# CHAPTER 1

# ENVIRONMENTALLY BENIGN MANUFACTURING

**William E. Biles, Ph.D., P.E.**
**Department of Industrial Engineering, University of Louisville, Louisville, Kentucky**

## 1 INTRODUCTION

How might mankind enjoy the fruits of an advanced civilization without endangering the viability of planet Earth for future generations? That is the fundamental challenge that we confront in the 21st century. In a time when the comforts and pleasures that can be derived from the products of modern technology are accessible for a significant portion of the world's population, how can we manufacture and deliver those products in an environmentally benign fashion?

## 2 ENVIRONMENTALLY BENIGN MANUFACTURING

The *environmentally benign manufacturing* movement addresses the dilemma of maintaining a progressive worldwide economy without continuing to damage our environment. How can companies—driven by the necessity for manufacturing the products sought by their customers in a cost-effective manner while maintaining market share and providing gains for their stockholders—also heed the growing clamor for a safe environment? This dilemma is fundamentally a trade-off between the needs of current generations and those of future generations. Will we seek creature comforts for ourselves without regard to the safety and well-being of our children and our children's children? Or will we reach a compromise that allows current generations to reap the benefits of our modern technological society while assuring the same benefits for future generations? The challenge for environmentally conscious manufacturers is to find ways to factor both economic and environmental considerations into their business plans.

The fundamental issue in environmentally benign manufacturing is to align business needs with environmental needs. That is, how do we manufacture market-competitive products without harming the air, water, or soil on planet Earth? How do we motivate companies to behave unilaterally to adopt environmentally benign manufacturing practices? Will nation-states unilaterally recognize the need to impose environmental standards on companies manufacturing products within their national boundaries? Recent experience informs us that progress is being made on each of these fronts, but that we have a long way to go to fully protect the environment from the offenses committed by the worldwide manufacturing community.

## 3 MANUFACTURING AND THE SUPPLY CHAIN

The issue of environmentally benign manufacturing is not isolated on the manufacturing function. Environmental issues abound from tier I and II suppliers to the manufacturing system all the way through the supply chain to the consumer. Figure 1 shows the position of the manufacturing function in the overall supply chain.

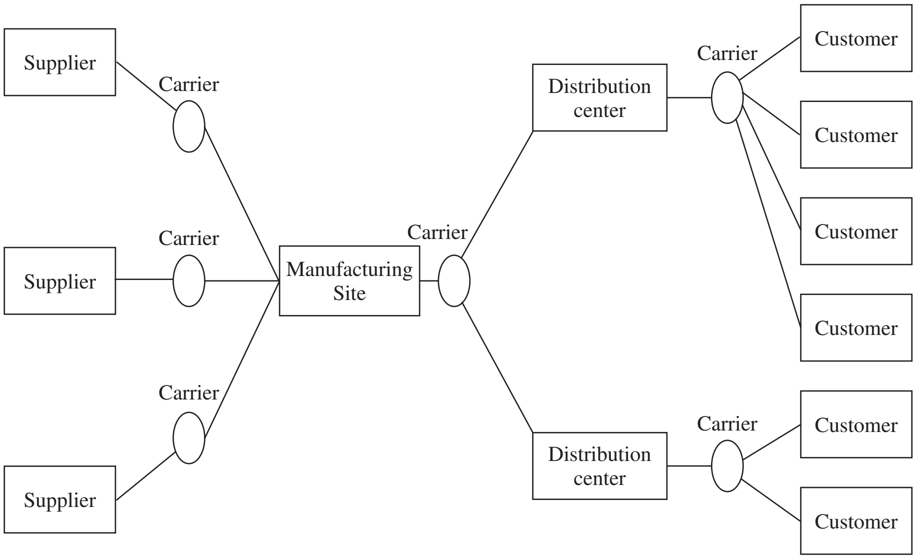


**Figure 1** Material and information flow in the supply chain: Material flow is usually left-to-right, information flow right-to-left.

### 3.1 Tier I and Tier II Suppliers

Each tier I or II supplier has its own *manufacturing processes,* each with its own environmental impacts. It is incumbent upon the primary manufacturer to qualify its tier I and II suppliers not only in terms of quality, cost, and on-time delivery, but on their environmental performance as well. Suppliers must be made to understand that their very financial viability depends on their adopting sound environmental practices. Their role in the supply chain cannot be ignored. It is the responsibility of the primary manufacturer to ensure that its tier I and II suppliers adhere to environmental standards.

### 3.2 Transporters

The transportation function in the supply chain is also important in terms of its environmental impacts. *Transporters* are those entities that move materials and products from one point to another in the supply chain. Transporters are typically selected and retained according to their cost and reliability performance. Scant attention is paid to the issue of energy expenditure per unit delivery. In an *environmentally conscious manufacturing* approach, primary manufacturers must give closer attention to *energy expenditure per unit delivery* in selecting the mode of transportation from among highway, rail, air, water, and pipeline.

Cost and delivery-time considerations must be balanced against energy expenditure in choosing the transportation mode. For example, consider the case of a refrigerator manufactured in the United States, which is to be shipped to a distribution facility located 500 miles away. It is probably reasonable to immediately exclude pipeline (infeasible), water (not accessible), and air (too costly) transporters from consideration in this application. The trade-off between highway and rail—both of which are feasible, accessible, and within acceptable cost boundaries for the transport of refrigerators—should incorporate a comparison of the energy expenditure per unit (refrigerator) transported. Such a comparison would very likely come down in favor of rail transportation in terms of both cost and energy expenditure, and in favor of highway in terms of delivery time. At present, the delivery-time consideration dominates the transporter selection decision in favor of highway transportation. The entire transporter selection issue needs to be reexamined to consider environmental effects of the supply chain transportation function.

## 4 MANUFACTURING PROCESSES

The manufacturing process itself is perhaps the most important stage in the supply chain in terms of overall environmental impact. Here we shall consider five manufacturing processes that apply to metals and plastics: (1) machining processes, (2) metal casting, (3) metal forming, (4) metal joining, and (5) plastics injection molding.

## 4.1 Machining Processes

Machining processes include such manufacturing operations as turning, milling, drilling, boring, thread cutting and forming, shaping, planning, slotting, sawing, shearing, and grinding.[1] Each of these processes involves the removal of metal from stock such as a cylindrical billet, cylindrical bar stock, or a cubical block. Metal-cutting economics seek to (1) minimize the cost of the metal cutting operation, (2) maximize tool life, or (3) maximize production rate. An environmentally benign manufacturing approach would add *minimizing environmental impact* to this list of economic objectives.

The achievement of these economic objectives in machining requires the use of *cutting fluids,* which act as coolants and/or lubricants in the machining process. The four major types of cutting fluids are: (1) soluble oil emulsions with water-to-oil ratios ranging from 20:1 to 80:1; (2) oils; (3) chemicals and synthetics; and (4) air. Cuttings fluids have six major roles in machining:

1. Removing the heat of friction
2. Minimizing part deformation due to heat
3. Reducing friction among chips, tool and work piece
4. Washing away chips
5. Reducing possible corrosion on both the work piece and machine
6. Preventing built-up edges on the product or part

The environmental impacts of machining processes are principally of two types: (1) the accumulation of metal chips; and (2) the release of cutting fluids into the environment. The best solution to the problem of chip accumulation is to recycle them by incorporating them as charge into the metal-casting operation. But recycling may involve transporting the chips to a distant site, thereby incurring the *transporter* impact. The best way to handle cutting fluids is to recycle them back to the machining operation, which requires that chips be separated from the machining effluent and that the cutting fluid be reconstituted to as close to its original state as possible. Each of these steps incurs an economic cost, which must be balanced against the cost of the environmental impact of simply placing the chips and used cutting fluid into a waste site.

