Materials and Manufacturing 2 Summary

1. Introduction

1.1 Aircraft history

1.1.1 Early history

Ever since the Wright brothers made the first flight in 1903, aircraft have continued to evolve. Especially during the early years, **wooden aircraft** were normal. During world war 1 aircraft production increased rapidly. Thanks to this war wood became a scarce material. So when a few pioneers started building metal aircraft, others quickly followed. By the 1930's wood was rarely used in aircraft anymore. Especially when a crash of a wooden aircraft in 1931 got a lot of media attention, the popularity of wood plummeted. The last big wooden aircraft, Howard Hughes' Spruce Goose, failed as a commercial success.

1.1.2 Other improvements

The next big improvement was the **semi-monocoque airframe**. By giving the aircraft a shape of a cylinder, the hull could also take loads. Because the skin of the aircraft is subject to stresses, it is called the **stressed skin**. After the airframe, also the wings started having a stressed skin. So stressed skins were applied often in aircraft. The downside of having thin skins is that they have a low stiffness. But by applying a sandwich structure this problem can be solved. Also composites started playing advancing roles in aircraft construction.

1.2 Designer's Tasks

1.2.1 Combining disciplines

Due to the improvements that were just mentioned, aircraft get increasingly complicated. Many disciplines need to be combined in a design. One should pay attention to aerodynamics, aircraft performance, stability and control, structural design and so on. Only if all these disciplines have been given the attention they need, then an aircraft can be lightweight, strong, efficient, reliable and safe.

2. Bulk Materials Fabrication Processes

2.1 Casting

2.1.1 Mould creation

Casting is a process in which molten metal is poured into a **mould**, after which they are cooled and separated. Casting is often cheaper than forging. However, the mechanical properties of cast products are usually less. Also the minimal achievable thickness of forged products is smaller.

To be able to cast, first a mould needs to be created. For that, a **pattern**, usually made from metal, is constructed. The pattern is placed in a **flask**, which supports the mould. Then sand (or some other mould material) is added. The sand is compacted, usually done by hammering. After this, the pattern is removed and the mould is ready.

The mould is, as was mentioned, supported by a **flask**. Two piece moulds consist of a **cope** on top and a **drag** on the bottom. The seam between them is the **parting line**. A mould always has a **pouring basin**, into which molten metal flows downward. The metal then flows downward via the **sprue**, which should decrease in cross-sectional area as the metal flows down. It enters the mould via the **running system** and **gates**. There are also **vents**, which let gases out, and **risers**. These risers supply additional metal to the casting as it shrinks during solidification.

There are several types of moulds. There are **expendable moulds**, usually made of sand or ceramics. There are **permanent moulds**, made from metal. These are designed such that they can be easily removed after the process. Finally there are **composite moulds**, made from a combination of materials.

A mould also has various properties. It can be **permeable**, meaning it allows gases to escape. It can be **collapsible**, meaning it can shrink. And finally it can have a good **surface quality**, minimizing the need for finishing.

Although casting can create many shapes, it is not suitable to create flat areas. Due to uneven cooling, such areas tend to **warp**. This is caused by internal stresses, which occur in every casting product. Sometimes a heat treatment can be necessary to lower these stresses.

2.1.2 Shrinkage

The **shrinkage** is something that needs additional attention. Usually the mould needs to be slightly larger than the final product. There is therefore a **shrinkage allowance**. Also products usually need to be machined at the end. So there is usually also a **machining allowance**.

Shrinkage can be split up in three phases. There is shrinkage during cooling of the metal before solidification. Thanks to risers, this shrinkage doesn't have to be taken into account for the shrinkage allowance. The metal shrinks further due to metal phase changes during solidification. Finally there is shrinkage due to cooling after solidification. This last part is the most important one.

If the shrinkage is locally obstructed, **hot tears** may occur. These are small cracks caused by the fact that the specimen couldn't shrink. To prevent this, sharp corners should be avoided.

Another phenomenon caused by shrinkage is **micro porosity**. At places with a relatively high thickness, the outside can solidify sooner than the inside. Now risers can't provide extra metal to the inside. Therefore a small cavity occurs, which is of course undesirable. The way to prevent this, is to prevent so-called **hot spots**. Hot spots are places with a large distance to the specimen edge. They earn their name because they cool down slowly. However, when hot spots can't be prevented, a local cooling, called a **chill**, can be applied.

2.1.3 Cast types

There are several types of casting. The method we have previously looked at was **sand-mould casting**. If the sand is replaced by plaster or ceramics, we are dealing with **plaster-mould casting** or **ceramic-mould casting**. When the sand is mixed with a thermoset binder, a shell will form in the mould. This process is called **shell-mould casting**.

If we change the mould production of sand-mould casting, we get various other casting types. If the pattern is not made from metal but from wax, the process is called **lost-wax process** or **investment casting**. After mould creation, the wax can be reused. If, however, the pattern is made from an expendable material, we have **expendable pattern casting**.

The above casting types usually use expendable moulds. When permanent moulds are used, the process is called **permanent mould casting**. Since the moulds are much more expensive, only large amounts of products are economically feasible.

We can also change the driving force pushing the metal through the mould. If we let the mould rotate quickly in one direction, we are dealing with **centrifugal casting**. If we topple the mould in three axes, the process is called **revolve casting**. When the liquid is forced by hydraulic or pneumatic pressure, the process is termed **pressure-die casting**.

2.2 Lay-Up

2.2.1 The lay-up process

Lay-up is the term used for placing fibre-reinforced polymers in a mould. The size of products is not limited, so very big parts are possible. Also high strengths can be achieved. Although it is a simple process, it is rather labour intensive.

First the individual **reinforcement** is profiled and cut to the right shape. From this, layer by layer, a **laminate** is made. Lay-up is always followed by other processes. When preimpregnated (**prepreg**) material is used, only polymerization is needed. This is achieved by **curing**, which will be discussed in the next paragraph.

The purpose of lay-up is to get a certain **fibre architecture**. It is very important that the fibres are oriented right and that the lay-up is performed in the right sequence. Due to this importance, there is often a special lay-up manual.

2.2.2 Curing

After lay-up, the laminate needs to be cured. The resin needs to harden. This can simply be done by waiting. However, when pressure is applied, the amount of resin and void content in the final product can be lowered, improving the mechanical properties.

The preferred way of applying pressure, is by putting the material in a vacuum, thereby applying the atmospheric pressure to it. To do this, the laminate is placed in a **vacuum bagging film**. To help the vacuum arise, a **breather fabric** ensures that the air can flow to the pump. There is also a **bleeder fabric**, which stores excess resin. Finally, there is the **peel-ply**, which ensure the other films can be removed after curing.

This process can be improved by **autoclaving**. If this is applied, the temperature is increased. Not only does this increase the pressure further, but the resin cures better at elevated temperatures.

2.2.3 Lay-up types

There are several types of lay-up. **Hand lay-up** was for a long time the dominant method for making composite parts. In this method resin layers and reinforcement layers are alternately placed in the mould. Fibre orientation is arranged by the worker. During **tape laying** a machine places the reinforcements into the mould. The use of machines significantly lowers fabrication costs. Since it is also more accurate than hand lay-up the mechanical properties are better controlled.

Another simple method is the **spray-up process**. Here a spraygun chops fibres in a predetermined length (of a few centimeters) and shoots it through a resin onto the mould. This method is fast and cheap, but the fibres are randomly oriented.

2.3 Resin Transfer Moulding

2.3.1 Resin transfer moulding

Resin transfer moulding (RTM) is the term used to describe a range of closed-mould low-pressure processes. In RTM processes the reinforcement fibres are put in the mould before the resin is added. Since the process is closed, personnel will not be exposed to hazardous vapours. The main advantage of RTM is the capability to rapidly manufacture large, complex, high-performance structures.

At RTM processes the process time should be as short as possible to decrease costs. Since the process takes place at low pressures, moulds are not subject to large stresses or high temperatures, so the mould costs are low. Although labour costs are a significant part of the process costs, most of the money gets spend on the raw materials.

2.3.2 Reinforcement

The **reinforcement** usually consists of weaves and mats of fibre material. Since the reinforcement is placed into the mould before resin is added, it first needs to be formed from an inital flat shape into the three-dimensional shape of the mould. The intermediate form is called the **preform**.

When creating the reinforcement, attention has to be given to many aspects. The most important one is the **permeability**. When the resin is added to the mould, it needs to be able to spread through it. Non-impregnated areas, called **dry spots**, need to be avoided. Another important factor is the **porosity**, which is an indication of how many voids are present. The higher the porosity, the longer it will take to fill the mould.

2.3.3 Resin

After the reinforcement has been placed into the mould, and the mould has been closed, **resin** will be added. Resin will flow from the **inlet** to the **outlet**. This flow must be caused by a pressure difference between the inlet and the outlet. This is achieved by pressurizing the resin at the inlet and/or by applying a vacuum at the outlet. An advantage of an increased pressure difference is the increase in resin flow, and thus a decrease in fill time. A disadvantage is that reinforcement fibres can move with the flow unexpectedly. Higher pressures also require stronger, and thus more expensive moulds.

