Summary of 'Production of Aerospace Materials'

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Contents

Chapter 1

Notes from the Author and overview:

The purpose of this document is to provide to the student a summary of the most important items of the reader used in the TU Delft 3rd year course "Production of Aerospace materials". Note that during this course you will have to learn a lot of vocabulary and keep in mind all the different processes.

That is why the main goal of this document is to facilitate your learning of all the keywords with the use mnemonics. These mnemonics have helped me to learn the vocabulary quite fast and retain most of it successfully already after the first go. Reviewing it is facilitated by the images, where one image can be the key to remembering several keywords. You may want to use the same mnemonics or replace them with your own. It helps a lot!

In the first chapters manufacturing techniques are discussed. These can be summarized as follows:

- Casting and injection processes, where **liquefied** material fills the cavity.
- **Shearing** processes such as cutting and machining, where material is removed (or cut). The final part consists of the remaining material.
- **Forming** processes, where applied forces deform the material into the desired product.
- **Assembly**: A part made of multiple joined sub-parts.

The assembly section is followed by the chapter of riveting and bolting as well as adhesive bonding and welding. These two chapters are quite well described in the reader and thus are not declared again in this document.

The final parts go over management topics describing quality control, lean manufacturing and organization.

Chapter 2

Introduction:

2.1 General background:

Due to the massive requirements that our society requires to function properly and in harmony with nature, production and manufacture of materials plays a huge role to maintain this equilibria. Aerospace engineers, with the mind already set a light weight and efficient structures/machines, have made considerable progress in this area. In fact, the aerospace industry will always be at the forefront of lightweight technological developments and applications.

From an historical point of view, new materials and technology allowed of course new creations, but it also opened new possibilities for the previous materials/technology.

> **Case study:** As an example the mosquito is mentioned, an aircraft that in combination with the newly commenced metal technology was build mainly of wood, proving to be one of the most successful aircraft in WW II, superior to many metal aircraft it had to compete with.

In addition the application of mathematics and other have improved the production of structures with far more reliability (instead of trial and error and not being able to describe unexpected events).

Finally, the engineers are not only meant to look for a technical solution to a problem, however must be able to trade off between different solutions. The application of organized research, only more or less applied after the Wright brothers success and the entering of the World wars (around 1914), has made it possible to make huge advancements in science and technology. (Before inventions in the field of aerospace were more of a random hobby which often would take their inventors to their death due to failures). Companies of different scales and purposes would emerge and start taking part in the innovation process of airplanes. (A few examples of companies are shown in the book at chapter 1.6)

2.2 Advances in aerospace structures and materials:

Every airplane requires a system of different aspects that have to work together. In fact, the dependency of each aspect is so important that an improvement of one part can have an impact on the rest of the airplane. In the following some of the important developments are mentioned below, more or less in order of their appearance.

- Engines:

> **Case study:** Before the first flying machines lots of inventors thought humans should be able to fly due to their far greater strength than birds. Nevertheless, the strength to weight ratio of a human is far lower than the one of a bird, as well as that the birds heart beats at around 800 beats per minute, much more efficient than a human. The requirement of greater strength while focusing on being lightweight needed the application of aero-structures (in order to be able to hold wings) as well as in the form of propulsion (such as engines).
>
> The Wright brothers had made their first successful aircraft. Before it could fly though, they had to invent and apply a new engine that was light and strong enough to be used on their airplane. Only through the technological advancement there, their airplane was possible to fly successfully.

- Wire braced structures: Components are held together with wires to make them lightweight. In combination with two wings on top of each other, biplanes could be built.
- (Semi) monocoque structures: Wire braced structures didnt allow the use of the space inside efficiently, a problem as planes got larger and started transporting. The application of the 'stressed skin', where the skin takes part in holding the structure allowed planes to be built much more space and material efficient. The American aviation industry applied this idea also to the wings, allowing large capacity fuselages.
- Airfoils: Another important improvement of airplanes was the application of thick airfoils, which not only had a better aerodynamic performance, but improved the wing structure, saving a lot of weight and allowing greater and faster airplanes (as they e.g. did not need two wings anymore).
- Wooden aircraft: From 1915-1935 the major material used on airplanes was wood, moving from open to closed structures. (At first bamboo was used, which later on moved to spruce due to being lighter, stronger and easier to produce). Production facilities were created that dealt with the sophisticated wood crafting. The research and progress made in this area allowed state of the art airplanes like the mosquito as mentioned before in this chapter (case study).

- Metal constructions:

  Case study: The move to metal constructions was caused partly due to political views, that regarded this as the material of the new era, leaving wood as something from the pre era. Additionally due to the world wars, wood became scarce and too slow to manufacture, thus requiring the application of metals. *(Junkers: 'metal can be given any desired shape and dimension compared to wood, is more reliable, stronger and less sensitive for corrosion...')* This was at a cost of some very promising wooden projects, but gave way to new machines/industries; still busy today in the research of these types of materials. Finally, in March 1931 a three engine Fokker (made of wood) crashed due to moisture weakening the glue holding the wings. The consequence was the requirement of several more routine inspections on the aircraft, which drove the costs of maintaining such aircraft up high, giving a boost to metal aircrafts.

- Production companies: Given the world wars and other requirements of airplanes, companies were created that would put together the various disciplines such as research, design and manufacture.

  Case study: A huge growth in airplane production was created, such as in England, where in 1914 only few hundred people worked with aircrafts, in 1918 it had increased to 350'000!

  Being a company though also forced the construction of airplanes that would always be at the state of the art by combining all disciplines together (material choice, manufacture, computer simulations, etc.) in order to compete in the market.

- Further improvements: With the success of the DC-2 and DC-3, metal semi monocoque structured airplanes, these became a standard in aerospace engineering. Further improvements continued with the reduction of rivets, improving fail safe structures and further research in new materials for better material efficiency.

- Applying fibres: The application of fibres due to their great material properties has allowed to make structures lighter and smoother. They have though weaknesses such as not being able to plastically deform, which causes safety issues to take into account.

- Applying sandwich structures: Sandwich structures are applied to increase the moment of inertia of the skin and improve its rigidity. Although extremely efficient, its construction and production is limited and complicated and thus still mainly used on small parts.

Chapter 3

Cutting

There are three types of cutting processes:

- Separating multiple parts with no chips such as shearing and punching
- Separating multiple parts with chips such as sawing and laser cutting
- Machining (single part and chips) such as milling and drilling

3.1 Separating multiple parts, no chips

During this process, shearing is used (through a cutting blade or a punch and a die, similar to scissors and a paper punch) to separate parts. This does not create any chips, but does create rough surfaces or other defects and usually requires further machining.

Keyword: Shearing; the general process of using *shear* forces to separate parts.

One can distinguish between two different shear processes, punching and blanking. In punching the sheared slug is discarded, in blanking it is the part and the rest is scrap.

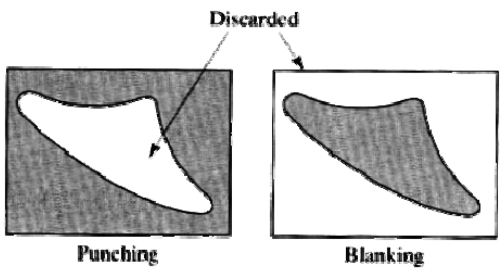
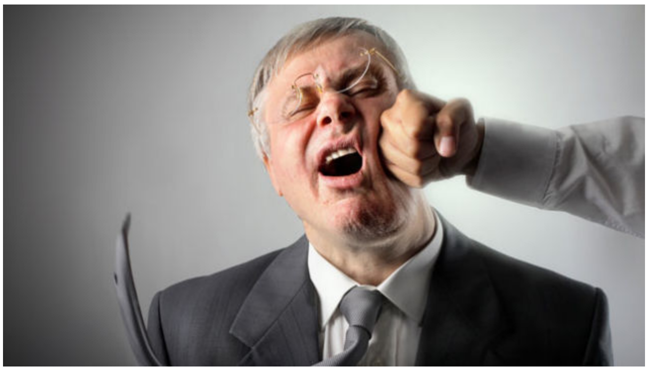


Figure 2.1.2 The difference between punching and blanking

Keyword: Punching; works similar to a paper punch. *What you punch becomes scrap, just like when you hit someone in the face.*

Keyword: Blanking; similar to a paper punch, but in this case the punched part is the product. *The doctor only cares about the punched face of the 'blanked' out guy, not the rest of the body.*

Keyword: Slug; the part that gets punched. *After the punch the face looked as disgusting as a big fat slug.*



During the process of shearing, there are three steps that cause the final cut:

- Indentation, its depth into the sheet is called roll over depth.
- Cutting, its depth is called Burnish depth and has a smooth finish due to the sliding of the sheet against the punch/blade. Ductile materials have a higher Burnish depth.
- Final shearing, its depth called fracture depth. This part of the sheet is rough and ends with a burr. The burr height increases with the clearance between the punch and die and the material ductility. Its size can be a problem for subsequent operations.

These produce a final cut product as the schematic shown. The equipment usually consists of a press with a punch and a die, where the material is laid and lubrication is added. The process is finished with some deburring equipment to smoothen the edges of the products. Here the major processing parameters:

- **Shape** of punch and die. Bevelling is the process in which the punch or dies are shaped at an angle. This reduces the force required to cut the material and noise made, while ensuring a better cut quality. Symmetric bevelling eliminates also lateral forces acting on the punch or die.
- **Material** of punch and die or the material laid. Cutting brittle material can cause small cracks which could reduce the fatigue resistance of the material. A good finish can reduce this risk. Composite materials also

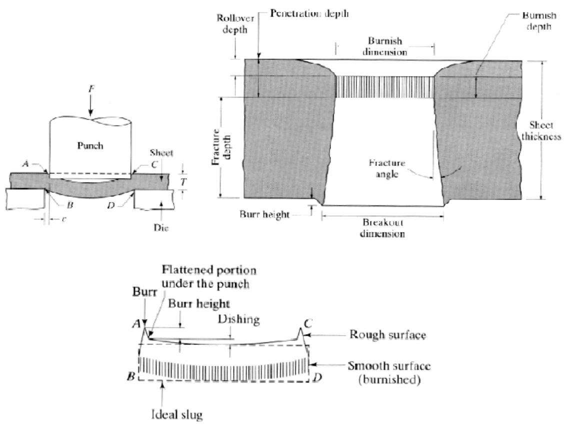


Figure 2.1.3 Schematic illustration of shearing with a punch and die. Characteristic features of a punched hole (top right) and the slug (bottom left).

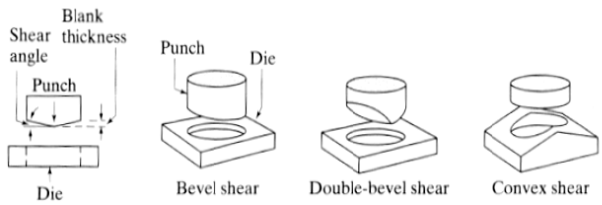


Figure 2.1.6 Examples of the use of shear angles on punches and dies.

tend to delaminate when punched or blanked or act abrasive on the cutting tools.

