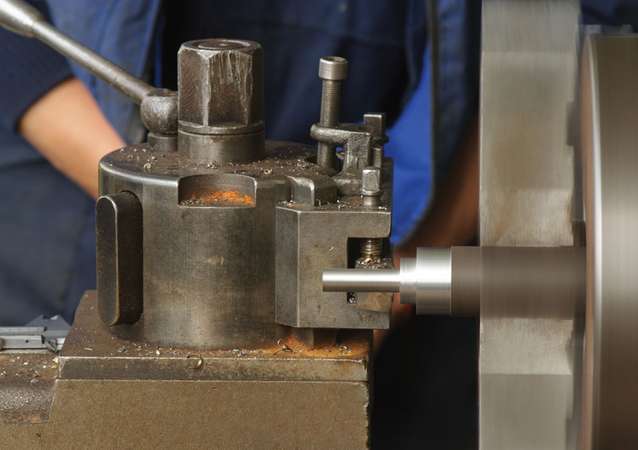
**Basic Machine Tools**

Hundreds of varieties of metal [machine](https://www.britannica.com/technology/machine) tools, ranging in size from small machines mounted on workbenches to huge production machines weighing several hundred tons, are used in modern industry. They retain the basic characteristics of their 19th- and early 20th-century ancestors and are still classed as one of the following: (1) turning machines (lathes and boring mills), (2) shapers and planers, (3) drilling machines, (4) milling machines, (5) grinding machines, (6) power saws, and (7) presses.

**Turning machines**

The [engine lathe](https://www.britannica.com/technology/engine-lathe), as the horizontal metal-turning machine is commonly called, is the most important of all the machine tools. It is usually considered the father of all other machine tools because many of its fundamental mechanical elements are incorporated into the design of other machine tools.

[[](https://cdn.britannica.com/02/131402-050-4A8B5BC2/Metal-lathe.jpg)](https://cdn.britannica.com/02/131402-050-4A8B5BC2/Metal-lathe.jpg)

[Metal being cut on a lathe.](https://cdn.britannica.com/02/131402-050-4A8B5BC2/Metal-lathe.jpg)*[© sima/Shutterstock.com](https://cdn.britannica.com/02/131402-050-4A8B5BC2/Metal-lathe.jpg)*

The engine lathe is a basic machine [tool](https://www.britannica.com/technology/tool) that can be used for a variety of turning, facing, and drilling operations. It uses a single-point cutting tool for turning and boring. Turning operations involve cutting excess metal, in the form of chips, from the external diameter of a workpiece and include turning straight or tapered cylindrical shapes, grooves, shoulders, and screw threads and facing flat surfaces on the ends of cylindrical parts. Internal cylindrical operations include most of the common hole-machining operations, such as drilling, [boring](https://www.britannica.com/technology/boring-machine), reaming, counterboring, countersinking, and threading with a single-point tool or [tap](https://www.britannica.com/technology/tap-tool).

Boring involves enlarging and finishing a hole that has been cored or drilled. Bored holes are more accurate in roundness, concentricity, and parallelism than drilled holes. A hole is bored with a single-point cutting tool that feeds along the inside of the workpiece. Boring mills have circular horizontal tables that rotate about a vertical axis, and they are designed for boring and turning operations on parts that are too large to be mounted on a lathe.

[**Shapers**](https://www.britannica.com/technology/shaper)**and planers**

Shaping and planing operations involve the machining of flat surfaces, grooves, shoulders, T-slots, and angular surfaces with single-point tools. The largest shapers have a 36-inch cutting stroke and can machine parts up to 36 inches long. The cutting tool on the [shaper](https://www.britannica.com/technology/shaper) oscillates, cutting on the forward stroke, with the workpiece feeding automatically toward the tool during each return stroke.

[Planing machines](https://www.britannica.com/technology/planer) perform the same operations as shapers but can machine longer workpieces. Some planers can machine parts up to 50 feet long. The workpiece is mounted on a [reciprocating](https://www.merriam-webster.com/dictionary/reciprocating) table that moves the workpiece beneath a cutting tool. This tool, which remains stationary during the cutting stroke, automatically feeds into the workpiece after each cutting stroke.

**Drilling machines**

Drilling machines, also called [drill presses](https://www.britannica.com/technology/drill-press), cut holes in metal with a [twist drill](https://www.britannica.com/technology/twist-drill). They also use a variety of other cutting tools to perform the following basic hole-machining operations: (1) reaming, (2) boring, (3) counterboring, (4) countersinking, and (5) tapping internal threads with the use of a tapping attachment.