The choice of resin is dominated by the ease with which the resin can flow through the mould. Also the **pot life** (the time until the viscosity of the resin starts to change) plays a mayor role.

When designing the mould, special care needs to be given to the positions of the inlet(s) and outlet(s). If these are not placed appropriately, dry spots will occur. Also so-called **runners** need to be prevented.

These are channels along which the resin can flow relatively easily. If runners exist, the resin will only flow along these runners, and therefore leave other places dry.

2.4 Filament Winding

2.4.1 Winding process

Filament winding is an open-mould process. Here, the reinforcement is wound onto the mould, which is called a **mandrel**. Since the reinforcement is placed in a computer controlled process, it is done in an accurate way. The quality consistence of this process is therefore high. After winding has been completed, the specimen is cured in a very simple way. Eventually the mandrel is removed.

The forces present during winding are low, so the costs of the computerized equipment are limited. The mould is usually simple, so mould costs are low. Also few labour is required. Materials costs are high, since the final product will consist of expensive fibres. These fibres don't need much preparations though, so the costs are limited.

Since the process is an open-mould process, resin emissions can be unhealthy for workers, and must be given special care. An advantage of filament winding lies in the possibilities to accurately orient the fibres. These fibres cause the final product to have a rough external surface, which may be disadvantageous when aerodynamic properties are required.

2.4.2 Reinforcement

When used, the dry reinforcement fibres are taken of a **reel**. They then get pulled through a resin bath. The fibres need to be prestressed to be impregnated. They are then placed on the mandrel under a certain angle. This angle is called the **winding angle**, denoted by α.

When the cross-section of the mandrel changes, also the winding angle changes, according to the **law of Clairaut**, stating that

$$r_i \sin \alpha_i = \text{constant}, \tag{2.4.1}$$

where r_i is the radius at cross-section i and α_i is the corresponding winding angle.

This expression is only valid when the reinforcement is wound **geodesically**. Geodesical means that the reinforcement takes the shortest route from one point to another. Although non-geodesical winding gives the designer more freedom, it complicates the design to a large extent and is therefore usually not preferred.

Since the winding angle is so important, names have been given to certain cases. If $\alpha \approx 90°$, it is called a **hoop winding**. If $\alpha \approx 0°$, it is called a **polar winding**. Winding under other angles is called **helical winding**.

Another important factor is the width of the reinforcement. A large width is usually preferred, as this shortens the time needed to wind the product. However, at highly curved surfaces the tape may have trouble adapting to the surface. So then high reinforcement widths aren't preferred.

2.4.3 Mandrel

The shape of the mandrel determines the shape of the final product. This shape is limited. The most important constraint is that the mandrel needs to be removed after winding. If this is not possible in a normal way, sometimes a **divisible mandrel** can be used. This can, however, be expensive. Also a **soluble mandrel** can be used. This is even more expensive, since a new mandrel will be needed for every product. Sometimes the mandrel isn't removed and becomes a part of the product.

Another limitation is caused by the fact that the reinforcement needs to stay on the mandrel. So only convex curvatures are possible. The winding will just bridge over any concave surface in a straight line.

2.5 Forging

2.5.1 Forging principle

Forging is a process in which the workpiece is shaped by compressive forces. The workpiece, called **slug**, **billet** or **preform** is metal, as composites can not be forged. Also, not all metals are suitable for forging. The **forgeability** is generally defined as the capability of a material to undergo a deformation without cracking.

The metal is placed between two dies, which are then pressed together. The material is then deformed to the desired shape. During pressing, **barreling** may occur. The cross-sectional size near the dies tend to increase less than the cross-sectional size in the middle of the workpiece. This is caused by friction between the dies and the workpiece. This friction can be reduced by using **lubricants**, which also can serve as a parting agent between the die and the product after forging.

The amount of material needed to fill the cavity between the dies can't be accurately determined. Therefore there may be some excess material after forging has been completed. This results in a **flash**, being a thin flat piece of metal attached to the product after forging. It needs to be trimmed off.

A typical characteristic of forging is that it produces components with locally varying grain structures. This adds a good strength and toughness to forged parts. Forging has low material costs. Also the labour costs aren't very high. Most of the money gets spend on the dies and the machinery. These need to be very strong, as high forces are present during forging.

2.5.2 Forging types

Forging machines are classified as either **presses** or **hammers**. Hydraulic presses are load limited, meaning that they press until a certain maximum pressure is reached. They are relatively slow. Mechanical presses are usually stroke limited. The forces which they exert on the workpiece are often very high. Finally, hammers are energy limited. They can operate at very high speeds. Since the material now hardly has any time to cool down, these are the most often used forging machines.

Forging is usually done at elevated temperatures (**hot forging**), but can also be done at room temperature (**cold forging**). Cold-forged parts have good surface finish and dimensional accuracy, while hot forging requires smaller forces. During hot forging one has to take into account the shrinkage of the part due to cooling.

A distinction can also be made between **open-die forging** and **impression-die forging**. In impression-die forging the shape of the final product is determined by the geometry of the die. In open-die forging this is not the case. A special type of forging is **precision forging**. This type of forging uses special dies and extra high forces to achieve a higher precision.

2.6 Extrusion & Pultrusion

2.6.1 Metal extrusion

Extrusion is a process in which a heated metal **billet** is squeezed through an opening, called a **die**. This die is just a thin disk. In this way a long **profile** is created. Since the grains of the metal are stretched, extruded materials are usually anisotropic. Extrusion is a semi-continuous process, since a new billet needs to be inserted once in a while.

The geometries available are profiles with a constant cross-section. The cross-section can be closed, even with multiple **voids** (hollow sections). Creating a hollow section can be slightly troubling. For an extrusion to have a hollow shape, the billet already must have a hole. Another possibility is that the billet is welded after being extruded. However, aluminium alloys are the only materials that show good welding properties during extrusion.

The product of an extrusion is usually not a straight bar. So straightening of the extrusion is often needed. After this is done, the material can be cut to the desired length.

The **scale** of the cross-section of an extrusion is given by the **circumscribing circle diameter** (CCD). This is the diameter of the smallest circle enclosing the profile. The **complexity** of a profile is given by the **extrusion category** and the **shape factor**. The three possible extrusion categories are solid, semi-hollow and hollow. The shape factor equals the perimeter divided by the cross-sectional area.

Extrusion is a relatively cheap process. The material costs and labour costs are low. Due to the high forces, the die and the machines are a bit more expensive.

2.6.2 Polymer extrusion

Next to metal, also thermoplastic polymers can be extruded. Due to a higher viscosity, the polymer is transported to the die using a **screw**. This screw also heats the polymer. Since small pieces of polymer can be added during extrusion, this process can be a continuous process.

An extra factor that needs to be considered now is the **swell** that occurs when the polymer exits the extruder. The screw compresses the polymer when it's in the extruder, but once the polymer exits the extruder, there is an **elastic springback**. The die should therefore be smaller than the final product.

2.6.3 Pultrusion

Composites can not be extruded. So for composites **pultrusion** is used. During pultrusion **rovings** (untwisted bundles of continuous filaments) are combined to a profile with a constant cross-section.

At the start of the process, the fibre materials are placed at the right positions. They are then passed through a **mould**. Although the die in extrusion is small, the mould in pultrusion is relatively long. This is because the mould needs to guide and cure the resin.

The size of pultrusion profiles can be larger than those produced via extrusion. This is caused by the low forces that occur during pultrusion. Due to this, also less expensive moulds are necessary. But since fibres are more expensive than metal, the material costs are higher.

2.7 Compression Moulding

2.7.1 The process

Most of all composite components are produced using **compression moulding**. In this manufacturing method a compressive force is applied to a mix of reinforcement and resin. This mix then flows between two mould-halves. After that, the mould is opened only slightly for a few seconds to allow formed gasses to escape.

The bottom section of the mould is called the **cavity**, while the top section is the **force** (or **plug**). The mix of reinforcement and resin is called the **moulding compound** or the **charge**.

A distinction can be made between **high-pressure compression moulding** and **low-pressure compression moulding**. Another distinction can be made by looking at the material forms (e.g. sheets) used during the process.

High forces occur in compression moulding. Therefore strong and thus expensive machines and moulds are necessary. Also the raw materials, containing fibres, aren't cheap. But the amount of waste material is very low and also few labour is necessary.

2.7.2 Reinforcement

The reinforcement consists out of continuous or chopped random fibres. Having control on the orientation of the reinforcement is very difficult, or sometimes impossible. To be sure of the properties of the final product, designers therefore try to get randomly oriented reinforcement.

