Belgium presents:

Summary Materials II

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Inhoud

Introduction

All over history people have used materials to make structures, first fulfilling their primary needs, e.g. food & defense – weapons are real technology pushers. They did this using the materials they found in their neighborhood, inventions were rare. When the limits of available materials were reached, new technology developments were only possible with the discovery of new materials. Those new materials did not make the old materials obsolete, in contrary the old materials are often necessary to 'support' the use of the new materials.

History of aerospace structures

The first planes were made of so-called **wire-braced structures**, e.g. the biplane of the Wright brothers. Rectangular frames which were held in shape by 2 wires, preventing the structure from collapsing. Only simple tooling was required. Today wire-bracing is still used in ultralights.

The next 30 years **wood** was used: it was light and it allowed to close the structure, improving the comfort of pilots & pax. The technology was known from shipbuilding industry. Famous wooden aircrafts: the De Havilland Mosquito and the Spruce Goose.

In the middle of the 1930s, wood was gradually replaced by **metal**, this transition was partly stimulated by cultural & political arguments (metal = sign of progress, wood shortage). The technology took quite some time to develop, but is up till now more or less the standard.

Early day fuselages consisted of internal cross-bracing, however as fuselages became bigger these kind of structures were in the way for e.g. pax seating. A much more open structure was preferred: the **stressed skin/semi monocoque**. The skin is reinforced with frames and stringers and also carries part of the load itself. In a next step the same technique was applied in the wings.

The transition wood-metal and the adoption of the semi monocoque set the standard for many decades and a major step forward. The DC-2 was an infamous example of the combination of these 2 new technologies.

Later improvements were mainly towards: reduction of number of **rivets** (by using large integral parts or by using adhesive bonding), reducing effects of **minor damage** (by adopting a fail-safe structure or by allowing easy inspection), using more and more **composite** materials (lighter than metals, number of parts is reduced, often better fatigue properties,…)

One of the problems with stressed-skins is that they lack rigidity under certain load cases and have to be made thicker than really necessary to avoid **buckling**. Extra rigidity can be added by creating **sandwich** structures: a fairly rigid core layer (mostly a **honeycomb**) with on both sides a very thin sheet (all adhesively bonded together). The technology comes from wooden aircraft. However curved sandwich panels are still difficult and expensive to make, slowing down the adoption of it, while composite materials in other forms have gained importance.

Another problem with stressed skins is **fatigue**, a possible solution is to make skin panels of fibre metal laminates, e.g. GLARE: several layers of Al, polymer resin and reinforcing glass fibres. GLARE only requires minor adaption to existing facilities.

In the future more and more aircraft parts will be made of **composites**, while in the beginning mostly secondary parts were made of composites, now also primary parts are made of composite materials.

The aircraft manufacturer

Has two important roles: **develop** the package of the whole system and afterwards integrate and **assemble** everything together. Overview of different companies and their aircraft can be found on pp 1.14-1.20.

Lightweight structures

When flying with a heavier than air structure, try to make it only a bit heavier: lightweight structures. This allows flying to be economically feasible, every structural kg. that has not to be carried allows an extra paying kilogram and reduces the fuel consumption.

Because the lift forces is only indirectly created by letting air flow very fast over a wing, much of the development work went into the development of **engines**, providing enough forward thrust to obtain the high velocities required to fly.

A lightweight structure begins with lightweight materials. During the age of the wooden aircraft these lightweight materials were **bamboo** (strong, flexible, simple tooling, stiffened with metal wires) in the early days, later replaced by **spruce** (stronger and better processable). The structure was often covered with thin wooden panels or linen.

During WWI wood became scarce and gradually metal was tried to replace wood in aircraft design (e.g. Junkers). Later on, political decisions in England gave and impulse to metal aircraft design. In the beginning metal fuselages were still combined with wooden wings, however a crash of a wooden Fokker wrongfully interpreted as a flaw in wood construction meant the end of wooden aircraft.

Fabrication processes related to bulk materials

Casting

A molten metal is poured into a mould, after which both cool down and the product is separated from the mould. The mould is supported by a **flask** (**cope** on top, **drag** on bottom; **cheeks** are additional parts; seam is called **parting line**). Via the **pouring cup** and **sprue**, the molten metal enters the **runner system** (prevent entrapment of gasses, prevent contaminants of ending up in the product, prevent turbulent flow, let solidification not prevent the cavity from being filled) which leads the metal to the **cavity**. **Risers** supply additional metal as the product shrinks during cooling. **Cores** are inserts from sand allowing hollow sections. **Vents** are in place to transport gasses away from the mould.

Mould cavities can be created by placing a pattern (representing the shape of the final product) into the flask, filling it up with sand, followed by compacting the sand. Often **draft angles** are applied to allow easy removal.

The **flow** of the metals depends on it **viscosity** (lower = easier flow), **surface tension** (lower = smaller details). The **cooling speed** has a great influence on the process costs. Cooling of the molten metal results in **shrinkage**, for which an allowance should be taken into account. Defects like **micro porosities** (riser cannot supply enough extra metal during cooling process, resulting in 'hollow' sections inside the products) or **hot tears** (shrinkage is restricted locally, giving rise to high stresses and cracking) should be avoid. In general cooling should take place in the direction to the riser, this is achieved by giving areas further away from the riser a smaller thickness.

Practically any shape can be created using casting, however sharp corners and increases in thickness should be avoided to reduce stress concentrations. Another reason why varying thicknesses should be avoided is because of the fact that thicker areas will cool down slower (= **hot spot**) and micro porosities can be expected. One way to solve this is by applying local cooling: a **chill**. Large flat areas are as well difficult to cast as they tend to **warp** due to uneven cooling, also internal stresses will occur, they can be relieved with a heat treatment afterwards. Parts which should be machined afterwards also require **a machining allowance**.

Several types of moulds can be distinguished: expendable (sand, plaster,…), permanent (metal), composite (2 or more different materials). Sand casting operations mostly use synthetic silica sand, important properties are: **permeability** (allow gasses/steam to escape), **collapsibility** (allow casting to shrink and prevent hot tears), **surface quality**.

Two main laws control the flow of the metal: continuity law & Bernoulli law, from these two laws it follows that the diameter of the sprue should decrease while the metal is falling downwards, otherwise the flow would separate from the walls and air would become entrapped. Turbulent flows should be avoided as they give rise to **dross** (=foam), by designing the channel system such that turbulent flows do not occur or by applying vacuum, such that dross does not occur.

The **shrinkage** during cooling is split up in 3 parts: cooling before solidification, phase change during solidification and cooling of solidified metal. Since the latter provides the largest shrinkage, the mould is allowed to collapse at the end of the process. If this is not possible (permanent moulds), hot tears will occur more frequently.

Another problem during the cooling is the **out gassing** of gasses present in the liquid metal, moulds with a good permeability allow easy escape of these gasses, for other moulds **vents** should be incorporated.

Variants

- ✓ **Plaster-mould/Ceramic-mould** casting: sand is replaced by plaster or ceramic, providing better surface quality and improved precision. However permeability is much less.
- ✓ **Shell-mould** casting: sand is mixed with small amount of thermoset binder and a heated pattern is used: a shell starts to grow around the pattern. Two shells combined provide a mould cavity. The surface quality is better, but the lower permeability and the degassing of the polymer require proper venting.
- ✓ **Permanent mould** casting: only feasible for larger product series, low permeability, good surface quality, smaller details can be incorporated. The moulds are often coated with graphite serving as parting agent and thermal barrier. Often the process time is shorter.
- ✓ **Lost-wax/Investment** casting: pattern is made of wax, which are assembled in a tree and coated with a ceramic, next the pattern is melted out (preferably in vacuum) and metal is poured into the ceramic moulds. A high accuracy can be obtained.
- ✓ **Expendable pattern** casting: pattern is made of e.g. polystyrene, coated with a slurry and surrounded by sand. Next metal is poured on the polystyrene, causing it to evaporate, hence the metal replaces the polystyrene.
- ✓ **Centrifugal** casting: for rotational symmetric products with hollow inside.
- ✓ **Revolve** casting: product toppled over 3 axes.
- ✓ **Pressure die** casting: liquid metal is pressurized, can solve venting problems, promotes flow of the liquid, hence thinner walls and more complex shapes can be cast, however the mould needs to be stronger.
- ✓ **Injection moulding**: for polymer products, temperature is much lower, viscosity is much higher, the materials is pressurized and transported with a screw, shearing it and lowering its viscosity.
- ✓ **Metal injection moulding**: metal powder is mixed with polymers, after this process the polymer is removed.

Mechanical properties are often lower with respect to forged products and the minimal thickness of the product is higher, however the process is cheaper and for non-critical parts with a casting factor of 2, no testing is required.

Investment casting is often used in aerospace, because of its precision, ability to combine several parts into one product, predictable fatigue levels and its corrosion resistance.

Lay-up

Is the placement of the reinforcement of FRP into a mould, typically used for materials with textile appearance. The individual reinforcements **lamina/ply** are cut from a roll into the required shape and next built ply-by-ply into a **laminate**. Both wet (impregnated with resin) and dry reinforcements can be used. Lay-up is always followed by other processes: impregnation with resin for dry reinforcements and **curing** (polymerization) by autoclaving or vacuum bagging for both type of reinforcements. The goal of this process is to have a desired fibre architecture and orientation. During cutting reinforcements of a roll scrap should be avoided as much as possible (expensive material). Also each layer should be handled with care to obtain the right orientation of the yarns and avoid damage of the material.

The **size** of the products in practically **unlimited**, only small products are not made with lay-up as the size of the reinforcements is in the order of mm, too small products would result into inhomogeneous materials. Moulds are used during this process, so draft angles are common, divisible moulds are more flexible, but more expensive and cause **flash lines**. Especially **shell-like** structures are made with lay-up, **sandwich** structures are also possible, but if the resin is added after lay-up open core material cannot be used, because it would fill up with the resin.

The mould is made from epoxy, wood or metal. It depends on the number of products to be made and whether the mould will be used during curing (180°C, 5 bar). The cutting process ranges from manual cutting with scissors and knives to automated cutting with machines.

Any type of materials (tape, woven yarns, dry fibre mats,…) can be used, narrow tapes are avoided because they require too much work. The **tackiness** of prepregs simplifies the lay-up as it prevents the material from slipping in the mould. However during **wet lay-up** (impregnation just before lay-up) the tackiness is very low and the resin can even be a lubricant. A **glue** sprayer might be used to attach the reinforcement locally to other layers. During the lay-up damage of the reinforcement might occur (folding, tearing, breakage,…) or misalignment, reducing the mechanical properties substantially.

The required equipment is minimal, thus equipment costs are low (even when using automated machines the costs are moderate due to the low forces). Mould can be cheap (low forces). The labor is extensive during hand lay-up. Costs of fibres is high (prepregs even higher). Typically low-medium sized series length. The cycle time is rather long.

Variants

- ✓ **Hand lay-up**: First **release film** (prevent sticking to mould), then resin layer (**gel coat**: high surface quality), then reinforcement layer rolled in the resin, followed by resin-reinforcement-resin-… Simple and cheap process.
- ✓ **Spray-up**: The spraygun **chops** the continuous fibres and **impels** it through resin. The fibres settle in the mould in a random direction, hence limiting mechanical properties. However this process is cheaper than hand lay-up (less labor, cheaper material).
- ✓ **Tape laying**: Machine places the reinforcements (often unidirectional tape) into the mould, forming a laminate. Much faster and less labor intensive process than hand lay-up, allows high volume production of flat/low curvature components and provides better mechanical properties (more precise).
- ✓ **Vacuum bagging**: After lay-up: curing to obtain a composite. Applying pressure during curing can lower the **void** content (better properties), this can be done by either applying vacuum or stacking metal sheets onto the product. Before curing the product is covered with a **peel-ply** (to remove other films after curing), **release film** (minimal bondage product-waste), **bleeder fabric** (storage of excess material), **breather fabric** (to let all air flow to the vacuum pump), **vacuum bagging film** (ensure vacuum arises).

