PRACTICAL GUIDE OF TECHNOLOGIES FOR THE REMANUFACTURING PROCESS

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I Introduction

The remanufacturing process, as has already been mentioned, consists of taking a used product (at the end of its service life) and modifying it to obtain a product that has the same or better characteristics than a new one. Figure I shows a simplified outline of the remanufacturing process and the point of the product lifecycle where remanufacturing intervenes. The process can be summarised in 7 phases: Collection, disassembly, cleaning, inspection, reconditioning, assembly and testing. Even though collecting the components is a phase of the remanufacturing process, it is not going to be analysed here as it is not a process applicable to the product but the other 6 are.

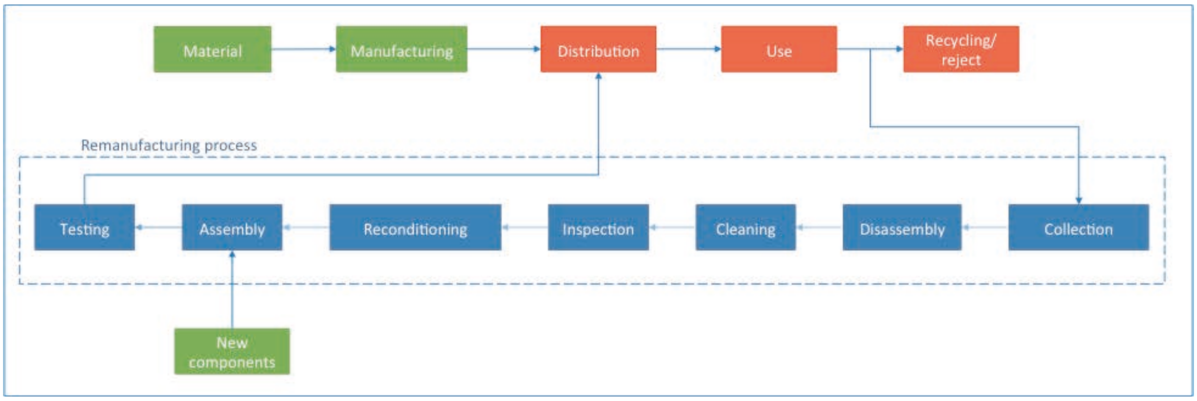


Figure I Lifecycle of a manufactured product (blue) and a remanufactured product (green) (A. Treat, 2012).

- Collection: The first phase of all remanufacturing processes. As its name indicates, it consists of collecting the out-of-service components and taking them to the remanufacturing plant.
- Disassembly: During this phase, the product is disassembled and the components that are going to be remanufactured are separated from the other components. Care has to be taken not to damage the components when disassembling them.
- Cleaning: The components are cleaned to remove any possible dirt (grease, rust, paint, etc.).
- Inspection: All the components are inspected thoroughly and any defective ones are rejected.
- Reconditioning: The component undergoes different operations, either to recondition it as a new component or to correct any small defects that it may have.
- Assembly: All the product components are assembled. The new and remanufactured components.
- Test: The product is tested to check its quality before it is put back on the market.

Even though Figure I shows the simplified outline of the remanufacturing process, it should be noted that the remanufacturing process is not a systematic one and there is no order that defines the process. Each product is a world unto itself and it is therefore impossible to design an outline that is valid for all products. Not all the products have the same phases or same order. Therefore, there is no order that defines the remanufacturing process. It is true that the same phases always appear, but the order varies depending on the product (Figure 2).

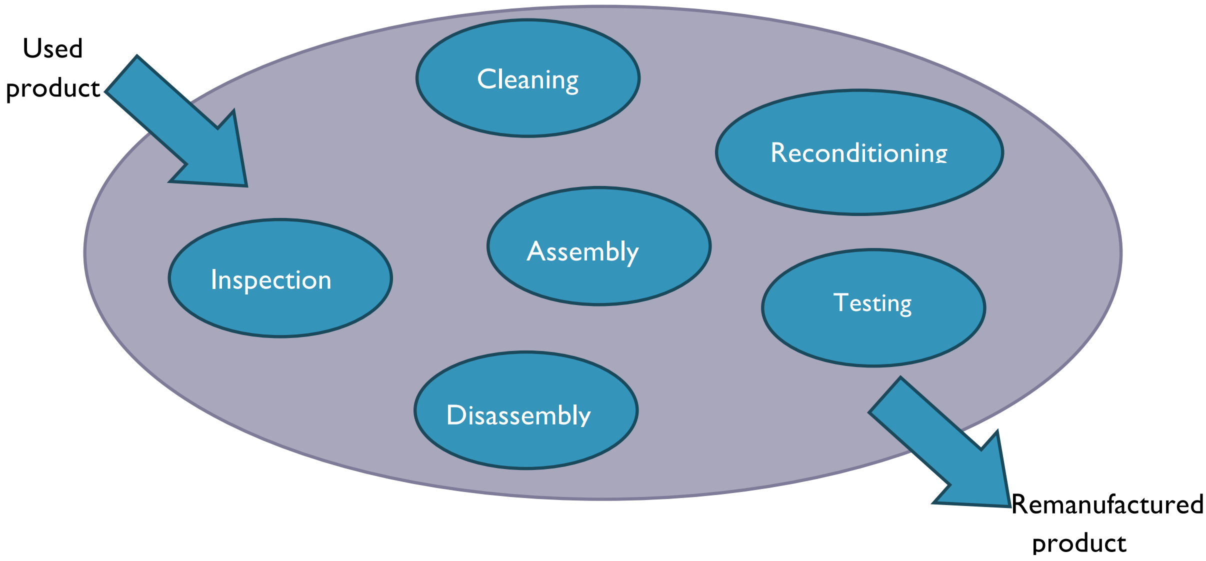


Figure 2 General remanufacturing process (E. Sundin, 2004).

Each product has its own process. Some products need cleaning before being disassembled; others, for example, can be disassembled and inspected without the need for prior cleaning. In other words, the product or the state of the product determines the remanufacturing process and the technologies needed for each phase. Even so, Figure 3 sets out the most common outline of the remanufacturing process. In that process, cleaning plays an important role, as it is the most repeated phase along with inspections.

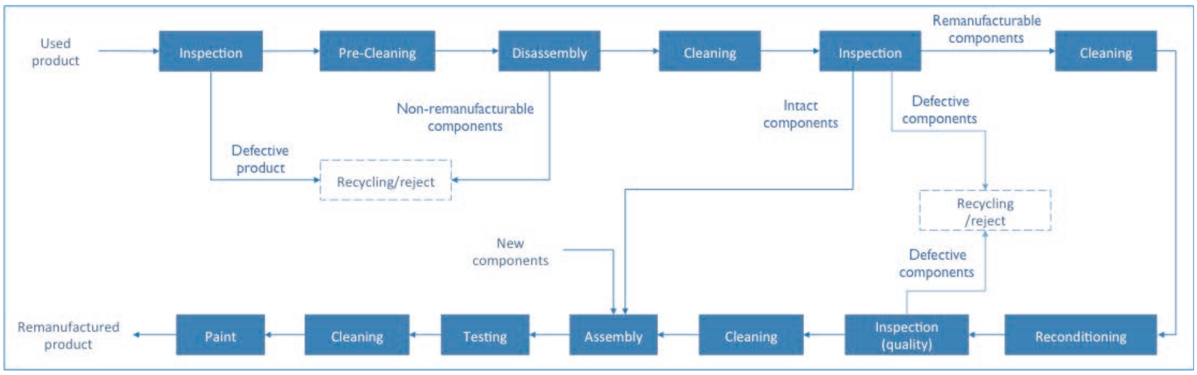


Figure 3 Most common outline in remanufacturing processes (W. Liu, 2013).

The first phase of the process consists of inspecting the product. This allows those products in poor condition to be identified and rejected before performing other operations to no avail (such as cleaning) and wasting money; in other words, an initial analysis is performed to establish where remanufacturing is worthwhile. Then, depending on the how dirty the product is, a rapid cleaning (pre-cleaning) is usually performed; which allows the product to be more easily disassembled and those areas to be inspected that were previously hidden by the dirt. In those cases, where the product cannot be inspected due to the dirt, pre-cleaning will be the first phase of the remanufacturing process. The following phases consists of disassembling the product. The components that can be remanufactured are separated from those that have no value or are in very poor condition. This is followed by the cleaning phase. All the dirt is here removed from the components. More than one cleaning technology is usually used, as different types of dirt cannot usually be cleaned using just one technology. The components are then inspected to reject any defective components. Depending on the component, different types of inspections are performed: surface, volumetric, dimensional and electric tests. The components would then be cleaned again.

This phase will need to be carried out depending on the type of inspection previously carried out, as this process will not be needed if no inspection method has been used that dirties the component. This is followed by the reconditioning phase. It is a phase that greatly depends on the component, as there are many different possible operations. However, the operations are usually very similar to the processes performed during the manufacturing. The reconditioning is followed by a quality control (inspection) to check that the reconditioning process has been completed correctly. It should be noted that even though this and the following phases are in the remanufacturing process, they are processes that appear during manufacturing and the company usually knows what has to be done. During the following phase, the components are cleaned again whenever necessary. In the same way as in the previous cleaning phase, this will depend on the operations performed during the reconditioning and inspection phase. The remanufactured components are then assembled with the new ones. A test is then conducted to check that the remanufactured product works properly. Finally, the product is cleaned again, is painted and packed (the cleaning and painting phase will be carried out as necessary for the product).

There are different technologies for each phase. Each technology is selected according to the type of product. Therefore, the following section is going to analyse some of the technologies that can be used in the different phases of the remanufacturing process. This is particularly the case of the technologies that can be used for the cleaning and inspection phases, due to the need for companies (with remanufacturing potential) to introduce new technologies for those phases (Table 1).

Table 1 Availability of technologies for the different phases of the remanufacturing process in companies of the BAC.

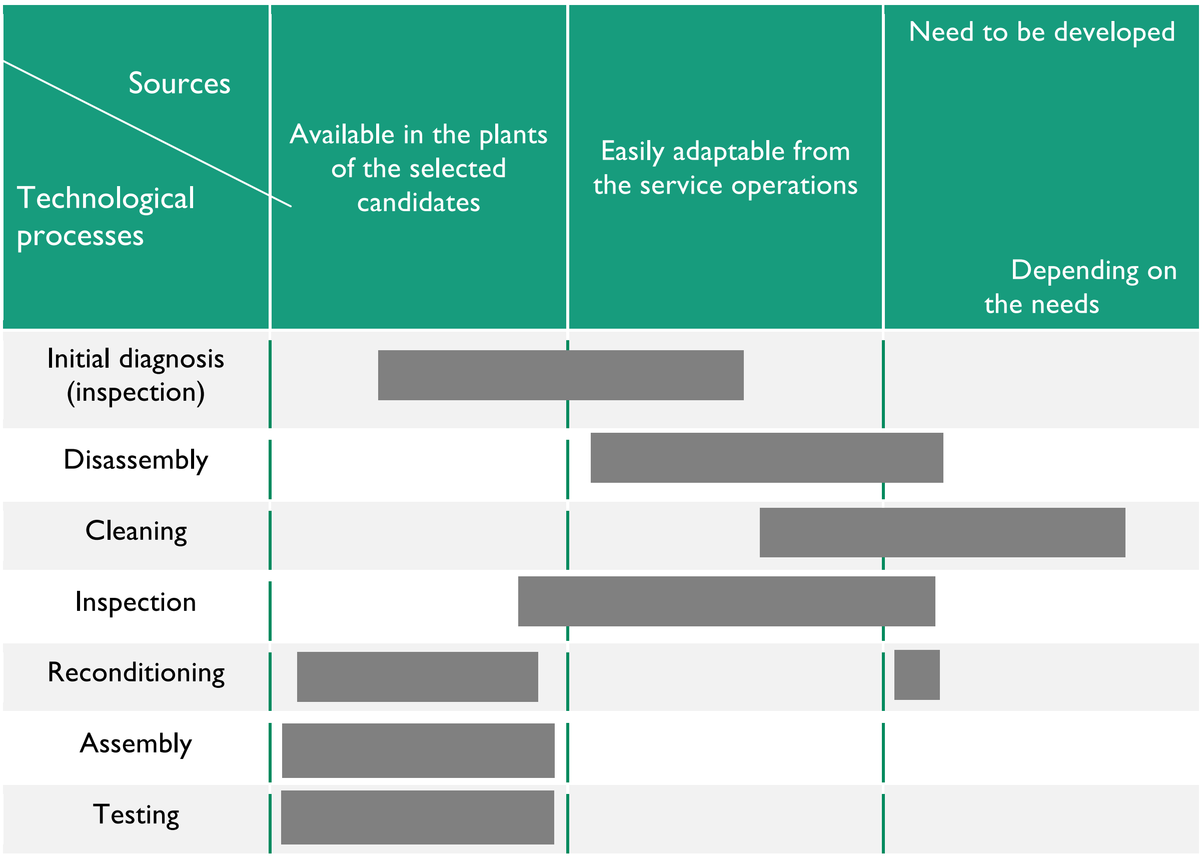


Table 1 shows which companies have sufficient technological prowess to conduct the reconditioning, assembly and test phases as they are identical to the manufacturing process. It is true that, in some cases, a type of technology has to be introduced for the reconditioning phase that is not used in the manufacturing process.

At the other end, there is the cleaning phase, which needs to be fully developed depending on the needs of each company. Therefore, this phase is the one that is going to be analysed in greater depth in the following section.

The inspection and disassembly phases are somewhere in between. Companies are not adapted for those processes, but they are easier to implement than the cleaning process, particularly in the case of disassembly, as, technologically speaking, it is not highly complex. Companies that assemble components know exactly the procedure that has to be followed to disassemble them. Inspections, however, are an unknown process (except for the quality controls); therefore, implementing them in the companies is more difficult.

2 Technical bases

The aim of this section is to classify the possible technologies that can be used during the remanufacturing process in order to help to select the most appropriate technology for each phase and product. The technologies are classified into 5 groups: cleaning, disassembly, inspection, assembly and testing.

2.1 Cleaning technologies

Cleaning is the most important phase of the remanufacturing process. The cleaning phase determines the quality of the final product, as the efficiency of the following phases is directly related to the quality of the cleaning. A dirty object cannot be inspected, assembled or painted correctly (M. Li, 2015). Therefore, it is important to select the most appropriate technologies for each product.

This phase is usually made up of two or more technologies, as it is difficult to remove all the dirt with a single cleaning process. This does not mean that there are not products that only need a single technology.

This section will provide a brief summary of the cleaning technologies applicable to the remanufacturing process.

2.1.1 Cleaning solutions

Cleaning solutions, as their name clearly indicates, are ones used to remove dirt. In some cases, a type of cleaning solution can be added to the cleaning technology in order to make the process more efficient. The solutions can, mainly, be divided into three groups: water based, semi-water based and solvents. The selection of one or other will depend on the material to be cleaned and the pollutant to be removed.

2.1.1.1 Water based

The need for more environmentally-friendly cleaning methods than solvents has meant that water-based solutions are playing a prominent role in the industrial cleaning sector. Water-based solutions are divided into three different types, depending on their acidity (pH): alkaline, acid and neutral.

Water-based solutions with a pH value higher than 7 are known as alkaline water-based solutions. They are used to remove organic pollutants, such as grease, oil, wax, etc. The more alkaline the solution is, the greater cleaning capacity the product will have.

Acid solutions are those with a pH value under 6. They are used to remove rust from the surfaces.

Water-based solutions with neutral pH ($5<pH<8$). As they do not have the same degreasing or rust removing capacities as the alkaline or acid solutions, they are used to improve mechanical cleaning processes, as those processes are not as dependent on a chemical reaction. One such example could be ultrasonic cleaning (Dürr, 2016).

2.1.1.2 Solvents

The solvents have been the most widespread cleaning solutions used in industry due to their low cost and great efficiency. However, they are being used less as they are deemed a product that is rather harmful to health and the environment (PPRC, 2016).

2.1.1.3 Semi-water based

A semi-water based cleaning solution is one that is made up of a solvent and water. There are therefore less emissions of volatile organic compounds during the cleaning process. It is a more environmentally friendly cleaning method than using solvents (Cleantool, 2016).

