Metals Handbook®
Ninth Edition
Volume 16
Machining

First printing, March 1989

Library of Congress Cataloging-in-Publication Data

ASM INTERNATIONAL

Metals handbook.

Vol. 16: Prepared under the direction of
the ASM INTERNATIONAL Handbook Committee.
Includes bibliographies and indexes.
Contents: v. 1. Properties and selection—
v. 2. Properties and selection—nonferrous alloys
and pure metals—[etc.]—v. 16. Machining

1. Metals—Handbooks, manuals, etc.
I. ASM Handbook Committee.
II. ASM INTERNATIONAL. Handbook Committee.
TA459.M43 1978 669 78-14934
ISBN 0-87170-007-7 (v. 1)
SAN 204-7586

ISBN 0-87170-022-0

Printed in the United States of America

Foreword

In the 22 years since the 8th Edition *Metals Handbook* volume on machining was published, material removal operations have undergone dynamic changes. The mechanics of the cutting process are better understood, new cutting tool materials have been developed, machine controls and computer-aided engineering have rapidly advanced, and nontraditional machining methods continue to be refined. The difficult challenges faced by industry have necessitated these developments. Requirements for high-strength materials and the introduction of difficult-to-machine structural ceramics, composites, and electronic components have placed new and greater demands on machining technology, and have also spurred continued research and development in material removal techniques.

Volume 16 of the 9th Edition describes the evolution of machining technology comprehensively, with great attention to detail and accuracy. In addition to providing valuable information on recent developments, the Handbook devotes exhaustive coverage to more standard, traditional machining methods. This new Volume is also the final step in the fulfillment of ASM's commitment to provide the materials science community with the most authoritative information available on the processing and fabrication of metals. *Machining* completes the coverage of metalworking technology in the 9th Edition, taking its place alongside Volume 6 (*Welding, Brazing, and Soldering*), Volume 7 (*Powder Metallurgy*), Volume 14 (*Forming and Forging*), and Volume 15 (*Casting*).

This enormous undertaking was made possible by the combined efforts of many dedicated and selfless authors and reviewers, the ASM Handbook Committee, and the ASM editorial staff. Special recognition is also due to Metcut Research Associates Inc. and its president, William P. Koster, for permission to use tabulated data published in Volumes 1 and 2 of the *Machining Data Handbook* (3rd Edition). To all the men and women who contributed to the planning and preparation of this Volume, we extend our sincere thanks.

Richard K. Pitler
President,
ASM INTERNATIONAL

Edward L. Langer
Managing Director,
ASM INTERNATIONAL

The Ninth Edition of Metals Handbook
is dedicated to the memory of
TAYLOR LYMAN, A.B. (Eng.), S.M., Ph.D.
(1917-1973)
Editor, Metals Handbook, 1945-1973

Preface

Machining is one of the most important of the basic manufacturing processes. Almost every manufactured product contains components that require machining, often to great precision. Yet material removal operations are among the most expensive; in the U.S. alone, more than $100 billion will be spent this year on machining. These high costs put tremendous economic pressures on production managers and engineers as they struggle to find ways to increase productivity. Compounding their problems is the increasing use of more difficult-to-machine materials, such as nickel-base superalloys and titanium-base alloys in aerospace applications, structural ceramics, high-strength polymers, composites (both metal-matrix and resin-matrix), and electronic materials.

The present Volume of *Metals Handbook* has been structured to provide answers to the questions and challenges associated with current machining technology. Following a general introduction to machining processes, 9 major sections containing 78 articles cover all aspects of material removal. Much of this material is new. In fact, 30 articles in this Volume were not included in its 8th Edition predecessor. Noteworthy are the articles that have been added to describe the mechanics of the cutting process and advances in new materials, new processes, new methods of machine control, and computer-aided engineering.

The first Section of the Handbook reviews the fundamentals of the machining process. Included are articles describing the mechanics of chip formation, the forces, stresses, and power at the cutting tool, the principles of tool wear and tool life, and the relationship between cutting and grinding parameters and surface finish and surface integrity.

