MATERIALS PROCESSING AND MANUFACTURING TECHNOLOGIES

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Keywords: Brazing, casting, ceramic, composite, deformation, drawing, extrusion, fiber, forging, glass, joining, manufacturing, materials, metal, moulding, plastic, powder, pressing, processing, recycling, rolling, sintering, soldering, welding.

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Summary

Probably the major growth area in recent years has been in the manufacture of composite materials. The potential advantages of combining materials with significantly different properties have been known for centuries but, in general, the technology did not exist to facilitate satisfactory industrial scale manufacture. However in the last two to three decades of the twentieth century, the technology has been developed and the tailoring of components for very specific purposes has become technically and economically feasible. Many of the breakthroughs have initially been made in “Hi-Tech” areas such as aerospace, communications, weapons, and electronics, but the technologies developed have “cascaded down” and many more “mundane” manufacturing industries have benefited. Recent refinements in the production of composite materials has seen the introduction of “functionally graded” materials in which the concentration and, indeed, type of reinforcement in the matrix varies with location in the component depending upon the local in-service property requirements.

Clearly the range of processes and techniques used in modern manufacturing industry is enormous. Improvements in process control via the use of on-line computers has enhanced the quality and reproducibility of manufactured components. This improved process control, together with major advances in the use of industrial robots and automated methods of measurement and inspection have increased production rates and process efficiency.

Enhanced computer control has also permitted increased economic efficiency in the manufacturing industry, by the adoption of the “Just In Time” philosophy, in which the stockpiles of raw materials and components processed to various stages in the manufacturing schedule are greatly reduced, if not completely eliminated.

1. Introduction

Producing an overview of the major processing methods used in the manufacture of components from mainstream engineering materials is a daunting task. This article is an attempt to provide the reader with a general appreciation of the range, complexity and diversity of processes utilized in the manufacturing industry today. For each of the seven major fields covered, the present “state of the art” techniques are described. Some historical background to the development of these techniques is also presented. Consideration of the main manufacturing problems encountered and the solutions developed is also included. The range of manufactured components is so vast that an almost infinite number of combinations and permutations of processes are used. In order to simplify this, whenever possible a “generic” manufacturing route has been described to provide the reader with some feel for the major stages in the production of a number of “key” engineering components.

2. Processing via the Liquid State

Liquid state processing is used for a wide range of materials including metals, plastics, glasses and, very occasionally, ceramics. Casting, for example, has been used for around 6000 years, as is evidenced by the discovery of a range of artifacts including copper ornaments and arrowheads. In order to form the material into a particular shape, it is often convenient to produce the material in the form of a liquid, which can be poured into a mold. This permits the production of complex shapes, internal cavities and hollow sections. The mold imposes the desired shape on the liquid and on subsequent solidification or setting the mold can be opened and the shaped component ejected. In this process, the high deformation forces required for solid state forming are unnecessary. However the final molding may require further processing in terms of finish machining or heat treatment, in some cases, to achieve satisfactory properties.

2.1. Metals

Many metallic components are produced by casting the molten metal or alloy in a mold and allowing it to solidify. The solidified component is then removed and given the appropriate finish machining treatments. The most important parameters of the casting operation are:

- The design of the mold cavity shape.
- How the molten metal flows into the mold and fills the cavities.
- How the heat flows within the metal and from the metal to the mold materials.
- The surface finish imparted to the casting, which depends on the mold material.
- The solidification behavior of the metal.

In general, casting processes may be divided into those that use disposable molds and those that use permanent molds.

2.1.1. Disposable Mold Casting

The classic example and single most widely used process is sand casting, a process used for thousands of years. A pattern (wood, plastic, metal or plaster), which has the shape of the component to be cast, is used to impart this shape to compacted sand. A gating system to feed the molten metal to the mold is also formed in the sand. The molten metal is poured and care is taken to ensure that all parts of the mold are filled. This involves the use of a top-up reservoir of molten metal to feed additional metal into the mold to compensate for shrinkage during solidification. When the casting has solidified, the sand mold is broken away and the casting removed. The relatively poor surface finish quality and lack of dimensional accuracy require the casting to be finish machined. There are a number of variations on the basic sand casting process.