[**Milling machines**](https://www.britannica.com/technology/milling-machine)

A [milling machine](https://www.britannica.com/technology/milling-machine) cuts metal as the workpiece is fed against a rotating cutting tool called a milling cutter. Cutters of many shapes and sizes are available for a wide variety of milling operations. Milling machines cut flat surfaces, grooves, shoulders, inclined surfaces, dovetails, and T-slots. Various form-tooth cutters are used for cutting concave forms and convex grooves, for rounding corners, and for cutting gear teeth.

Milling machines are available in a variety of designs that can be classified as the following: (1) standard knee-and-column machines, including the horizontal and the vertical types; (2) bed-type or manufacturing machines; and (3) machines designed for special milling jobs.

[**Grinding machines**](https://www.britannica.com/technology/grinding-machine)

Grinding machines remove small chips from metal parts that are brought into contact with a rotating [abrasive](https://www.britannica.com/technology/abrasive) wheel called a [grinding wheel](https://www.britannica.com/technology/grinding-wheel) or an abrasive belt. Grinding is the most accurate of all of the basic machining processes. Modern grinding machines grind hard or soft parts to tolerances of plus or minus 0.0001 inch (0.0025 millimetre).

The common types of grinding machines include the following: (1) plain cylindrical, (2) internal cylindrical, (3) centreless, (4) surface, (5) off-hand, (6) special, and (7) abrasive-belt.

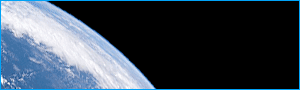
**Power saws**

Metal-cutting power saws are of three basic types: (1) power hacksaws, (2) [band saws](https://www.britannica.com/technology/band-saw), and (3) circular disk saws. Vertical band saws are used for cutting shapes in metal plate, for internal and external [contours](https://www.merriam-webster.com/dictionary/contours), and for angular cuts.

[**Presses**](https://www.britannica.com/technology/press-machine-tool)

This large class of machines includes equipment used for forming metal parts by applying the following processes: shearing, blanking, forming, drawing, bending, forging, coining, upsetting, flanging, squeezing, and hammering. All of these processes require presses with a movable ram that can be pressed against an anvil or base. The movable ram may be powered by gravity, mechanical linkages, or hydraulic or pneumatic systems.

Appropriate [die](https://www.britannica.com/technology/die) sets, with one part mounted on the movable ram and the matching part mounted on the fixed bed or platen, are an [integral](https://www.merriam-webster.com/dictionary/integral) part of the machine. [Punch presses](https://www.britannica.com/technology/punch-press) stamp out metal parts from sheet metal and form the parts to the desired shape. Dies with cavities having a variety of shapes are used on forging presses that form white-hot metal blanks to the desired shapes. Power presses are also used for shearing, bending, flanging, and shaping sheet metal parts of all sizes. Power presses are made in various sizes, ranging from small presses that can be mounted on a workbench to machines weighing more than 1,000,000 pounds (450,000 kilograms).

[](https://www.britannica.com/explore/space)

**Modifications Of Basic Machines**

Certain [machine](https://www.britannica.com/technology/machine) tools have been designed to speed up production. Although these tools include features of the basic machine tools and perform the same operations, they incorporate design modifications that permit them to perform complex or repetitive operational sequences more rapidly. Furthermore, after the production machine has been set up by a skilled worker or machinist, a less skilled operator also can produce parts accurately and rapidly. The following are examples of production machine tools that are modifications of basic machine tools: (1) turret lathes, including screw machines; (2) multiple-station machines; (3) gang drills; and (4) production milling machines.

[**Turret lathes**](https://www.britannica.com/technology/turret-lathe)

Horizontal turret lathes have two features that distinguish them from engine lathes. The first is a multiple-sided main turret, which takes the place of the tailstock on the engine [lathe](https://www.britannica.com/technology/lathe). A variety of turning, drilling, boring, reaming, and thread-cutting tools can be fastened to the main turret, which can be rotated intermittently about its vertical axis with a hand wheel. Either a hand wheel or a power feed can be used to move the turret longitudinally against the workpiece mounted on the machine spindle.

The second distinguishing feature of the turret lathe is the square turret mounted on the cross slide. This turret also can be rotated about its vertical axis and permits the use of a variety of turning tools. A tool post, or [tool](https://www.britannica.com/technology/tool) block, can be clamped to the rear of the cross slide for mounting additional tools. The cross slide can be actuated either by hand or by power.