- ✓ **Autoclaving**: Adds extra temperature (lets the resin cure better/faster) and pressure (squeeze out more voids) to vacuum bagging. Often prepregs are used for this. The products can show thermal stresses, however thermosets show stress relaxation.

Resin Transfer Moulding (RTM)

Collection of closed mould, low pressure processes. The dry, often **pre-shaped, reinforcements** are placed first into the mould (which is treated with a release agent), the **resin** (often **2 components**, mixed right before insertion, to release **air entrapped** during mixing, the mixed resin is often placed in a vacuum chamber) is inserted afterwards to impregnate the reinforcement. Afterwards the product is cured.

Flow of the resin is possible by applying a higher **pressure** at the inlet and/or lower pressure at the outlet. The higher the pressure difference, the quicker the process, but the reinforcements might move with the flow and greater forces occur.

For short cycle times, tooling must be capable of being heated, be rigid enough to compress the reinforcements and be able to resist the abrasive nature of the reinforcement. Several attempts are being made to use epoxy moulds: lower weight, lower costs, shorter cycles, easier,…

Critical resin selection parameter are the minimum viscosity, **pot life** (how long and at which temperature does the resin keeps this viscosity) and permeability of the reinforcement. Mostly **thermosets** are used (thermoplastics: too high viscosity).

Reinforcements are usually weaves & mats of fibre materials. They should be preformed into their 3D-shape before placement in the mould. To ease placement the reinforcement can be made sticky. The permeability is often **anisotropic** (flow of the resin is different in different directions), **dry spots** (non impregnated areas) must be avoided, the higher the **porosity** (number of voids present), the longer the process will take (all voids must be filled).

Size of the products is less important (both small & big products can be made). The geometry and especially the placement of the in- and outlets are important, because if this is not done correctly resin free regions will be present. If a short-cut is formed between the in- and outlet (**runner**), large dry areas will be left in the product. Curved shells can be created easily, as well as sandwich structures, curved shells with stiffeners are much harder to produce.

This is a rather low speed process, hence the series length is rather short. Smart placement of the in- and outlets, as well as the use of multiple in- and outlets can reduce the process time considerably. The machines can be quite cheap (low forces, moderate accuracy is sufficient,…) Labor forces are moderate (also take into account turnaround times, because this is a low series process).

Variants

- ✓ **Vacuum Assisted RTM**: vacuum is applied at the outlet (next to increase pressure at inlet), shortening the cycle time.
- ✓ **Vacuum infusion**: flow depends solely on vacuum applied at the outlet. Lower forces, one mould can be replaced with foil (only 1 smooth surface though), lower costs, unlimited product size, other resin distribution techniques possible.

- ✓ **Structural Reaction Injecting Moulding**: a highly reactive 2 component resin is fed under high pressure into a mixing chamber and then immediately injected into the mould, where it retains its low viscosity for 20s after which is cures rapidly. Short process times.
- ✓ **High-speed RTM**: combination of the previous processes. Preferably steel tooling (moderate pressure, good heat transfer characteristics).

Most RTM processes are very slow, because the moulds are often built from cheap materials, hence pressures must be kept low, which gives rise to long filling time. The cure times are often long as well, due to the inability of the mould to tolerate elevated temperatures. So some research is done into the high speed variants of this process.

However RTM allows the manufacture of large, complex (maximal integration) and high performance structures at minimal costs. Due to the placement of the reinforcements, the flexibility is high and tailored designs are possible.

Filament winding

Open mould process in which the reinforcement (**yarns, tapes** or **roving**) is wound onto a mould (**mandrel**, treated with release agent, mostly rotational symmetric), which is rotating on a **lathe**. The reinforcement are stored onto a **reel** and before it is wound onto the mandrel it goes through a resin bath to impregnate it, to allow impregnation the reinforcement needs to be pretensioned. The angle w.r.t. the rotation axis under which the reinforcement is wound onto the mandrel is: **winding angle** (90° hoop winding, 0° polar winding, rest: helical winding). If the reinforcement is wound **geodesically** (path is as short as possible, automatically, when there is no friction between reinforcement-mandrel) there holds (Clairaut law):

$$r_i \sin \alpha_i = constant$$

Non-geodesical winding provide more freedom, but this depends on the available friction and applied loads will try to straighten the reinforcement. Hence for simplicity geodesical winding is preferred.

During curing the mandrel should still be rotating, to allow an evenly distribution of the resin.

There are 2 important limits on the shape. First of all the mandrel should be able to be **removed** after the curing (by using tapered shapes, divisible mandrels (expensive), soluble mandrels (for each product new mandrel required), use the mandrel as a part of the product,…). Second, the reinforcement must **stay** on the mandrel during the process: therefore the allowed curvature is limited and the reinforcement should never see concave (hollow) curvatures. It is possible to create non rotational symmetric shapes, the machines get more complex though. When the loads are very well known (pressure vessels), each reinforcement can be placed such that they all carry the same amount of load, this results in a certain prescribed shape (**isotensoide**), assuring minimal material use.

For larger products the mandrel is often placed vertical to prevent sagging (bending) of the mandrel under the weight of the applied reinforcements.

The resin is mostly a **thermoset**, the most important requirement is that they do **not cure at room temperature** (or at least not very fast, as the winding is a long & slow process), curing is mostly done in an oven or autoclave.

Thermoplastics are generally solid at room temperature, however there are some methods to filament wind with thermoplastics: heating the mandrel locally right before the reinforcement is placed onto the mandrel (gives local expansion and internal stresses); solving the thermoplastic resin in a solvent (however only very aggressive solvents are suitable); winding the thermoplastic en reinforcement together (available as strands), followed by heating, pressing & cooling (buckling can occur).

The reinforcement is continuous, the **width** is an important parameter, together with the winding angles it determines whether a cross section can be covered completely without overlaps. The width should be chosen so that the overlap is minimal. When winding non cylindrical products, a complete covering should be realized at the largest cross section, implying that at the other smaller cross sections there is some overlap (= increased thickness of the product). A large width also has advantages: shorter process time, however on double curved surfaces tape width a large width have the tendency to come off the surface at the sides.

This is a very low force process (light thus cheap equipment, moulds,…), limited labor, high raw material cost, slow process time, so short series.

Variants
Strive to wind large mandrels or shorten the process time

- ✓ **Vertical mandrel**
- ✓ **Increase rotation speed**: however limited with wet resins (would otherwise fling away) and limited by centrifugal accelerations
- ✓ **Tumble winding machine**: increase winding speed, while still low forces (mandrel follows wobbly path)
- ✓ **Multiple reels**: called **braiding** when the reels are placed in a circular away around a translating mandrel (only dry reinforcements)

Filament winding provides high mechanical properties at reasonable costs.

Forging

A work piece (a metal alloy, called **billet**, **slug**, **preform**) is shaped by compressive forces through various dies & tools. Can be done at elevated (hot forging) as well as room temperature (cold forging), the latter requires greater forces but requires less surface finish and has better dimensional accuracy. There exist **open-die** forging (shape final product not fixed in the die geometry, a solid workpiece is just placed between 2 flat dies which compress it) and **impression-die** forging (here the initial material is often pre-shaped so the deformations should not be too extreme).

During pressing the cylindrical shape will change into a **barrel** (due to friction workpiece-die & ends of cylinder –near the die- cool down quicker, changing the properties). Applying lubricants and using heated or insulated dies will reduce these effects. Because the amount of material required to fill the cavity cannot really be determined in advance, a **flash** will be present after forging (can be removed by trimming).

Forging is **not suitable** for **thin walled** parts, or parts with large thickness variation, because the material will cool of too quickly, changing its properties and making further thinning difficult, eventually resulting in cracks & tearing. Other defects can occur as well when either there is too few material to fill the cavity (buckling will occur) or if the web is too thick (internal cracks will develop).

A variety of forging machines exists:

- ✓ **Hydraulic presses:** load limited (press until certain pressure is reached), slow (workpiece tends to cool).
- ✓ **Mechanical presses**: stroke limited, varying speed during the forcing process, high forces at the end of the stroke.
- ✓ **Hammers**: energy limited, high speeds, short process time & low cooling rate (allows complex shapes with thin & deep recesses).

Dies should have enough strength & toughness at elevated temperatures and be resistant to mechanical/thermal shocks & wear. To reduce friction & wear, lubricants can be applied, they also lower the required forces, improve the flow of the metal, act as a thermal barrier & parting agent.

Forgeability = capability to undergo deformation without cracking. Generally low density and low temperature materials (e.g. Al & Mg) appear to be forged easiest. During forging the material is locally stretched, resulting in a **non uniform grain pattern** (it can however be controlled up to a certain amount and will in general provide better properties, however when flow lines are perpendicular to the surface area, the grain boundaries are prone to be attacked by the environment causing rough surface and acting as stress raisers), forged parts often have good mechanical properties and can be applied in critical areas of the structure.

During hot forging, internal stresses will occur due to the **non-uniform cooling** down: outside cools down quicker (compressive stresses) in comparison with the inside (tensile stresses), this is however often advantageous for the fatigue properties. Due to the shrinkage, a shrinkage allowance should be applied.

Machine & die costs are mostly moderate-high, in aerospace, forged parts are often produced in several steps. This in combination with the limited series results in high costs for forged products, however for certain highly stressed, critical areas there is no other choice.

Variants

- ✓ **Precision forging:** special dies are used with greater precision that require much less finishing processes, forces are higher (equipment should be stronger thus), Al & Mg are preferred because they allow fairly low forging loads. Costs of dies (more complex) & equipment (higher forces, more accuracy required) are higher, but less finish processes are required and there is less material waste.
- ✓ **Coining:** for making coins, require fine details (very high pressures), lubricants cannot be applied.
- ✓ **Heading**: produce a larger cross section at the end of a rod/wire, used to make screws, bolts, rivets,… High production rate. Caution to avoid buckling.

Extrusion

A metal **billet** is squeezed through an opening (= die), creating a long profile. It is a semi-continuous process (billets are size-limited), performed at elevated temperatures and followed by a straightening process. Afterwards the profiles are sawn and if required heat treated.

The only limit to the geometry is that it has a constant cross section, but it can even contain multiple voids. The scale is denoted by the **CCD**, a measure for the complexity is the **shape factor** (perimeter divided by cross section). Voids in cross section can be created in 2 ways: the billet already contains a hole or the billet is moulded and welded (especially suitable for Al extrusions), though the right pressure & temperature are required.

The wall thickness has a lower bound and should be as constant as possible. Also sharp corners should be avoided.

To lower the required forces a lubricant can be used (e.g. glass for metals), this is however not possible when extruding hollow sections using welding.

The better the mechanical properties of a metal the less suitable it is for extrusion.

Because most metals have an **oxide layer** that should not end up in the extruded product, often a small layer of the billet is left in the pressing container. The grains of the billet are stretched during the extrusion process, hence extruded products will have some amount of anisotropic behavior.

