

GRINDING

Grinding is the most widely used single method of all the different categories of metalworking processes, when basing the comparison on the number of machine tools in use. In this respect, grinding exceeds even such basic processes as turning or drilling.

Grinding is an abrasive process, thereby distinguished from most other metalworking processes. These latter processes are considered metalcutting because they operate by removing chips from the worked metallic part by means of distinctly shaped cutting edges of the tool. Grinding, however, removes the work material by means of abrasive grains. These grains, although not having distinct edge forms, also penetrate into and remove workpiece material elements that, while irregular in size, resemble in their shapes the chips produced by metalcutting operations.

Abrasives as tools of metalworking have wide applications in other processes. All metalworking processes which operate with abrasives as a tool material are designated "abrasive methods." Under the broad designation of abrasive methods, grinding processes, per se, are covered in this chapter. Abrasive methods used primarily for surface-finish refinement such as lapping, super finishing, etc., are covered in Volume III of this series, "Materials and Finishing."

Shaping work materials with abrasives such as hard natural minerals is probably the oldest method by which specific forms have been given to nonplastic materials, first to stone, then to metals. With primitive abrasive methods, weapons were made in ancient times, even in prehistoric ages.

The fact that abrasive methods in general and grinding, more particularly, occupy a prominent position in modern metalworking is due to the important and, in some respects, unique advantages which these methods of metalworking provide in many areas of industrial production. The more important advantages of abrasive methods for metalworking applications are pointed out in the following text in a sequence which is not intended to represent an order of importance. Every listed advantage does not benefit all the applications of abrasives as means of metalworking. Nevertheless the savings in cost and operation time, the high level of the methods'

adaptability, the often superior quality of the produced work surfaces, and several other properties of ground parts have significant positive merit in many applications. The manufacturing engineer should consider abrasive methods as a potentially promising alternative to other methods. This is true even in applications beyond those for which grinding and other abrasive methods are now recognized as the proper or only feasible metalworking procedure.

ADVANTAGES OF GRINDING AND OTHER ABRASIVE METHODS

Working hard materials. Grinding facilitates the machining of hardened steel, which is the work material of practically all precision parts used in machinery production. Considering the unavoidable distortions, surface damage, and dimensional variations resulting from heat treatment during the hardening process, without the availability of a means for correcting these deteriorations, the production of tightly toleranced parts with increased strength and wear resistance would not be feasible.

Wide range of stock removal rates. Metalworking by means of abrasives offers an extensive range of rates at which stock can be removed for widely different purposes. Grinding and related abrasive methods, as a category of metalworking processes, are well adapted for operations varying from grinding delicate sizes, forms, or surface-texture corrections, which require the removal of work surface material to a depth of about 0.001" (0.03 mm) or less (for example, by means of fine grinding or lapping), to abrasive machining, which provides stock removal rates comparable to those of any other metalworking method.

Size control significantly superior to other metalworking processes. Grinding can be carried out in a continuous, fully automated process with a consistent size-holding accuracy exceeding by far the level accomplished by any other system of metalworking, with the possible exception of diamond turning, which is applied very rarely. One reason for the high degree of dimensional and form accuracy maintained by grinding is the easily ensured uniform cutting capacity of the grinding wheel by truing and dressing. Truing and dressing are often performed in an automatic process; the

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Contributors of sections of this chapter are: John G. Burgess, Technical Sales Manager, Grinding Machines, Brown & Sharpe Mfg. Co.; Gerald C. Cotter, Manager of Test, Service and Quality Control, Machine Tool Operations, Bendix Corp.—Industrial Tools Div.; Paul H. DeRamo, Hill Division Manager, The Hill Acme Co.; Everett W. Emery, Sales Engineer, Cone-Blanchard Machine Co.; Dr. Francis T. Farago, CMfgE, Author: Abrasive Methods Engineering I & II, Senior Research Engineer, General Motors Corp. (Retired); Robert M. Gauvreau, Supervisor, Technical Services, Coated Abrasives Div., Norton Co.; Don Greenburg, Vice President, Engineering, Barnes Drill Co.; Robert S. Hahn, DSc., P.E., CMfgE, Consulting Engineer, Hahn Associates; Edward G. Hoffman, Technical Writer/Consultant, E.G. Hoffman Co.; Burton R. Leathley, Vice President, Oliver Instrument Co.; Dr. Richard Lindsay, Research Associate, Norton Co.; Robert M. Perry, Product Research Engineer, Moore Special Tool Co., Inc.; W. D. Pollard, Principal Engineer, Diamond Products Branch, Carborundum Co.; Thomas Z. Richards, Supervisor, Product Safety, Grinding Wheel Operations, Norton Co.; William A. Sluhan, Vice President and General Manager, Master Chemical Corp.; D. M. Syed, Project Manager, Rollway Bearing International; Thomas J. Turner, Systems Application Manager, AirTronics Div., American Gage & Machine Co., A Katy Industries Inc., Co.

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layer removed from the surface of the grinding wheel by truing is accurately controlled and can be compensated by automatic position correction.

The force exerted on the workpiece in fine grinding is considerably less than that exerted in metalcutting methods. Therefore, deflections of the part while it is being worked are minimized. Workpiece deflection, a condition interfering with strict size control, occurs to a much lower degree in grinding than in metalcutting processes used for comparable purposes.

Single operation for roughing and finishing. Grinding is adaptable to combining successive processes in a single operation, with a roughing phase followed by a finishing phase, carried out with changed cutting parameters at different stock removal rates. The last phase is usually preceded by wheel truing and position compensation, both performed automatically. Such removal rate variations in successive phases of a single operation, carried out on the same machine without necessitating the transferring and reloading of the workpiece, can make grinding preferable even for operations which, because of less rigorous tolerance and/or the nonhardened condition of the workpiece, could be accomplished by conventional metalcutting processes. However, operations such as abrasive machining and subsequent semifinishing can be consolidated into a single operation instead of being performed on two or more metalcutting machines.

Changing rate of wheel penetration during the grinding process. Conventional metalcutting processes operate with a constant depth of tool penetration set at a level which balances two divergent requirements: greatest depth possible for increased rate of stock removal and the observance of specifications regarding dimensional accuracy and surface texture, these latter limiting the applicable depth of cut. In grinding, particularly in plunge grinding, the depth of total penetration results from the rate of wheel advancement during the operation and the time span of its application. Varying the rate of wheel advancement during the operation by decreasing it from a maximum at the start of a process to zero at the end of the process produces economically a satisfactory high average rate of stock removal while assuring the specified conditions of the finished part.