*Electrical discharge machining* (EDM) removes electrically conductive material from the raw material stock by means of rapid, repetitive spark discharges from a pulsating D.C. power supply, with dielectric flowing between the workpiece and the tool (Figure 2). The cutting tool (electrode) is made of an electrically conductive material, usually carbon. The shaped tool is fed into the workpiece under servocontrol. A spark discharge then breaks down the dielectric fluid. The frequency and energy per spark are set and controlled with a D.C. power source. The servocontrol maintains a constant gap between the tool and the workpiece while advancing the electrode. The dielectric oil acts as a cutting fluid, cooling and flushing out the vaporized and condensed material while

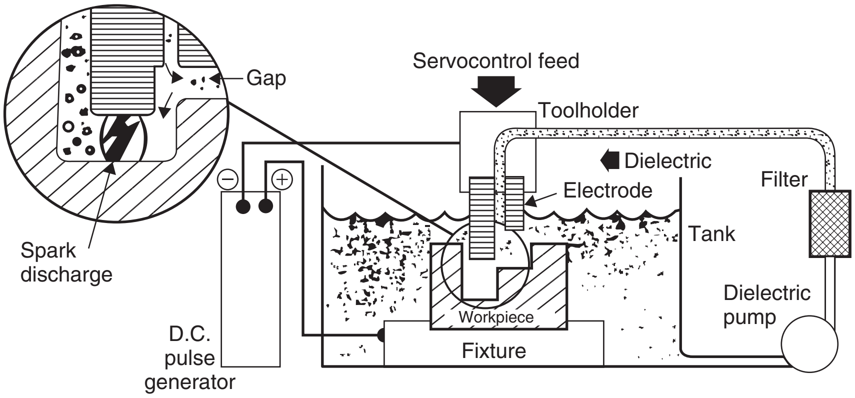


**Figure 2** Electrical discharge machining.

reestablishing insulation in the gap. Material removal rate ranges from 16 to 245 cm$^3$/h. EDM is suitable for cutting materials regardless of their hardness or toughness. Round or irregularly shaped holes 0.002 inches (0.05 mm) in diameter can be produced with $L/D$ ratio of 20:1. Narrow slots with widths as small as 0.002 to 0.010 inches (0.05–0.25 mm) can be cut by EDM.

## 4.2 Metal Casting

Metal-casting processes are divided according to the specific type of molding method, as follows: (1) sand casting; (2) die casting; (3) investment casting; (4) centrifugal casting; (5) plaster-mold casting; and (6) permanent casting. This section discusses the first three of these.[2]

### *Sand Casting*

*Sand casting* is one of the most ancient forms of metalworking. The first sand casting of copper dates to about 6,000 years ago. Sand casting consists of pouring molten metal into shaped cavities formed in a sand mold, as shown in Figure 3. The sand used in fabricating the mold may be natural, synthetic, or artificially blended material.

Sand casting is a relatively simple process and consists of the following steps:

1. Mold preparation
2. Core preparation
3. Core setting
4. Metal preparation
5. Metal pouring
6. Part shakeout
7. Part cleaning

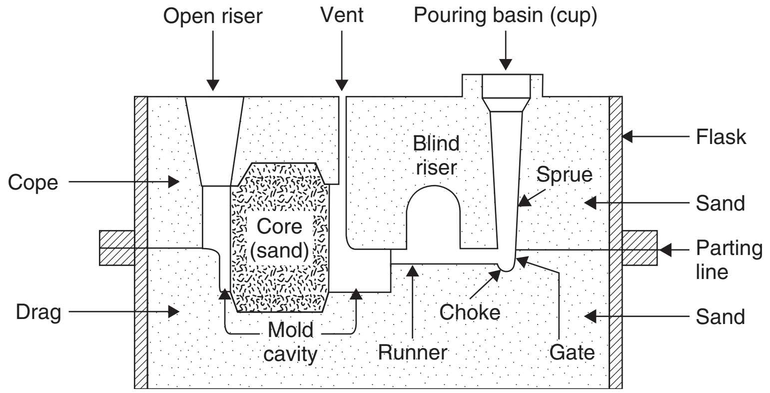


**Figure 3** Sectional view of a sand-casting mold.

8. Sand reclamation
9. Sprue and gate reclamation

This section describes each step.

*Mold Preparation.* A mold is fabricated from foundry sand. It is created by pouring and compacting sand around a pattern. Once the sand is compacted the pattern is withdrawn, leaving a cavity in the shape of the part to be produced. The cavity holds the molten metal in the desired shape until it cools. Molding *sand* is a mixture of approximately 85 percent sand, from 4 to 10 percent clay, and from 2 to 5 percent water by mass. Small quantities of additives are used to prevent the metal from oxidizing as it cools. These additives are usually bituminous coal, anthracite, or ground coke.

*Core Preparation.* Cores are necessary for parts that are especially complicated or have internal cavities. Cores are created from sand and a binder—usually in the form of a resin—that cures through heat or gasification. The sand and binder are put in a mold called a *core box* that forms the desired shape. They are then removed from the core box and allowed to cure before placing them in the sand casting mold. The placement of the core is illustrated in the left half of Figure 3.

*Core Setting.* Once the mold and cores have been prepared, the cores are set in place inside the mold and the mold is closed.

*Metal Preparation.* Metal—usually iron, steel, or aluminum—is prepared by melting ingots or scrap with the additives or alloying materials needed to give the finished product its desired properties. Most sand casting is accomplished by melting and blending scrap material.

*Metal Pouring.* Metal is poured manually from a ladle or tilting furnace, or most commonly from an automatic pouring ladle, that is charged from holding furnaces.

*Shakeout.* Molds containing cooled parts are transferred by conveyor to a large rotary drum, where the sand molds are broken and the sand is separated from the newly molded parts.

*Part Cleaning.* Usable parts are separated from gates and risers, and damaged or incompletely formed parts are sorted out. Further cleaning may also be accomplished in the form of pressing, hand grinding, sandblasting, or tumbling the parts to remove the parting lines and rough edges as well as any burnt sand.

*Sand Reclamation.* All modern foundries reclaim molding sand for reuse. The sand is run through a process where lumps are broken up and any solids are removed by screening. New sand, clay, and water are added as needed to return the sand to a usable condition. Some sand that cannot be reclaimed is discarded. Most foundries have a sand laboratory whose responsibility is to monitor and manipulate the condition of the molding sand.

*Sprue and Gate Reclamation.* Any metal that is not a usable part is returned to the scrap area to be used in a future melt.

### ***Environmental Concerns with Sand Casting***

With respect to sand casting, the environmentally benign manufacturing function is concerned with minimizing the impact of the manufacturing steps just listed on the environment by changing or replacing processes that produce an environmentally offensive result or hazard. Consideration will be given here to each of the sand-casting subprocesses.