- **Lubrication** between punch and die. The reduction in friction allows clean cuts and a reduction in tool wear.

- **Clearance** between punch and die. Typical clearance is around 2-8% of the sheet thickness. Softer material have smaller clearances.

- **Nesting**, highly important to reduce scrap material as much as possible. On the minimum side though, the material should not be drawn into the of the die, the ligaments should not fail, and no excessive burrs should occur while also guaranteeing the safety of the operator.

- **Deburring and Shaving**; used to smoothen the edges.

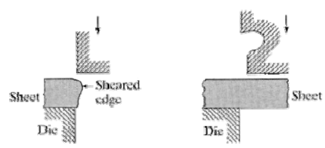


Figure 2.1.5 Schematic illustrations of the shaving of a sheared edge. Left: shaving a sheared edge; Right: shearing and shaving combined in one stroke.

This process is often used for pre-processing and making small or large product series with a high cut accuracy. The time required is short, but the process can mostly be dedicated only to sheets. Other limitations are the sheet thickness (0.3 - 15 mm) and the unsuitable choice for cutting continuous fibre reinforced polymers.

Keyword: Burr; the excess material perpendicular to the sheet surface created by shearing process. *Biting straight into a 'burr'ito leaves edges on the side.*

Keyword: Blank; the slug after blanking, used as a product. *The doctor left his face as a clean and 'blank' product.*

Keyword: Bevelling; angling the punch or die to reduce cutting force and increase cut quality. *Adopting a better angle allows you to 'be well'.*

Keyword: Burnished; the Burnish dimension/depth/surface. *Its so smooth you can use the surface to shine the light on paper and 'burn' it.*

Keyword: Fracture depth and Breakout dimension. *You use the rough surface of a stone to fracture the prison wall and break out.*

Keyword: Dishing; the slug is curved after leaving the press. This is called dishing. *The product of a shearing process can later be used as 'dishes'.*

3.2 Separating multiple parts with chips

Another method to separate parts is by removing a narrow zone (kerf) in between. The removal of material can be done in several ways:

- mechanically, like sawing, grinding, water jet cutting, where chips are created and removing them.
- thermally, like plasma arcs, lasers, electron beams, electrical charges, where the material is evaporated, melted or burned away.

Keyword: Kerf, the narrow zone where material is removed to split a piece. *You can only cut straight into the wood. The lack of 'curv'es made us want to call that straight a 'kerf'.*

Here a short summary on the different more elaborate methods used to cut pieces by removing material:

3.2.1 Laser Cutting

- Laser Cutting uses optical energy on the surface of the work piece to melt or evaporate portions of it. The kerf is typically 0.2mm wide. Unfortunately, the laser itself is at most 10% efficient and the laser has to be close to the material (0.5mm), making 3D laser cutting very expensive.
- It can cut metallic and non metallic materials. One has to pay attention to the reflectivity (aluminium can give problems!) and thermal conductivity as well as the specific and latent heats for melting and evaporating processes. The lower each of them, the better.
- May be used in combination of suction process or gas stream to improve energy efficiency. Gases like oxygen, nitrogen or argon are used. Inert gases are used for metals to leave an oxide free edge.
- The process is numerically controlled through a computer for accurate control.
- Can cut plates as thick as 32mm (although due to focusing thick plates will be finished with a taper) and with a minimum radius till 0.005 mm. One should pay attention to high local temperatures as they may heat treat the metals or in the case of composites degrade or burn at the edges.

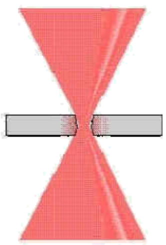


Figure 2.2.4 A highly exaggerated sketch of the focussing of a laser beam.

- The equipment cost is high, since it requires computers and a large energy feed (due to inefficient lasers). However from then on, the costs drastically drop, such as for labour, raw material cost and programming. Additionally, the flexibility this process offers with different materials and the low set up times make it capable to compete in the market.

3.2.2 Electrical discharge wire cutting

- Electrical discharge wire cutting is based on the erosion of metals by spark discharges. Charging the metal work piece (needs to be conductive!) and a wire (made of brass, copper, tungten, etc.), the wire can be passed through the material while creating sparks which act like saw tooth (similar to contour cutting with a band saw).
- This process allows to cut plates as thick as 300mm at an incredible accuracy of up to 2.5 μm. Although slow (5-6 mm/min) it is very flexible and since it doesnt involve mechanical energy, properties such as hardness and toughness of the workpiece dont affect the removal rate. (Useful for producing products like punches and dies).
- The removal rate and surface roughness increase with increasing current density and decreasing frequency of sparks. Also, the melting and latent heats of the material, their increase will cause a decrease in the rate of material removal.

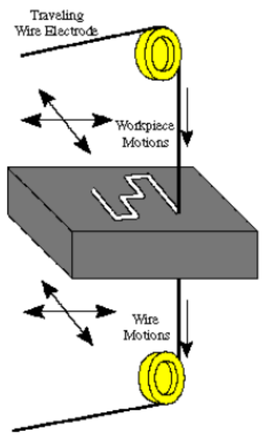


Figure 2.2.6 The principle of electrical-discharge wire cutting.

3.2.3 Water jet cutting

- Water jet cutting makes use of the force delivered by a jet of water to cut through work pieces. A pressure level of 400 MPa (4000 bar) is generally required in order to propel the water to speeds up to Mach 2 and 3, leaving a nozzle diameter in the range of 0.05 - 0.4mm.
- This process can only cut 'soft' materials such as foam, soft rubber, paper, leather, etc. In order to cut stronger materials, abrasive particles are added to the water, creating a new process: abrasive water jet cutting.
- During this process no heat is produced, thus heat sensible materials won't be affected.
- The **orifice** of the nozzle is usually made of very hard materials such as rubies (50 to 100 cutting hours) and diamonds (800 to 1200 cutting hours, but 10 to 20 times more expensive).

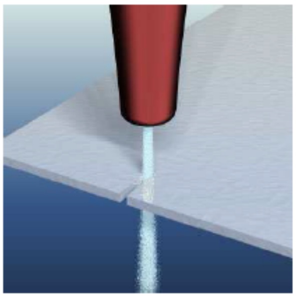


Figure 2.2.7 A schematic idea of water jet cutting

3.2.4 Abrasive water jet cutting

- Abrasive water jet cutting is similar to water jet cutting, except that fine abrasive particles are added. Their roughness/size is similar indicated as with sandpaper, 120 Mesh making smooth surfaces and 50 Mesh making rough, fast cuts.
- The wear occurs mostly in the mixing tube, not the orifice.
- Most materials can be cut with an abrasive water jet, such as steel, aluminium, ceramics, glass, etc. In the case of composites though there might be a risk of delamination, especially if the cut is not started from the edge.
- A typical occurrence is the **jetlag**, where the jet of water is bent, since it does not have any bending stiffness. Therefore cutting through corners will leave behind tapers. The moving rate can be decreased, however one may also risk **kickback**s, where the jet is deflected into a different path.

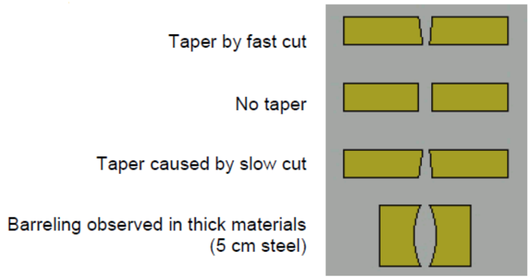


Figure 2.2.12 Different cutting speeds give different tapers of kerf.

- It has the ability to cut a kerf of 0.75 mm through a thickness up to 25 cm.

3.3 Machining (single part and chips)

Machining is the process of removing small chips from a material to create a product, similar to an artist chiseling a sculpture. The chisel removes the chips of the material, and thus a suitable material for it must be chosen. In addition the chisel should have a certain geometry for efficient cutting.

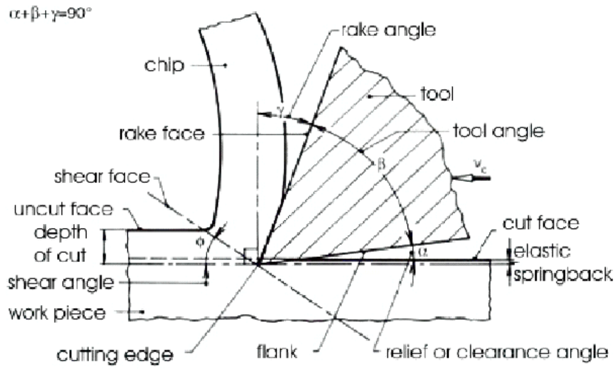


Figure 2.3.4 The general layout of a cutting tool.

Keyword: Rake face, the area which pushes the chip away. It is set at an angle (rake angle), which typically is from -10 to 30 degrees. The larger it is, the less force is required (its sharper). Rake is a synonym for collecting, gathering, etc. *If someone scratches metal away, it will sound like 'rake, rake, rake'.*

Keyword: Tool angle, the angle of the chisel.

Keyword: Clearance or relief angle (typical 6 degrees), to allow spring back and decrease contact with the material, thus lower heat transfer.

The deformation process of the chip removal will cause heat, which lowers the properties of the chisel and increases wear. Coolant and lubrication are used to reduce these effects.

The force on the chisel can be decomposed into three forces:

- Thrust force
- Feed force
- Cutting force

The cutting speed times the cutting force (largest of all three forces) will give the power required to cut the product. Since power is usually fixed, and greater cutting force is required with harder materials, the variable that is most often changed is the cutting speed. Controlling it visually helps, since it is usually desirable to have discontinuous chip removal. Depending on the hardness of the material, one may require also different types of chisels made of different materials and coatings. For very hard materials ceramics can even be used, however they are only suitable is no shocks are present during cutting. Below a figure laying out some of these options: In general machining only requires

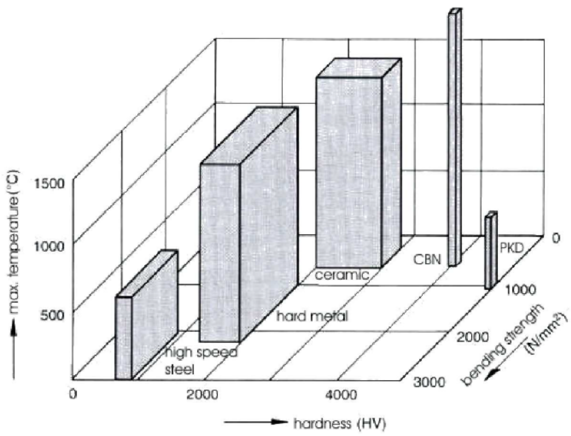


Figure 2.3.16 "3D" graph of the properties of different cutting tool materials.

an initial high cost for the equipment and all other costs remain low from then on, however this is a process that usually is only used for small to moderate quantities. If added automation, the process can be sped up even more and more products can be made at very high accuracy.

