Technology of MACHINE TOOLS

NINTH EDITION

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TECHNOLOGY of MACHINE TOOLS

ninth edition

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Mc Graw Hill

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preface

Today's modern machine shops and tool and die shops are now environmentally controlled with dedicated metrology labs for quality control and inspection. They have integrated the use of more computer numerical control (CNC) machine tools, but they have still retained the ability to use conventional machines. A modern jobbing shop today will still have conventional machines such as mills, lathes, assorted drill presses, saws, and some of the precision equipment used prior to CNC (such as surface grinders, jig borers, and cylindrical and tool and cutter grinders).

Because the technology of machining is changing rapidly, the machinist (student) must learn to operate a wide range of machine tools and understand the unique cutting properties of these different machines, cutting tools, and workpiece materials as well as be able to use conventional hand tools and measuring tools.

The purposes of this text are to assist instructors in providing basic training on conventional machine tools, to cover basic programming for CNC machines (such as turning and machining centers), and to introduce new manufacturing technologies and processes to remain competitive in the global environment.

The use of computers continues to change how machine tools are used to manufacture products. Computers have improved until they are now highly sophisticated units capable of controlling the operation of a single machine, a group of machines, or even a complete manufacturing plant. Section 17, "Computer-Age Machining," now includes not only computer numerical control machine tools, such as turning and machining centers, but also newer manufacturing technologies. To increase manufacturing productivity, machine tools have been equipped with modular tooling and work-holding systems, as well as new cutting tools to produce accurate parts faster and at competitive prices.

Today's industries are putting more emphasis on using new manufacturing technologies and manufacturing intelligence systems to improve their productivity and remain competitive in the world. Section 17 gives an overview of 9 technologies or processes that are giving manufacturers an advantage over their competition. A few of these are additive manufacturing, Industry 4.0, multi-tasking, and robotics. Through the use of DVDs and online videos, students can learn how the machine tool trade will be changing in the future.

This book is based on the authors' many years of trade experience and experience as specialists in teaching. To keep up-to-date with technological change, the authors have researched the latest technical information available and have visited industries that are leaders in their field. Key personnel in manufacturing firms and leading educators reviewed many sections of this book, so that accurate and up-to-date information is presented. The authors are grateful to the reviewers for the technical and practical suggestions that were incorporated into the text.

The business and manufacturing world today is very different from what it was as little as 5 or 10 years ago. Ever more highly productive advanced technology and global competition are the driving forces behind this never-ending change. It seems that new technological developments are occurring every month, and the days when we used to do the same thing month after month are gone.

Globalization and the fierce competition it has brought have created a need for industry to produce high-quality products quickly and at less cost. This is a real challenge for some industries that have not kept pace with the constant-changing technology and that still hope 5- to 10-year-old technology will keep them in business. In order to survive, we must develop and use manufacturing systems that produce better products, faster, and at lower cost than our competitors. These highly productive systems are available to anyone in the world. Those companies that use them first are very likely to survive, while those that do not will gradually fade away.

To make this course interesting and challenging for students, online videos can be used to cover new technologies. DVDs and videos are also available on loan or for a small fee from technical societies, manufacturers, and publishers. The instructor's manual includes sources of videos, along with answers to the review questions in the text. A student workbook is also available.

Steve F. Krar
Arthur R. Gill
Peter Smid
Jonathan A. Gill
Robert J. Gerritsen

about the authors

STEVE F. KRAR

Steve F. Krar spent 15 years in the trade, first as a machinist and finally as a tool and die maker. After this period, he entered Teachers' College and graduated from the University of Toronto with a Specialist's Certificate in Machine Shop Practice. During these 20 years of teaching, Mr. Krar was active in vocational and technical education and served on the executive committee of many educational organizations. For 10 years, he was on the summer staff of the College of Education, University of Toronto, involved in teacher training programs. Active in machine tool associations, Steve Krar is a Life Member of the Society of Manufacturing Engineers and former associate director of the GE Superabrasives Partnership for Manufacturing Productivity. He was inducted into the Canadian Manufacturers Hall of Fame in March 2009.