In the following Section, extensive data are provided on the applications, advantages and limitations, properties, tool geometries, and typical operating parameters for seven classes of tool materials: high-speed tool steels (both conventional wrought and powder metallurgy), cast cobalt alloys, cemented carbides, cermets, ceramics, and ultrahard tool materials (polycrystalline diamond and cubic boron nitride). Recent developments in wear-resistant coatings that are applied on high-speed steel, carbides, and ceramics are also discussed.

The third Section focuses on cutting and grinding fluids—their functions, selection criteria, and application. Coverage of proper maintenance procedures (storage, handling, recycling, and disposal) and the toxicology and biology associated with cutting and grinding fluids is included.

The next Section contains 21 articles that summarize the process capabilities, machines, cutting parameters and variables, and applications of traditional chip removal processes, such as turning, drilling, and milling. Advanced tooling used in multiple-operation machining, proper tool fixturing, and tool condition monitoring systems are also discussed, along with computer numerical controlled machining centers, flexible manufacturing systems, and transfer machines.

Although near net shape technology, including a greater use of precision casting, powder metallurgy, and precision forging, has lessened the need for some traditional machining operations, abrasive machining is being employed to a greater extent than in the past. The fifth Section of the Handbook examines the principles, equipment, and applications of grinding, honing, and lapping as well as recent developments in super-abrasives, used for precision grinding of difficult-to-machine and/or brittle materials.

The sixth Section looks at a variety of nontraditional machining methods that do not produce chips or a lay pattern in the surface. Mechanical, electrical, thermal, and chemical nontraditional techniques are described. Applications of these methods are emphasized, with practical examples involving nontraditional machining of metals, ceramics, glasses, plastics, and electronic components.

The next Section describes high-speed and high removal rate processes that have been developed to dramatically increase productivity. The effects of high-speed processing on chip formation and tool wear are discussed, along with materials that are being machined using these processes.

The eighth Section introduces the reader to two of the most rapidly developing and important areas in machining technology: machine controls and computer applications. Although the basic configurations of many machine tools have not changed significantly, the advent of numerical control and adaptive control has substantially improved manufacturing productivity and workpiece quality. Machine controls and the integration of CAD/CAM technology into machine tools are described in articles written with the engineer, not the software expert, in mind.

The last Section of the Handbook covers specific machining practices for 23 different metal systems, including all structural alloy systems, and relates the latest information on such topics as powder metals, metal-matrix composites, and honeycomb structures. Machining parameters (speeds, feeds, depth-of-cut, etc.) and the influence of microstructure on machinability are described in detail. Coverage includes difficult-to-machine aerospace alloys and high-silicon cast aluminum alloys, as well as materials such as beryllium and uranium that require special considerations during machining. Finally, an article on machinability test methods examines various types of tests used to study cutting tool and workpiece machining characteristics.

Much of the credit for the content and organization of this Handbook must be given to the Steering Committee that worked with the ASM staff during the early stages of the project. This group includes Professor George E. Kane, Lehigh University; Dr. William P. Koster, Metcut Research Associates Inc.; Dr. Ranga Komanduri, National Science Foundation; Dr. Richard P. Lindsay, Norton Company; Mr. Gary F. Benedict, Allied-Signal Aerospace Company, Garrett Engine Division; and Mr. Michael E. Finn, Stelco Inc. We are also indebted to the officers of the Society of Carbide and Tool Engineers for their assistance in the planning of the Volume. Finally, we gratefully acknowledge the countless hours of time and expertise loaned to the project by the nearly 200 authors and reviewers. Without the collective efforts of all these individuals, the successful completion of this Handbook would not have been possible.

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Policy on Units of Measure

By a resolution of its Board of Trustees, ASM INTERNATIONAL has adopted the practice of publishing data in both metric and customary U.S. units of measure. In preparing this Handbook, the editors have attempted to present data in metric units based primarily on Système International d'Unités (SI), with secondary mention of the corresponding values in customary U.S. units. The decision to use SI as the primary system of units was based on the aforementioned resolution of the Board of Trustees and the widespread use of metric units throughout the world.