2.1.1 Manual cleaning

Manual cleaning is the most simple method and virtually does not require any technical equipment. However, the exposure of the workers to chemical agents is much greater than with automated cleaning. The dirty parts are cleaned using clothes or sponges impregnated with a cleaning agent, while ensuring that the operator has the necessary personal protective equipment (rubber gloves, eye protection and apron). Generally, the cleaning agent is left to act for several minutes (2 or 3 minutes are usually sufficient) and are then rinsed with water (Cleantool, 2016).

2.1.2 CO_2 cleaning

This cleaning technology consists of using carbon dioxide in its different phases to remove the dirt from a wide range of materials. This does not involve producing CO_2, a gas which is harmful for the environment, but rather the CO_2 is used that has been created in another process. This gas, which would otherwise have been released to the atmosphere, is thus harnessed and used. This technology results in non-destructive and waste-free cleaning.
Furthermore, the environmental problems are removed that may occur from the use of other cleaning methods, such as the chlorofluorocarbons (CFC) or the water-based cleaning systems, as it is not toxic, or inflammable, or harmful for the ozone layer. It is also a technology that is not a hazard for the operator and the only risk is skin being directly in contact with high pressure CO_2. The details are set out below of the different CO_2 cleaning processes that have been adapted from *Handbook for Critical Cleaning: Cleaning Agents and Systems* (B. Kanegsberg, 2011).

2.1.2.1 CO_2 powder

Small particles of dry ice are here used to blast and clean the dirty surface by means of physical interactions or solvents. There is no chemical reaction and not even an abrasive process is involved when removing the dirt.

Characteristics

It is a versatile technology, as it removes particles of a large variety of sizes, both those that can be seen with the naked eye and 0.03 μm particles. It can also remove small amounts of organic waste as efficiently as the solvents. Furthermore, dirt produced by hydrocarbons can be removed using this technology.

Limitations

Cleaning with CO_2 powder can be used with a large range of materials, as there is no change to the surface in the majority of cases. Therefore, the limitations of the material will be related to thermal shock and its mechanical resistance.

It should be noted that using this technology to clean microelectromechanical systems is complicated, due to the components containing KBr and LiF.
Furthermore, this technology is not the most appropriate to clean surfaces with large amounts of organic waste.

Equipment

As can be seen in Figure 4, the equipment needed to use this technology is quite simple. It consists of a high pressure spray system, a hose, a valve, a CO_2 source (a cylinder for example) and a nozzle.

Figure 4 CO_2 powder equipment.

Applications

CO_2 powder can be used to remove particles and organic waste from the following surfaces: metal, ceramic, polymer, glass, optical elements and wafers.
It can be used to clean hard disk components, X-ray optical systems or circuit boards as can be seen in Figure 5.

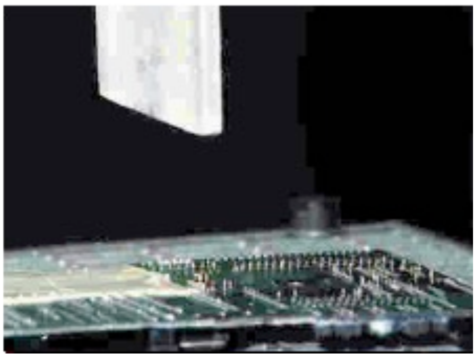


Figure 5 Cleaning circuit boards (CO_2 powder).

2.1.2.2 CO_2 pellets

Cleaning using CO_2 pellets consists of releasing dry ice macroscopic pellets at high pressure on the surface. The high speed impact and the thermomechanical force are the basis of the cleaning. It is a type of blasting but without using sand.

Characteristics

It is used to remove unwanted coatings, such as paint, grime and mould and casting waste. The advantage is that the pellets sublime into gas and only the waste remains of the object to be cleaned.

Limitations

The thermal shock is the greater limitation of this technology. Therefore, care has to be taken when cleaning objects at a high temperature.

There are usually no abrasion problems in industrial applications as the pellets are not very hard. However, care has to be taken with fragile and soft materials, as they can be damaged.

Equipment

The CO_2 pellet equipment is more complex than the one used for CO_2 powder. This is because an air compressor and a mixing chamber have to be attached to the CO_2 source, to the hose and to the nozzle (Figure 6).

Figure 6 CO_2 pellet equipment.

Applications

As has already been mentioned, this technology is very useful to remove unwanted coatings, such as paint, on surfaces where there could be abrasion problems. This is because the CO_2 pellet is much softer than other abrasives (sand, glass…).

It is used in the aircraft sector to strip paint. It is also used to clean furnaces, hoppers, tanks and foundry and forge moulds.

2.1.2.3 Supercritical CO_2

This technology uses CO_2 in a supercritical state (using pressures and temperatures higher than the critical point) to remove dirt. It is a low density method, with good transivity, permeability and high diffusivity. The CO_2 is in an intermediate state between liquid and gas. A fluid is thus obtained that has the high solubility of liquids and a similar diffusivity to gas (W. Liu, 2015).

This technology is being used instead of the traditional thermal cleaner, when remanufacturing materials with low melting points (M. Li, 2015). It is suitable for removing grease and hydrocarbons.

Characteristics

The low melting point problems of the material is not a drawback with this technology. This means that a greater range of material can be cleaned than by thermal cleaning. Furthermore, the high temperatures used in thermal cleaning can make the material dramatically softer, something which does not happen with supercritical cleaning. Therefore, if the part has a low melting point when being cleaned or if its becoming softer may be a problem, this technology is highly recommended.

The majority of organic compounds are removed when using supercritical CO_2. It creates cracks in the most resistant ones and thus facilitates their removal in the following cleaning technology (W. Liu, 2015). Yet it should be stressed that it is a very appropriate technology to remove non-polar hydrophobic organic compounds. These include oils and lubricants, silicone oil, traces of petrol, plasticisers, grease, wax, hydrocarbon compounds, perfluorocarbons or marks. It also removes most carbonised sediments (W.-w. Liu, 2015).

Limitations

It is hard to remove rust or layers of inorganic compounds. The greatest limitation of this technology is its price. As the equipment is designed to withstand high pressure, it is usually rather more expensive than the cleaning technologies that use atmospheric pressure (W.-w. Liu, 2015).

Equipment

A machine is needed that is designed to withstand high pressures (Figure 7), which means the technology is expensive.

Figure 7 Supercritical CO_2 equipment.

Applications

The main application of supercritical fluid is to remove oil and grease. Even though it cannot completely remove the carbonised sediments, it does soften them. This makes the cleaning of the following technology easier. One such example is the remanufacturing of a diesel engine valve (W.-w. Liu, 2015), where supercritical CO_2 and water blasting are combined to remove carbon sediments with very good results (Figure 8).

Figure 8 Cleaning an engine valve: part to be remanufactured (a), supercritical cleaning (b), supercritical + water blasting cleaning (c).

It is used in the automotive sector when remanufacturing engines. Where changing the properties of the surface (thermal cleaning) may be a problem in terms of the quality of the final product.

Summary of CO_2 cleaning

Table 2 Summary of CO_2 cleaning.

CO_2 cleaning summary		
Cleaning Method	**Advantages**	**Disadvantages**
CO_2 powder	• There is no abrasion or chemical reaction on the surface. • The surface is not usually damaged. • Removes particles of a great variety of size. • Simple and cheap equipment. • Can be used with many materials.	• Is not the most suitable method to remove large amounts of organic waste. • Cleaning MEMS is complicated. • Thermal shock is possible.
CO_2 pellet	• Abrasive cleaning with no abrasion problems. • Pellet sublimation.	• Thermal shock is possible. • Equipment more complex than when cleaning with CO_2 powder. • Care needed with very soft and fragile materials.
Supercritical CO_2	• Highly efficient at eliminating grease and hydrocarbons (The best of the three). • Most organic compounds are eliminated. • There is no melting point limit for the material. • The mechanical properties of the material do not change.	• Expensive equipment. • Is difficult to eliminate rust or inorganic compounds.

2.1.3 Ultrasonic cleaning

Ultrasonic cleaning consists of using high-frequency sound waves to (20-400 kHz) to stir the solution. The cavitation bubbles, caused by the stirring, remove the waste (oil, grease, dust, etc.) stuck to the surface. This technology adapts to objects in a large variety of shapes, dimensions and materials. It is able to clean blind holes, cracks and small gaps (R. Lu, 2013). The cleaning solution is usually water based (D. S. Liebl, 1993).

The main objective of this technology is to be able to clean surface areas that are difficult to access using conventional technologies. It removes oil, grease, dust, particles or inorganic dirt. This technology is applicable to a wide range of materials: metal, plastic, glass, ceramics or rubber (W. Lui, 2013). Furthermore, there is usually no damage to the surface to be cleaned (P. Duan, 2014).

Characteristics

Ultrasonic cleaning is fast and low cost (P. Duan, 2014). In addition, components can be cleaned without needing to be completely disassembled, either because it is complicated to dismantle them or because it is not necessary (T.J. Mason, 2016), which speeds up the remanufacturing process.

In addition to obtaining a high level of cleaning (P. Duan, 2014), it is fairly uniform through the objected to be cleaned, provided that the standing waves are removed (T.J. Mason, 2016).

This technology uses water-based solutions for the cleaning process, solutions that are much more environmentally friendly than chlorinated solvents or hydrocarbons (T.J. Mason, 2016).

Limitations

Ultrasonic cleaning can cause erosion to the material. The erosion depends on the material being cleaned. The cleaning efficiency is related to the time involved, the shape of the part, temperature and chemical additives (D. S. Liebl, 1993). Correctly selecting the cleaning parameters for each pollutant is very important, not only due to the fact that it will determine the efficiency of the process, but also because an incorrect selection will damage the surface of the part (W. Liu, 2013).

It is not the most appropriate process to clean materials with a soft texture or which has a great sound wave absorption capacity (P. Duan, 2014).

Equipment

Figure 9 shows both the basic equipment (a) and automated cleaning equipment (b). The basic equipment consists of:

- Tank (normally stainless steel)
- Transducer
- Generator (Usually 40 kHz)
- Cleaning solution

Figure 9 Ultrasonic cleaning equipment: Basic equipment (a) and automated equipment (b).

Applications

The main advantage of ultrasonic cleaning is its capacity to clean surfaces that are hard to reach. Therefore, one of the main application is cleaning complex geometrical shapes and objects with many nooks. The fact that it is a rapid cleaning method means that it is also of interest when seeking greater productivity.

It should be noted that cleaning known as megasonic is the appropriate option for small and delicate components, such as silicon wafers, circuit boards or computer components (D. S. Liebl, 1993).

Megasonic

Megasonic cleaning is the same as ultrasonic cleaning but using sounds waves with a higher frequency (700-1000 kHz), which makes it possible to clean surfaces that would be damaged using ultrasonic cleaning. The disadvantage of this technology is that it can only be used to clean the surface that is facing the transducer. This slows down the cleaning process (D. S. Liebl, 1993).

Summary of ultrasonic cleaning

Table 3 Summary of ultrasonic cleaning.

Ultrasonic cleaning summary		
Cleaning Method	**Advantages**	**Disadvantages**
Ultrasonic cleaning	• Cleans surfaces that are difficult to access. • Eliminates grease, oil, dust, particles and inorganic dirt. • Can be applied to a large range of materials • The surface is not usually damaged. • Quick and low cost • Uses water-based solutions. • Can be automated.	• Can cause erosion. • The efficiency is greatly determined by the cleaning parameters. • It is complicated to select the cleaning parameters (corrosion). • Not applicable for materials with a soft texture or which absorb a large number of sound waves. • Cannot clean delicate components (except with megasonic). • The solution used needs to be treated.

2.1.4 Laser cleaning

Laser cleaning consists of using a high energy laser ray to irradiate the surface. The laser ray removes dirt, rust or paint from the surface (P. Duan, 2014). Radiation cleans the surface using different mechanisms. Those mechanisms are divided into three main groups: evaporation process, impact process and vibration process (R. V. Fox, 2013).

Characteristics

This technology allows surfaces to be cleaned that contain common pollutants such as grease, oil or rust. It also removes radioactive contaminants, decontaminates surfaces exposed to chemical war agents and even to remove contaminants such as arsenic or mercury from the surface (R. V. Fox, 2013). It should be noted that several rounds of cleaning are needed to remove some contaminants. Laser cleaning is used for paint stripping in large-scale works (W. M. Steen, 2010).

It is a technology that does not need either abrasive particles (there is no mechanical contact) or solvents to work. Therefore, it is very useful to clean components where the impact of the abrasive particles may be a problem (R. V. Fox, 2013). It also allows large amounts of water to be saved. Laser cleaning is a technology that is very efficient, quick, accurate and reliable (P. Duan, 2014).

Limitations

Laser cleaning is a technology that is currently being developed. Therefore, the only limitation of the technology is its high cost (P. Duan, 2014).

Equipment

Laser cleaning equipment may be portable or fixed (Figure 10), where the size of the equipment will vary depending on the power of the laser. Fixed equipment can be used to automate the cleaning, which ensures highly precise cleaning.

Figure 10 Laser cleaning equipment: portable equipment (a) and fixed equipment (b)

Applications

As it is an expensive technology and can be used to clean sensitive surfaces, its main application is currently to conserve cultural heritage (restoration and conservation industry), where the high cost of the technology is not an impediment when it comes to using it. It can be used to clean marble sculptures and to restore paintings and manuscripts (W. M. Steen, 2010).

Laser cleaning is also used in the microelectronic industry, as it is a gentle method. It allows the delicate silicon wafer to be washed, for example (R. V. Fox, 2013). Another of the applications is paint stripping in the aeronautics sector (D. S. Liebl, 1993).

Summary of laser cleaning

Table 4 Summary of laser cleaning.

Laser cleaning summary		
Cleaning Method	**Advantages**	**Disadvantages**
Laser cleaning	• Eliminates a large variety of contaminants. • Paint stripping. • Does not use abrasive particles or solvents. • Does not use water. • Is accurate, fast and gentle cleaning. • Can be used on delicate surfaces. • Can be automated or transported. • Main sector: Conservation and restoration, microelectronics and aeronautics.	• Technology in development. • High cost.

2.1.5 Thermal cleaning

This technology consists of using high temperatures to evaporate or break down the contaminants in the part. The high temperature breaks down the bonding strength of the waste, which means it can be removed easily (M. Li, 2015). An additional technique is usually needed to finish cleaning the object.

Characteristics

This technology allows both surfaces stained with oil or grease, as those components evaporate at that temperature, and hydrocarbons not containing chlorine or fluoride to be cleaned (W. Liu, 2013).

Thermal cleaning is used for the initial processing of the components in order to remove contaminants such as grease, oil or dust. Therefore, the cleaning phase usually needs to be complemented by a more physical technology such as ultrasonic cleaning or blasting (M. Li, 2015).

Furthermore, thermal cleaning can also be used to remove paint from surfaces involving a reasonable temperature and time (R. Lu, 2013), achieving high levels of efficiency (M. Li, 2015).

Limitations

As has been previously mentioned, thermal cleaning consists of using high temperatures to break down contaminants. Therefore, materials cannot be cleaned that have a low melting point or which are inflammable (P. Duan, 2014). The use of high temperatures means that the energy consumption is great. It is only cost-effective on a large scale. It also involves a long cleaning time (M. Li, 2015).

Thermal cleaning may alter the properties of the part, due to the fact that the part is heated to high temperatures and then cooled. (M. Li, 2015). It is a very important factor when remanufacturing, as the aim of the remanufacturing is to obtain a product that has the same or better characteristics than a new one.

Equipment

The equipment consists of an industrial furnace (Figure 11).

Figure 11 Industrial furnace (thermal cleaning).

Applications

Traditionally, this technology has been used for the initial cleaning of engines (M. Li, 2015), where the dirt to be removed is usually grease and paint. This technology allows grease to be removed from the surface and the coat of paint to be stripped or softened. This makes the cleaning of the following technology easier.

Another of the applications of this technology is to clean components that have a high melting point, such as cast iron. This ensures high productivity. One such example is the disk of a gear box that can be seen in Figure 12 (R. Lu, 2013).

Figure 12 Gear box disk.

Summary of thermal cleaning

Table 5 Summary of thermal cleaning.

Thermal cleaning summary		
Cleaning Method	**Advantages**	**Disadvantages**
Thermal cleaning	• Eliminates grease, oil and hydrocarbons. • Can be used to remove paint. • Able to clean many parts at the same time.	• Cannot be used either with materials that have a low melting point or which are inflammable. • Can alter the properties of the part. • Energy consumption. Only cost-effective in large productions.