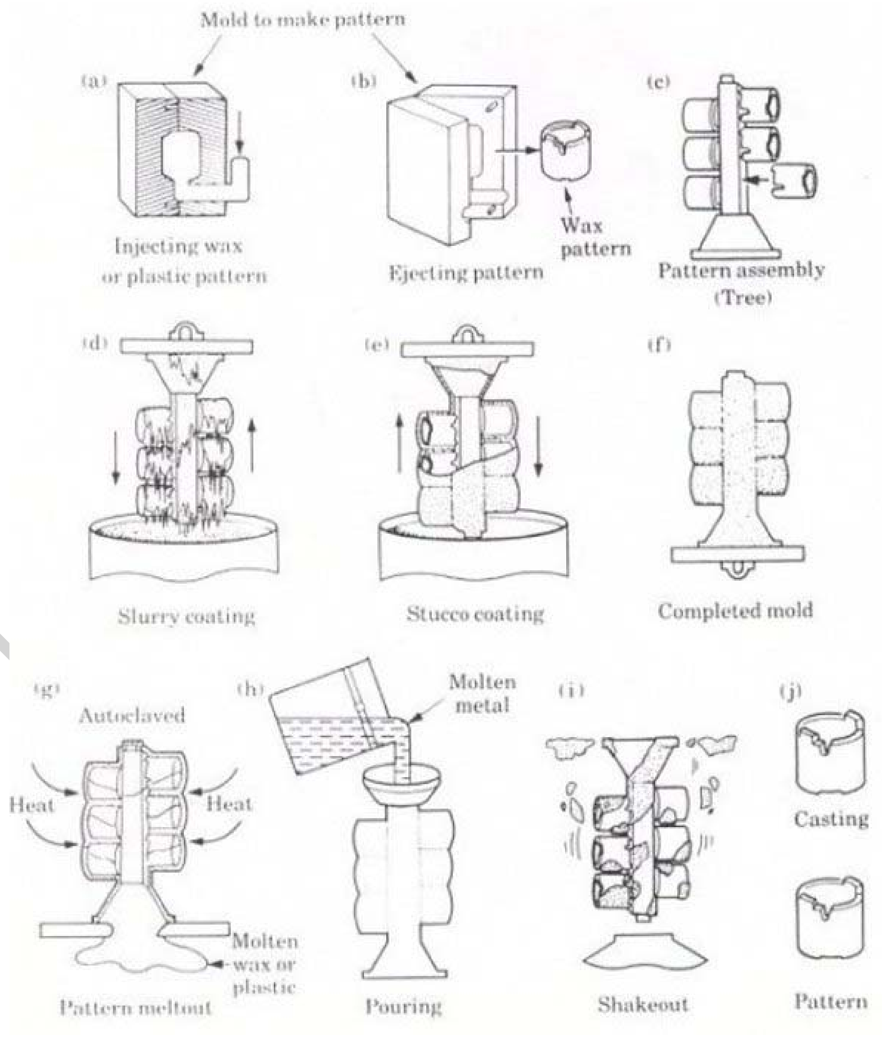

Figure 1. Schematic Illustration of Investment Casting (Lost-wax Process)
Castings by this method can be made with very fine detail and from a variety of metals

