Pollution Prevention in Machining and Metal Fabrication

A Manual for Technical Assistance Providers

Excerpts

March 2001

CHAPTER 1
Overview of Metal Fabrication Industry

Background

Everywhere we look, we see fabricated metal products. From paper clips to HVAC housings, from car bodies to spiral stair cases, countless products start out as metal stock that fabricators bend, punch, drill, grind, thread, and cut to produce various shapes. The metal fabrication process varies greatly depending on the material being machined, the rate of production, the desired geometry, and other physical requirements of the part or product.

The metal fabrication[1] industry also varies greatly in the size, type, and distribution of facilities found in different states throughout the United States. For example, metal fabrication facilities in the Northeast are usually small-to-medium sized with older equipment, and the key products they manufacture are bearings, fire arms, aerospace, automotive, machine and perishable tools, electrical components, and wire and cable (U.S. EPA 1995). Table 1.1 lists the number of fabricated metal product and machinery manufacturers in the U.S.

States with the largest number of metal fabrication plants are New York, Ohio, Pennsylvania, Michigan, Illinois, Texas, and California. Throughout the U.S., fabricators use 175 million gallons of metalworking fluids, valued at $800 million, and accounting for 15 percent of the overall value of sales of industrial oils. Worldwide global annual metalworking fluid consumption is more than 600 million gallons (Glenn, 1998).

There are a variety of processes involved in the manufacture of complex metal parts including: casting, shaping, metal removal, coating, finishing, heat treating, welding, soldering, brazing, and adhesive joining. This Chapter discusses the processes involved in metal shaping and removal and provides in-depth background on the properties and types of metalworking fluids. This Chapter also includes an overview of heat treating, brazing and soldering, adhesive joining, welding, tumbling, buffing, polishing, and honing.

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[1]Metal fabrication, as it is referred to in this manual, is any process that changes the geometry of a metal workpiece by deforming it or removing metal from it. Other processes covered in this manual are metal and surface treating, such as heat treating and case hardening, as well as metal joining processes, such as welding and soldering. Although the manufacturing of metal parts may involve other processes including plating, coating, and casting, these processes will not be covered in this manual because they were covered in earlier manuals in this series, specifically *Pollution Prevention for the Metal Finishing Industry*, *Pollution Prevention for the Metal Coatings Industry*, and, *Pollution Prevention for the Primary Metals Industry*, available online at http://www.newmoa.org/publications/.

Table 1.1. Number of Fabricated Metal Product and Machinery Manufacturers by State[2]

State	NAICS 332	NAICS 333	Total	State	NAICS 332	NAICS 333	Total
Alabama	986	293	1,279	Montana	122	47	169
Alaska	49		49	Nebraska	276	205	481
Arizona	835	316	1,151	Nevada	254	86	340
Arkansas	498	254	752	New	454	206	660
California	8,127	3,112	11,239	New Jersey	1,806	915	2,721
Colorado	798	363	1,161	New Mexico	234	59	293
Connecticut	904	520	1,424	New York	2,771	1,315	4,086
Delaware	102	32	134	North	1,483	757	2,240
Florida	1,998	957	2,955	North Dakota	85	86	171
Georgia	1,114	555	1,669	Ohio	4,332	2,260	6,592
Hawaii	46		46	Oklahoma	969	430	1,399
Idaho	232	129	361	Oregon	929	437	1,366
Illinois	3,782	2202	5,984	Pennsylvania	3,185	1,531	4,716
Indiana	1,897	1,064	2,961	Rhode Island	440	176	616
Iowa	594	443	1,037	South	722	360	1,082
Kansas	1,391	347	1,738	South Dakota	115	93	208
Kentucky	729	370	1,099	Tennessee	1,146	547	1,693
Louisiana	671	226	897	Texas	4,359	1,726	6,085
Maine	241	96	337	Utah	459	164	623
Maryland	510	166	676	Vermont	25		25
Massachusetts	1,762	833	2,595	Virginia	768	348	1,116
Michigan	3,788	2,849	6,637	Washington	1,184	503	1,687
Minnesota	1,536	904	2,440	West Virginia	274	98	372
Mississippi	386	185	571	Wisconsin	1,968	1,258	3,226
Missouri	1,168	579	1,747	Wyoming	82	33	115
United States					62,501	30,665	93,166

Metal Shaping and Removal Processes

Metal Shaping Processes

In metal shaping, stock is formed into its desired geometries through the application of mechanical force. Forming processes are non-chip making processes and may or may not use fluids depending on the severity of the application. Fluids are the primary source of waste in metal shaping processes. Table 1.2 lists some of the characteristics of various forming processes, including the types of stock in use and the shapes that are produced.

Figure withheld due to copyright restrictions.

Figure 1.1 *Profiles Attainable with Roll Forming*

[2]The data for this table are taken from the 1997 U.S. Economic Census Report for the North American Industry Classification System (NAICS) three digit subsector codes 332 and 333. NAICS 332 is the subsector for fabricated metal product manufacturing. This subsector includes industries that transform metal into intermediate or end products. It does not include machinery, computers and electronics, metal furniture, or the treating of metals and metal formed products fabricated elsewhere. NAICS 333 is the three digit classification for machinery manufacturing. This subsector includes industries that create products that apply mechanical force.