Thermoplastic polymers can be extruded as well, however just as with injection moulding, they need to be transported using a screw, which also sheares the material. Because small billets can be fed to the screw, this variant of extrusion has a continuous nature. Polymers are much less stiff than metals and will tend to **swell** when they exit the extruder, because of springback in radial direction.

The only product dependent piece of equipment are the dies, as they should withstand the elevated temperatures and high forces they are made of steel. The **dies** are rather **expensive** giving rise to large product series.

Variants

- ✓ **Standard/Direct/Forward extrusion**
- ✓ **Indirect/Reverse/Backward extrusion:** billet moves away from profile
- ✓ **Hydrostatic extrusion:** billet is smaller than container which is also filled with a fluid that transports the pressure applied with a ram

Pultrusion

Variant of extrusion that is used for composite materials. It is however completely different from extrusion: rovings are pulled through a resin, to form a profile with a constant cross section. The curing of the resin afterwards determines the shape of the profile.

Pultrusion products can have a larger CCD (because the forces are lower). Hollow sections are created by placing the fibre materials in advance in predetermined places, which automatically ensures the creation of hollow sections where needed.

Moulds for pultrusion are much longer because they have to support the impregnated rovings and it is also the place where curing takes place. They are product dependent and because of the long changeover time, high product series are required.

Generally a thermoset resin is used, that cures while in the mould. Pultruded products show a high degree of anisotropic behavior. To enhance properties in perpendicular direction, layers of random mat can be added, this also lowers the risk of **splitting** (when only a few rovings get loaded).

When a thermoplastic resin is used (much higher viscosity), the process is changed, the resin is now added as yarns and in the end melted/consolidated together by temperature & pressure.

Variant

- ✓ **Wire drawing**

Compression moulding

A mix of reinforcement and resin (theromset/thermoplastic), called **charge** or **moulding compound**, flows between 2 moulds (treated with release agent, bottom is called cavity, top force/plug) by applying a pressing force, resulting in a composite part. The moulds often consists of 2 blocks that when assembled, the matching surfaces form the outline of the final product.

Both pressure (to let the mix flow) and temperature (to cure the thermoset resin or make the thermoplastic resin less viscous) are required. After initial pressure, often the 2 moulds are opened for a short while to allow entrapped gasses to escape (**breathing**).

The size of the products is limited by the size of the press and the maximal force that the press can generate. Sharp corners must be avoided, draft angles should incorporated. Stiffening elements can be added, however when the material shrinks, **sink marks** (dents) can occur at the outside of the shell on the places where stiffeners are attached to the shell (on the inside).

Thermoset resins are generally created in advance using an extruder (to mix it with the reinforcements). When storage is required this should be done at low temperatures. At the start of the actual process the resin is heated (either by bringing it out of the fridge to room temperature or by using a heating device). The moulds are heated as well, and when the resin hits the heated moulds, the viscosity is lowered, allowing the resin to start flowing from there. Some resins require degassing.

Thermoplastic resins are also create in advance by combining it with reinforcement at elevated temperatures in an extruder, this requires rather high forces (due to higher viscosity). Just before insertion the compound is heated, lowering the viscosity. The moulds remain cold, this way the mould cools down the resin during the process such that it is rigid just after the whole cavity is filled. The charge is a kind of block (a plate would cool down too fast) and the flow takes place at the middle of the compound.

When 2 flowfronts merge, **knitlines** are created, they are weak sections as the reinforcements do no cross such a knitline.

The reinforcements are either chopped or continuous fibres, both randomly orientated to let the flow of the resin govern the process. When fibres break in the extruder during mixing, mechanical properties will be lowered. The design is based on a random fibre orientation, however in some areas the fibres will rotate and align themselves in the flow, leading to areas with aligned fibres, hence creating a product with properties that are not expected. Control of the fibre orientation is difficult.

This is a high force process, requiring a heavy, strong & expensive press, the same holds for the moulds. Labor is low, raw material cost is moderate to high. It is a fast process, with long series length. Material waste is minimal.

Variants

- ✓ **Sheet Moulding Compound:** charge has the form of one or more sheets, shorter flow trajectories.
- ✓ **Bulk Moulding Compound:** charge has some kind of block form.
- ✓ **Glass Mat Thermoplastic sheet**: continuous fibres with thermoplastic resin.
- ✓ **Transfer moulding**: comparable to injection moulding.

Fabrication processes related to sheet materials

Introduction

Deformation mechanisms

Forming = (permanent) deformation or deflection of a material

- ✓ **Plastic deformation of metal sheet**: through the displacement of dislocations (causing strain hardening).
- ✓ **Superplastic forming of metal sheet**: certain metals under certain special conditions show superplastic behavior: extreme plastic deformations under small loads. In this case the grain boundaries slide along each other, the grains themselves do not deform.
- ✓ **Shear deformation in FRTP**: the fibres prevent most of the deformation in fibre direction, however through intra-ply (Trellis effect) shear & inter-ply shear these composites can still be formed.
- ✓ **Flow of short FRP**: flow of polymer material (mixed with small fibres) at rather low temperatures. E.g. compression moulding.

Relation material-geometry-manuf. process

- ✓ **Shape <-> Material:** complexity of the shape depends on formability of the material (often expressed as max. applicable strain), following is an overview of various classes of sheet metal parts ranked in order of complexity:
  - Undeformed
  - Single curved (straight bend line), large bend radius
  - Single curved (straight bend line), small bend radius (few times the sheet thickness)
  - Double curved, large bend radii
  - Double curved, one small and one large bend radius (e.g. stringers with curved flanges)
  - Double curved, locally small bend radii in orthogonal directions
- ✓ **Shape <-> Manuf. process:** each of the above shapes requires its own particular manufacturing operations. Some shapes only require simple bending, other also require in-plane deformations, which cannot be performed with a bending machine.
- ✓ **Material <-> Manuf. process:** dominated by the formability of a material (ability to be deformed permanently), indicated by 2 properties: maximum applicable deformation & required deformation loads. As the formability of a material improves, more complex products can be made, requiring other machines & processes.

Plastic deformation of sheet metals

In a stress-strain graph, 4 areas can be denoted:

- ✓ **Elastic area**: complete spring back.
- ✓ **Homogeneous deformation**: deformation is combination of elastic & plastic deformation, area is ended by the point where the applied force is maximal.
- ✓ **Diffuse necking**: further deformation is concentrated in a limited part of the specimen, where the thickness locally reduces.
- ✓ **Local necking**: just before failure, the necking gets concentrated in a very narrow band over the cross section, very shortly afterwards the specimen fails.

For plastic forming processes often the end of the homogeneous deformation is taken as the forming limit (sometimes the end of diffuse necking is taken).

Elastic deformations are eliminated once the loads are released: **springback**. This can occur either **in-plane** (does not change overall shape) or **out-of-plane** (common after bending, geometry does change and tools and dies should take this into account, hence shape tool ≠ shape product).

In real life stress & strain are 3D (or when considering sheets: 2D stress-state), the strain has a big influence on the maximum applicable strain, this influence is shown in the **FLC** curve, showing the max strain in 2 directions.

The formability can often be changed by **heat treatments**, generally good mechanical properties give rise to a low formability and vice versa. Hence hard materials are often annealed or solution treated (+ quenched) first, then formed and afterwards treated again to improve the mechanical properties.

Bending

During pure bending, **no** in-plane stresses occur

Bending model

- ✓ Isotropic, homogeneous material
- ✓ Congruent stress-strain curve (compressive & tensile curves symmetrical about the origin)
- ✓ Bending is applied by a pure bending moment
- ✓ Cross section flat before bending, remain flat after bending (in reality this does not hold for small strips where the outside of the curvature will contract, and the inside will expand: **saddle-back**)
- ✓ Bend radius is constant in the bend zone (not true in reality, as the transition: bend zone (finite radius) – non deformed zone (infinite radius) would be discontinuous)
- ✓ No internal stresses before the start of the bending

- ✓ There exists a neutral line (stress & strain free)
- ✓ Strain increases linearly w.r.t. neutral axis
- ✓ $\varepsilon_{max} = \frac{t}{2r} \times 100\%$

The stress distribution is non-linear w.r.t. neutral axis (only the part that is purely elastically deformed shows a linear stress distribution). The elastic part of the bending deformation will cause springback, changing the bend angle, bend radius & position of the **heel-line**. Whenever the elastic part is not fully retrieved by springback residual stresses will remain in the part. Because in the cross-section both elastic & plastic deformations are present, generally some residual stresses will remain in bended parts.

Many bending operations are performed on a press brake consisting of a stationary lower bed (with bending die attached to it) & a moving upper bed (with the bend radius attached). Both are considered universal tools, reducing process costs. Several techniques exist: **V-die/air bending**, **matched die bending** (sheet makes full contact with rigid lower die and is squeezed, reducing springback), **rubber die** (sheet is bended on a rubber pad, high quality bend radius, higher forces required).

Bending over a very large radius can be accomplished with **bending rolls**: a 3 point bending moment is applied, large springback. Generally multiple passes are required.

The minimum bend ratio is given by $(r/t)_{min} = 100\%/(2 \times \varepsilon_{\max})$, the end of the **diffuse necking** can be selected as the failure limit (local thinning is compensated by thickness increase on the other side of the neutral axis).

Springback is related to the ratio (elastic energy stored during bending)/(total energy required for bending)

- ✓ **High E-modulus**: reduced springback
- ✓ **High yield strength**: increased springback
- ✓ **Bend ratio increases**: springback increases
- ✓ **Bend angle increases**: springback increases

Bending is usually used to create prismatic (stringers, profiles, stiffeners,…) or box-like parts. Limitations on the process are either machine limitations (max size/force), shape limitations (everything should be foldable in a logical order), material limitations (depends on max strain).

Product series vary from very small to very large: **press brake** processes for creating complex parts (with many bend lines) require a lot of labor and hence result in limited series, **wipe & guided bending** are often used in automated processes, product series are very large, **roll forming** tools are product related, thus a long product series is required.

Variants

- ✓ **Roll forming:** a metal strip is gradually transformed into a stringer/profile by a set of rolls placed in line, each adds to the final cross section (the last rolls can be placed out of line for curved profiles). Some in-plane strains occur. This is a continuous process. Costs are rather high.

Stretching

Used for the manufacturing of large & slightly double curved shells. During this process **bending & stretching** is combined in one process. The stretching forces are under an angle to the vertical axis of the machine, causing a bending moment in transverse direction.

Stretching eliminates springback (perpendicular to the surface, thus decreasing the bend radius) to a great extent, because the sheet is in its full thickness plastically deformed. Some in-plane springback still occurs.

A large **double action press** is required as the material should be stretched while a die is forced into the sheet. Generally a single die is required, because of the negligible springback the dimensions of the die are equal to those of the final product.

In aerospace, mostly Al alloy are stretched, the required strains are usually much higher than what the Al can take. Hence multiple **stretching operations** are required, often with **intermediate heat**

treatments, however not too much to not deteriorate the grain structure of the alloy. High strain hardening coefficients (steep slope stress-strain curve in plastic region) are advantageous (large areas participate in the plastic deformation, resulting in smaller strains).

Stretch forming can also be used to produce single curved parts with a relatively large radius but with a complex cross sectional shape (e.g. parabolic) and/or high required tolerances.

A disadvantage is the high amount of scrap.

Costs of the die (1-to-1, thus simple; only product related tool) are and tooling are rather cheap, however the machines are expensive and labor costs are high. The series size of an aircraft is just about right for stretching.