Unattended operation of the machine tool. Grinding in general, and external grinding in particular, employs tools with extended effective service life, because grinding wheels permit a significant number of on-the-spot trueings before requiring toolchanging. The useful life of grinding wheels exceeds, in most cases by a significant factor, that obtained from cutting

tools; traditional metalcutting tools are not adapted to reconditioning while installed in the machine tool.

The extended tool life is only one of several conditions which facilitates unattended operation of grinding machines. Other conditions beneficial to automatic operation in grinding are the simple loading and holding of many types of workpieces, in-process gaging, and automatic size correction. A common practice is to have a batch of grinding machines operating while attended only by a single, semi-skilled person. With metalcutting-type machine tools, this level of unattended operation generally can be approximated by use of rather specialized control instruments.

Controlling the texture of the produced work surface. The roughness and particularly the lay of the work surface produced by grinding generally is a function of the metalworking method employed and of the applied cutting parameters. Grinding and other abrasive processes offer a large amount of flexibility in the selection of results. It is generally known that abrasive methods such as fine grinding, honing, and particularly lapping are often the only practical processes for producing very fine surfaces. Less commonly realized is the fact that in many cases the proper lay of the finished work surface also has an important functional role, such as for adequate lubricant retainment or for assuring well sealing surfaces. In these latter respects, many applicational choices of abrasive methods exist, for example, between peripheral and face grinding, honing with various cross-hatch patterns, grinding and lapping, or plunge and traverse grinding.

Form producing capabilities of grinding. The advantages of grinding over alternate metalcutting processes reveal themselves in several respects when workpieces having irregular cross-sectional contours (profiles) have to be produced. Of course, there are the advantages characterizing all precision grinding operations, namely greater consistent accuracy, both of size and form, and the capability of producing the final form in the hardened state of the workpiece. In many cases, these characteristics alone will dictate that grinding is the preferable, or even exclusively applicable, method for finishing workpieces with particular profiles.

A further category of advantages results from the fact that a particular wheel profile is produced and easily reproduced by form-truing which, for small or medium-volume production, can be developed by means of relatively inexpensive tools, specifically profile bars. In contrast, profile tools for metalcutting operations, including in their simplest version as turning tools, are more expensive to produce in quantities satisfying the need of even medium-sized production runs. Substantially

Reviewers of sections of this chapter are: Wayne W. Althen, Director, Abrasive Research and Development, Sunnen Products Co.; Carol Anderson, Office Manager, Timesavers, Inc.; Howard R. Anderson, Vice President—Sales, Cone-Blanchard Machine Co.; J. E. Barber, Vice President, Black & Webster, Inc.; Roald Cann, Research Supervisor, Bryant Grinder Corp.; Charles F. Carter, Jr., Technical Director, Cincinnati Milacron, Inc.; Gerald C. Cotter, Manager of Test, Service and Quality Control, Machine Tool Operations, Bendix Corp.—Industrial Tools Div.; E. Bruce Crabtree, General Sales Manager, Bryant Grinder Div., Ex-Cell-O Corp.; Albert Crespo, Manager, Sales Engineering, O. S. Walker Co., Inc.; Malcolm Davis, Research Associate, Technology Development Dept., Cincinnati Milacron, Inc.; Paul H. DeRamo, Hill Division Manager, The Hill Acme Co.; August Dobert (Retired); Dr. Ernest J. Duwell, Research Manager, Industrial Abrasives Div., 3 M Co.; R. G. Eckels, Senior Manufacturing Engineer, Rollway Bearing International; Everett W. Emery, Sales Engineer, Cone-Blanchard Machine Co.; Dr. Francis T. Farago, CMfgE, Author: Abrasive Methods Engineering I & II, Senior Research Engineer, General Motors Corp. (Retired); Dr. Michael Field, Chief Executive Officer, Metcut Research Associates, Inc.; Roger H. Fournier, Supervisor, Liaison and Engineering Services, Engineering Department, Warner & Swasey Co.; Franz J. Frei, President, Grinding Technology Inc.; Robert S. Hahn DSc., P.E., CMfgE, Consulting Engineer, Hahn Associates; Marcel R. Hanard II, CMfgE, Project Development Engineer, Manufacturing Processes and Methods Development, Caterpillar Tractor Co.; Edward G. Hoffman, Technical Writer/Consultant, E. G. Hoffman Co.; Virginia Smith Hopkins, Documentation Specialist, Documentation Div., Moore Special Tool Co., Inc.; Charles Horn, Chief Engineer, Design Department, Vulcan Tool Co.; Edgar Hotz, Treasurer and General Manager, ELB Grinders Corp.; William R. Jenkins, Vice President & General Manager, Vulcan Tool Co.; Glenn D. Johnson, Manager, Blanchard/Springfield Engineering, Cone-Blanchard Machine Co.;

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more expensive are the form-cutting tools required when the workpiece characteristics necessitate metalcutting methods other than turning, for example, milling.

The productivity of profile grinding can, in many cases, be vastly superior to other metalcutting processes. This concept is a further factor in favor of grinding for production of a size group of workpieces with particular contours. Grinding also offers significant benefits in the production of many types of workpieces having three-dimensional forms that require for their development a generating type of metalworking process—workpieces such as gears with closely toleranced involute teeth.

Simplified work holding in grinding. In grinding, the force of the tool acting on the workpiece is significantly smaller than in metalcutting operations used for comparable purposes. This distinguishing condition beneficially affects the required workholding system. Consequently, the clamping force needed for ensuring dependable retention of the workpiece is lessened resulting in substantially simplified methods and operation as well as reduced cost of workholding devices for grinding. A typical example is magnetic holding devices for workpieces carrying out either rotating or reciprocating movements. Magnetic chucks or plates are used widely on grinding machines. Equivalent metalcutting operations employ mechanical lathe chucks or other workholding devices that exert considerable clamping force. These workholding devices often are designed expressly for a particular type of workpiece. In other grinding machine operations, specifically in centerless grinding, no workholding device is needed; the grinding force acting on the workpiece is sufficient to ensure secure retention of the workpiece against a solid support element, the work blade.

Several specific advantages of grinding resulting from simplified workholding methods are:

- Faster loading and unloading of workpieces, thereby reducing total time of the operation.
- Simplified application of process automation.
- Workholding devices that are often less expensive to procure and operate than those for other processes.
- Delicate work handling permitted by light clamping force, which reduces the incidence of workpiece distortion and/or surface marring.
- Consistently accurate location of the workpiece held in grinding machines. The location is much less dependent on the skill of the operator than in metalcutting operations which require work clamping with considerable force that has a potential dislocating effect.