2.1.6 Water blast cleaning

This cleaning technology consists of using water at high pressure to remove the dirt from the surface by means of the kinetic energy of the water. It is a highly efficient cleaning method (R. Lu, 2013). When the surface to be cleaned contains contaminants that are difficult to remove, hot water is used to improve the cleaning. Furthermore, some equipment offer the possibility of add a cleaning solution to the water to enhance the cleaning efficiency (A. Arrieta, 2006).

Characteristics

Water blasting removes grease and other contaminants from the surface (W. Liu, 2013). It can also be used to remove rust and paint (D. S. Liebl, 1993).

The high cleaning efficiency and low cost of this technology means that it is highly competitive and versatile, and can be automated or transported depending on the equipment acquired (P. Duan, 2014).

Limitations

It is a process that also consumes large amounts of water, as the contact time between the surface and the water is very short and contaminates it. However, equipment designed to clean and to recirculate that water exists (D. S. Liebl, 1993). The use of water also limits the technology for applications where damp may be a problem (A. Arrieta, 2006).

On the other hand, it may cause a dent in the surface if the latter is not hard or thick enough. It should be remember that a physical force is being used to remove the dirt.

Equipment

The basic equipment (Figure 13) consists of:

- A high-pressure pump
- Hose
- High pressure gun

Figure 13 Basic water blasting equipment.

As has already been mentioned, the cleaning can be automated in some cases. In that case, more complex equipment is needed, as can be seen in Figure 14.

Figure 14 Automatic water blasting equipment.

Applications

Water blasting can be used to clean inside pipes (A. Arrieta, 2006). One example is cleaning the pipes of a heat exchanger (Figure 15), as ultrasonic cleaning of such a bulky object is complicated.

Figure 15 Cleaning a heat exchanger.

Another application can be to remove grease and dust from the surface of a gear box in the pre-cleaning phase as can be seen in Figure 16 (R. LU, 2013). There is the drawback of having to dry the gearbox if the aim is to continue the remanufacturing process with a dry object.

Figure 16 Pre-cleaning of a gear box (water blast cleaning).

Summary of water blast cleaning

Table 6 Summary of water blast cleaning.

Water blast cleaning summary		
Cleaning Method	**Advantages**	**Disadvantages**
Water blasting	• Eliminates grease, rust, paint (high pressure) and other contaminants. • Low cost and high efficiency. • Versatile (mobile or automatic equipment).	• Consumes and pollutes water. • Problems of humidity in the part. • Part deforming.

2.1.7 Abrasive blast cleaning

Abrasive blast cleaning consists of using an abrasive material as a means of cleaning, which is usually mixed with water or air. A compressor is used to accelerate the mix which removes the ground-in dirt on impact from the surface. This happens as the result of the great kinetic energy and hardness of the abrasive material (D. S. Liebl, 1993).

The most abrasive means are: metal particles, glass particles, sodium bicarbonate, plastic pellets, CO_2 pellets and wheat starch (D. S. Liebl, 1993).

Characteristics

It is a very efficient process when removing surface coats such as paint, rust or fouling (D. S. Liebl, 1993). It is therefore very useful to clean objects whose surface is dirty with a contaminant and where the coat of paint is also to be removed. This means that a cleaning process can be saved. In some cases, it needs to be complemented with a chemical cleaning to prevent corrosion problems. It is a widely used process to remove large areas of paint (D. S. Liebl, 1993).

The abrasive mixed with a liquid instead of gas is used for more delicate operations (D. S. Liebl, 1993).

Limitations

It has to be remembered that it is a process that removes the surface layer of the part. It is therefore not very appropriate for cleaning liquid waste. It might also damage the item to be cleaned, thus damaging the dimensional and surface finish (D. S. Liebl, 1993).

The resistance of materials to corrosion may be affected if the abrasive is a material prone to corrosion. At the same time, the fact that abrasive cleaning may make some materials harder during the cleaning process likewise has to be taken into account (D. S. Liebl, 1993).

The operators need to use special protection due to the suspended particles in the air (D. S. Liebl, 1993).

Equipment

There are different types of cleaning equipment, but the following three are the most common (CLEMCO, 2016):

- Portable blasting equipment (Figure 17): As its name indicates, the equipment can be transported to where it is needed.

Figure 17 Portable blasting equipment (Abrasive).

- Jet blasting cabinets (Figure 18): They can clean and blast large items from outside the cabinet. They are usually used to clean car and metal industry parts, etc.

Figure 18 Jet blasting cabinets (Abrasive).

- Blasting rooms (Figure 19): They can be used to clean very large parts. The rooms can have automatic recovery, transport, sorting and cleaning of the abrasive. They are usually used in the railway, shipbuilding industry, etc.

Figure 19 Blasting rooms (abrasive cleaning).

Applications

Abrasive cleaning can be used for a large variety of materials: stainless steel, copper, iron, aluminium, bronze, titanium, brass, plastic, glass, etc, provided that the abrasive is used in the appropriate operating conditions (Snow White Services, 2016).

One of its applications may be paint stripping when remanufacturing a component of the aeronautical sector as can be seen in Figure 20 (Armex, 2016). The part is nickel and aluminium.

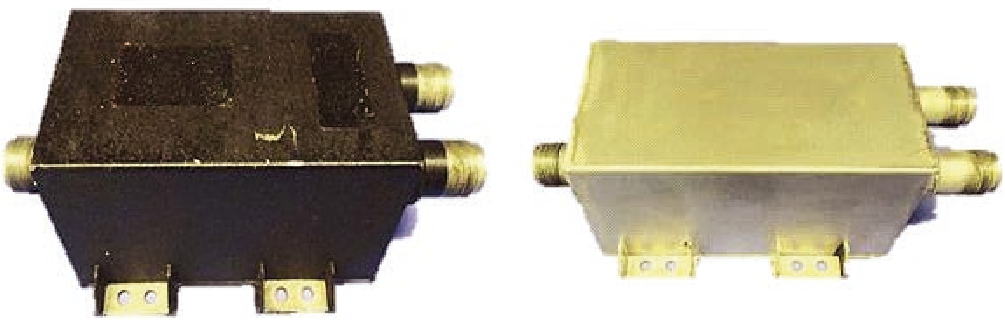


Figure 20 Paint stripping by means of abrasive cleaning: before (a) and after (b).

Summary of abrasive cleaning

Table 7 Summary of abrasive cleaning.

Abrasive cleaning summary		
Cleaning Method	**Advantages**	**Disadvantages**
Abrasive cleaning	• Highly efficient at removing surface coats: paint, rust or embedded dirt. • Allows bulky objects to be cleaned. • Great variety of abrasive resources, which allows different surfaces to be cleaned.	• Not efficient at removing liquid waste. • Can damage the surface. Aggravates the dimensional and surface finish. • Can affect the corrosion-resistance of the object. • Can increase the hardness of the materials. • The operator needs special equipment (except in the blasting rooms).

2.2 Disassembly technologies

Disassembly is usually one of the first phases of the remanufacturing process. It consists of disassembling the part to be able to wash and inspect all the components to be remanufactured correctly. Disassembly is broken down into three types: non-destructive, semi-destructive and destructive. These three forms of disassembly have been adapted from *Disassembly Automation* (S. Vongbunyong, 2015).

2.2.1 Non-destructive disassembly

During the disassembly process, there is no damage to any of the components of the part. Therefore, it is the ideal type of disassembly for maintenance and remanufacturing. On the other hand, it is usually expensive as it is a delicate process. Furthermore, great flexibility is needed due to the different connecting elements that exist on the market. In general, it is not an economically viable disassembly method.

2.2.2 Semi-destructive disassembly

Semi-destructive disassembly consists of breaking the connecting elements to be able to obtain the desired components without their suffering any or nearly any type of damage. This makes the process more efficient and it is more economically viable in many of the cases. The automation of this process is much simpler than for the non-destructive process. For example, when loosening screws, the machine only has to deform the screw and unscrew it, without having to identify its measurements and shape to select the appropriate screwdriver.

2.2.3 Destructive disassembly

It consists of dismantling a part by breaking the components. A quick, efficient and flexible disassembly is thus achieved. One of its main applications is to destruct the components that make it difficult to obtain a valid component within the part quickly and economically.

2.3 Inspection technologies

In this phase, it is assessed whether it is worth remanufacturing a component or if, conversely, a new component is needed to remanufacture the part. Obviously, the inspections are performed by means of a non-destructive test (NDT) so as not to damage the component.

Those inspections have been classified into three groups: surface/volumetric, dimensional and electrical test.

2.3.1 Surface/Volumetric

The surface/volumetric inspections allow internal or surface defects, such as cracks or pores, to be identified. The details of the different technologies obtained from *Manufacturing, Engineering and Technology* (S. Kalpakjian, 2008) are set out below.

2.3.1.1 Visual inspection

Visual inspection consists of inspecting the part using the naked eye to look for imperfections (Figure 21). It is the first test that must be performed before resorting to more sophisticated and expensive NDTs, as the imperfection may be so clear that money does not need to be wasted on using more complex techniques

Figure 21 Visual inspection.

The main tool of this test is the naked eye, but complementary instruments can be used, such as microscopes or cameras, to facilitate and improve the accuracy of the test. Nevertheless, an NDT should be used that complements the visual inspection if greater accuracy is required (IAEA, 1999).

2.3.1.2 Dye penetrant

Dye penetrant inspection is a non-destructive test that is used to detect and indicate surface-breaking discontinuities (surface defects) in non-porous solid materials (cracks, seams, pores, etc.). The principle on which this non-destructive technique is based is the capacity of the capillary action of a liquid to penetrate and be retained in surface-breaking discontinuities such as cracks and pores (Figure 22).

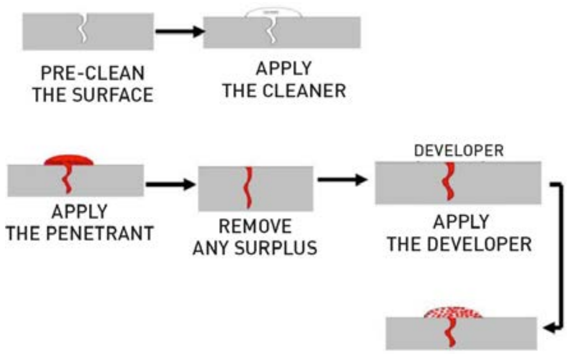


Figure 22 Dye penetrant procedure

The main advantage is that the equipment is simple and easy to use; furthermore, it can be portable and it is less expensive to use than other methods. However, it can only detect surface-breaking defects or ones that are external (Figure 23).

Figure 23 Example of defects (dyes penetrant).

2.3.1.3 Magnetic particle inspection

This technique consists of placing fine ferromagnetic particles on the surface of the part. The particles can be applied dry or using a carrier fluid, such as water or oil. When magnetised with a magnetic field, the surface-breaking discontinuity (defect) attracts the particles around the defect (Figure 24).

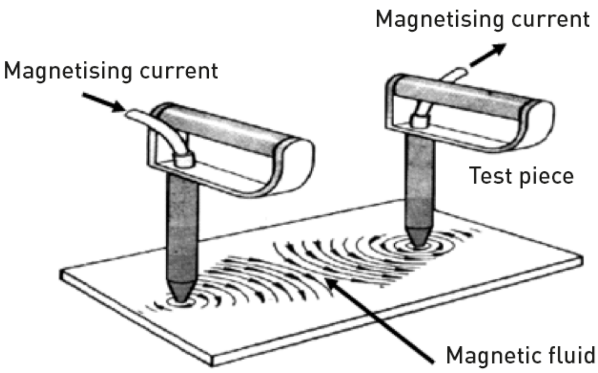


Figure 24 Magnetic particle inspection.

In general, the particles take the shape and size of the defect. Defects under the surface can also be detected using this method, provided that they are not deep. The particles can be coloured using dyes to improve visibility on metal surfaces (Figure 25).

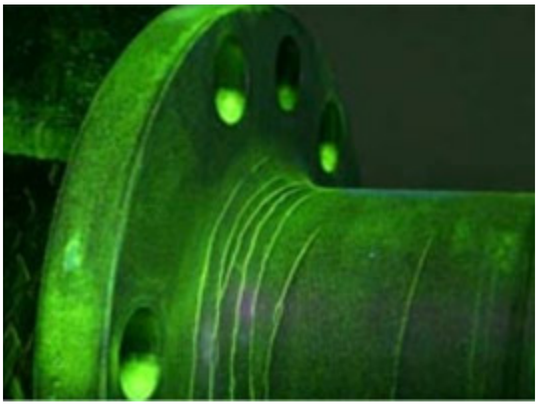


Figure 25 Dyed magnetic particles.

Magnetic fields can also be generated using alternating or direct current, using yokes, bars or coils. Direct current is the best way of detecting defects under the surface. The magnetic particle method can only be used with ferromagnetic materials, but the parts can be demagnetized and cleaned after the inspection. The equipment can be portable or stationary.

2.3.1.4 Ultrasonic inspection

In this technique, an ultrasonic wave travels through the part. Internal defects (such as cracks) break the wave and reflect part of the ultrasonic energy. The amplitude of the reflected energy and the time required for its return indicate the presence and location of any defect in the workpiece (Figure 26).

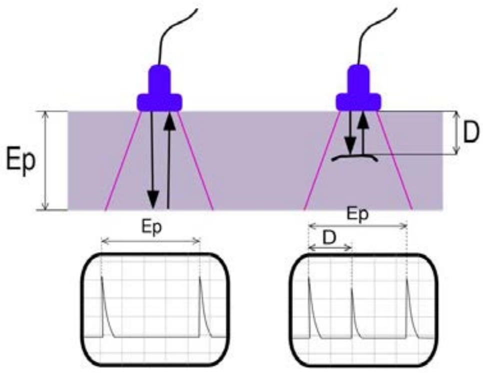


Figure 26 Functioning of the ultrasonic inspection.

Ultrasonic waves are generated by means of transducers (waves), available in different types and sizes. The transducers function on the basis of the principle of the piezoelectricity using materials such as quartz, lithium sulphate and different ceramic materials. The majority of the inspections are performed at a frequency interval of 1 to 25 MHZ. Couplers are used to send the ultrasonic waves from the transducer to the test piece. The most common ones are water, glycerine and grease.

The ultrasonic inspection method has great penetration and sensitivity power. It can be used for both surface and volumetric inspections. Different directions can be used to inspect defects in large parts, such as railway wheels, pressure vessels and die sets. The main disadvantage of this method is the need for an experience operator to conduct the inspection and interpret the results correctly (Figure 27).

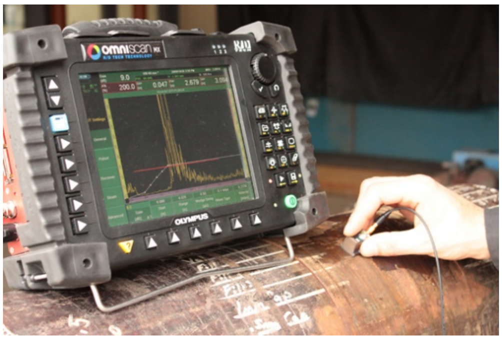


Figure 27 Results: ultrasonic inspection.

2.3.1.5 Acoustic methods

The noise emission technique detects signals (high-frequecy stress waves) generated by the workpiece itself during the plastic deformation, crack initiation and propagation, the phase transformation and abrupt reorientation of the grain limits. Bubbles forming during the boiling of a liquid and the friction and wear of the sliding interfaces are other sources of acoustic signals.

Noise emission inspections are usually performed by applying elastic stress to the part or structure, such as bending a beam, applying torque to a die or pressure to the inside of a recipient (Figure 28). In general, the sensors consist of piezoelectric ceramic elements that detect acoustic emissions. This method is very effective for the continuous inspection of load-bearing structures.

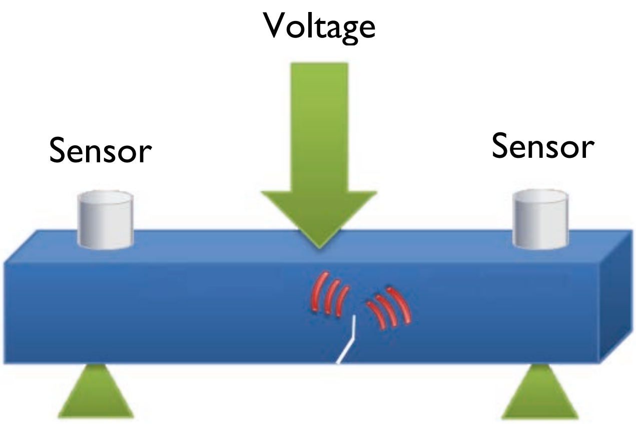


Figure 28 Noise inspection method.

