at the pile-up is

\[
  n = \frac{k \pi \tau_s D}{4 G b}
\]

...Eq. 2

Where

- \( \tau_s \) is the average resolved shear stress
- \( k \) is a factor close to unity

The *stress at the tip of the pile-up* must exceed some critical shear stress \( \tau_c \) to continue slip past the grain-boundary barrier.

\[
  \tau_c = n \tau_s = \frac{\pi \tau_s^2 D}{4 G b}, \quad \tau_s = \tau - \tau_i
\]

Then

\[
  \tau = \tau_i + \left( \frac{\tau_c 4 G b}{\pi D} \right)^{1/2}
\]

...Eq. 3

Note: for large pile-ups
Grain size determination

Since the size of the grain is usually associated with mechanical properties of the materials, determination of the grain size is therefore of importance.

- There are a number of techniques utilised for grain size measurement:
  1) Intercept method
  2) ASTM standard comparison charts (grain number)
  3) Image analyser

- The obtained parameters can be specified in terms of:
  1) Average grain volume
  2) Average grain diameter
  3) Average area
  4) Maximum diameter
  5) Minimum diameter
  6) Aspect ratio
**Intercept method**

*Intercept method* is carried out by measuring the mean number of intercepts of random test lines with grain boundaries per unit length of test line $N_L$.

- Strength lines of the same length $L$ are drawn through several photomicrographs with a known scale.
- The grain intersected $N_L$ by each line segment are counted.
- The *average grain diameter* is obtained by

$$D = \frac{L}{N_L M}$$

Where $M$ is a linear magnification of the photomicrograph.

Note: The grain size obtained by this method will be somewhat **smaller** than the actual grain size. In some case, a factor $2/3$ is used.

...Eq. 4
The ASTM grain-size number $G$ is related to $n_a$, the number of grains per mm$^2$ at a magnification of 1 x by the relationship

$$G = -2.9542 + 1.4427 \ln n_a$$

...Eq. 5
Example: If a steel has a value of $\sigma_i = 150 \text{ MPa}$ and $k = 0.70 \text{ MPa.m}^{1/2}$, what is the value of the yield stress if the grain size is ASTM no.6.

From Eq. 6

\[
\ln n_a = \frac{(G + 2.9542)}{1.4427}
\]

\[
n_a = \exp\left(\frac{6 + 2.9524}{1.4427}\right) = 496 \text{ mm}^{-2} = 496 \times 10^6 \text{ m}^{-2}
\]

Grain diameter

\[
D \approx \sqrt{\frac{1}{n_a}} \quad \text{or} \quad D^2 \approx \frac{1}{n_a}
\]

\[
D^2 \approx 20 \times 10^{-10} \text{ m}^2, \quad D \approx 44.7 \times 10^{-6} \text{ m}
\]

\[
\frac{1}{\sqrt{D}} = 149 \text{ m}^{-1/2}
\]

\[
\sigma_o = \sigma_i + kD^{-1/2} = 150 + (0.70)(149) = 254.3 \text{ MPa}
\]
Yield point phenomenon

Metals, particularly low-carbon steel, show a localised heterogeneous transition from elastic to plastic deformation. → Yield point elongation.

- The load after the upper yield point suddenly drop to approximately constant value (lower yield point) and then rises with further strain.
- The elongation which occurs at constant load is called the yield-point elongation, which are heterogeneous deformation.
- Lüder bands or stretcher strains are formed at approximately 45° to the tensile axis during yield point elongation and propagate over the specimen.

Note: The yield point phenomenon has also been observed in other metals such as Fe, Ti, Mo, Cd, Zn, Al alloys.
The upper yield point

The upper yield point is associated with small amounts of interstitial or substitutional impurities.

- The solute atoms (C or N) in low carbon steel, lock the dislocations, raise the initial yield stress.
- The breakaway stress required to pull a dislocation line away from a line of solute atoms is

\[
\sigma \approx \frac{A}{b^2 r_0^2} \quad \text{...Eq. 6}
\]

Where \( A = 4Gba^2, \) \( a \) is atomic radius, \( r_0 \) is the distance from the dislocation core to the line of solute atoms \( \sim 0.2 \) nm.