Turret lathes may be classified as either bar machines or chucking machines. Bar machines formerly were called screw machines, and they may be either hand controlled or automatic. A bar machine is designed for machining small threaded parts, bushings, and other small parts that can be created from bar stock fed through the machine spindle. Automatic bar machines produce parts continuously by automatically replacing of bar stock into the machine spindle. A chucking machine is designed primarily for machining larger parts, such as castings, forgings, or blanks of stock that usually must be mounted in the chuck manually.

**Multiple-station machines**

Several types of multiple-station vertical lathes have been developed. These machines are essentially chucking-type turret lathes for machining threaded cylindrical parts. The machine has 12 spindles, each equipped with a chuck. Directly above each spindle, except one, tooling is mounted on a ram. Parts are mounted in each chuck and indexed for up to 11 machining operations. The finished part is removed at the 12th station.

**Gang drills**

A gang-drilling machine consists of several individual columns, drilling heads, and spindles mounted on a single base and utilizing a common table. Various numbers of spindles may be used, but four or six are common. These machines are designed for machining parts requiring several hole-machining operations, such as drilling, countersinking, counterboring, or tapping. The workpiece is moved from one drilling spindle to the next, where sequential machining operations are performed by one or more operators.

**Production millers**

Milling machines used for repet-itive-production milling operations generally are classified as bed-type milling machines because of their design. The sliding table is mounted directly onto the massive bed of the machine and cannot be raised or moved transversely; table movement is longitudinal only. The spindle head may be adjusted vertically to establish the depth of cut. Some machines are equipped with automatic controls that require only a semiskilled operator to load parts in fixtures at each end of the table and start the machine. One part can be unloaded and replaced while the other is being machined.

**Special-Purpose Machines**

Special-purpose machine tools are designed to perform special machining operations, usually for production purposes. Examples include gear-cutting and gear-grinding machines, broaching machines, lapping and honing machines, and boring machines.

**Gear-cutting machines**

Three basic cutting methods are used for machining [gears](https://www.britannica.com/technology/gear): (1) form cutting, (2) template cutting, and (3) generating. The form-cutting method uses a cutting tool that has the same form as the space between two [adjacent](https://www.merriam-webster.com/dictionary/adjacent) teeth on a gear. This method is used for cutting gear teeth on a [milling machine](https://www.britannica.com/technology/milling-machine). The template-cutting method uses a template to guide a single-point cutter on large bevel-gear cutting machines.

Most cut gears produced in large lots are made on machines that utilize the gear-generating method. This method is based on the principle that two involute gears, or a gear and rack, with the same diametral pitch will mesh together properly. Therefore, a cutting tool with the shape of a gear or rack may be used to cut gear teeth in a gear or rack blank. This principle is applied in the design of a number of widely used gear-cutting machines of the generating type. Gear-generating machines that cut with [reciprocating](https://www.merriam-webster.com/dictionary/reciprocating) strokes are called [gear shapers](https://www.britannica.com/technology/gear-shaper).

Gear-hobbing machines use a rotating, multiple-tooth cutting tool called a hob for generating teeth on spur gears, worm gears, helical gears, splines, and sprockets. More gears are cut by hobbing than by other methods because the hobbing cutter cuts continuously and produces accurate gears at high production rates. In gear-making machines gears can be produced by cutting, grinding, or a combination of cutting and grinding operations.

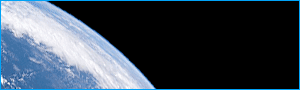
[**Broaching machines**](https://www.britannica.com/technology/broaching-machine)

In general, broaching is classified as a planing or shaping art because the action of a broaching tool resembles the action of [planer](https://www.britannica.com/technology/planer) and [shaper](https://www.britannica.com/technology/shaper) tools. Broaching tools of various designs are available. The teeth on broaching tools are equally spaced, with each successive tooth designed to feed deeper into the workpiece, thus completing the broaching operation in a single stroke. Examples of internal broaching applications include cutting keyways in the hubs of gears or pulleys, cutting [square](https://www.britannica.com/technology/square-tool) or hexagonal holes, and cutting gear teeth. External grooves can be cut in a shaft with an external broaching tool. Some broaching machines pull or push broaching tools through or over the workpiece.