*Molds and Cores.* Molds and cores are made from sand. For every ton of castings produced, the process requires about 5.5 tons of sand. Problems occur when the sand and binders are exposed to the heat of the molten metal and sometimes during curing processes of mold preparation. This releases a wide variety of organic pollutants that are regulated by the *Clean Air Act* or the *Clean Water Act*. These pollutants come primarily from the chemical binders use to make cores stronger, or in some cases from binders added to the sand. When stronger molds are required, chemical binders are added to the mold sand. These binders include furanes, phenolic urethanes, and phenolic esters. The binder is chosen depending on the strength required for the metal being cast and the size of the mold. Other concerns are molding sand additives used to prevent the metal from oxidizing as it cools. These additives are usually bituminous coal, anthracite, or ground coke. Although these additives are a very small component by mass,

**Table 1** Some Pollutants Associated with Binders Used in Mold Preparation

| | Benzene | Methanol | Phenol | Toluene | Formaldehyde | MMDI |
|---|---|---|---|---|---|---|
| Furane | ● | ● | ● | ● | | |
| Phenol urethane | | | ● | | ● | ● |
| Phenol ester | | | ● | | ● | |

*Note*: MMDI is an acronym for Monomeric Methylene Diphenyl Diisocyanate.

as they burn off on contact with the molten metal they create an assortment of hazardous air pollutants. Table 1 shows several pollutants associated with binders used in mold preparation.

*Metal Preparation and Pouring.* While the use of scrap metal can contribute to pollutants, the most significant contributor for these subprocesses are related to the heat input to melt the metal. Pollutants include large amounts of particulates and carbon monoxide, as well as smaller amounts of $SO_2$ and VOCs. Emissions are dependent on the type of furnace being used. Electric furnaces have a reduced environmental impact as compared to coke-fired furnaces of older foundries. Many foundries use pollution-control technology in the form of scrubbers to clean air before releasing it to the outside. These are used on all types of furnaces. Wet scrubbers are also used, but are less common and are used primarily on coke-fired cupola furnaces. These methods are effective at controlling air emissions, but they produce waste streams in the form of solid waste or contaminated water, which must be processed further. Table 2 shows pollutants generated by melting metal for several types of furnaces. Table 3 gives the energy requirements at the foundry for both fuel-fired and electric furnaces.

**Table 2** Approximate On-site Emissions from Various Furnaces in lb./ton of Metal

| | PM | CO | $So_2$ | VOC |
|---|---|---|---|---|
| Fuel-fired Reverberatory Furnace | 2.2 | Unknown | N/A | Unknown |
| Induction Furnace | 1 | ∼0 | ∼0 | Unknown |
| Elec Arc Furnace | 12.6 | 1–38 | ∼0 | 0.06–0.30 |
| Coke-fired Cupola | 13.8 | 146 | 1.25+ | Unknown |

*Note*: Does not include emissions from electricity generation or fuel extraction.

**Table 3** Energy Requirements at the Foundry in MBtu/ton Saleable Cast Material for Foundry Furnaces

| Fuel Source | Furnace Type | MBtu/ton |
|---|---|---|
| Fuel-fired | Crucible | 1.8–6.8 |
| | Reverberatory | 2.5–5.0 |
| | Cupola (coke) | 5.8 |
| | Cupola (NG) | 1.6 |
| Electric | Induction | 4.3–4.8 |
| | Electric arc | 4.3–5.2 |
| | Reverberatory | 5.2–7.9 |
| | Cupola | 1.1 |

*Cleaning.* Cleaning the product can involve the use of organic solvents, abrasives, pressurized water, or acids, often followed by protective coatings. Techniques used to remove sand and flashing include vibrating, wire-brushing, blast cleaning band saws, cutoff wheels, and grinders.

*Removing Sprues, Runners, and Flashing.* Although particle, HAP, and effluent pollutants are created in this stage, they are largely contained by filters and closed systems.

*Sand Reclamation.* Up to 90 percent of molding sand can be reused in a green sand foundry after filtration for fine dust and metal particles. Sand with chemical binders can be used only in small quantities, however. Sand that is not reused is sometimes used in road bases and asphalt concrete.[3] In the United States, from 7 to 8 million tons of mold sand (about 0.5 tons of sand/ton of cast metal) per year ends up in landfills. Spent sand makes up almost 70 percent of foundry solid wastes,[4] AIS, 1999.

From an environmental perspective, the foundry industry has improved remarkably in recent years. U.S. and off-shore foundries have been forced by both legislation and automakers to reduce their pollutants and waste streams—hence, the positive influence of manufacturers (automakers) on tier I suppliers (foundries). Foundries are relying more on electric and natural gas furnaces, thereby reducing the amount of input energy required and minimizing the amount of pollutants. Sand reclamation and use of spent sand for other purposes reduces the impact on landfills. The recent use of trimming presses helps to eliminate the need to grind parts to remove gates and sprues. One of the areas that could benefit from continued research is the development of benign binders for core and mold making processes. Redesigning parts to eliminate cores would also be helpful.

Another environmental concern for the sand casting process is the generation of waste from the machining of cast metal parts. Machining allowances are required in many cases because of unavoidable surface impurities, warpage, and surface variations. Average machining allowances are given in Table 4. Good practice dictates use of the minimum section thickness compatible with the design. The normal section recommended for various metals is shown in Table 5 (see Zohdi and Biles, 2006).

### *Die Casting*

Die casting may be classified as a permanent-mold casting system. However, it differs from the process just described in that molten metal is forced into the mold or die under high pressure (1000–30,000 psi [6.89–206.8 MPa]). The metal solidifies rapidly (within a fraction of a second) because the die is water-cooled. Upon solidification, the die is opened. Ejector pins automatically eject the casting from the die. If the parts are small, several of them may be made at one time in what is termed a *multicavity die*.

There are two main types of machines used: the hot-chamber and the cold-chamber types.

*Hot-Chamber Die Casting.* In the hot-chamber machine, the metal is kept in a heated holding pot. As the plunger descends, the required amount of alloy is automatically forced into the die. As the piston retracts, the cylinder is again filled with the right amount of molten metal. Metals such as aluminum, magnesium,

**Table 4** Machining Allowances for Sand Castings (in./ft.)

| Metal | Casting Size | Finish Allowance |
|---|---|---|
| Cast irons | Up to 12 in. | 3/32 |
| | 13–24 in. | 1/8 |
| | 25–42 in. | 3/16 |
| | 43–60 in. | 1/4 |
| | 61–80 in. | 5/16 |
| | 81–120 in. | 3/8 |
| Cast Steels | Up to 12 in. | 1/8 |
| | 13–24 in. | 3/16 |
| | 25–42 in. | 5/16 |
| | 43–60 in. | 3/8 |
| | 61–80 in. | 7/16 |
| | 81–120 in. | 1/2 |
| Malleable irons | Up to 8 in. | 1/16 |
| | 9–12 in. | 3/32 |
| | 13–24 in. | 1/8 |
| | 25–36 in. | 3/16 |
| Nonferrous metals | Up to 12 in. | 1/16 |
| | 13–24 in. | 1/8 |
| | 25–36 in. | 5/32 |

**Table 5** Minimum Sections for Sand Castings (in./ft.)

| Metal | Section |
|---|---|
| Aluminum alloys | 3/16 |
| Copper alloys | 3/32 |
| Gray irons | 1/8 |
| Magnesium alloys | 5/32 |
| Malleable irons | 1/8 |
| Steels | 1/4 |
| White irons | 1/8 |

and copper tend to alloy with the steel plunger and cannot be used in the hot chamber.