Table 1.2 Characteristics of Forming Processes (Goetsch 1991)

Process	Characteristics
Bending & Straightening	• sheet and plate bending • types: straight, flange, contour, and stretch • stressing metal beyond its yield strength, but not beyond its ultimate tensile strength
Roll Forming	• sheet, strip, or coil stock • stock 0.0005 to 3/4" thick by 0.125 to 72" wide • any material that can withstand bending to desired radius • forms any shape that the metal can withstand the bend radius
Spinning	• chipless process of forming axially symmetrical shapes • metal disks, cylindrical workpiece, or preform • stock 1/4" to 26' in diameter, up to 3" in thickness • forms shapes such as cones, hemisphere, tubes, and cylinders
Shearing	• larger sheets cut into smaller lengths • crosshead may be manual, mechanical, hydraulic, or pneumatic • shear types: gapless, gap, alligator, pivot, ironworkers, cut-off machines, bar-billet, computer numeric control (CNC), or rotary
Punching	• performed on sheet metal • ferrous and nonferrous metals • various shapes of punches
Cold Drawing	• pulling the stock through a die of similar shape, but smaller size • metal bar, rod, tube (to about 12"), or wire stock • bars 1-1/4" and smaller having the same cross-sectional shape throughout, including square, and hexagonal • uses grease, dry soap, oil, or other lubricants • similar shape to stock, but smaller
Hot Extruding	• heated billets[3] forced through one or more dies to form uniform cross sections • types: direct, indirect, and hydrostatic • in hydrostatic, entire billet surrounded by fluid • uniform cross sections along continuous lengths
Warm and Cold Extruding	• process is similar to hot extruding • performed on slugs of most steels, nonferrous metals, and superalloys • types: backward, forward, radial, combination, impact, and continuous • for warm extruding, requires more heat resistant lubricants and tools • used for large, hollow extrusions that were formerly formed by tubing (e.g., wheel spindles and axles)
Swaging	• solid or tubular stock, ranging in diameter from 0.5 mm to 150 mm • formed by delivering rapid series of impact blows • applications: tapering, reducing, pointing, external and internal forming, compacting, sizing, and assembling
Hot Forging	• plastic deformation of working metal by pressure or impact blows, or both • types: open-die forging and impression-die forging • stock may range in size from 30-1000 pounds
Specialty Forming	• types: explosive forming, electrohydraulic forming, electromagnetic forming, high-velocity forging, peen[4] forging, and ultrasonic-activated forming

[3]A billet is a bar of metal.

[4]Peening means to draw, bend, or flatten by or as if by hammering, usually with a hemispherical or wedge-shaped end of the head of a hammer that is opposite the face and is used especially for bending, shaping, or cutting the material struck

Metal Removal Processes

In metal removal processes, stock is given its final geometry through the removal of metal from stock by a number of processes including: broaching, sawing, turning, boring, drilling, reaming, milling, and grinding. Fluids are used in these processes to provide lubricity, cooling, chip removal, corrosion resistance, and to prevent built-up edge (BUE)[5] on the tool bit. The type of fluid used is dependant on a number of factors including substrate compatibility, and the amount of lubricity and cooling required. For more information on fluid characteristics, see the Metal Working Fluid Overview later in this chapter. The two typical wastes from metal removal processes are spent metal working fluids and metal scrap. In the following sections more specific information is presented on the metal removal processes listed above including tool types, chip characteristics, and fluids used.

Broaching and Sawing

Broaching

Broaching is a metal removal process that is performed on flat, round, or contoured substrates. The multitoothed cutting tools used in broaching have teeth that are generally higher than the preceding tooth, each removing more material as it passes over the substrate.   The tool material generally used is high-speed steel (HSS); however, tungsten carbide tools bits may be used in high-speed broaching applications or broaching of gray cast iron. A variety of metalworking fluids may be used in broaching, depending on the machining conditions (i.e., speed of cutting, type of material being broached, and design of machine). Broaching may also be performed dry, as fluids are usually not required for planing, shaping, and slotting operations because of the intermittent contact of the blade with the workpiece, and the chips formed generally fall away without the use of fluids.

Power Hacksawing

Power hacksawing is performed using a relatively short, straight blade that is drawn back and forth over the workpiece. Power hacksaws are used extensively as chop saws and in facilities where production requirements are not high. These saws may be used on all sizes of stock and practically all materials.

Bandsawing

Bandsawing uses a continuous band with small teeth that perform one-directional cutting. A variety of fluids may be used in bandsawing, depending largely on the metal being cut. Metalworking fluids are applied to the cutting area and are carried across the cross section of material being cut. Fluid may be applied through the blade guides, or through nozzles, spray mists, pressurized mists, and curtain applicators. Bandsawing is more precise than the other methods and complex cuts are easily achieved. Compared to other sawing methods, bandsawing is more energy-

[5] Built-up edge, or BUE, is the condition of chip material adhering or becoming joined to the tool bit.

and materials-efficient and creates a smaller kerf.[6] The chips that are formed from bandsawing are usually full and uniform.

Figure 1.2 *Broach Tool*

Figure withheld due to copyright restrictions.

Circular Sawing

Circular sawing may be used on billets, forgings, extrusions, bars, tubes, and similar stock, generally five inches in diameter or less. The use of metalworking fluids is recommended for all metals except brass and cast iron. However, fluids are not generally used when using carbide-tipped blades. Fluids are used in circular sawing more to facilitate flow of the chips than for cooling action, and soluble oils and synthetics are used at a relatively rich mix. Circular sawing creates a wider kerf. Chips generally act as heat sinks allowing workpieces to stay cool, thereby reducing the need for fluid cooling.

Turning and Boring

Turning

In turning operations, a workpiece is rotated about its longitudinal axis on a machine tool called a lathe. Material is removed by tools mounted on the lathe to create the desired shape. Turning is performed on surfaces that are concentric with the longitudinal axis of the workpiece. Turning may be performed with or without the use of fluids; however, dry turning is generally only performed on cast iron or short-run applications. A variety of fluids are used in turning operations, depending largely on the material feed rate, tool speed, and workpiece substrate.