- When the dislocation is pulled free from the solute atoms, slip can occur at lower stress. \( \rightarrow \) the lower yield point.
- The magnitude of the yield-point effect depends on interaction energy, concentration of solute atoms.

Note: Upper yield point is promoted by using elastically rigid machine, careful axial alignment of specimen (free from stress concentrations, high strain rate, low temperature.)

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Strain ageing is a phenomenon in which the metal increase in strength while losing ductility after being heated at relatively low temperature or cold-working.

The reappearing of the (higher) yield point after ageing is obtained, see fig.

- Reloading at X and straining to Y does not produce yield point.
- After this point if the specimen is reloading after ageing (RT or ageing temp) the yield point will reappear at a higher value.
- This reappearance of the yield point is due to the diffusion of C and N atoms to anchor the dislocations.
- N has more strain ageing effect in iron than C due to a higher solubility and diffusion coefficient.
Stretcher strains

- Strain ageing should be eliminated in deep drawing steel since it leads to surface marking or stretcher strains.
- To solve the problem, the amount of C and N should be lowered by adding elements such as Al, V, Ti, B to form carbides or nitrides.

Relation of stretcher strain in stress-strain curve

Stretcher strain in low-carbon steel
Serrata stress strain curves

- Strain ageing increases yield point but lower ductility.
- Strain ageing is also associated with serrated stress-strain curves or repeated yielding, due to high speed of diffusion of solute atoms to catch and lock dislocations.
- This dynamic strain ageing is also called Portevin-LeChatelier effect.
**Blue brittleness**

Blue brittleness occurs in plain carbon steel in which discontinuous yielding appears in the temperature range 500 to 650 K.

During this blue brittleness region, steels show

- Decreased tensile ductility.
- Decreased notched-impact resistance.
- Minimum strain rate sensitivity.

**Note:** This is just an accelerated strain aging by temperature.
Solid-solution strengthening

Solute atoms are introduced into the matrix (solvent atoms).

There are two types of solid solutions:

1) **Substitutional solid solution**: The solute and solvent atoms are similar in size, rendering the solute atoms to occupy lattice point of the solvent atoms.

2) **Interstitial solid solution**: The solute atoms are of smaller size than the solvent atom, rendering the solute atoms to occupy the interstitial sites in the solvent lattice.

*Note:* solid solution is compositionally homogeneous, the solute (impurity) atoms are randomly distributed throughout the matrix.
Factors affecting solubility of solute atoms

The **solubility of the solute atoms** in the host matrix (solvent) can be determined by several factors;

1) **Atomic size factors**: Solid solution is appreciable when the difference in atomic radii between the two atoms is < \( \sim 15\% \), otherwise creating substantial lattice distortion.

2) **Crystal structure**: Similar crystal structure of metals of both atom types are preferred.

3) **Electronegativity**: The more electropositive one element and the more electronegative the other, the more tendency to form an intermetallic compound than solid solution.

4) **Valences**: A metal will have more of a tendency to dissolve another metal of higher valency than one of a lower valency.
Effects of solute alloy additions on stress-stain curve

- The addition of solute atoms raises the yield stress and the stress-stain curve as a whole.
- Therefore from Eq. 1
  \[ \sigma_0 = \sigma_i + kD^{-1/2} \]
- The solute atoms should have more influence on the frictional resistance to dislocation motion \( \sigma_i \) than the locking of dislocation \( k \).

Alloys
- \( C_2 > C_1 \%, \text{solute} \)

Effects of solute atoms on stress-strain curves.
Effects of solute alloy additions on tensile properties

- Impurity atoms
- Tensile strength
- Yield stress
- Ductility

Variation with nickel content of (a) tensile strength, (b) yield strength, and (c) ductility (\% EL) for copper-nickel alloys, showing strengthening.
Lattice strain due to solute atoms

Lattice strains produced by the introduction of solute atoms can be divided into:

1) Tensile lattice strain

Smaller solute atoms are introduced, imposing tensile lattice strain to the host atoms.