APPLICATIONAL FORMS OF ABRASIVES

Abrasives, mostly manufactured and crushed to grains, are used in various forms for carrying out their applicational objective of controlled stock removal.

Abrasive grains of specific sizes are bonded into solid bodies, generally of disc shape, referred to as wheels. These wheels offer the great advantage of being rotated at high speed around an essentially fixed axis position. Contacting and penetrating at high speed into the work material, grinding-wheel application provides the most efficient use of abrasives for the purpose of controlled stock removal. The speed resulting from the fast rotation of the wheel is, of course, the highest at the periphery, which actually is the most commonly used operating area of grinding wheels.

Bonded abrasive grains are also used regularly, although much less frequently, in shapes other than wheels, such as rectangular blocks. In some cases these blocks are operated by reciprocating movements comparable to a file or by slow rotary movement (honing) with a set of several blocks called “stones” installed into a power-driven tool. Rectangular or similarly shaped bonded abrasive blocks called segments also are used. They are often mounted on the face of special chucks for heavy grinding operations on flat work surfaces.

Another category of uses for abrasive grains that is rapidly gaining in applicational importance is coated abrasives. By bonding a layer of abrasive grains to a flexible backing made of cloth or paper, a very effective abrasive surface is provided. In application, coated abrasives combine the efficiency of high cutting speed and large contact area with the availability of an effective operating surface which frequently may be several times larger than the total periphery of a wheel of comparable size, thereby maintaining very high stock removal rates over extended operational periods.

Abrasive grains used loosely, or bonded into small blocks, also provide a wide range of applications which vary from fine and rigorously controlled stock removal, such as in lapping, to highly effective, although much less critically accurate, abrading action. Examples of the latter group of uses include those in which a mixture of workpieces and abrasive media is kept in a continuous movement, causing the harder abrasives to remove stock from the surface of the parts, a system used in tumbling and vibratory finishing. A mode of application specifically for loose abrasives is that of propelling the abrasives, either by a fluid medium or air causing them to hit with considerable force

Reviewers, cont.: James V. Keefe, Vice President, Speedfam Corp.; Henry J. Kirsch, Director of Manufacturing, Acme Abrasive Co.; Ken Kummer, President, Midwest Precision Services; E. W. LaPrade, General Manager, White Sundstrand Machine Tool Co., Syracuse Div.; James Lawson, President, O. S. Walker Co., Inc.; Dr. Richard Lindsay, Research Associate, Norton Co.; Kermit A. Lundell, Chief Engineer, Ring Div., Producto Machine Co.; David P. MacKenzie, Technical Writer, Advertising Department, Bryant Grinder Div., Ex-Cell-O Corp.; Fred McDonald, Regional Product Sales Manager, Bryant Grinder Div., Ex-Cell-O Corp.; Allan R. McMillan, Supervisor, Development Engineering, Machining, Manufacturing Development, General Motors Corp.; Arthur Meyers, Director of Training, DoALL Co.; William Mitchell, Spindle Supervisor, Bryant Grinder Corp.; Wesley W. Mowry, Senior Research Engineer, Research & Development-VGWD, Norton Co.; Robert M. Perry, Product Research Engineer, Moore Special Tool Co.; Edward Peonski, President, AirTronics Div., American Gage & Machine Co., A Katy Industries, Inc. Co.; Dominic Pignataro, Product Manager, O. S. Walker Co., Inc.; William D. Pollard, Principal Engineer, Diamond Products Branch, Carborundum Co.; Fred L. Schierloh, Supervisor, Machining Dept., General Motors Technical Center; Roger O. Schultz, Manager, Marketing, The Warner & Swasey Co.; Warren K. Seward, Senior Technical Applications Specialist, Abrasives Marketing—North America, Abrasives Products Div., The Carborundum Co.; David A. Shuffleburg, Advertising Manager, Bryant Grinder Div., Ex-Cell-O Corp.; Everett L. Sinclair, Technical Director, Grinding Wheel Operations, Norton Co.; Paul E. Soden, Manager, Abrasive Application Service, Products Div., Cincinnati Milacron, Inc.; R. A. Stellarini, Section Leader, Bearing Finishing Operations, Advanced Process Bearings, Timken Co.; James Stewart, Product Manager, Micromatic Operations, Ex-Cell-O Corp.; Stanley A. Swenson, Technical Service Supervisor, Metalworking, 3 M Co.; D. M. Syed, Project Manager, Rollway Bearing International; Robert L. Vaughn, Chief Manufacturing Engineer, Space Systems Div., Lockheed Missiles & Space Co., Space Systems Div.; Robert Woodard, Vice President & Manager, Machine Div., Gardner Machine Co.

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the exposed work surface and thereby effect the desired abrading action.

RESEARCH AND DEVELOPMENT IN GRINDING PROCESSES

The significant benefits provided by the diverse grinding processes at their current state of technology have been accomplished by continuous development, resulting in general from systematic research. The continuity of this research, several important directions of which are indicated in the following discussion, promises the attainment of even higher levels of grinding productivity and still further improved quality of performance.

The tools of grinding. Research is continuously conducted on the tools of grinding (1) chemical composition of manufactured abrasives, aiming at greater strength and wear resistance as well as at sharper edges in a more uniform distribution over the grain surface, and (2) bond materials providing characteristics desirable for specific applications or a combination of several such characteristics.

Improved cutting performance. Improvements of cutting performance in grinding has resulted in (1) increased rates of stock removal by optimized cutting parameters; (2) application of high and very high cutting speeds whenever beneficial to the performance level and cost; and (3) grinding conditions,

including cutting fluid application, capable of assuring a more consistent retainment of the wheel's cutting capacity and form.

Upgraded grinding processes. The research of grinding process variables has resulted in the following advancements:

1. Mechanized material handling applied when warranted by production volume and permitted by the characteristics of the workpiece.
2. Automation of the machine controls, also by the expanding application of NC and CNC for grinding machines.
3. Widening use of multistep grinding machines.
4. Automatic size control with in-process gaging and wheel position adjustment applied to an increasing range of grinding operations.
5. Wheel truing and size compensation initiated and controlled automatically in a steadily growing number of applications.
6. Form grinding by plunge as well as by automatically controlled traverse movements of the wheel, applied to an increasing array of workpieces, in some cases expressly designed to be adaptable to these efficient operations.
7. Development of new and wider uses for uncommon methods, such as creep-feed grinding.
8. New systems of multiple-head grinding machines performing a series of grinding operations in a single setup of the workpiece.