During the flow of the resin through the moulds, merging of the flow fronts can occur. This should be avoided, as it creates so-called **knitlines**. The reinforcement can't cross such lines, and therefore parts without reinforcement will occur.

3. Fabrication Process with Sheet Materials

3.1 Sheet Forming

3.1.1 Sheet processing

Many different products can be formed from **sheets**. These sheets are at most only a few millimeters thick. Usually metal sheets are used, but also composite sheets are a possibility.

Sheets are usually used by the concept of **forming**. This term is mainly used to express the deformation of a material. The materials are manipulated such that the required shape is obtained. This can be done with multiple techniques, depending on the material you are using.

3.1.2 Forming techniques

Normal metal sheets are usually deformed using plastic deformation. This causes dislocations to move through the sheet, increasing the dislocation density. This method therefore causes **strain hardening**.

Sometimes metal alloys are superplastic. **Superplasticity** is a phenomenon through which very high plastic deformations can be reached through very small loads.

Plastic deformation isn't an option for composites, since no plastic deformation can be applied to fibres. Therefore the so-called **intra-ply shear** and **inter-ply slip** mechanisms need to be applied, shifting fibres with respect to each other.

From now one, we mostly consider plastic deformation, which is the most common form of material manipulation. At the end of this chapter, we consider the other two deformation methods.

3.1.3 Formability

An important factor in forming materials is the so-called **formability**. The better the formability of the material, the more complex a part can be. This formability is expressed by the maximum applicable strains (limit strains). Also the loads at which these strains are reached play a role.

The stress-strain curve of a metal alloy is a useful tool to evaluate its formability. The first area is the **elastic area**, ranging from zero load to the yield point. Then we have the **homogeneous plastic area**, ranging from the yield point to the maximum stress. The third area is the **necking area**, in which diffuse necking occurs. The fourth area is the **local necking area**, where local necking occurs and the part actually fails. In plastic forming processes often the end of part two is used as the forming limit, but sometimes the end of part three can also be used.

There is one downside to examining the formability like this. In tensile tests there is only stress in one direction. When forming sheets, there is a **two-dimensional stress state**. Since the sheet will also change in thickness, there even is a **three-dimensional strain state**. This strain state has an influence on the formability. This is expressed by the **forming limit curve** (FLC). This curve expresses the forming limits as a function of the two in-plane strains.

Next to plastic deformation, also elastic deformation occurs. When the loads are released, **spring back** occurs. There are two types of spring back. **In-plane spring back** usually doesn't change the overall shape of the part. This usually occurs at tensile loads. **Out-of-plane spring back** does change the overall shape of the product. This usually occurs at bending. A downside of out-of-plane spring back is that the die should have a different geometry than the final product.

3.1.4 Part types

Parts that have been formed can be classified in categories. One way to do this is by placing parts in the following categories:

- Undeformed parts.
- Single curved parts, with a large bend radius.
- Single curved parts, with a small bend radius.
- Double curved parts, with large bend radiuses.
- Double curved parts, with one large and one small bend radius.
- Double curved parts, with small bend radiuses in orthogonal directions.

3.2 Bending

3.2.1 The bending principle

Bending is one of the most common processes for manufacturing simple elements. We can describe bending by using a simple model. This model is based on various assumptions. Among others, we assume that the bending is performed by a pure bending moment and that the bend radius is constant everywhere in the bend zone.

Based on these assumptions, we can find that the stress in the centre line of the bend (the so-called **neutral axis**) is zero. Also the strain distribution is proportional to the distance to the neutral axis. Using this, we can find the strain in a particular layer of the bend zone, using

$$\varepsilon(x) = \frac{L - L_0}{L} = \frac{(r + x) - r}{r} = \frac{x}{r}, \tag{3.2.1}$$

where r is the bend radius and x is the distance from the neutral axis. The **maximum strain** then becomes $\varepsilon_{max} = t/(2r)$. Keep in mind that the stress $\sigma(x)$ is not proportional to x, since plastic deformation occurs.

Let's look at the **minimum bend radius** r_{min}, or even better, the **minimum bend ratio** $(r/t)_{min}$. This ratio can be expressed as $(r/t)_{min} = 1/(2\varepsilon_{max})$. So the minimum bend radius depends on the maximum strain and thus on the formability. The more formable a material is, the smaller the radiuses it can be bend over.

3.2.2 Spring back

When bending a material, there will be both elastic and plastic deformation. Upon release, this elastic deformation will cause **spring back**. If the material was bend to an angle α_0 and springs back to an angle α_1, then the **spring back angle** γ is defined as

$$\gamma = \alpha_0 - \alpha_1. \tag{3.2.2}$$

Different parts of the sheet will have different amounts of elastic deformation energy after bending. After spring back, some internal stresses called **residual stresses** will remain in the part. If these stresses are significant, additional stress relief treatments are required.

What can we say about the amount of spring back? This amount is related to the elastic energy, or to be more precise, to the ratio $E_{elastic}/E_{total}$. When the E-modulus is high, $E_{elastic}$ will be reduced and so will the spring back. Also the bend ratio r/t plays a big role. If this is small, then E_{total} will be small as well, so the ratio $E_{elastic}/E_{total}$ will be big. Thus the spring back will be big.

3.2.3 Bending a plate

Many bending processes are performed using a **press brake**. A press brake has a stationary lower bed and a moving upper bed. A (usually V-shaped) die is placed on the lower bed, while a bending radius is attached to the upper bed. A plate is placed between the two beds. The upper bed then descends to the plate, bending it.

When a sheet has to be bent over a large radius, **bending rolls** are used. As the sheet runs through the machine, three bending rolls cause a three-point bending moment in the sheet, bending it. This bending method usually has a large spring back.

Another method of bending a plate is **roll forming**. This is a process in which a metal strip is gradually transformed by a set of rolls. Every set of rolls changes the shape of the strip slightly more. This method is a continuous process, which is an advantage. A disadvantage is that many part-depended rolls need to be created. So this method is only suitable for long series of products.

3.3 Stretch forming

3.3.1 The process

Stretching or **stretch forming** is a process used to manufacture large and slightly double curved shells. Here bending and stretching of a metal sheet are combined in one process. First the tensile forces will stretch the material such that the sheet is deformed plastically. Then a die is pressed into the sheet causing it to stretch even more, but also to bend. Since the bending only takes place in the plastic region, spring back only takes place in the plane of the sheet. The die can therefore have the same shape as the final product.

Stretch forming can also be applied for single curved parts with complex cross-sectional shapes. Some parts of an airplane are made using stretch forming, due to the high accuracy that is required.

Most aluminium sheets have a maximum strain of 15-20%. However, the maximum applicable strain in stretch forming is about 6%. This is because the product needs some toughness after being formed. It is, however, possible (and sometimes necessary) to reach strains as high as 25%. To reach this, several intermediate heat treatments are necessary.

Stress forming is usually a rather expensive process. The die needs to be quite accurate, the machine has many parts with a lot of high forces, the process is labour intensive and there is a lot of waste material.

3.4 Deep drawing

3.4.1 The process

Deep drawing is a process using a punch to stamp a metal sheet to the desired shape. The variety of different shapes that can be obtained with this method is enormous. It is therefore used very often in non-aerospace industries. The usage in aerospace industries is much lower. This is mainly due to the fact that deep drawing involves big product series.

First a **metal blank** is clamped between a **die** and a **blank holder**. The metal blank should be free to move between the die and the holder (often a lubricant is used for that), but it should not be able to wrinkle. Then a punch is used to give the metal blank the desired shape.

The dies used for deep drawing can be expensive. However, the costs per product are reduced, since deep drawing has relatively long product series. Therefore the costs of deep drawing products can be relatively low.

3.4.2 Stresses and limits

Usually the final product consists of a **bottom**, a **product wall** and a **flange**. The bottom is subject to tensional stresses in both radial and circumferential direction. The same goes for the walls. The flange is still stressed in tension in radial direction. However, in circumferential direction compression occurs.

The forming limits are often expressed by the **deep drawing ratio** β. This is defined as the ratio $\beta = D_0/d$ of the original blank diameter D_0 and the punch diameter d, such that the flange is completely drawn into the product wall.

3.5 Rubber forming

3.5.1 The process

Rubber forming is a press forming process using a soft rubber press and a rigid die. The **die** (usually made from laminated wood) is placed into the press. The metal blank is placed on top of it. The rubber pad is then pressed on the die, forming the metal blank. Instead of a solid rubber pad, also a fluid cell, enclosed by a rubber membrane, can be used for pressing.

This method is the most important process to form metal parts in the aircraft industry. This is because it is very suitable for small product series. It is a very simple process and only one product related part (the die) is necessary. A disadvantage is the high pressure that is necessary. Strong machines are therefore necessary. Also the cycle time (time per product) is relatively high.

