Materials & Manufacturing Summary

1 Material Types and Properties

1.1 Material Types

There are many kinds of materials, but most of them can be divided into four groups:

- Metals - Metals are composed of one or more metallic elements and often also nonmetallic elements in relatively small amounts.
- Ceramics - Ceramics are compounds between metallic and nonmetallic elements.
- Polymers - Most polymers are made up of organic compounds. Polymers have a very large molecular structure.
- Composites - A combination of two or more of the above material types is called a composite material.

When designing anything in general, an engineer has to keep in mind the product triangle, containing the materials, designing and processing. Some materials aren't suitable for a certain design, whilst other materials may be too difficult to process to meat certain design requirements. When choosing the right materials for a design, an engineer has to keep in mind what properties the material has. Important material properties are: strength, stiffness, durability, manufacturability and, especially important in aerospace engineering, the strength/density ratio.

1.2 Testing Materials

There are many different ways to test the properties of a material. The most common way is a tensile test. Here, a certain force F is put on a specimen with cross-sectional area A and length l. Now the stress σ and the strain ε (sometimes also indicated as ϵ) can be calculated:

$$\sigma = \frac{F}{A_0} \qquad \varepsilon = \frac{\Delta l}{l_0} \tag{1.1}$$

Where A_0 and l_0 are the cross-sectional area and length, respectively, of the specimen at the start of the test. The relation between stress and strain is known as Hooke's law:

$$E = \frac{\sigma}{\varepsilon} \tag{1.2}$$

Where E is the E-modulus, (also called modulus of elasticity or Young's modulus).

Other tests are the compressive test (where σ and ε are negative), the shear test and the torsion test. The tensile test is for basic material applications by far the most often used test.

When performing a shear test or torsion test, the shear strain $\tau = \frac{F}{A_0}$ can be found. The relation between the shear stress and the shear strain γ is known as $G = \frac{\tau}{\gamma}$, where G is the shear modulus.

When a material is put under tension, it elongates in the direction of the force (ε_z is positive), but the specimen length decreases in the directions perpendicular to the force (ε_x and ε_y are negative). The amount in which this happens, is the Poisson's ratio ν, for isotropic materials (meaning the material properties are the same in every direction) defined as:

$$\nu = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z} \tag{1.3}$$

The negative sign is included so that ν will always be positive. ν should theoretically be 0.25 and can be 0.50 at maximum. ν also has a relation with the modulus of elasticity and the shear modulus. This relation, for isotropic materials, is:

$$\frac{E}{G} = 2(1+\nu) \tag{1.4}$$

1.3 Tensile Test

The tensile test is an example of a quasi-static load. The load is not constant, but gradually increases. When performing a tensile test, the strain can be displayed with respect to certain stresses. This gives a stress-strain diagram. From this diagram certain properties can be derived. These properties have been sorted in table 1.1 and visualized in figure 1.1. All these properties depend on the material type and a number of other variables, for example temperature.

Name	Sign	Property for high values	Property for low values
E-modulus	E	Stiff	Flexible
Yield stress	$\sigma_{0.2}$	Rigid	Soft
Ultimate stress	$\sigma_{ultimate}$	Strong	Weak
Plastic strain	$\varepsilon_{plastic}$	Ductile	Brittle
Strain hardening	$\sigma_{ultimate} - \sigma_{0.2}$	Large strain hardening	Small strain hardening

Table 1.1: Material properties and their corresponding names.