In shell mold casting, a resin binder is mixed with the sand, which is then used to form a thin shell as a deposit on a heated metal pattern. The assembly is then heated in an oven to cure the resin. Finally the shell is removed and is then used for casting the molten metal. In expandable pattern casting, the pattern is made from polystyrene and actually remains in the cavity while the molten metal is poured. The molten metal causes the polystyrene to vaporize. In plaster or ceramic mold casting, the mold is made of either plaster (only used for low melting point metals) or refractory materials, such as silica, zircon and alumina (used for ferrous and high melting point metals). These techniques give a better quality surface finish than sand molds. The investment casting (or lost wax) process (Figure 1) uses a pattern made from wax (reusable), or a low melting temperature plastic (not reusable). The pattern is coated with slurry of refractory metal, which is allowed to dry. Repetition of this coating process allows a refractory layer of adequate thickness to be built up. The mold is then heated to melt the wax or plastic, which is poured out. The mold is fired and is then ready to receive the molten metal. This process, although relatively expensive, can be used for high melting point metals and gives good surface finish and dimensional accuracy.

2.1.2. Permanent Mold Casting

In the basic process, the mold is made of a metal, such as cast iron, steel or a refractory and is formed in two halves to facilitate opening and closing and the molten metal is poured in under the action of gravity. A mold will be used repeatedly in this process. The gating system is machined into the mold halves. A clamping system is required to ensure that mold is firmly closed during metal pouring and solidification. If internal cavities are required in the casting metal cores are placed in the mold prior to closure. The mold is usually heated to improve metal flow during the pouring stage. This process produces good surface quality finish and dimensional accuracy and lends itself to automation for the production of large numbers of components. One variation on this process is pressure casting in which the metal is forced into the mold by use of gas pressure or a vacuum. Generally, this process is used for high quality components. Another variation is die casting. Here the molten metal is forced into the mold (or die) via a nozzle under pressure using a piston. The die is water cooled to reduce the solidification time and to prolong die life. The pressure is maintained until solidification is complete. Then the die is opened and the molding ejected. This process is commonly used for low melting point metals such as zinc, fairly small size components, and is capable of extremely high production rates.

2.2. Glasses

In the manufacture of glass components the glass is initially heated above its transition temperature until it becomes a viscous fluid. The molten glass may then be formed into the desired shape by one of a number of processes. To form flat sheet and plate three generic processes are available: drawing, rolling and float processing.

2.2.1. Drawing

In this process, a pair of horizontal rolls, in contact with the surface of a reservoir of molten glass, rotate, and draw the glass vertically upwards into the roll nip. The glass is squeezed by the rolls into a sheet and is then passed over a single “turning” roll, which redirects the glass into the horizontal direction. It is then transported horizontally over a series of carriage rollers while it cools.

2.2.2. Rolling

This process was established in the early 1920s for plate glass production. Here an upstream pool of molten glass is maintained to feed glass continuously into the roll gap of a pair of rolls. The rolls form the sheet, extract heat from the glass and can also be embossed to imprint a pattern on the glass surfaces. The cooling sheet is transported horizontally over a series of carriage rollers. This process is no longer used for producing plate glass, but it is still the main process for the production of patterned, and wire rolled glass.

2.2.3. Float Process

This process was developed in the 1950s to produce plate glass with a very high quality surface finish, effectively free from distortion. Previously plate glass manufacture had required the grinding away of up to 20% of the glass thickness of sheet produced by drawing or rolling. The Float process is now used for practically all the plate glass manufactured and for a high percentage of all flat glass products. The molten glass is supplied from a continuous melting furnace. It passes into a bath containing molten tin and floats as a continuous sheet on the surface of the metal. The atmosphere above the bath consists of a nitrogen/hydrogen mixture to prevent the oxidation of the tin. The sheet is fed directly into a horizontal annealing lehr, where solidification occurs. The annealed glass is carried forward on rollers as it cools. It is then ready for on-line cutting to the final dimensions.

Glass rod and tubing is manufactured using a tubular, spinning metal mandrel inclined to the horizontal. The mandrel is continuously coated with molten glass. If tube is to be manufactured, air is blown though the center of the hollow mandrel to initially form a tubular cross section. The tube is drawn through an orifice ring via rollers.