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AA See arithmetical average.

abrasive The material from which the grains in the wheel are made—usually crystalline aluminum oxide, silicon carbide, or diamond.

abrasive disc See disc wheel.

adapter flange A flange used to mount wheels.

air clamp An air-operated device for holding workparts against a nonmagnetic driver.

air orifice The air escape vent of an air gage which directs the air onto the work surface.

air sizing Size control by use of an air gage.

alumina Aluminum oxide, Al_2O_3 .

arbor The spindle of a grinding machine on which the wheel is mounted.

arc of contact The portion of the circumference of a grinding wheel in contact with the work.

arithmetical average (AA) A mathematical measure of surface finish.

automatic size correction Automatic device for making corrections in the machine or the cycle in response to gage signals in order to correct drift.

back-off stop See dress stop.

balance (dynamic) A wheel in static balance is also in dynamic balance if, upon rotating, there is no vibration or whip due to unequal distribution of weight throughout its mass.

balance (static) A grinding wheel is in static balance when, centered on a frictionless horizontal arbor, it remains at rest in any position.

balancing Testing for balance; adding or subtracting weight to put a grinding wheel into either static or dynamic balance.

bed The base of the machine on which most of the major components are mounted.

bell mouth An enlargement at the end of the hole, caused by wheel pressure.

blind hole A hole closed wholly or partially by a face at one end.

blotter A pliable, compressible paper disc used between a grinding wheel and its mounting flanges.

bond The material which cements the grains together making up the wheel. Bond may be rubber, shellac, resin, silicate, vitreous material, or metal, depending upon the abrasive material.

bore diameter Diameter of the ground ID.

bore length The length of the ground hole.

bort Diamond not of gem quality.

burn Visible discoloration or sub-surface damage from excessively high temperature produced by grinding.

center height The relationship of work to wheel centers.

center of rotation The axis of rotation.

centerless grinding Grinding in which the workpiece is supported on its OD and rotated around an axis created by this reference surface. The workpiece is free to shift, and if the support surface is the one being ground, the axis of rotation also shifts.

centerline The axis of rotation.

centers Conical pins of a grinding machine upon which the work is centered, supported, and rotated during grinding.

centertype grinding Grinding by rotating the workpiece around a fixed centerline established by the chuck or centers in which it is held.

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- chatter** A surface finish pattern caused by vibration of the wheel and/or work.
- checks** Very small, often microscopic, cracks.
- chuck** A device attached to the work spindle that holds the workpiece for grinding, usually gripping it with jaws or fingers.
- chuck jaws** The actual gripping members in a chuck. Also referred to as fingers.
- compensator** The device that advances (crossfeeds) the wheel to compensate for wear and dressing.
- contact sizing** Controlling size with a caliper-like device having fingers that touch the work surface and respond electronically to changes in size.
- coping** Shaping stone or other hard nonmetallic material with a grinding wheel.
- corner wear** The tendency of a grinding wheel to wear on its corner so that it does not grind up to a shoulder without leaving a fillet.
- corundum** A natural abrasive of the aluminum oxide type.
- counterfeed** A force directed against the feed mechanism opposing the infeed force, thereby decreasing backlash.
- counterfeed cylinder** A cylinder that exerts a constant force opposing the crossfeed force.
- cracks** Fissures in the work occurring or exposed during grinding.
- creep-feed grinding** A technique of plunge grinding with special design in which the table speeds are kept very low and the wheel is fed down to full depth of cut in one or two passes.
- critical speed** That rotating speed beyond which the vibration of a spindle carrying an abrasive wheel or point would be hazardous.
- crossfeed** In surface grinding, the amount of horizontal feed of the wheel across the table, or of the table across the wheel.
- cross slide** The slide that gives the wheel its cross-axis or crossfeed motion.
- crossfeed mechanism** The screw and nut assembly that regulates the crossfeed motion.
- crush dressing** The process of using rolls or special forms to form or dress the face of a grinding wheel to a specific contour.
- cup wheel** A grinding wheel shaped like a cup or bowl.
- cutoff wheel** A thin abrasive wheel used to cut off or slot any material or part; usually made with an organic bond.
- cutting fluid** Fluid used during grinding or dressing to cool, lubricate, and clean the work, wheel, and diamond. Sometimes called grinding fluid.
- cycle** The sequence of events necessary for one operation on one workpiece.
- cylindrical grinding** Grinding the outer surface of a part that rotates on centers or in a chuck.
- DAF** See Dressing After Finishing.
- DBF** See Dressing Before Finishing.
- deflection** Bending or displacement of the wheel, wheelshaft, workpiece or a machine member from its normal position. Usually refers to the wheel and wheelshaft.
- diamond** The diamond (carbon) crystal usually mounted in a nib or steel shank and used for truing or dressing the wheel.
- diamond holder** Usually a heavy shank which holds the diamond nib and which in turn is held in the wheel dresser. The dresser mechanism which supports the diamond nib.
- diamond sizing** Controlling workpiece size by infeeding a fixed distance from the point of the diamond, which has been preset in relation to the work center.
- diamond tool** The diamond crystal and nib into which it is set.
- diamond turner** A device for holding the diamond and which provides a means of indexing the diamond easily without loosening the nib. Indexing can be either automatic or manual, and it allows dressing with a new face on the diamond.
- disc grinder** A machine on which abrasive discs are used.
- disc wheel** A grinding wheel shaped like a straight wheel, but usually mounted on a plate for grinding on the side of the wheel. Also referred to as abrasive disc.
- dish wheel** A grinding wheel shaped like a dish.
- dog** A machine tool attached to the workpiece by means of which the work is revolved. A trigger which limits the advance of a traversing table.
- downfeed** In surface grinding, the rate at which the grinding wheel is fed into the work.
- dress lead** The distance between successive diamond cuts for each revolution of the wheel; usually given in thousandths of an inch or millimeters.
- dress pass** One dressing traverse of the diamond across the wheel.
- dress rate** Time it takes to dress the length of the wheel.
- dress stop** An adjustable stop that determines the amount of wheel withdrawal for dressing. Also called back-off stop.
- dresser** Device for manually or automatically dressing or truing the grinding wheel. Also referred to as wheel dresser.
- dresser arm** Arm that carries the diamond holder.
- dresser stop** Stop pads or stop screws on the dresser to limit its travel relative to the wheel.
- dressing** Resharpener and renewing the cutting face of the wheel by removing or severing dull grains with a diamond or other type of dressing tool. Also referred to as truing.
- Dressing After Finish (DAF)** Cycle in which dressing comes after finish grinding.
- Dressing Before Finish (DBF)** Cycle in which dressing is done before finish grinding.
- driver** In shoe centerless grinding, usually a flat plate attached to the work spindle and against which the part is held. It drives, but does not actually support the workpiece.
- driver contact** Area in which driver and work touch each other.
- dull diamond** See worn diamond.
- dull wheel** A wheel needing dressing.
- dwell** See sparkout.
- dynamic balance** See balance (dynamic).
- early light** Indicates that workpiece has reached finish size before the low limit position setting is reached.
- eccentric** Condition existing when a hole and the locating OD do not share the same center.
- electro-magnetic driver** A magnetic driver energized by the machine's power supply, as distinguished from one having permanent magnets.
- emery** A natural abrasive of the aluminum oxide type.
- end stop** Adjustable stop that limits forward traverse of wheel.
- face** A flat surface, usually at right angles and adjacent to the ground hole.
- feed** Controlled movement of the wheel toward or away from the work surface.
- feed back** A unit for evaluating gage signals and sending them to the automatic size-correction device.
- feed backoff** A controlled rapid feed away from the work surface (opposite of quick approach).
- feed, cross** See crossfeed.