*Cold-Chamber Die Casting.* This process gets its name from the fact that the metal is ladled into the cold chamber for each shot. This procedure is necessary to keep the molten-metal contact time with the steel cylinder to a minimum. Iron pickup is prevented, as is freezing of the plunger in the cylinder.

*Advantages and Limitations.* Die-casting machines can produce large quantities of parts with close tolerances and smooth surfaces. The size is limited only by the capacity of the machine. Most die castings are limited to about 75 pounds (34 kg) of zinc; 65 pounds (30 kg) of aluminum; and 44 pounds (20 kg) of magnesium. Die casting can provide thinner sections than any other casting process. Wall thicknesses as thin as 0.015 inch (0.38 mm) can be achieved with aluminum in small items. However, a more common range on larger sizes will be 0.105 to 0.180 inch.

Some difficulty is experienced in getting sound castings in the larger capacities. Gases tend to be entrapped, which results in low strength and annoying leaks, causing an air pollution problem. One way to reduce metal sections without sacrificing strength is to add ribs and bosses into the product design. An approach to the porosity problem has been to operate the machine under vacuum.

The surface quality of the casting is dependent on that of the mold. Parts made from new or repolished dies may have a surface roughness of 24 μin. (0.61 μm). A high surface finish means that, in most cases, coatings such as chromeplating, anodizing, and painting may be applied directly. More recently, decorative texture finishes are obtained by photoetching. This technique has been used to simulate woodgrain finishes, as well as textile and leather finishes, and to obtain checkering and crosshatching patterns in the surface finish.

*Investment Casting.* Casting processes in which the pattern is used only once are variously referred to as *lost-wax* or *precision-casting* processes. These involve making a pattern of the desired form out of wax or plastic (usually polystyrene). The expendable pattern may be made by pressing the wax into a split mold or by using an injection-molding machine. The patterns may be gated together so that several parts can be made at once. A metal flask is placed around the assembled patterns, and a refractory mold slurry is poured in to support the patterns and form the cavities. A vibrating table equipped with a vacuum pump is used to eliminate all the air from the mold. Formerly, the standard procedure was to dip the patterns in the slurry several times until a coat was built up. This is called the *investment process*. After the mold material has set and dried, the pattern material is melted and allowed to run out of the mold.

The completed flasks are heated slowly to dry the mold and to melt out the wax, plastic, or whatever pattern material was used. When the molds have reached a temperature of 100°F (37.8°C), they are ready for pouring. Vacuum may be applied to the flasks to ensure complete filling of the mold cavities. When the metal has cooled, the investment material is removed by vibrating hammers or by tumbling. As with other castings, the gates and risers are cut off and ground down.

*Ceramic Process.* The ceramic process is somewhat similar to the investment casting in that a creamy, ceramic slurry is poured over a pattern. In this case, however, the pattern, made out of plastic, plaster, wood, metal, or rubber, is reusable. The slurry hardens on the pattern almost immediately and becomes a strong green ceramic of the consistency of vulcanized rubber. It is lifted off the pattern, while it is still in the rubberlike phase. The mold is ignited with a torch to burn off the volatile portion of the mix. It is then put in a furnace and baked at 1,800°F (982°C), resulting in a rigid refractory mold. The mold can be poured while still hot.

*Full-mold Casting.* Full-mold casting may be considered a cross between conventional sand casting and the investment technique of using lost wax. In this case, instead of a conventional pattern of wood, metals, or plaster, a polystyrene foam or Styrofoam is used. The pattern is left in the mold and is vaporized by the molten metal as it rises in the mold during pouring. Before molding, the pattern is usually coated with a zirconite wash in an alcohol vehicle. The wash produces a relatively tough skin separating the metal from the sand during pouring and cooling. Conventional boundry sand is used in backing up the mold.

## 4.3 Metal-forming Processes

Metal-forming processes use a remarkable property of metals—their ability to flow plastically in the solid state without concurrent deterioration of properties. Moreover, by simply moving the metal to the desired shape, there is little or no waste. Figure 4 shows some of the metal-forming processes. Metal-forming processes are classified into two categories: hot-working processes and cold-working processes.

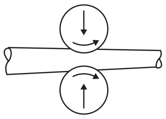
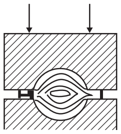
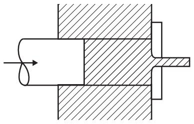
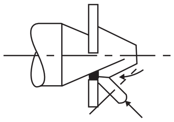
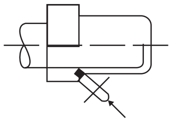
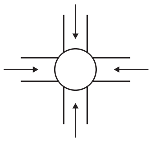
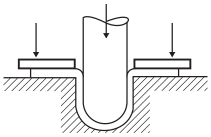
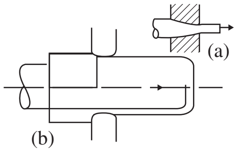
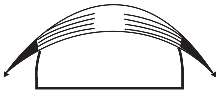
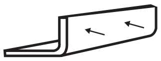
| Process | Schematic Diagram |
|---|---|
| Rolling |  |
| Forging |  |
| Extrusion |  |
| Shear spinning |  |
| Tube spinning |  |
| Swaging or kneading |  |
| Deep drawing |  |
| Wire and tube drawing |  |
| Stretching |  |
| Straight bending |  |

**Figure 4** Several metal-forming processes.

### Hot-Working

*Hot working* is defined as the plastic deformation of metals above their recrystallization temperature. Here it is important to note that the crystallization temperature varies greatly with different materials. Lead and tin are hot worked at room temperature, while steels require temperatures of 2,000°F (1,100°C). Thus, hot working does not necessarily imply high absolute temperatures.

Hot working can produce the following improvements in metal products:

1. Grain structure is randomly oriented and spherically shaped, which results in a net increase not only in the strength but also in ductility and toughness.
2. Inclusions or impurity material in metal are reoriented. The impurity material often distorts and flows along with the metal.
3. This material, however, does not recrystallize with the base metal and often produces a fiber structure. Such a structure clearly has directional properties, being stronger in one direction than in another. Moreover, an impurity originally oriented so as to aid crack movement through the metal is often reoriented into a “crack-arrestor” configuration perpendicular to crack propagation.

### Isothermal Rolling

The ordinary rolling of some high-strength metals, such as titanium and stainless steels, particularly in thicknesses below about 0.15 inch (3.8 mm), is difficult because the heat in the sheet is transferred rapidly to the cold and much more massive rolls. This difficulty has been overcome by *isothermal rolling*. Localized heating is accomplished in the area of deformation by the passage of a large electrical current between the rolls, through the sheet. Reductions up to 90 percent per roll have been achieved. The process usually is restricted to widths below 2 inches (50 mm).