The acoustic impact technique consists of lightly tapping the surface of an object, and listening to and analysing the signals to detect discontinued ones and defects. The principle is basically the same as when a person taps a wall, desktops or backdrops in different places with a finger or with a hammer and listens to the sound made. The acoustic impact technique is easily performed and can be implemented and automated. However, the results depend on the geometry and mass of the part and a reference standard is therefore needed to identify the defects.

2.3.1.6 Radiography

Radiography uses x-ray inspection to detect internal defects such as cracks and porosity; therefore, it can used to inspect volumes and surfaces. The principle is based on the density differences within the part (Figure 29). For example, the metal surrounding a defect is often denser and, therefore, it appears as lighter than the defects on an x-ray film.

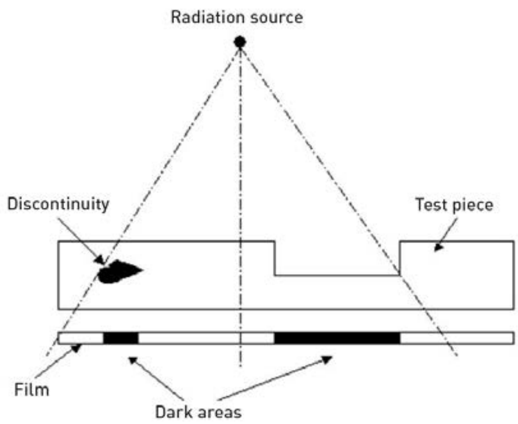


Figure 29 Functioning of the radiographic inspection.

In general, the radiation source is an x-ray tube that produces a permanent image visible on the radiographic film or in an array of sensors (digital radiography). This can be seen in Figure 30. Fluoroscopes are also used to produce X-ray images quickly and are a real-time radiography technique that shows events as they occur.

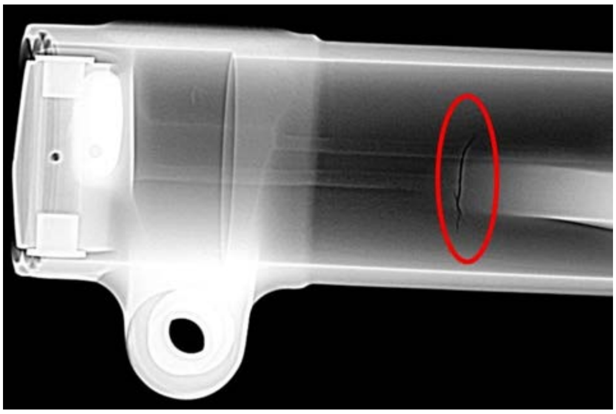


Figure 30 Result of a radiography.

Radiography requires expensive equipment, the appropriate interpretation of the results and there can be a risk of radiation.

2.3.1.7 Eddy current inspection

This method is based on the principle of electromagnetic induction. The part is placed in an electric coil or next to it, and through which an alternating current flows at frequencies ranging from 60 HZ to 60 MHz. Thus current causes eddy currents in the part. Defects in the part prevent and change the direction of the eddy currents and cause changes to the electromagnetic field that affect the drive coil (inspection coil), whose voltage is monitored to determine the presence of defects (Figure 31).

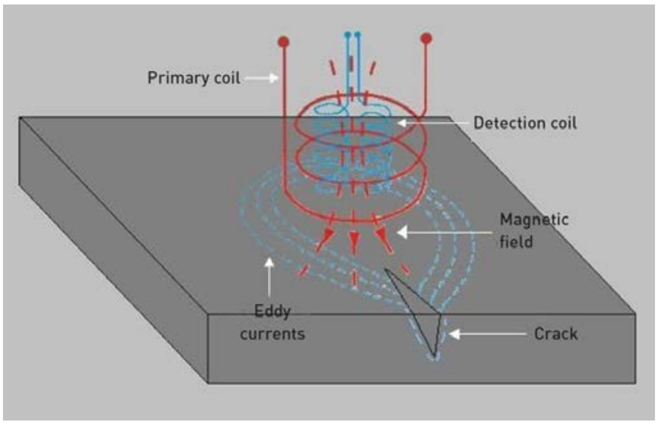


Figure 31 Functioning of the eddy current inspection.

Inspection coils can be manufactured in different sizes and shapes to adapt to the geometry of the part to be inspected. The parts must be electrically conductive and, in general, the depth of the defects is limited to 13 mm. The technique requires the use of a reference standard sample to adjust the sensitivity of the tester (Figure 32).

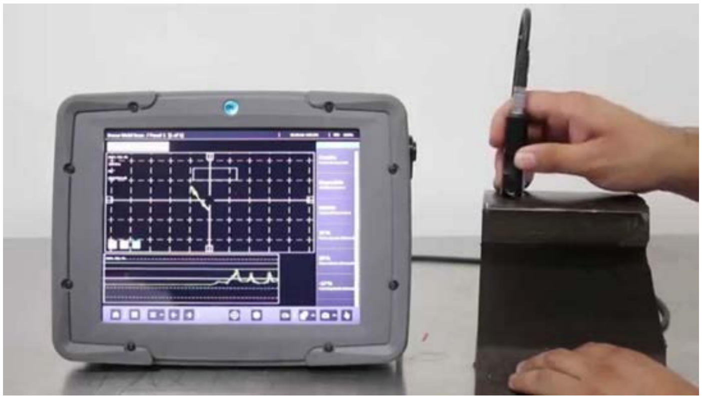


Figure 32 Obtaining the reference standard.

2.3.1.8 Thermal inspection

Thermal inspection involves the use of contact and contactless heat sensors that detect changes in temperature. The defects in the workpiece (such as cracks, separate regions in laminated structures and deficient unions) cause a change in the distribution of the temperature. It also allows the correct functioning of the electronic components to be verified by comparing them to the reference standard (Figure 33).

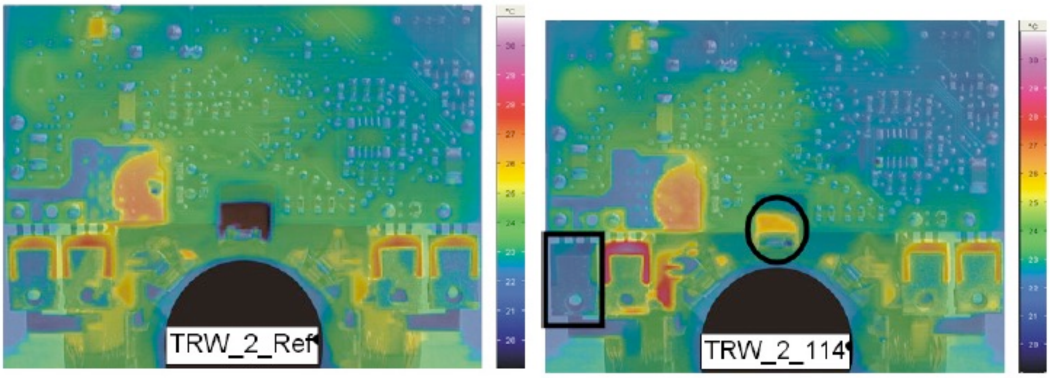


Figure 33 Thermal inspection of a circuit board: reference standard (a), component with defects (b).

In the thermal inspection, materials (such as heat-sensitive paper and paint, liquid crystals and other coatings) are applied to the surface of the workpiece. Any change to its colour or appearance indicates defects. The most common method of contactless thermographic inspection uses infrared light sensors (usually microscopic or infrared scanning cameras), which have a high response time and high sensitivities of 1 °C. Thermometric inspection, on the one hand, uses devices such as thermocouples, radiometers and pyrometers.

2.3.1 Dimensional

Dimensional inspection consists of measuring the dimensions of the components to check if their dimensions had altered in any way during their use. Different technologies are used depending on the accuracy, rapidity or the inversion to be performed.

2.3.1.1 Manual measurement

This consists of measuring an object with the help of a human eye and a scaled instrument. The instrument can be a gauge (Figure 34), a meter, a micrometer, etc.

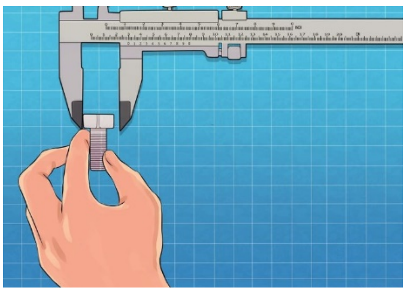


Figure 34 Measuring using a gauge.

2.3.1.2 Laser measurement

Laser measurement is based in the change of at least one parameter of the laser radiation due to the interaction with the object to be measured (R. Poprawe, 2011). This allows the components to be measured without any type of mechanical contact. It is a quick measurement technology, apart from being easy to adapt to different shapes and materials (Figure35).

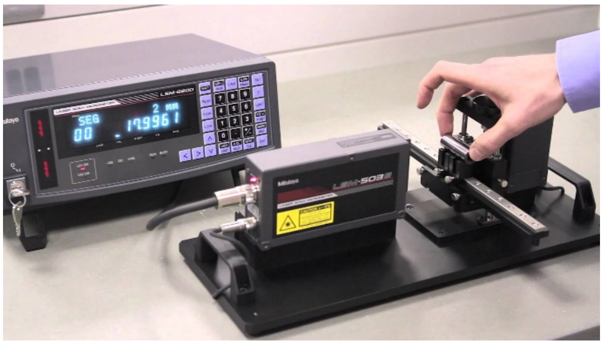


Figure35 Laser micrometer.

2.3.1.3 3D scanner measurement

3D scanner measurement consists of analysing an object in order to obtain data on its shape without any type of contact (Figure 36). The scanning of the object is compared to the CAD design or using a previous scan of a new part to look for an error in the object. This allows the part to be inspected quickly. It can also be used for inverse engineering (Caddy, 2017).

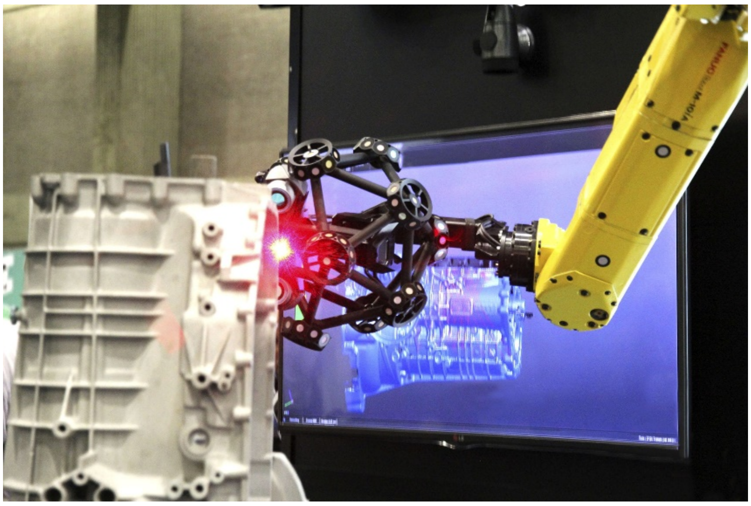


Figure 36 3D scanner.

2.3.1.4 Contact measurement

The technology is based on obtaining a series of coordinates to measure the part. That information is obtained by measuring the contact of the sensor with the part (Figure 37). This technology is noted for its accuracy, but it should be noted that it is slower than laser measurement.

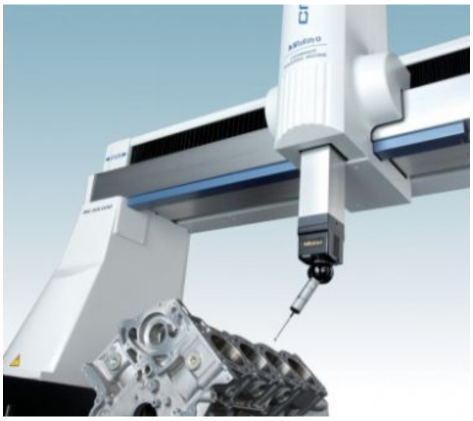


Figure 37 Contact measurement.

2.3.1 Electrical test

The electrical test analyses whether the electronic or electric components of an object function correctly. One technology or other will be chosen depending on the complexity of the object.

2.3.1.1 Functional test

This test is used to check whether the device is working correctly. In other words, the device is started up and the test analyses whether there is any anomaly in its functioning. It is the simplest test of all.

2.3.1.2 Multimeter

The multimeter is an instrument that allows different electrical quantities, such as voltage (direct and alternating), intensity (direct and alternating) and resistance to be measured. It also allows aspects such as ratings, temperature, frequency or the continuity between two points.

This technique is used to identify the components of the device that do not work correctly (Figure 38). It is a cheap technology, but it means that the inspection times are long as the process is totally manual as each component is analysed individually.

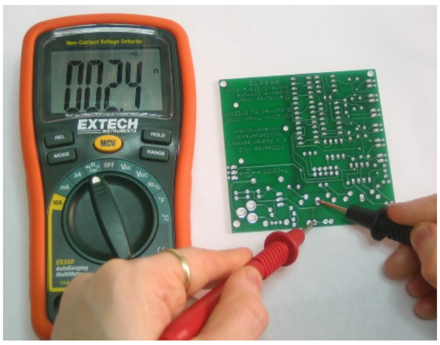


Figure 38 Multimeter.

2.3.1.3 Bed of nails or spikes

The bed of nails test allows the operating of a circuit board to be tested quickly. In the same way as with the multimeter, the test consists of inspecting each component to search for defects. However, there is one main difference. All the components are analysed at the same time, and not one by one as is the case of the multimeter. This means the test can be completed in the matter of seconds. The drawback, apart from being a much more expensive technology, is that fact that a specific bed of nails has to be designed and manufactured for each circuit (Figure 39). It is therefore not a very versatile technology (Radio-electronics, 2017).

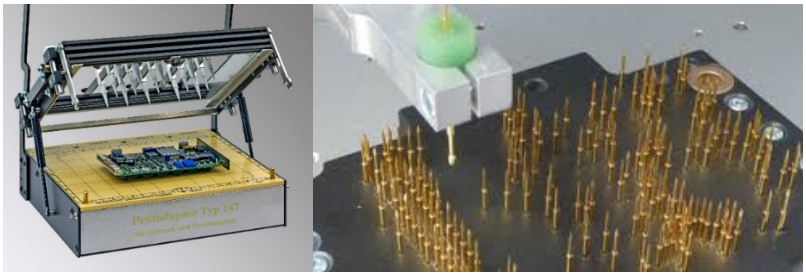


Figure 39 Bed of nails machine: machine (a), bed of nails (b).

2.3.1.4 Flying probe

The flying probe test is a type of automatic multimeter. It uses probes to each the functioning of each component (Figure 40). These probes are controlled by software. It is a slower test that the bed-of-nails one, but is much more versatile as if there is any modification in the circuit board, it can be easily solved by applying the change to the software (Radio-Electronics, 2017)

Figure 40 Flying probe tester.

2.4 Reconditioning technologies

Reconditioning technologies are those that are used to repair or manufacture the damaged components. It is impossible to produce a list that classifies all the technologies, as many of the operations needed by the part to be manufactured or repaired varies greatly from one product to another. Furthermore, the majority of companies are already equipped to perform this phase.

Nevertheless, the following images show the main processes that a part can undergo. The processes have been classified into 6 groups: machining and finishing processes (Figure 41), casting processes (Figure 42), moulding and forming processes (Figure 43), sheet metal working (Figure 44), polymer processing (Figure 45) and joining processes (Figure 46).