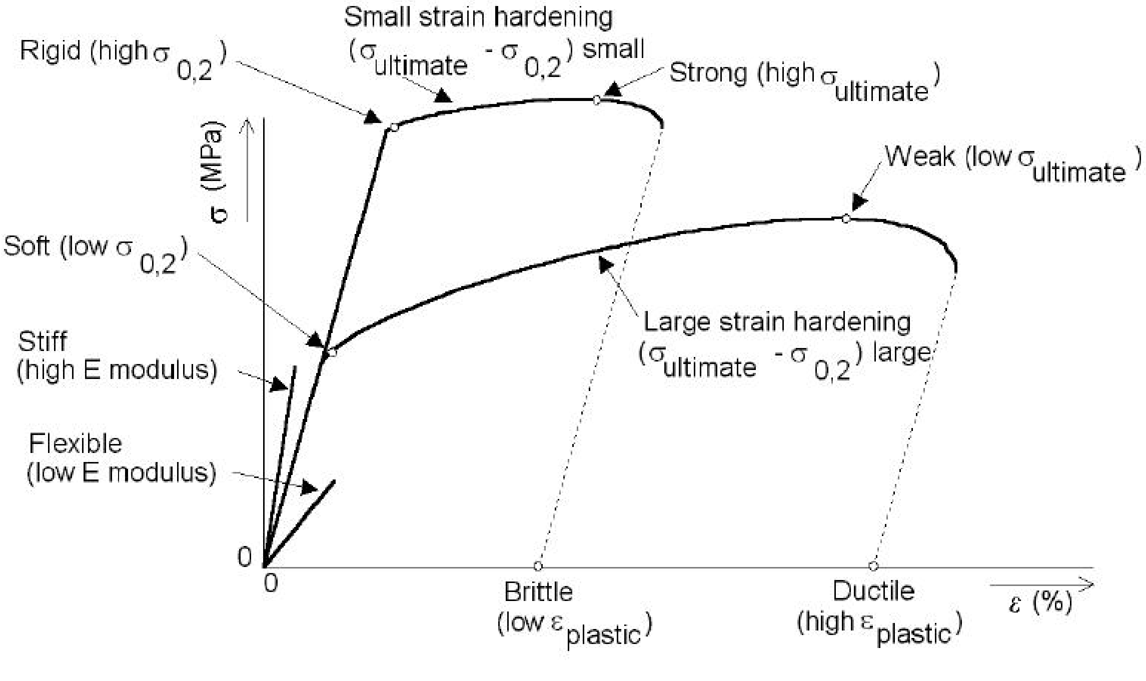

Figure 1.1: Important terms following from a stress-strain diagram.

The first part of the graph is elastic deformation. When the stresses are released, the structure returns to its former shape. The yield stress, also known as the yield strength, was originally the point at which the deformation switches from elastic to plastic deformation. However, for practical reasons, the yield point is defined as the point at which plastic deformation occurs causing a permanent strain of 0.002. Plastic deformation is permanent deformation. Next to elastic and plastic deformation, there is also anelastic deformation. When anelastic deformation occurs, the structure will return to its original shape over time.

The ultimate stress, also known as the tensile strength, occurs at the necking point. When this stress is reached, necking occurs. Necking is the local deformation of the specimen at the end of the tensile test. This means that at a certain position in the specimen, the cross-sectional area decreases rapidly. This is also the point at which fracture will occur.

It may look like the strength of the material after ultimate stress is decreasing. This is not true. The reason for the diagram to go downward, lies more in the fact that the cross-sectional area decreases because necking occurs. It is sometimes convenient to look at true stress σ_T, defined as $\sigma_T = \frac{F}{A_i}$ where A_i is the cross-sectional area over which deformation is occurring. The true strain is defined as $\varepsilon_T = \ln \frac{l_i}{l_0}$. After the yield point, the true stress and true strain for metals often have the relation $\sigma_T = K\varepsilon_T^n$ where K and n are constants. n is called the strain-hardening exponent.

1.4 Material Properties

There are many kinds of material properties that influence decisions made by designers. Some of them, the yield strength and the tensile strength, have already been discussed in the previous chapter.

Ductility is the degree of plastic deformation that has been sustained at fracture. It can be expressed as either percent elongation $\%EL$ or percent reduction in area $\%RA$ as follows:

$$\%EL = \left(\frac{l_f - l_0}{l_0}\right) \times 100\% \qquad \%RA = \left(\frac{A_0 - A_f}{A_0}\right) \times 100\% \tag{1.5}$$

Where l_f and A_f are the length and cross-sectional area, respectively, of the specimen. $\%EL$ and $\%RA$ are usually not equal for a given material. Ductility usually decreases when temperature decreases.

Other properties are resilience and toughness. Both indicate the energy a material can absorb under tension. Resilience is the energy absorbed per unit volume until yielding, and toughness is the energy per unit volume until fracture. Both properties are expressed as the area under the stress-strain diagram, for resilience the area until the yield point (U_{yield}), and for toughness the entire area (until fracture, $U_{ultimate}$).