### Forging

Forging is the plastic working of metal by means of localized compressive forces exerted by manual or power hammers, presses, or special forging machines. Various types of forging have been developed to provide great flexibility, making it economically possible to forge a single piece or to mass produce thousands of identical parts. The metal may be: drawn out, increasing its length and decreasing its cross section; upset, increasing the cross section and decreasing the length; or squeezed in closed impression dies to produce multidirectional flow. The state of stress in the work is primarily uniaxial or multiaxial compression. The most common forging processes are as follows:

- Open-die hammer
- Impression-die drop forging
- Press forging
- Upset forging

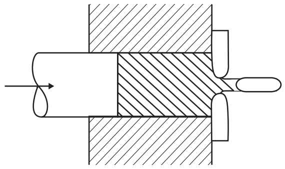


**Figure 5** The metals extrusion process.

- Roll forging
- Swaging

### *Extrusion*

In the extrusion process shown in Figure 5, metal is compressively forced to flow through a suitably shaped die to form a product with a reduced cross-section. Although extrusion may be performed either hot or cold, hot extrusion is employed for many metals to reduce the forces required, to eliminate cold-working effects, and to reduce directional properties. The stress state within the material is triaxial compression.

Lead, copper, aluminum, and magnesium, and alloys of these metals are commonly extruded, taking advantage of the relatively low yield strengths and extrusion temperatures. Steel is more difficult to extrude. Yield strengths are high and the metal has a tendency to weld to the walls of the die and confining chamber under the conditions of high temperature and pressures. With the development and use of phosphate-based and molten glass lubricants, however, substantial quantities of hot steel extrusions are now produced. These lubricants adhere to the billet and prevent metal-to-metal contact throughout the process.

Almost any cross-section shape can be extruded from the nonferrous metals. Hollow shapes can be extruded by several methods. For tubular products, the stationary or moving mandrel process is often employed. For more complex internal cavities, a spider mandrel or torpedo die is used. Obviously, the cost for hollow extrusions is considerably greater than for solid ones, but a wide variety of shapes can be produced that cannot be made by any other process.

### *Drawing*

Drawing, shown in Figure 6, is a process for forming sheet metal between an edge-opposing punch and a die (draw ring) to produce a cup, cone, box, or shell-like part. The work metal is bent over and wrapped around the punch nose. At the same time, the outer portions of the blank move rapidly toward the center of the blank until they flow over the die radius as the blank is drawn into the die cavity by the punch. The radial movement of the metal increases the blank thickness as the metal moves toward the die radius; as the metal flows over the die radius, this thickness decreases because of the tension in the shell wall between the punch nose and the die radius and (in some instances) because of the clearance between the punch and the die.

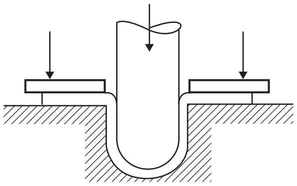


**Figure 6** Deep drawing of a metal part.

## 4.4 Metal Joining Processes

The most common forms of metal joining are welding, soldering, and brazing. Each of these processes has the potential to be environmentally offensive, by generating noxious gases as part of the joining process or by producing metal wastes that must be disposed. Degarmo, Black, Kohser, and Klamecki provide an excellent discussion of these various joining processes (and indeed, any of the manufacturing processes discussed in the chapter).[5] Figure 7 gives the various classifications of welding processes employed in manufacturing.

Welding is the most common metal joining process. The principle classes of welding processes include: (1) gas-flame welding, which utilizes a high-temperature gas to melt selected surfaces of the mating parts; (2) arc-welding processes, which utilize an electric arc to produce molten material between

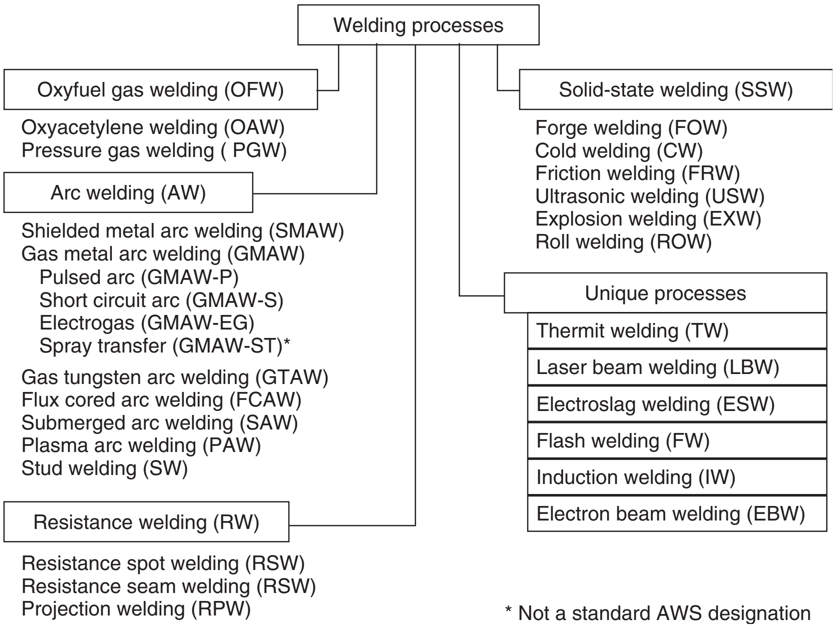


**Figure 7** Classification of several common welding processes.

mating parts; and (3) resistance-welding processes, which utilize both heat and pressure to induce coalescence. Brazing and soldering are utilized when the mating surfaces cannot sustain the high temperatures required for welding mating parts. The ensuing sections give brief discussions of each of these joining processes and describe how environmental offenses can be avoided.

### *Welding Processes.*

As just stated, three of the most common classes of welding processes used in manufacturing are oxyfuel gas welding, arc welding, and resistance welding. The coalescence between two metals requires sufficient proximity and activity between the atoms of the pieces being joined to cause the formation of common crystals.

*Gas-flame Processes.* Oxyfuel gas-welding processes utilize as their heat source the flame produced by the combustion of a fuel gas and oxygen. The combustion of *acetylene* ($C_2H_2$)—commonly known as the oxyacetylene torch—produces temperatures as high as 5850°F (3250°C). Three types of flames can be obtained by varying the oxygen/acetylene ratio: (1) If the ratio is between 1:1 and 1.15:1, all oxygen-acetylene reactions are carried to completion and a *neutral flame* is produced; (2) If the ratio is closer to 1.5:1, an *oxidizing flame* is produced, which is hotter than the neutral flame but similar in appearance; (3) Excess fuel produces a *carburizing flame.*

Almost all oxyfuel gas welding is of the *fusion* type, which means that the metals to be joined are simply melted at the interfacing surfaces and no pressure is required. This process is best suited to steels and other ferrous metals. There is a low heat input to the part, and penetrations are only about 3 mm.

The environmental impacts of oxyfuel gas welding include the generation of combustion products, which have to be *scrubbed* before release to the atmosphere, and the production of slag and waste metal that must be safely disposed.

*Arc-welding Processes.* Arc-welding processes employ the basic circuit shown in Figure 8. Welding currents typically vary from 100 to 1000 amps, with voltages in the range from 20 to 50 volts.

In one type of arc-welding process, the electrode is consumed and thus supplies the molten metal. A second process utilizes a nonconsumable tungsten electrode, which requires a separate metal wire to supply the molten metal. Filler materials must be selected to be compatible with the mating surfaces being welded. In applications where a close fit is required between mating parts, gas-tungsten arc welding can produce high-quality, nearly invisible welds.