For the most part, numerical engineering data in the text and in tables are presented in SI-based units with the customary U.S. equivalents in parentheses (text) or adjoining columns (tables). For example, pressure, stress, and strength are shown both in SI units, which are pascals (Pa) with a suitable prefix, and in customary U.S. units, which are pounds per square inch (psi). To save space, large values of psi have been converted to kips per square inch (ksi), where 1 ksi = 1000 psi. The metric ton (kg × 10^3) has been shown in megagrams (Mg). Some strictly scientific data are presented in SI units only.

To clarify some illustrations, only one set of units is presented on artwork. References in the accompanying text to data in the illustrations are presented in both SI-based and customary U.S. units. On graphs and charts, grids corresponding to SI-based units appear along the left and bottom edges. Where appropriate, corresponding customary U.S. units appear along the top and right edges.

Data pertaining to a specification published by a specification-writing group may be given in only the units used in that specification or in dual units, depending on the nature of the data. For example, the typical yield strength of aluminum sheet made to a specification written in customary U.S. units would be presented in dual units, but the sheet thickness specified in that specification might be presented only in inches.

Data obtained according to standardized test methods for which the standard recommends a particular system of units are presented in the units of that system. Wherever feasible, equivalent units are also presented.

Conversions and rounding have been done in accordance with ASTM Standard E 380, with attention given to the number of significant digits in the original data. For example, an annealing temperature of 1570 °F contains three significant digits. In this case, the equivalent temperature would be given as 855 °C; the exact conversion to 854.44 °C would not be appropriate. For an invariant physical phenomenon that occurs at a precise temperature (such as the melting of pure silver), it would be appropriate to report the temperature as 961.93 °C or 1763.5 °F. In some instances (especially in tables and data compilations), temperature values in °C and °F are alternatives rather than conversions.

The policy on units of measure in this Handbook contains several exceptions to strict conformance to ASTM E 380; in each instance, the exception has been made in an effort to improve the clarity of the Handbook. The most notable exception is the use of g/cm^3 rather than kg/m^3 as the unit of measure for density (mass per unit volume).

SI practice requires that only one virgule (diagonal) appear in units formed by combination of several basic units. Therefore, all of the units preceding the virgule are in the numerator and all units following the virgule are in the denominator of the expression; no parentheses are required to prevent ambiguity.

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C. Zimmerman
GTE Valenite
Emory W. Zimmers, Jr.
Lehigh University

Contents

Introduction to Machining Processes

J T. Black, Auburn University

MACHINING is a term that covers a large collection of manufacturing processes designed to remove unwanted material, usually in the form of chips, from a workpiece. Machining is used to convert castings, forgings, or preformed blocks of metal into desired shapes, with size and finish specified to fulfill design requirements. Almost every manufactured product has components that require machining, often to great precision. Therefore, this collection of processes is one of the most important of the basic manufacturing processes because of the value added to the final product. By the same token, machining processes are often the most expensive.

The majority of industrial applications of machining are in metals. Although the metal cutting process has resisted theoretical analysis because of its complexity, the application of these processes in the industrial world is widespread.

Machining processes are performed on a wide variety of machine tools. Figure 1 shows an example of a machine tool—a dual-turret numerically controlled (NC) lathe. Workpieces are held in workholding devices, such as a three-jaw chuck. The tools used to cut metal are in the turrets. Other examples of basic machine tools are milling machines, drill presses, grinders, shapers, broaching machines, and saws.

Each of the basic machine tool types has many different configurations. Lathes, for example, may be engine lathes, turret lathes, tracer lathes, or automatic-screw machines. Lathes have followed the trend of other machine tools, and NC lathes can now be routinely purchased.

The primary chip formation processes are listed below, with alternative versions in parentheses. Each process is performed on one or more of the basic machine tools. For example, drilling can be performed on drill presses, milling machines, lathes, and some boring machines:

- Turning (boring, facing, cutoff, taper turning, form cutting, chamfering, recessing, thread cutting)
- Shaping (planing, vertical shaping)
- Milling (hobbing, generating, thread milling)
- Drilling (reaming, tapping, spot facing, counterboring, countersinking)
- Sawing (filing)
- Abrasive machining (grinding, honing, lapping)
- Broaching (internal and surface)

Processes can be combined into multiple-capability machines, known as machining centers. The machining center shown in Fig. 2 is capable of performing the machining processes normally performed on a milling machine, drilling machine, and a boring mill and is numerically controlled. The position and velocity of the tool with respect to the work is under feedback control. Different tools can be automatically inserted into the spindle as needed to do different machining processes. The horizontal spindle machine shown in Fig. 2 was one of the first NC machining centers to be able to change workpiece pallets.