Mr. Krar's continual research over the past 50 years in manufacturing technology has involved many courses with leading world manufacturers and an opportunity to study under Dr. W. Edwards Deming. Mr. Krar spent a week researching Nanotechnology at leading research centers, universities, and industry in Switzerland. He is coauthor and consultant of over 80 technical books, such as *Machine Shop Training, Machine Tool Operations, CNC Simplified, Superabrasives—Grinding and Machining,* and *Exploring Advanced Manufacturing Technologies,* some of which have been translated into 5 languages and used throughout the world.

ARTHUR R. GILL

Arthur R. Gill served an apprenticeship as a tool and die maker. After 10 years in the trade, he entered the Ontario Community College system. Mr. Gill served as a professor and coordinator of precision metal trades and apprenticeship training for 30 years at Niagara College in St. Catharines. He was a member of the Ontario Precision Metal Trades college curriculum committee for apprenticeship training and Heads of Apprenticeship Training. Mr. Gill is a member of the Society of Manufacturing Engineers and worked closely with industry to continually improve manufacturing technology. He spent time researching new technologies in Switzerland at leading research centers, universities, and industries.

Mr. Gill has coauthored a number of textbooks, including *CNC Technology and Programming, Computer Numerical Control Simplified,* and *Exploring Advanced Manufacturing Technology* with Steve Krar. In 1991, he was invited by China to assist in developing a Precision Machining and Computer Numerical Control (CNC) training facility at Yueyang University in Hunan Province.

Other Highlights (Krar and Gill)

- Consulting editor, manufacturing technology, for Industrial Press, New York, and contributing editor, *Advanced Manufacturing Magazine,* Burlington, Ontario
- Judge at the annual SkillsUSA competition for CNC programming and machining, held in Kansas City
- Research in new developments in Manufacturing Technology in North America and Nanotechnology at universities, industries, and the IBM Research Lab in Switzerland

PETER SMID

Peter Smid graduated from high school with a specialty in machine shop training. He then entered industry, completed an apprenticeship program, and gained valuable experience as a machinist skilled on all types of machine tools. Mr. Smid immigrated to Canada in 1968 and spent the next 26 years employed in the machine tool industry as a machinist and tool and die maker.

In the early 1970s, he became involved in Computer Numerical Control (CNC) as a programmer/operator and devoted the next 18 years to becoming proficient in all aspects of computerized manufacturing. In 1989, he became an independent consultant, and hundreds of companies have used Mr. Smid's CNC and CAD/CAM skills to improve their manufacturing operations. He wrote a comprehensive, 500-page CNC programming handbook, which is rapidly becoming the Bible of the trade, as well as books on Fanuc CNC Custom Macros and CNC Control Setup.

In 1995, he became a consultant/professor of Advanced Manufacturing focusing on industrial and customized training in CNC, CAD/CAM, and Agile Manufacturing. His many years of teaching, training, lecturing, and designing curriculum give him the opportunity to pass along his vast knowledge of modern manufacturing technology to students of all ages.

JONATHAN A. GILL

Jonathan A. Gill graduated from high school with an Ontario Secondary School Diploma. He entered Ryerson University in the industrial engineering program and then went into geographical analysis. Mr. Gill attended Humber College for electronics engineering and then spent 2 years at Mohawk College for computer networking and security analysis.

Mr. Gill is currently an independent contractor providing factory floor networking and information technology for the aerospace and automotive industry, jobbing shops, and production discrete manufacturing facilities.

Mr. Gill assisted the authors with the research, artwork, and final production of manuscript for the textbook *Computer Numerical Control Simplified* and is coauthor of the book *Changing World of Manufacturing*.

ROBERT J. GERRITSEN

Robert J. Gerritsen is a Professor of Mechanical Engineering with the School of Engineering Technology at Mohawk College in Hamilton, Ontario, Canada, where he specializes in the areas of computer-aided design and 3D printing.

Upon graduation from Mohawk College's Mechanical Engineering Design program in 1986, Mr. Gerritsen spent more than 25 years in industry, primarily in engineering design and management. After completing his MBA, Mr. Gerritsen continued to be active in the areas of research and product development before entering academia. Mr. Gerritsen now spends his time educating young engineering students in the areas of CAD/CAM/CAE, mechanical design, 3D printing/additive manufacturing, and virtual and rapid prototyping.