[6]Kerf is a slit or notch made by a saw or cutting torch, or the width of a cut made by a saw or cutting torch.

Boring

In this precision metal removal process, internal cylindrical holes are generated using a single-point or multiple-edge cutting tool. Boring may be performed by rotating the tool or the workpiece. Boring may produce long, stringy chips depending on the substrate being bored. A variety of fluids are used in boring operations, depending largely on the material feed rate, tool speed, and workpiece substrate.

Drilling and Reaming

Twist Drills

Drilling is the production or enlarging of holes in a workpiece by the relative motion of a cutting tool. Water-based emulsified oil is the most common metalworking fluid used in these operations. These metalworking fluids minimize friction between the drill and workpiece and reduce friction between the sliding chip and the drill. Because of the limited space involved in drilling, for chips to leave the cutting zone, it is desirable to have small chips form. Coiling of chip material may pack drill flutes, interfering with chip ejection and fluid flow. Hence, more ductile metal may require more complex tool designs and geometries.

Counterboring, Spotfacing, and Countersinking

Enlarging a hole for a limited depth is called counterboring. If the cut is shallow so that it leaves only finished face around the original hole, it is called spotfacing. The cutting of an angular opening into the end of a hole is known as countersinking. A counterbore toolbit usually has straight or helical flutes for the passage of chips or fluids. Speeds and feeds used in counterboring and spotfacing are generally less than those used in drilling. A variety of fluids are used in counterboring, spotfacing, and countersinking operations, depending largely on the material feed rate, tool speed, and workpiece substrate.

Reaming

This process is used for enlarging, smoothing, and/or accurately sizing existing holes by means of a multi-edge fluted cutting tool. Tools used may be bore, carbide, or coolant-fed reamers. Like counterboring, spotfacing, and countersinking, there are a variety of fluids that may be used in reaming depending on feeds, speeds, and substrate.

Milling and Grinding

Milling

Milling involves the removal of metal in small, individual chips made by each milling cutter. In face milling, chip thickness varies from a minimum at the entrance and exit, to a maximum along the horizontal diameter.

Grinding

Grinding is performed through basically the same functions as cutting operations. Fluid is applied to lubricate the chip/grit and grit/workpiece interface, reducing the power required to remove a volume of material and thereby reducing the heat generated. In metal cutting, the energy required to form a chip is about twice that required to overcome friction between the tool/workpiece and chip/workpiece interface. In grinding, the force necessary to overcome friction is approximately the same as that required for chip formation, therefore lubrication is critical from a standpoint of power, wheel life, surface finish, heat development, and possible surface damage.

Nontraditional Machining

The category of nontraditional machining covers a broad range of technologies, including some that are used on a large scale, and others that are only used in unique or proprietary applications. These machining methods generally have higher energy requirements and slower throughputs than traditional machining, but have been developed for applications where traditional machining methods were impractical, incapable, or uneconomical. An added benefit of these techniques is that there is little to no localized damage such as cracks, residual stresses, recrystallization, or plastic deformation (Goetsch 1991). Although nontraditional machining methods are not widely used, some have inherent P2 benefits. Nontraditional machining methods are typically divided into the following categories: mechanical, electrical, thermal, and chemical processes. Table 1.3 lists the categories and specific types of nontraditional machining.

Figure 1.3 *Schematic of Electrochemical Machining (ECM)*

Figure withheld due to copyright restrictions.

Table 1.3 Nontraditional Machining Processes

Category	Processes
Mechanical	• Ultrasonic Machining (USM) • Rotary Ultrasonic Machining (RUM) • Ultrasonically Assisted Machining (UAM)
Electrical	• Electrochemical Discharge Grinding (ECDG) • Electrochemical Grinding (ECG) • Electrochemical Honing (ECH) • Hone-Forming (HF) • Electrochemical Machining (ECM) • Electrochemical Turning (ECT) • Shaped Tube Electrolytic Machining (Stem™) • Electro-Stream™ (ES)
Thermal	• Electron Beam Machining (EBM) • Electrical Discharge Machining (EDM) • Electrical Discharge Wire Cutting (EDWC) • Electrical Discharge Grinding (EDG) • Laser Beam Machining (LBM)
Chemical	• Chemical Milling • Photochemical Machining

Electrical discharge machining and laser beam machining are discussed further in Chapter 5, Innovative Pollution Prevention Technologies.

Metalworking Fluid Overview

Metalworking fluids perform numerous functions in metal fabrication processes. Fluids can:

- provide cooling for the workpiece and tool
- remove chips from the cutting zone
- provide lubrication between the tool and the workpiece
- prevent corrosion of the workpiece and tool, and
- prevent built-up edge (BUE)

This Section will cover tool and workpiece cooling, chip removal, lubrication, the classifications used for fluids, and the types of fluid components.

Tool and Workpiece Cooling

Metalworking fluids provide cooling action to the workpiece and the tool. This prevents thermal damage to the workpiece, minimizes thermal stressing and brittle hardening of the tool bit, and prevents BUE. Fluids help to reduce these problems by absorbing heat through convection and by reducing the frictional forces, thereby reducing the force and energy requirements and heat generation (Kalpakjian 1992). In place of fluids for cooling, some operations may use pressurized air, a combination of pressurized air and fluid, or other means. For more information on machining without using fluids, see Chapter 5, Dry Machining.