A final material property is hardness: the measure of resistance against localized plastic deformation. In hardness tests a small indenter is forced into the surface of the material.

When using material properties, a certain safety factor always has to be used. The stresses occurring during usage of a material may not always be exactly what they were predicted to be. Therefore a safety factor N is introduced as follows:

$$\sigma_w = \frac{\sigma_y}{N} \tag{1.6}$$

Where σ_w is the working stress and σ_y is the yield stress. Since the working stress must be smaller than the yield stress, N is always greater than unity.

1.5 Isotropy and Homogeneity

Materials can be either homogeneous or inhomogeneous. Suppose you have a sheet of metal, take multiple specimens from it (in the same orientation) and test them. If the material properties are identical for every position in the metal sheet, the metal sheet is homogeneous. So if a piece of material is not homogeneous, the material properties depend on the place in the material from which the test specimen is taken. Almost all materials are homogeneous.

Materials can also be either isotropic or anisotropic. Isotropic materials have the same property in every direction. Suppose you have an homogeneous sheet of metal, and take two specimens from it, orientated in a different way (for example, one in the longitudinal axis, one in the axial axis). If the properties of the two specimens are identical, then the piece of material is isotropic. Otherwise it is not. Most metals and polymers are isotropic, but most composites are not. This is due to the orientation of the fibres in most composites. Metal sheets produced by a rolling process are often also anisotropic.

1.6 Materials with Fibres

Over the past decades, materials with fibres have become popular in material science. Applying fibres in a material is a way to tailor the properties of the material. To start, there are many different kinds of fibres. Also the length of the fibres matter. Fibres can be classified in short fibres (millimeters), long fibres (centimeters/decimeters) and continuous fibres (meters). Short fibres often result in isotropic materials, while continuous fibres almost always result in anisotropic materials.

In the case of continuous fibres, the fibre orientation matters for the material properties. A composite material where the fibres are continuous fibres and are orientated in one direction is called an Uni-Direction (UD) composite. Also, multiple UD-layers are possible in a composite. For example, two UD-layers, one tangent to the loading, and one perpendicular to it, is called "cross ply". Two UD-layers, one in the X° direction, and one in the $-X^\circ$ direction, with X as an angle, is called "angle ply".

Suppose two UD-layers of fibres, with perpendicular fibre orientations, are attached to each other. Both layers have different material properties in different directions. Therefore a force applied on the material results in a shear force between the layers (since one of the layers deforms more than the other, which isn't possible, since they are attached). If the shear force gets too big, the bonding between the layers will break. This is called delamination. In short, delamination is the cracking of the bond between layers.

1.7 Dynamic Loading

Next to quasi-static loading (as was discussed along with the tensile test), there are also static and dynamic loading (static loading will be discussed next paragraph). Dynamic loading can cause fatigue failure, which, especially in metals, is the most often occurring type of failure. Fatigue failure is caused by the repetition of relatively small loads (under the yield stress) causing crack growth. Cracks grow perpendicular to the loading direction. There are three stages of fatigue. Initiation, where the crack appears. Growth, where the crack grows, and failure, where the crack size reaches a critical level.

There are many indicators for dynamic loads, to characterize the fluctuating stress cycle. The stress amplitude alternates about a mean stress σ_m, defined as:

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \tag{1.7}$$

Furthermore, the range of stress σ_r and the stress amplitude σ_a are defined as:

$$\sigma_r = \sigma_{max} - \sigma_{min} \qquad \sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{max} - \sigma_{min}}{2} \tag{1.8}$$

Finally, the stress ratio R is the ratio of minimum and maximum stress amplitudes:

$$R = \frac{\sigma_{min}}{\sigma_{max}} \tag{1.9}$$

When looking at dynamic loading, the stress amplitude can be plotted against the number of cycles until failure. This $S - N$ curve (stress amplitude versus number of cycles) is often called the Whöler curve. Given a certain dynamic loading amplitude and mean stress, the fatigue life can be determined. The fatigue limit, is the maximum stress amplitude level at which no fatigue failure will occur during service. This is therefore the horizontal line to which the Whöler curve converges.