**Lapping and honing machines**

Lapping and honing operations are classified under the basic art of grinding. Lapping is a process in which a soft cloth impregnated with [abrasive](https://www.britannica.com/technology/abrasive) pastes or [compounds](https://www.merriam-webster.com/dictionary/compounds) is rubbed against the surface of a workpiece. Lapping is used to produce a high-quality surface finish or to finish a workpiece within close size limits. Dimensional tolerances of two millionths of an inch (0.00005 millimetre) can be achieved in the hand or machine lapping of precision parts such as gauges or [gauge](https://www.britannica.com/technology/gauge-instrument) blocks.

Honing is a low-speed surface finishing process used for removing scratches, machine marks, or small amounts of metal, usually less than 0.0005 inch (0.0125 millimetre), from ground or machined surfaces. Honing is done with bonded abrasive sticks or stones that are mounted in a honing head. In a typical honing operation, such as honing automotive engine cylinder walls, a honing machine with one or more spindles is used. The honing head rotates slowly with an oscillating motion, holding the abrasive sticks against the work surface under controlled light pressure.

[](https://www.britannica.com/explore/space)

[**Boring machines**](https://www.britannica.com/technology/boring-machine)

Boring can be done on any type of machine that is equipped to hold a boring [tool](https://www.britannica.com/technology/tool) and a workpiece and that is also equipped to rotate either the tool or the workpiece in the proper relationship. Special boring machines of various designs are used for boring workpieces that are too large to be mounted on a [lathe](https://www.britannica.com/technology/lathe), [drill press](https://www.britannica.com/technology/drill-press), or [milling machine](https://www.britannica.com/technology/milling-machine). Boring and turning operations are also performed on large vertical turret lathes or on larger boring mills. Standard boring machines are able to bore or turn work of up to 12 feet (3.6 metres) in diameter.

**Automatic Control**

To be truly [automatic](https://www.britannica.com/technology/automation), a machine tool must be capable of producing parts repetitively without operator assistance in loading parts, starting the machine, and unloading parts. In this sense, some bar-turning machines are automatic. In practice, however, some machine tools designated as automatic are actually semi-automatic, since they require an operator to load the workpiece into the machine, press the start button, and unload the part when the operation is completed.

The tooling for automatic machines is more complex than for hand-controlled machines and usually requires a skilled worker to make the setup. After the setup, however, a less skilled operator can operate one or more machines simultaneously. Tracer lathes and numerically controlled machine tools are examples of machines that use varying degrees of automatic and semi-automatic control.

**Tracer techniques**

The tool slide on a tracer lathe is guided by a sensitive, hydraulically actuated stylus that follows an accurate template. The template may be an accurate profile on a thin plate or a finish-turned part. Although tracing mechanisms generally are accessory units attached to engine lathes, some lathes are especially designed as automatic tracing lathes. Optional accessories for use on tracing lathes include automatic-indexing toolheads and one or more cross slides for operations such as facing, grooving, and chamfering.

Tracing lathes can machine all common cylindrical shapes, straight and tapered shoulders, and irregular curves. Accessory tools permit facing, grooving, and chamfering operations. An unlimited combination of cutting speeds, feeds, and types of cuts may be used, including roughing cuts and finishing cuts. On machines equipped for automatic operation, changes in speed, feed, and cutting tools are automatic.

[*Willard J. McCarthy*](https://www.britannica.com/contributor/Willard-J-McCarthy/1827)[*The Editors of Encyclopaedia Britannica*](https://www.britannica.com/editor/The-Editors-of-Encyclopaedia-Britannica/4419)

[**Numerical control**](https://www.britannica.com/technology/numerical-control)**(NC)**

Many types of [machine](https://www.britannica.com/technology/computer) tools and other industrial processes are equipped for numerical control, commonly called NC. The earliest forms of NC were developed in the 1950s when the movements of the axes of machine tools were assigned numerical values to [facilitate](https://www.merriam-webster.com/dictionary/facilitate) the replacement of handwheels and dials by control logic. NC requires accurate product design values; early systems were limited by the lack of detailed analyses for the geometrical drawings of the components to be manufactured. Later in the decade, this problem was overcome when [computers](https://www.britannica.com/technology/control-system) were developed that could describe geometric tool movements as functions of a part-programming language. One of the best known of these early languages of tool instructions was [APT](https://www.britannica.com/technology/APT) (Automatically Programmed Tools).