All in all there are three basic ways to machine the parts: Turning (lathing) or milling.

3.3.1 Turning

During turning the work piece is rotating and the chisel is pushed into it. The revolutions per minute times the diameter equals the cutting speed. It is important to note that the smoothness of the surface is dependent on two things: The wear of the chisel, responsible for the smoothness in the direction of rotation, and the feed speed, responsible for the smoothness in the axial direction. To guarantee also that the work pieces don't wobble during rotation, the pieces are clamped with very stiff clamps from the lathing machine.

3.3.2 Milling

Milling is used for non rotational products and thus has a larger range of possible products. In this case, the work piece remains fixed, while the milling tool is translated. Note that there are two ways to mill, slab and face milling.

In the case of slab milling, when looked closely to the cutter, one can recognize the angles mentioned before for the chisel. In the case of face milling, mostly the perimeter performs the cuts. Of course, there are still a few other

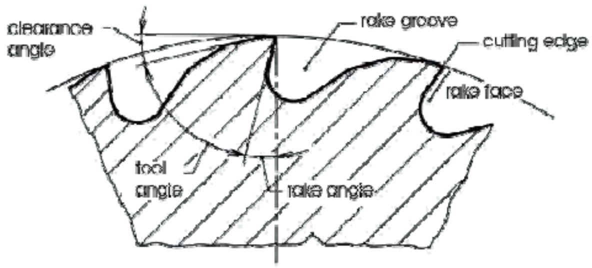


Figure 2.3.26 The typical geometry of a slab mill.

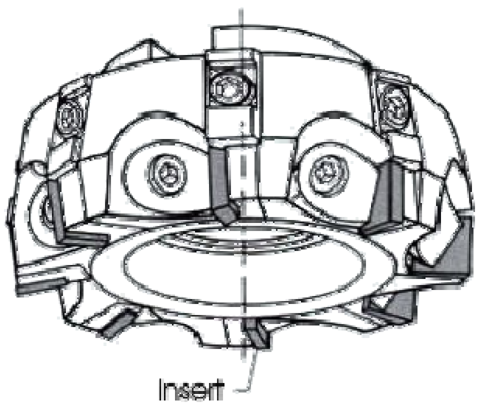


Figure 2.3.27 A face mill with inserts

tools, each having their purpose during milling operations. It is crucial however for the production of these tools that they are made precise.

An important addition to the milling processes is drilling, sometimes also made with a separate machine. Since holes are common in structures, drilling is widely applied. Observe how once again we can find the chisel geometries: No-

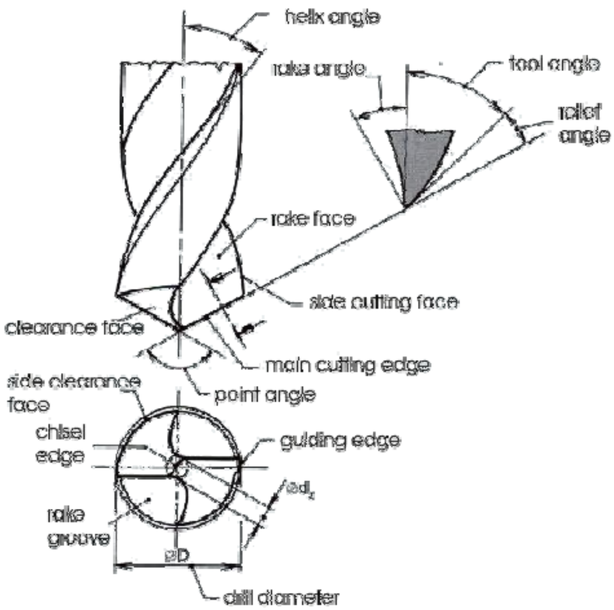


Figure 2.3.29 The lay out of a drill

tice as well that in the middle, cutting is more difficult due to low cutting speed.

If two the holes or columns it is wished to add threading, one has to use taps and screw plates. (This can also be done with lathing.)

Keyword: Tap; used to make an internal threading. *When you open the 'tab', the water goes inside the sink.*

Keyword: Screw plate; used to make an external threading. *When you wash the 'plates' you put them outside of the sink.*

One last alternative for the milling machine is the use of a grinder, used to finish products. In this case the heat is one important factor to take into account (due to rake angle being negative as low as -60 degrees or more), as it could melt the surface and make the grinder ineffective. Adding a coolant to metals like aluminum will avoid this. If done properly, the heat, although high, is carried away by the chips, and thus only a fraction of the heat produced is conducted to the work piece. (Cutting speeds are very high, 30 m/s, and the removed layer is much smaller than e.g. milling)

Chapter 4

Liquid Phase Processing

Liquid Phase Processing is the process in which a material is used in its liquid state to shape it to the end product. This process is different with metals (casting) than with polymers, but they both make use of molds, dies and similar. The difference in the process in mainly made due to the viscosity of the liquid material, some of which will flow by themselves, some will require the addition of forces.

First the metal processing shall be discussed, then the polymer will be reviewed.

4.1 Casting

Casting is the process in which molten metal is poured into a mold, left for cooling, and finally the product is recovered by separating it from the mold.

> **Keyword:** Foundry, the place where casting products are made. *At the foundry the make yummy metal 'fondue'.*

Important aspects in molding are the temperature such as the melting temperature of the material and the pressure.

> **Case study:** Low melting point materials allow metallic molds. You can cast aluminum in steel molds, however this is not possible with steel in steel molds. For this one would require a ceramic mold, which can be as simple as a sand mold.

All molds can withstand low pressure, however to increase production rate, pressure may be applied, in which ceramic molds wont be an option, since they are too brittle to use. Ceramic molds tend to be however cheaper, and thus depending on the product series, one will have to choose between the two types: Expendable molds (ceramic, sand, plaster, etc.), permanent molds (metal, composites of metal and graphite, etc.).

In addition, there is the option to choose between perishable molds and reusable ones. Perishable molds allow a greater freedom of geometrical features, since one can damage the mold when removing it from the product.

4.1.1 Sand casting:

As a basic procedure in casting, sand casting shall be used as an example here.

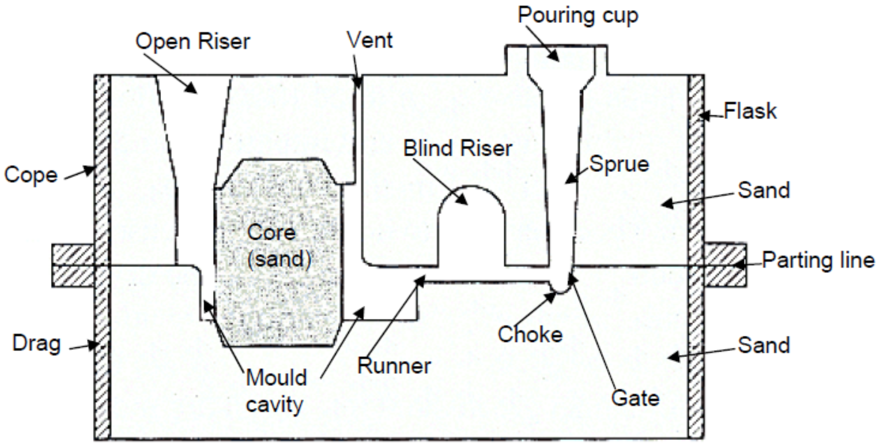


Figure 3.1.2 The layout of sand casting

- The mold itself is supported by a **flask**. Two piece molds consist of a **cope** on top and a **drag** on bottom. The seam between them is the **parting line**. (In case that more than two pieces are used, the middle ones are called **cheeks**).
- A **pouring basin** or **pouring cup** is used to pour the molten metal into.
- A **sprue**, through which the molten metal flows downward. Its shapes assures that the metal flows in a laminar way, so no air bubbles are mixed.
- The **runner system**, which has channels that guide the molten metal from the sprue to the mold cavity, a.k.a. **gates**.
- **Risers**, which store additional metal so when the product starts cooling and shrinking, more metal can be supplied into it. One can make a distinction between **open** and **blind** risers.
- The **Core**, which contains the inserts to add to the product such as holes or lettering.
- **Vents**, which are placed in the mold to transport gases and hot air.
- The **Mold cavity**, in which the liquid metal will gather and form the final product.

> **Keyword:** Flask, in which the mold is preserved. *You use 'flask's to hold the best liquor for the best times.*

Keyword: Cope, the upper mold piece. *The 'cop', 'on top' of his massive motorcycle.*

Keyword: Drag, the bottom mold piece. *The cops motorcycle is so big, it produces massive amounts of 'drag'.*

Keyword: Pouring cup and sprue, where the metal is poured into. *The cop refills his motorcycles tank by 'pouring cups' of fuel through the 'sprue'. Once it full, the motorcycle tank indicator blinks the word 'true'.*

Keyword: Runner and Gates, the pathways for the liquid metal to pass. *As the cop is refilling his motorcycle, a 'runner' with stolen money runs by and away through a 'gate' to the nearby forest.*

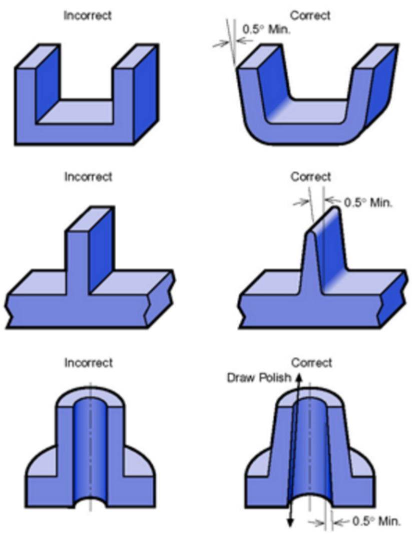
Keyword: Riser, space to store extra liquid metal. *The cop, in action of the lost runner, writes flyers with a 'rise' on the money award for whomever would catch him, hanging them in the forest.*

Keyword: Core, an 'inner' mold to add hollow features to the product such as holes. *Finally the cop finds in the 'core' of the forest the runner.*

Inside the flask there is cop riding his massive motorcycle which produces massive amounts of drag. He fills his motorcycles tank by pouring cups of fuel into the sprue. Once the tank is full, the motorcycle indicator blinks 'true'. As the cop is standing there, a runner with stolen money runs along and away through a gate into the forest. The cop, in action of the lost runner, goes to the forest and hangs flyers with a rise of money to whomever would find him. When arriving to the core of the forest, he finally finds the runner.

One starts inserting a **pattern** into the flask, after which the flask is filled with sand. The sand is then compacted with e.g. hands or other. One can choose between a **one piece pattern** or **split pattern**. It may be necessary to add **draft angles** to the pattern to ensure easy removal from the sand molds.

Draft (Draft Angles)



Draft guidelines.