Professor Gerritsen was also the founding faculty member of Mohawk College's Additive Manufacturing Resource Center (AMRC), where he received the President's Award of Excellence in 2015.

NEW TO THE NINTH EDITION OF *TECHNOLOGY OF MACHINE TOOLS*

The text has been updated throughout to reflect the latest standards and processes and includes up-to-date coverage of computer numerical control (CNC) machines. Some other highlights of this new edition are:

- A discussion of Creep feed grinding and its advantages in Unit 73
- New and emerging technologies added in Unit 93
- Hot Wire Deposition (HWD) in Unit 94
- Two new forms of Micro-machining in the Electrical Discharge Machining (EDM) processes are detailed in Unit 97

The ninth edition of *Technology of Machine* Tools is now available with Connect, McGraw Hill Education's integrated assignment and assessment platform. This will include end-of-chapter assessment content, as well as assessment from the Student Workbook. Connect also offers SmartBook for the new edition, which is the first adaptive reading experience proven to improve grades and help students study more effectively.

Additional instructor resources are also available through Connect, including:

- An Instructor's Manual with teaching tips, answers to review questions, and additional projects.
- Lecture PowerPoint Slides for instructor use in class.

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The authors wish to express their sincere thanks and appreciation to Alice H. Krar for her untiring devotion in reading, typing, and checking the manuscript for previous editions. Without her supreme effort, this book would not have been possible.

The authors wish to thank all the teachers and industrial reviewers who took their valuable time to offer concrete suggestions for the manuscript, which we were happy to include. Their suggestions will make this book, which is considered to be a world leader, even more valuable as an educational tool.

Our sincere thanks go to the following firms that reviewed sections of the manuscript and offered suggestions that were incorporated to make this text as accurate and up-to-date as possible: ABB Robotics; American Iron & Steel Institute; Buffalo Abrasives; Cincinnati Machines; Dorian Tool International; FBT Inc.; GE Superabrasives; Moore Tool Co.; Norton Co.; Nucor Corporation; and Stelco, Inc.

We also extend our thanks to the team at McGraw Hill: Beth Bettcher, Portfolio Manager; Erin Kamm, Product Developer; Lisa Granger, Marketing Manager; Maria McGreal, Content Project Manager; and all the rest who assisted in getting this revision published.

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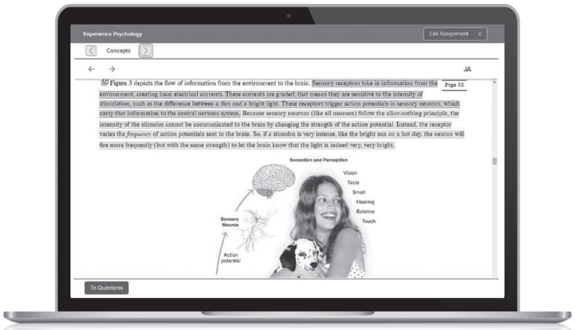

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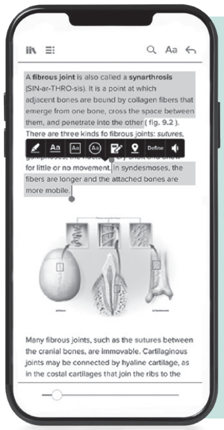

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- Jordan Cunningham, Eastern Washington University

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Section 1

(RAUSINPHOTO/Getty Images)

INTRODUCTION TO MACHINE TOOLS

The progress of humanity throughout the ages has been governed by the types of tools available. Ever since primitive people used rocks as hammers or as weapons to kill animals for food, tools have governed our standard of living. The use of fire to extract metals from ore led to the development of newer and better tools. The harnessing of water led to the development of hydropower, which greatly improved humanity's well-being.

With the industrial revolution in the mid-18th century, early machine tools were developed and were continually improved. The development of machine tools and related technologies advanced rapidly during and immediately after World Wars I and II. Since World War II, processes such as computer numerical control, electro-machining, computer-aided design (CAD), computer-aided manufacturing (CAM), and flexible manufacturing systems (FMS) greatly altered manufacturing methods.