A significant development of the early 1960s was a system known as [Sketchpad](https://www.britannica.com/technology/Sketchpad), which enabled engineers to draw designs on a [cathode-ray tube](https://www.britannica.com/technology/cathode-ray-tube) by using a light pen and a keyboard. When this system was connected to a computer, it enabled designers to study drawings interactively and [facilitated](https://www.merriam-webster.com/dictionary/facilitated) the modification of their designs.

An NC system or device is one that controls the actions of a machine or process by the direct insertion of numerical data at some point; the system also must automatically interpret at least some portion of the data. Various kinds of numerical control systems use data coded in the form of numbers, letters, symbols, words, or a combination of these forms.

The instructions necessary for machining a part by NC are derived from the part drawing and are written in coded form on a program manuscript. The following kinds of data may be included on the manuscript: (1) sequence of operations, (2) kind of operation, (3) depth of cut, (4) coordinate dimensions for the centre of the cutting tool, (5) feed rate, (6) spindle speed, (7) tool number, and (8) other miscellaneous operations.

The coded information is punched into a ribbon of one-inch-wide machine-control tape with a tape-punching machine similar to a typewriter. The tape, usually made of paper or plastic, is inserted into the NC system, which is connected to the machine tool. The NC system interprets the information on the tape, thus activating relays and electrical circuits that cause the machine’s servomechanisms and other controls to perform a sequence of operations automatically. On some NC systems, the coded information is inserted into the machines on punched cards or magnetic tape instead of punched tape. The tape can be stored for future use on the same machine or on others like it at any location. NC machines can produce parts accurately to tolerances of 0.001 or 0.0001 inch (0.025 or 0.0025 millimetre) depending on the design of the machine, the NC system, and other factors, such as environmental temperature.

NC systems on machine tools can be classified into two basic types: (1) point-to-point and (2) continuous-path. Point-to-point systems, commonly used on machines that perform hole-machining and straight-line milling operations, are relatively simple to program and do not require the aid of a computer.

Continuous-path NC systems are commonly used on machines that perform [contouring](https://www.merriam-webster.com/dictionary/contouring) operations, such as milling machines, lathes, flame-cutting machines, and drafting machines. Program preparation for continuous-path machines is more complex and usually requires the aid of a computer.

**Computer-Aided Machining**

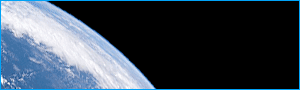
[**Computer numerical control**](https://www.britannica.com/technology/computer-numerical-control)**(CNC)**

Altering the operating procedures of early NC systems required changing the hardware of the machine tool itself. In the 1970s CNC systems, controlled by dedicated mini- or microcomputers, were developed to enable machine tools to be readily adapted to different jobs by altering the control program, or software. Consequently, CNC machine tools are easier to operate and more versatile than their NC counterparts, and their programming is simpler and can be rapidly tested. Since they have less control hardware, they are cheaper to maintain and are generally more accurate. CNC systems can be used with a wide range of machine tools such as milling machines and lathes. Many are equipped with graphic displays that plot the shapes of the components being machined. Some simulate tool movements, while others produce three-dimensional views of components.

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**[computer numerical control](https://cdn.britannica.com/17/197117-050-E0626858/Rows-computer-numerical-control-milling-machines-factory.jpg)**[Rows of computer numerical control (CNC) milling machines at the Taylor Guitars factory in El Cajon, California, U.S.](https://cdn.britannica.com/17/197117-050-E0626858/Rows-computer-numerical-control-milling-machines-factory.jpg)*[© Marcin Wichary (CC BY 2.0)](https://cdn.britannica.com/17/197117-050-E0626858/Rows-computer-numerical-control-milling-machines-factory.jpg)*

When several CNC machine tools receive instructions for machining from a large central computer that stores and processes operational procedures, they are said to be under [direct numerical control](https://www.britannica.com/technology/direct-numerical-control) (DNC).

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[**Adaptive control**](https://www.britannica.com/technology/adaptive-control)

Improvements in CNC [machine](https://www.britannica.com/technology/machine) tools depend on the refinement of adaptive control, which is the automatic monitoring and adjustment of machining conditions in response to variations in operation performance. With a manually controlled machine [tool](https://www.britannica.com/technology/tool), the operator watches for changes in machining performance (caused, for example, by a dull tool or a harder workpiece) and makes the necessary mechanical adjustments. An essential element of [NC](https://www.britannica.com/technology/numerical-control) and CNC machining, adaptive control is needed to protect the tool, the workpiece, and the machine from damage caused by malfunctions or by unexpected changes in machine behaviour. Adaptive control is also a significant factor in developing unmanned machining techniques.