For the actual casting process a few more things have to be taken into account:

- The flow of the metal depends on its material properties such as viscosity (the lower, the easier the metal flows) and the surface tension (the lower, the better achievable details are possible).
- The cooling speed influences the solidification of the metal (alloy) and the process time (the lower, the cheaper the process). During solidification the metal will shrink (10 - 20 mm/m), reason why the mold cavity is larger than the actual product. To avoid hot tears during shrinkage, the mold should be allowed to be collapsible.
- The cooling direction should go from bottom up, such that the riser keeps feeding liquid metal into the product while it cools and shrinks. Also parts that are further away should cool first, so that the riser keeps effective.
- Parts should have the same thickness throughout if possible. A change in thickness means that the larger part will take more time to cool down, a hot spot, which means solidification will be different and affect the material integrity. (Microporosity can be expected). If the thickness cannot be changed, local cooling might also help, a.k.a. **chill**.
- Large flat areas should also be avoided, as they tend to warp after cooling. If other high stresses are expected on the part after casting, they may be relieved through heat treatment afterwards.

- Most sand casting operations use silica sand (SiO_2) since its common and easy to handle while being resistant to high temperatures. To select the sand it must have enough strength so it wont change during casting, **permeable** to allow gases and steam to escape, **collapsable** to allow casting to shrink and avoiding hot tears and **surface quality** to minimize the need for finishing the product.
- As the smoothness of the finishing product increases, more attention will have to be put on allowing gases to escape.

If these are not taken into consideration, failures such as hot tearing may occur, in which local shrinkage is obstructed, resulting large stresses and ultimately ending with cracks (and making the product often unusable).

4.1.2 Investment Casting

In the aerospace industry, what is more often used than sand casting is investment casting. Sand casting is not a feasible option for the often needed thin thickness, but in addition allows the casting of multiple parts at the same time.

This process is also sometimes called lost-wax process, since the pattern is made of wax. These parts can be connected into a tree, after which it is coated with a ceramic. Later on, the ceramic is heated up, thus all wax is melted away, and what is left is a ready to use mold. The metal is poured in and once cooled, the ceramic is broken down through vibrations. A high accuracy can be obtained from this process. Sometimes instead of wax polymers are used since they are less delicate, however polymers are harder to remove and reuse.

4.1.3 Certification

To use cast products in aircraft/spacecraft, certain JAR/FAR requirements apply. The structural elements are classified as:

- **Class 1:** Critical single load path
- **Class 2:** Critical multiple load path
- **Class 3:** Non critical

A sub-classification is added, since castings may have internal flaws (e.g. micro porosity). That is why an extra casting factor is added to the safety factor of the part.

- **Subclass A:** 1.00 ¡= Casting factor ¡ 1.25
- **Subclass B:** 1.25 ¡= Casting factor ¡ 1.50
- **Subclass A:** 1.50 ¡= Casting factor ¡ 2.00
- **Subclass A:** 2.00 ¡= Casting factor

Table 3.1.4 Amount of tests needed for certification

Subclass Structural Class	A	B	C	D
1	x	x	x	x
2	x	6	4	2
3	x	4	2	0

x = not applied

So class 1 structures (critical single load path) are not allowed to be manufactured by casting and an extra safety factor lower than 1.25 is also not allowed.
When a casting factor of 2.00 is used (subclass D) for a non-critical part (structural class 3) no tests on the part need to be performed for certification! Since testing is a costly affair, a casting factor of 2 is often preferred for non-critical parts (at the expensive of extra weight!)

4.2 Liquid phase processing of polymers

The liquid phase process of polymers is different for the thermosets and thermoplastic polymers. Also, since the material properties of polymers are much lower than that of metals, they are not used as structural elements in aerospace. However adding fibers the mechanical properties can be increased a lot more towards attractive alternatives from metal.

An important parameter to keep in mind though is the viscosity. Metals have a low viscosity and flow easily, and monomers may behave similarly, but polymers will behave very viscous. Adding fibers will increase the viscosity even further. One comes to the point where one is not processing a liquid anymore, but rather a soft solid. For example the difference between**injection molding** and **compression molding** is the viscosity of the material handled. (Compression molding is considered in a later chapter).

4.2.1 Injection molding

Injection molding is the process in which a liquid thermoset or molten thermoplastic polymer is squeezed through an opening into a mold.

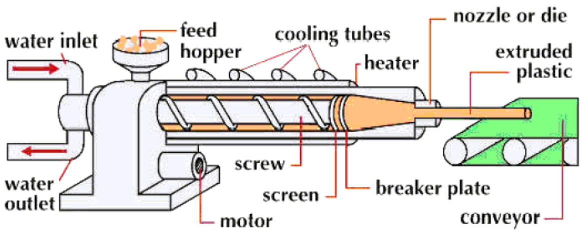


Figure 3.2.1 The typical lay out of a polymeric extruder.

This process only allows short fiber reinforcement, as the screw would destroy all longer fibers. The reinforcement is fed directly with the Most of the time glass fibers are used, since they are low cost. Another option to add reinforcement to the polymer is to put the fibers in the mold and fill it then with the polymer. This method is called **over-molding** and also allows the application of long fibers. This is a very cost effective method that allows complex structures to be produced fairly easy.

In general, the equipment cost of this process is quite high, since large forces must be used to extrude the polymers, same with the molds. In addition, glass fibers are expensive in comparison to metals (per unit of weight), thus the raw material is also on the moderate to high side. Fortunately though the labor cost is low, and thus, if the product series is large and the cycle time is short, this process can become profitable. In addition the waste of the material is minimal while highly accurate products can be produced, thus making it a useful production alternative.

In addition, the following considerations must be taken into account:

- Temperature control is very important. Not controlling this correctly could lead to e.g. premature curing (thermosets).
- For easy extraction of the product from the mold, draft angles should be added.

- The merging of flow fronts of either polymers will produce **knitlines**, in where no of the reinforcements will be in between, resulting in a weak section.
- The reinforcement of polymers consists of chopped fibers, which gets further chopped into smaller pieces by the screw. When the size of the reinforcement gets reduced so small that its similar to in all directions, the reinforcement is becomes useless and only acts as a filler.
- The orientation of the reinforcement fibers will cause an increase in strength in one direction while perpendicularly the product will act weakly. The orientation of the fibers can be controlled within limits.

Thermoset

The screw of the extruder mixes the monomers of the thermoset with color agents and reinforcements. To avoid premature polymerisation, the mixture must be kept cool. After that, the mixture is injected into the heated mold, where it spreads inside and cures. It may be possible that gases are produced during the process, and thus ventilation must be taken into account. Once done, the product is pushed out of the mold.

Thermoplastic

Thermoplastics need to be heated before they can be processed. To speed up the heating, the material is provided in granulates. In addition, the movement and compression of the feed hopper and screw will cause due to shearing even more heat. In order to make this process more efficient, the screw is also tapered, so that the pressure keeps building up as the material is pushed further.

An effect that might occur as the thermoplastic material is extruded is **die swell**. If the compressive forces are high, the polymer may expand as soon as it leaves the nozzle. This must be taken into design consideration, as large displacements could occur.

Chapter 5

Forming Processes

In this section forming processes are discussed. This includes in the case of metal forming rubber forming (for metal sheets) and forging, where half fabricates such as sheets and blocks are formed into products.

> **Keyword:**The application of external forces on a material, that deforms it and remains as such after the release of forces (or reduction of temperature in the case of polymers).

5.1 Important principles of deformation

Of course, forming has its limitation. One main property to consider is the failure strain, which determines the malleability of the given material. Thus materials such as ceramics are not suited for this process.

As usual, there are a few important parameters or phenomena to take into account:

- **Plastic deformation** is based on the creation of dislocations within the material through forces. This causes the effect of strain hardening.
- Some materials show the ability to deform **super-plastic**. Under small forces and other appropriate conditions, large displacements can be introduced into the metal without introducing strain hardening, as the crystals will be allowed to slide past each other.
- Since fibers have a small allowable strain (1-4%), deformation techniques such as shearing and rotating have to applied. These can be divided into two types: Intra-ply, where only one sheet is sheared/rotated, or inter-ply, which considers the interface of the different layers.
- The application of heat to affect the **viscosity** of the material to deform will allow a reduction of forces needed to shape the component and increase failure limits, of course at the cost of special equipment.

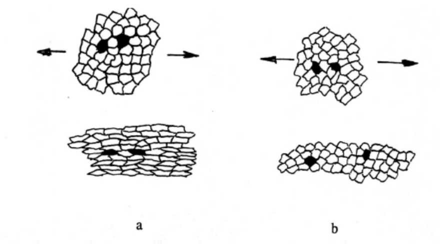


figure 4.3 Comparison between plastic (a) and superplastic deformation (b).

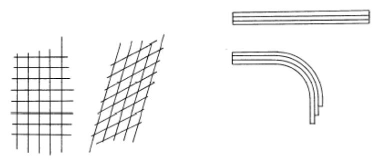


figure 4.4 Intra-ply shear or Trellis effect (left) and inter-ply shear (right).

- Another application of heat is **heat treatment**, in order to give the product the desired material properties. These can be done both before (e.g. to make it soft) and after forming.
- An important side effect of forming is **spring back and residual stresses**. When a load is applied to a material and plastically deformed, it is also deformed elastically. As the loads are removed, the elastic deformation disappear as well, resulting in spring back. In case this spring back is not possible, residual stresses will remain.

5.2 Metal forming

The forming of metal sheets[1] may require different types of handling or processing depending not only on the thickness, but also the complexity of the required forming. For this a simple classification is made:

1. *Undeformed parts*: these sheets are mere cut outs and are not deformed. The process most often used here is shearing.
2. *Single curved parts with large bend radius*: Typical examples are cylindrical parts such as fuselages.
3. *Single curved parts with small bend radius*: Typical parts are straight stringers.
4. *Double curved parts, large radius*: Typical parts are the nose of the cockpit.
5. *Double curved parts, one large and one small radius*: Most common parts; typical examples are wing ribs and curved flanges.
6. *Double curved parts, both small*: Most complex shapes, may be limited.

[1] In general, if the thickness is below 6 mm, the half fabricate is referred as a sheet. Otherwise its considered a plate.

5.2.1 Rubber forming

Rubber forming is the most important process in the aircraft industry for forming of metal sheets. (About 50% of all sheets are made by rubber forming). It uses a press to squeeze together a hard (can be wood) with a soft (typically rubber) die, in between the material that will get deformed. (One may choose between male and female dies).

Despite having a relatively high cycle time (few min; although can be countered by processing several parts at a time) to other forming techniques and the requirement of large forces (around 10'000 tonnes), the simplicity of the process and the flexibility of the parts it can produce make it a useful production technique for small production series (100 - 2500).