Today we are living in a society greatly affected by the development of the computer. Computers affect the growing and sale of food, manufacturing processes, and entertainment. Although the computer influences our everyday lives, it is still important that you, as a student or an apprentice, be able to perform basic operations on standard machine tools. This knowledge will provide the necessary background for a person seeking a career in the machine tool trade.

UNIT 1

History of Machines

OBJECTIVES

After completing this unit, you will be familiar with:

1. The development of tools throughout history
2. The standard types of machine tools used in shops
3. The newly developed space-age machines and processes

The high standard of living we enjoy today did not just happen. It has been the result of the development of highly efficient machine tools over the past several decades. Processed foods, automobiles, telephones, televisions, household appliances, clothing, books, and practically everything else we use are produced by machinery.

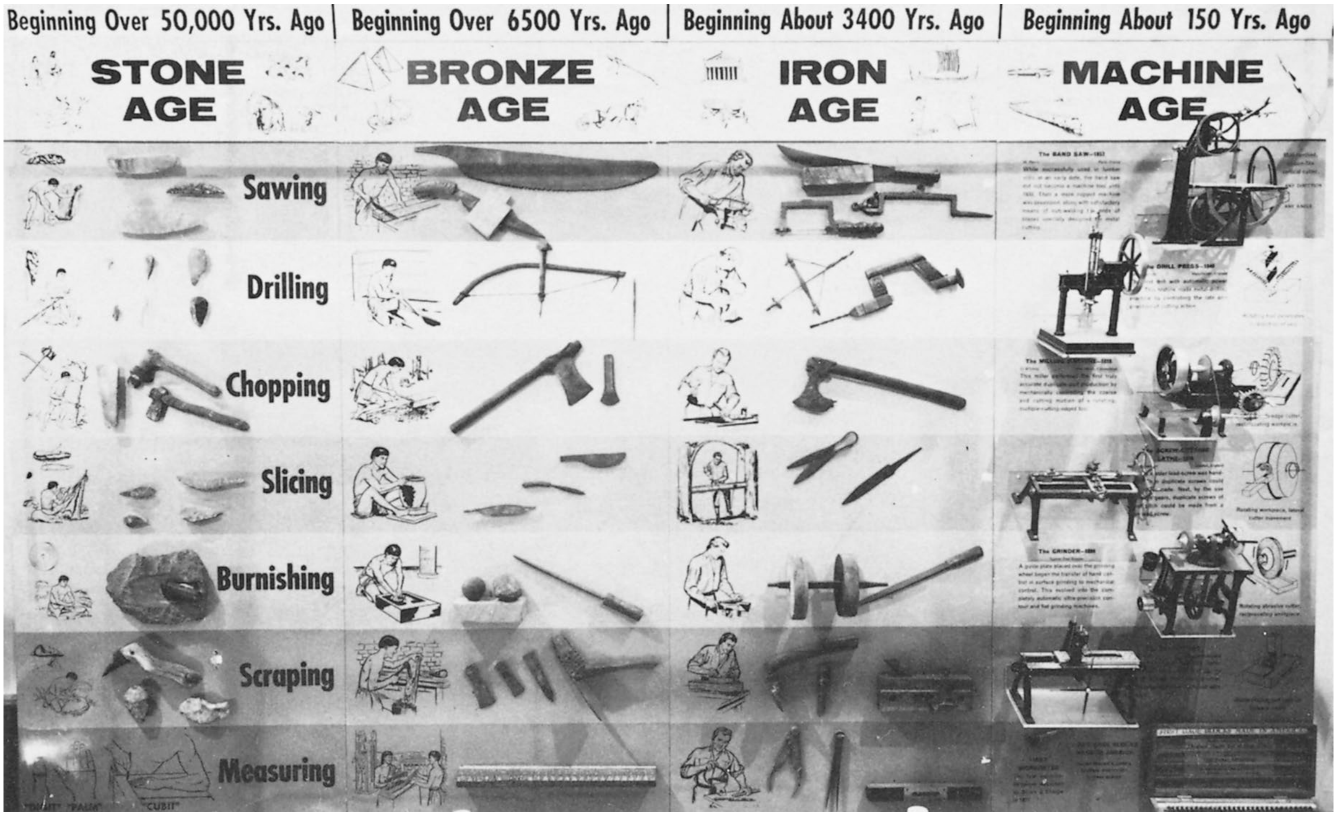
The history of machine tools began during the stone age (over 50,000 years ago), when the only tools were hand tools made of wood, animal bones, or stone (Fig. 1-1 on page 5).