For each of the basic machine tool types, there are many different kinds of workholders, cutting tools, and cutting tool holders, resulting in a rather formidable list of equipment and processes. In this Volume, a Section entitled "Fundamentals of the Machining Process" is presented first, with the intent of putting these processes into perspective and helping the reader to understand the problems associated with using machining processes in the manufacture of products.

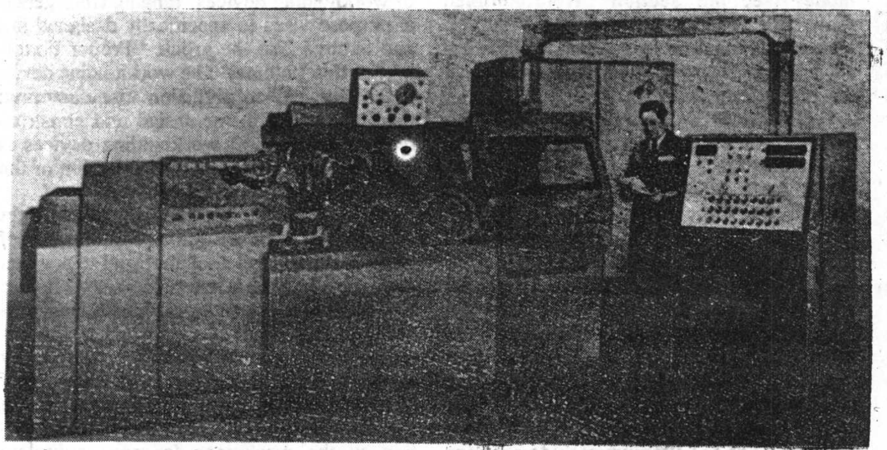

Fig. 1 A dual-turret NC turning center with 16 tool stations. Courtesy of Cincinnati Milacron

Overview of Machining Process Variables

Metal cutting processes can be viewed as consisting of independent (input) variables, dependent variables, and independent-dependent interactions or relationships. The engineer or machine tool operator has direct control over the input variables and can specify or select them when setting up the machining process. Several input variables are described below. Figure 3 summarizes the input/output relationships associated with metal cutting.

Independent Input Variables

Workpiece Material. The metallurgy and chemistry of the workpiece can either be specified or is already known. Quite often, a material is selected for a particular application chiefly because it machines well. Cast iron and aluminum, for example, are known to machine easily. Other metals, such as stainless steel or titanium, are difficult to machine. They often have large cutting forces or poor surface finishes, which can result in short cutting tool life, yet these metals are selected to meet other functional design criteria. Machining practice for specific workpiece materials are reviewed in the Section "Machining of Specific Metals and Alloys" in this Volume.