In *plasma arc welding* an arc is maintained between a nonconsumable electrode and the workpiece in such a way as to force the arc to be contained within a small-diameter nozzle, with an inert gas forced through the stricture. Plasma-arc welding is characterized by extremely high (30,000°F) temperatures, which offers very high welding speeds and hence high production rates.

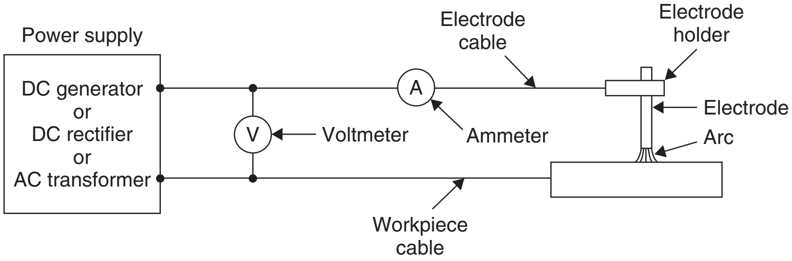


**Figure 8** Basic circuit for the arc-welding process.

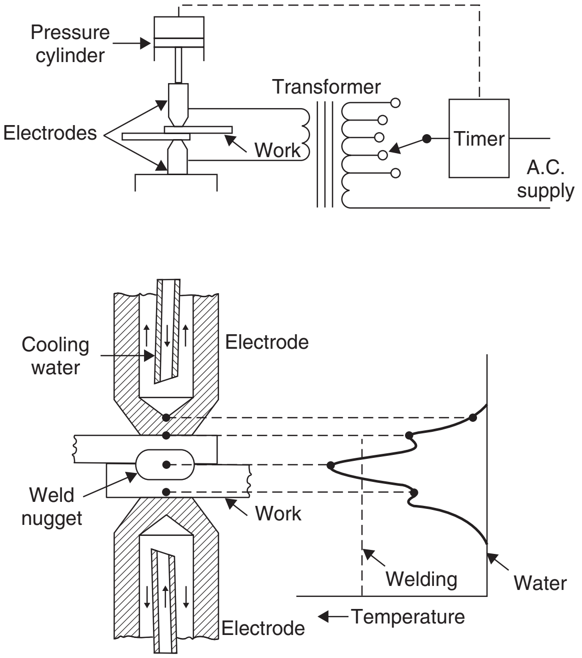


**Figure 9** A typical resistance-welding circuit and configuration.

The environmental impacts of arc-welding processes include the generation of metal waste and the requirement for relatively high power.

*Resistance Welding Processes.* In *resistance welding,* both heat and mechanical pressure are used to induce coalescence. Electrodes are placed in contact with the material, and electrical resistance heating is utilized to raise the temperatures of the workpieces and the space between them. These same electrodes also supply the mechanical pressure that holds the workpieces in contact. When the desired temperature has been achieved, the pressure exerted by the electrode is increased to induce coalescence. Figure 9 illustrates a typical resistance welding circuit. It is important to note that the workpieces actually form part of the electrical circuit, and that the total resistance between the electrodes consists of three distinct components: (1) the resistance of the workpieces; (2) the contact resistance between the electrodes and the workpieces; and (3) the resistance between the surfaces to be joined.

The most important environmental consideration in resistance welding is the electrical power consumed.

*Electron-Beam Welding.* *Electron-beam welding* is a fusion welding process which utilizes the heating resulting from the impingement of a beam of high-velocity electrons on the metal parts to be welded. The electron optical system for the electron-beam welding process is shown in Figure 10. An electrical current heats a tungsten filament to about 4,000°F, causing it to emit a stream of electrons by *thermal emission*. Focusing coils are employed to concentrate the electrons into a beam, accelerate them, and direct them to a focused spot that is

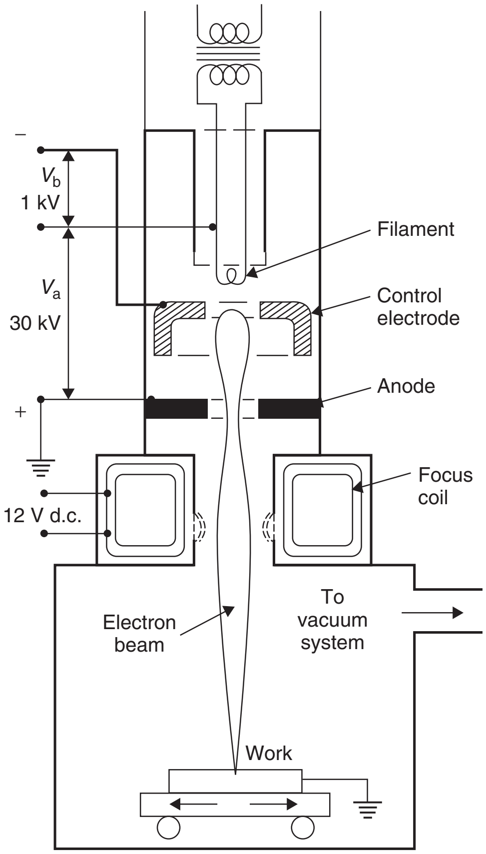


**Figure 10** Schematic diagram for the electron-beam welding process.

between 0.8 and 3.2 mm in diameter. Since the electrons, which are accelerated at 150 kV, achieve velocities near two-thirds the speed of light, intense heat is generated. Since the beam is composed of charged particles, it can be positioned by electromagnetic lenses. To be effective as a welding heat source, the electron beam must be generated and focused in a high vacuum, typically at pressures as low as 0.01 Pa.

Almost any metal can be welded by the electron-beam process, including those that are very difficult to weld by any other process, including tungsten, zirconium, and beryllium. Heat-sensitive metals can be welded without damage to the base metal.

From an environmental standpoint, the absence of shielding gases, fluxes, or filler materials means that the waste material produced by the process is negligible. Only the high power requirements stand as a problem.

***Brazing and Soldering.***

*Brazing* is the permanent joining of similar or dissimilar metals through the application of heat and a filler material. Filler metals melt at temperatures as low as 800°F, typically much lower than those of the base metals, which makes brazing a useful joining process for dissimilar metals (ferrous to nonferrous metals, metals with different melting points, or even metal to ceramic). Strong permanent joints are formed by brazing.

*Soldering* is a type of brazing operation in which the filler material has a melting temperature below 850°F. It is typically used for connecting thin metal pieces, connecting electronic components, joining metals while avoiding high temperatures, and filling surface flaws and defects in metal parts. Soldering can be used to join a wide variety of shapes, sizes, and thicknesses, and is widely used to provide electrical coupling or airtight seals. The primary means of heating the filler material is to apply an electrically heated iron rod to melt the filler metal and position it in the proper location on the workpiece. Soldering filler materials are typically low melting temperature metals such as lead, tin, bismuth, indium, cadmium, silver, gold, and germanium. Because of their low cost and favorable properties, alloys of tin and lead are most commonly used.

The environmental impacts of brazing and soldering trace to the filler materials used in their application. Since 1988, the use of lead and lead alloys in drinking water lines has been prohibited in the United States. Japan and the European Union prohibit the use of lead in electronic applications.