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- feed, down** *See* downfeed.
- feed, index** *See* index feed.
- feed lines** An objectional spiral pattern produced on the work during grinding.
- feed rate** The rate of advance, usually expressed in thousandths of an inch (millimeters) (or smaller increments) per revolution of workpiece.
- feed reversal** A slow feed of the wheel away from the work. Used to improve the finish.
- fingers** *See* chuck jaws; also *see* flux guides.
- finish** Surface quality.
- finish feed** Feeding in small increments for finishing the part.
- finish grind stop** Stop which limits crossfeed of wheel into work.
- finish size** The required part diameter or thickness.
- finishing** The final cuts taken with a grinding wheel to obtain the accuracy and surface finish desired.
- fishtails** Short, comet-like scratches caused by loose grains, or grains in the coolant, which are carried around by the wheel for only part of a revolution.
- flanges** The circular metal plates which retain and drive a grinding wheel.
- flux guides** Replaceable, adjustable fingers projecting from the face of the driver and used to carry the magnetic force to the workpart. Also referred to as fingers.
- freehand grinding** *See* offhand grinding.
- friability** The ability of abrasive grains to shatter under pressure.
- gaging** Checking the workpiece for size with gages.
- gaging finger** On an air gage, that part of the gage having the orifice and holding it just over the work surface. On a contact gage, the sensing member which actually contacts the work surface. Also referred to as probe.
- glazed wheel** A wheel with a cutting surface too smooth (or dull) to grind efficiently. Glazing is caused by worn or improperly dressed grains.
- grade** The strength of bonding of a grinding wheel; sometimes referred to as hardness.
- grain** The tiny particles of abrasive which, with the bond, make up the wheel. Grains do the actual cutting. Also referred to as grit.
- grain spacing** The relative density of the abrasive particles in a grinding wheel. Usually referred to as structure and designated by a numeral in the wheel marking.
- grinding** Removing material from a workpiece with a grinding wheel or coated abrasives.
- grinding fluid** *See* cutting fluid.
- grit** *See* grain.
- hard-acting wheel** Grinding wheel that retains its dull abrasive grains or is less friable.
- hardness** *See* grade.
- high-band waviness** From 17 to 330 high (or low) points around the circumference.
- high-frequency wheelhead** Wheelhead housing a high-frequency electric motor, the rotor of which is integral with the wheel shaft.
- honin** An abrasive process, usually performed on internal cylindrical surfaces, which employs bonded abrasive stones in a special holder to remove stock and improve surface finish.
- horizontal offset** Displacement of the work center horizontally.
- hydraulic power unit** A separate unit holding the hydraulic oil, pump motor, cooler filters, and other hydraulic controls.
- ID** *See* inside diameter.
- index feed** In cylindrical grinding, an arrangement by which the amount of infeed is indicated on a dial. On most machines, the reference is to the diameter of the work; on a few machines, the reference is to the radius.
- infeed** The advance of the wheel toward and into the material (stock) to be ground away.
- in-process gaging** Continuous gaging of the part while being ground.
- inserted nut** Designating disc, segmental, or cylindrical wheels with nuts embedded in the back to facilitate mounting on the grinding machine.
- inside diameter (ID)** Usually refers to inside circumference.
- interceptor finger** On some loading arms, the part that intercepts and holds back the other parts in the loading chute.
- internal grinding** Grinding the surface of a hole in the workpiece.
- jog switch** A switch for manually advancing machine members in small increments or for actuating functions that are parts of a full cycle.
- late light** Light indicating that a workpiece has reached finish size after the high limit position setting has been reached.
- leaf cams** Cams which synchronize the wheelslide traverse with other activities.
- line of contact** Line created by the contact of wheel and work.
- loaded wheel** A wheel with the voids between the grains filled with metal particles or grinding debris.
- loader** The mechanism for loading workpieces into the workholder. Usually also combines unloading.
- loading arm** Swinging arm that carries the workpiece to the workholder. In some cases, also unloads the workpiece.
- loading chute** A chute to convey workparts to the workholder or to the loading arm.
- loading finger** On some loading arms, that part which guides the workpiece into the workholder.
- loading magazine** Storage rack for workpieces ready to grind.
- loading plug** A plug on some loading arms which serves to carry the workpiece.
- lobiness** From one to three high (or low) points around the circumference of a workpiece.
- locating surface** Surface of the workpiece used for locating; may be a face, an OD, or an ID.
- low-band waviness** Between 3 and 17 high (or low) points around the circumference of a workpiece.
- magnetic driver** A driver which holds workpieces against its face magnetically.
- manual compensator dial** The handwheel or dial that provides the manual crossfeed.
- manual feed dial** *See* manual compensator dial.
- microinch** One millionth of an inch (0.000001"), 0.0254 μ m.
- mounted wheels** Small bonded abrasive wheels permanently mounted on shafts.
- new wheel** A wheel that has not been trued.
- nib** Short steel shank in which the diamond crystal is set.
- OD** *See* outside diameter.
- offhand grinding** Grinding work that is held in the operator's hand; also known as freehand grinding.
- offset** In centerless grinding, the displacement of the work center from the driver center.
- operational controls** Those controls of a grinder used for manual operation.
- organic bond** A bond consisting of an organic material such as rubber, synthetic resin, or shellac.