2) Compressive lattice strain

Larger solute atoms are introduced, imposing compressive lattice strain to the host atoms.
Interactions between solute atoms and dislocations

Solute atoms can interact with dislocations by the following mechanisms:

1) Elastic interaction
2) Modulus interaction
3) Stacking-fault interaction
4) Electrical interaction
5) Short-range order interaction
6) Long-range order interaction

Note: 1, 2, 6 are insensitive to temperature and influence at about 0.6T_m.
**Elastic interaction**
- Strengthening due to elastic interaction is proportional to the *misfit between solute atoms and dislocations* giving elastic field around surrounding them.

**Modulus interaction**
- The presence of the solute atom locally alter the modulus of the crystal. Solute atom with *small shear modulus* will reduce the energy of the strain field.

**Stacking-fault interaction**
- Solute atoms within the stacking fault
- Stacking fault energy
- Separation between partial dislocations
**Electrical interaction**

- The solute atoms having charge can interact with dislocation which have electrical dipoles. → *weak.*

**Short-range order interaction**

- Strengthening by short-range order interaction is due to more work which has to put in when dislocations try to move pass through the short range ordered atoms.

**Long-range order interaction**

- Alloys having a long-range periodic arrangement of dissimilar atoms develop *superlattice.* The stress required to move a dislocation through a long-range region is high and the rate of *strain hardening* is higher in the ordered condition than the disordered state.
Many commercial alloys are composed of two or more metallurgical phases which provide strengthening effects:

- Two phase aggregates
- Second phase/intermetallic particles
- Precipitation hardening
- Fibering structure

Note:  
1) These are heterogeneous on a microscopic scale or maybe homogeneous on a macroscopic scale.
2) Strengthening from second phases is normally additive to the solid solution strengthening produced in the matrix.
Strengthening by two-phase aggregates

The size of the second phase particles are of similar size to that of the matrix.

**Examples:**

- Beta brass particles in an alpha brass matrix
- Pearlite colonies in the ferrite matrix in annealed steels
Strengthening by second phase particles

- The **second phase or intermetallic particles** are much finer (down to submicroscopic dimensions) than the grain size of the matrix.
- The second phase particles produce **localised internal stresses** which alter the **plastic properties** of the matrix.

**Examples:**

- Second phase particles in matrix.
Factors influencing second-phase particle strengthening

- Particle size
- Particle shape
- Number \((V_f)\)
- Distribution (interparticle spacing)

Strength
Ductility
Strain hardening

If the contributions of each phase are independent, the properties of the multiple phase alloy is the summation of a weighted average of individual phases.

For example:

\[
\sigma_{avg} = V_1 \sigma_1 + V_2 \sigma_2 + \ldots + V_n \sigma_n \quad \ldots \text{Eq. 7}
\]

\[
\varepsilon_{avg} = V_1 \varepsilon_1 + V_2 \varepsilon_2 + \ldots + V_n \varepsilon_n \quad \ldots \text{Eq. 8}
\]

Where the volume fraction \(V\)

\[
V_1 + V_2 + \ldots + V_n = 1
\]

Note: Its almost impossible to vary these factors independently in experiments.
Estimate flow stress of two-phase alloy

- The average property in the **two-phase alloy** will increase with the volume fraction $V_f$ of the strong phase.

- It is more often that the **second phase is stronger than the matrix** but not all second-phase particles produce strengthening effects.

- The **strong bonding between particles** and matrix is required to be able to produce strengthening effects.
Deformation in two ductile phase alloys

- Depending on the $V_f$ of the two phases and the total deformation.
- Slip will occur first in the weaker phase.
- Not all second phase particles produce strengthening effects.

Deformation in alloy of a ductile and brittle phase

- Mechanical properties depend on how the hard brittle phase distribute throughout the softer matrix.
- Homogeneously distributed hard particles promote strength.
- Continuously distributed along the grain boundaries leads to brittle fracture. → reduce strength.
Microstructure dependence of yield stress in steels

• Gensamer et al studied the influence of different microstructures obtained from annealed, normalised and spheroidized steels (aggregates of cementites and ferrite).

• The $\sigma_{0.2\%}$ was inversely proportional to the logarithm of mean free ferrite path (interparticle spacing).

Flow stress vs. log of mean free ferrite path in steels.
Precipitation hardening or age hardening requires the second phase which is soluble at high temperature but has a limited solubility at lower temperatures.

Solution treating at high temperature, then quenching

Second phase is in solid solution.