Discrete glass components such as bottles, flasks, jars and light bulb envelopes are made by blowing. In this process, a glob of molten glass is inflated by blown air, which expands the glass and pushes it against the walls of the mold (previously coated with a parting agent). It is difficult to control the wall thickness accurately but a reasonably good surface finish is obtained. The process can be automated and operated at high speeds, e.g., light bulb envelopes can be made at a rate of 1000/min. Other discrete components, which are not hollow, are made in a pressing operation using a plunger to force the glob of molten glass into a mold.

3. Powder Methods

The origins of powder processing techniques can be traced back thousands of years. In the Iron Age, components were manufactured by a crude process starting with sponge iron, which are really agglomerated iron particles. These agglomerates were consolidated by the application of heat and pressure, which caused plastic welding. This is still the basis for many of the techniques used today.

Powder processing routes are commonly used for the manufacture of many ceramic and also a number of metal components.

3.1. Metals

Powder metallurgy techniques offer a number of advantages over conventional techniques.Near-net shape manufacturing of structural parts permits a large saving in tooling costs because of the reduction in the number of forging/machining operations required. In addition to energy savings (up to 55%), material utilization in excess of 95% can be achieved. Structural components account for by far the largest tonnage of powders used. Ferrous, copper, brass, bronze and aluminum parts are produced with ferrous components for the automotive industry accounting for almost 80%.
Powder metallurgy techniques are employed for:

- High melting point metals and alloys, e.g., refractory metals, which would prove extremely difficult, if not impossible, to process by conventional casting techniques, can be fabricated.
- Novel alloys, which could not be processed conventionally via the liquid state due to the non-miscibility of the constituents, can be produced.
- Alloys, which are brittle, or have extremely high flow stresses and could not be processed by conventional hot working techniques can be produced, e.g., high speed steels and superalloys.
- Some composite materials. Examples include: electrical contact materials, such as copper/tungsten, hard metals (cemented carbides) such as WC/Co for cutting tools, friction materials for brake and clutch linings, e.g., copper matrix based for surface temperatures up to 800 °C and ferrous matrix based for temperatures up to 1000 °C, diamond particles embedded in a metal matrix for grinding wheels, dispersion strengthened materials (ODS), which have superior elevated temperature properties and particulate and short fiber MMCs can be fabricated by mixing the reinforcement with a metal powder, which will form the matrix after consolidation.
- Rapid solidification processing, such as atomization, yield fine powders, which enable the microstructure of the final component to be refined, leading to improved mechanical properties.
- Reduction of Anisotropy of properties in the final component via a reduction in the crystallographic texture intensity due to the reduced number of plastic deformation operations required.
- Control of the porosity content in the manufacture of self-lubricating bearings such as Cu/Sn bearings for household appliances and bronze. Nickel and steel filters for the oil and chemical engineering industries.

A vast range of processing routes is used in the PM industry, and so a “generic” manufacturing process is described below to illustrate the major stages.

3.1.1. Production of Metal/Alloy Powders

A range or techniques are used including:

Atomization by water or gas (Figure 2). In these processes a liquid metal stream is disintegrated by impingement of high pressure water or gas. The fine metal droplets formed are then cooled to produce powder. Water is used for ferrous powders. Argon is used for the more reactive materials such as chromium containing alloys.