GLOSSARY OF GRINDING TERMS

- oscillation** A reciprocating grinding stroke.
- out-of-round** Having some points on the profile not equidistant from the common center (see roughness).
- out-of-square** More or less than 90° from the reference surface.
- out-of-true** Rotating eccentrically.
- outside diameter (OD)** Usually refers to the outer circumference.
- peripheral speed** The speed at which a point on the face of a wheel is traveling when the wheel is revolving, expressed in surface feet per minute (sfm), or meters per second (m/s).
- piloted wheel screw** See wheel screw, piloted.
- pivoting shoe** A shoe with a pivoting head which enables the wear pads to line up with the locating surface on the workpart.
- plate shoe** A shoe with a flat wear pad or work contact.
- plug sizing** Controlling size of a hole by using a reciprocating plug gage.
- plug-out** Point in cycle at which a plug gage enters hole.
- post-process gaging** Gaging the work after finish grinding.
- post-process sizing** Controlling sizing by gaging finished parts and making necessary corrective changes, commonly by automated functions.
- pressure plate** On an air clamp, the rotating ring that actually clamps the part.
- probe** See gaging finger.
- Profilometer** An instrument for measuring the degree of surface roughness in microinches or micrometers.
- programming cams** A group of cams which govern the wheel slide motion and sequence.
- quick approach** A controlled rapid feed up to the work surface (opposite of feed backoff).
- quill projection** See wheel shaft.
- revolutions per minute (rpm)** The number of rotations of the wheel or workpiece per minute.
- rms** See root mean square.
- roll grinding machine** A special type of cylindrical grinding machine for grinding cylindrical rolls to be used for rolling metals, paper, or rubber.
- root mean square (rms)** A mathematical measure of surface finish.
- rough feed** Feeding with relatively large increments. Usually done early in the cycle for fast stock removal.
- rough size** An arbitrary predetermined diameter obtained prior to finish size. Usually attained by rough feeding.
- roughness** Surface finish characterized by sharp, closely spaced high and low spots.
- round** Having a curved profile, all points of which are equidistant from a common center.
- rpm** See revolutions per minute.
- rubber bond** A bonding material whose principal constituent is natural or synthetic rubber.
- scleroscope** An instrument for determining the relative hardness of materials by a drop-and-rebound method.
- scratches** Annular marks on the surface usually caused by the wheel.
- segmental wheel** A wheel composed of segments assembled by the manufacturer to form a complete wheel.
- segments** Bonded abrasive sections of various shapes to be assembled to form a continuous or intermittent circular grinding surface.
- seven o'clock shoe** A shoe positioned under the workpart 30° to the front of the vertical centerline.
- sfm** See surface feet per minute.
- sharp wheel** A wheel that has just been dressed properly.
- shoe** A nonrotating work rest with attached wear pad for supporting a cylindrical workpiece during grinding.
- shoe holder** The fixture in shoe centerless grinding which holds the shoes.
- shoe holder support** A bracket for attaching the shoe holder to the machine.
- shoe marking** Burnishing of the surface where the part rests against the shoes (in centerless grinding).
- short stroke** In plunge grinding, a slight grinding stroke imparted to the wheel (by a special device) to improve surface finish and geometry.
- silica** Silicon dioxide, SiO₂.
- silicon carbide** An abrasive made in the electric furnace from coke and silica, SiC.
- size** Used loosely to mean part diameter.
- size control** The control of part diameter or thickness.
- size early** Finish size reached too soon in the preset cycle.
- size late** Finish size reached too late in the preset cycle.
- size light** Indicates that finish size has been reached.
- sizing** The act of controlling size.
- sizing plug** In the plug sizing method, the plug gage which is used to measure the bore.
- skip dress** Grinding more than one workpiece for each wheel dressing.
- slippage** The constant sliding of the workpiece, on the driver face, as it seats itself in the shoes.
- snagging** Grinding which removes relatively large amounts of material without regard to finish; typically the removal of gates, fins, sprues, and parting lines from castings, surface defects from billets, and excess metal from welds.
- soft-acting wheel** Grinding wheel that loses its abrasive grains before they are dull.
- sparkout** A period of halting the reciprocating motion of the worktable in surface grinding at the end of its stroke to achieve equal stock removal along the entire ground length. Also referred to as tarry or dwell.
- sparkout timer** Adjustable electrical device for controlling length of sparkout interval.
- static balance** See balance (static).
- steadyrest** A supplementary support for pieces being ground on a cylindrical grinding machine.
- stock** Material to be ground from the workpiece to produce the required diameter.
- stock sensor** Electrical device used when the crossfeed is delayed to start it at the instant the wheel contacts the work surface.
- straight dress** Truing a wheel to a cylindrical shape.
- straight wheel** A grinding wheel of any dimensions which has straight sides and a straight face and is not recessed, grooved, dovetailed, or rendered otherwise than cylindrical.
- stroke position** Axial position of grinding stroke relative to workpiece.
- stroke positioning knob** Control for positioning the grinding stroke relative to the work.
- structure** A general term referring to the proportion and arrangement of abrasive and bond in a wheel.
- surface feet per minute (sfm)** The rotational speed of the cutting surface of the wheel or the surface of the work. Derived by multiplying the circumference in feet by the rpm. (In metric: meters per second [m/s] derived by multiplying the circumference in m by the rpm and dividing by 60.)
- surface finish** The quality of the surface with respect to smoothness. Also referred to as surface texture.
- surface grinding** Grinding a plane surface.

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surface texture See surface finish.

swarf Accumulated chips, wheel particles, and other debris produced by grinding.

swiveling shoe A shoe with a head mounted on a ball, which allows the wear pads to line up in any direction.

taper Condition in a hole when the sides are not parallel.

tarry See sparkout.

three o'clock shoe A shoe positioned on the horizontal centerline at the rear of the workpiece.

trueing Shaping the cutting surface of the wheel to the required form and bringing it into concentricity (making it true) with the axis of rotation (see dressing).

universal grinding machine A machine on which cylindrical, taper, internal, or face grinding can be done as required in toolrooms and machine shops.

unloading arm On some machines, an arm that unloads the workpart.

unloading chute A discharge chute for finished workparts.