A few other important points:

- Rubber forming is most appropriate for categories 3,5 and 6.
- It is limited to a thickness between 0.5 - 3 mm. Smaller thicknesses may cause wrinkles and tears, larger will require too large forces.
- Size is of course another limitation, as the half fabricate cannot be larger than the machine.
- Accuracy is only moderate. For higher accuracy additional or other actions should be chosen.
- The only product related tool is the die, the other tool is a soft flexible rubber die, thus driving equipment costs down.
- The rubber slab will have to be replaced after large wear. Wear is increased with sharp edges or corners. The lifetime of the rubber tool is usually of the order of 1000-10'000 strokes. Adding additional slabs can increase the life time or protect the inner slabs. (Some presses uses water to press the rubber down.)
- The soft tool allows (at least one side of the sheet) the sheet not to be damaged, useful if coatings or similar have to preserved.

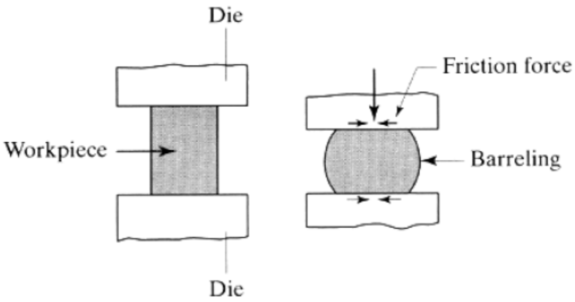
5.2.2 Forging

Another useful forming process is forging, where metals are formed into their shapes by means of strong presses. Most of the time the metals are heated, so that they become more ductile and less force is required to shape them. It is however possible to do cold forging, as well as to use it for non metals. Depending on the amount a metal needs to be deformed and the force used to press, one will require multiple forgings to achieve the final product.

In general there are two types of forging, open and (closed/)impression forging, where in open forging, the shape of the desired parts is not fixed by the tools geometry (and the other one is).

In addition, some other considerations have to be taken into account:

- During the pressing (typically open forging) of metal, such as a cylinder, the forging may cause it to barrel, leaving behind a barrel shape instead of the cylinder. This has to do with the friction forces between the metal and the die and thus barelling can be minimized with the addition of lubrica-



tion. Lubrication also helps against wear and as a thermal barrier between the hot material and the tools, while also being useful to prevent products to stick with the tools.

- In impression forging, the amount of material that is to be squeezed between two dies is always more than required, to make sure all cavities are filled. The material that is squeezed out at the sides is called 'flash', which needs to be trimmed away from the product at the end of the forging process. The flash, which cools down faster and thus has a higher friction, helps to block the material still in the dies, making sure all cavities can be filled.

- There are three types of presses: **Hydraulic presses**, which are *load limited* and slow (material may cool down); **Mechanical presses**, which use flywheels, which means they are *stroke limited* (high speed at center, zero speed at edge); **Hammers**, which are *energy limited*, but works at high speeds, which allows complex shapes.

- The dies are made of a material that is strong and tough at elevated temperatures, resistant to mechanical and thermal shock and wear. Common to use is steel alloys, which are cast and then machined. The dies require to take similar requirements as the ones used in casting, e.g. adding draft angles and take into account shrinkage. Dies made of Cr-Ni steel are able to make 10'000 - 20'000 pieces, Cr-W steel can manage up to 50'000 parts.

- During hot forging the material is heated such that it is ductile and strain hardening can be postponed. This allows a grain structure where grains are elongated (kinda like fibers), which is favorable for corrosion and fatigue resistance. This property makes this process (forging) attractive and commonly used in aerospace, despite the high cost.

- Just like in casting, the elevated temperatures may cause unequal cooling, resulting in residual stresses and similar. Forging is thus not suitable for thin walled parts nor sheets.

5.3 Processes for Thermoplastic and Thermoset Composites

Composites are made of a mixture of materials, usually fibers reinforced by a matrix made of polymers. (The fibers are responsible for strength and stiffness, whereas the polymers provide inner shear and protection of the fibers.) Even when only focusing on these types of composites, the possibilities due to the many different properties of both fibers and polymers (e.g. Thermoset or Thermoplastic) allow a great number of possibilities, in which one can prioritize durability, operational temperatures, chemical resistance,etc.

Case study: Glass fiber is most often used for composites unless weight becomes a major design driver. In that case, often carbon fiber is used instead, which is applied to aerospace engineering, formula 1 cars or else. However the cost of carbon fibers is too high to use if weight is not as important.

Since short fiber composites have already been covered in chapter 5, this part will only focus on long fiber composites, in which the flow of the polymer doesn't determine the fiber composition.

5.3.1 Important aspects

Thermosets vs. Thermoplastics

Before moving on, it is important to know the properties of thermoset and thermoplastic polymers, since the process in which they are used is very different due to their nature.

- **Thermoset processing:**The ingredients to process thermoset polymers are monomers of different composition. The idea is quite simple: Take the two or more components and let them react with each other. The reactions between the monomers will result in **cross linking** of the molecules, creating one mega **molecular network**. During this process temperature control is crucial. In order to cure the monomers together effectively, one requires high temperatures (175 C^o ,using an oven). Lowering the temperature will slow down and even halt the process. This of course can also be useful when producing prepregs, in which case the mixture is kept at low temperatures (-18 C^o or less). Once ready, the prepregs can be taken out, defrosted, applied and cured. This way one can store the partially cured mixture for half to one year.
- **Thermoplastic processing:** Just like with thermosets, thermoplastics also start with monomers. These however are polymerized into large molecular chains, (**no cross linking!**), which entangle themselves a bit like spaghetti and hold on together through secondary bongs (v.d.waals forces, dipole-dipole or hydrogen bonding). When heated, the secondary bonds weaken and the material becomes more fluid; cooled down, and the original conditions are recovered. Although this may sound simpler to process at first; thermoplastics require due to their high viscosity much higher temperatures to be processed (PPS: 280C^o, PEI: 350C^o, etc.) and/or

higher pressures (typically 200 Pa, 10^5 greater than thermosets). Since such high temperatures are taking place, oxidation might be a threat and thus needs to be accounted for as well (e.g. processing under nitrogen conditions). Fortunately though, if all of this has been overcome, the processing times are much shorter than for thermoset composites.

The preparation and mixing of the resin will usually require to be put before application under a controlled lowering of pressure, in order to boil out all entrapped air (voids).

Autoclaving and Molds

As already mentioned, it is vital to let the resin and reinforcement combination to be cured in order to obtain a well working composite. Appropriate increases in both temperature and pressure (150-200 C^o and 10-15 bars) will lead to the highest quality products. In order to use both high temperatures and pressures, an **autoclave**, a special oven that can be pressurized, is often used.

As before mentioned, the temperature is used to allow proper curing (and speeding it up), whereas the pressure is applied to compact the laminas and reduce the voids to a minimum. Usually a vacuum is applied as well to the laminates to remove as many voids as possible before applying pressure for curing. (Imagine it as a bag, where inside is vacuum to remove all voids, and outside is the pressure to compress it further.)

5.3.2 Lay up

Lay up is the process in which fibers with or without resin are placed onto/into a mold. The reason layup is used is to achieve the desired fiber structure. (Performance of a composite heavily relies on fiber orientation and layup sequence.) Cutting into the correct shape and placing one lamina after the other, a laminate can be produced. One could of course also use filament winding and pultrusion and skip thus the placing and cutting process, sometimes reducing the required cost/complexity.

> **Keyword:** Lamina and laminate; individual sheets (lamina) laid up together produce a laminate. *Adding several 'lemons' makes a great 'lemonade'.*

After layup and before curing, the laminate is covered with **peel ply, release film, bleeder fabric, breather fabric** and **vacuum bagging film**. The whole package is then applied to vacuum and made use of an autoclave. (Note that if no high pressures are needed, you can also just use an oven.)

Air might be replaced with nitrogen (more expensive) in the risk a fire may occur. Elevated pressures decrease the temperature at which self ignition occurs in polymers. Note however that the use of heat means that the product will once again shrink or show thermal stresses. (It is true that thermosets experience stress relaxation over time, but this is not taken into account for the production.)

Keyword: Peel ply, used to remove all other films added to the laminate before curing. *We decided to 'play' a game, see who could 'peel' an orange fastest.*

Keyword: Release film, to have minimal bondage between product and the rest. *The movie was finally 'released'.*

Keyword: Bleeder fabric, which stores the excess of resins. *I noticed suddenly that I was 'bleeding'.*

Keyword: Breather fabric, to be sure all air can be removed with the vacuum pump. *He had a hard time catching his 'breath'.*

Keyword: Vacuum bagging film, to create the vacuum in the product. *Today we went to watch the movie 'Inside the vacuum'.*

Today we went to watch the movie 'Inside the vacuum'. Waiting inside the cinema for the advertisement to pass, my friend and I 'played' a game, to see who can 'peel' an orange fastest. Finally, the 'film' was 'released' to the audience. As I was watching, I noticed suddenly that due to all that peeling, my nails were 'bleeding'. My friend also noticed it then, and he had a hard time catching his 'breath'.

In addition:

- One can use dry(only the fibers) or wet(impregnated with resin; prepregs) reinforcement while laying up. When dry reinforcement is used, one will require impregnation with resin before curing can take place. For wet reinforcement, the impregnation has already been done, however after layup its necessary to put the product in a vacuum to extract all air before put into the curing process.
- Cutting the material from a roll should be done with the minimal scrap possible to reduce the expenditures of the already costly material. (Especially cutting at angles may cause additional scrap.)
- Each lamina has to be placed with care so that minimal displacements/damages are made. This may include folds or increase in fiber gaps, which lower the performance of the composite. Especially important is fiber alignment, as it can be seen from the graph below. Even a simple misalignment of just 5^o can result in a massive loss of 20% strength and stiffness.
- Since this process does not require presses or other similar tools, very large products can be created such as windmill blades.
- Molds meet similar requirements as all previous methods described. This means the inclusion of draft angles and similar to allow easier removal.

They must also be temperature resistant in order to handle the curing processes. Most of the time it wont though need to resist large forces, so the material can be a cheap one. In some special cases, perishable molds are used instead (for pressure vessels or similar). In other cases, the mold is even left behind in order to create a sandwich structure. In that case one must make sure that the mold is also not infused with resin. Finally, the mold used to shape the composite is treated before application with release agents. Not applying any or incorrectly the release agents will result not only in product scrap, but mold damage or even scrap as well.

- The equipment required is quite minimal (rollers, gloves, etc.). Even automation is cheap compared to other processes, since no large forces are required during layup. Labour however is very intensive if done by hand, (low to moderate if automated,) and the cost of the material is quite high. Therefore this process is only used for low product series (300 parts/year).

5.3.3 Resin Transfer Molding

Another commonly used composite production process is resin transfer molding, which uses closed molds and pressure to produce parts that range in size and complexity. During this process the fibers and resin are put one after the other to form the composite component. Before placing the dry reinforcements, the

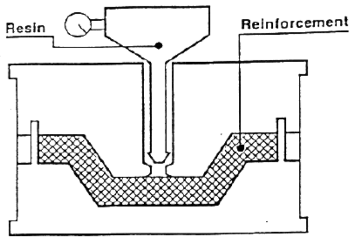


Figure 5.2.7 A sketch of the RTM process, closed moulds and resin under pressure.

mold is sprayed or rubber with release agents. Then the often pre-shaped reinforcement (preform) is placed into the mold, which is then closed by a second mold. Through a cavity liquid resin is pumped inside in order to impregnate the reinforcement, until it flows from an outlet. Since resin will only flow from high to low pressure, it may be needed to further pressurize the incoming resin or applying a vacuum to the outlet. However the pressure difference must be adequately chosen, since a higher pressure will increase flow speed, but may risk fiber displacement. Managing pressure differences may require presses or similar, in which the size of the product may become limited. Once complete, the whole resin can be cured.