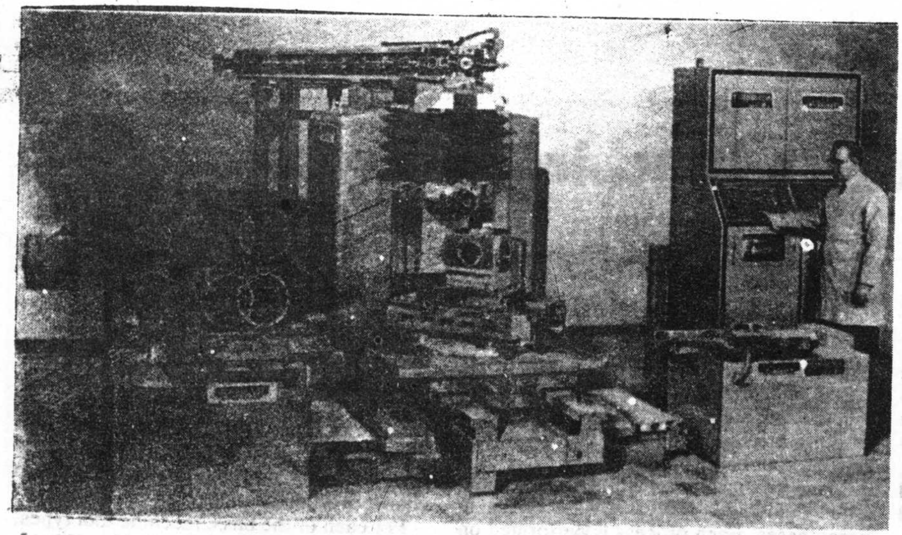

Fig. 2 Numerically controlled machining center that can change workpieces as well as cutting tools. Courtesy of Kearney and Trecker Corporation

Starting Geometry. The size and shape of the workpiece may be dictated by preceding processes (casting, forging, forming, and so forth) or may be selected from standard machining stock (for example, bar stock for screw machines). Usually this variable directly influences the machining process or processes that are selected, as well as the depths of cut.

Specific Machining Processes. The selection of machining processes required to convert the raw material into a finished product must be based on the geometry of the part (size and shape, rotational or nonrotational), the required finishes and tolerances, and the quantity of the product to be made. Machining processes can be grouped into three broad categories. These include traditional chip formation processes, abrasive machining processes, and nontraditional machining processes.

Chip Formation Processes. As described earlier, there are seven basic chip formation processes: turning, shaping, milling, drilling, sawing, broaching, and abrasive machining. The equipment and principles of operation associated with each of these processes (with the exception of abrasive machining, which is treated separately) are described in the Section titled "Traditional Machining Processes" in this Volume.

Abrasive machining is the basic process by which chips are formed by very small cutting edges that are integral parts of abrasive particles. The principles of abrasive machining, the fundamental differences between metal cutting and grinding, and the abrasives and equipment used for abrasive machining operations are described in the Section "Grinding, Honing, and Lapping" in this Volume.

Nontraditional Machining Processes. Machining processes that involve compression/shear chip formation have a number of inherent disadvantages. These include:

- High costs incurred with chip formation (high energy output and chip removal, disposal, and/or recycling)
- Heat buildup that often results in workpiece distortion
- High forces that create problems in holding the workpiece and which can also cause distortion
- Undesirable cold working and residual stresses in the workpiece that often necessitate further processing to remove the harmful effects
- Limitations as to the size and delicacy of the workpiece

In order to avoid these limitations, nontraditional machining processes are increasingly being used. Nontraditional methods usually do not produce chips or a lay pattern in the surface and often involve new energy modes (see the Section "Nontraditional Machining Processes" in this Volume). Volumetric material removal rates, however, are much lower than with traditional machining processes.

Tool Materials. The three most common cutting tool materials currently in use for production machining operations are high-speed steel (HSS), both in wrought and powder metallurgy (P/M) form; carbides; and coated tools. Cubic boron nitride (CBN), ceramics, and diamonds are also being widely employed. Generally speaking, HSS is used for general-purpose tools, for tools of complex design or for tools used when cutting speeds are more modest. Carbide and ceramic tool materials, which can operate at faster cutting speeds, come in a wide variety of grades and geometries. Titanium nitride and titanium carbide coatings for HSS and carbides are now commonplace. Selection of a tool material that provides reliable service while fulfilling the functional requirements is still an art. The harder the tool material, the better it can resist wear at faster cutting speeds. The faster the cutting speed, the higher the cutting temperature and the shorter the tool life. Retention of hardness at elevated temperatures as well as long tool life are desirable characteristics in cutting tools. See the Section "Cutting Tool Materials" in this Volume for descriptions of the processing, properties, and applications associated with the aforementioned materials.

Cutting Parameters. For every machining operation, it is necessary to select a cutting speed, a feed, and a depth of cut. Many factors impinge on these decisions because all of the dependent variables are influenced by them. Proper selection of variables also depends on the other input variables that have been selected; that is, the total amount of material to be removed, the workpiece and tool materials, and the machining process or processes. These need to be selected before preliminary choices for speed, feed, and depth of cut can be made.