3.5.2 Product types

The die can be either a **male die** or a **female die**. If a male die is used, the metal blank is formed over the die. This type is usually used for **flanged parts**. A flanged part consists of a web plate with straight/curved flanges at the edges. Curved flanges are divided in **shrink flanges** and **stretch flanges**. In shrink flanges there is a compressive forces in the flanges, while in stretch flanges there is a tensile force. The strain in the flanges is always proportional to the distance from the bend line.

If a female die is used, the process is slightly similar to deep drawing. There are, however, a few important differences. In deep drawing the metal blank was stretched by a punch. In rubber forming the metal blank is pushed into the die by a rubber pad. There are slight disadvantages to this. Therefore male dies are more often used than female dies.

3.6 Superplastic Forming

3.6.1 The principle

Superplastic forming (SPF) is a rather unconventional forming process. During normal plastic forming the crystals of the metal alloy are deformed. In superplastic forming the crystals simply slide along each other. The prefix super means that very high deformations can be reached (often 30 times greater than normal). This also happens at very low forces. Gas pressure is usually enough to reach the desired deformations.

Sometimes superplastic forming is combined with **diffusion bonding** (DF). If two metal surfaces are squeezed together at a high pressure and temperature, a bond can be created by means of atomic diffusion.

A disadvantage of SPF is **cavitation**. Since the grains slide along each other, small mismatches may occur, causing cavities. This may be countered by a **back pressure**, being an additional pressure over the entire part. Also **excessive thinning** can play a negative role. Since the parts often become highly elongated, the thickness also decreases massively. This can be undesirable.

3.6.2 Necessities for superplastic forming

Superplastic forming is not always applicable. First an elevated temperature is required. This temperature depends on the metal that is used, but is often close to the melting point of that metal. Also, SPF doesn't occur in all metal alloys. Metals subject to SPF need to have equally sized grains (preferably small ones). These grains also need to be stable, even at high temperatures. Sometimes even a special atmosphere (e.g. one without oxygen) needs to be created to achieve superplasticity.

To achieve superplastic forming, we also need a certain (often low) **strain rate** $d\varepsilon/dt$. Since the strain rate is low, the time needed to achieve the (usually big) deformations is high (often about one hour). This is of course undesirable.

Superplastic forming requires special equipment, which should be able to sustain high temperatures. It is also a slow process. It is therefore very expensive. However, the number of parts, joints and such can be significantly reduced by SPF. So in some cases it is worth using this method.

3.7 Forming of Fibre Reinforced Thermoplastics

3.7.1 Deformation mechanisms

Composites consist of fibres (the reinforcement) and polymers (the resin). Since the fibres have virtually no plastic deformation, deformation mechanisms used for metal sheets don't really work. For the **forming of fibre reinforced thermoplastics** (FRTP) different methods are used. (Since the forming of thermosets is very difficult, we won't consider that.)

The deformation mechanisms applicable on an FRTP highly depend on the fibres used. If short/medium fibres are used, then the fibres will flow within the resin. The resin will dominate the forming. If, however, long/continuous fibres are used, the fibre reinforcement will dominate the forming. Often **intra-ply shear** (the so-called **Trellis effect**) will be used. This causes the fibres to orient differently with respect to each other. Previously orthogonal fibres may not be orthogonal anymore. Sometimes, in the case of a laminate (a stack of layers) also **inter-ply slip** can be used. Now the different layers will slip with respect to each other.

3.7.2 Forming an FRTP

To form an FRTP, first a heating unit is needed. The composite is then preheated. This is because the thermoplastic resin needs to be heated above the **glass transition temperature**. Above this temperature, the resin becomes a soft and rubber-like material.

When forming metals, no heating unit is used, and the deformation mechanisms are very different. But besides that, similar tools are used to deform FRTPs and metals. The deep drawing of an FRTP is very similar to the deep drawing of metal. The same goes for rubber forming. However, for metal sheets failure limits are known. These limits are very hard to determine for composites. This is because they depend on various factors, such as resin type, fibre type, fibre orientation, etcetera.

4. Fabrication Processes by Separating

4.1 Separation by Shearing

4.1.1 Separating types

Cutting is the broad term used to describe the separation of materials and the removal of material from a workpiece. We can distinguish three types. First, there is separation with multiple parts and no chips, like punching. That's what this part is about. Second, we will examine separation with multiple parts and chips, like sawing. Finally we look at separation with a single part and chips, like machining.

Separating material using a **cutting blade** or a **punch** and **die** are essentially the same process, denoted by the term **shearing**. During the process a sheet is subject to shear stresses. We can make a distinction between **punching** and **blanking**. In blanking the shape we punch out (the **slug**) will be our product. In punching the slug is discarded, and the material around it will be the product. Both methods are often used for pre-processing. Shearing is not very suitable for composites and therefore mostly used on metals.

4.1.2 The process

During shearing, the sheet is placed on top of a **die**. Then a **punch** is pressed onto the sheet. First the sheet is indented and cut over a fraction of its thickness. It is then sheared over the remainder of it. The cutting area will therefore consist of a small smooth part (caused by the indentation) and a bigger rough surface (caused by the shear failure). The bottom of the plate will often also be deformed slightly in a downward direction. This causes a sort of ridge to form around the hole. This small edge is called a **burr**.

The punch and the die are product related. They are therefore relatively expensive, especially for small product series. The machines are subject to medium forces, and have a moderate cost as well. The raw materials (being only metal sheets) are relatively cheap.

4.1.3 Considerations

When punching, there are several parameters to consider. First there is the rather important **clearance**, which is the distance between the punch and the die. This is usually a few percent of the thickness of the metal sheet. When punching out multiple parts from a sheet, also the distance between parts, the so-called **width of walls**, is important. There should be a minimum to this, which depends on material properties. Finally the punching should be performed in such a way that there is as few scrap material as possible. This is called **nesting**. Often computer programs are used for this.

Sometimes it is convenient to apply so-called **bevelling** of the punch. By giving the punch or blade a small angle with respect to the sheet, there is more control on where the cut is initiated. Another way of getting more control is by using **fine blanking**. Here the metal sheet is not only supported by the die, but also clamped by using an upper pressure pad. Fine blanking is a very precise method, but also more expensive.

4.2 Separation by Removal

4.2.1 Mechanical removal

Some separation processes remove a narrow zone, called **kerf**, from the workpiece, separating it. This can be done either **mechanically** or **thermally**. We will first examine mechanical removal.

In mechanical removal sharp tools cut away **chips** from the workpiece. The most well-known form is **sawing**. Another form of mechanical removal is **grinding**. There is a fundamental difference between these two methods. In sawing the geometry of the cutting tool is well-defined. In grinding the cutting is performed by small randomly shaped elements imbedded in the tool.

Another form of mechanical removal is **water-jet cutting**. Here a small jet of water is shot at the metal. It is pressurized several thousands times the atmospheric pressure, resulting in velocities up to Mach 3. The materials that can be cut are soft materials. Hard materials can not be cut using normal water-jet cutting.

However, by adding small abrasive particles to the water, we have a new process called **abrasive jet cutting**. These particles are usually specially screened and sized sand particles. Abrasive jet cutting can cut hard materials.

A negative phenomenon during jet cutting is the so-called **jetlag**. As the water jet moves forward, the flow tends to bend away in the backward direction. This can leave marks on the specimen, potentially damaging it. Jetlag can be prevented by applying the right **feedrate** (the rate at which the jet moves forward). However, a slow feedrate is not desirable, since the manufacturing time should be minimized. So often a compromise is necessary.

4.2.2 Thermal removal

It is also possible to create kerfs by applying heat, melting/evaporating/burning away material. This is called **thermal removal**. The most common form of thermal removal is **laser cutting**. Now the source of energy is a laser, melting away portions of the workpiece. Laser cutting is sometimes difficult to apply on aluminium, as it is too reflective. Dull and unpolished surfaces are preferred.

A downside of laser cutting is that it has a low efficiency. A lot of energy is required. This can be reduced slightly, by applying suction or by blowing, removing loose material. This ensures that no energy is wasted on material that is already removed. But still energy is a big part of the operating costs of laser cutting. Also the equipment is often very expensive. However, no mould/die is needed, the raw materials are cheap and the process requires few manual labour.

There are also various other ways of thermal removal. In **oxyfuel gas cutting** metal is forced to react with oxygen, producing heat and oxidizing the metal. In **plasma arc cutting** a plasma beam is shot at the sheet of material. It is a slightly cheaper method than laser cutting, but it is less accurate. A similar method is **electron-beam cutting**, where the source of energy are high-velocity electrons. Since this method requires a vacuum, it is applied much less than laser cutting.

Finally we examine **electrical discharge wire cutting** (EDWC), being one of the most important production technologies in manufacturing industries. When two current-conducting wires are allowed to touch each other, a spark discharge occurs. This causes erosion. EDWC is based on this phenomenon. A slow moving wire travels through the material. The discharge sparks created by this wire then act like cutting teeth, cutting the workpiece.