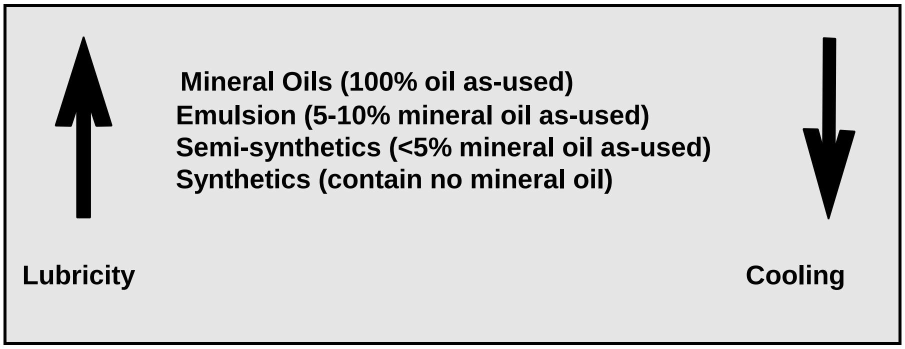
Chip Removal

Chips that are formed during chip-making processes can have a tendency to build up in the cutting area and cause undue stress on the machine tool. Fluids are used to flush chips out of the work zone. The amount of fluid necessary to perform this function is dependant on the chip formation characteristics of the given application. Some processes may be modified to use alternative means of chip removal, such as compressed air or compressed air combined with fluid mist application, which are equally successful at removing chips from the work zone without the use of excessive amounts of fluids and the subsequent waste generation. In other cases, retooling may be performed to modify chip formation and ejection to prevent chips from building up on the tool or in the work zone. Additionally, some substrates may be surface treated to modify the chip making characteristics, allowing the chips to break away and exit the cutting area. For more information on alternatives to fluid for chip removal, see Chapter 5, Dry Machining.

Lubrication

The amount of lubrication provided by the fluid largely depends on the type of fluid and fluid additives used. Straight oils provide fair lubricity, but when compounded with active chemical agents such as chlorine, sulphur, or phosphate, they provide a great deal more lubrication. The additives react with the surface of the workpiece, causing the bonds between metallic fibers to weaken, making it easier for the chip to be formed and removed (Peterson 1995).

Figure 1.4 *Lubricity Versus Cooling Capacity of Lubricants (Peterson 1995*)



Fluid Classification

Metalworking fluids have been characterized and classified into many different groups, and the classifications vary depending on the source of information. In Table 1.4 fluids are characterized by base fluid type and additives.

A class of lubricants not covered in the table is paste and solid lubricants. They are sometimes used on grinding wheels, sanding disks or belts, and band or circular saws. Types of solid and paste lubricants are: sulphur, solid waxes, grease sticks, molybdenum disulfide, tripoli, graphite, mica, talc, glass, pastes, and soaps (MA TURI 1996).

Fluid Components

Metalworking fluids have evolved from straight mineral oils, which were widely used at the turn of the century, to extremely complex chemistries today. In addition to base oils, fluids may contain additives, such as emulsifiers, corrosion inhibitors, emulsion stabilizers, anitfoaming agents, buffers, extreme pressure additives, biocides, and antimisting agents. The amount of information available from the formulators varies, but often is no more than the formulator is required to list on the Material Safety Data Sheet (MSDS), plus the fluid’s compatibility with various substrates, and examples of processes for which it is well suited.

Metalworking fluids may contain inactive or active chemical additives that provide increased lubricity. Inactive extreme-pressure (EP) additives, such as chlorine, sulfur or phosphorus, are added to mineral or compounded oils for machining applications where forces are high. These same chemicals may also be added in concentrations high enough that they become active, and chemically interact with the substrate material to further decrease the mechanical energy needs and frictional forces between the tool and the workpiece.

Biocides are used in water-based metalworking fluids to control the growth of bacteria, algae, and fungi. Classes of compounds used are phenolics and nonphenolics, formaldehyde release agents, aliphatic derivatives, organosulphur-nitrogen compounds, and some mixtures of these (Shennan 1983).

Table 1.4 Metalworking Fluid Types, Characteristics, and Uses (MA TURI 1996)

	Type	Characteristics and Uses
Cutting Fluids	Straight Mineral Oils	• used in light duty operations that require low levels of cooling and lubrication • if kept clean, can be reused indefinitely • lower in cost than compounded oils
	Animal and Vegetable Fatty Oils	• most common types are lard and rapeseed oil • sunflower oils and soybean oils also used • high anti-friction properties but lower oxidation points
	Compounded Cutting Oils	• made by blending mineral oils with polar additives and/or chemically active additives
	Fatty-mineral Oils	• straight mineral oils blended with up to 40 percent fatty oil
Emulsifiable Oils	Emulsifiable Mineral Oil	• suspension of mineral oil made by blending the oil with an emulsifying agent • emulsifiers break the oil into minute particles and keep the particles dispersed in water for a long period of time
	Extreme-pressure Emulsifiable Oils	• sometimes referred to as heavy-duty soluble oils • contain sulfur, chlorine, or phosphorus; may also contain some fatty oils to increase lubricity
Synthetic Fluids	True Solution Fluids	• chemical solutions containing rust inhibitors, sequestering agents, amines, phosphates, borates, glycols or ethylene oxide condensates • have a tendency to leave a residue of hard or crystalline deposits that are formed when water evaporates
	Surface-active Chemical Fluids	• fine colloidal solutions of organic or inorganic materials dissolved in water • wetting agents are usually added to provide moderate lubricity • have low surface tensions, usually contain rust inhibitors • when dried on a workpiece usually leave a powdered residue
	EP Surface-active Chemical Fluids	• similar to surface-active fluids but contain extreme pressure (EP) additives, such as chlorine, sulfur, and phosphate, to give the fluid EP lubrication qualities

Heat Treating

Parts are heat treated for a variety of reasons. Table 1.5 lists the types of heat treating processes and the characteristics they promote.