Tool Geometry. Cutting tools are usually designed to accomplish specific operations, and thus the tool geometry (angles) is selected to accomplish specific machining functions. Generally speaking, large rake and clearance angles are preferred, but they are possible only on HSS tools. Tools made from carbides, ceramics, and other very hard materials must be given small tool angles, which keep the tool material in compression during machining and thereby avoid tensile failure and brittle fractures of the tool. The greater the precision required of the process, the better the geometry of the cutting edge itself must be.

Workholding Devices. Workpieces are located (held in specific position with respect to the tools) and clamped in workholding devices in or on the machine tools. For every machine tool, there are many different kinds of workholding devices, ranging from general-purpose vises to specifically designed jigs and fixtures (see the article "Proper Fixturing" in this Volume). The workholding devices are the key to precision manufacturing; thus, the selection (or design and construction) of the correct workholding devices is every bit as important as the selection of the right cutting tool and machine tool.

Cutting Fluids. The selection of the right cutting fluid for a particular combination of work material and tool material can mean the difference between success and failure in almost every production machining process. Cutting fluids serve to cool the workpiece, tool, and chips; reduce friction by means of lubrication; carry the chips away from the cutting region; help improve the surface finish; and provide surface protection to the workpiece (a more complete discussion may be found in the article

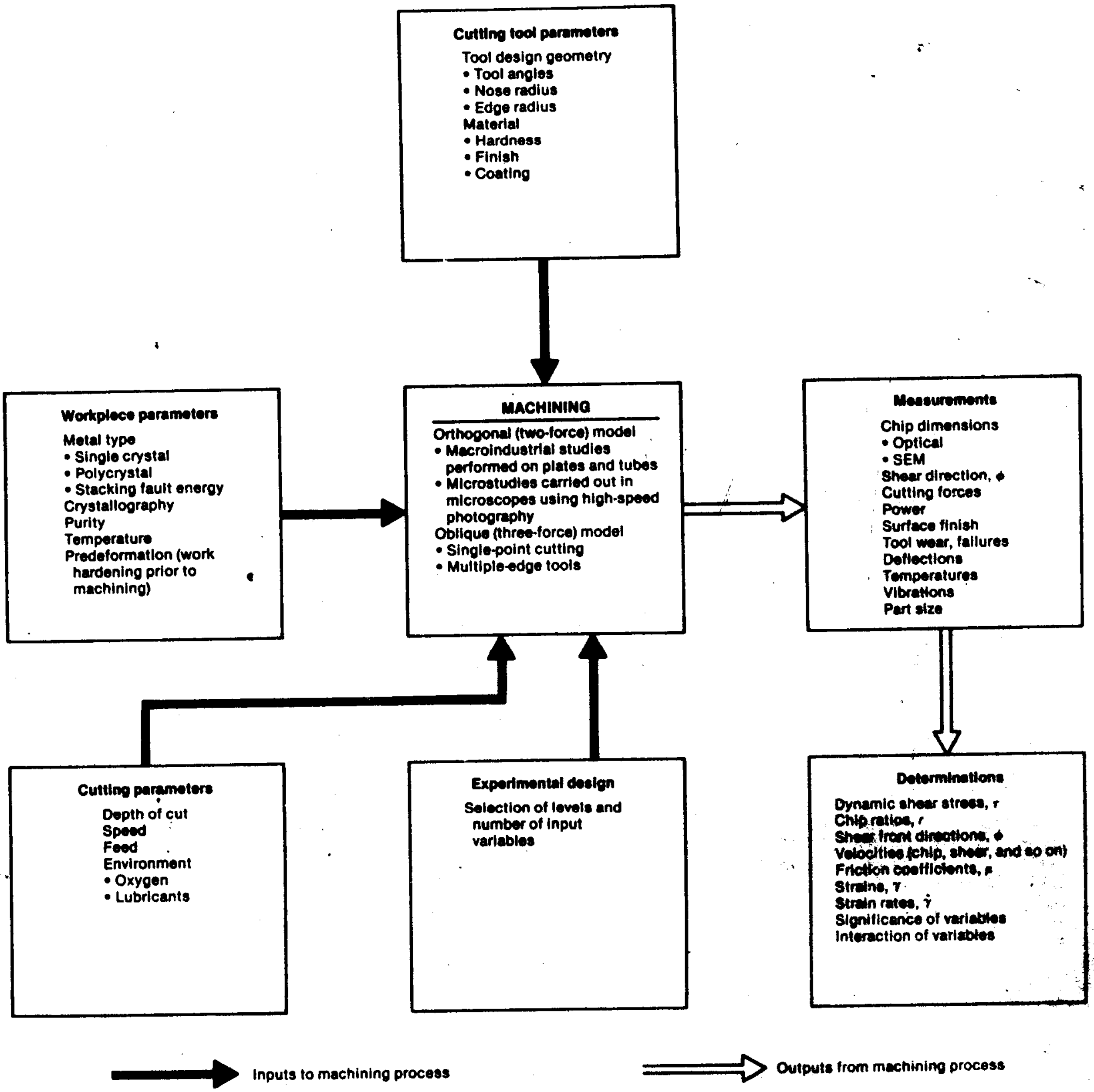

Fig. 3 Input/output relationships in metal cutting (machining)

"Metal Cutting and Grinding Fluids" in this Volume).

Dependent Variables

Dependent variables are determined by the process based on the prior selection of the input or independent variables. Thus, the manufacturing engineer's control over these is usually indirect. The important dependent variables are cutting force and power, size and properties of the finished product, surface finish, and tool wear and tool failure.

Cutting Force and Power. To machine metal at a specified speed, feed, and depth of cut, with a specified lubricant, cutting tool material, and geometry, generates cutting forces and consumes power. A change in any of the variables alters the forces, but the change is indirect in that the engineer does not specify the forces, only the parameters that generate those forces. Forces are important in that they influence the deflections in the tools, the workpieces, and the workholders, which in turn affect the final part size. Forces also play a role in chatter and vibration phenomena common in machining. Obviously, the manufacturing engineer would like to be able to predict forces (and power) so that he can safely specify the equipment for a manufacturing operation, including the machine tool, cutting tool, and workholding devices. The basic concepts associated with the modeling and understanding of cutting forces and power are explained in the article "Forces, Power, and Stresses in Machining" in this Volume.