One example of adaptive control is the monitoring of torque to a machine tool’s spindle and servomotors. The control unit of the machine tool is programmed with data defining the minimum and maximum values of torque allowed for the machining operation. If, for example, a blunt tool causes the maximum torque, a signal is sent to the control unit, which corrects the situation by reducing the feed rate or altering the spindle speed.

**Machining centres**

A further development in the automation of machine tools is the “machining centre,” usually a vertical [milling machine](https://www.britannica.com/technology/milling-machine) fitted with automatic tool-changing facilities and capable of several axes of control. The tools, of which there can be more than 100, are generally housed in a rotary magazine and may be changed by commands from the machine tool program. Thus, different faces of a workpiece can be machined by a combination of operations without moving it to another machine tool. Machining centres are particularly suitable for the batch production of large and complex components requiring a high degree of accuracy.

[**Computer-aided**](https://www.britannica.com/technology/computer-aided-engineering)**design and computer-aided manufacturing (CAD/CAM)**

The [technology](https://www.britannica.com/technology/technology) of CNC machine tools has been [enhanced](https://www.merriam-webster.com/dictionary/enhanced) by parallel advances in CAD/CAM. In the first NC systems, CAD and CAM were regarded as separate functions. Gradually they have come to be treated as an [integrated](https://www.merriam-webster.com/dictionary/integrated) operation, with manufacturing processes being considered at the product design stage.

CAD enables designers to use computers to analyze and manipulate design data. Using a graphics workstation or computer terminal to display three-dimensional figures, the designer can examine a proposed design from different angles, in various cross sections, and in many sizes. Details of the completed design are transferred to a second terminal on which a set of engineering drawings can be produced. All aspects of the design are closely scrutinized at this stage, and, after final changes are made, the finished, fully dimensioned design is drawn on a specialized [computer printer](https://www.britannica.com/technology/computer-printer) called a plotter.

CAD/CAM systems also allow design data to be stored in numerical (digitized) form, from which machine-control tapes and disks may be prepared directly. The CAD and CAM systems may then be linked by computer-assisted part programming. With this technique a CAD system can produce a geometrical profile of a required component as, for example, a series of connected points. The position of each point, and the ways in which it can be reached by movements of the tool, is fed to the computer. After calculating the necessary tool movements, the computer develops a complete machining program for the part to be manufactured on the CNC machine.

**Robots**

The utilization of CNC machine tools has been stimulated by the introduction of [robots](https://www.britannica.com/technology/industrial-robot)—devices designed to move components, tools, and materials by specific motions and through defined paths. Robots can have memories (stored sets of instructions) and may be equipped with mechanisms that automatically perform many tasks such as the loading and unloading of parts, assembly, inspection, [welding](https://www.britannica.com/technology/welding), painting, and machining. Its arm and wrist move like those of humans, each axis of motion being driven by an electric or hydraulic motor. The wrist is usually fitted with an “end effector,” an element to which devices are added to help perform specific required operations. These devices can include a two- or three-finger gripper for material handling, a power tool for drilling, or an arc-welding gun. “Intelligent” robots are also available. These have end effectors fitted with [tactile](https://www.merriam-webster.com/dictionary/tactile) or visual sensing devices that can determine the proximity of the object to be manipulated or machined.

[**Flexible manufacturing system**](https://www.britannica.com/technology/flexible-manufacturing-system)**(FMS)**

A group of manufacturing cells linked by an automatic material handling system and a central computer is called a flexible manufacturing system. The computerized coordination of FMS enables components to be produced at very low costs, even when only small quantities are to be made. The main feature of FMS is its ability to switch from the machining of one component to another (or between separate manufacturing processes) without undue interruption. Each machine control unit stores many part-producing programs in its [computer memory](https://www.britannica.com/technology/computer-memory). The FMS master computer uses direct numerical control (DNC) to select and activate these programs as they are needed during the manufacturing process. As the master computer governs the supply of workpieces to the machine, the part program controls individual tooling. If a variety of machining operations are needed, a large number of tools may have to be carried: some milling operations, for example, require 60 to 100 tools.