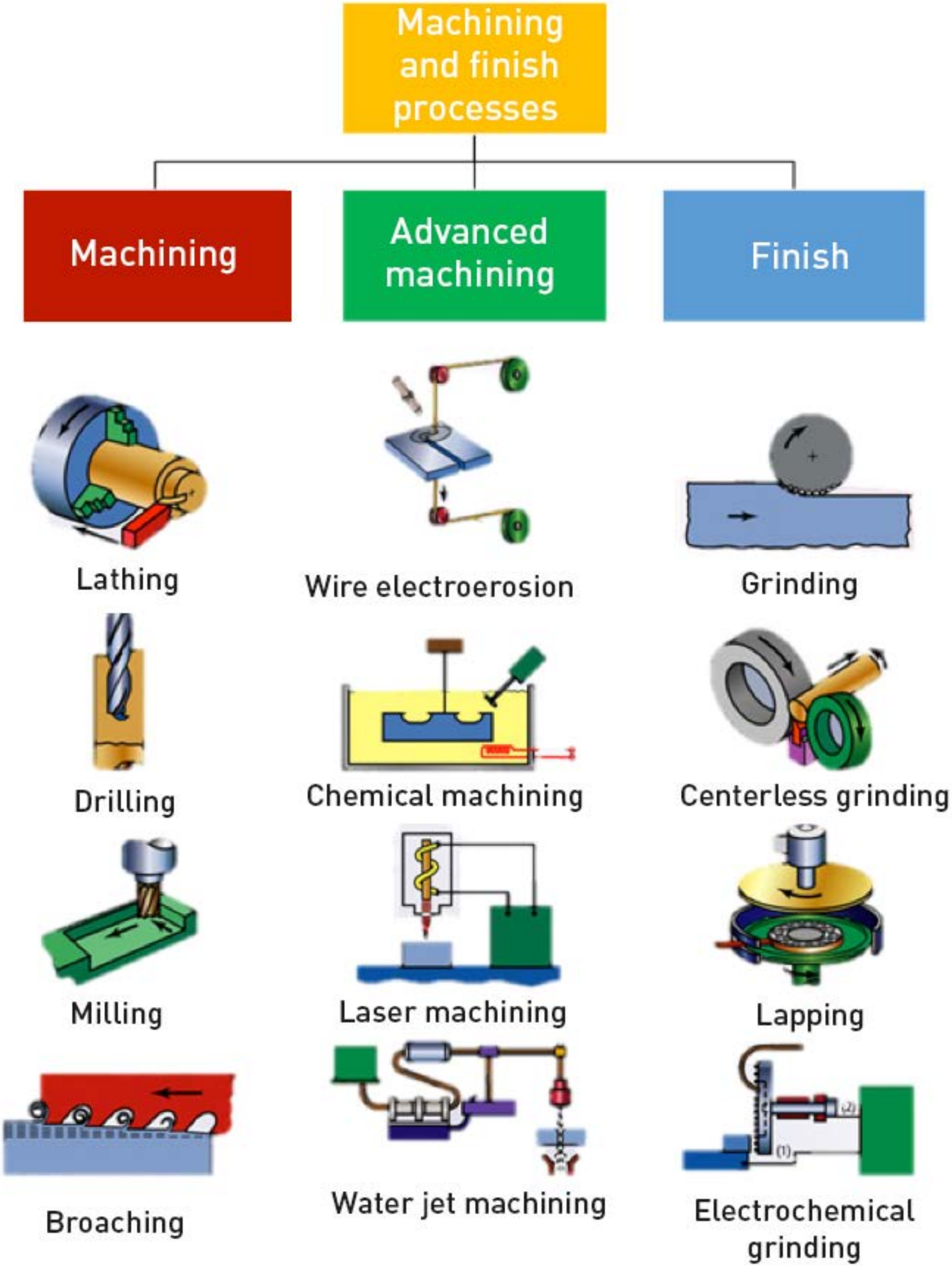


Figure 41 Machining and finish processes.

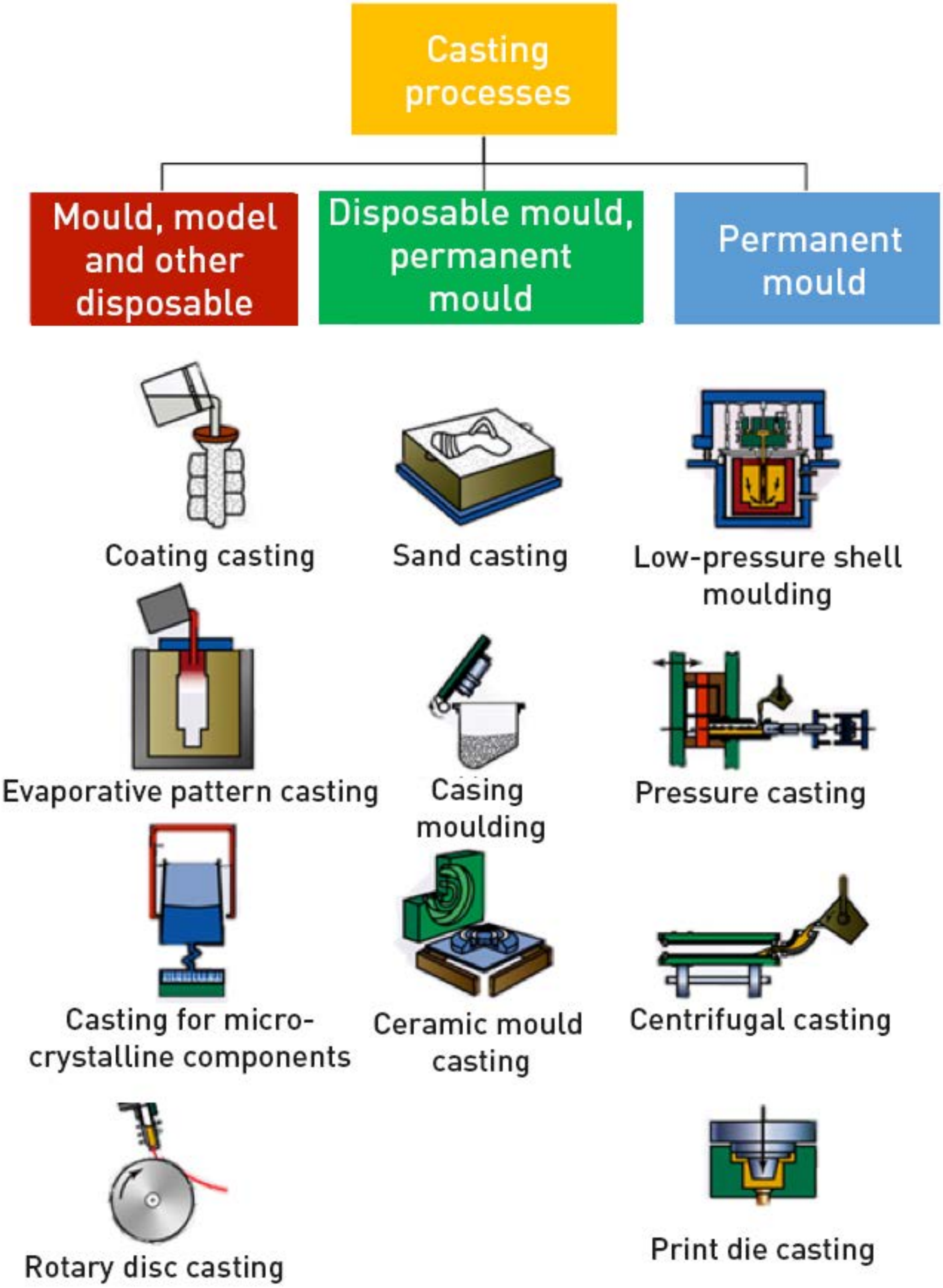


Figure 42 Casting processes.

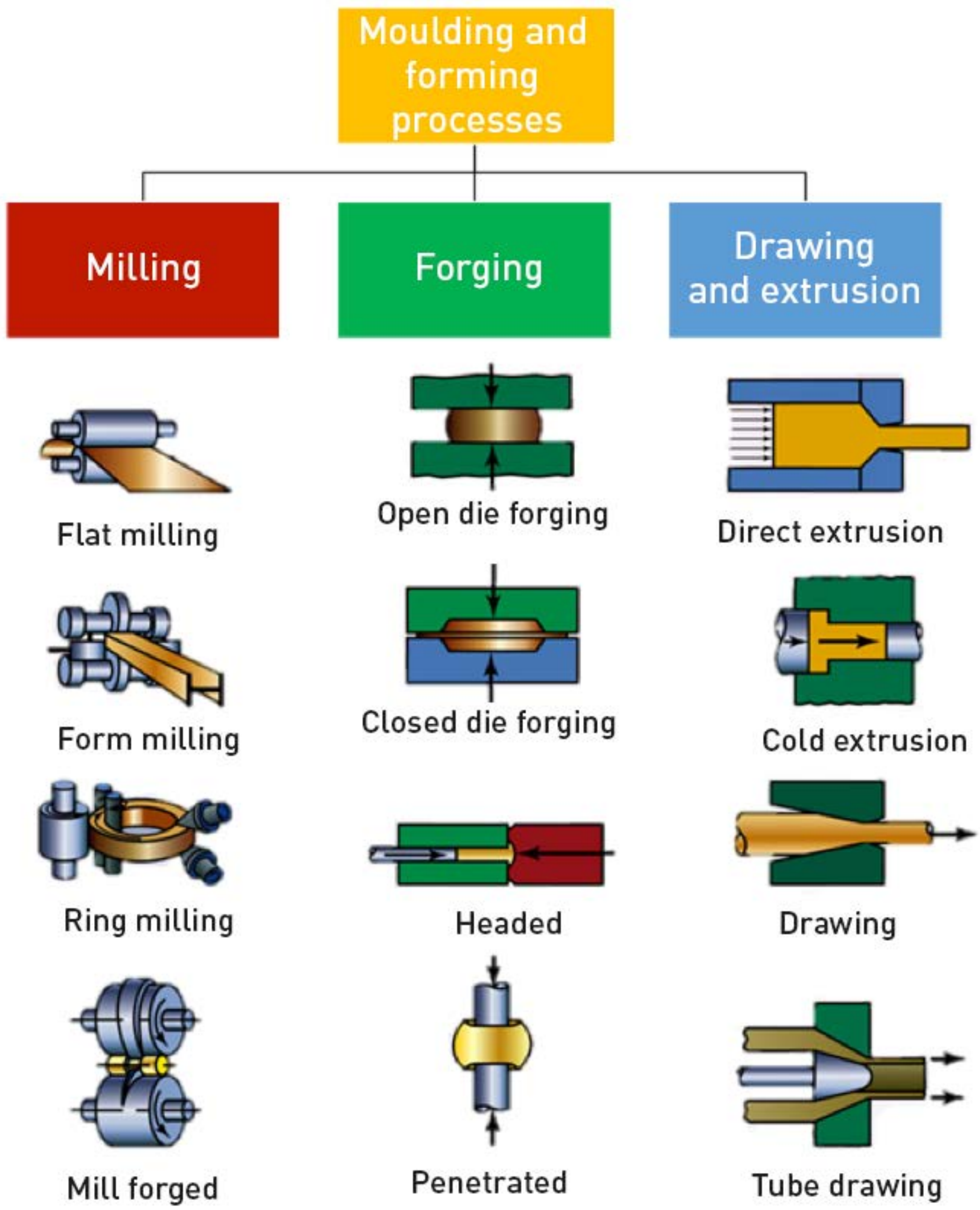


Figure 43 Moulding and forming processes.

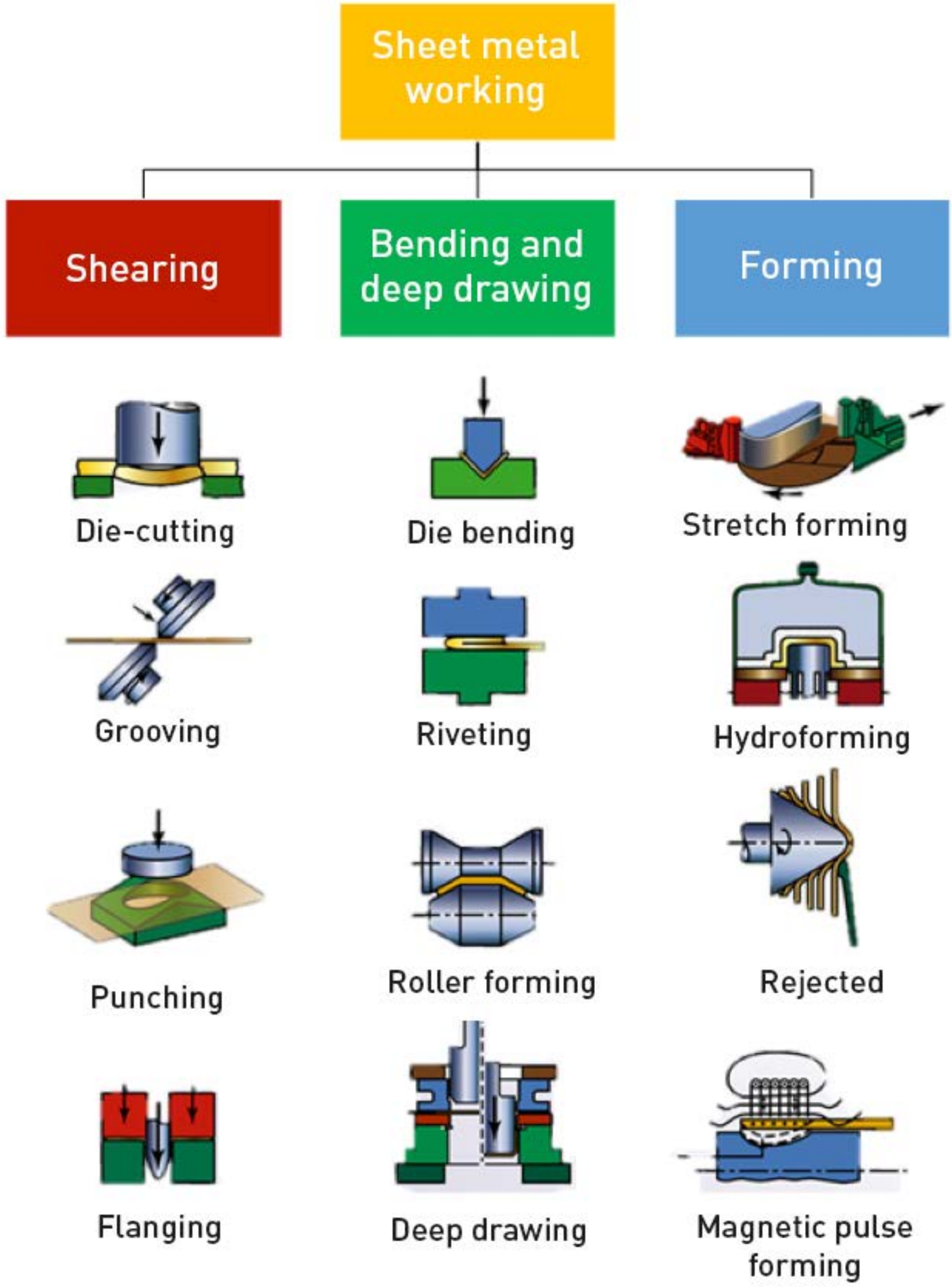


Figure 44 Sheet metal working.