Ageing at low temperature

Precipitation of the second phase, giving strengthening effect.

Example: Age hardening aluminium alloys
Copper-beryllium alloys

Note: In precipitate-hardened system, there is coherency between the second-phase particle and the matrix.
But in dispersion-hardened system, there is no coherency.
The formation of coherency precipitate

A number of steps occurs during precipitation hardening.

• After quenching from solid solution the alloy contains areas of solute segregation or clustering. → GP zone. This clustering is GP[1] produces local strain giving higher hardness than the matrix.

• The hardness of the GP zone increases with ageing time, developing GP[2] or θ”.

• Precipitate θ’ is coherent with the matrix. → further increase in hardness.

• Further ageing produces θ, (not coherent with the matrix). → lowering the hardness.
Deformation of alloys with fine particle strengthening

Case study in deformation of Al-4.5%Cu single crystal

- After solution treated and quenched, copper is in supersaturated solid solution, giving higher yield stress than pure aluminium.

- The yield stress increases when the crystal is aged to form coherent GP zone. Yield drop and low strain hardening suggest that dislocations cut through the zone once the stress reaches a high enough value.

- Strain hardening significantly increase when the crystal is aged to peak hardness. Dislocations are short and move around particles.

- Over-aged condition produces coarse noncoherent particles, giving low yield stress, high strain hardening.
Factors affecting precipitation hardening

Particle size, shape, volume fraction and distribution are key factors in improving precipitation hardening (cannot vary independently).

- High strength alloys seem to consist of fine strong particles well distributed in deformed matrix.
- Fine hard particles increase strength by cutting dislocations → dislocation tangles → increasing strain hardening.
- Deformed matrix bares the load which makes fracture more difficult.

Example: For a given \( V_f \)

Particle size \( \uparrow \) Interparticle spacing

\[ \lambda = \frac{4(1-V_f)r}{3V_f} \] ...

Where \( V_f \) is the volume fraction of spherical particles of radius \( r \).
Properties affecting strengthening mechanisms by particles

- **Coherency strain**
  - Misfit between particles and matrix produces strain field → improving strength.

- **Stacking-fault energy**
  - Yield stress increases with the difference in stacking fault energy between the particle and the matrix.

- **Ordered structure**
  - Introduce anti-phase boundaries.
  - Good high temperature strength.

- **Modulus effect**
  - Modulus difference between the matrix and the particles produces strength but it is not the case in most alloys.

- **Interfacial energy and morphology**
  - High particle-matrix surface energy leads to higher strength. (rely on surface-to-volume ratio or morphology)

- **Lattice friction stress**
  - Peierls stress in particle and matrix produce strengthening effect.
Interaction between fine particles and dislocations

**Second phase particles** act in two distinct ways to retard the motion of dislocations.

1) Particles maybe cut by dislocation

- When the particles are small / soft.

2) Particles allow dislocation to bypass/bow around them.

- In over aged noncoherent precipitates. Bowing of dislocations around particles leaving dislocation loops behind.

- Stress required to force dislocation between particles;

\[ \tau_o = \frac{Gb}{\lambda} \]  

...Eq. 10
The slip character can be characterised into:

- **Planar or wavy**
- **Coarse or fine**

**Coarse planar slip** → promotes brittle failure. Particles which are easily sheared by dislocations tend to produce coarse planar slips.

**Fine wavy slip** → homogeneous deformation, giving best ductility at a given strength level. Particles which are by passed by dislocations lead to fine wavy slip.
Fibre strengthening

- **Ductile metals** can be reinforced using relatively **stronger fibres**.
- Very high strength whiskers of $\text{Al}_2\text{O}_3$, or **SiC** fibres have been used for this purpose.
- **Fibre-reinforced materials** (metal or polymer as matrix) are also known as composite materials.

- The matrix transmits the load to the fibres.
- protect fibres from surface damage.
- separate individual fibres and blunt crack from fibre breakage.

- High modulus fibres in Fibre-reinforced metals carry more load than dispersion-reinforced metals.
- Fibre-reinforced materials are highly anisotropic.

*Note: Variation of stress between fibres and matrix is complex.*
Strength and moduli of composites

The rule of mixtures is used to approximate the modulus and strength of a fibre-reinforced composite.