Deep drawing

In this (non-aerospace) process a metal sheet, clamped between a **drawing die** and a **blank holder** (preventing wrinkling & buckling), is pushed through the die opening, transforming it into a cup with a bottom and vertical walls.

Deep drawing requires a **double action press** as well: one action for the clamping of the sheet and one action for the movement of the **punch** (providing the shape of the part, it's the product related tool). The **drawing die** assures the material in the flange of the blank is transformed into the **product wall** (clearance punch-die: larger than thickness, but not too large: secondary wrinkling). Surfaces of both dies should be smooth, as the metal sheet should be free to move between both dies (without buckling though).

The material in the bottom of the cup is stretch formed into 2 directions, the flanges are deformed in shear mode, the product walls are only strained in height direction, the circumferential strain is zero (however stress in this direction is not equal to zero). The weakest point is generally the transition of the punch radius to the product wall.

Materials suitable for deep drawing show **planar anisotropy** (large ratio (strain in width direction)/(strain in thickness direction), thus resistance towards excessive thinning), also a high strain hardening coefficient is beneficial.

A great variety of products can be created. The forming limits are expressed by the maximum depth-to-width ratio or the deep drawing ratio β (= D_0/d, original blank diameter divided by punch diameter for which the flange is completely drawn into the wall of the cup.)

Deep drawing requires multiple dies for one part, therefore tooling costs are high and the product series should be large, that's why it is only applied in aerospace for parts where there is no real alternative.

During **matched die forming** 2 (very expensive) dies are made which match perfectly w.r.t. each other, the geometrical difference between the 2 tools is related to the sheet thickness that is to be formed. During the several steps of the process (often using multiple dies) a metal sheet is stretched, bend and sheared into its final shape. Because of the high series length, this process is not used in aerospace industry.

Rubber forming

Is very often used in aerospace industries (due to the low production & tooling costs and the lack of many product related tools, a large variety of parts in limited series can be made at a reasonable price, perfectly suited for aerospace industries).

Rubber forming uses a **soft (universal) rubber tool** and a rigid **(product related) tool** (often made from laminated wood). The rubber tool (usually consisting of a thick permanent part and a thin part that is replaced when the surface wear becomes too high) forces the metal sheet over the rigid tool using pressure. A variant uses a fluid cell (covered by a rubber membrane) to form the blank over the die. The rigid tool is either a **male tool** (flanged products, machined before forming, relatively small strains) or a **female tool** (deep-drawn like products, trimmed afterwards, usually much larger strains).

Rubber forming has many advantages: small product series, simplicity, universal tooling, low costs, surface of sheets is not damaged. However there are some disadvantages: wear of the rubber tool, high pressure required, long cycle time.

The **presses** are very big (should produce enormous forces) and are used as much as possible, to reduce the effects of the long cycle time, often multiple parts are formed at the same time.

Most parts are **heat treated** before the forming operation (to reduce springback), by applying solution treatment and quenching, in a refrigerator they can be kept in this unstable state up to 2 days. After the forming operation the material attains the required hard condition without further treatment.

Rubber forming is primarily used for parts with (curved) flanges, both **shrink** and **stretch flanges** exist. During the forming of stretch flanges the flanges are formed by bending the flanges over a curved bend line and tensile stresses in the flanges. These tensile stresses will result in both in-plane and bend angle springback. The rigid die should be compensated for this, this makes the male dies rather difficult to design. The forming of shrink flanges is very similar, one big difference is that the flange tends to wrinkle, however as pressure is further increased, the wrinkles are reduced and eliminated.

During the forming of deep-drawn like parts, during the first stage the material is drawn into the die cavity, secondly, when the material already makes contact with a significant part of the bottom, the drawing into the die cavity stops and further deformation is accomplished by stretching the material nearby the bottom radii. The achievable complexity is lower w.r.t. deep drawing, however details can be incorporated in the same step.

Superplastic Forming

In contrary with plastic forming, deformations occur by the sliding of crystals along each other, no deformation of the crystals occurs. Only **certain materials** under **certain conditions** show superplastic behavior. Superplastic forming may lead to **large strains**, hence complex, integral parts can be created, reducing the need for costly joints.

Superplastic forming is performed at **elevated temperatures** (500°C-900°C), requiring special equipment and in the case of Ti a special inert atmosphere is required as well (to prevent the diffusion of oxygen into Ti, making it brittle). As the stresses and forces are very low, gas pressure is sufficient to stretch the material into a die cavity. To prevent the sheet from excessive thinning, the material is often prestretched with a male tool before being drawn into the die cavity, or preformed by gas before getting its final shape over a male tool.

Some material features are required for superplastic forming:

- ✓ **Forming at high temperature**: the elevated temperature is required to provide the right viscosity at which the grains can slide along each other. The grains do not melt & remain solid though.
- ✓ **Equi-axed structure of small grains**: equi-axed grains allow sliding in any directions, small grains slide more easily as the gliding surface is bigger.
- ✓ **Stable grain structure at high temperature**: most metals recrystalize or reorganize their grain structure at elevated temperatures, metals suitable for SPF have in-built mechanisms to prevent grain growth at elevated temperatures.
- ✓ **High strain rate sensitivity at some strain rates**: under some circumstances the stress is a function of the strain rate solely, under these conditions and a certain (usually very low) strain rates, SPF behavior occurs. The low strain rates often mean very long process times.

The large strains allow the production of complex, very integrated parts with a lot of details incorporated. Sometimes SPF is combined with diffusion forming (where a bond between 2 metal surfaces, that are squeezed together at high pressures & temperatures, is created by atomic diffusion).

Some disadvantages are:

- ✓ **Cavitation:** due to the gliding small mismatches (cavities, pores) can be created, during further deformation these pores can grow and link up in larger cavities. The application of **back-pressure** might counter cavitation.
- ✓ **Excessive thinning:** massive and non uniform decrease of thickness over the sheet.
- ✓ **Expensive process:** high equipment costs (high temperature & pressure), long process cycles

Forming of FRTP

Deformation in the direction of the fibres is virtually impossible (low maximal strain and generally fibres only deform elastically). Different deformation methods are used, based on the **Trellis-effect** (angle between fibres changes due to applied shear force) and/or **interply slip** (slipping of the various layers of a laminate over each other).

The sort of fibres used determines to a great extent the possible shapes and production methods: short and long fibres will flow with the resin, continuous fibres will on the other hand will dominate the formation of the composite.

The presses for FRTP are very similar to metal forming presses, the most importance difference is the presence of a **heating unit** to heat the thermoplastic above its glass transition temperature. The dies depend on the production method being used, however matching dies are not used (trellis effect can locally change thickness, in matching dies the composite part would be damaged).

Biaxial straining is very difficult to impose on FRTP with continuous fibres. Failure limits of composites are less known in comparison to metals, as these limits depend on a wide variety of parameters.

Variants

- ✓ **Press forming:** composites are preheated and during the press forming cooled down below the glass transition temperature.
- ✓ **Compression moulding**
- ✓ **Deepdrawing**
- ✓ **Rubber forming**
- ✓ **Diaphragm forming:** laminate is clamped between 2 foils with vacuum, next a vacuum is also applied underneath the package

Most processes show a lot of resemblance to the metal sheet forming processes, however the failure limits are less known and more complex.

Manufacturing processes related to cutting technology

Separating (multiple parts, no chips)

All processes denoted in this part have in common that material is separated by **shearing** using a cutting blade or a punch and die. One can distinguish **punching** (sheared **slug** is discarded, compare making holes in paper) and **blanking** (slug is the part, the rest is discarded).

During shearing operations, the materials is first indented and cut (results in a smooth and shiny edge), next the sheet is sheared over its remainder (gives rise to **burrs**, rough fracture surfaces). Burrs are tiny edges or ridges, their height is proportional to the clearance and ductility, also dull tools create burrs. Major processing parameters: lubrication & clearance die-punch.

Scrap can be significant, that's why some effort has to be put in proper **nesting** of the blanks.

There is a minimum distance between the product walls while cutting products from a sheet, such that: width of the wall should not fail when die exerts pressure on it, remaining material should not end up in the hole of the die, remaining material should not give rise to burrs, remaining material should not injury craftsmen.

The **clearance punch-die** is an important parameter: if it increases more materials is pulled into the clearance zone, edges get rougher, zone of deformation gets larger. Clearance distance depends on: type, temper, thickness, size of the blank, proximity to the edges, ductility,… Generally: smaller clearance means better edge quality. Ductile materials have a greater smooth to rough surfaces ratio.

The location of the region being sheared can be controlled by **beveling** the punch or blade surfaces (the cutting zone progresses along the cutting line), it also reduces the force at the beginning of a stroke and lowers the noise level. Symmetric beveling eliminates lateral forces.

Often (especially with brittle materials) a **tiny crack** runs in front of the cutting zone, that may become large and affect the quality, these cracks have a zero initiation period and negatively affect fatigue life.

Composites are generally not punched or blanked as they tend to delaminate, the fibres also increase wear on the punch or cutting blade.

Cutting processes with punch and die are relatively cheap but require big product series (product specific tools), for small series other non dedicated tools are more appropriate.

Variants

- ✓ **Fine blanking:** used for producing very smooth and square edges, a V-shaped stinger or impingement locks the sheet tightly and prevents distortion. The costs are usually much higher.
- ✓ **Guillotine shears:** consists of fixed cutting blade, holding-down plate and moving cutting blade. A proper clearance is needed to prevent that the bending moment becomes too big.
- ✓ **Nibbling:** create many overlapping holes after each other, any desired path can be followed. Usually additional finishing operations are required due to the rough edges.

Separating (multiple parts, chips)

This processes remove a narrow zone of material (**kerf**), splitting the workpiece in multiple parts, this can be either done mechanical or thermal (heat melts, burns or evaporates material).

During **mechanical** removal sharp tools cut through the material, generating **chips**. Most mechanical cutting tools are variants of machining. **Thermal** removal creates kerfs by evaporating (plasma arc cutting), burning (oxyfuel gas cutting) or melting (laser cutting) material away. Loose material is often blown or sucked away to reduce the required energy (less material must be heated then).

During **laser-beam** cutting, highly focused optical energy is added to the material, it melts material away. Laser-beam cutting does **not** require **vacuum** and works with both metallic, non-metallic, ceramics and composite materials.

Materials with **low reflectivity** (e.g. dull and unpolished surfaces) and **low thermal conductivity** are better suited for laser-beam cutting (they require less energy to be added), Al is not very suitable. Laser-beam cutting leaves a rough surface and a heat affected zone, hence often requiring heat treatment. Often a **gas-stream** is flowing along the cutting zone: it blow away loose material and sometimes adds an oxide-free edge.

In general only **flat sheets** are laser-beam cut, as the distance between the sheet and the laser is small (difficult 3D-control). Sharp corners should be avoided as well as deep cuts (laser tends to taper, since its focusing is limited).

The laser-equipment itself is very expensive, but all other costs are low, because cutting is usually highly automated and very flexible (no dedicated tooling).