4.3 Machining

4.3.1 Machining introduction

Machining is the general name for processes that remove small pieces, from a workpiece, creating a product. The tool that removes the chips from the workpiece is called a **chisel**. The pieces that are removed from the workpiece are called the **chips**.

There are three chip states. A **continuous chip** is just one long flake that is pulled off the workpiece. **Discontinuous chips** are small pieces that are separately torn off the material. The intermediate form is the **segmented chip**, in which the chip seems to consist out of multiple parts, but is still connected as one chip. Usually discontinuous chips are preferred, as they can not entangle with the cutting tool.

During machining, most of the money is spend on the machines and the tools. High forces are often present, so strong machines are a necessity. Few labour is needed, so the labour costs are low. However, always a compromise needs to be made, considering the **cutting speed** (the speed at which the chisel moves through the workpiece). For low cutting speeds labour costs and machine costs tend to be high for every product made. However, for high cutting speeds the tool costs are getting high. Therefore a cutting speed has to be chosen for which labour costs and tool costs are at an acceptable level.

4.3.2 The chisel

Let's look at the chisel. The area of the cutting tool, on which the chip pushes, is called the **rake face**. The other side of the chisel is called the **flank**. Also a **rake angle** α, a **tool angle** β and a **flank angle** γ can be distinguished, as can be seen in figure 4.1.

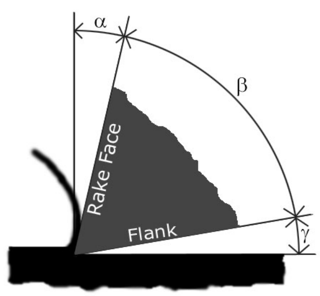

Figure 4.1: Machining parameters.

The rake angle influences the force needed to cut through the material. It can also be negative. The flank angle influences friction. This friction generates heat, which is undesirable. Therefore the flank angle is usually about 6°, which causes relatively few friction. Also a **lubrication** can be used to lower friction. And if the heat still becomes too high, **coolant** can also be added.

The chisel **wears** as it is used. There is **rake face wear**. The magnitude of this usually expressed using the **crater depth**. There is also **flank wear**. Its magnitude is often expressed by the **width of the wear**. Chisels often have a certain **life span**. This can be expressed by the **life time** (the time that can be cut), the **life length** (the distance that can be cut) or the **life amount** (the amount of products that can be made). When the chisel is worn, it can be sharpened or replaced.

The force that acts on the chisel during machining can be decomposed in three direction. First, there is the **thrust force** F_p, pushing the chisel on the workpiece. Second, there is the **cutting force** F_c, used to cut through the material. And finally there is the **feed force** F_f, which causes the chisel to continue its way through the material. The power which is needed for the process can now be found by multiplying the total force by the cutting speed.

What kind of material is the chisel made from? A chisel needs to have hardness at high temperatures and should also be able to resist shocks. The most used material is the so-called **hard metal**. This is a cutting material based on metalcarbides. When the carbide degree is increased, the heat resistance and the hardness is improved, but the brittleness also increases (reducing toughness). To profit optimally from both properties, **coatings** are applied, increasing the life time of the tool. Under special circumstances also other materials can be used. Ceramics, for example, perform better than hard metal under very high temperatures.

4.3.3 Turning

Turning is a type of machining in which the workpiece is rotating and the chisel is pushed into it. It is therefore usually only applicable to rotationally symmetric workpieces. The machine used for turning is called the **lathe**.

The chisel is similar to what was described in the previous paragraph. The top face is still called the **rake face**. There are, however, two cutting edges. There is the **side cutting edge**, positioned above the **side flank**, and there is the **end cutting edge**, positioned above the **end flank**. Which edge is cutting depends on the tool geometry.

Sometimes specials chisels can be used, for dedicated product shapes. It simplifies the work of the operator, but reduces the usability of the chisel. However, sometimes it is simply necessary. For example, for **screw threads** a so-called **thread cutting chisel** is needed.

4.3.4 Milling and grinding

Milling is the process which is suitable for non rotational symmetric products. During milling the tool (called the **mill**) is rotating, and not the workpiece. Different variations exist. In **face milling** the rotational axis is perpendicular to the machined face (just like is the case in drilling). In **slab milling** the rotational axis is parallel to the machined face. When both types are combined into one operation, we are dealing with a **side and face cutter**.

For slab milling two rotational directions are possible. In **conventional milling** the mill is pushing the workpiece away. For example, when the mill is rotating clockwise, it is moving to the left. Since the vertical force acted on the workpiece alternately points downward and upward, **flapping** of the workpiece may occur, which is undesirable. In **climb milling** the mill is pulling the workpiece towards itself. When the mill is, for example, rotating clockwise, it is moving to the right. This time no flapping can occur. But when the mill makes a stroke, it can pull the workpiece towards itself. If the workpiece is not properly constrained, **play** may occur. The stroke of the mill will then be too big, and the tool may break.

During face milling conventional milling and climb milling simply occur simultaneously. So the designer then does not have to choose between the two milling types.

Grinding is a process similar to milling. However, it uses a disk of individual abrasive grains as the cutting tool. The average rake angle of grains is highly negative. This has several implications. Only small layers can be removed at a time. Cutting also needs to take place at very high speeds. During grinding the temperature often increases rather much (up to $1600°C$). The depth of the cut has the greatest influence on this temperature increase.

4.3.5 Drilling

Drilling operations create holes. In a drill a rake face and rake angle are present, just like in a chisel. However, there is also a **point angle**. Drills with a very sharp points have a point angle of close to $0°$, while drills with a nearly flat top have a point angle of about $90°$. Which drill needs to be used depends mostly on the material that needs to be drilled.

The rake angle is usually not constant throughout the drill. In the center often negative rake angles occur, while at the edge more normal rake angles (of 20-30°) are present. Therefore cutting in the middle of the drill is often difficult. The fact that lower velocities occur near the center also contributes to this.

When very accurate or smooth holes are required, extra finishing processes can be applied. Processes like **reaming** and **honing** may improve the surface quality and roundness of the hole.

5. Assembly of Aircraft

5.1 The Assembly Line

5.1.1 Production types

Industrial production can be divided into four parts, being **single piece production** (1-10 products), **serial production** (100-1000 products), **mass production** (100000-1000000 products) and **process industry** (continuous production). Since aircraft are mainly produced in a series of a few hundred, they are made by serial production. That's why we only look at that kind of production. In serial production, **mechanization** is often not worth while. Creating aircraft is therefore often rather labour intensive.

In an aircraft factory, we can also distinguish three production stages. **Part production** is done in departments. In every department usually one kind of work is executed. During **small and medium assembly** all the (house-made and purchased) parts are assembled into sub-assemblies. In **final assembly** everything comes together. In stages the aircraft is build up from the sub-assemblies. Final assembly usually takes place in a specially designed factory.

5.1.2 Assembly line

The aircraft are created in the **assembly line**. This line has several stations. The product goes from station to station and remains in each station for a set amount of time. This time is the so-called **delivery time**.

This method has as advantage that transport cost is minimal. A more important advantage is the **routine forming**. Since every station performs the same task every delivery time, they tend to get better at it as time passes by. A well-designed assembly line can also save costs. For example, expensive parts like engines are build in as late as possible to save interest costs.

However, an assembly line is rather vulnerable. When one station is delayed, the whole line is delayed. Therefore often buffer stations are placed at critical points in the line. As the experience of the line increases, buffer stations can be removed and crew amounts can be reduced. Sometimes stations can be merged as well. An assembly line is therefore rather dynamic.

5.2 Divisions

5.2.1 Dividing the assembly line

Splitting up the production of an aircraft in multiple stages requires a lot of considerations. First of all, the work has to be split up into parts, and every part needs to be performed in exactly the delivery time. Also a good transportation must be arranged between the different stations.

Also economics are important. As was already mentioned, expensive parts need to be added as late as possible. Attention should also be payed to the workers. They often should get exactly the amount of work that has been noted in their contract. To all these factors needs to be paid attention.

5.2.2 Dividing the airplane

The airplane is made in parts, before it eventually will be assembled. The designer needs to determine how to split up the designed aircraft in these sub-assemblies. There are two types of divisions. **Mounting divisions** are for the use and maintenance of the aircraft. They include doors, hatches, removable parts, etcetera. **Manufacturing and production divisions** are needed for structural/manufacturing reasons. It is of course not possible to create an aircraft from one part.

Mounting divisions play an important role. They should divide parts that need to be detachable and exchangeable. There are three types of exchangeability. Parts that need to be exchanged regularly belong to type A. Type B consists of parts that need to be exchanged on a non-regular base, often caused by damage. Type C contains parts that only need to be exchanged in exceptional cases.

One of the most important manufacturing and production divisions in an aircraft is the wing fuselage division, since it is subject to high loads. There are three concepts to arrange this. The wing can be uninterrupted. In this case the fuselage needs to be interrupted. It is also possible to make the fuselage uninterrupted. But now there are two separate wings. The third possibility is to design the fuselage-wing section as one. This is the method most found in commercial aircraft. The fuselage and wing now have to be jointed to the same section.