Table 1.5 Heat Treating Processes

Category	Characteristics
Solution Treating and Aging	• produces a homogeneous solid solution • quenches rapidly to room temperature • ages to produce fine precipitates in solid solution
Tempering	• provides toughness and ductility, protecting the part from cracking • relieves quenching stresses • provides impact resistance, improved elongation, and area reduction
Annealing	• reduces hardness or brittleness • relieves stresses • improves machinability or facilitates cold working • produces desired microstructure or properties • removes gases • alters the electrical or magnetic properties
Normalizing	• enhances the mechanical properties • still-air to ambient temperature

(U.S. EPA 1992a, Heine 1998)

Heat treating may take place at various stages throughout the fabrication process, depending on the preceding and subsequent processing of the parts, and the desired characteristics of the substrate at that stage in the metal fabrication process. Below are a few examples of process flows that employ heat treating at various production stages. Typical wastes generated from heat treating processes are spent media, contaminant metalworking fluids, metal fines, and salts.

Parts are heat treated using a number of different methods to supply the heat. Furnace types include:

- salt-bath
- vacuum
- fluidized-bed
- induction
- laser
- electron beam

In salt-bath heat treating, parts are heated by immersion in molten baths of nitrates, chlorides, carbonates, cyanides, or hydroxides. Salt-bath furnaces are used to either heat or cool parts, and are within a temperature range of 300°F to 2400°F. There are two basic types of salt-bath furnaces, ceramic or metal pot furnaces. Ceramic lined furnaces are primarily used for neutral chloride applications (Goetsch 1991).

Figure 1.5 *Process Flow Diagram for the Manufacturing of Steel, Aluminum, or Titanium Parts (U.S. EPA 1995b)*

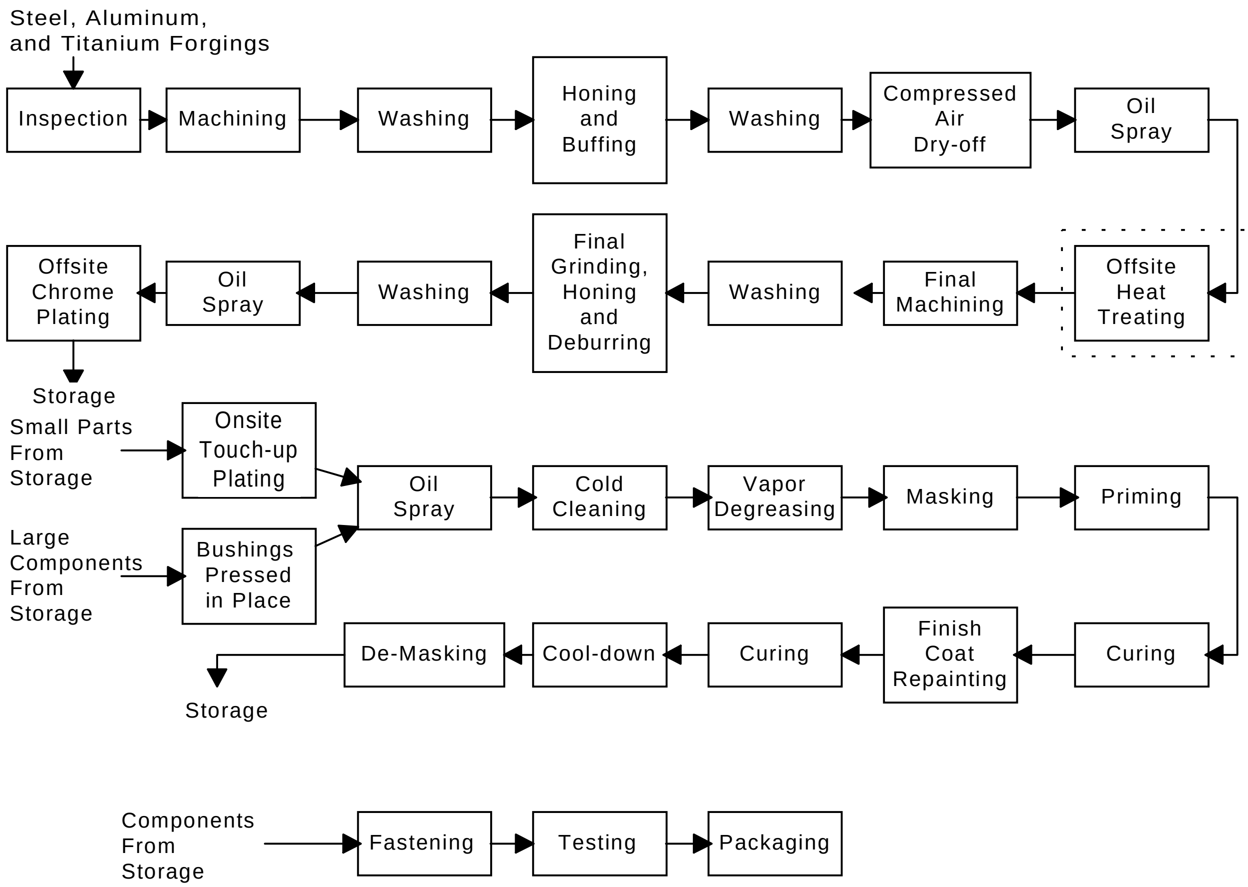
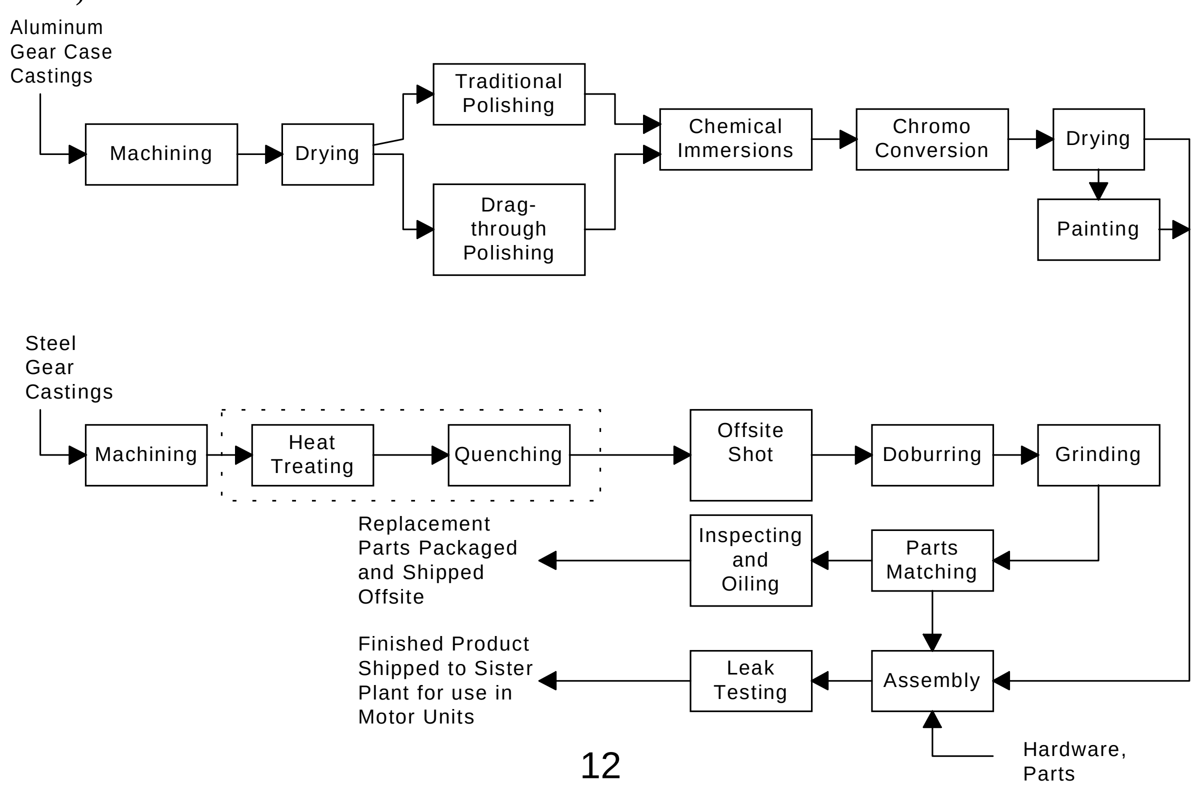