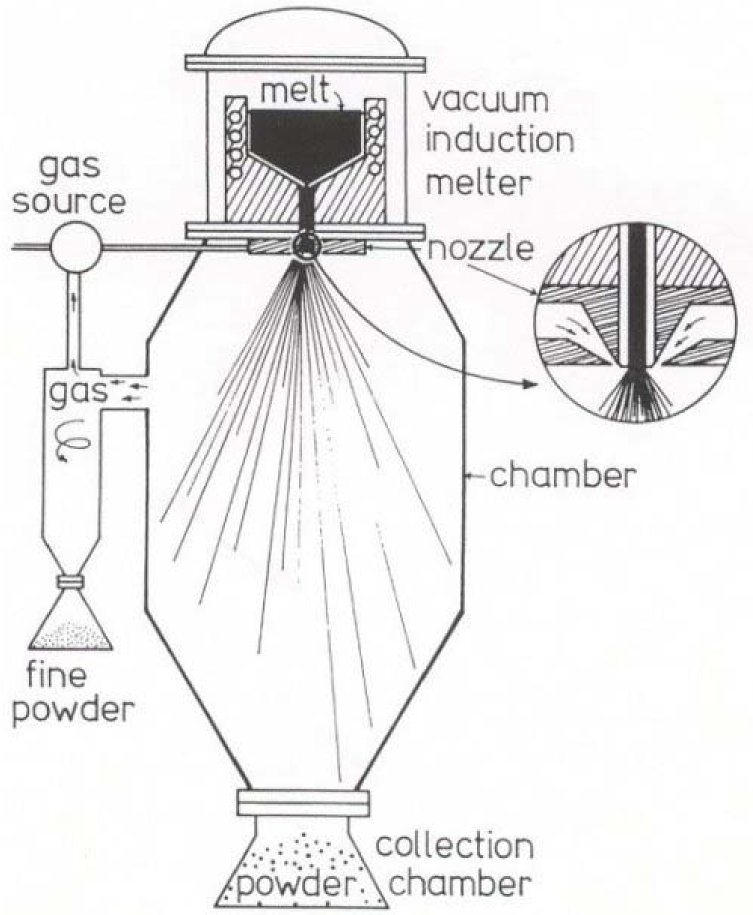

Figure 2. A Vertical Gas Atomizer. The main features are a vacuum induction furnace, gas expansion nozzle, gas recirculation/supply system, free-flight chamber and powder collection chamber

Solid State Reduction used for iron powder. Iron oxide is reduced by carbon at 1200 °C to produce sponge iron.

Electrolysis used for copper. An aqueous solution of copper sulfate is decomposed, using a high current density, in an electrolytic cell, to produce dendritic copper particles.

Mechanical Comminution (ball and rod milling) used for brittle, intermetallic compounds such as ferro-chromium or ferro-silicon. Coarse particulate feedstock is mechanically broken up to produce fine powders (<5 μm) by attrition using hard metal or ceramic balls or rollers in a continually rotating cylindrical container. Greater efficiency is achieved by adding an organic liquid to the mill to form a slurry with the powder charge.

Chemical Processes. Nickel and iron powders are produced by the carbonyl process. Carbon monoxide is used in a reversible, chemical reaction to refine crude converter nickel or coarse iron particles.

Sizing/Screening. It is important that the powder particle size distribution be controlled to optimize the consolidation processes and in turn the final component properties. For this reason, a sieving or gas classification process is used to achieve the correct powder particle size distribution. Many commercially used powders have particles in the range 5 to 45 μm.

Mixing. Lubricant must be combined with the powder to facilitate subsequent pressing operations by reducing powder/tool friction. Stearic acid or metallic stearates are commonly used. If composite materials are being fabricated, this step is also vital to ensure that a homogeneous distribution of matrix and “reinforcement” is produced.

Pressing. This may be carried out unidirectionally or isostatically. Isostatic pressing, in which a liquid or gaseous medium is used to apply pressure equally in all directions, offers an improvement in the uniformity of compact density and also permits components with very large height/width aspect ratios to be pressed. Often the compaction is performed at room temperature but for hard metals and diamond cutting tools, hot pressing is used. A porous green compact is produced, which has sufficient strength for handling during subsequent processing operations.

Sintering. This leads to consolidation and densification by growth of necks between powder particles and elimination of porosity. It is carried out under a controlled atmosphere to prevent oxidation. For porous (self-lubricating) bearings, sintering is controlled to permit retention of some porosity for subsequent oil impregnation.

Hot Isostatic Pressing (HIPing) or Forging or Extrusion. A combination of high temperature and pressure is used to consolidate by plastically deforming the powder particles causing welding and elimination of porosity.