Variants

- ✓ **Oxyfuel gas cutting:** the workpiece is first preheated with fuel gas, after which oxygen is added, the reaction that then takes place gives rise to very high temperatures. Most material is removed by oxidation (burning). Thicker sheets can be cut (w.r.t. laser beam cutting), tolerance control is reasonably good, the flame leaves drag lines and surfaces usually end up somewhat rough. (particularly suitable for steel)
- ✓ **Plasma arc cutting:** plasma is a thermally highly heated up, electrically conductive gas (4^{th} stage of material existence). Temperatures during plasma arc cutting can become as high as 10,000°C. It is less accurate than laser beam cutting, but cheaper. It is not used for composites as they degrade too much during plasma arc cutting.
- ✓ **Electron beam cutting:** high velocity electrons strike the surface of the workpiece and generate heat. It requires a vacuum environment. It is very expensive & dangerous (X-rays), though more precision can be obtained as well as a narrower kerf zone.
- ✓ **Electrical discharge wire cutting:** a slow moving conductive wire travels along a prescribed path, generating discharge sparks which remove the material bit by bit. It can cut through very thick and hard materials, as long as it is an electrical conductor. It is a very accurate but fairly slow process. Because it does not use mechanical but electrical energy, it is especially useful for very hard materials.
- ✓ **Water-jet cutting:** water under high pressure is aimed at a material to cut through it. It is only applicable to soft materials (rubber, soft wood,…). Some advantages are that: no heat

generated, cutting can start everywhere, minimal burr production,… To be able to cut through hard materials, abrasive particles can be added to the water stream:

- ✓ **Abbrasive jet cutting:** abrasive sand particles (**garnet**) are added to the water jet stream. Now also harder materials can be cut.

A typical characteristic of the 2 last processes is the occurrence of **jet lag** due to the zero stiffness of the water beam, this gives rise to **tapering** effects, **kickback** (beam is bend differently w.r.t. the machine itself). Thick sheets can show barreled kerfs. Composites can be cut as well without much damage.

Machining (single part and chips)

Machining is removing **many small chips** from the workpiece with a tool that is called a **chisel**. The area of the chisel on which the chip pushes is called the **rake face**, the angle between the chip and the rake face is called the **rake angle**, the larger this angle is, the lower the forces to cut and the less the chips is deformed. The rake angle is usually positive but can be negative during e.g. grinding. The chip is **sheared** away from the workpiece, the deformation during the shearing generates heats, as well as the rubbing between the rake face and the chip. The other face of the chisel, the **flank** also rubs against the workpiece (due to the springback of the workpiece after it was elastically deformed by the chisel), generating heat.

Thus there are 3 heat sources during machining, to keep the temperature in range and avoid excessive wear **coolant** (reduce temperature) and **lubricants** (reduce friction) are often used. To lower friction a larger **flank angle** could also be used. Also the cutting speed can be reduced. The wear on the rake face is denoted by the c**rater depth**, the wear on the flank angle by the **width of the wear**. When the crater depth becomes too big, the edge of the chisel will break, leading to a blunt tool which can destroy a workpiece if cutting would be continued. If the width of the wear becomes too big, the surface quality will decrease. The life span of a chisel can be expressed as: **life time** (the amount of time that the chisel can cut), **life length** (total distance that the chisel can cut), **life amount** (number of products that can be made). When it is worn it can be sharpened or replaced.

Forces on the chisel can be decomposed in thrust force, feeding force and cutting force. Most cutting machines are power limited, thus if the required force becomes too big, the rotation speed should be lower. Decreasing the rake angle, increases the required force.

Size of the product is mostly limited by the machine used, shape generally by the process itself, as well as how the workpiece can move relative to the chisel. The wall thickness has a minimum (thin walls are elastically deformed, resulting in uncontrolled wall thickness) that depends on the stiffness.

The workpiece materials greatly influences how the machining is performed, the tool life,… Chips formed during machining are preferably discontinuous (cannot entangle with cutting tool). Softer alloys (from e.g. Al) are not necessarily more suitable for grinding, as they usually form continuous chips that can adhere to the cutting tool. Also due to the high thermal expansion coefficient and low stiffness, dimensional control can be difficult.

Some steels are easy to machine (e.g. when alloying elements act as stress raisers in the shear zone), others very difficult (e.g. martensitic steels which are very abrasive and form edges on the cutting tool).

FR composites are not machined, their fibres are very abrasive and the material delaminates easily.

Cutting materials must possess: **hot hardness**, **mechanical shock resistance**, **thermoshock resistance**, **resistance against adhering** to workpiece material. There exist

- ✓ **Unalloyed steels**: not enough hardness at high temperature
- ✓ **High speed steels:** much better hot hardness
- ✓ **Hard metal:** most used cutting material, properties are compromise between toughness and wear resistance. That's why often **coatings** are applied which add wear resistance while not compromising the toughness. Usually the cutting materials are applied as **inserts**, making them easy to replace.
- ✓ **Ceramic cutting materials:** much higher allowable temperature during cutting, however they are much more brittle and should only be applied during cutting processes where no mechanical shocks are expected.
- ✓ **Cubic Boron Nitride**
- ✓ **Diamond:** hardest material, is only stable up to temperatures of 600-700°C. Steels tend to absorb the carbon. Hence it is usually used during finishing operations of non-ferro metals to produce very smooth surfaces.

Tools during machining are not product depend, hence small-moderate series length is the most ideal, mass production can be accomplished with other cheaper processes. By considering costs independent of cutting speed, tool cost (increases with cutting speed) & labor cost (decreases with cutting speed), an optimum cutting speed can be found.

Variants

- ✓ **Turning:** the workpiece itself is rotating on a **lathe** and the chisel is pushed (speed = **feed**) into the workpiece. The chisel has 2 cutting edges: **side cutting edge** and **end cutting edge**, the mutual top face is called the **rake face**, the flanks are called **side flank** and **end flank**. During **straight turning** the side cutting edge cuts most material away, during **facing** the end cutting edge performs most work.

  To make the chips discontinuous **chip breakers** or **chip breaker grooves** can be added to the chisel's rake face (when a chip hits it, it must deform to keep following it, but as it has already sheared, it will break).

  The **roughness** is different in the **two directions**: in turning direction it depends on the wear of the cutting tool, in axial direction it depends on the feed and the cutting tool geometry.

  The lathe should be very stiff, if it would continuously wobble, the final shape of the product would be seriously affected.

  Chisels can be dedicated product shapes, that however limits the flexibility.

- ✓ **Tracer lathe**: variant of turning, the shape of another product is copied via a mandrel to the workpiece.
- ✓ **Milling**: used to create non rotation symmetric products, during milling the tool is rotating. One can distinguish:
  - **Slab milling** (rotation axis parallel to machined face), the cutting tool also has a clearance angle, tool angle and rake angle. The **rake groove** in front of the rake face transports the chips away.
    - **Conventional milling:** the cutter starts to form a very thin layer (sort of rubbing action: decreased surface quality), gradually the chips become bigger and the rubbing action becomes a real cutting action. The cutting forces is initially directed downwards, but changes direction during the process: **flapping** can occur.
    - **Climb milling:** the cutter cuts immediately (better surface quality), the chips are from thick to thin. The cutting force always pushes onto the workpiece (no flapping). However as the feeding force is pulling onto the workpiece, any play of the table would feed too much extra material to the cutter, eventually breaking it.
  - **Face milling** (rotation axis perpendicular to machined face) both conventional and climb milling occur. Most cutting is done with the perimeter of the mill. Inserts can be used if the mill is large enough.
  - **Side and face cutter** (combination of the above)
- ✓ **Drilling:** used to create holes. Chips are transported away by the rake groove, however this can prove to be difficult for certain materials. Cutting is most difficult in the middle of the drill (slow speeds and highly negative rake angle), however as the material in the middle of the whole is to be removed, this is not really a problem. At the edge of the drill the rake angles are positive and normal cutting takes place.

  Different materials need different drills, e.g. concrete needs a hard soldered metal tip, cooling should be sufficient in that case (otherwise the tip would come lose obstructing further drilling operations).

  After drilling operations, the surface quality of the whole often needs to be improved by means of **reaming** or **honing**.

- ✓ **Grinding:** removing chips using individual abrasive grains as cutting tool. Rake angles are usually highly negative (giving the chips a much bigger deformation), cutting speeds are very high and the thickness of the removed layer is much smaller (w.r.t. other machining processes).

  Temperature should be well controlled: too high temperature will cause residual thermal stresses and distortions by thermal expansion/contraction. Temperature increases with grinding speed, depth of cut,… Temperature can become very high but chips carry away a lot of the heat, however often coolant is still needed to keep the temperature away from the melting point. When workpiece material melts and is absorbed by the grinding disc, no more grinding is possible.

- ✓ **In-** and **external screw thread** can be created using special tools like **screw-plate** (ext) and **screw tap** (int), tapping must be done with caution: a broken tap is often impossible to remove.

Assembly of the aircraft

Aircrafts are produced in **series production**, as the series are **limited**, mechanization does not pay-off therefore the production of aircraft is a **very labor intensive** process. In the production of an aircraft, one can distinguish: **part production**, **small/medium assembly** & **final assembly**.

The final assembly is done in a so-called **assembly line**, consisting of a **number of stations**, each with its **own crew** and **tools** doing the **same kind of work**. The product goes **from station to station**, remaining the **same amount of time** in each station (**delivery interval**). There are numerous advantages on this way of assembling: minimal transport, simple planning, good progress indications, maximal equal shaped product & maximal routine forming (provides maximal cost reduction). Large production series require more stations and a shorter delivery interval, the opposite is true for small series.

Divisions should be planned in early during the design, some considerations on doing that:

- ✓ Most final assembly lines consists of multiple **sidelines**
- ✓ **Special/complex** parts are treated **separately** (e.g. cockpit section)
- ✓ The line is **vulnerable**, at critical places **buffer stations** can be included
- ✓ **Installations** are usually built in **early**
- ✓ **Expensive parts** are usually built in as **late** as possible
- ✓ During **extreme workloads**, stations can be **doubled** or **more shifts** can work on a station
- ✓ When experience increases, buffer stations can be removed

Divisions can be either **mounting divisions** (are there for an effective **usage** of the aircraft), **manufacturing divisions** (for **structural** & **economical manufacturing** reasons).

Requirements on mounting divisions are that they need to be **detachable** & **exchangeable**. Assembly & disassembly must be **simple**, need for **special tools** should be **minimized**, parts & subassemblies should be rigid & not easily damaged (they often need to be **transported**). Three sorts exist:

- ✓ **Type A:** need to be exchanged on a **regular base**, **quickly** and in a **straightforward** manner.
- ✓ **Type B:** exchanged on a **non-regular base** (often after incidents), may take **some time**
- ✓ **Type C:** exchanged in **exceptional cases**, can take **several days**, often requires **large amount of work**, often carried out in **factory**

Some requirements on manufacturing divisions:

- ✓ Everything should be divided in **equal**-**sized work packages**
- ✓ Work should be **maximally accessible**
- ✓ Parts cannot be bigger than the **machines** used
- ✓ Non-detachable joints should be as **light** as possible and joints should be **simple** & **cheap**
- ✓ Divisions must be made on **natural locations** and the **structural shape** must be taken into account
- ✓ More divisions require more (simple) jigs, less divisions require less (but more expensive) jigs, so a trade-off must be made

The **wing-fuselage** division is a very important one: high loads are transferred, fatigue problems, sealant problems (pressure cabin) & fuel tanks make this a challenging area. Three concepts exist:

- ✓ **Wing NOT interrupted:** fuselage contains cut-out for the wing, the large normal stresses in the girders do not have to be transferred to the fuselage. A division in the wing is often made some distance from the fuselage (loads are less over there). No moment have to be transferred between the wing & the fuselage, so the fuselage-wing fitting is relatively light. The cut-out in the fuselage creates certain problems: loads in the fuselage need to be transferred around the wing and sealant problems might occur.
- ✓ **Fuselage NOT interrupted** (only when wings should be detachable)**:** 2 separate wings, spars transfer load from wing to fuselage (so load carrying skin not possible near the fuselage), due to the large girder stresses to be transferred, this is a heavy joint. Sealant problems do not occur.
- ✓ **Wing-Fuselage designed as one** (done in most commercial aircraft)**:** both fuselage and wing need to be joined to a special section, the **wingbox**.