Figure 1.6 *Process Flow Diagram for the Manufacturing of Aluminum or Steel Gears (U.S. EPA 1995*c)



In fluidized-bed furnaces, the parts are placed in a furnace filled with media and flowing gaseous media that gives the furnace its fluidized properties. The temperature that the parts are heated to depends on the substrate and the desired characteristics. Parts are then cooled by quenching (see below) or by allowing them to return to ambient air temperature. There are a variety of media available for use in fluidized-bed furnaces, such as aluminum oxide, silicon carbide, or zirconia sand.

A vacuum furnace is a container that is evacuated and heated by electric radiant heat. Because of advances in design and control, vacuum furnaces are being used as an alternative to salt-bath and atmosphere-controlled furnaces. Vacuum, induction, laser, and electron beam heat treating are covered in more depth in Chapter 6 because they are relatively low polluting methods of heat treating.

Surface (Case) Hardening

Similar in nature to heat treating, surface or case hardening involves heating parts to impart certain surface characteristics. Surface hardening is a thermochemical treatment in which the chemical composition of the steel surface is altered. The types of surface hardening are carbonizing, nitriding, carbonitriding, chromizing, and boronizing. Each type involves heating the substrate in a controlled environment with the presence of a source of the desired case material. Another type of hardening is selective surface hardening, which does not alter the chemical composition of the metal surface but alters the physical properties of the metal surface. The different types of selective surface hardening are: induction hardening, high-frequency resistance hardening, flame hardening, electron-beam hardening, and laser hardening (Goetsch 1991).

Quenching

Metals are cooled after heat treating at varying rates and to varying degrees depending on the type of metal and the desired characteristics. Cooling media may be air, oil, polymer, water, or molten salts, and may be applied in streaming gaseous form, liquid baths, fog, or mist. The quenchant media and application method used depends on the rate of cooling desired, which is again dictated by the phase characteristics of the substrate and the desired characteristics. Typical wastes from quenching operations are spent quenchant and contaminant metalworking fluid.

Quenching is an integral part of liquid carburizing, liquid cyaniding, and liquid nitriding. When the part absorbs sufficient quantities of carbon, cyanide, or nitrogen from a liquid salt bath, it is often quenched in mineral oil, paraffin-based oil, water, or brine to develop a hard surface layer (except tool steels which are liquid nitride cooled) (Goetsch 1991).

Brazing and Soldering

Brazing and soldering use heat and filler metals to produce metallurgical bonds between metal surfaces without melting the base metals. In brazing, the filler metals have liquate temperatures above 840^{o}F, but below those of the metals being joined. The filler metals are distributed between the surfaces to be joined by capillary[7] action. In soldering, the filler metals have liquate

[7]Involving, held by, or resulting from surface tension.

temperatures below 840°F and the filler metals are distributed by both capillary action and wetting between the surfaces of the components being soldered (Goetsch 1991). Typical wastes and emissions from brazing and soldering processes are used or vaporized fluxes, spent dip baths, filler metal splatter or scrap, and spent rinse baths.