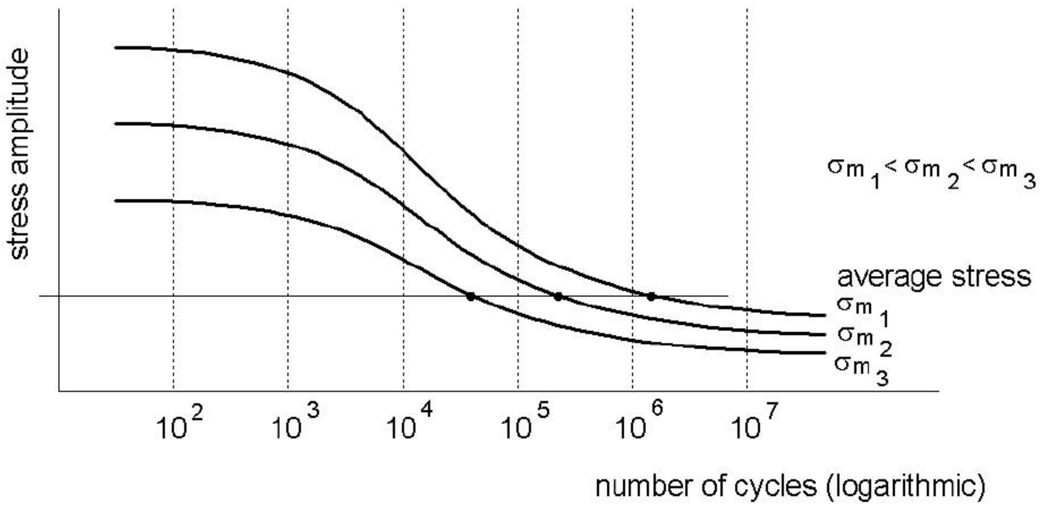

Figure 1.2: Three Whöler curves with a different average stress.

Next to fatigue failure, also impact failure is a dynamic load. Impact is the deformation process during the collision of two or more objects. During the impact process kinetic energy is transformed. Part of this energy gets absorbed by the materials. The amount of energy a material can absorb depends on its toughness, as was discussed in paragraph 1.4.

1.8 Static Loading

Creep is something that can occur in the case of static loading. Creep is a time dependent deformation under static loading due to an applied stress. Creep plays a role in materials that are under tension for a long time, and consists of three stages:

- Primary - During the primary stage the creep strain increases, but the speed at which this happens decreases.
- Secondary - During the secondary stage the creep strain increases more or less linearly. This is the most important part of the creep process, and the slope of the creep curve $\frac{\Delta\varepsilon}{\Delta t}$ is an important factor.
- Tertiary - During the tertiary stage the creep strain increases faster, until rupture occurs.

When creep has occurred in a specimen and the load is released, often anelastic deformation is present, meaning the specimen will return to its original shape over time.

Another thing that can be caused by static loading is stress relaxation. Stress relaxation is a time dependent change in stress under static loading due to an applied displacement.

1.9 Damage Tolerance

Damage tolerance shows to what extend damage of the structure influences the function of that structure. When talking about damage tolerance, often the residual strength is used. The residual strength of a damaged structure is the strength of the structure with damage. Because of damage, the strength of the structure might decrease, or stress concentrations might occur, which increases the chance of material failure.

Suppose there is a sheet of material loaded under a tension σ_n. If there is a hole in the sheet, stress concentrations will occur. Suppose that the hole is elliptical in shape, and has a diameter a perpendicular to the tension, and a diameter b tangential to the tension. The maximum load σ_{max} is then equal to $\sigma_{max} = k_t \sigma_n$ where the stress concentration factor k_t is $k_t = 1 + 2\frac{a}{b}$.

2 Materials on an Atomic Level

2.1 Bonding Types

Atoms are bonded together to form materials. They can be bonded in multiple ways. The three strongest bonding types, the primary bonding types, are:

- Ionic Bonding - When metallic elements give up their electrons to nonmetallic elements, the metallic elements become positively charged, while the nonmetallic elements get a negative charge. These different kinds of charges attract each other.
- Covalent Bonding - In covalent bonding, stable electron configurations are assumed by the sharing of electrons between adjacent atoms.
- Metallic Bonding - Metallic bonding is, more or less, caused by a negative electron cloud (consisting of valence electrons), holding together the positive ion cores, consisting of nonvalence electrons and atomic nuclei.