**Computer-integrated manufacturing**

Computers have come to be used in all stages of manufacture: design, scheduling, management, manufacturing, and testing. The [integration](https://www.merriam-webster.com/dictionary/integration) of these phases of computer involvement is called [computer-integrated manufacturing](https://www.britannica.com/technology/computer-integrated-manufacturing). For further information about robots, see the article [automation](https://www.britannica.com/technology/automation).

**Nonconventional Methods Of Machining**

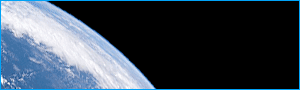
Traditional machining processes work on the principle that the tool is harder than the workpiece. Some materials, however, are too hard or too brittle to be machined by conventional methods. The use of very hard nickel-based and titanium alloys by the aircraft engine industry, for example, has stimulated nonconventional machining methods, especially “electrical methods.”

[**Electrical**](https://www.britannica.com/science/electricity)**methods of machining**

Some machining methods rely on electrical phenomena—rather than mechanical means—for cutting and machining workpieces.

**Electron-beam machining (EBM)**

The EBM technique is used for cutting fine holes and slots in any material. In a vacuum chamber, a beam of high-velocity electrons is focused on a workpiece. The [kinetic energy](https://www.britannica.com/science/kinetic-energy) of the electrons, upon striking the workpiece, changes to heat, which vaporizes minute amounts of the material. The vacuum prevents the electrons from scattering, due to collisions with gas molecules. EBM is used for cutting holes as small as 0.001 inch (0.025 millimetre) in diameter or slots as narrow as 0.001 inch in materials up to 0.250 inch (6.25 millimetres) in thickness. EBM is also used as an [alternative](https://www.merriam-webster.com/dictionary/alternative) to light optics manufacturing methods in the semiconductor industry. Because electrons have a shorter wavelength than light and can be easily focused, electron-beam methods are particularly useful for high-resolution lithography and for the manufacture of complex integrated circuits. Welding can also be done with an [electron beam](https://www.britannica.com/science/electron-beam), notably in the manufacture of aircraft engine parts.

[](https://www.britannica.com/explore/space)

[**Electrical-discharge machining**](https://www.britannica.com/technology/electrical-discharge-machining)**(EDM)**

EDM involves the direction of high-frequency electrical spark discharges from a graphite or soft metal [tool](https://www.britannica.com/technology/tool), which serves as an electrode, to disintegrate electrically conductive materials such as hardened steel or carbide. The electrode and workpiece are immersed in a dielectric liquid, and a feed mechanism maintains a spark gap of from 0.0005 to 0.020 inch (0.013 to 0.5 millimetre) between the electrode and the workpiece. As spark discharges melt or vaporize small particles of the workpiece, the particles are flushed away, and the electrode advances. The process is accurate, but slow, and is used for machining dies, molds, holes, slots, and cavities of almost any desired shape. In CNC wire machining, a thin copper wire is used as the tool for cutting out two- and three-dimensional fretwork profiles.

[**Electrochemical machining**](https://www.britannica.com/technology/electrochemical-machining)**(ECM)**

ECM resembles electroplating in reverse. In this process metal is dissolved from a workpiece with [direct current](https://www.britannica.com/science/direct-current) at a controlled rate in an [electrolytic cell](https://www.britannica.com/technology/electrolytic-cell). The workpiece serves as the anode and is separated by a gap of 0.001 to 0.030 inch (0.025 to 0.75 millimetre) from the tool, which serves as the cathode. The electrolyte, usually an aqueous salt solution, is pumped under pressure through the inter-electrode gap, thus flushing away metal dissolved from the workpiece. As one electrode moves toward the other to maintain a constant gap, the anode workpiece is machined into a complementary shape. The advantages of ECM are lack of tool wear and the fact that a softer cathode tool can be used to [machine](https://www.britannica.com/technology/machine) a harder workpiece. Applications of ECM can be found in the aircraft engine and automobile industries, where the process is used for deburring, drilling small holes, and machining extremely hard turbine blades.

Other versions of ECM include electrolytic grinding, which includes about 90 percent ECM with 10 percent mechanical action; electrochemical arc machining (ECAM), in which controlled arcs in an aqueous electrolyte remove material at a fast rate; and capillary drilling, in which acid electrolytes are used to machine very fine holes.