## 4.5 Plastic Injection Molding

The injection-molding process involves the rapid pressure filling of a shape-specific mold cavity with a fluid plastic material, followed by the solidification of the material into a product. The process is used for thermoplastics, thermosetting resins, and rubbers.

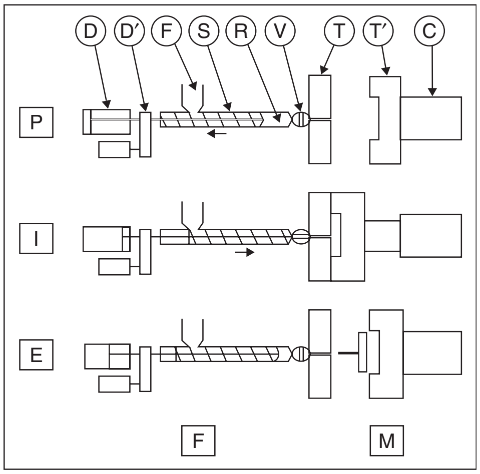


Figure 11 The principle of injection molding. (From Ref. 6.)

### *Principle of Injection Molding*

The injection molding of thermoplastics can be subdivided into several stages as illustrated in Figure 11. At the plastication stage P, the feed unit F operates in much the same way as an extruder, melting and homogenizing the material in the screw/barrel system. The screw, however, is allowed to retract, to make room for the molten material in a space at the cylinder head, referred to here as the material *reservoir*, between the screw tip and a closed valve or an obstruction of solidified material from the previous shot. At the injection stage I, the screw is used as a ram (piston) for the rapid transfer of the molten material from the reservoir to the cavity between the two halves (T and T′) of the closed mold. Since the mold is kept at a temperature below the solidification temperature of the material, it is essential to inject the molten material rapidly to ensure complete filling of the cavity. A high holding or packing pressure (10,000 to 30,000 psi) is normally exerted to partially compensate for the thermal contraction (shrinkage) of the material upon cooling. The cooling of the material in the mold is often the limiting time factor in injection molding because of the low thermal conductivity of polymers. After the cooling stage, the mold can be opened and the solid product removed.

### *Equipment*

Injection molding machines are now most commonly of the reciprocating screw type, as illustrated in Figure 12. Two distinct units, referred to as the feed unit F and the mold unit M, are mounted on a frame (F′). The feed unit F consists of the plastication/injection cylinder (screw, barrel, and feed hopper), the axial screw drive, and the rotation screw drive.

Although injection-molding machines may occasionally be dedicated to the molding of a single product, a machine is normally used with a variety of tools

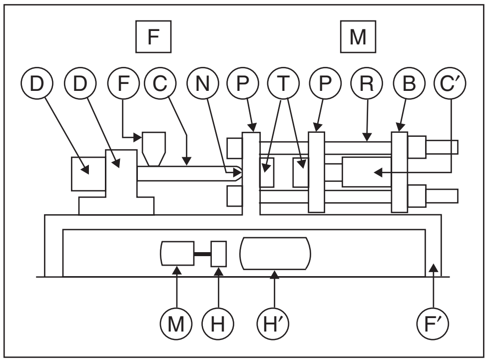


**Figure 12** The injection molding machine. (From Ref. 6.)

(molds), which may imply frequent mold changes and the associated costly set-up period. Injection-molding machines are available in a broad range of sizes. They are normally rated by their maximum clamping force, with normal ranges from about 25 to 150 tons for "small" machines, 150 to 70 tons for "medium-sized" machines, and 750 to 5,000 tons for "large" machines; the current maximum is 10,000 tons.

### *Tooling*

The interchangeable injection-molding tool, the *mold*, must (1) provide a cavity corresponding to the geometry of the product and (2) allow the ejection of the product after its solidification. Primary mold opening is achieved by fastening one-half of the mold to the stationary platen (T), as shown in Figure 12, and the other half to the moving platen (T′). The stationary mold half is sometimes referred to as the *front, cavity,* or *negative block*, and the moving mold half as the *rear, force*, or *positive block*. The removal of a product from a cavity surface requires, in addition to an ejection system, a suitable surface finish and an appropriate taper or draft. It need not require a mold release agent.

During injection, the material flows from the nozzle at the tip of the injection unit to the single cavity, or to each of several cavities, through what is referred to here as the *feed system*, generally comprising sprues, runners, and gates. In most cases, injection-molded products need to be removed from one mold half by an ejection (knockout, stripping) device. This device is normally incorporated in the moving mold half. Retractable secondary mold sections may be required when products feature undercuts, reentrant shapes, internal or external threads, and so on.

Runners are machined in mold halves, next to the parting surface. One solution, applicable to chemically stable thermoplastics, consists of having large runners cooled in such a way that a sleeve of insulating solid plastic forms around a molten core, where the intermittent injection flow takes place; this method is referred to as *insulated* or *Canadian* runner molding. Another solution, referred to as *hot runner molding*, involves a heated runner, or manifold block, and is often used in conjunction with valve gating. *Gates* serve several purposes in injection molding. Their easily altered, smaller cross-section permits a convenient control of the flow of the molten material, the rapid freezing of the material to shut off the cavity after injection, and the easy separation of the products from the feed appendage (de-gating). Important savings can be made by using hot runners.

The maximum pressure in injection molds is normally in the range of 4,000 to 12,000 psi corresponding to a clamping force per unit projected area of cavity and feed system in the range of 2–6 tons/square inch. The construction of injection molds requires materials with a combination of good thermal conductivity and resistance to mechanical wear and abrasion. Prototype molds can be cast from low-melting alloys. For short-run molds (about 10,000 to 100,000 moldings), tool steel is normally used. Long runs involving millions of moldings require special hardened and chrome-plated steels.

A variety of techniques are used to form mold cavities: machining of a solid block, computer-aided machining (CAM) centers, hobbing (cold forming), electrochemical machining (ECM), electrical discharge machining (EDM), or spark erosion, electroforming, plating, and etching. For short runs—fewer than 10,000 parts—a mold cavity can be fabricated using a selective-laser-sintering rapid prototyping process to build a copper-infiltrated iron part.

### *Auxiliaries*

Many thermoplastic resins require thorough drying prior to molding, to avoid the formation of voids or a degradation of the material at molding temperatures. Mold temperature control is often achieved by the circulation of a fluid through a separate heater/chiller device. With increased interest in automation, robots have been introduced for the removal of products and feed appendages from open molds, and for separation (degating) and sorting. Feed appendages, startup scrap, and occasional production scrap are normally reground in granulators and recycled as a fraction of the feed material.

### *Materials*

All thermoplastics are, in principle, suitable for injection molding, but since fast flow rates are needed, grades with good fluidity (high melt index) are normally preferable.

### *Products*

A major advantage of injection-molded products is the incorporation of fine details such as bosses, locating pins, mounting holes, bushings, ribs, flanges, and so on, which normally eliminates assembly and finishing operations. Thermosetting resin systems, such as phenolics (PF); or unsaturated polyester (UP), often used with fillers or reinforcements, are increasingly injection molded at relatively high speeds. Curing, which involves chemical reactions, takes generally much longer than the injection, and multimold machines are thus often used with shuttle or rotary systems. Injection molding is increasingly used for producing relatively small rubber products significantly faster than by compression molding and, normally, with a smaller amount of scrap and a better dimensional accuracy. As in the case of thermosetting resins, a heated mold is needed for vulcanization (curing).