Next to the primary bonding types, there are also secondary bonding types. These van der Waals-bonds are weak in comparison to the primary bonds, and are caused by atomic or molecular dipoles, existing whenever there is a separation of positive and negative portions of an atom or molecule.

2.2 Crystallinity

Solid materials may be classified according to the regularity with which atoms or ions are arranged with respect to one another. If the atoms are situated in a repeating or periodic array over large atomic distances, it is called a crystalline material. Otherwise it is a noncrystalline or amorphous material. All metals, many ceramics, and also certain polymers form crystalline structures under normal solidification conditions.

The crystal structure of a material is the manner in which atoms, ions or molecules are spatially arranged. Some of the properties of a material depend on this crystal structure.

2.3 Unit Cells

The atomic order in crystalline solids indicates that small groups of atoms form a repetitive pattern. It is often handy to look for a small unit cell that, when put together multiple times, forms the regular pattern in which the atoms are arranged. Unit cells have multiple properties:

- The crystal system the unit cell belongs to. This depends on the shape of the unit cell.
- The size of the unit cell. (Also the shape can be important, if this has not been set by the crystal system the unit cell is a member of.)
- The atoms per unit cell.
- The atomic packing factor (APF). This is the part of the unit cell filled by atoms, and can be calculated by dividing the volume of atoms in a unit cell by the total unit cell volume.
- The coordination number. This is the amount of neighboring atoms every atom has.

There are three kinds of metallic crystal structures: the face centered cubic (FCC), the body centered cubic (BCC) and the hexagonal close packed (HCP). Their properties can be found in table 2.1.

Also the crystal structure density ρ can be determined, using the following formula:

$$\rho = \frac{nA}{V_c N_A} \tag{2.1}$$

Structure	Shape	Size (R = Atom radius)	Atoms/cell	APF	Coordination #
FCC	Cubic	Cube length = $2\sqrt{2}R$	4	$\frac{\pi}{3\sqrt{2}} \approx 0.74$	12
BCC	Cubic	Cube length = $\frac{4R}{\sqrt{3}}$	2	$\frac{\sqrt{3}\pi}{8} \approx 0.68$	8
HCP	Hexagonal	Hexagon Length = $2R$ Height = $4\sqrt{\frac{2}{3}}R \approx 3.266R$	6	$\frac{\pi}{3\sqrt{2}} \approx 0.74$	12

Table 2.1: Properties of the FCC, BCC and HCP crystal structures.

Where n is the amount of atoms per unit cell, A is the atomic weight, V_c is the volume of a unit cell and N_A is Avogadro's number ($6.022 \cdot 10^{23}$ atoms/mol).

2.4 Amount of Crystals

Some materials may have more than one crystal structure. This phenomenon is known as polymorphism, and is sometimes also termed allotropy. The prevailing structure depends on both temperature as external pressure.

Most materials only have one crystal structure, but are composed of a collection of many small crystals or grains. This means that there are multiple grains inside the specimen, each having the same crystal structure, but are orientated in a different way. Every crystal or grain itself is therefore anisotropic. But since there often is an extreme high amount of different grains in a specimen, all having random orientations, the specimen itself is isotropic.

When a specimen is made in such an ordered way that all grains have equal orientation, and therefore become one grain or crystal, the specimen becomes a single crystal. Single crystals exist in nature, and can also be produced artificially, but they are rather difficult to grow. In single crystals the crystal structure extends itself throughout the entirety of the specimen without interruption. Materials not consisting of a single crystal are termed polycrystalline materials.

The place where two grains meet is called a grain boundary. More about this will be explained in paragraph 2.8.

2.5 Irregularities

Only under perfect situations is the atom pattern in a material perfectly regular. Many irregularities or imperfections may occur. It might occur that there is an empty spot in the atom roster, where normally an atom should have been. This is called a vacancy. It is also possible that there is an atom in a place where normally there would not be an atom. This event, which occurs in only very small concentrations, is called a self-interstitial. Naturally, materials consisting of only one element are impossible to make as well. Impurities always occur in a metal. Sometimes this is done intentionally, for example in the creation of an alloy. The addition of impurity atoms to a metal will often result in the formation of a solid solution (also a new phase might form, but that is an entirely different topic). In a solution, the solvent is the compound present in the greatest amount, while the solute is the compound present in minor concentrations.