Brazing

Brazing is used in a broad range of applications, from jewelry to aerospace. The use of brazing over welding, adhesive joining, or other methods of joining metals depends on the complexity of the geometries to be joined, the size of the components to be joined, the number of joints to be made, the thickness of the sections, and the service requirements. Heat is applied to the joint to be brazed by one of the following means: torch, induction, dip, infrared, furnace, resistance, laser, electron beam, and exothermic. The method of applying filler metal to the joint is application specific and some of the filler metals may only be brazed by one of the heating methods. Filler metals may be in the form of rings, shims, paste alloys, molten baths, or bars.

Fluxes are used in brazing to facilitate the flow of molten metal into the joint and eliminate oxides that could have a harmful effect on the integrity of the joint. Fluxes are available in both powder and paste form and the type used depends on the application. One of the most commonly used flux materials is borax,[8] although there are a variety of other fluxes available. Brazing of aluminum requires special flux that contain metallic halide salts, sodium chlorides, and potassium chlorides. Like the use of a specific filler metal, the method for applying filler metals depends on the type of brazing employed. After brazing, residual flux is usually removed by immersing in a hot water bath. This is necessary due to the corrosive nature of many of the fluxes used in brazing. Table 1.6 lists some of the advantages and disadvantages of brazing compared to other joining methods.

Soldering

Soldering is a metallurgical intermetallic-type bond[9] between the filler metal and the base metals. Types of soldering, as shown in Table 1.7, are generally classified by the source of heat applied to form the solder joint. In soldering it is important to have a clean joint because unlike brazing, solder fluxes do not eliminate dirt or oxides. The method of application of flux to the joint depends on the process. Fluxes may be either corrosive or noncorrosive. The most widely used noncorrosive flux is rosin.[10] It is used for copper, brass, tin, cadmium, and silver-plated parts soldering. The most widely used corrosive fluxes are muriatic acid and zinc/ammonium chloride, used for soldering bronze, steel, and nickel joints. Table 1.8 lists some of the advantages and disadvantages to soldering compared to other metal joining methods.

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[8] Borax is a white crystalline compound that consists of a hydrated sodium borate that occurs as a mineral or is prepared from other minerals.

[9] Intermetallic-type bonds, by definition, are composed of two or more metals or a metal and a nonmetal.

[10] Rosin is a translucent amber-colored to almost black brittle friable resin that is obtained by chemical means from the oleoresin or deadwood of pine trees or from tall oil.

Table 1.6 Advantages and Limitations of Brazing Compared to Other Joining Methods

Advantages	Limitations
• effective on joints inaccessible to welding • thin-walled tubes and light-gage sheet metal can be brazed • can join dissimilar materials • creates leaktight joints • joining of materials at temperatures below 1300^{o}F • multiple joints can be made at one time • less skilled operators required for high speed applications • brazed joints are ductile • brazing is readily automated	• requires close mating of parts • large assemblies, although brazable, may be more economically made by welding

(Goetsch 1991)

Table 1.7 Types of Soldering and Their Characteristics

Heating Method	Heat Source	Characteristics
Conduction Heating	Irons and Guns	• generally used when the number of joints is few
	Hot Plates	• suitable for automation • longer cooling time required
	Dip	• high production volumes • minimal equipment costs • dross formation is an issue • bath requires skimming
	Wave	• for printed wire board (PWB) manufacturing
	Jet	• jet nozzles of various configuration allow more precise application of solder • may be used with oil for better wetting • requires post cleaning for oil removal
Convection Heating	Torches	• used for soldering preforms and paste alloys • also used for line-soldering enclosures for hermetic sealing
	Ovens or Furnaces	• controlled atmospheres used to eliminate oxidation and the need for corrosive fluxes
	Vapor-phase Soldering	• boiling fluorinated hydrocarbon used as heat-transfer medium • used for joining small parts with unusual configurations
	Hot Gas Blankets	• used for joining small assemblies
Resistance Soldering	NA	• used for electronics
Radiation Heating	Unfocused	• uses ordinary lamps (light waves) as heat source

Table 1.7 Types of Soldering and Their Characteristics (continued)

Radiation Heating (continued)	Focused	• laser is one source of heat used • often used on miniature soldering
Induction Soldering	NA	• electromagnetic induction • part to be soldered is the heating element • flux and solder may be applied prior to joining
Ultrasonics Soldering	NA	• cavitation removes oxides from surfaces • does not require flux in many applications • no wetting provided • may need to pretin or use preformed or solid wire solder on the joint
Other:	NA	• spray gun • screen • abrasion • sweat

(Goetsch 1991)

Table 1.8 Advantages and Disadvantages of Solder Joining Compared to Other Joining Methods

Advantages	Limitations
• versatility • reliability • precise control • fast production • low cost	• poor mechanical properties

Adhesive Joining

Adhesive joints are prepared by applying adhesives and then curing or setting the adhesive. Curing is the change in physical properties of the adhesive by chemical reaction, which may be condensation, polymerization, or vulcanization, often accomplished by heat and/or catalyst, and with or without pressure. Setting is the conversion of an adhesive into a fixed or hardened state by chemical or physical reaction (Goetsch 1991). Typical waste streams and emissions from adhesive joining processes are excess adhesives and volatile organic compound (VOC) and hazardous air pollutant (HAP) emissions from carrier solvents and primers. Adhesive joining operations are defined by the type of adhesive, the method of curing, and the method of adhesive application. Table 1.9 lists the most commonly used types of adhesives.