Size and Properties of the Finished Product. Ultimately, the objective of machining is to obtain a machined surface of desired size and geometry with the desired mechanical properties. Because machining is a localized, plastic deformation process, every machined surface will have some residual deformation (stresses) left in it. These residual stresses are usually tensile in nature and can interact with surface flaws to produce part failure from fatigue or to cause corrosion. In addition, every process has some inherent process variability (variations about average size) that changes with almost all of the input variables. Thus, the manufacturing engineer must try to select the proper levels of input variables to produce a product that is within the tolerance specified by the designer and has satisfactory surface properties.

Surface Finish. The final finish on a machined surface is a function of tool geometry, tool material, workpiece material, machining process, speed, feed, depth of cut, and cutting fluid. Surface finish is also related to the process variability. Rough surfaces have more variability than smooth surfaces. Often it is necessary to specify multiple cuts, that is, roughing and finish cuts, to achieve the desired surface finish, or it may be necessary to specify multiple processes, such as following turning with cylindrical grinding, in order to obtain the desired finish. The effect of various machining processes on surface finish and on the properties of the final products are described in the article "Surface Finish and Surface Integrity" in this Volume.

Tool Wear and Tool Failure. The plastic deformation and friction inherent in machining generate considerable heat, which raises the temperature of the tool and lowers its wear resistance. The problem is subtle, but significant. As the tool wears, it changes in both geometry and size. A dull cutting edge and change in geometry can result in increased cutting forces that in turn increase deflections in the workpiece and may create a chatter condition. The increased power consumption causes increased heat generation in the operation, which accelerates the wear rate. The change in the size of the tool changes the size of the workpiece. Again, the engineer has only indirect control over these variables. He can select slow speeds, which produce less heat and lower wear rates, but which decrease the production rates because the metal removal rate is decreased. Alternatively, the feed or depth of cut can be increased to maintain the metal removal rate while reducing the speed. Increasing either the feed or depth of cut directly increases the cutting forces. Therefore, while tool life may be gained, some precision may be lost due to increased deflection and chatter. Wear mechanisms, determination of modes of tool failure, and tool life testing are examined in the article "Tool Wear and Tool Life" in this Volume.