The solute can dissolve in the solvent in multiple ways. The solute can consist of substitutional impurity atoms. These atoms take up the place of one or more solvent atoms. The solute can also consist of interstitial impurity atoms, which take up a position between the solvent atoms. The way in which the solute dissolves in the solvent depends on multiple parameters, of which the most important one is the atomic size factor.

2.6 Specification of Composition

In the case of an alloy, it is often necessary to express the composition of an alloy. The most common way is to use the weight percentage (wt%) or the atom percentage (at%), which are, respectively:

$$C_1 = \frac{m_1}{m_1 + m_2} \times 100\% \qquad C_1' = \frac{n_1}{n_1 + n_2} \times 100\% \tag{2.2}$$

Where C_1, m_1, C_1' and n_1 are the weight percentage, the mass, the atom percentage and the number of atoms/moles, respectively, of a certain element 1. m_2 and n_2 naturally are the mass and the number of atoms/moles, respectively, of a certain element 2. The percentages of element 2 can be calculated in a similar way.

2.7 Dislocations

A dislocation is a linear or one-dimensional defect around which some of the atoms are misaligned. One type of dislocation is when the edge of an extra plane of atoms terminates within the crystal. This is termed an edge dislocation. The line at which the edge terminates is termed the dislocation line.

Another type of dislocation, called a screw dislocation, exists, which may be thought of as being formed by a shear stress that is applied to produce a distortion. However, most dislocations found in crystalline materials exhibit components of both types. These dislocations are termed mixed dislocations.

As was previously mentioned, the dislocations cause an irregularity in the crystal structure. This irregularity causes internal strains in the crystal structure, called lattice strains. The term lattice is indicates a three-dimensional array of points coinciding with atom positions (or sphere centers).

To indicate the amount of dislocations, the dislocation density is defined as the length of the dislocations per unit volume or, equivalently, the number of dislocations that intersect a unit area of a random section. The dislocation density therefore has as unit m^{-2} (per square meter).

2.8 Interfacial Defects

Interfacial defects are boundaries that have two dimensions, and normally separate regions of the materials that have different crystal structures and/or crystallographic orientations. One of the most obvious boundaries is the external surface, along which the crystal structure terminates.

Inside a specimen are also boundaries between multiple grains, called grain boundaries. (Single crystals are an exception.) These boundaries separate two small grains or crystals having different crystallographic orientations. Grain boundaries aren't necessarily flat planes. Various degrees of misalignment between adjacent grains are possible. When the orientation mismatch is small (in the order of a few degrees), then the term low-angle grain boundary is used. Otherwise the term high-angle grain boundary is used.

Other types of grain boundaries are tilt boundaries and twin boundaries. Also other miscellaneous interfacial defects may occur in a material.

2.9 Diffusion

Diffusion is material transport by atomic motion. There is no external force in diffusion. For example, when two types of metal are hold together and heated, diffusion usually occurs (depending on things as material type, of course). The atoms of one metal start mixing up in the other. This process of migration of impurity atoms is called interdiffusion or impurity diffusion. A migration of the host atoms itself is called self-diffusion. This kind of diffusion does not cause concentration changes. Diffusion is caused by the fact that the atoms of a material are always moving (the higher the temperature, the faster the atoms move).

Two diffusion mechanisms are possible. One mechanism of diffusion is vacancy diffusion, where an atom adjacent to a vacancy, moves to the vacancy, leaving a new vacancy on its former position. Another mechanism of diffusion is interstitial diffusion, where interstitial atoms change position between the other atoms.

If M is the mass diffusing through and perpendicular to a unit cross-sectional area A of solid per unit time, and t is the elapsed diffusion time, then the diffusion flux J is defined as:

$$J = \frac{M}{At} \tag{2.3}$$

If the diffusion flux does not change with time, a steady-state diffusion exists. Otherwise a nonsteady-state diffusion exists. This diffusion flux also has a relation with the rate at which diffusion occurs. This rate is indicative of the rate of atomic motion, being strongly dependent on the temperature.

2.10 Dislocation Movement

Dislocations can move around in a crystal structure. This is often caused by external forces, but sometimes also by internal strain energy. When some of the internal strain energy is relieved by virtue of dislocation motion, there is some reduction in the number of dislocations, and dislocation configurations are produced having low strain energy. This process is called recovery.