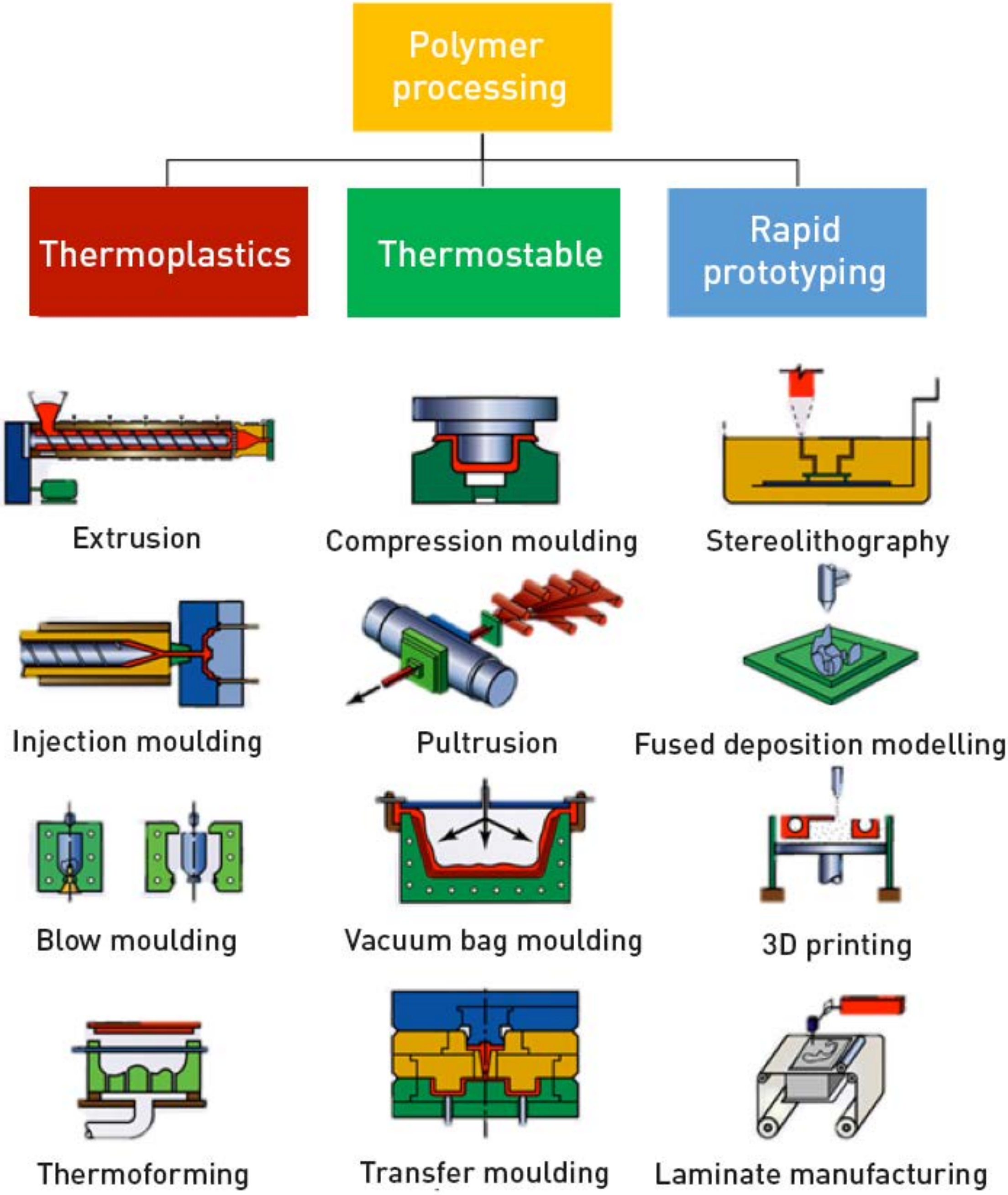


Figure 45 Polymer processing.

Figure 46 Joining processes.

2.5 Assembly technologies

The same technology is used for the assembly phase as when putting a new product together. There is no difference between manufacturing and remanufacturing. Each company has its assembly system and the technology needed.

2.6 Test technologies

In the same way as with the assembly technologies, there is no difference in this phase between the manufacturing and remanufacturing process. The remanufactured product must have the same characteristics as a new one and will therefore have to undergo the same tests. In other words, the same technology will have to be used.

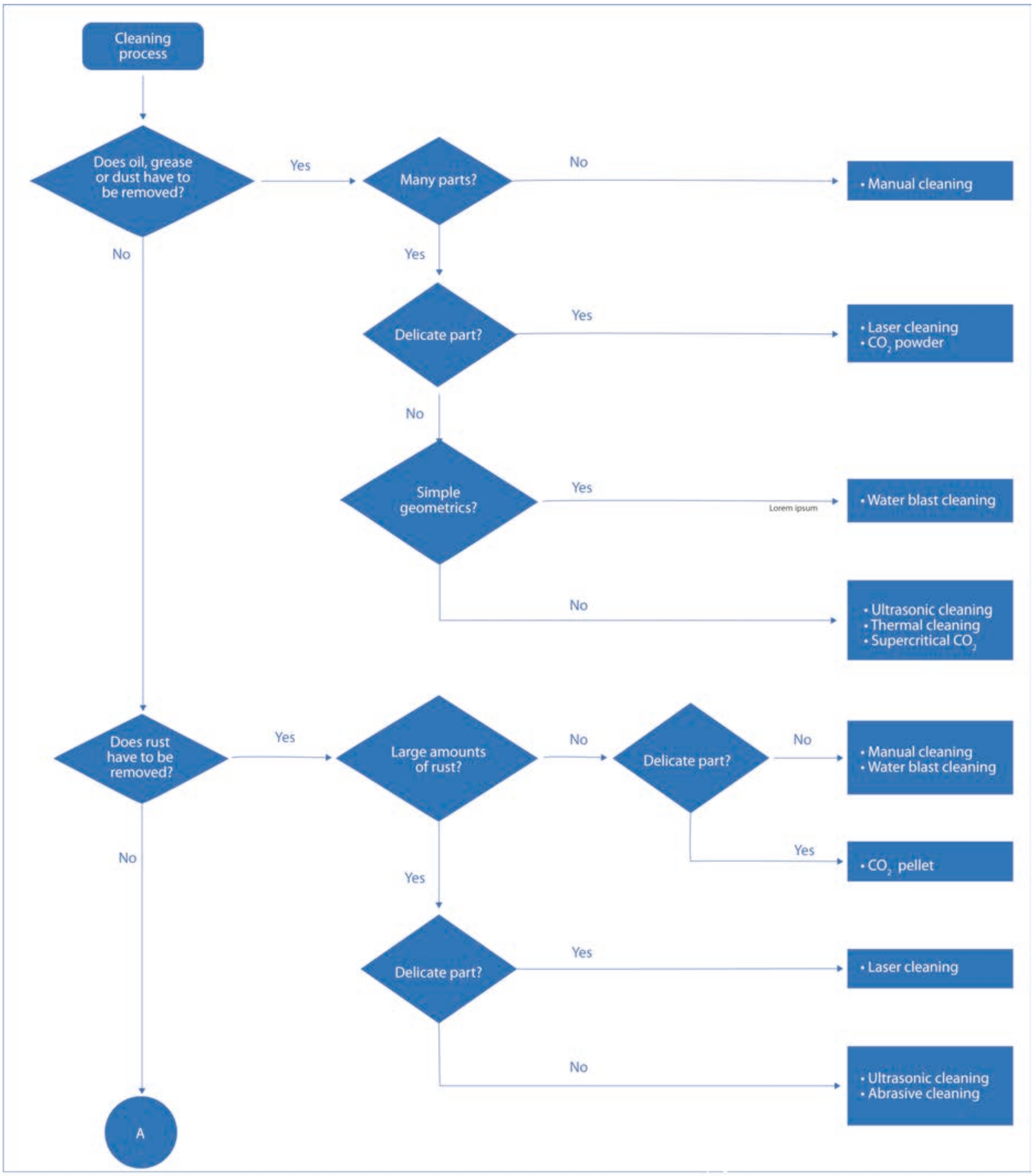
3 Technology selection methodology

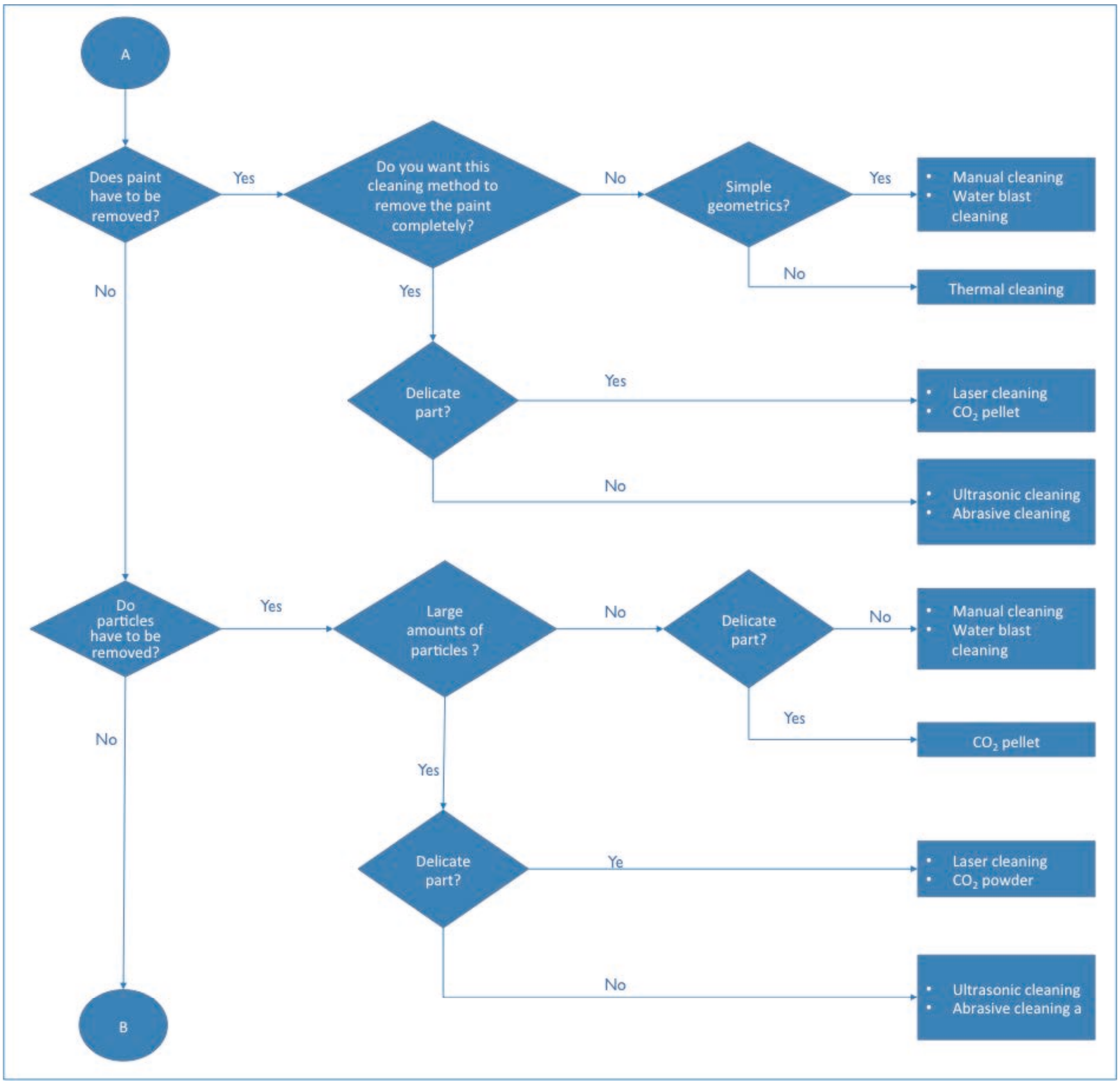
In order to help to select the most appropriate technology for each phase of the process, tables and flow diagrams of the technologies that need to be implemented in the companies (cleaning, disassembly, inspection and reconditioning) to implement the remanufacturing process have to be produced. It should be noted that the diagrams are merely approximations, as the selection of each technology is conditioned by many, many factors, and it is impossible to produce a diagram that takes them all into account.

3.1 Cleaning technologies

Two tables and a flow diagram have been produced to facilitate the selection of the cleaning phase technologies. The diagram (Figure 47), is designed to be able to select the most appropriate technology for each component when removing different types of dirt. Table 8 allows the compatibility of the different technologies with the material to be cleaned to be analysed. Finally, Table 9 compares the efficiency of each technology when removing the most common types of dirt. This table aims to provide an overview about the type of dirt that each technology can remove.

The selection process consists of first using the Figure 47 diagram, to choose the technology or technologies that best adapts to the characteristics in question. Subsequently, Table 8 is used to confirm that there is no impediment to using that technology with the component to be cleaned. If no suitable technology is found using the diagram, Table 9 can be used to select all the technologies capable of removing the dirt in question; and, thus, choose the one that is best adapted to the needs of each company.


Cleaning process
Does oil, grease or dust have to be removed?
Yes
Many parts?
No
• Manual cleaning
No
Yes
Delicate part?
Yes
• Laser cleaning
• CO_2 powder
No
Simple geometrics?
Yes
Lorem ipsum
• Water blast cleaning
No
• Ultrasonic cleaning
• Thermal cleaning
• Supercritical CO_2
Does rust have to be removed?
Yes
Large amounts of rust?
No
Delicate part?
No
• Manual cleaning
• Water blast cleaning
Yes
• CO_2 pellet
No
Yes
Delicate part?
Yes
• Laser cleaning
No
• Ultrasonic cleaning
• Abrasive cleaning
A


A
Does paint have to be removed?
Yes
Do you want this cleaning method to remove the paint completely?
No
Simple geometrics?
Yes
• Manual cleaning
• Water blast cleaning
No
Thermal cleaning
No
Yes
Delicate part?
Yes
• Laser cleaning
• CO_2 pellet
No
• Ultrasonic cleaning
• Abrasive cleaning
Do particles have to be removed?
Yes
Large amounts of particles ?
No
Delicate part?
No
• Manual cleaning
• Water blast cleaning
Yes
CO_2 pellet
No
Yes
Delicate part?
Ye
• Laser cleaning
• CO_2 powder
No
• Ultrasonic cleaning
• Abrasive cleaning a
B

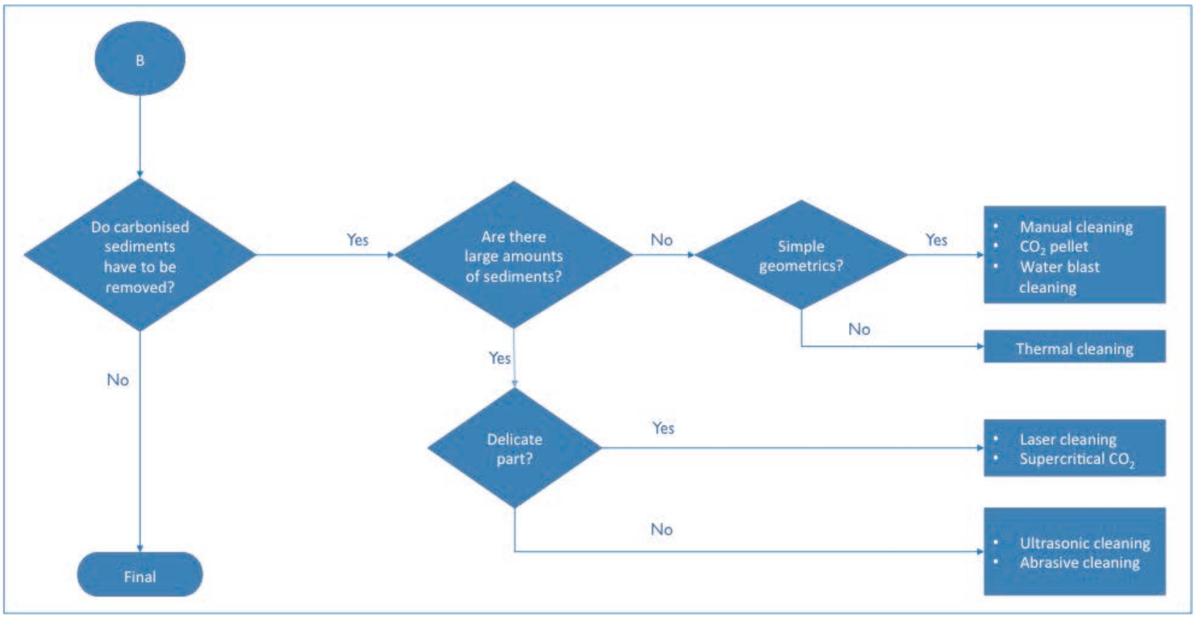


Figure 47 Flow diagram: cleaning.

As has been already discussed, Table 8 allows the compatibility of the technologies with the material to be cleaned to be analysed. Green means that the technology can be applied to that material without any problem. Red is at the other end and means that technology is not compatible with the material. Orange, in turn, means that it is possible in some cases, but not in others. In other words, each case has to be analysed.

Table 8 Compatibility of the material with the technology: cleaning.

Technologies		Materials								
		Metals					Polymers		Electronic components	Ceramics
		Ferrous		Non-ferrous						
		Steel	Cast iron	Aluminium	Copper alloys	Others	Thermoplastic	Thermostable		
Manual cleaning		Green	Green	Green	Green	Green	Green	Green	Green	Green
CO_2 cleaning	CO_2 powder	Green	Green	Green	Green	Green	Green	Green	Green	Green
	CO_2 pellet	Green	Green	Green	Green	Green	Orange	Orange	Red	Green
	Supercritical CO_2	Green	Green	Green	Green	Green	Red	Red	Red	Green
Ultrasonic cleaning		Green	Green	Green	Green	Green	Green	Green	Megasonic (Orange)	Green
Laser cleaning		Green	Green	Green	Green	Green	Green	Green	Green	Green
Thermal cleaning		Green	Green	Red	Red	Red	Red	Red	Red	Green
Water blast cleaning		Green	Green	Green	Green	Green	Green	Green	Red	Green
Abrasive cleaning		Green	Green	Orange	Orange	Orange	Red	Red	Red	Green

Table 9 shows how efficient the different technologies are when removing different types of dirt. The technologies that are able to completely remove the dirt appear in green and those that are not are in red. Orange means that the technology can remove the dirt, but either it needs the help of another technology to remove it completely or that it is not able to remove the dirt in large amounts. There is an asterisk beside the name of some of the technologies. This means that the technology needs some type of cleaning solution to achieve the efficiencies that appear in the table.