**Ion beam machining (IBM)**

In IBM a stream of charged atoms (ions) of an [inert gas](https://www.britannica.com/science/noble-gas), such as argon, is accelerated in a vacuum by high energies and directed toward a solid workpiece. The beam removes atoms from the workpiece by transferring energy and momentum to atoms on the surface of the object. When an atom strikes a cluster of atoms on the workpiece, it dislodges between 0.1 and 10 atoms from the workpiece material. IBM permits the accurate machining of virtually any material and is used in the semiconductor industry and in the manufacture of aspheric lenses. The technique is also used for texturing surfaces to [enhance](https://www.merriam-webster.com/dictionary/enhance) bonding, for producing atomically clean surfaces on devices such as laser mirrors, and for modifying the thickness of thin films and membranes.

[**Laser machining**](https://www.britannica.com/technology/laser-machining)**(LM)**

LM is a method of cutting metal or refractory materials by melting and vaporizing the material with an intense beam of light from a [laser.](https://www.britannica.com/technology/laser) Drilling by laser, although costly in energy since material must be melted and vaporized to be removed, is used to cut small holes (0.005 to 0.05 inch [0.13 to 1.3 millimetres]) in materials that are too difficult to machine by traditional methods. A common application is the laser drilling of diamonds to be used as dies for drawing wire. Lasers also are used to [drill](https://www.britannica.com/technology/drill-tool) and cut ceramics and substrates for [integrated](https://www.merriam-webster.com/dictionary/integrated) circuits; the [aircraft industry](https://www.britannica.com/technology/aerospace-industry) uses CNC-controlled lasers to cut profiles and to drill holes in engine parts.

**Plasma arc machining (PAM)**

PAM is a method of cutting metal with a [plasma-arc](https://www.britannica.com/science/plasma-state-of-matter), or tungsten inert-gas-arc, torch. The torch produces a high-velocity jet of high-temperature ionized gas (plasma) that cuts by melting and displacing material from the workpiece. Temperatures obtainable in the plasma zone range from 20,000° to 50,000° F (11,000° to 28,000° C). The process may be used for cutting most metals, including those that cannot be cut efficiently with an oxyacetylene torch. With heavy-duty torches, aluminum alloys up to six inches (15 centimetres) thick and [stainless steel](https://www.britannica.com/technology/stainless-steel) up to four inches (10 centimetres) thick have been cut by the PAM process. The process is used for the profile cutting of flat plate, for cutting grooves in stainless steel, and, on lathes, for turning large, hardened steel rolls.

**Other methods of**[**machining**](https://www.britannica.com/technology/machining)

**Ultrasonic machining (USM)**

In USM, material is removed from a workpiece with particles of [abrasive](https://www.britannica.com/technology/abrasive) that vibrate at high frequency in a water slurry circulating through a narrow gap between a vibrating tool and the workpiece. The tool, shaped like the cavity to be produced, oscillates at an amplitude of about 0.0005 to 0.0025 inch (0.013 to 0.062 millimetre) at 19,000 to 40,000 hertz (cycles per second). The tool vibrates the abrasive grains against the surface of the workpiece, thus removing material. Ultrasonic machining is used primarily for cutting hard, brittle materials that may be conductors of electricity or insulators. Other common applications of USM include cutting semiconductor materials (such as germanium), [engraving](https://www.britannica.com/art/engraving), drilling fine holes in glass, and machining ceramics and [precious](https://www.merriam-webster.com/dictionary/precious) stones.

A modified version of the process is ultrasonic twist drilling, in which an ultrasonic tool is rotated against a workpiece without an abrasive slurry. Holes as small as 80 micrometres have been drilled by this type of USM.

**Chemical machining (CHM)**

This nonelectrical process removes metal from selected or overall areas by controlled [chemical action](https://www.britannica.com/science/chemical-reaction). Masking tape can be used to protect areas not to be removed. The method is related to the process used for making metal printing and engraving plates. Two types of chemical machining processes include chemical blanking, which is used for cutting blanks of thin metal parts, and chemical milling, which is used for removing metal from selected or overall areas of metal parts.

**Photochemical machining (PCM)**

PCM is an extension of CHM that uses a series of photographic and chemical etching techniques to produce components and devices in a wide range of metals, especially stainless steel.

**Water-jet machining**

In the water-jet machining process, water is forced through tiny nozzles under very high pressures to cut through materials such as polymers, brick, and paper. Water-jet machining has several advantages over other methods: it generates no heat, the workpiece does not deform during machining, the process can be initiated anywhere on the workpiece, no premachining preparation is needed, and few burrs form during the process. An abrasive is occasionally added to the water to improve the rate of material removal, especially in finishing work. The offshore industry uses seawater as the working fluid when applying this technique.