If a tensile force $P$ is applied in the direction of the fibre, and assuming that the strain of fibre and matrix are similar, $e_f = e_m = e_c$.

$$P = \sigma_f A_f + \sigma_m A_m \quad \text{...Eq. 11}$$

Where $A_f$ and $A_m$ are the cross-sectional areas of fibre and matrix.

The average composite strength $\sigma_c$ is

$$\sigma_c = \frac{P}{A_c} = \frac{\sigma_f A_f}{A_c} + \frac{\sigma_m A_m}{A_c}$$

$$\sigma_c = \sigma_f V_f + \sigma_m V_m \quad \text{...Eq. 12}$$

where

$$A_c = A_f + A_m$$

$$V_f + V_m = 1$$

Likewise

$$E_c = E_f V_f + E_m V_m \quad \text{...Eq. 13}$$
**Example:** Boron fibre, $E_f = 380$ GPa, are made into a unidirectional composite with an aluminium matrix, $E_m = 60$ GPa. What is the modulus parallel to the fibres for 10 and 60 volume%.

\[
E_c = E_f V_f - (1 - V_f) E_m
\]

\[
V_f = 0.10 \ , \ E_c = 380(0.10) + 0.9(60) = 92 \ \text{GPa}
\]

\[
V_f = 0.60 \ , \ E_c = 380(0.60) + 0.4(60) = 252 \ \text{GPa}
\]
Stress-strain curves of the fibre, matrix and fibre-reinforced composite

- **Stage 1**: Both fibres and matrix undergo elastic deformation.
- **Stage 2**: Matrix deforms plastically but fibres deform elastically.
- **Stage 3**: Both matrix and fibres undergo plastic deformation.

- The load is transferred from ductile matrix to strong fibres.
- Breakage or pull-out of fibres increase the strength.
Theoretical variation of composite strength with volume fraction of fibres

• The critical fibre volume which must be exceeded for fibre strengthening to occur.

\[ V_{f\,\text{(crit)}} = \frac{\sigma_{mu} - \sigma'_m}{\sigma_{fu} - \sigma'_m} \]  \hspace{1cm} \ldots \text{Eq. 14}

• The minimum volume fraction of fibre which must be exceeded to have real reinforcement.

\[ V_{f\,\text{(min)}} = \frac{\sigma_{mu} - \sigma'_m}{\sigma_{fu} + \sigma_{mu} - \sigma'_m} \]  \hspace{1cm} \ldots \text{Eq. 15}

\( \sigma_u \) is the ultimate tensile strength of the composite
\( \sigma_f \) is the strength of the fibre
\( \sigma'_m \) is the flow stress in the matrix

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Martensite strengthening

- **Martensitic strengthening** is obtained when austenite is transformed into martensite by a *diffusionless shear-type process* in quenching.

- **Martensitic transformation** occurs in many alloy systems but steels has shown the most pronounced effect.

**High strength of martensite is due to two main contributions:**

- **Slip barriers** from (1) conventional plate martensite structure with a unique habit plane and an internal parallel twins of each 0.1 mm thick within the plate and (2) Block martensite structure containing a high dislocation density of $10^9$ to $10^{10}$ mm$^{-2}$.

- **Carbon contents** ($<0.4\%$) lead to carbon atom clustering and dislocation interaction $\rightarrow$ increased strength and hardness, see fig.
**Ausforming process**

Ausforming is a thermo-mechanical process where steel is plastically deformed (>50%) usually rolling and then quenched to below the $M_s$ to form martensite.

- Plastic deformation of austenite should be done *without transformation to pearlite or bainite*.
- **Highest strengths** are achieved by the greatest possible deformation at the lowest temperature at transformation does not occur.

- Uniformly distributed dislocations of high density ($10^{11}$ mm$^{-2}$) and precipitation provides sites for *dislocation multiplication* and *pinning*, contribute to very high strength (2-3 GPa) with 40-20% RA.
Strain hardening or cold working

**Cold-work structure** occurs when plastic deformation carried out at in a temperature region and over a time interval such that the strain hardening is not relieved.