Repressing/Final Machining. These processes are required to obtain the required dimensional accuracy and provide a satisfactory surface finish.

3.1.2. Future Trends

Metal injecting molding, for the production of small, precision components is growing in importance. A high volume fraction of metal powder in a plastic binder is injected into a mold. After ejection from the mold the plastic binder is removed leaving a metallic “skeleton,” which can then be sintered. The densities reached are generally superior to those achieved by conventional sintering and comparable to those from hot deformation processing techniques, such as hot extrusion. Although not strictly a “powder” process, spray deposition has great potential. Molten metal is gas atomized and sprayed onto a former, to produce a dense metal layer. The process can be used for a wide range of metals, including copper, aluminum, steel and superalloys. Of particular significance is the flexibility in terms of the product shape, which can be produced. Products include solid billets, strip, sheet, tube and clad materials.

3.2. Ceramics

Most ceramic components are manufactured by a powder processing technique, because they cannot be readily produced in the molten state, due to their high melting points and/or tendency to decompose, and because they are extremely brittle with very high strengths in the solid state, even at elevated temperatures, precluding mechanical working. A generic processing route is outlined later.

3.2.1. Powder Production

This is achieved by crushing or ball milling, which may be performed either wet or dry. Wet crushing is more efficient and prevents the formation of "dustclouds," suspensions of fine particles in air. Sol-gel processing is also used.

3.2.2. Sizing

The powder is then sieved to achieve the desired particle size distribution.

3.2.3. Mixing

The powder is then mixed with binders and lubricants, which facilitate pressing and mold release, respectively. Plasticizers are added if the ceramic is to be plastically formed in the next stage.

3.2.4. Shaping/Forming

Several techniques are employed to produce the component shape in the "green" (unfired) state. Slip casting is the most common process. A colloidal suspension of ceramic particles in water is poured into a porous mold. The mold absorbs the water leaving a build-up of the ceramic on the mold wall. This is used for common plumbing and kitchenware. Plastic forming involves extrusion, injection molding or casting. Pressing, either wet or dry is also used. More complicated shapes are wet pressed. If uniform density is particularly important, e.g., in automotive spark plugs, isostatic pressing is used.

3.2.5. Drying

The moisture present in the green ceramic must be removed carefully under controlled temperature and humidity. This is to prevent warping and cracking. Considerable shrinkage occurs during this stage.

3.2.6. Firing (Sintering)

In this process, the green ceramic is heated to high temperature in a controlled atmosphere. Consolidation occurs by formation of necks between powder particles and elimination of porosity. The heating and cooling rates are carefully controlled to prevent thermal shock cracking.

3.2.7. Finishing

This is required to improve the surface finish, remove surface flaws (which would otherwise have a deleterious effect on mechanical properties, particularly strength) and achieve the dimensional tolerances required. Due to the hardness of most ceramics, the finishing is left to a minimum. Grinding, lapping and, less frequently, machining may be used. In some cases a surface glaze is added. This is produced by a glaze material, which forms a glassy coating during the firing process.

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Biographical Sketch

Henry McShane graduated with a B.Sc. (Eng) degree in Materials Science and Engineering from Imperial College, London, in 1974. He joined the materials processing research group there and completed a Ph.D. on the production of metal matrix alloy composites in 1978. After a period as a research assistant at Imperial College, he moved to ALCOA, as a senior engineer, and worked in the fabrication technology division at their Technology Center in Pennsylvania. His work there included projects on texture control in flat rolled aluminum alloy products, and modeling of microstructural evolution during deformation processing. He returned to the Materials Department at Imperial College as a lecturer in 1985, and continued work on microstructural evolution during deformation processing in aerospace alloys and composites. He has also worked on the development of powder processing techniques for metal matrix composites. In 1992, he was promoted to senior lecturer. Since 1995, he has been heavily involved in the organization and running of the undergraduate courses on materials science and engineering. He is the author of over 70 technical publications.