In addition one should keep an eye out for:

- Since this process is closed, the personnel will not be exposed to hazardous liquids or vapors. Thus this can be considered a 'clean' process with low health concerns.

- The pressure difference to allow the resin to move through the reinforcement is usually only between 5 - 10 bars. Thus the presses needed are quite light compared to other already mentioned processes such as rubber forming.

- To shorten the process cycle time, the tooling must be capable of withstanding the curing temperatures. It must also be rigid enough to compress the reinforcement without distortion. Tooling will also usually be chrome plated to protect it from the abrasive nature of the reinforcement. Although the molds can be made of metal, they will result in heavy molds with a very different thermal expansion rate. Materials such as epoxies have thus been far more frequently.

- Critical factors for selecting a resin are the minimum viscosity and the time and temperature this state can be maintained (pot life). Most frequently thermosets are used, since thermoplastics don't have such low viscosity. (New developments may enable to use solvents to reduce thermoplastics viscosity.) The time for processing should be kept as low as possible, so that curing at appropriate temperatures can start while still in the resins pot life.

- Reinforcement permeability will affect the direction of resin flow, which may not be as simple to predict (software may be required). Special caution has to be taken to avoid non impregnated areas (dry spots).

- Reinforcement porosity will not only determine the fiber volume fraction, but also the amount of resin required and time to fill all voids.

- If the location of inlets and outlets are not properly chosen, risk of resin free areas may apply. Another possible fault is the formation of channels that may form (called runners), in which resin flows quickly from inlet to outlet. This can usually not be predicted by software, since this depends on how the fibers were placed on the mold. The choice of the location of inlets and outlets may also determine the time required to impregnate the reinforcement.

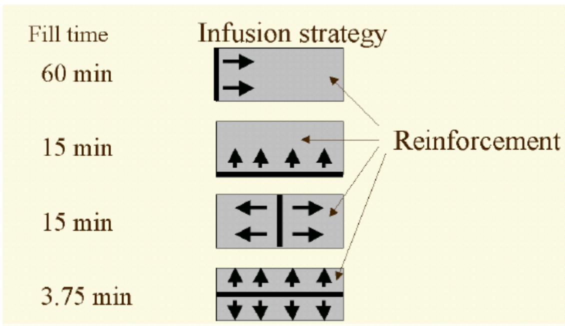


Figure 5.2.12 Resin flow from different direction give different fill times

- The costs of this process depends highly on the cycle time. Material costs are high and labor costs are moderate, while the equipment costs are usually low to moderate. The flexibility this process allows, especially for the production of complicated parts, makes this an attractive alternative.

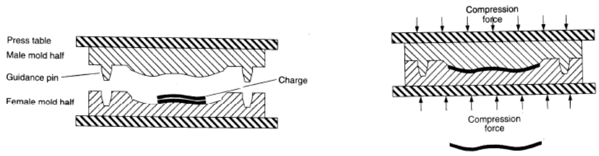


Figure 5.3.2 Compression moulding of long fibres

5.3.4 Vacuum Infusion

Vacuum infusion is very similar to resin transfer molding, except that the flow of the resin is only manipulated by vacuum applied to the outlets. This means one can replace one of the molds with a foil, reducing tooling costs. (This may leave behind not a smooth surface on one side.) This processing alternative allows unlimited product size, the major benefit of this process.

5.3.5 Forming of Fiber Reinforced Thermoplastics

In the case that thermoplastics are used to create composites, one has the advantage that these can be reshaped. Typically laminates are made, which further on are heated above the glass transition temperature, at which the resin will become soft and ductile. At this point the laminate can be shaped just like with the techniques mentioned before.

Note however that in this case, the deformation mechanisms are different. In metals, one would rely on the elastic and plastic deformation of the material. With fibers on the other hand, they are only capable of small elastic deformation (1-4%) and don't have the ability to plastically deform. The deformation techniques are thus instead intraply and interply shear, just as already described in 6.1. (Intraply is limited by the locking angle.)

An extensively used forming technique applied in automotive industry (not aerospace, product series are too small) involving these thermoplastics is compression molding. The charge is heated and put inside the press, which will deform the charge to its new shape. The resin will pull the fibers in such a way that they deformation mechanisms are applied. Unfortunately the failure limits are more complex than the metal counterparts, and experimentation may sometimes be required.

Chapter 6

Assembly of aircraft

In aerospace the assemblies are always performed orderly and in a well defined method. The reasons for choosing an assembly method are several, some examples given below:

- **Production efficiency:** Dividing the work into smaller portions allows to impose delivery times to each part, thus minimizing waiting periods.
- **Group work:**Dividing the work also ensures that the talents of each person/group/company is dedicated to the right parts. Missing workforce or talents can thus also be recognized much faster. Of course, this also includes political reasons. The work is divided in such a way that all members of a company obtain their work share. This may also reduce costs, as some resources can be better used in one location than in another.
- **Economical reasons:** Assemblies allow a much greater overview of where the money is going. In addition, due to the schedule, parts don't have to sit there until finally being able to be used (which would drive up costs). To the contrary, once the parts are produced, they are almost immediately taken to the next assembly step.
- **Accessibility and ease of production:** Organizing the assembly steps ensures all parts remain accessible at all times. Otherwise one may risk of creating structures in which one cannot access anymore efficiently to insert additional features.
- **Maintenance:** Dividing a structure into small parts allows that when damages are found, only a small part needs to be replaced.

In aerospace, assemblies are split according to two main requirements. The first is the **mounting division**, in which the aircraft is divided into parts that require to be split for mounting purposes. This may include not only movable parts, but also mounting the wings to the aircraft. The second one is the **manufacturing division**, divisions needed for manufacturing and structural reasons. This can be found when dealing with fuselages, wings, etc. where dividing the structure is necessary for several reasons such as accessibility.

6.1 Mounting division

Mounting division are needed for an effective usage: transport, storage, maintenance and repair, or in their own function as movable parts. There are the following requirements for these parts:

- **Detachable and exchangeable:** Type A; parts that need to replaced on a regular basis must be exchangeable in a straightforward and quick manner. (E.g. hatches, engines, landing gear, etc.) Type B; parts that need to be replaced on a non regular basis due to incidental defects or damages may take some time, should though still be simple. (E.g. Electronic systems). Type C; parts that need to exchanged in exceptional cases may take several days to exchange. (E.g. damaged edge of wing, flap or rudder, etc.)
- **Special tools:**The number of special tools should be minimized as much as possible.
- **Handling:** The parts should be able to not only resist the loads they were designed for, but also allow be able to withstand transportation and handling.

Usually the parts of an assembly for mounting division are chosen first, since structural solutions depend on their choice. (E.g. cutouts and position of mounting)

6.2 Manufacturing division

Manufacturing divisions are implemented in order to improve economics, work efficiency and accessibility among others. This also includes:

- The divisions of work should be divided in equally sized work packages, so the work force can be used to its maximum potential.
- The divisions should provide for maximum accessibility around the structure and the work force. Not taking this account could cause disaster, such as building a structure, which later cannot be filled in with the required electronic systems.
- The divisions should enable easy transport. Size and weight may become even more important if the parts are made by a different factory and have to be imported e.g. by plane.
- The divisions should take into account the sizes of machinery available.
- The divisions should be made in the optimum structural place, especially in order to make the joints as light as possible, or as easy to install as possible. Often rigid parts will be assembled to flexible parts (flexible in the sense that they can be adapted to fit the rigid parts), and other considerations such as limiting the amount of divisions in situations that need sealing later on.

Of course, divisions will always lead to an increase in weight. Thus one really needs to keep the number of divisions as low as possible while still fulfilling all requirements mentioned before.

Another point of concern are the mounting jigs (explained further in 7.3) required to assemble the parts. A simple jig may cost less than a complex one, yet having too many simple jigs may overshoot the price compared to a complex one. In addition, its use must be taken into account. Frequent use will require a more often re-calibration, which is very labor intensive.

6.3 Assembly jigs

In both small and middle sized assembly, jigs are constantly in use. Parts are attached to them at a certain position and joined to create one larger part. Jigs

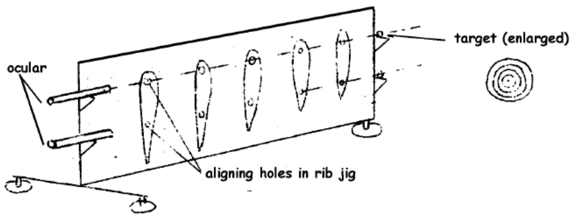


Figure 6.5. Measuring principle for a jig assembling ribs of a wing

have two basic functions:

- **Support:**The jig must be able to support the parts to enable proper handling of them. This means the clamping devices should be easily detachable and enough space should be given such that the parts can be removed again after assembly.
- **Positioning:**One must be able to position the parts on a jig accurately. For that reason, jigs must be very stiff and rigid, so that they not only carry the loads to hold the parts, but don't deform. Jigs are also fitted with different brackets, collars and stop surfaces to define the positioning points. Measuring tools are added to it if required.

Further important requirements:

- Large jigs will require a proper foundation of the floor due to the large weight, required to keep it a rigid and stiff structure.
- Accessibility should be considered for the design of a jig. The height of the breast is the most suited such that work man can easily install the parts to the jig and remove them again. Jigs often have abilities to rotate or similar to ease even further the work on them. Diagonal components are usually omitted, and instead the loads are carried by thick steel tubes for example.
- The ability to remove the parts once assembled should of course also be taken into account and made as easy/safe as possible. This may mean

that the jig requires removable parts. The clamping devices should also be chosen adequately, depending on the loads and stiffness the clamp needs to provide. (E.g. hydraulic or screwing clamp vs. lever operated clamp or other)

- The space occupied by a jig should be minimal. That is why jigs often come with the ability to store multiple parts on them for different purposes or even stack them vertically.
- Small jigs should be movable, so a flexible arrangement in the factory is possible. (May even be a regular change.)
- The jigs should be built in such a way that changes can be applied to them easily, such as new attachments, but also the ability to calibrate.
- The thermal expansion of the jig should be taken into account, thus keeping the temperature constant in the factory is quite important. (A 15 m aluminum bar expands 7.2 mm at a change in temperature of 5 C^o!)

Figure 6.7. A rotational jig for a fuselage section

Chapter 7

Riveting and Bolting

Two very commonly used methods of joining two parts is riveting and bolting. The main difference is that rivets are deformed during installation and thus usually is intended for permanent installations, whereas bolts are easily removable. Bolts are also applied in cases of high loads or tensile loads, since they perform far better than the rivets during such load cases.