Between 4500 and 4000 B.C., stone spears and axes were replaced with copper and bronze implements, and power supplied by humans was in a few cases replaced with animal power. It was during this bronze age that human beings first enjoyed "power-operated" tools.

Around 1000 B.C., the iron age dawned, and most bronze tools were replaced with more durable iron implements. After smiths learned to harden and temper iron, its use became widespread. Tools and weapons were greatly improved, and animals were domesticated to provide power for some of these tools, such as the plow. During the iron age, all commodities required by humans, such as housing and shipbuilding materials, wagons, and furniture, were handmade by the skilled craftspeople of that era.

About 300 years ago, the iron age became the machine age. In the 17th century, people began exploring new sources of energy. Water power began to replace human and animal power. With this new power came improved machines and, as production increased, more products became available. Machines continued to be improved, and the boring machine made it possible for James Watt to produce the first steam engine in 1776, beginning the industrial revolution. The steam engine made it possible to provide power to any area where it was needed. With quickening speed, machines were improved and new ones invented. Newly designed pumps reclaimed thousands of acres of the Netherlands from the sea. Mills and plants which had depended on water power were converted to steam power to produce flour, cloth, and lumber more efficiently. Steam engines replaced sails and steel replaced wood in the shipbuilding industry. Railways sprang up, unifying countries, and steamboats connected the continents. Steam-driven tractors and improved farm machinery lightened the farmer's task. As machines improved, further sources of power were developed. Generators were made to produce electricity, and diesel and gasoline engines were developed.

With further sources of energy available, industry grew and new and better machines were built. Progress

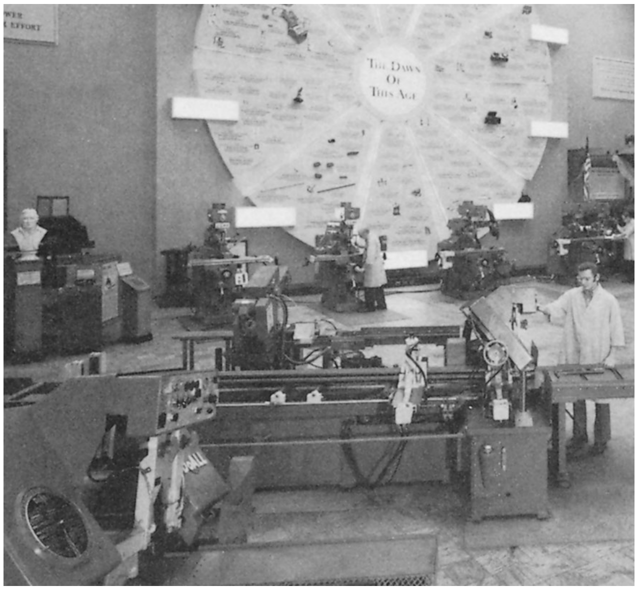


■ **Figure 1-1** The development of hand tools over the years. *(Courtesy of DoAll Company)*

continued slowly during the first part of the 20th century except for spurts during the two world wars. World War II sparked an urgent need for new and better machines, which resulted in more efficient production (Fig. 1-2).

Since the 1950s, progress has been rapid and we are now in the space age. Calculators, computers, robots, and automated machines and plants are commonplace. The atom has been harnessed and nuclear power is used to produce electricity and to drive ships. We have traveled to the moon and outer space, all because of fantastic technological developments. Machines can mass produce parts to millionths of an inch accuracy. The fields of measurement, machining, and metallurgy have become sophisticated. All these factors have produced a high standard of living for us. All of us, regardless of our occupation or status, are dependent on machines and/or their products (Fig. 1-3).