Table 1.9 Types of Adhesives and Their Characteristics

Type of Adhesive	Characteristics
Natural Adhesives	• not typically used in metal joining applications due to poor bond strength • gums, resins, starch, dextrin,[11] casein,[12] soya flour, and animal products such as blood and collagen
Inorganic Adhesives	• principally sodium silicate and magnesium oxychloride • low cost • poor strength • not very flexible • may be sensitive to moisture
Synthetic Adhesives	• high-strength bonds • elastomers and resins • thermoplastic resins: styrene block copolymers, acrylic, polyolefin, nylon, and vinyl • thermoset resins: acrylic (anaerobics), epoxy, phenolic, polyurethane, and silicone

(Goetsch 1991)

In addition to being classified by type of chemical, adhesives are classified by the methods in which they are converted from a liquid to a solid. The conversion classes and their characteristics are presented in Table 1.10.

There are a relatively large number of Class I adhesives, or chemically reactive adhesives. Therefore, they are further categorized by type of chemical compound, the way in which the reaction is initiated, and other characteristics. The types of Class I adhesives are:

- Plural Components (Class IA)
- Heat-Activated Adhesives (Class IB)
- One-Part Specially Catalyzed Adhesives (Class IC)
- Radiation-Curing Adhesives (Class ID)
- Moisture-Curing Adhesives (Class IE)

Surfaces that are going to be adhesively joined need to be carefully prepared by cleaning, etching, rinsing, and drying. Primers are used in structural adhesive applications for surface protection and adhesion promotion and may be a significant source of air emissions.

There are a variety of adhesive application methods and the method selected depends on the economics, bond filling, and production needs. Table 1.11 lists the various application methods. Vacuum impregnation is commonly used when applying adhesives to die-cast parts, laminates, and powdered metal. In this process, air is evacuated and adhesive is added. Due to vacuum pressures, the adhesive is forced into the microscopic pores of the substrate. The excess adhesive is removed by spinning the parts.

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[11] Dextrin is any of various water-soluble gummy polysaccharides $(C_6H_{10}O_5)_n$ obtained from starch by the action of heat, acids, or enzymes.

[12] Casein is a phosphoprotein of milk.

Table 1.10 Adhesive Classes and Their Characteristics

Adhesive Class	Characteristics
Chemically Reactive Adhesives (Class I)	• undergo curing or crosslinking within the adhesive • high lap-shear strengths • generally have low peel strengths • to improve peel strength, polymer alloys are often employed using thermoplastics and elastomers
Evaporative Adhesives (Class II)	• curing occurs through loss of solvent or water • shear and tensile strengths are low • one of the adherents must be porous or sufficient drying time must be allowed
Hot-Melt Adhesives (Class III)	• must be formulated with thermoplastic resins because a thermoset resin will not form a melt condition upon reheating • polymers used include: ethylene vinyl acetate (EVA), polyethylene, styrene block copolymer, butyl rubber, polyamide, polyurethane, and polyester • must be applied molten
Delayed-Tack Adhesives (Class IV)	• nontacky solids that are heat-activated • blends of resins: polyvinyl acetate, polyamide, or polystyrene
Film Adhesives (Class V)	• similar adhesives as Class IB with similar bond properties • may also be similar to Class III & VI • controlled glue-line thickness • ease of application • freedom from solvent • requires precise heating for extended periods of time • hand application only • most common use in metal laminations • large use in aerospace applications
Pressure-Sensitive Adhesives (Class VI)	• not used in metal joining

(Goetsch 1991)

There are a variety of automatic applicators including stationary, torch, advancing nozzle, rotospray, pressure-time vacuum dispensing systems, and positive-displacement systems.

Table 1.11 Adhesive Application Methods

- manual roller
- screen or stencil printing
- brushing
- extrusion and flow
- troweling
- spraying
- roll coaters
- vacuum impregnation
- manual applicators
- automatic applicators
- robotic applicators

Welding and Weld Cutting

Nearly all metal fabrication processes employ some form of welding. Welding processes vary by heat source, pressure, and filler metals. The various welding processes are:

- oxyfuel gas welding and cutting
- arc welding and cutting
- laser beam welding and cutting
- Thermit welding
- diffusion welding
- friction welding
- ultrasonic welding
- explosive welding and cladding
- other solid-state welding

Typical wastes from welding and weld cutting processes are dross, slag, spent electrodes, and scrap metal.

Buffing and Polishing

Buffing and polishing are performed to smooth and shine the surface of parts to give the product its finished look. A variety of buffing and polishing machines are used, including polishing and buffing lathes, high-speed polishing machines, or off-hand buffing and polishing pads. Wheels, or buffs, are typically made of muslin cloth,[13] mill-treated cloth, sisal,[14] denim, and flannel. The wheels are treated with buffing or polishing compounds that are selected based on the substrate and the level of polishing required for the specific application. Buffing and polishing compounds come in various forms including spray, paste, stick, and powder. Typical wastes from buffing and polishing operations include excess polishing or buffing compounds and spent wheels or pads.

Tumbling and Vibratory Finishing

Tumbling and vibratory finishing are performed for cleaning, oxide removal/descaling, polishing, brightening, and edge-breaking/burr removal. There are wet and dry tumbling and vibratory processes that use a variety of media including ceramics, stone, glass beads, metal shot, nut shells, corn husks, hardwoods, and plastic/resin beads. For wet processes, these media are used in combination with chemistries, such as cleaners and detergents, chelated burnishing compounds, acids, or water. Machines for wet and dry processes may be vibratory bowls, tumblers, centrifugal discs, centrifugal barrels, and continuous vibratory finishers. Typical waste streams from tumbling and vibratory finishing operations are spent media, spent baths, and metal fines.

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[13]Muslin is a plain-woven sheer to coarse cotton fabric.

[14]Sisal is a strong durable white fiber used especially for hard fiber cordage and twine.