V-type shoe A shoe with two wear pads forming a vee.

vertical offset Displacement of the work center vertically.

vitrified wheel A grinding wheel made with a vitrified ceramic bond.

wheel A grinding wheel; a straight or formed abrasive tool which is rotated to remove metal during the grinding process.

wheel breakthrough The distance the edge of the wheel projects beyond the edge of the bore at each end of the stroke.

wheel dresser See dresser.

wheel drive Means of revolving the wheel.

wheel form The shape created on the wheel during trueing and dressing.

wheel path The imaginary line a wheel travels during one wheel slide stroke.

wheel screw A screw which fastens the wheel to the wheel shaft without use of a pilot.

wheel screw, piloted A screw, having a pilot shared by the wheel shaft and the wheel, which fastens the wheel to the wheel shaft.

wheel shaft The shaft on which the wheel is mounted. Also called quill projection and wheel spindle.

wheel slide The slide that holds the wheelhead and gives the wheel its traversing or longitudinal motion.

wheel slide cam Cam governing the wheel slide traverse.

wheel slide cylinder The hydraulic cylinder that provides the traverse stroke.

wheel slide housing The housing containing the cross slide—wheel slide assembly.

wheel slide stroke Total axial travel of the wheel slide; including grinding, dressing and loading stroke.

wheel speed Rotary speed of the wheel in sfm (m/s).

wheel spindle See wheel shaft.

wheel structure The character of the wheel as determined by the proportion and arrangement of the grains and bond composing it.

wheelhead Unit comprised of the wheel shaft and bearing assembly and the housing.

wheelhead axis The centerline around which the wheel revolves.

work The workpiece or workpart.

work area Central area between the workhead and the wheelhead in which the loading, grinding, and dressing are done.

work axis The centerline around which the workpiece revolved.

work drive The means of rotating the work spindle.

work holder The chuck collet or arbor attached to the work spindle which holds and may also rotate the workpart. On a shoe centerless machine the shoe holder and shoes.

work speed Rotary speed of the work in sfm (m/s).

work spindle Spindle within the workhead which rotates the workpiece.

work surface That part of the work being ground.

worn diamond A diamond worn too flat on its exposed face to properly dress the wheel. Also referred to as dull diamond.

worn wheel A wheel worn or dressed down too small to be useable.

worn wheel light Light indicating that wheel has worn down to the point that it is too small for further use.

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The development of quantitative relationships between important grinding process variables is spurred by the desire to gain increased understanding of the grinding process, resultant greater productivity, and lower costs. Over the past several decades, numerous theoretical and empirical relationships have been defined in attempts to more fully describe the grinding phenomenon. Experience has shown that these relationships often cannot be universally applied because not all types of grinding applications are the same in the way that manipulations of machine movements and parameters effect the grinding action. Although this is true, many advances in grinding technology are credited directly to research aimed at greater understanding of the basic grinding relationships. In this section, several select relationships are presented. The following is a list of symbols and definitions employed in the discussion. (When unit analyses are presented in metric, customary U.S. unit conversions are omitted for clarity and to conserve space.)

Symbol	Description
c	2 x diamond depth of dress (μ m)
d	Grain diameter (μ m)
D	Grain depth of cut (m)
D_e	Equivalent diameter (cm)
D_s	Wheel diameter (mm)
D_w	Work diameter (mm)
E	Modulus of elasticity (N/mm ²)
ef	Grain depth of cut, maximum (m)
f	Surface finish R_a (μ m)
F_{bd}'	Wheel breakdown force intensity (N/mm)
F_n	Normal force (N)
F_n'	Normal force intensity (N/mm)
F_{pc}'	Plowing/cutting transition force intensity (N/mm)
F_t	Tangential force (N)
F_{th}'	Threshold force intensity (N/mm)

Symbol	Description
h	Wheel depth of cut (μ m)
I	Moment of inertia (mm^4)
K	Stiffness (N/μ m)
K_{cw}	Cutting stiffness of work (N/mm)
K_s	System stiffness
l	Dress load (μ m/rev)
l_e	Length of cantilever (mm)
L	Lead
L_c	Arc of contact of wheel and work (m)
n	Number of cutting particles per meter of wheel circumference (#/m)
N_s	Wheel speed (rpm)
N_w	Work speed (rpm)
P	Grinding power (W)
P_s	Specific power (J/mm^3)
R_C	Rockwell hardness, C scale
S	Wheel sharpness (m^2/N)
T	Unit of time (s)
v_f	Feed rate (μ m/s)
v_s	Radial wheel wear velocity (μ m/s)
v_w	Penetration velocity of wheel into work (μ m/s)
V_s	Wheel surface speed (m/s)
V_t	Traverse speed (m/s)
V_w	Work surface speed (m/s)
vol	$1.33H + 2.25S - 8$ (vol % of bond in wheel)
	where:
	$H = 0, 1, 2, 3, \dots$ for H, I, J, K hardness
	S = wheel structure number
W	Width of wheel/work contact (mm)
WRP	λ_w = Work removal parameter ($\text{mm}^3/\text{min} \cdot \text{N}$)
WWP	Wheel wear parameter ($\text{mm}^4/\text{min} \cdot \text{N}^2$)
$\ddot{x}$	Rate of deflection
Z_s	Volumetric wheel wear rate (mm^3/s)
Z'_s	Wheel wear rate per unit width (mm^2/s)
Z_w	Volumetric rate of stock removal (mm^3/s)
Z'_w	Stock removal rate per unit width (mm^2/s)
κ	Angular stiffness (N/rad)
α	Dimensionless machining—elasticity number
τ_o	Time constant (s)

GRAIN DEPTH OF CUT

When an abrasive starts to enter and penetrate the work material, the depth of cut is zero. As the wheel and work revolve, the depth of cut gradually increases to a maximum somewhere along the arc of contact of the wheel and the workpiece. Since the wheel usually rotates much faster than the work, this point of maximum cut depth is almost at the point at which the wheel leaves the work. This maximum depth is known as the "grain depth of cut."

Grain Depth of Cut Theory

In Fig. 11-1, C and C' are centers of the grinding wheel and the workpiece, respectively, on a center-type grinding machine; ab is the radial depth of cut, ad is the arc of contact of wheel and work, and ef is the grain depth of cut. Dimensions are exaggerated for clearer illustration, but the same conditions apply in practice.