Table 9 Efficiency of the cleaning technologies depending on the dirt.

		Type of dirt						
Technologies		Oil	Grease	Dust	Rust	Painr	Particles	Carbonised sediments
Manual cleaning*								
CO_2 cleaning	CO_2 powder							
	CO_2 pellet							
	Supercritical CO_2							
Ultrasonic cleaning*								
Laser cleaning								
Thermal cleaning								
Water blast cleaning*								
Abrasive cleaning								

3.2 Disassembly technologies

As has already been explained, the components of a part may be dismantled using three techniques: non-destructive, semi-destructive or destructive disassembly. Figure 48 can be used to know when to use each technique and it indicates the most appropriate disassembly for each component.

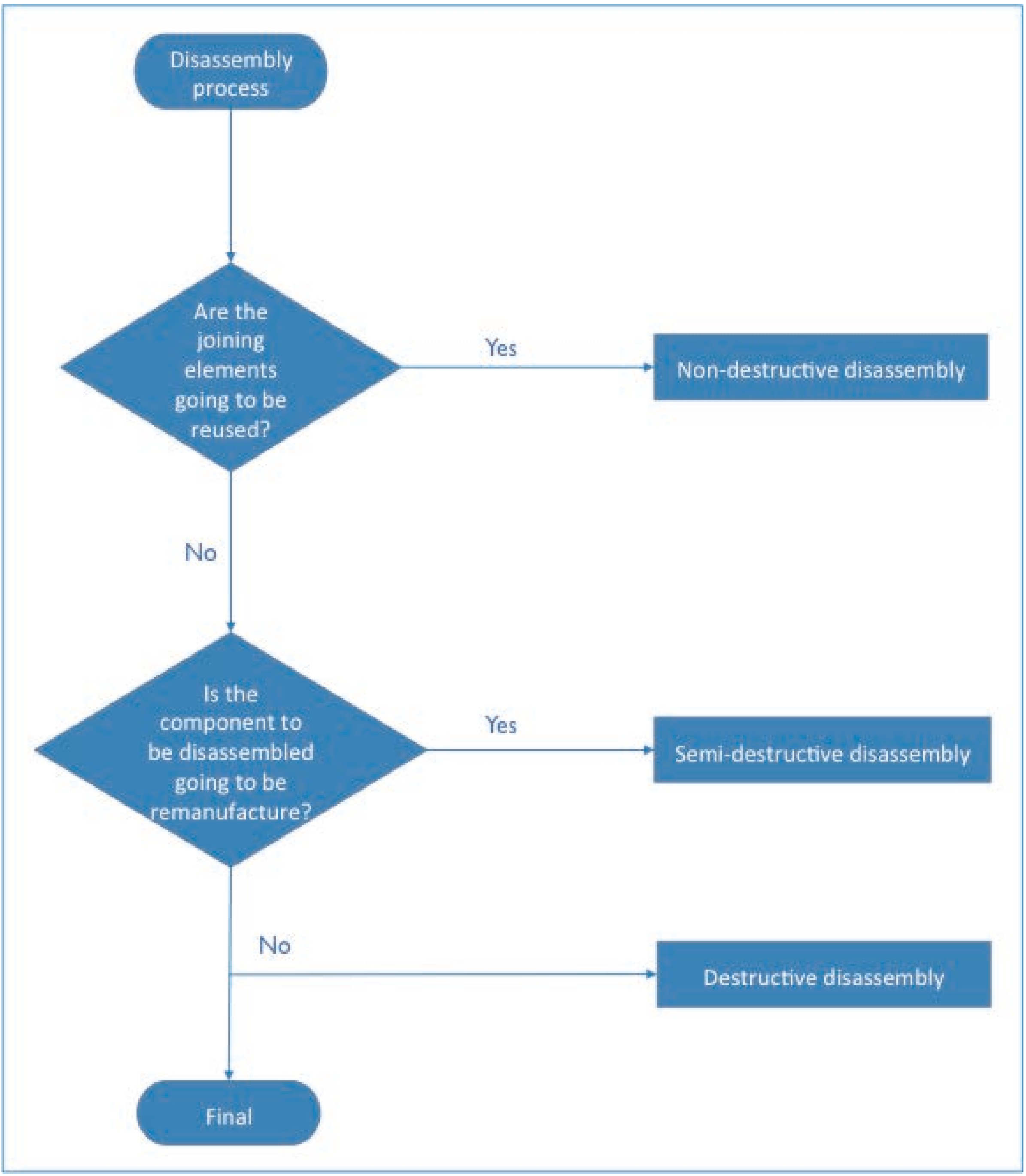
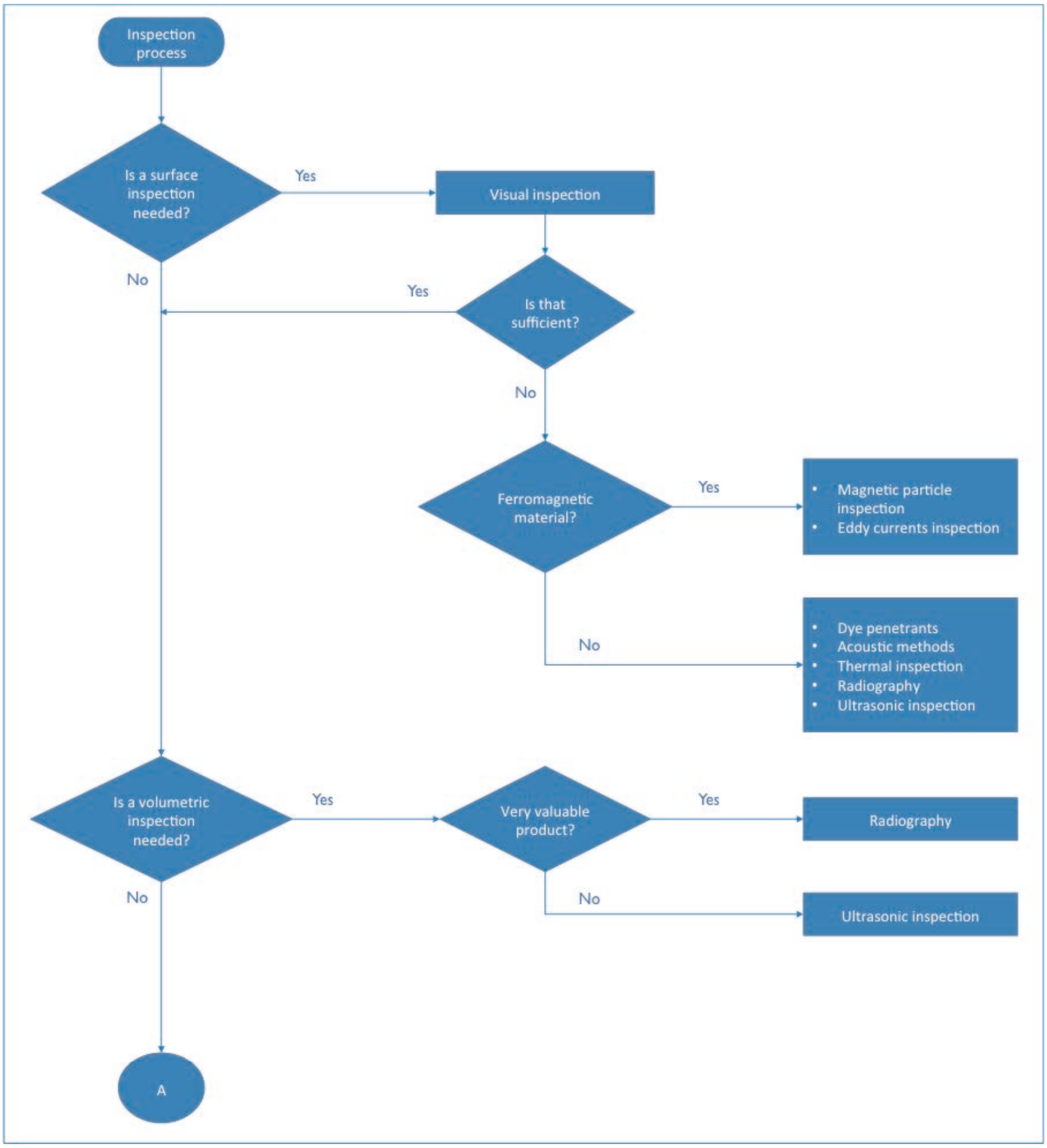


Figure 48 Flow diagram: disassembly.

3.3 Inspection technologies

A flow diagram and a table have been designed for the inspection phase. The flow diagram is a quick way to find the technology or technologies that may be most appropriate for the component to be tested. In turn, Table 10 shows the compatibility between the inspection technology and the material to be tested. This allows the technologies to be removed that are not applicable to the material (component) to be tested.

The procedure to be followed is the same as for the cleaning phase. It involves using the diagram in Figure 49 to select the technology or technologies that best adjust to the type of inspection to be carried out (surface, volumetric, dimensional or electric testing). Once the technologies have been selected, the following step is to use Table 10 to check whether that technology is compatible with the component.



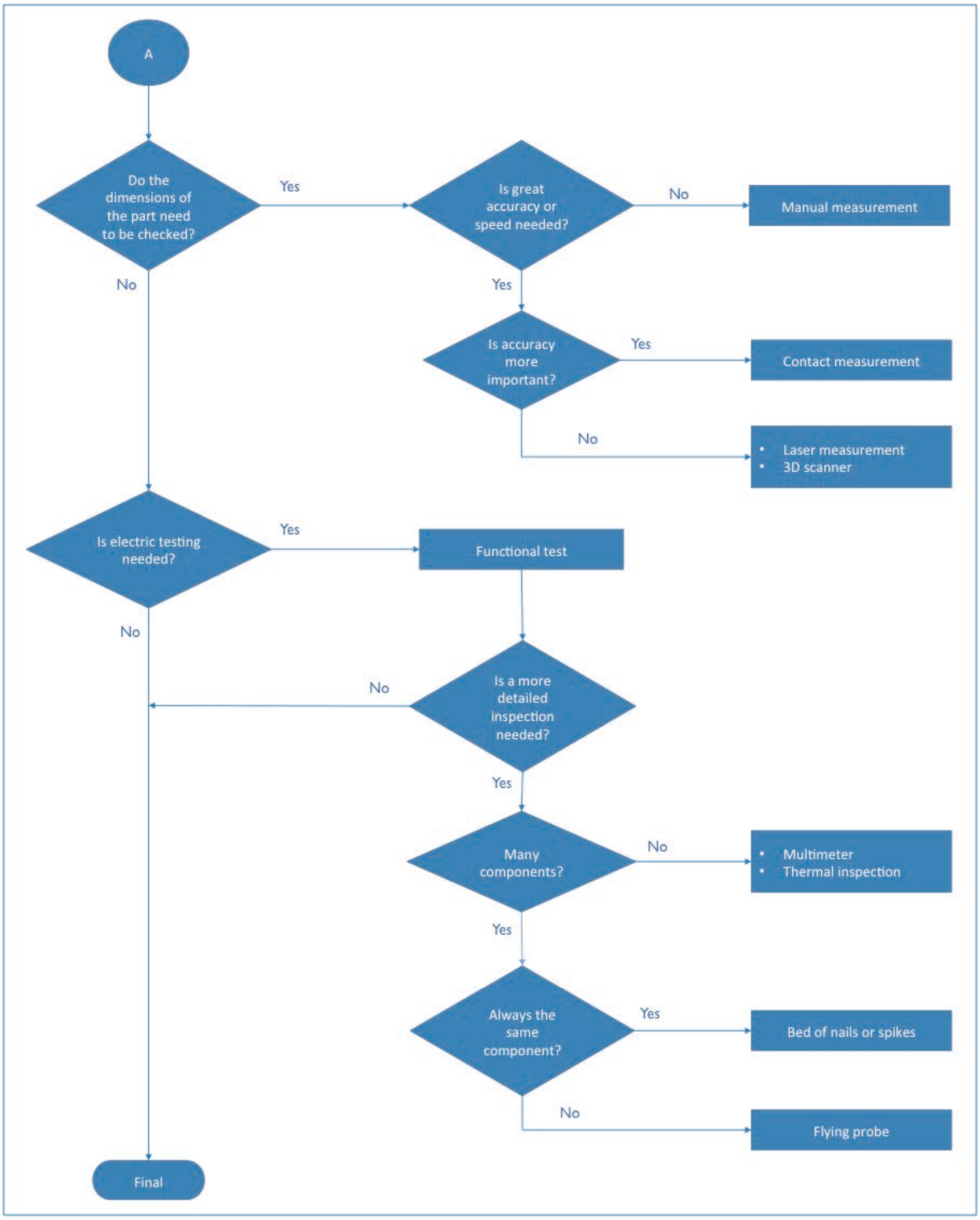


Figure 49 Flow diagram: inspection.

Table 10 Compatibility of the material with the technology: inspection.

		Materials							
		Metals					Polymers		Electronic components
		Ferrous		Non-ferrous					
Technologies		Steel	Cast iron	Aluminium	Copper alloys	Others	Thermoplastic	Thermostable	
Surface/ Volumetric*	Visual inspection	Green	Green	Green	Green	Green	Green	Green	Green
	Dye penetrants	Green	Green	Green	Green	Green	Red	Red	Red
	Magnetic particle inspection	Green	Green	Red	Red	Red	Red	Red	Red
	Ultrasonic inspection*	Green	Green	Green	Green	Green	Green	Green	Red
	Acoustic methods	Green	Green	Green	Green	Green	Red	Red	Red
	Radiography*	Green	Green	Green	Green	Green	Green	Green	Green
	Eddy currents inspection	Green	Green	Red	Red	Red	Red	Red	Red
	Thermal inspection	Green	Green	Green	Green	Green	Red	Red	Green
Dimensional	Manual measurement	Green	Green	Green	Green	Green	Green	Green	Red
	Laser measurement	Green	Green	Green	Green	Green	Green	Green	Red
	3D scanner	Green	Green	Green	Green	Green	Green	Green	Red
	Contact measurement	Green	Green	Green	Green	Green	Green	Green	Red
Electric testing	Functional test	Red	Red	Red	Red	Red	Red	Red	Green
	Multimeter	Red	Red	Red	Red	Red	Red	Red	Green
	Bed of nails or spikes	Red	Red	Red	Red	Red	Red	Red	Green
	Flying probe	Red	Red	Red	Red	Red	Red	Red	Green

3.4 Reconditioning technologies

The reconditioning phase technologies, as has been previously mentioned, have not been analysed in as much detail as the cleaning or inspection ones. However, Table 11 has been produced to facilitate the implementation of a new technology for this phase and it sets out the most common reconditioning technologies. The table is designed to rule out those technologies that are not compatible with the material to be processed. The colour green means that it is possible to use the technology on that material without any problem. Orange can mean two things: that it is complicated to use this technology with that material or that each case needs to be analysed separately, as is the case with the other non-ferrous materials. The boxes that appear in red mean that it is very difficult to use this technology with that material. Finally, there are the boxes that are dotted out. Those boxes means that using that technology for that material makes no sense.

Table 11 Compatibility of the material with the technology: reconditioning.

Technologies			Materials							
			Metals					Polymers		Electronic components
			Ferrous		Non-ferrous					
			Steel	Cast iron	Aluminium	Copper alloys	Others	Thermoplastic	Thermostable	
Chip removing		Lathe								
		Milling machine								
		Machining centre								
		Drill								
		Boring								
		Grinding machine								
		Broaching								
Forming	Forging/die cutting	Cold								
		Hot								
	Cast iron	Disposable mould								
		Permanent mould								
Sheet metal working		Cutting or shearing								
		Bending								
		Deep drawing								
Material contribution		Welding								
		Thermal spraying								
		3D								
Polymers		Extrusion								
		Injection								
Composites		Compression moulding								
		Vacuum bag moulding								
		Contact moulding								
		RTM								

4 Applications

Once the technologies have been classified, the next step is design the process to remanufacture a large bearing and an internal combustion agricultural engine. The phases making up the remanufacturing process and the technologies to be used for each phase are going to be explained for each product. Both the diagrams and the tables of the previous phase have been used.