Parts are either **purchased** or **produced** by the manufacturer itself. This is done in **departments**, at every department one kind of work is done: maximal occupation of personnel and machines. The parts are produced in batches and then stored.

Those parts are assembled together into **small** & **medium sized** sub-assemblies, this is also done in **departments**. When the work-time is short, the work is carried out in batches, when production time becomes longer small sub-lines are used which produces a small amount of sub-assemblies after which the sub-line is ceased. The tendency is to produce more & more integral parts, reducing the need for sub-assemblies.

Finally all the sub-assemblies are assembled together on the **final assembly line**, the work can either be done **in-jig** or **out-of-jig** (cheaper & more suitable for larger series with a short delivery interval, but it requires that the parts are rigid enough to form a stable unit, often involves computer aided positioning of parts). Jigs are some kind of scaffolds to which all the subparts are fastened at their respective positions, after which they are joined together. They serve 2 goals: **support** the handling and weight of the parts and **position** the sub parts in a well defined way. Requirements on jigs are:

- ✓ They should be **stiff, rigid** and have the right **dimensional stability** (they should not/hardly deform/vibrate)
- ✓ Parts should be **clamped firmly** at the right position, so that they cannot move anymore
- ✓ **Accessibility** should be at right height, without straining craftsmen too much and without endangering them. Often they can rotate (also no diagonal member: hinder access)
- ✓ They should be as **cheap** as possible
- ✓ **Not hinder removal** of finished parts
- ✓ **Minimal space occupation**, e.g. by assembling parts vertically
- ✓ **Small jigs** must be **movable** (flexibility)
- ✓ **Prototype** jigs must also be used for serial production
- ✓ **Changes** must be incorporated **easily**
- ✓ **Thermal expansion** must be incorporated during design

Connecting stiff parts to more flexible parts, allows easier assembly (joining 2 stiff parts requires very accurate tolerances, otherwise one will have to force the 2 parts to be able to joint hem). Once those parts are assembled together they form a stiff(er) part

Joining techniques

Introduction

Joining always adds extra material (the joining material itself and often as well extra material around the joint to compensate for stress concentrations). Reasons for joining & making divisions are:

- ✓ **Functional requirements:** e.g. ancient axe: chisel must be made from stone to be sharp and strong, handle must be made from wood to be light and to be able to provide a useful shape.
- ✓ **Size of the part:** large parts often require divisions to decrease manufacture and handling difficulties.
- ✓ **Complexity of the part:** e.g. Al skin with stiffeners, frames, ribs,… cannot be produced as one integral part with the common manufacturing method (although some methods allow much more integration).
- ✓ **Maintainability:** sometimes parts must be able to be replaced regularly, this cannot be done if everything is made from one piece.
- ✓ **Flexibility:** e.g. the seating configuration inside an aircraft must be easy to change, therefore the seat should be attached with a removable joint to the floor.
- ✓ **Inspectability:** the low weight aircraft structures are designed according to a fail safe concept, this implies that regular inspections are necessary, to allow these inspections, hatches are required to be able to look inside the structure.
- ✓ **Movability:** some parts like e.g. flaps require one or more degrees of freedom, this parts require hinges (non-fixed joints that allow one or more degrees of freedom).
- ✓ **Costs:** it might turn out that adding divisions is cheaper than making everything as one integral part (e.g. because the production method for the integral part is very complex and expensive).
- ✓ **Political:** e.g. Airbus; when different countries take part into a company (often with government funds), each country gets his part of the share, so every member gets profit.
- ✓ **Economical:** e.g. for risk sharing, different companies work together on one product so the investments and risk are spread over multiple firms. Or expensive parts (e.g. engines) are attached at the very end to avoid interest losses.
- ✓ Divisions in aircraft are inherent on the **way** aircraft are **produced**: on an assembly line consisting of stations.
- ✓ **Accessibility** of the work **during assembly** might require divisions, e.g. to facilitate the installation of system into a fighter aircraft, a lengthwise division is often found. Afterwards the 2 halves are assembled in a **marriage-jig**.
- ✓ Parts can not be bigger than the **size of the tools** used.
- ✓ When **stringers** & **frames** meet they cannot both continue, generally the stringers are divided.

Overview of hinges

Hinges = joints with one or more degrees of freedom. The **safe life** philosophy is applied often as joints are difficult to inspect and inside a joint there is usually only one load path. Multiple joints together form together off course a fail safe structure.

- ✓ **Revolute hinge:** e.g. door hinge, carries all loads, except moment around rotation axis.

- ✓ **Translational hinge:** only allows translational movement, moments around rotation axis are difficult to transfer (instead opt for cylindrical hinge + torsion link).
- ✓ **Cardan (universal) hinge:** 2 rotational movements, transfers forces in all directions, used in rotation shafts.
- ✓ **Cylindrical hinge:** translational hinge + rotational movement around translation axis.
- ✓ **Spherical hinge:** three possible rotations, only forces can be transferred.
- ✓ **Planar joint:** 2 translational movements + 1 rotational movement (used e.g. to transport cargo around inside an aircraft).

Next an overview of the most common fixed joints is given, although 2 parts are firmly attached not all loads can be transferred though (e.g. bonding: no peel forces).

Adhesive bonding

This type of bond can only take **shear loads**, normal forces (**peel forces**) result in **debonding**. The design is usually **safe life** (difficult to inspect and repair, because the joints are **not detachable**). If repair is necessary, generally the whole joints is replaced by a new joint.

Some characteristics:

- ✓ **Long lifetime** (no stress concentrations, so a bonded joint is insensitive to fatigue).
- ✓ **No weakening of the sheet metal** (no holes, hence no stress concentrations).
- ✓ **Smooth & airtight surface**
- ✓ **Specialized structures** like **sandwich** panels can be made as well as **laminates**
- ✓ **Different materials** can be joined together
- ✓ During the **bonding process** both material sides should be accessible, certain adhesives require high temperature & pressure to **cure**
- ✓ **Pre-treatment** is necessary to obtain a high-quality joint
- ✓ **Difficult** to **repair/disassemble**
- ✓ **Can** be **corrosion resistant**
- ✓ Only **shear stresses**

In a **single lap** joints the stress is not constant in the cross section: the stress has **peak levels** towards the **edges** and if there is a large overlap, the stress almost goes to zero in the middle of the joints. If the maximum allowable stress of an adhesive is given and the relation between the peak and average stress is known, then the maximum allowable applied force is given by: $F_{max} = bl\tau_{avg}$.

As already mentioned before τ_{avg} approaches zero for very large overlaps ($\sqrt{t}/l$ is small value), in the opposite case when the overlap is small ($\sqrt{t}/l$ is large value), τ_{avg} will approach τ_{max}. Thus changing the overlap length l does not really affect the maximal load that can be carried. What happens physically is that an increase in l only affects the least effective area, the peek stress remain about the same. A bond with a **small overlap** is much more **effective** as the stress is high along the whole length and all the adhesive is involved in transferring loads.

If it is assumed that the sheet fails before the adhesive fails, the following relation holds:

$$\tau_{avg} = \sigma_{failure}\sqrt{t}\sqrt{t}/l$$

When the average shear stress is plotted as a function of $\sqrt{t}/l$ as well as the maximal allowable stress in the sheet, the optimal overlap can be found graphically: it is the point where both curves intersect (in the ideal case, bond and sheet fail simultaneous), in practice a slightly less optimal overlap length will be chosen (guarantee sheet fails first).

If both curves do not intersect, then either the sheet is too thick or its $\sigma_{failure}$ is too high, this shows that thick and strong materials are less suitable for (single lap) bonded joints.

The bonding process for **thermoset** adhesives consists of four steps. First the material to be bonded is **pretreated** (cleaning, degreasing, sanding or grind blasting to remove oxide layers, applying a primer to let the adherent surfaces keep their bonding qualities,…), e.g. Al alloys are pretreated such that an anodized layer is created, which adheres very well and is corrosion resistant. Not performing pretreatment will reduce the strength of the bond as well as the lifetime. Next the **adhesive** is **applied** in quantity by hand/machine or as a ready-made film (more expensive, but easier control of thickness, often used in load critical parts). Before the parts are **joined together** (caution to eliminate adhesive flow when pressure is applied, it decreases the thickness) they must be positioned such that they do not shift during **curing**. Curing is generally performed at elevated temperatures, this might introduce residual stresses.

When **thermoplastic** adhesives are used, the process is more or less comparable, but since most thermoplastics are rather viscous, most of the work is done at elevated temperatures to make the application of adhesive easier.

Riveting

Is only used for joining **all types** of **metal plates** (composites will fail due to the high bearing loads at the edges of the whole, while metal plates can deform plastically), caution for galvanic corrosion. Both hollow & solid rivets exist (stronger, but require heavier machinery, thus only used for joints requiring high strength). Riveting is performed by filling a hole with a rivet by deforming the rivet plastically. Loads are transferred via shear and bearing loads are exerted on the edges of the hole.

Characteristics

- ✓ **Reliable, well-documented, easy inspection**
- ✓ **Readily applicable** (variants even exist where only one side of the surface needs to be accessible).
- ✓ **Simple tools**
- ✓ **Simple repair** (drill-out, replace with slightly larger rivet)
- ✓ **Fatigue-sensitive**
- ✓ **Corrosion sensitive** (deformed material is chemically more active, fretting corrosion, galvanic corrosion)
- ✓ **Uneven surface, not air/water-tight**
- ✓ **Poor efficiency** (hole weakens material, joint is always weaker than sheet)
- ✓ Only **shear**, **no axial loads**
- ✓ **High-labor costs**

A riveted joint can fail in 3 ways, the rivet itself can fracture at F_{ult} (through shear), the sheet can fracture at F_{ult} (through bearing pressure), the hole shows **2%** permanent ovalisation at F_{lim}.

Fracture of the rivet occurs at (α and β are factors to correct for very thin sheets, where the bearing pressure between the rivet and the sheet negatively affects the rivet strength), the diameter of the hole is always 0.1mm larger than that of the rivet.

$$\begin{cases} F_{ult} = \propto \pi/4\, D_{hole}^2 \tau_{fracture}^{rivet} & (single\ joint) \\ F_{ult} = 2\beta\pi/4\, D_{hole}^2 \tau_{fracture}^{rivet} & (double\ joint) \end{cases}$$

Bearing fracture of the sheet occurs at a certain bearing pressure ($p_{b\text{-fracture}}$), for which values can looked up in tables, the ultimate force is then (choose thickness where the plate will fail first).

$$F_{ult} = p_{b-fracture} D^{hole} t^{sheet}$$

Bearing pressures for which 2% ovalisation occurs are also listed in table, the ultimate force is then:

$$F_{ult} = 1.5\, p_{2\%} D^{hole} t^{sheet}$$

The lowest of the above values gives the strength of the joint. (Countersunk rivets weaken the joint, therefore: shear failure rivet: 0.85 reduction, bearing pressure: 0.5 reduction; dimpled rivets are considered as flat plates).

Failure of the rivet through shear or failure by exceeding the 2% deformation are considered as **rivet failure**, if the rivets are strong enough and the sheet tears along the joint, then the failure is called **sheet failure**.