Through constant improvement, modern machine tools have become more accurate and efficient. Improved production and accuracy have been made possible through the application of hydraulics, pneumatics, fluidics, and electronic devices such as computer numerical control to basic machine tools.



■ **Figure 1-2** New machine tools were developed during the mid-20th century. *(Courtesy of DoAll Company)*

■ **Figure 1-3** Machine tools produce tools and machines for manufacturing all types of products. *(Courtesy of DoAll Company)*

▸▸ Common Machine Tools

Machine tools are generally power-driven metal-cutting or -forming machines used to shape metals by:

> The removal of chips
> Pressing, drawing, or shearing
> Controlled electrical machining processes

Any machine tool generally has the capability of:

> Holding and supporting the workpiece
> Holding and supporting a cutting tool
> Imparting a suitable movement (rotating or reciprocating) to the cutting tool or the work
> Feeding the cutting tool or the work so that the desired cutting action and accuracy will be achieved

The machine tool industry is divided into several different categories, such as the general machine shop, the toolroom, and the production shop. The machine tools found in the metal trade fall into three broad categories:

1. *Chip-producing machines,* which form metal to size and shape by cutting away the unwanted sections. These machine tools generally alter the shape of steel-produced products by casting, forging, or rolling in a steel mill.
2. *Non-chip-producing machines,* which form metal to size and shape by pressing, drawing, punching, or shearing. These machine tools generally alter the shape of sheet steel products and produce parts which need little or no machining by compressing granular or powdered metallic materials.
3. *New-generation machines,* which were developed to perform operations that would be very difficult, if not impossible, to perform on chip- or non-chip-producing machines. Electro-discharge, electro-chemical, and laser machines, for example, use either electrical or chemical energy to form metal to size and shape.
4. *Multi-tasking machines,* a combined machining and turning center, capable of both subtractive and additive machining can produce virtually any shape of part, starting with a rough piece of material to a finished part in a single machine setup. These machines consist of a turning center with two independent spindles and a vertical machining center having a rotary tool spindle. They combine information technology (IT) and manufacturing technology (MT) for the efficient multiple-face machining of workpieces. Besides the conventional turning and milling operations, it is possible to hob gears, machine molds, harden a workpiece, and cylindrical grind in the same work setup.

The performance of any machine tool is generally stated in terms of its metal-removal rate, accuracy, and repeatability. *Metal-removal rate* depends upon the cutting speed, feed rate, and depth of cut. *Accuracy* is

■ **Figure 1-4** Common machine tools found in a machine shop. *(Courtesy of DoAll Company)*

determined by how precisely the machine can position the cutting tool to a given location once. *Repeatability* is the ability of the machine to position the cutting tool consistently to any given position.

A general machine shop contains a number of standard machine tools that are basic to the production of a variety of metal components. Operations such as turning, boring, threading, drilling, reaming, sawing, milling, filing, and grinding are most commonly performed in a machine shop. Machines such as the drill press, engine lathe, power saw, milling machine, and grinder are usually considered the *basic machine tools* in a machine shop (Fig. 1-4).