Divisions almost always lead to an increase in weight. They give rise to stress concentrations, which demands reinforcements. Especially mounting divisions cost a lot of weight, as they need to be easily detachable. Divisions should therefore be minimized.

5.2.3 Jigs

During assembly, **jigs** and **fixtures** are used. These are basically scaffolds, in which the parts are joined to create one large part. The most important function of the jig is to support and handle the weight of the parts. Also the dimensions in the jig must be well defined, or parts may be wrongly positioned. The jig is therefore also a measuring tool. It should be stiff and have a good dimensional stability. It also needs to be accessible to workers. To accomplish this, jigs can often be rotated. When a part has been assembled inside a jig, it still needs to be removed from the jig. Jigs are therefore often separable.

During assembly, parts are clamped to the jig. This can be done in many ways. For stiff clamping, screwing or hydraulic clamping can be used. If the clamping needs to be easily detachable, lever operated clamps are often convenient. Also elastic clamps are possible. Preferably clamps do not coincide with reference positions. This is because clamps carry loads. If a reference position is subject to loads, it may deform and will not be an accurate reference position any more.

5.2.4 Lean manufacturing

In aircraft production new flexible cost-effective manufacturing principles often evolve. This is necessary, as aircraft are often custom made. The term **lean manufacturing** is often used for this kind of optimized manufacturing. In lean manufacturing the activities with no value are eliminated, while adjusting the production flow according to the costumer's demands.

Much attention is given to doing work out-of-jig instead of in-jig. **In-jig** assembly is applied when the parts are not rigid enough and need support. The jig then carries most of the loads. **Out-of-jig** assembly is used when the part is rigid enough by itself. The jig carries few of the loads. By using computer aided design and temperature controlled environments, sub-parts can be accurate enough to enable out-of-jig assembly.

More information on lean manufacturing will be given in chapter 7.

6. Joining Techniques

6.1 Joining Introduction

6.1.1 Joining reasons

Aircraft aren't made from a single part. Parts are therefore joined. There are several reasons for creating several parts and then joining them. We will be looking at those reasons now.

There can be **functional requirements**, often concerning different materials. Although the aircraft hull is made from aluminium, you don't want the windows to be made from aluminium too. So the windows and the aircraft hull need to be joined. Also the **size of the part** plays a role. Sometimes joining two parts together is more cost-efficient than creating one big part. Also the **complexity of the part** is important. You can't make a wing skin and stiffeners in one piece. That's just too complex.

To **inspect** the aircraft, often detachable hatches need to be present. These hatches of course need to be joined to the airplane. And if a part is broken and needs to be replaced, it's convenient if the broken part can be detached easily. So **maintenance** also requires (removable) joints.

Aircraft companies also prefer **flexibility**. If chairs can be detached and moved through the cabin, different flight classes can be created. And finally there may be political reasons two split the construction of a part up in sub-parts. Countries often invest in aircraft, and they would like to get some extra workplaces in return. So several parts will be created in every country, which eventually need to be joined together.

6.1.2 Hinges

Sometimes two parts shouldn't be entirely fixed, but should have some degrees of freedom. Examples for this are the doors and cargo hatches. This is accomplished by using **hinges** (sometimes called **kinematic joints**). Hinges are joints that have one or more degrees of freedom. There are 6 common types of hinges.

The **revolute hinge** is the most commonly applied hinge. It enables rotation about a single axis (taking loads and moments in all other directions). The **cardan (universal) hinge** allows two rotational movements. The **spherical hinge** or **ball and socket joint** enables rotation in all three direction. However, still no translation is possible.

The **translational hinge** offers translation in only 1 direction. No rotation is possible. However, moments around the translation axis are difficult to transfer. If such moment will be present, the **cylindrical hinge** is preferred. This hinge enables translation and rotation about the same axis. And finally there is the **planar joint**. This joint allows two translational movements and only one rotational movement. The planar joint enables rotation about the axis perpendicular to the translational plane.

6.2 Bonding

6.2.1 Bonding procedures

Bonding is the technique in which two plates are attached using an **adhesive**. It has many advantages. It requires no holes in the structure. There is therefore no weakening of the sheet, no stress concentrations and no sensitivity to fatigue. Since the bonding can't be detached, the structure is designed as safe life. Bonding also has a long lifetime. However, creating a bonding requires high temperatures and pressures. Next to this, a pretreatment is required. Bondings are also difficult to repair.

Another disadvantage of bondings is that it can't take stresses perpendicular to the adhesion plane. Such normal stresses are called **peel stresses** and result in debonding. That's why only stresses in longitudinal direction are considered here. But longitudinal loads can also cause problems. When a bonded joined is under constant stress, **creep** can occur. A larger overlap (meaning a large bonding length l in the direction of the force) will increase creep resistance.

Bondings can be created using thermoset and thermoplastic adhesives. Thermosets are more common, so we consider those first. First the surfaces that will be bonded, need **pretreatment**. This usually covers cleaning, degreasing and sanding, removing oxide layers. After this, the adhesives are applied to the surface. These surfaces are then joined and the adhesive is cured. During curing, the surfaces may not shift relative to each other. Fixing pins are usually used for this.

Pressure if often applied during curing. If this is the case, **adhesive flow** may occur, causing the adhesion thickness to decrease. To prevent this undesirable event, yarns/threads can be added to the adhesive. Thermoplastics are much less subject to adhesive flow, because of their high viscosity. However, the major downside of using thermoplastic adhesives is that they need to be applied in a heated state, making the process more complicated.

6.2.2 Bonding stresses

It would be nice to know what stress a bonding can sustain. The stress is however not constant throughout the cross-section of the bond. The edges of the bonding take up most of the stress. Stress calculations are therefore complicated. One calculation method is developed by **Volkertsen**. He stated that

$$\tau_{max}^{adhesive} = \frac{e^{\lambda l}+1}{e^{\lambda l}-1}\frac{\lambda l}{2}\tau_{average}^{adhesive}, \qquad \text{where} \qquad \lambda l = \frac{l}{\sqrt{t^{sheet}}}\sqrt{\frac{2G^{adhesive}}{E^{sheet}}t^{adhesive}}. \tag{6.2.1}$$

If the τ_{max} of an adhesive is known, and the relation between τ_{max} and $\tau_{average}$ is known, then the strength F_t of a bond can be found by

$$F_t = w\, l\, \tau_{average}, \tag{6.2.2}$$

where w is the width of the bond (perpendicular to the loading direction) and l is the length (parallel to the loading). An increase in l will, however, not mean F_t increases, as $\tau_{average}$ will decrease. A bond with a small overlap (small l) is therefore often more efficient.

To make a bonding efficient, the bonding needs to have the same strength as the plates it connects. So if t is the plate thickness and σ_{max} is the maximum plate stress, then

$$F_t = w\, l\, \tau_{average} = w\, t\, \sigma_{max} \qquad \Rightarrow \qquad \tau_{average} = \sigma_{max}\frac{t}{l} = \sigma_{max}\sqrt{t}\frac{\sqrt{t}}{l}. \tag{6.2.3}$$

The latter part is written as a function of $\sqrt{t}/l$, as this also occurs in Volkertsen's model. If we express both $\tau_{average}$ and σ_{max} as a function of $\sqrt{t}/l$, we can find the optimal $\sqrt{t}/l$ and thus the optimal l. In practice however, the value of l is chosen slightly larger to make sure sheet failure occurs before adhesive failure.

6.3 Welding

6.3.1 Weld introduction

Welding joins two pieces of similar material together to form a continuous section. This involves local melting of the material. Due to this heating, the welder's face and eyes must be protected by a mask.

In welding, the joint has a continuous character, so no stress-concentrations occur. Also there is no overlap of sheets. However, the quality of the weld is often inconsistent, and therefore welds can be unpredictable. Welds are also notorious for their poor performance under fatigue.

The heat that is necessary provides several other disadvantages. During welding the material is heated and partially liquefied. This can introduce residual stresses in the weld region. Sometimes an additional treatment is necessary to reduce these stresses. Also, any heat treatment that has been performed on the material will be undone near the weld. Welding is therefore not suitable for materials that have been subject to heat treatments. Because of this, and because the welding of thin sheets is difficult, welding is rarely applied in aerospace industries. It is slightly more common in space industries though.

6.3.2 Weld types

Two kinds of welds can be distinguished. There are **melt-welds** and **pressurized welds**. For each type, we can examine various parameters. Since welding requires local heating, a **heat source** is necessary. The heat can come from a flame, from an electric arc, from electrical resistance or even from an electron beam. Also the weld material is important. **Weld material** is material that is added to the weld. This can be done in the form of wires or rods.