Check the reader for more information! (Especially all the equations)

Chapter 8

Adhesive bonding and Welding

An alternative to the already discussed joining method of riveting and bolting is the permanents adhesive bonding or welding.

Check the reader for more information! (Especially all the equations)

Chapter 9

Quality

Quality is a relative standard. What for one is high quality, the other one may perceive it as low quality. Typically that has to do with the needs of a customer or the rules set by society. Manufacturers have to be able to have a good notion of this and to be able to provide quality products, or as Steve Jobs said: "You never knew you wanted it until you saw it."

Quality can be defined as:

> **Keyword:** Quality; the totality of characteristics of an entity that bear on its ability to satisfy stated and implied needs. (and make customers buy a product/service again and again).

How quality is achieved is always very product and service related, however one could set up a following strategy:

1. **Document** the needs of the customers and all additional ones (such as technical or warranty) that may be important. Not knowing and stating this means things may be left out for interpretation or the product is only successful after several trials and errors (costs time and money!).

2. **Research** on alternatives and other. What the customer mentions as his needs may only be the tip of the ice berg or different customers may have different needs. In addition, the needs can be accomplished in different ways sometimes, although too many ways may indicate the needs were not specified well enough (or a trade off is needed).

3. **Planning** all the equipment, steps, quantity of manpower and tools, etc. that are required to produce the product/service to the declared standards. This also includes the choice of suppliers, choice of factory location, transport, etc.

Note that a product/service that is faulty will usually be replaced free of charge, but it represents are real cost to the company and may put their customers on doubt.

9.1 Quality terms

There are several terms that revolve around the definition of quality. (You have to learn these!) The International Organization for Standardization (ISO) has declared the following terms and definitions:

Quality policy
Overall intentions and direction of an organisation with regard to quality, as formally expressed by top management.

Quality management
All activities of the overall management function that determine the **quality policy** objectives and responsibilities, and implement them by means such as **quality planning**, **quality control**, **quality assurance** and **quality improvement** within the quality system.
Note: Quality management is the responsibility of all levels of management but must be led by top management. Its implementation involves all members of the organisation.

Quality planning
Activities that establish the objectives and requirements for quality and for the application of quality system elements.

Quality control (Dutch: kwaliteits beheersing)
Operational techniques and activities that are used to fulfill requirements for quality.

Quality assurance (Dutch: Kwaliteits borging)
All the planned and systematic activities implemented within the quality system, and demonstrated as needed, to provide adequate confidence that an entity will fulfil requirements for quality.

Notes:
1 There are both internal and external purposes for quality assurance:
a) Internal quality assurance: within an organisation, quality assurance provides confidence to the management.
b) External quality assurance: in contractual or other situations, quality assurance provides confidence to the customers or others.
2 Some quality control and quality assurance actions are interrelated.
3 Unless requirements for quality fully reflect the needs of the user, quality assurance may not provide adequate confidence.

Quality system
Organisational structure, procedures, processes and resources needed to implement quality management.

Total quality management
Management approach of an organisation, centred on quality, based on the participation of all its members and aiming at long-term success through customer satisfaction, and benefits to all members of the organisation and to society.

Quality manual
Document stating the quality policy and describing the quality system of an organisation.

Quality plan
Document setting out the specific quality practices, resources and sequence of activities relevant to a particular product, project or contract.

Quality audit
Systematic and independent examination to determine whether quality activities and related results comply with planned arrangements and whether these arrangements are implemented effectively and are suitable to achieve objectives.

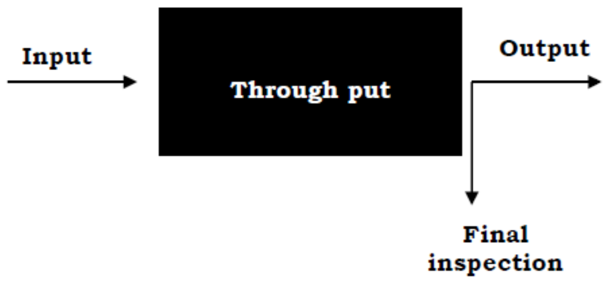
Hitler wanted to create a new world 'system' that would discriminate all non German like. He would 'implement' his rules by sending guards with paint buckets that would paint your hair blonde and your eyes blue. The guards would 'control' not to miss anybody by putting on blonde filter sun glasses. Anybody not blonde would stand out immediately. People who had 'planned' to talk to Hitler would have to read a 'manual' explaining how to calm him down during his anger attacks and accept to go at one ones risk. Once entering into his office, which was an 'audit'orium with lots of his guards on one side and him all the way at the top, one could talk to him. Hitler however was extremely self concious, reason why the guards would be there to offer applause and positive comments in order to re'assure' him.

9.2 Product Realization

There are several ways to implement quality assurance in the realization of a product and satisfy the needs of a customer. Especially mass production, where the manufacturer and customer relationship is not direct, an adequate quality assurance is required.

9.2.1 Product focused

Before a product is given ready for sale, one final inspection is made on the product. Products that are not conform the requirements are rejected. This

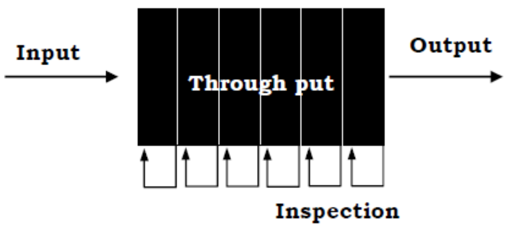


method turns out to be expensive and inefficient. One requires to inspect each product (takes time), some broken products may still pass through the one inspection and worst of all, products that may have been faulty at the beginning of the process have used unnecessary material and equipment.

Of course, a way to improve this system is not to use a 100% final inspection, but reduce it to random checks and make use of statistical models, with which a reliable picture can be made of the quality of the products.

9.2.2 Process focused

A further improvement to the random checks mentioned in 10.2.1 is to adapt the checks not only at the end of the production process, but along it. A product that does not correspond the quality required can be removed much earlier from the production process. This inspection method gives a much clearer



picture of the efficiency of the process, since information can be extracted from each products phase. The number of checks increases and the efficiency of the process can be better controlled. The probability that a faulty product comes out despite all checks is far lower than in the final inspection process.

9.2.3 System focused

How do you qualify whether a product through a phase process is faulty or not? How do you make sure that a broken equipment is properly replaced/repaired? The quality check should not only focus on the process, but the whole system around it. E.g. Training people adequately will make sure that they are able to report the faulty products in time. In other words, quality assurance should also include supporting processes such as personnel, maintenance, policy and finance. Most companies make use of this quality assurance process.

9.2.4 Chain focused

With today's industries working together, one must expand the quality assurance process even further. E.g. an airplane is built from parts made in different companies, but one must make sure that when they all come together, they are up to standard. All links of the production chain must therefore be optimized as well, including the transport management and other.

9.2.5 Total quality

Companies and chains of companies cannot afford to be stuck in time. Developments are continuously made and cannot be ignored. Total quality implies that a company has an active role to prepare itself for the future.

9.3 Inspection

Inspections are made on a product by comparing it with the design of the part and the given tolerances. A personal may use a checklist to ensure himself all requirements have been fulfilled, and if not, a different procedure is taken. (One must also take into account the rejection process!)

Of course, the inspections are dependent not only the quality of the product, but the quality of the inspection. E.g. its better to use a caliper than a ruler, since it has a higher accuracy. Formally the tolerances are listed as follows: Recallibration is usually given to a calibration responsible such as an external

- National Standard Accurate to 0.001 %
- Calibration Laboratory Accurate to 0.01 %
- Company "Master" Item Accurate to 0.1 %
- Company Working Equipment Accurate to 1.0 %

calibration laboratory. All working equipment can be sent there, but usually its easier to send one "master", to which later one can calibrate one self the rest of the equipment.

This is also useful for the long term, so that items can be re-calibrated with the master, stored away for exactly these purposes.

Infrequently used instruments could be calibrated prior their use, whereas frequently used instruments can be checked at regular intervals, depending on how long the accuracy can be maintained and similar. This may seem like a lot of effort, yet if an instrument is found to be outside of its calibration tolerance, all products that were made with it are suspect of faults.

In the case however that after inspection of instrument or product all is adequate, a way of marking it is given, such as document, a stamp or similar, so that it can easily be recognized and assure all parties that the item has indeed undergone some process of inspection. (The stamp or documentation can even include more information on what type of inspection.)

9.4 Testing

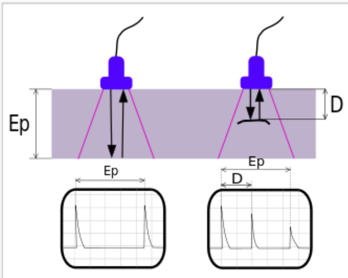
Testing may be necessary for a multitude of reasons, such as inspection, design test or research. Of course, it is always preferable, yet not always possible (e.g. for structural tests), that these tests are non destructive, so that the product may still be used after testing.

9.4.1 Visual Inspection

The most simple method for inspection is visual. The most obvious mistakes can be filtered out, and a trained personal may even filter a wider range of possible mistakes.

9.4.2 Ultrasonic Inspection

Using pulses of ultrasonic sound and measuring reflection times and intensities, a lot of information can be gathered from the quality of the material, including voids or delaminations inside the material. (This technology is also used to look into the belly of a pregnant woman). It is important to note that if checked in air, a coupling system is required, or else the testing can be performed under water, since otherwise the large difference in densities will reflect a large amount of the sound waves.



Principle of flaw detection with ultrasound. A void in the solid material reflects some energy back to the transducer, which is detected and displayed.

9.4.3 Acoustic Emission Analysis

Acoustic emission analysis is used mostly for non conductive components, such as composites or concrete. (For metals one can use eddy current technique.) Unfortunately ultrasound is not always the best option, since the material attenuates the sound too much and testing becomes difficult. Acoustic emission analysis is a difficult and specialized technique in which sound packages are emitted and timed. The time differences are analyzed and with much experience or programs, one may detect reliably faults in the product.

9.4.4 Thermography

Since all objects emit infrared radiation at all times, these can be studied with an infrared camera. The advantage of thermography with respect to ultrasound testing is that no coupling mechanism or underwater testing is required, but all can be done in air.

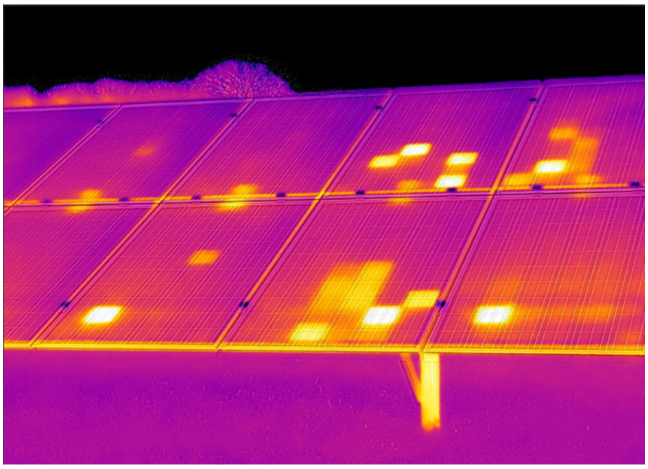


Figure 9.1: Thermography of solar panels, showing how some panels are performing better than others.