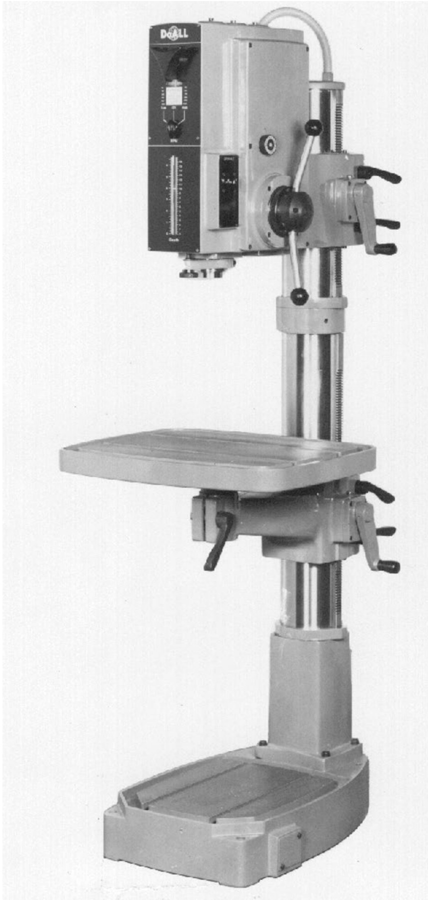
▸▸ Standard Machine Tools

DRILL PRESS

The drill press or drilling machine (Fig. 1-5), probably the first mechanical device developed prehistorically, is used primarily to produce round holes. Drill presses range from the simple hobby type to the more complex automatic and numerical control machines used for production purposes. The function of a drill press is to grip and revolve the cutting tool (generally a twist drill) so that a hole can be produced in a piece of metal or other material. Operations such as drilling, reaming, spot facing, countersinking, counterboring, and tapping are commonly performed on a drill press.

ENGINE LATHE

The engine lathe (Fig. 1-6) is used to produce round work. The workpiece, held by a work-holding device mounted on the lathe spindle, is revolved against a cutting tool, which produces a cylindrical form. Straight turning, tapering, facing, drilling, boring, reaming, and thread cutting are some of the common operations performed on a lathe.



■ **Figure 1-5** A standard upright drill press. *(Courtesy of DoAll Company)*

■ **Figure 1-6** An engine lathe is used to produce round work. *(Courtesy of Clausing Industrial, Inc.)*

METAL SAW

The metal-cutting saws are used to cut metal to the proper length and shape. There are two main types of metal-cutting saws: the bandsaw (horizontal and vertical) and the reciprocating cutoff saw. On the vertical bandsaw (Fig. 1-7) the workpiece is held on the table and brought into contact

■ **Figure 1-7** A contour-cutting bandsaw. *(Source: DoAll Company)*

with the continuous-cutting saw blade. It can be used to cut work to length and shape. The horizontal bandsaw and the reciprocating saw are used to cut work to length only. The material is held in a vise and the saw blade is brought into contact with the work.

MILLING MACHINE

The horizontal milling machine and the vertical milling machine (Fig. 1-8) are two of the most useful and versatile machine tools. Both machines use one or more rotating milling cutters having single or multiple cutting edges. The workpiece, which may be held in a vise, fixture, accessory, or fastened to the table, is fed into the revolving cutter. Equipped with proper accessories, milling machines are capable of performing a wide variety of operations, such as drilling, reaming, boring, counterboring, and spot facing, and of producing flat and contour surfaces, grooves, gear teeth, and helical forms.

GRINDER

Grinders use an abrasive cutting tool to bring a workpiece to an accurate size and produce a high surface finish. In the grinding process, the surface of the work is brought into contact with the revolving grinding wheel. The most common types of grinders are the surface, cylindrical, cutter and tool, and bench or pedestal.

Surface grinders (Fig. 1-9) are used to produce flat, angular, or contoured surfaces on a workpiece.

■ **Figure 1-8** A vertical milling machine. *(Steve Krar)*

■ **Figure 1-9** A surface grinder is used to grind flat surfaces. *(Source: South Bend Lathe Co.)*

Cylindrical grinders are used to produce internal and external diameters, which may be straight, tapered, or contoured.

Cutter and tool grinders are generally used to sharpen milling machine cutters.

Bench or pedestal grinders are used for offhand grinding and the sharpening of cutting tools such as chisels, punches, drills, and lathe and planer tools.

SPECIAL MACHINE TOOLS

Special machine tools are designed to perform all the operations necessary to produce a single component. Special-purpose machine tools include gear-generating machines; centerless, cam, and thread grinders; turret lathes; and automatic screw machines.