Finally **environmental screening** can sometimes be necessary. This can be done in two different ways. In **slag protection** extra material is liquefied during welding. This prevents contact of the weld with the environment. In **gas protection** an inert gas is blown across the weld point, preventing the atmosphere from reaching the weld.

6.3.3 Melt-welding

In **melt-welding** there is a weld material that is added to the weld. Often the workpieces that will be welded need to be bevelled first, creating space for the weld material.

In **autogeneous welding** (also called **gas welding**) the heating is achieved by the flame of a burning gas. The welding process is protected by the combustion of the gas. Its usage has, however, been significantly reduced over the years.

A more common form of welding is **electric welding** (also called **arc welding**). Heat is supplied by an electrode. As the electricity jumps from the electrode to the workpiece, heat is created. There are two popular sub-methods. In **T.I.G.** (tungsten inert gas) the electrode is water-cooled, so only the product is heated. Weld material is added separately. In **M.I.G.** (metal inert gas), the weld material and the electrode are combined. As heat is created, part of the electrode (which isn't cooled) melts, thereby serving as weld material.

Finally in **electron beam welding** a highly focused electron beam is aimed at the welding point. It is a very specialized and accurate form of melt-welding, and needs to take place in a vacuum. It is therefore a rather expensive method.

6.3.4 Pressure-welding

In **pressure welding**, the two parts are kept together by physical pressure. No weld material is added and environmental screening isn't used. It is therefore a relatively simple weld method.

The most common variant is **spot welding**. Here two sheets of material are pressed together by water-cooled electrodes. A short burst of electricity heats the product, partially melting it at the contact point. Therefore a so-called **weld-lens** occurs at the contact point of the two sheets. If the electrodes are replaced by rollers, a continuous weld can also be created.

There is also **upset butt welding** in which bars/tubes are joined end-on. The welding principle is the same as in spot welding, so we won't discuss it further.

6.4 Rivets

6.4.1 Rivet introduction

During **riveting** a rivet is put in the hole of two or three sheets of metal. It is then plastically deformed, such that it holds the metal sheets together. Riveting can't be applied to composites, as the hole will be subject to high loads. A distinction can be made between rivets. **Solid rivets** are used for high strength joints, while **hollow rivets** are used for joints requiring less strength.

We can also make a distinction between **single joints** and **double joints**. In a single joint, the rivet is simply holding together two metal sheets, going in opposite direction. In a double joint the rivet holds together three sheets. The middle sheet is going in the opposite direction than the other two.

Rivets are reliable due to their well-documented use. They can often be applied using simple tools. Also repair is efficient, as they can be easily removed and replaced. However, they are fatigue-sensitive and require a lot of labour. They are also inefficient, as they weaken the sheets they connect.

6.4.2 Rivet strength

We would like to know the strength F_{ult} of a rivet connection. To find this, we have to examine the ways in which it fails. First of all there is **shear failure**. This occurs when the shear force in the rivet gets too high. For a single joint, the strength is

$$F_{ult} = \alpha \frac{1}{4} \pi D^2 \tau_{fracture}^{rivet}, \tag{6.4.1}$$

where D is the rivet diameter. The factor α is usually just 1. Only for thin sheets, where $D/t > 3$, is this correction factor present. In that case $\alpha = 1 - 0.04\,(D/t - 3)$. For a double joint, the strength can be calculated similarly, using

$$F_{ult} = 2\beta \frac{1}{4} \pi D^2 \tau_{fracture}^{rivet}, \tag{6.4.2}$$

where β now only exists if $D/t_{middle} > 1.5$ (with t_{middle} the thickness of the middle plate). If that is the case, then $\beta = 1 - 0.13\,(D/t_{middle} - 1.5)$.

The rivet presses against the hole in the metal sheet (the so-called **bearing**) with a force F. The **bearing pressure** is now defined as

$$p_b = \frac{F}{D^{hole} t^{sheet}}. \tag{6.4.3}$$

It can be determined at which bearing pressure $p_{b_{failure}}$ failure occurs. If this is known, then the strength against bearing failure is

$$F_{ult} = p_{b_{failure}} D^{hole} t^{sheet}. \tag{6.4.4}$$

A rivet can also fail due to deformation of the hole. An ovalization of 2% of the diameter D is allowed. The bearing pressure related to this is called $p_{2\%}$. The strength now is

$$F_{ult} = j p_{2\%} D^{hole} t^{sheet}, \tag{6.4.5}$$

where j is an added safety factor (often $j = 1.5$).

When all three strengths are calculated, the actual strength of the connection can be known. It is simply equal to the lowest of the three strengths.

6.4.3 Rivet row strength

When two plates are joined, a rivet row is used. This rivet row has a **rivet pitch** s (being the distance between rivets). When this connection fails, either the rivets fail (because of shear failure, bearing failure or deformation), or the plates fail.

Let's call Q the load per unit length. To prevent rivet failure, we need to set the spacing s such that

$$s \leq \frac{F_{ult}}{Q}. \tag{6.4.6}$$

Let's call the maximum stress in the sheet $\sigma_{failure}^{sheet}$. To prevent sheet failure, we must have

$$Qs \leq \left(s - D^{hole}\right) t^{sheet} \sigma_{failure}^{sheet} \qquad \Rightarrow \qquad s \geq \frac{D^{hole}}{1 - \frac{Q}{t^{sheet}\sigma_{failure}^{sheet}}}. \tag{6.4.7}$$

The optimum pitch is when both the rivets and the sheets fail at the same load. This occurs if

$$s = \frac{F_{ult}}{t\sigma_{failure}^{sheet}} + D. \tag{6.4.8}$$

So this is how the rivet pitch can be determined.

In the above calculations only static loads have been considered. When the connection is subject to dynamic loads, fatigue will occur. If the number of load cycles is high enough, the sheet will always fail through cracks between holes.

6.5 Bolts

6.5.1 Bolt stress

Bolts and **nuts** are often used in situations where the joint should be detachable. Bolts are not only detachable, but also strong, and they may be loaded both in tension and in shear. They are, however, slightly more expensive than rivets.

Due to the complicated cross-section, an exact stress calculation is impossible. However, we can look at the weakest point of the bolt. If a bolt with **inner diameter** d_c is loaded by a force F, then the average stress will be equal to

$$\sigma_{average} = \frac{F}{\frac{1}{4}\pi d_c^2}. \tag{6.5.1}$$

The stress is not evenly distributed. To find the maximum stress, we use a **stress concentration factor**, such that $\sigma_{max} = k\sigma_{average}$. This implies that the **strength of a bolt** is equal to

$$F_{ult} = \frac{\sigma_{failure}}{k}\frac{1}{4}\pi d_c^2. \tag{6.5.2}$$

Sometimes the surface of the metal plate isn't perpendicular to the bolt axis. The resultant force acting on the bolt then won't be in the middle of the bolt. It will be at a distance e sideward, where e is the **eccentricity**. Therefore a moment of Fe will be induced. This increases the stress at the edge of the bolt by

$$\sigma_M = \frac{My}{I} = \frac{Fe\,d_c/2}{\frac{1}{32}\pi d_c^4} = \frac{16Fe}{\pi d_c^3}. \tag{6.5.3}$$

6.5.2 Bolt prestressing

Bolts that undergo cycling tensile loads are subject to fatigue. Prestressing the bolts can reduce the effect of fatigue. This is done by tightening the nut more than normal, such that a prestress F_{pre} is created in the bolt. This compresses the flanges.

When an external force F_{ext} is acting on the joint, only a part will change the stress in the bolt. The other part of the external force is used to reduce the stress in the flanges. In fact, the part of the external force that will effect the bolt is only

$$\Delta F_B = F_{ext} \frac{E_B A_B}{E_B A_B + E_F A_F}, \tag{6.5.4}$$

where E_B and A_B are the E-modulus and the cross-sectional area, respectively, of the bolt. E_F and A_F are the same for the flanges. So if the flanges are much stiffer than the bolt (and thus $E_F A_F > E_B A_B$), then external forces hardly effect the bolt, as desired. Sometimes it's even wise to make the bolt more flexible, by reducing A_B. This is called **narrowing**.

It is an important demand that the pre-tension needs to be big enough, to prevent separation of the components of the construction. Therefore at all times we must have

$$F_{pre} > F_{ext} \frac{E_B A_B}{E_B A_B + E_F A_F}. \tag{6.5.5}$$

However, if the pre-tension is too large, the effects of fatigue resistance can disappear again. So pre-tension should be administered carefully.

6.5.3 Hi-loks

Hi-loks are a family of fasteners residing between bolts and rivets. They may be expensive, but they are much lighter than bolts. They are often used in places where riveting isn't possible to perform.

The holes in which the hi-loks are placed are not only drilled. They are also reamed, ensuring a good fit. After a hole is made, the nut of the hi-lok is being rotated, tightening the hi-lok. At a certain torque, the nut breaks. This ensures that the maximal force with which the hi-lok can be fastened is reached.