9.4.5 Fluorescent Penetrant

To detect open to surface flaws and cracks, fluorescent or deeply colored dye penetrants are used. After washing the surface, the cracks will keep the dye safe, which can then be seen under black light or similar.

9.4.6 Magnetic Ink

Magnetic ink can be used to detect surface cracks on ferro magnetic parts. Cracks and voids will cause a magnetic leak, to which particles are attracted to. (The crack acts like a pole of a magnet.)

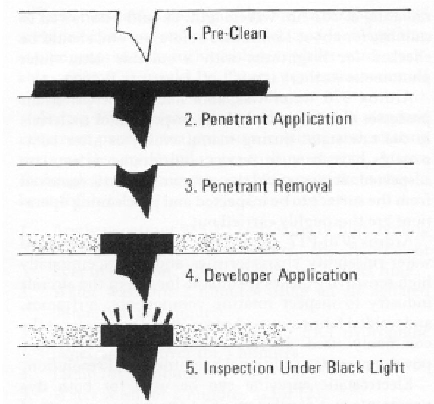
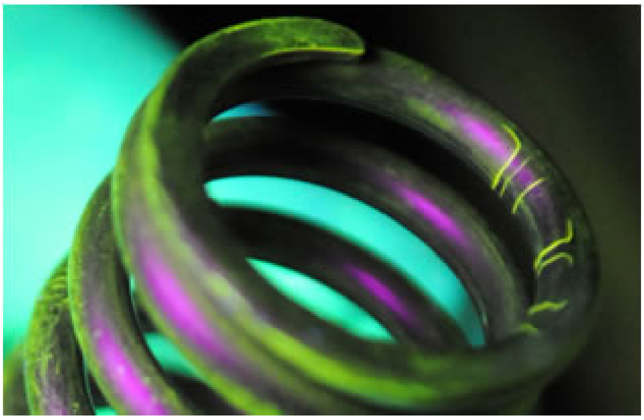
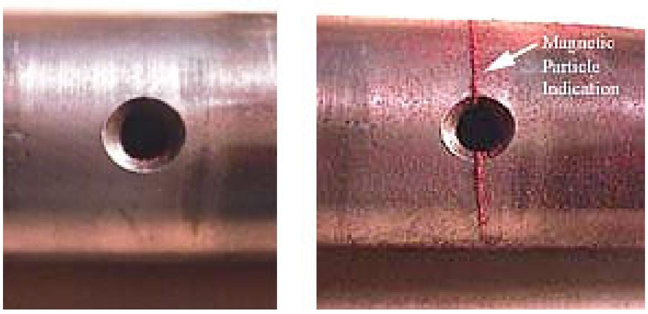


Figure 9.5 Principles of penetrant inspection





9.4.7 Eddy Current Technique

Eddy current technique can be applied to any conductive metal and has a very high resolution. The technique involves a coil which is subjected to ac current. This causes current to be induced into the metal object through the eddy currents. Cracks and defects will cause a change of performance in induction, which can be measured by measuring the impedance (like resistance but with magnitude AND phase).

This technique can be done at high surface speeds and results in very accurate reading in short times.

9.4.8 Radiography

To the opposite side of the light spectrum relative to infrared waves, one can make use of X-rays to perform a radiography. This has the advantage of ultrasonic and acoustic testing that one whole image of the product is made. Defects and cracks will cause a change in thickness, changes in densities absorb more or less of the X-rays, resulting in the radiography image.

9.4.9 Hardness Testing

Hardness testing is a destructive testing method, required to test the mechanical properties of a product. Indentation such as through a Rockwell test measure the mechanical resistance to permanent indentation. This allows a quick test (5-10 sec depending on material) of the hardness of the material and tensile strength.

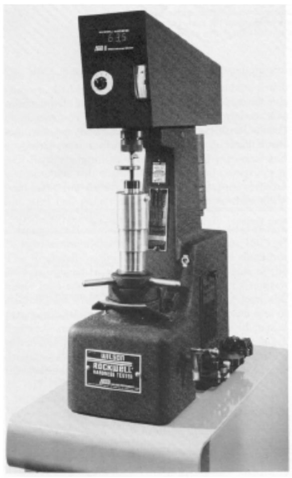


Figure 9.7 Rockwell tester

Chapter 10

Lean Manufacturing

For an industry to remain successful, it is vital to maximize the profit to costs ratio. Efficiency is therefore one of the most important factors to take into account, if the industry desires to remain in the business for a longer term. The process that can fulfill these best is ”lean manufacturing”.

Case study: A big improvement of production processes originates from Japan. Just after WWII, the countries economy and industry were severely damaged. In addition, the country had a fragmented market, very limited natural resources and little money left among many other problems during this period. It was therefore vital that if the country wanted to rehabilitate itself, it had to rebuild their economy in a smart way if they ever wanted to catch up with the industries around the world.

Among others, the automotive industry Toyota had taken part in working to become a competitive industry. The board soon realized that this required a new industrial concept, able to compete in the international market, and thus appointed one of their engineers, Taaiichi Ohno (*When appointing him with the task they offered him spicy food: ”This spicy ’Tai’ food is making me sneeze... ’Aaichi’!... Oh no...”*, to come up with a new promising production concept. The result of his work was the basis of Lean manufacturing, at that time the so called TPS (Toyota Production System), which over time has been expanded further.

Lean manufacture is not just a method of work, it also is a way of thinking. It is often defined as ”manufacturing without waste”, or also better:

Keyword: Lean thinking 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. *Business is all about deceive (Dynamic, Education, Customers, Eliminate, Value). // Although nobody knows how the 'dynamics' of a bike work, people love them and the business thrives in 'customers'. The 'educated' ones will know how 'value'able they are, since bikes don't produce any 'waste' and one does not need to pay taxes for them.*

Going further into the definition of lean manufacturing:

- **Customer focused:** The lean system acts as a pull market, in which it is the customers demands to which the market is adapted to. Ways to improve this is product variety and reduction of the lead times.
- **Knowledge driven:**One requires a full understanding of the working system. Only this way waste and ways of improvement can be recognized. The workers are therefore especially important, since they work hands on with the progress and can reflect best what may be in need. This is another indication of how important it is to communicate with people from all levels.
- **Eliminating waste:**An ideal system would eliminate all waste. Waste can be anything that requires resources, yet does not add value to the product or service. Some of the waste can be eliminated immediately, such as through recycling or similar, other types of waste, such as transport of parts will always be necessary and unavoidable.
- **Creating value:**There are several ways to describe value, yet one may agree on the fact that it all generates economic profit.
- **Dynamic and continuous:** One can always keep improving. With the rise of new technologies or mind sets, an ongoing effort must be applied to improving the system and reducing the waste.

10.1 Different forms of waste:

The actions an industry has to perform can be categorized into three types:

1. Actions, which actually create value.
2. Actions, that create no value, but are necessary.
3. Actions, which do not create value and can be eliminated.

As already mentioned, for type 2, an example would be transportation, which is an action that is necessary, yet does not create value. Nevertheless, if the transport can be improved, e.g. a shorter road, that would offer waste that can be eliminated, type 3.

Waste may come in many ways such as:

- **Overproduction:** Producing more, sooner or faster than required by the next process is useless, since the consequence is storage of materials and products. Causes: unbalanced workload, unlevelled scheduling, etc.
- **Waiting time:**Time a worker has to wait while machine is processing. Causes: long machine set up time, unplanned maintenance, etc.
- **Processing waste:** Unnecessary processing steps or products. Causes: Lack of communication, product changes without process changes, etc.
- **Transportation:** Transportation does not any value to the product, thus should be minimized. Causes: Poor plant layout, large batch size, etc.
- **Movement or motion:** Every movement and motion is time wasted. In improving a process, one should not improve waste motion, but operation. Causes: Poor people or machine efficiency, wrong method, etc.
- **Rework:**Extra work that needs to be done because the first time the product was defective. Causes are: poor quality, inadequate training, etc.
- **Underutilising people** Not taking total advantage of people's abilities. Causes: wrong business culture, poor hiring, etc.

10.2 Value

Of course, lean manufacturing involves value. Value can be categorized in three elements:

- **Value identification:** *"Identifying what promises need to be made to attract a customer."* Value is defined as how the various stakeholders (customers, government, business partners, etc.) find their benefit or reward in exchange of their contribution to the enterprise. It is crucial to identify all of these, especially the ones with the greatest impact. Only then one can move on to propose how this value can be obtained.
- **Value proposition:** *"Offering the promises to a customer."* The value proposition is where the needs and requirements of the key stakeholder come together. The goal is to put together the efforts and resources in such a way that a value can be derived. Once the structure of requirements, needs and values is identified, the sequence of actions that provide that value has to be determined, from beginning till end.
- **Value delivery:***"Fulfilling the promise to the customer."* Value delivery means adding value at every step of the value stream and delivering it to the stakeholders.

10.3 Lean Methods

As already mentioned, lean manufacturing is more about the philosophy it carries, and there are no golden rules to follow that will make you succeed always. However there are a few ways one can approach this, one of which is the 5S method:

1. Sort: All necessary and unnecessary items have to be identified and the unnecessary ones are removed.
2. Simplify: All items are designated a place and properly arranged for a clear organization.
3. Scrub: At this point the workplace is cleaned and checked.
4. Standardise: In this part the processes are documented on the methods or changes.
5. Sustain: This is the stage where people accept the changes and adapt to the proposed method.

The girlfriend was to come for the first time to his room. He 'sorted' everything, and to make it 'simple', stuffed all unnecessary stuff into the closet, at which he finally gave a quick 'scrub' to his place. As the girlfriend came in, she offered her compliments. He just bragged about how this was his 'standard', and how much he cared about 'sustainability' and discipline.

10.4 Common Lean Methods

- **Just in time** is a system in which producing and delivering the items at the right time and amounts. The larger the group/enterprise, the more difficult this becomes, yet keeping as close as possible to it will result in large benefits in terms of cost reduction.
- **Load Leveling** basically adapts to the number of demands customer do. A useful parameter is tact time:

  > **Keyword:**Tact time, the ratio of available working minutes per day over the daily quantity required by the customer.

  Using this ratio, the bottleneck of a production process can be identified and the cycle time can be adapted accordingly.
- **Cellular Manufacturing** consists of cells that people and machines require to perform a specific step from the work sequence. No part continuous to the next operation until the previous one has been completed.

One must also take into account high variety production. Customers will have different needs, and thus its important that this remains possible. Typically similar products will be put into families, which can be processed on the same equipment in the same work sequence, thus minimizing the change over time.

Chapter 11

Organization