- **Cold worked structure** contains dislocation $\sim 10^{11}$ mm$^{-2}$, while annealed structure possesses $\sim 10^4$ to $10^6$ mm$^{-2}$.
- As the deformation proceeds, the high density dislocations tangles form the **cell walls**.
- About 10% of energy input in cold work process is stored in the lattice.

**Dislocations in cell walls.**

<table>
<thead>
<tr>
<th>Temp</th>
<th>Strain rate</th>
<th>Stored energy</th>
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<tbody>
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<td>↓</td>
<td>↑</td>
<td>↑</td>
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Strain hardening

- Strain hardening or cold working is used to harden alloys that do not respond to heat treatment.

| Cold work | Strength | Ductility |

- The rate of strain hardening is lower in HCP than in cubic metals.
- The final strength of cold-worked solid solution alloy is almost always greater than that of the pure metal cold-worked to the same extent.

Variation of tensile properties with amount of cold-work.
Annealing of cold-worked metal

- **Annealing** of the cold worked structure at high temperature **softens the metal** and reverts to a strain-free condition.

- Annealing restores the ductility to a metal that has been severely strain hardened.

- Annealing can be divided into **three distinct processes**;
  1) Recovery
  2) Recrystallisation
  3) Grain growth
Recovery, recrystallisation, grain growth

• **Recovery**: the restoration of the physical properties of the cold-worked metal without any observable change in microstructure. *Strength is not affected.*

• **Recrystallisation**: the cold-worked structure is replaced by a new set of strain-free grains. *Hardness and strength decrease but ductility increases.*

• **Grain growth**: occurs at higher temperature where some of the recrystallised fine grains start to grow rapidly. *Grain growth is inhibited by second phase particles to pin the grain boundaries.*

Properties change during recovery, recrystallisation and grain growth
There are six variables affecting recrystallisation behaviour.

1) The amount of prior deformation
2) Temperature
3) Time
4) Initial grain size
5) Composition
6) Amount of recovery prior to start the recrystallisation.

- **Impurity** decrease recrystallisation temperature.
- **Solid solution alloying** additions raise the recrystallisation temperature.

**Degree of deformation**
- $T_{\text{recrys}}$ increase

**Degree of deformation**
- $T_{\text{anneal}}$ decrease, $G_{\text{recrys}}$ decrease

**$G_{\text{original}}$** increase
- Cold work increase
Preferred orientation (texture)

• Severe deformation produces a **reorientation of the grains** into a **preferred orientation**. Certain crystallographic planes tend to orient themselves in a preferred manner with respect to the maximum strain direction.

• The **preferred orientation** resulting from plastic deformation is **strongly dependent on the available slip and twining systems**, but not affected by processing variable such as die angle, roll diameter, roll speed, etc.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Wire (fibre texture)</th>
<th>Sheet (rolling texture)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bcc</td>
<td>[1 1 0]</td>
<td>{1 1 2} ({1 1 0}) to {1 0 0} (0 1 1)</td>
</tr>
<tr>
<td>fcc</td>
<td>[1 1 1], [1 0 0] double fibre</td>
<td>{1 1 0} (1 1 2) to {3 5 1} (1 1 2)</td>
</tr>
<tr>
<td>cph</td>
<td>[2 1 0]</td>
<td>{0 0 0 1} (1 0 0 0)</td>
</tr>
</tbody>
</table>

**Note:** the deformation texture cannot in general be eliminated by an annealing operations
Grain orientation by EBSD analysis

- EBSD analysis employs **back scattered electrons** to give grain orientation information.

**SEM micrograph** | **Orientation map** | **Pole figure** | **Inverse pole figure**
---|---|---|---
Normal to processing direction
Extruded bar | 50 µm
Rolled plate | 50 µm
Homogeneously distributed
Preferred orientation
Mechanical fibering (fibrous texture)

- **Fibrous texture** is produced along the maximum stress direction acting on the materials.

- Inclusions, cavities and second phase constituents are aligned in the main direction of mechanical working.

- The **geometry of the flow** and the **amount of the deformation** are the most important variables.

- Mechanical fibering increases mechanical properties along the working (fibre) direction, with the transverse direction having inferior properties. → **anisotropic properties.**
References


• www.composite-bydesign.com

• www mdi.espci.fr

• www.mtm.kuleuven.ac.be