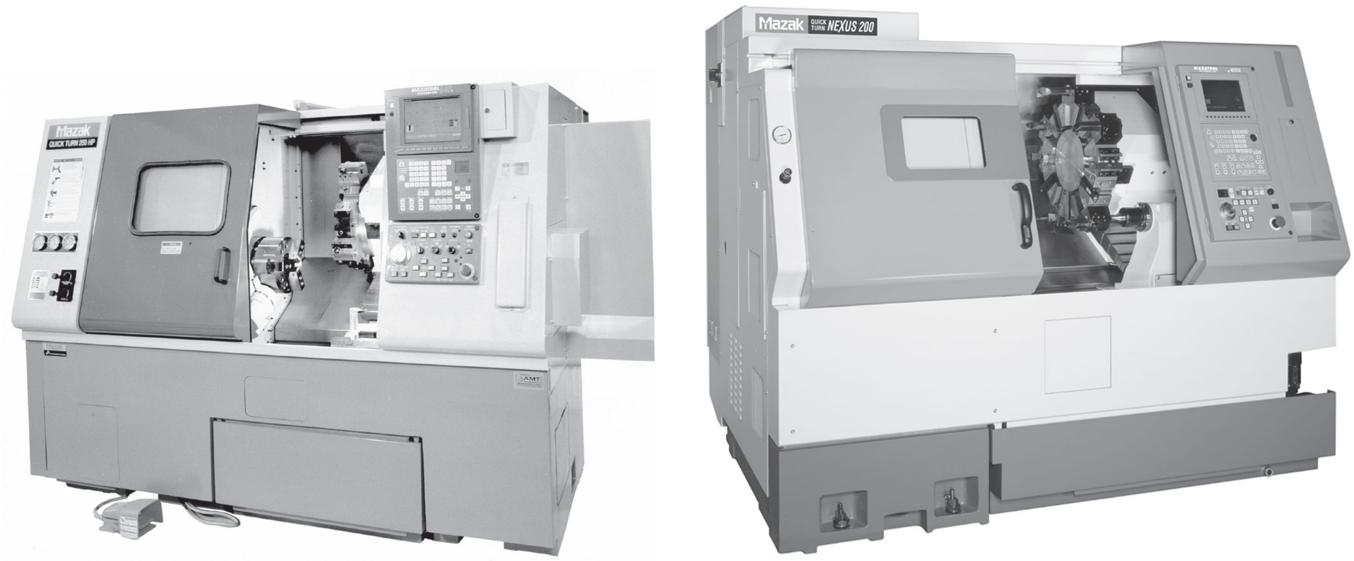
Computer Numerical Control Machines

Computer numerical control (CNC) has brought tremendous changes to the machine tool industry. New machine tools, controlled by computers, have allowed industry to produce parts quickly and to accuracies undreamed of only a few years ago. The same part can be reproduced, to the exact accuracy, any number of times if the part program has been properly prepared. The operating commands that control the machine tool are executed with amazing speed, accuracy, efficiency, and reliability. In many cases throughout the world, conventional machine tools operated by hand are being replaced by CNC machine tools operated by computers.

Chucking and turning centers (Fig. 1-10a and b), the CNC equivalent of the engine lathe, are capable of machining round parts in a minute or two that would take a skilled machinist an hour to produce. The *chucking center* is designed to machine parts in a chuck or some form of holding and driving device. The *turning center,* similar to a chucking center, is designed mainly for shaft-type workpieces that must be supported by some type of tailstock center.

The machining centers (Fig. 1-11a and b), the CNC equivalent of the milling machine, can perform a variety of operations on a workpiece by changing its own cutting tools. There are two types of machining centers, the vertical and the horizontal. The *vertical machining center* (Fig. 1-11a), whose spindle is in a vertical position, is used primarily for flat parts where three-axis machining is required. The *horizontal machining center* (Fig. 1-11b), whose spindle is in a horizontal position, allows parts to be machined on any side in one setup if the machine is equipped with an indexing table. Some machining centers have both vertical and horizontal spindles that can change from one to another very quickly.

Electrical discharge machines (EDM) (Fig. 1-12) use a controlled spark erosion process between the cutting tool and the workpiece to remove metal. The two most common EDM machines are the *wire-cut* and the vertical *ram type*. The wire-cut EDM uses a traveling wire to cut the internal and external shapes of a workpiece. The vertical ram-type EDM, commonly called the die sinking machine, generally feeds a form tool down into the workpiece to reproduce its form.



(a) (b)

Figure 1-10 Chucking (a) and turning centers (b) are capable of producing round parts quickly and accurately. *(Courtesy of Yamazaki Mazak Corporation)*