Even after recovery, the grains are still in a relatively high strain energy state. When there is enough energy (which is the case when the temperature is high enough), recrystallization occurs. Recrystallization is the formation of a new set of strain-free grains that have low dislocation densities. The average size of the new grains is a function of the temperature. The recrystallization behavior of a particular metal alloy is sometimes specified in terms of a recrystallization temperature, which is the temperature at which recrystallization just reaches completion in one hour.

Dislocations often have a certain plane in which they 'prefer' to move, the so-called slip plane, and also a certain direction in which they prefer to move, which is called the slip direction. This combination of the slip plane and the slip direction is termed the slip system. The slip system is such that the atomic distortion that accompanies the motion of a dislocation is a minimum.

2.11 Strain Hardening

Strain hardening, also called cold working, is the phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed. Percent cold work is defined as:

$$\%CW = \left(\frac{A_0 - A_d}{A_0} \right) \times 100\% \tag{2.4}$$

Where A_0 is the original area of the cross-section that experiences deformation, and A_d is the area after deformation. Strain hardening increases yield strength and tensile strength, but decreases the ductility. The dislocation density increases because of cold working, causing dislocation multiplication and the formation of new dislocations. Since the dislocations are packed closer together, their ability to move decreases, which hardens the material, but also makes it brittle.

The effects of strain hardening can be removed by an annealing heat treatment, i.e., an exposure to an elevated temperature followed by cooling at a slow rate. This often causes recrystallization, decreasing the amount of dislocations in the material. The new-formed grains during recrystallization are characteristic of the pre-cold-worked condition.

3 Phase Diagrams

3.1 Putting Elements Together

When making an alloy, one should usually dissolve a solute in a solvent. Both the solute and the solvent are now termed components of the alloy. However, there is often a maximum concentration of solute atoms that may dissolve in the solvent to form a solid solution. This limit is called the solubility limit. The addition of solute in excess of this limit results in the formation of another solid solution or compound that has a distinctly different composition.

Putting together elements is usually done when elements are in the liquid state, since they would not mix well otherwise. A solid solution is usually required, so the liquid solution needs to be cooled down. The temperature at which the solution coagulates depends on the concentrations of the components of the solution. Therefore, the phase of a solution depends on both the temperature, as the concentration. A phase diagram can then be drawn, showing at what temperatures and at what concentrations what phase is present. An example of a phase diagram of copper and aluminum can be found in figure 3.1.

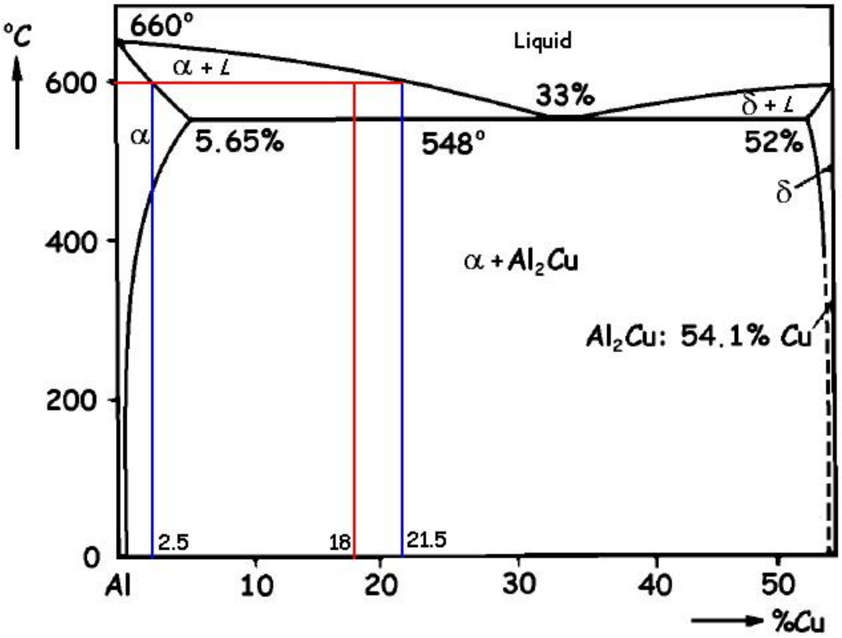

Figure 3.1: Example of a phase diagram.