If the rivets are too far apart, then each rivet has to carry too much load, thus rivet failure will occur, therefore:

$$s \leq \frac{F_{ult}^{rivet}}{Q}$$

On the other hand, if the rivets are too close, then the sheet will be weakened too much, therefore:

$$s \geq \frac{D^{hole}}{1 - \frac{Q\, \sigma_{failure}^{sheet}}{t^{sheet}}}$$

The optimal pitch is found by equalizing both equations:

$$s_{opt} = \frac{F_{ult}}{t\sigma} + D$$

In practice s > 3d (to avoid damage to surrounding rivets) and s is normalized to a ‘round’ number, if s is increased then the rivet row will be weakened, if s is decreased then the sheet is weakened.

All of the above considers static strength, when considering dynamic loading a rivet row will always fail through cracks between the holes. Where adhesive bonds usually have a strength that is equal to the sheet strength, riveted joints generally have a way lower strength.

Bolting

Bolts (and nuts) are applied when joints need to be **detachable**, when **thick plates** needs to be joined or to **increase fatigue life** by **pretensioning**.

Characteristics

- ✓ **Detachable**
- ✓ The joints usually require a **special construction**, making them generally **heavier** and more **expensive**
- ✓ Bolts are **strong** and are often applied in places where **large, concentrated forces** are expected
- ✓ Can be loaded both in **tension** and in **shear**
- ✓ **Improper assembly** leads to very high **stress concentrations** and drastically **weakens the joint**
- ✓ When applying **pretension**, **fatigue life** is **increased**
- ✓ The **joints** should be made **fail-safe**, the **bolts safe-life**

The stress-situation in a bolt is quite complex (tension, shear in the thread, torsion,…) The weakest section is that of the core where the thread is present (k is factor to correct for stress concentrations, depending on the manufacturing method):

$$F_{max} = \frac{\sigma_{failure}}{k}\frac{\pi}{4}d_c^2$$

If the bolt is not flush with the surface, not only tension but also large bending moments are generated, leading to very high stresses and failure at much lower loads or after a lot less cycles:

$$\sigma_{tot} = \frac{kF}{\pi/4\ d_c^2} + \frac{Fe}{\pi/32\ d_c^3}$$

Fatigue life can be drastically improved by pretensioning the bolt, i.e. *tightening the nut beyond the limit of 'tight enough'*. In that case the bolt is elongated and the force inside the bolt is a tension force F_{pre}, the flanges of the parts to be joined are squeezed together and experience the same force F_{pre} but in a compressive way.

If now an external (tension) force is applied the bolt is further elongated and the flanges become less squeezed together, part of the external force is carried by the flanges (to reduce the compressive pre-tension), part by the bolt. If the **flanges** are **much stiffer** (greater Young's modulus and/or greater load-carrying area: $E_FA_F >>> E_BA_B$), the part of the external load carried by the bolt is even very small:

$$\Delta F_{bolt} = F_{ext}\frac{E_BA_B}{E_BA_B + E_FA_F}$$

Doing this will drastically lower the amplitude of the applied dynamic loading, on the condition that the flanges remain in compression, the moment all the pretension in the flanges is gone, the full external load is carried again by the bolt, therefore:

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

However the pretensioning force in the bolt must not become too big, as this could decrease the lifetime.

Variant

- ✓ **Hi-loks:** hold the middle between rivets & bolts. They are a lot more **expensive** than bolts but might mean a serious **weight reduction**. They are applied if riveting is not possible (not enough space, material can not withstand riveting (composites),…). They do not deform during installation. They provide a high-clamping force which can be used to improve the joint's sealing capabilities. The holes for hi-loks are drilled and reamed such that the tolerance results in a press fit. During the fastening the nut that tightens the hi-lok breaks when a certain torque is applied, assuring the optimal force to fasten the hi-lok.

Welding

During welding pieces of **similar material** are attached together to form one continuous section by **local melting**. It can either by used to make a complex from one piece of material by welding several smaller parts together or it can be considered as an alternative for the above joining methods. Welds can be categorized as **melt-welds** and **pressurized welds**.

Characteristics

- ✓ **Continuous character**
- ✓ Joining occurs **head-on**, giving a **smooth joint**
- ✓ **Air/water-tight**
- ✓ **Affects heat-treatment**
- ✓ Generally the **quality varies** along the length of the joint
- ✓ During **automation** the process can be speeded up and the joint will be much more homogeneous, however complex joints generally require a craftsman

During the welding process **material** is **added**, this happens in the **fluid state**, thus a large amount of thermal **energy** needs to be added. In the weld-boundary the structural metal will also melt and become a part of the welded joint.

Welding is a very **traumatic** process for the material's **structure**: it goes from solid to fluid an back to solid in a short period of time. The result is often **not** very **homogeneous**, making it susceptible to **chemical attacks**. Also by bringing the metal back to its fluid phase or even by heavily heating it up, the effect of **heat treatments** can be **undone**, lowering mechanical properties. The consecutive heating & cooling will also introduce **residual stresses**. During welding, **reactions** with the **atmosphere** are possible, if these are unacceptable, the liquid metal must be protected from the environment.

The **major influences** on the welding process are:

- ✓ **Heat supply**: can be done with a **flame** (gas & oxygen), **electric arc** (electricity), **resistance heating** (electricity), **concentrated electron-beam** (electricity)

- ✓ **Weld material**: in the form of **wire/rod**, often also serves as **electrode** (pressure welding usually does not require material to be added)
- ✓ **Environment screening**:
  - o **Slag protection**: liquefying extra materials (often added as a clad layer around the welding rod/wire) that remains as a slag at the surface of the molten metal preventing contact with the environment
  - o **Gas protection:** an inert gas is blown across the weld point, preventing contact with the surround atmosphere

Melt welding variants

- ✓ **Autogeneous welding (gas welding):** heating is achieved by **burning** a **gas**, the welding rod is clad with flux, and the process is protected by the combustion itself
- ✓ **Electric welding (arc welding):** both slag & gas protection can be used, the most common form is using a flux-clad electrode
- ✓ **Electron-beam welding:** heating occurs by a **highly focused electron beam**, complete **vacuum** is required, the heat is highly **localized**: only a small region of the workpiece needs to be heated and no extra material is added. This makes electron-beam welding suitable for the welding of high-grade (aerospace) materials, however this is an **expensive** process, which requires an extreme **accuracy**.

Pressure welding variants (using physical pressure & resistance heating, no weld material is added, environment screening is not applied)

- ✓ **Spot welding:** 2 sheets are pressed together by 2 electrodes which the send a burst of **high tension** through the material. The heat is highest at the boundary between the 2 sheets, there the material becomes liquid. It requires **little preparation** and is **quick.**
- ✓ **Seam welding:** continuous variant of spot welding, the electrodes are replaced by **rollers**
- ✓ **Upset butt welding:** used for joining bars head-on. Heat is generated by a high current while the 2 bars are forced together.

Several defects can occur during welding: **under-cutting**, **insufficient weld-through**, **slag inclusions**, **gas bubbles,…** These defects compromise the strength and fatigue properties.

Normally welds are only slightly less strong than the parent material, defects however with defects presents this is no longer the case. The toughness is usually less than that of the parent material, if it is much more **brittle**, the presence of cracks can have serious consequences. Welds have a **poor fatigue performance**, however if welding is properly done fatigue life is still acceptable, internal stresses and defects (they incur **notching**: insufficient weld-through and slag inclusions already have characteristics similar to a crack; undercuts will produce stress concentrations) however seriously reduce the fatigue life. Parts welded head-on are likely to be imperfect (center lines are not properly lined up, e.g. thickness variations) generating bending stresses.

Welding is applied very **rarely** in **aerospace**, because the high-grade alloys used are not suitable for welding and because thin sheets are difficult to weld: they tend to warp and also give rise to other technical difficulties. Some examples of welding in aviation industry: welded space-frame structures, spot-welding to attach stringers, ribs,… to skin-panels (however adhesive bonding is usually far better), jet engines,…

In **space industry** welding is more common, because welded joints are **impermeable** and disadvantages as **surface smoothness** and **low fatigue resistance** are less important when constructing spacecrafts.

Soldering: solder material is completely different from weld material, also the **melt temperature** is **lower**. Solder material needs to have **high capillary tendency**, **low viscosity**, **high affinity** for the materials it is to adhere to. Parts to be joined by soldering should be **clean** and free from an **oxide layer**.

Lean manufacturing

Lean manufacturing is a **philosophy** (and not just a method to be implemented) developed in Japan, it could be defined as:

> "Manufacturing **without waste**", or somewhat more detailed:
>
> "It is the **dynamic**, **knowledge driven** and **customer-focused** process, through which all people in a defined enterprise, continuously **eliminate waste** with the goal of **creating value**"

- ✓ **Customer-focused**: refers to the fact that contemporary markets are **pull-markets**, it is important to respond to **customers' demands** (increase product variety, short cycle times)
- ✓ **Knowledge-driven**: a full understanding of the system allows the recognition of all waste from frontline workers to managers
- ✓ **Dynamic/Continuous**: the philosophy is being developed and improved over time, eliminating waste should be an ongoing process
- ✓ **Creating value**: the definition of value is different for every **stakeholder**
- ✓ **Eliminating waste:** everything that uses resources, but does not add real value (as perceived by the different stakeholders) to the product or service. Three kind of actions exist: (1) actions that do add value, (2) actions that do not create value but cannot be eliminated yet, (3) actions that do not create value and can be eliminated immediately

As lean manufacturing is all about eliminating waste, it is important to recognize the various forms of waste:

- ✓ **Overproduction:** producing more/sooner/faster than required, can be recognized by **storage**
- ✓ **Waiting:** time a worker has to wait while a machine is processing, while a machine is unavailable,…
- ✓ **Work in progress:** is related to product or inventory at the various stages of completion throughout the plant from raw material to completed product
- ✓ **Processing waste:** unnecessary processing steps or products
- ✓ **Transportation**
- ✓ **Movement/Motion:** every movement/motion of a worker/machine is waste
- ✓ **Rework**: extra work because a defective product was made
- ✓ **Underutilizing people**

The goal of lean manufacturing is to create value (economical profit), the following framework can be used to recognize and create value:

- ✓ **Value identification**: value is how the different stakeholders find worth/benefit/utility or reward in exchange for their contribution to the enterprise. The process starts with **identification** of the **stakeholders** together with their **needs** & **requirements**. Next the parts of the project that add value for a certain stakeholder have to be determined.
- ✓ **Value proposition**: a plan about how to create value. The sequence of actions that provide value have to be determined to ensure that the resources are used in such a way that value is created for the stakeholders.
- ✓ **Value delivery**: by delivering value to the stakeholders.

Several method exist to create a lean process, a brief overview is given in the next of this section:

5S approach: is an effective method to eliminate waste

- ✓ **Sort:** all items should be looked at and segregated, necessary & unnecessary items separated, the latter removed from the workplace
- ✓ **Simplify:** all items should be arranged in designated areas
- ✓ **Scrub:** workplace is **cleaned** on a regular basis, machinery on a daily basis
- ✓ **Standardize:** improved methods & changes to the production process should be **documented**, visual control agreements for labeling & quantity levels are established. A frequent **reflection** of the previous steps has to be performed
- ✓ **Sustain:** 5S agreements and safety practices are developed & utilized, established results should motivate people and convince them from the benefits of the 5S approach

JIT: producing the right items at the right time at the right place, no stocks or buffers.