7. Lean Manufacturing

7.1 Lean Manufacturing Definition

7.1.1 Definition

After the second world war, the Toyota motor company came up with the so-called **Toyota Production System** (TPS). This is where the origins of lean manufacturing lie. Lean manufacturing is not a method that can be implemented. It is a way of thinking (so-called **lean thinking**).

In short, lean manufacturing is manufacturing without waste. A more precise definition is: Lean thinking is the **dynamic**, **knowledge driven** and **costumer-focused** process, through which all people in a defined enterprise **continuously eliminate waste** with the goal of **creating value**. We will now examine this definition a bit closer.

7.1.2 Parts of lean manufacturing

First of all, lean manufacturing is **costumer-focused**. The market is developing more and more form a **push market**, in which the producer has most influence on the products, to a **pull market**, in which the costumer influences the product. So product variety needs to increase.

A lean system also has to be **knowledge-driven**. This is because a system must be understood, before waste can be recognized and reduced. It is also a dynamic process. Lean manufacturing is developed over time and will continuously evolve.

The goal is to reduce waste. But what is waste? **Waste** is anything that uses resources, but does not create value. There are many types of waste. There is **overproduction** (implying storage), **waiting time** (when for example workers wait for machines), **work in progress** (when parts wait to be processed), **processing waste**, **moving/transportation** (movement of parts/personnel between machines/factories) and **rework** (in case of errors).

7.1.3 Value creation

The most important part of the definition of lean manufacturing is to create value. Creating value is where economic profit is generated. But what is value? The **value** depends on what the stakeholders define as value. To make sure value is created, a framework can be followed.

The first step is **value identification**. It has to be examined how the stakeholders find worth, utility, benefits and rewards for their contribution. Then there is **value proposition**. A plan is proposed about how to create value. Finally, in **value delivery**, value is created and delivered to the stake holders.

7.2 Lean Manufacturing Methods

7.2.1 The 5S approach and JIT

How do we achieve a lean manufacturing process? One of the most efficient methods is the 5S approach. This approach consists of 5 steps, being sort, simplify, scrub, standardize and sustain.

- During **sort** the items in the workplace have to be sorted on necessity. Unnecessary items are scrapped.
- During **simplify** items and machines are arranged, such that everything has a logical position.

- The **scrub** step requires that everything needs to be cleaned and maintained regularly, reducing costly failures.
- In the **standardize** step the continuously improved methods need to be documented and followed.
- Finally the **sustain** step should ensure that the made improvements will continue to exist and evolve.

Another method to improve lean manufacturing is **Just-In-Time** (JIT). This is a system for producing the right items at the right time, in exactly the right amounts. Ideally no buffers are needed.

7.2.2 Other methods

Load levelling is defined as levelling out the amount of products produced to the needs of the costumer. Only the products that are sold should be produced. A way of examining load levelling is by using the **Takt time**, which is defined as

$$\text{Takt time} = \frac{\text{Available working minutes per day}}{\text{Daily quantity required by the costumer}}. \tag{7.2.1}$$

Using the Takt time, the bottleneck of a production process can be found.

Cellular Manufacturing is the approach in which equipment and workstations are arranged in a sequence. This is done in such a way that smooth flow of materials and components through the process is ensured. Transport waste should be minimal. By placing similar products (needing the same equipment) into families (cells), changeover time can be reduced.

Total productive maintenance (TPM) is a series of methods to ensure that every machine is always able to perform. To ensure this, there is **preventive maintenance**, preventing failures, **correcting maintenance**, repairing failures, and **maintenance prevention**, preventing maintenance by using good equipment.

8. Quality Systems

8.1 Achieving Quality

8.1.1 Quality introduction

The **quality** of an object is defined as the totality of characteristics that satisfy the needs and requirements. To obtain quality, the costumer's needs need to be known. The product should then be made such that those needs will be satisfied.

To achieve quality, there needs to be a **quality system**. This consists of all the things that are needed to enable the company to achieve quality. Having a quality system provides various benefits. The most important factor is the improved efficiency. Workers have less unproductive time and fewer times errors are made in the production process. If a quality system is present, there are often third-party companies providing certification. This certification can be used for marketing purposes.

In a quality system, there should be **quality control**. This consists of all the activities that are used to assure quality. When errors are found, there should be systems that fix those errors as soon as possible.

Also **quality assurance** should be present. This is the ability to demonstrate that the products consistently comply with the requirements. It is necessary, because costumers require assurance that the products they buy fulfill their requirements.

8.1.2 Management's tasks

The management has a large responsibility in the functioning of the quality system. They formally express the ways in which quality should be achieved in a written **quality policy**. It should contain all the objectives and guidelines on how quality should be obtained and controlled.

All the activities the management then performs to comply to this quality policy are part of the **quality management**. The quality control and assurance are often part of this quality management. The management also needs to review the quality system regularly, to see whether it's still functioning as it should. Measuring costumer satisfaction can help in this.

The management is often also responsible for managing resources. The three most important resources are financing, time and personnel availability, although the latter two are closely coupled.

8.2 Checking Quality

8.2.1 Testing requirements

A part of quality control is inspecting the quality level of the products. One way to check products is to only perform **final inspection**. This is so-called **product focused**. A check is performed when the product is completed. This way of checking is, however, very time-consuming. The time needed can be reduced by taking samples. In this way a good picture of the quality can be obtained.

However, there are disadvantages to performing checks only at the end of production. Sometimes a product is doomed to fail at the start of production. If it still goes all the way through production, the waste will increase. In the so-called **process focussed** approach inspection is performed regularly throughout the production process.

Finally also the supporting process, consisting of the personnel and their environment, can be examined. This is so-called **system focussed**. By improving and checking on the quality of the workfloor, product quality can be improved.

All the inspection should be documented. This will confirm that inspection has taken place. Also if an error in the inspection has been discovered, it is possible to trace back possible faulty products.

When a product is found that doesn't comply with the requirements, it is examined by an independent engineer. Sometimes it can still be used, possibly after a bit of reworking. It is also possible that it is entirely discarded.

Machines that perform testing should also be checked and calibrated regularly. Calibration can be done in so-called **calibration laboratories**. However, sending all the machines to a calibration lab can be expensive. Often one **master machine** is send. All the other machines are calibrated using this master machine.

8.2.2 Testing methods

There are several ways to perform testing. The most common way is **visual inspection**. Here obvious mistakes can be filtered out. In **ultrasonic measurements** pulses of ultrasonic sound are send into the product. The reflection times and intensities give information about the product. In this way variations in thickness and voids can be found.

In the **fluorescent penetrant method** a fluorescent penetrant is applied to a surface. After a treatment, cracks and flaws can be found under UV light. Using **magnetic ink** goes similar. However, now a magnetic field is needed to detect flaws. **Eddy-current techniques** can also be used to finding cracks. In these methods a magnetic field is formed by very high frequency alternating currents. These tests often provide a very high resolution.

When polymers are tested, **acoustic emission analysis** can be applied. It's a difficult and specialized technique, which uses packets of acoustic waves. These are generated when an object is subject to stress. Another method suitable for composites is **thermography**. All objects emit infrared radiation. This can be detected by an infrared camera. Information about the product can then be derived.

More advanced methods, using radiation, are **radiography** and **fluoroscopy**. And finally there are also **hardness tests**. A material's resistance against permanent indentation says something about its strength. The most popular variant in aerospace engineering is the **Rockwell test**. It's fast, and it usually requires no further processing.

9. Working Conditions

9.1 Employer and Employee Obligations

9.1.1 The employer

An **employer** is a person for whom another person is obliged to carry out work. The other person is the **employee**. Employers are responsible for the working environment of their employees. Since safety measures cost money, employers often tend to ignore this. Therefore the **Working Conditions Act** protects employees. It obliges employers to provide a safe working environment. In case of accidents, the employer will be liable. To ensure a save working environment, the employer is often assisted by **OH&S experts** (Occupational Health and Safety).

9.1.2 The employee

An employee is obliged to follow instruction of OH&S officers. Employees also have the right to refuse work, if an unsafe situation is encountered. If a company has over 30 employees, a representation of those employees can have influence concerning matters of safety and health.

9.2 Dangerous Objects

9.2.1 Motorized equipment

There are regulations for machines. In Europe, motorized equipment should comply with European guidelines. If this is the case, an OE label will be present. If not, a worker should contact his boss.

9.2.2 Chemicals

When working with chemicals, you first need to know what you will do. What are your objectives? How will you reach it? You need to make a plan. If this is known, chemicals may be ordered.

To make working with dangerous chemicals (or something similar, like radiation) as safe as possible, several steps can be taken. First alternatives should be considered that are less dangerous. If this isn't possible, the chemicals should be shielded as good as possible. If this doesn't provide sufficient protection, it is finally possible to protect the workers by using personal protective equipment (PPE). However, PPE is often unpleasant for workers and is therefore preferably avoided.