3.2 The Lever Rule

When a phase diagram is present, it is possible to calculate the composition of a certain phase at a certain composition and temperature. For that, the lever rule (or the inverse lever rule) should be applied. This will be demonstrated with the example phase diagram of figure 3.1. Suppose we want to find the composition of an alloy with $C_0 = 18\%$ solute, and at temperature $T = 600°$. First find the point at which you want to calculate the phase by drawing a horizontal line at the right temperature T, and a vertical line at the right composition C_0 (see red lines in figure 3.1). The point at which we wish to know the composition is of state α + Liquid. Then look at the points at which the horizontal line intersects with lines of the α- and the Liquid-region. Draw vertical lines from those points and read the percentages. Call the position of the left vertical line C_α and the right C_L. To find W_α, the part of the alloy which has state α, we need to look at the section of the line furthest away from the α-region (this is why they call it the lever rule), and divide it by the total line length. In formula:

$$W_\alpha = \frac{C_L - C_0}{C_L - C_\alpha} = \frac{21.5 - 18}{21.5 - 2.5} = 18.4\% \tag{3.1}$$

And to find the part of the alloy which has a liquid state, we need to look at the part of the line furthest away from the liquid region. Naturally, a value of 81.6% will follow.

It is also possible to find the composition of the 18.4% α, in terms of copper and aluminum. This is relatively easy to find. Just look at the vertical line closest to the α-region, which has position $C_\alpha = 2.5\%$. The composition of α is therefore 2.5% copper and 97.5% aluminum. In an identical way can be determined that the composition of Liquid is $C_L = 21.5\%$ copper and 78.5% aluminum.

It is always worth checking whether the found percentages add up to the real concentration of copper in the mixture. There is 2.5% copper in 18.4% of the solution, and 21.5% copper in the other 81.6%. Now make the multiplication: $0.025 \cdot 0.184 + 0.215 \cdot 0.816$. Note that this is equal to 18%, the concentration of copper in the solution. If it is not, something is wrong with the calculations.

Phase diagrams can have multiple types of horizontal axes. Both weight percentage as atom percentage can be the horizontal axis. Therefore you should always take a second look at what kind of concentration you should calculate, to prevent making stupid mistakes.

3.3 Eutectic Reactions

The shape of the phase diagram shown in figure 3.1 occurs for more alloys than for just copper and aluminum. It is therefore named the binary eutectic phase diagram. Also the lines in the diagram has been named:

- Liquidus line - The line between Liquid and $\alpha + L$, and the line between Liquid and $\delta + L$.
- Solidus line - The line between α and $\alpha + L$, and the line between δ and $\delta + L$.
- Solvus line - The line between α and $\alpha + \delta$, and the line between δ and $\alpha + \delta$.

Note that the two liquidus lines coincide in a point at 33%. This point is called an invariant point. Upon melting, the two solid α and δ phases transform to a liquid phase. This reaction is called a eutectic reaction (eutectic means easily melted). Often, the horizontal solidus line at $T = 548°$ is called the eutectic isotherm.

3.4 Precipitation Hardening

Precipitates are extremely small uniformly dispersed particles of a second phase within the original phase matrix. The strength and hardness of some alloys may be enhanced by the formation of precipitates, accompanied by phase transformations that are induced by appropriate heat treatments. This process is called precipitation hardening.

Precipitation hardening, sometimes also called age hardening, is accomplished by two different heat treatments. We once more bring in figure 3.1 as an example. Suppose we want to use precipitation hardening on a specimen with 2.5% copper. The first heat treatment is a solution heat treatment, in which the material is heated within the α-region, until all the δ-parts disappear. It is then rapidly cooled (called quenching), so the δ-particles will not be able to form.

The second heat treatment, called precipitation heat treatment, consists of heating the specimen to a temperature still within the $\alpha + \delta$ region, at which temperature diffusion rates become appreciable. Now the δ precipitate phase begins to form as finely dispersed particles. The precipitates often form without this second heat treatment, but this treatment speeds up the process. The forming of precipitates is a time consuming process. Since the material hardens over time, this form of hardening a material is also called age hardening.

The strengthening phenomenon is explained in terms of an increased resistance to dislocation motion by lattice strains. These strains are established in the vicinity of the microscopically small precipitate particles.