Load leveling: leveling out the product types & volumes in accordance with the needs of the customer. For this the **takt time** can be used, it is defined as "the available working minutes per day" divided by "the daily quantity required by the customer". It can be used to recognize bottlenecks and afterwards improve bottleneck locations.

Cellular manufacturing: equipment & workstations should be arranged in a sequence that supports the smooth flow of materials/components through the process. It helps to achieve (1) **single piece flow** (see JIT) and (2) **high variety production**: flexibility is required to serve customers' varying needs, by grouping similar products into product families that can be processed with the same equipment, changeover time is shortened.

A cell consists of **people** and **machines** which performed the required steps in the processing sequence. An ideal cell is **self-contained** with everything within reach.

Total productive maintenance: has as goal to ensure that every machine is always capable of performing its required tasks, hence breakdowns, defects, accidents,… must be avoided. This is done by doing:

- ✓ **Preventive maintenance**: (1) daily maintenance to prevent deterioration, (2) periodic inspections to measure wear/deterioration, (3) restoration to recover from deterioration
- ✓ **Corrective maintenance**: repairing breakdowns once they have occurred
- ✓ **Maintenance prevention**: using equipment that requires little or no maintenance

Another important aspect is **safety**: address dangerous conditions/behavior before accidents can happen.

Quality system

"The totality of characteristics of an entity that bear on its ability to **satisfy** stated & implied **needs**"
"Sum of all factors that enable ownership satisfaction and bring customers back to buy a product or service again and again"

- ✓ **Know the customers' needs** (otherwise only trial-and-error is possible)
- ✓ **Design to meet them** (needs should be documented, so no confusion is possible)
- ✓ **Planning** (decide on everything that is required during the production)
- ✓ **Reliable brought-in equipment and materials** (choose the right suppliers)

Definitions:

- ✓ **Quality:** see above
- ✓ **Quality policy:** overall intentions/directions w.r.t. quality, as expressed by top management
- ✓ **Quality management:** activities of the management to determine the quality policy objectives and implement them
- ✓ **Quality planning:** activities that establish objectives and requirements for quality and for the application of quality system elements
- ✓ **Quality control:** techniques/operations to fulfill quality requirements
- ✓ **Quality assurance:** activities to demonstrate confidence that quality requirements will be fulfilled
- ✓ **Quality system:** organizational structure/procedures/processes/resources needed to implement quality management
- ✓ **Total quality management:** approach based on participation of all members, aiming at long-term success through customer satisfaction
- ✓ **Quality manual:** document stating quality policy & describing quality system
- ✓ **Quality plan:** document describing the required resources, actions… for a particular project, product,…
- ✓ **Quality audit:** examination to check whether quality activities and results comply with the planned arrangements

Quality management system

A quality system is the organizational structure, responsibilities, procedures, processes & resources used for implementing quality management. The quality management system includes: **quality management** (achieving business success and continual improvement of the performance of the organization to sustain customer satisfaction; make sure quality system functions well, make adjustments if necessary), **quality assurance** (achieve conformance to established requirement and managing processes to provide confidence), **quality control** (achieve awareness of quality in all layers of the factory and make sure quality is maintained through inspection).

Benefits of quality systems: both **marketing-wise** (some customers require registered companies; ISO standards are internationally accepted; customers should perceive improved value for the price from registered companies; enhanced reputation) and with respect to **efficiency** (reduced unproductive time; reduced rectification (product does not satisfy demands), ideally: first time, every time; reduced warranty costs (product is defective); reduced liability (by not delivering faulty products)).

Quality control starts with **education**, ensuring everyone in the organization is aware of the importance of quality, safety & efficiency. Next step is **checking**: everybody inspects his own work, under supervision. Third, systems are established to make the whole process more **fool-proof**. Final aspect is specification linking with customer's/authority's requirements.

For the approval of an aircraft design by airworthiness authorities, the latter recognizes the competence of certain companies/individuals that are allowed to decide upon the airworthiness of designs, off course under constant supervision. This is called **acceptable reporting**.

Quality assurance is demonstrating consistent compliance with requirements. It is repeating good performance time after time on every contract. It offers control at each stage of the process and not only at the end. Thus faults are much quicker recognized.

Management responsibilities

Top management must be dedicated and committed to quality, they cannot just delegate their responsibilities. Their responsibilities involve:

- ✓ **Quality policy**: written document containing the mission, objectives & guidelines, it must be understood, implemented and maintained at all levels of the organization.
- ✓ **Organization**: define the responsibility and authority of all personnel whose work affects the quality of the product.
- ✓ **Management review**: quality system is to be reviewed regularly.
- ✓ **Business plan:** plan with both short- and long-term projections, plans, expectations,…
- ✓ **Analysis and use of the company-level data**: maintain records related to quality, productivity, efficiency, effectiveness and current quality levels.
- ✓ **Customer satisfaction**: documented progress to determine customer satisfaction.

Resource management

Most important resources: time, money, availability of personnel. Failing to allocate one of these will probably fail the introduction of a quality management system.

Product realization

Several ways exist to implement quality assurance, an overview of its historical developments

- ✓ **Product focused:** Judgment happens by final inspection, initially all products were inspected before leaving the factory, non-conform product were rejected. This method is expensive and inefficient (takes a lot of time, a lot of needless value is added to products with early errors,…) A first step towards optimization is doing random checks, based on statistics.
- ✓ **Process focused:** random checks take place at different places of the production process, hence number of checks & efficiency are increased. The production process is no longer a closed box.
- ✓ **System focused:** quality assurance is not only focused at the primary process but also at supporting processes (personnel, maintenance, finance,…)
- ✓ **Chain focused:** the quality not only depends on your own work but also on the quality of the parts from external suppliers.
- ✓ **Total quality:** a company is not passive regarding the future, but prepares itself actively towards future events.

Measurement, analysis & improvement

Non conformance reports

If deviations between the real product and designed product are discovered an action is started to investigate if this deviations poses an airworthiness problem. A 'non-conformance report' is written and it is presented to a 'material review board', which is independent such that judgments are not influenced by economical or commercial reasons. Several outcomes are possible: use as is, rework, refit, repair, scrap,…

Inspection

Upon receiving: check that the goods received are those that were ordered and if the quality is ok. The amount of inspection should be compatible with the risk or inconvenience if the item is later to be found faulty. The inspection should be documented to confirm that it has been done.

In-process: the product is inspected at various stages throughout the process, goal is to identify rejects before further value is added.

Final inspection & testing: a decision based on test with measuring instruments requires a good level of confidence in the accuracy of it. This is normally achieved by calibrating those instruments. Recalibration from time to time is required, either by: sending all instruments to a calibration laboratory, sending one item to a laboratory and calibrate all other items against it or test whether a known good & fault product can be recognized.

Each instrument should be uniquely identified, calibration results should be kept, the next calibration date should be clearly indicated, means to adjust calibration should be sealed.

Once product have been inspected, there should be a clear & concise method for the easy identification of acceptable & unacceptable products. (marking, stamping, segregating, labeling, reports, documents,…)

Marking & identification of materials & components: an accurate system of records is necessary in order to identify materials and to trace their origin throughout any stage of the production: the raw material supplier must deliver a certificate stating the specifications and how they were verified. During raw material processing a job card is filled in with information about the part. Job cards must be marked, stamped,… after each operation.

Non destructive testing

= testing the properties of a part, structure,… without compromising it's functionality, load carrying capabilities,…

- ✓ **Visual inspection:** most simple way of inspecting, most obvious mistakes can be detected
- ✓ **Ultrasonic measurements:** using ultrasonic sound pulses and measuring reflection times & intensities. Test can be done in air/submerged in water; manually/automatically, experience is required to analyze the results. These test can measure:
  - **Thicknesses**
  - **Voids & delaminations**

Internal discontinuities in **Al/Ti** can be discovered, voids & delaminations in **composites** (though the sensitivity is rather low), bonding qualities,…

- ✓ **Acoustic emission analysis:** for **fibre reinforced plastics** or **composites**, it can detect fibre breakage, bond breakage between resin & fibres, voids,… It is a very specialized technique that requires much experience or highly automated systems.
- ✓ **Thermography:** to detect **voids** or defects in **composites**, no submerging in water is required
- ✓ **Fluorescent penetrant:** for **metals** and other **non-porous** materials to detect **open-to-surface** flaws & cracks. A penetrant is applied on the part to be tested, next the penetrant is removed (but it stays behind in surface cracks). When the penetrant is dried and developed, flaws can be revealed under UV light.
- ✓ **Magnetic ink:** for **ferro-magnetic materials**, it is a very **sensitive** method. A high magnetic field is applied while spraying black magnetic ink onto the surface. **Surface defects** will be visible in a plane that forms a right angle w.r.t. the poles of the magnet.
- ✓ **Eddy**-**current techniques**: both **ferrous** and **non-ferrous** materials, it can detect **surface cracks** & **defects**. It provides a **high resolution**. It is especially useful for rotational symmetric objects.
- ✓ **Radiography**: this way of testing provides a visual image, which is often easier to understand than a fluctuating signal. It can be used to inspect: critical locations of helicopter blades, critical spots in the engine, undercarriage, door locking systems, composites,…
- ✓ **Fluoroscopy**: is a complementary technique to radiography, it provides continuous images (radiography only shows a single image). **Light alloy castings** (both thin & thick) can be inspected for very **small details**.
- ✓ **Hardness testing**: there is a reliable link between a part's hardness and other mechanical properties as strength.

Working conditions

Employer vs. Employee: The employer pays the employee to carry out work for him. Usually an employment contract is made up, often referring to a collective employment agreement (CAO). Civil law obliges the employer to provide a safe working place and safe material. In case of an accident the employer is liable.

The Employees Council Act obliges companies with over 30 employees to have a representation of the personnel that has the right of consultation in issues like safety, well-being, health,…

The Working Conditions Act is a part of the penal law (though it is mere a framework): negligence leading to dangerous situations, accidents, diseases,… is considered a criminal offence, even if nothing has happened (yet). This act is compatible with European guidelines (just as in every member country of the EU).

Because the WCA is more a framework than a real law, more details can be found in ministerial orders,etc.

The employer must make an inventory of all the risks present at the working place, evaluate them and make a plan of approach on how the hazard can be eliminated. An employee is entitled to sufficient information & instructions to do his job in a safe and proper way. Any (near)-accident must be reported as well as occupational diseases. Employers with over 15 employees must organize an in-company rescue team to render first aid, fights fire until fire services arrive, sounds the alarm, evacuates & co-operates with emergency services.

Every employer must have himself assisted by health and safety expert, often an external organization, called Occupational Health & Safety Bureau (OH&S). These experts are generally: a medical practitioner specialize in company health care, an expert on occupation and organization, a specialist on occupational safety and an industrial hygienist.

The employee must take care of his own safety, by using personal protection equipment, taking & following instructions, co-operating with OH&S officers.

Motorized equipment must comply with machinery guidelines (based on European Standards), complying equipment can be recognized by the CE-label. The machine must be placed in a safe location, maintained properly and should be operated properly by a well-instructed operator and without bridging safety devices.

Preventive measures from dangerous goods can be done in 3 ways: shield (reduction of intensity of exposure), shortening the duration and if those are not possible: use proper PPE.

If one has to work with chemicals, a plan must be made (objective, description of the process,…), also it is necessary to evaluate what chemical products will come out of the process as waste and how they can be removed. One should know what can go wrong, possible effects and how to cope with them. Ordering of chemicals should be done via an internal department, they keep track of all chemicals, know how to handle & store (usually in a fume cabinet) them.