Relations Between Input Variables and Process Behavior

Understanding the connections between input variables and process behavior is important knowledge for the manufacturing engineer. Unfortunately, this knowledge is difficult to obtain. Machining is a unique plastic deformation process in that it is constrained only by the cutting tool and operates at very large strains and very high strain rates. The tremendous variety in the input variables results in an almost infinite number of different machining combinations. Basically, there are three ways to deal with such a complex situation.

Experience requires long-term exposure, because knowledge is basically gained by trial and error, with successful combinations transferred to other, "similar" situations. This activity goes on in manufacturing every time a new material is introduced into the production facility. It took years for industry to learn how to machine titanium. Unfortunately, the knowledge gained through one process may not transfer well to another even though their input variables appear very similar.

Experiments. Machining experiments are expensive, time consuming, and difficult to carry out. Tool life experiments, for example, are quite commonly done, yet tool life data for most workpiece/tool material combinations are not available. Even when laboratory data have been published, the results are not necessarily transferable to the particular machine tools and cutting tools on the shop floor. Tool life equations are empirically developed from turning experiments in which all input variables except cutting speed are kept constant. The experimental arrangement may limit the mode of tool failure to wear. Such results are of little value on the shop floor, where tools can and do fail from causes other than wear.

Theories. There have been many attempts to build mathematical models of the metal cutting process. Many of the theories are extensions of the mechanics presented in the following Section, "Fundamentals of the Machining Process." These theories try to predict the direction of the shearing process of metal cutting. These models range from crude, first-order approximation to complex, computer-based models using finite-element analysis. Recently, some modest successes have been reported in the literature in which accurate predictions of cutting forces and tool wear were made for certain materials. Clearly such efforts are extremely helpful in understanding how the process behaves. However, the theory of plastic deformation of metals (dislocation theory) has not yet been able to predict values for shear stresses and tool/chip interface from the metallurgy and deformation history of the material. Therefore, it has been necessary to devise two independent experiments to determine the shear strength (τ_s) of the metal at large strains and high strain rates and the sliding friction situation at the interface between the tool and chip (see the article "Mechanics of Chip Formation" in this Volume).

Future Trends

The metal cutting process will continue to evolve, with improvements in cutting tool materials and machine tools leading the evolution. More refined coatings on cutting tools will improve tool life and reliability, as will more robust, rigid machine tools. The challenge for machining will involve dealing with the new types of materials that will need to be machined, including aluminum and titanium alloys, alloy steels, and superalloys. These materials, because of improved processing techniques, are becoming stronger and harder and therefore more difficult to machine. The objective should be to design and build cutting tools that have less variability in their tool lives rather than longer tool lives. The increasing use of structural ceramics, high-strength polymers, composites, and electronic materials will also necessitate the use of nontraditional methods of machining. In addition, grinding will be employed to a greater extent than in the past, with greater attention to creep feed grinding and the use of superabrasives (diamond and cubic boron nitride).

As the cutting tools improve, the machine tools will become smarter, with on-board computers providing intelligent algorithms interacting with sensory data from the process. Programmable machine tools, if equipped with the proper sensors, are capable of carrying out measurements of the product as it is being produced. These product data will be fed back to the control program, which is then modified to improve the product or corrected for errors. Thus, the machine will be able to make the adjustments necessary to prevent defective products from being produced. The goal of such control programs should be improved quality (designed not to make a defect), rather than optimum speed or lowest cost. Advancements in computer-aided machining processes are discussed in the Section "Machine Controls and Computer Applications in Machining" in this Volume.

Another area in which significant advances will be made is the design of workholders that are capable of holding various parts without any downtime for setups. Included in this search for flexible fixtures will be workholding devices that can be changed over by a robot—the same robot used to load or unload parts from the machine.

Fundamentals of the Machining Process