### *Environmental Analysis of Injection Molding Processes*

Plastic components are major parts in electrical and electronic (E&E) products. About 8.5 percent of the plastic parts produced are for these products. Large number of plastic parts used for automobile industry. Some 33 percent of all small house appliances incorporate plastic components, and about 42 percent of all plastic materials are used in the manufacture of toys.

This environmental analysis of injection molding highlights a few important points. The type of injection molding machine (hydraulic, hybrid, or electric) has a large impact on energy consumption. Table 6 shows the energy related emissions for the injection molding process, including the compounder stage. Table 7 gives the total annual production of injection molded plastics. Table 8 gives the total annual energy consumption associated with the production of injection molded plastics. The impact of injection molding on the environment may seem benign, but it can be significant. We must take into consideration energy consumption, manufacturing process, and raw material usage. The product life cycle is important because it affects the production, energy, and raw material. The majority of plastic parts that are used in electrical and electronic products are parts made through the injection-molding process. Injection molding involves melting polymer resin together with additives and then injecting the melt into the mold to make the final products. This process may have an impact on the environment, but we have to reduce the effect of this process and make it benign as much as possible.

**Table 6** Energy-related Air Emissions for the Compounder Stage and the Injection Molder Stage

| | | Energy Related Emissions | | | | |
|---|---|---|---|---|---|---|
| Stage | SEC (MJ/Kg) | $CO_2$ g | $SO_2$ g | $NO_x$ g | $CH_4$ g | Hg mg |
| Compounder | 5.51 | 284.25 | 1.26 | 0.51 | 10.32 | 0.01 |
| Injection molder | | | | | | |
| Hydraulic | 13.08 | 674.82 | 2.98 | 1.22 | 24.29 | 0.01 |
| Hybrid | 7.35 | 379.33 | 1.68 | 0.68 | 13.77 | 0.01 |
| All-electric | 6.68 | 344.57 | 1.52 | 0.62 | 12.50 | 0.01 |

**Table 7** Injection-molded Polymer Totals in kg/year

| | Injection Molded—Million kg/yr | |
|---|---|---|
| | U.S. Only | Global |
| Six main thermoplastics | 5,571 | 23,899 |
| All plastics | 12,031 | 38,961 |

*Note*: The subdivision "6 main thermoplastics" refers to HDPE, LDPE, LLDPE, PP, PS and PVC.

**Table 8** Total Energy Used in Injection Molding

| Compounder and Injection Molder | U.S. GJ/year | Global GJ/year |
|---|---|---|
| Six main thermoplastics | 9.34E + 07 | 4.01E + 08 |
| All plastics | 2.06E + 08 | 6.68E + 08 |

*Note:* The subdivision "6 main thermoplastics" refers to HDPE, LDPE, LLDPE, PP, PS and PVC.

Injection molding is used primarily to produce plastic parts with specific geometrics. The process starts by mixing polymer resin with additives that are specific to the part to gain desired properties such as increased strength. The mix of polymer resin and additives is also combined with colorants if needed at this point and is stored in a hopper. The material is gravity fed into a feeding tube that has screws to push material forward. When in the screws, the material is melted and mixed. The material is fed into the die that will shape the material to the desired part. During the fill stage, hydraulic clamps hold the two ends of the die together until all the necessary material has entered the die and cooled to the desired temperature for removal. Then the clamps release the part and it is removed from the die.

### *Life Cycle of a Plastic Product*

When tracing the life cycle of the process to the beginning we need to look at how the polymer pellets are manufactured. In injection molding the overall process starts at production stage. This stage takes raw materials from the earth and transforms them with addition of energy into polymers. The raw polymer is shipped in bulk to the compounder, which mixes it with additives in order to give it required properties for application. The polymer is shipped to the injection molder, which transforms the polymer into finished products. The injection molder might add some additives in the process, such as coloring. After being injection molded and packaged, the product is ready for the consumer. When trying to develop the polymer resin used in the injection mold process, the manufacturer uses large amounts of petroleum, and large energy costs are associated with the production of the material. The additives added to the polymer base can be hazardous in large concentrations. The majority of the byproducts to the process can be hazardous and are not biodegradable.

*Environmental Impact of Plastics Injection Molding.* When considering the life cycle of a plastic-based product, it is important to understand the emissions that come from the polymer production stage. The emissions can be divided into energy-related emission and processing emission. Processing emission at the site is small compare to energy-related ones. It should be noted that plastics don't break down in landfills. Two solutions have been used over the last few years. The first is to burn the plastic that leads to toxic material into the air. This method is most commonly used today because plastics are petroleum based and have high heating properties. Countries like Japan and England have laws limiting the amount of petroleum-based products that can be incinerated and are moving toward more methods that recycle the product. Due to this trend, more effort is placed in the design phase of projects to ensure the correct mixture of recycled plastics, new polymer material, and additives for product performance. The second method is to recycle the plastic and make it into other products. This second solution can be used only for one of the two types of plastics. Thermoplastics can be melted, while thermoset plastics cannot be melted and have to be scrapped if a product is defective or at its end-of-life cycle. One area that has large opportunity for recycling is the plastic in automobiles. Current U.S. methods of recycling cars focus only on reusing the metal components. The plastic products are considered scrap and sent to landfills.

If we compare injection molding to other conventional manufacturing processes, injection molding appears to be on the same order of magnitude in term of energy consumption. For example, of processes such as sand and die casting have similar energy requirements (11–15 MJ/kg). However, when compared to processes used in the semiconductor industry, the impact of injection molding seems significant. But in order to understand this point, we have to understand the product's widespread effect on the economy. Injection-molding processes are more widely used and are growing in countries like China and India.

Although waste material is low and low levels of coolant are used in the process, the amount of energy used in the process has resulted in the research and development of ways to make the process more benign. It is critical to continue to improve the efficiency of the process in order to reduce the impact on the environment. It is essential to make a process that uses less energy, especially at this time when energy prices continue to rise.

## 5 THE MANUFACTURED PRODUCT

Most of the discussion in this chapter has focused on ways to ensure that manufacturing processes are environmentally benign. Any company that is morally and ethically committed to the goals of environmentally benign manufacturing cannot scrutinize its manufacturing processes without first giving due consideration to the manufactured product itself. It could legitimately be argued that the energy expenditure of certain products will easily surpass any savings in environmental impact achieved through optimally designed manufacturing processes very early in the product life cycle. An example is the large gas-guzzling truck or automobile, which is manufactured with the quaint notion of "bowing to customer demand" for large vehicles despite their poor fuel mileage performance.

It is curious, though, that a considerable marketing budget is expended to cultivate this customer demand. It is also curious that an automobile manufacturer recently withdrew from the marketplace a plug-in, all-electric vehicle that had managed to gain a great deal of approval from its customers. Yet, manufacturers offer the excuse that they cannot act unilaterally without suffering competitively in the marketplace. Lawmakers, too, are prone to succumb to the notion that "people should be free to buy the products they want." Where does that leave the premise, or promise, of environmentally benign manufacturing? And where does that leave future generations, who are predestined to live in the environment we leave them?

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