4.1 Large bearings (Kaydon, 2017)

The component to be remanufactured is a large bearing. It should be noted that it is no coincidence that a large and not a small bearing is being remanufactured. Small bearings do not have sufficient value added to be remanufactured; in other words, it would not be cost-effective.

Table 12 Specifications table: bearings.

Bearings	
Components to be remanufactured	Rings
New components	Balls and joints
Main dirt	Grease and small amounts of rust
Material	Steel

Bearings are made up of rings, ball and joints. Only the rings out of those components are remanufactured, as the reconditioning of the rings will modify the dimensions of the bearings (Table 12).

The main dirt of these bearings is grease, which is usually applied abundantly to make sure they function correctly. There may also be small amounts of rust (Table 12).

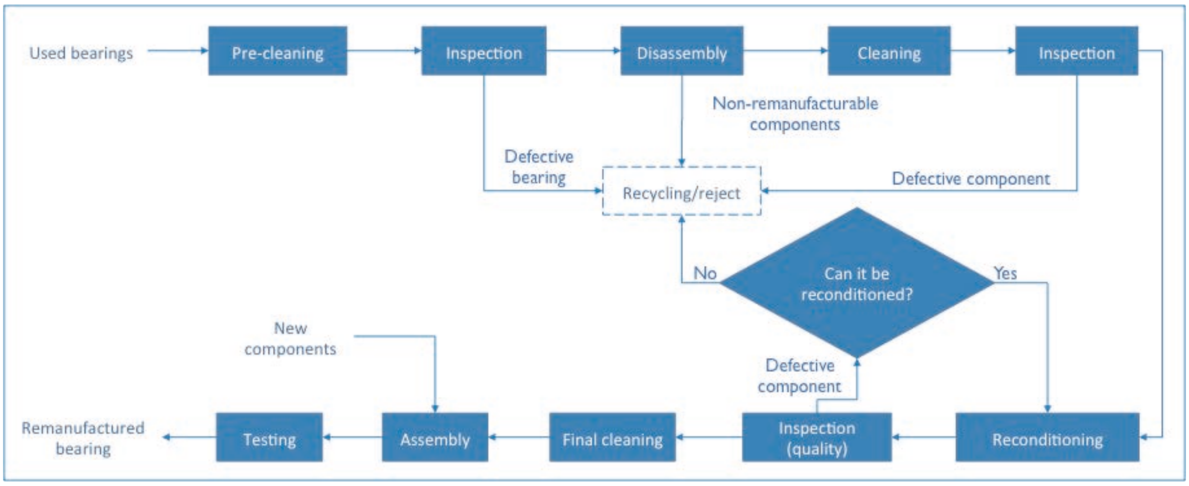


Figure 50 General outline of the remanufacturing process: bearings

The remanufacturing process (Figure 50) consists of 10 phases. The first phase (pre-cleaning) consists of a quick clean of the bearing in order to make it easier to inspect. The initial inspection is conducted to rapidly reject any components that have a very visible defect meaning they cannot be remanufactured. Afterwards, the bearing is disassembled by separating the rings from the balls and joints. The rings are then cleaned, inspected thoroughly and reconditioned. From this point onwards, the same process is followed as for new bearing. The rings undergo a quality control, are cleaned and all the components are assembled. Finally, the bearings are tested to check the correct functioning.

1. Pre-cleaning (If the bearing is very dirty)

   A simple and cheap cleaning method is needed for the pre-cleaning phase, as the aim here is to remove the dirt that prevents the part from being easily inspected (Figure 51). Therefore, high water pressure cleaning has been chosen, with the help of Table 9 and Table 8, to remove any excess grease on the bearings. It is a simple and appropriate technology to remove grease. That cleaning can be manual or automatic, depending on the investment that they want to make.

Figure 51 Dirty bearing with grease.

2. Inspection

   A visual inspection is carried out to reject any defective bearings.

3. Disassembly (Figure 52)

   As not all the components are going to be remanufactured, a semi-destructive and destructive disassembly will be used. The rings are carefully disassembled so as not to damage them, but the components are dismantled in the easiest possible way.

Figure 52 Disassembled rings.

4. Cleaning

As has been previously mentioned, there is grease and rust (mainly grease) on the rings. Therefore, Table 9 is used to find a technology that fully remove the grease, but which can also remove the rust. This technology will have to be compatible with steel (Table 8). The most appropriate of the different possible options for this case is water blasting automatic cleaning. The water will be mixed with a cleaning solution to make the process more efficient. As there are not usually large amounts of rust, a second cleaning process is not necessary, such as abrasive cleaning to remove that rust.

Figure 53 Water blasting cleaning.

5. Inspection

The ring is inspected carefully to pinpoint any possible defects and thus reject defective rings.

1) Magnetic particle inspection has been chosen for the surface. This technique allows the whole part to be easily inspected. It can be seen in Table 10 that any of the other techniques can be used for that inspection. However, this technique has been chosen as the ring is made out of steel (ferromagnetic material).
2) There are two options out of the technologies analysed to carry out the volumetric inspection and both are possible in this case (Table 10). Ultrasound or x-ray inspection. The most convenient and quickest option would be using an x-ray, but the value of the part would have to be higher to justify its use. Ultrasound inspection will therefore be used (Figure 54).

Figure 54 Ultrasound inspection of the ring.

3) The hardness of the surface is analysed to establish if there has been any changes to the microstructure of the ring during its use. Therefore, either the Rockwell or Brinell test could be used.

4) The dimensions of the rings are checked by means of manual inspections and contact measurement (those points where the traditional tools cannot be used). The most appropriate techniques have been used for this component, as there is no restriction due to the material (Table 10).

6. Reconditioning

Once the rings have passed the inspection, they all undergo precision grinding (Figure 55). As the rings are made out of steel, this operation can be performed without any type of problem (Table 11).

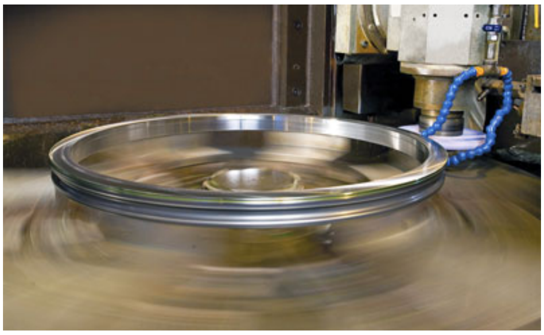


Figure 55 Grinding the ring.

7. Inspection (quality)

After the reconditioning process, there is a quality control to check that the rings meet the minimum characteristics required, in the same way as in a manufacturing process.

8. Final cleaning

Before assembling the rings with the new components, the rings are cleaned to remove any adhered dirt during the reconditioning process.

9. Assembly

The bearing components (remanufactured rings and the new balls and joints) are assembled in the same way as if all the components were new (Figure 56).

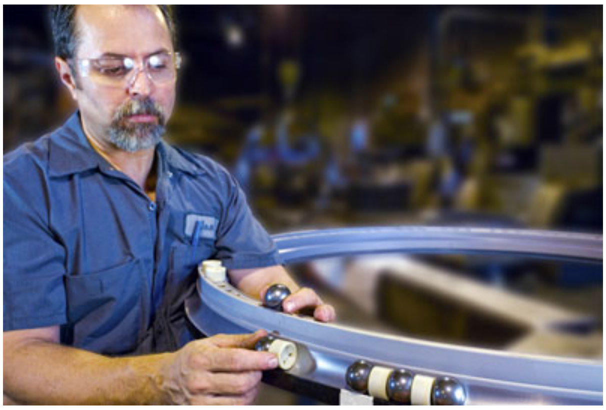


Figure 56 Assembling the bearing.

10. Testing

A test is conducted to ensure that the bearing is working correctly

4.2 Internal combustion agricultural engine (CNH Reman, 2017)

In this case, the remanufacturing process of an internal combustion agricultural engine has been analysed. The engines have great potential in the remanufacturing industry, as the most expensive components can be remanufactured.

Grease or oil is the main dirt to be found in this type of engines. However, as combustion occurs near to those components, some carbonised sediment can be found. In addition, the engine block may be painted.

Table 13 Specifications table: table.

Engine	
Components to be remanufactured	Engine block, crankshaft, camshaft and rods
New components	Bearings, caps and pistons
Main dirt	Grease, oil, carbonised sediments and paint (engine block)
Material	Steel: Engine block, crankshaft and camshaft Cast iron: Rods

The main components of the engine are: engine block, crankshaft, camshaft, rods, bearings, caps and pistons. The last three components are not remanufactured, as they either do not have a great value added (bearings and caps) or the modifications made to the engine block during that process remove any remanufacture option (pistons).

Grease or oil is the main dirt to be found in this type of engines. However, as combustion occurs near to those components, some carbonised sediment can be found. In addition, the engine block may be painted.

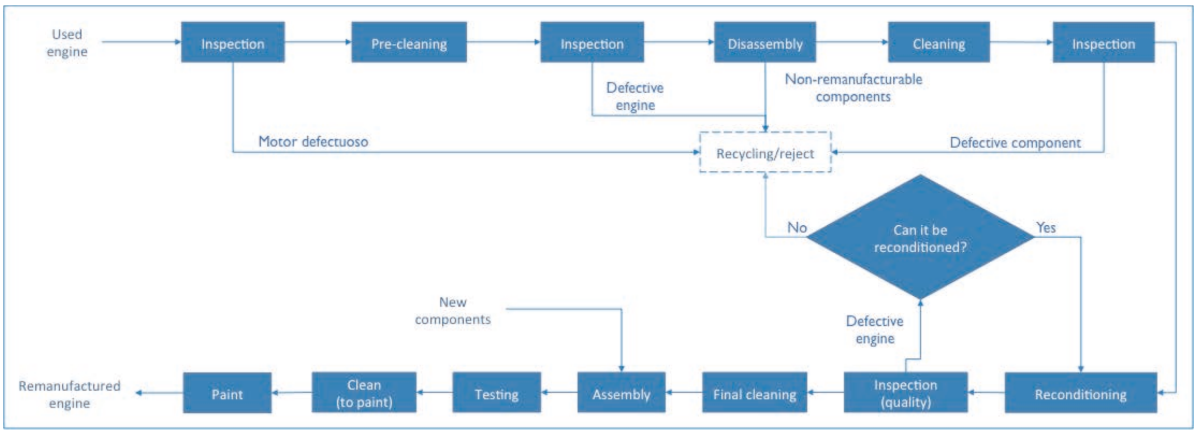


Figure 57 General outline of the remanufacturing process: engine

The remanufacturing process of the engines is more complex than the one for bearings. In this case, the process has 13 phases (Figure 57). The first step is to perform a quick inspection of the engine to reject those engines that are not in condition to be remanufactured. Pre-cleaning is then carried out so the dirtiest areas can be inspected. Once the engine has been inspected as a whole, the components that are going to be remanufactured (engine block, crankshaft, camshaft and rods) are disassembled and cleaned. Each component is then inspected one by one to establish if it meets the minimum characteristics to be able to manufacture it. Reconditioning is the next phase. The component then undergoes different operations to correct the wear suffered during its lifecycle. This can be said to be the last phase of the remanufacturing process in itself, as the following phases appear in all the manufacturing processes of an engine. In these phases, a quality control (inspection) is performed, the components are cleaned, assembled and tested. Finally, the engine is cleaned so it can then be painted.

1. Inspection

   An initial visual inspection is performed to reject defective engines.

2. Pre-cleaning

   The engine is cleaned quickly in order to be able to inspect the dirtiest areas.

   1) A technology has been chosen for this cleaning phases that is good at removing grease and oil, without paying attention to the carbonised sediments. Using (Table 9 and Table 8), the best cleaning option for this phase was deemed to be water blasting (Figure 58). It can be manual or automatic cleaning, depending on the investment and the production level of the company.

Figure 58 Pre-cleaning of the engine.

3. Inspection

   The first step is repeated, paying special attention to the areas that were covered by the dirt.

4. Disassembly (Figure 59)

   A semi-destructive disassembly, along with a destructive one for some components, will be used. As not all the components are going to be remanufactured, some can be broken to facilitate the disassembly process.

Figure 59 Disassembly of the engine .

5. Cleaning

All the parts, to a greater or lesser extent, have grease, oil and carbonised sediments. However, only the engine block is painted. Therefore, a complementary cleaning needs to be applied to remove the paint.

1) In line with the tables, water blasting with a cleaning solution is used to clean the components (Figure 60). Table 9 shows that it is a technology which allows the grease and oil to be completely removed and is compatible with steel and cast iron (Table 8). It can also remove paint and carbonised sediments. It should be noted that the components have no nooks (after the engine block has been removed). Therefore, the simplest and cheapest technology was chosen from among the different options.

Figure 60 Water blasting cleaning.

2) Engine block: Thermal cleaning was chosen as complementary cleaning, which will help to remove the paint from the surface. Apart for looking for a technology to help to remove the paint, as some parts have complex geometry that could make it difficult to clean using water blasting, Table 9 was used to select a technology that could remove the dirt from those nooks (grease, lubricant and some carbonised sediment) and which are compatible with steel (Table 8). That cleaning will take place before the water blasting, as it cannot remove all the paint from the surface, but can soften it and make it easier to then clean.

6. Inspection

The components are inspected carefully to pinpoint any possible defects and thus reject defective components. A component will be remanufactured, provided that it passes all the inspections.

1) The surface inspection is the first one to be carried out. According to Table 10, all the inspections can be conducted, as all the components are steel or cast iron. As a

ferromagnetic material has to be tested, the magnetic particle inspection technique has been selected (Figure 61). All the components are analysed using this technique.

Figure 61 Magnetic particle inspection: engine block (a), crankshaft (b).

2) The rod is the only component that needs a volumetric inspection, as it is the one that withstands most forces. The most appropriate of the two possible options is the ultrasonic inspection. It is not as fast and straightforward as an x-ray, but it is much cheaper.
3) The hardness of the surface is analysed to establish if there has been any changes to the microstructure during its use. Therefore, either the Rockwell or Brinell test could be used.
4) Finally, all the components undergo a dimensional inspection. Table 10 shows all the possible measurement techniques. Therefore, the most suitable for each case has been selected.
    i. Engine block: A manual optical inspection is performed. The diameter and the alignment of the holes are measured.
    ii. Crankshaft and camshaft: the dimensions are checked by means of a manual optical inspection.
    iii. Rod: the diameter of the holes are measured manually.

7. Reconditioning

Once they have passed all the inspections, the components are ready to be reconditioned. Table 11 was used to check whether the selected operation can be used for each component (material).

1) Engine block (Figure 62): The first operation is grinding of the upper part of the block. Then, the piston holes are milled. A large surface finish is not necessary, as they will be put in the liners. Finally, once in the liners, they are brushed.

Figure 62 Reconditioning the engine block: grinding (a), milling (b).

2) Crankshaft and camshaft (Figure 63): The same operations are carried out for both components. They are first ground and then micro-polished.

Figure 63 Reconditioning the crankshaft and camshaft: grinding the camshaft (a), micro-polished crankshaft.

3) Rod: Boring is the only operation carried out to the rods (Figure 64).

Figure 64 Rod boring operation.

8. Inspection

After the reconditioning process, there is a quality control to check that the components meet the minimum characteristics required, in the same way as in a manufacturing process. (Figure 65).

Figure 65 Quality inspection: engine block (a), camshaft (b).

9. Final cleaning

    All the remanufactured components are cleaned before being assembled. This removes any dirt that may be left from the previous processes.

10. Assembly

    All the components, both the remanufactured and new ones, are assembled (Figure 66). The same procedure is followed as when assembling a new engine.

Figure 66 Engine assembly: remanufactured component (a), new components (b).

11. Testing

    Once all the components have been assembled, the engine undergoes a final test that checks it is operating correctly (Figure 67).

Figure 67 Testing the engine.

12. Clean before painting.

Before painting, the engine may need to be cleaned so that it can be painted correctly.

13. Painting

The last step is to paint the engine (Figure 68). This ends the remanufacturing process.

Figure 68 Painting process (engine).

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