Assuming that only one abrasive grain is cutting at a in Fig. 11-1, the rotation of the wheel will cause the grain to move to d in a unit of time. In this unit of time, the point d on the

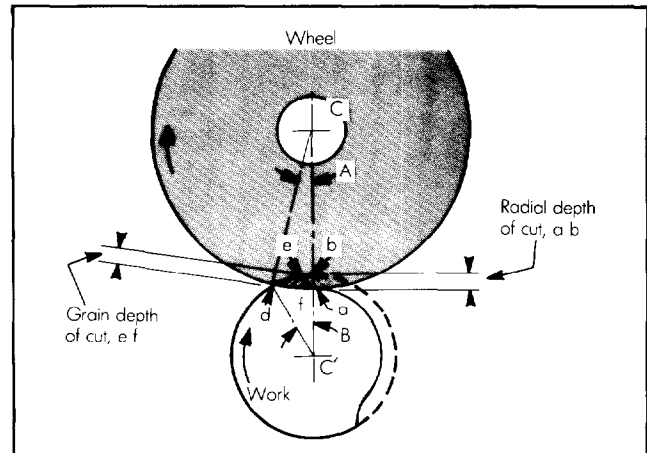


Fig. 11-1 Grain depth of cut, center-type machine. (Norton Co.)

workpiece will move to e . Since the work usually runs much more slowly than the wheel, the length de will be less than ad . This grain will then remove a chip ade in unit time.

From the shape of the chip, it is evident that, when the grain begins to cut at a , it has no depth but eventually increases to a maximum ef . The length ef is called the grain depth of cut. Grinding wheels can be made to act softer or harder by either increasing or decreasing the grain depth of cut. In addition, ef can be varied by either increasing or decreasing the work speed or radial depth of cut (feed).

An illustration of wheel wear is shown in Fig. 11-2. If the work and the wheel run at the same rpm, both when the wheel is full size and when it is worn down, the length ad' is greater than ad ; therefore, the chips cut by both wheels are of the same volume, but since the arc of contact ad' of the smaller wheel is less, the chip thickness will be greater. In other words, the grain depth of cut increases as the wheel diameter diminishes, the bond should wear away faster, and the smaller wheel should appear softer.

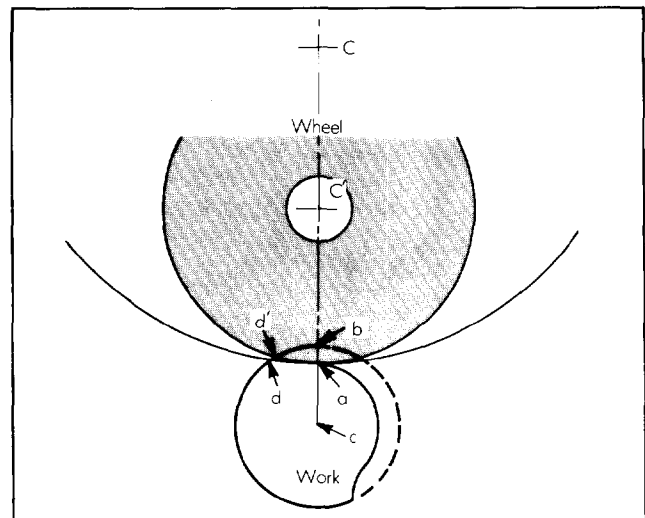


Fig. 11-2 Grain depth of cut for varying wheel size. Work and wheel rotation is clockwise. (Norton Co.)

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Referring to Fig. 11-1, mathematical analyses are used to develop the general equations:

$$L_c = V_s T \text{ or } T = \frac{L_c}{V_s} \quad (1)$$

$$de = V_w T \quad (2)$$

$$ef = V_w T \sin(A + B) \quad (3)$$

$$D = \frac{ef}{nL_c} = \frac{V_w T}{nL_c} \sin(A + B) \quad (4)$$

by substituting T from Eq. (1):

$$D = \frac{V_w}{nV_s} \sin(A + B) \quad (5)$$

where:

$L_c = ad$ = arc of contact of wheel and work (m)

V_s = surface velocity of wheel (m/s)

V_w = surface velocity of work (m/s)

T = unit of time (s)

ef = grain depth of cut, maximum (m)

D = grain depth of cut (m)

n = number of cutting particles per unit length of wheel circumference (#/m)

Equation (5) shows that radial depth of cut varies directly as work speed, inversely as wheel speed, and directly as $\sin(A + B)$. Doubling the radial depth of cut will increase the grain depth of cut by 40%. The following conclusions relate to wheel action during cutting, other factors remaining constant. (Note: Experience has shown that these relationships must be applied according to specific geometry of the grinding operation as discussed in the subsequent section.)

1. Increase of work speed increases grain depth of cut and makes wheel act softer.
2. Decrease of work speed decreases grain depth of cut and makes wheel act harder.
3. Increase of wheel speed decreases grain depth of cut and makes wheel act harder.
4. Decrease of wheel speed increases grain depth of cut and makes wheel act softer.
5. Reducing diameter of grinding wheel increases grain depth of cut and makes wheel act softer.
6. Increasing diameter of grinding wheel reduces grain depth of cut and makes wheel act harder.
7. Reducing diameter of work increases grain depth of cut and makes wheel act softer.
8. Increasing diameter of work reduces grain depth of cut and makes wheel act harder.

Application of Grain Depth of Cut Theory

The grain depth of cut theory, as presented in the previous section of this chapter, is based on the geometric relationships found in cylindrical grinding. In other types of grinding, different geometric relationships exist such that the grain depth of cut theory does not apply as developed for cylindrical grinding. The following sections explain how and where the theory can be applied to predict results in various types of grinding operations.

Reciprocating-table, horizontal-spindle surface grinding. The movements of these machines are downfeed, crossfeed, and table speed, but the relationship is cyclical, or incremental, in that for each table reversal the length of the workpiece stays the same. The variable is table or work speed. As it is increased or decreased, the other increments occur in a cycle more or less

times per minute. Faster work speed creates more cycles per minute or time period, more work for the wheel, and more wheel wear, or a "softer" action. Slower table speed creates fewer cycles per minute or time period, less work for the wheel, and less wheel wear, or a "harder" action. In addition, as crossfeed is increased, the wheel acts softer; as it is decreased, the wheel acts harder.

Rotary-table, vertical-spindle surface grinding. In this situation, downfeed of the grinding wheel is practically continuous at a specified rate per minute, for example, multiples of 0.004" (0.10 mm). The work table rotates at a specified rate of revolutions per minute. The relationship between the two is on a basis of time vs. time in that a change in one affects the value of the other; for example, if the wheel is downfeeding at the rate of 0.012" (0.30 mm) per minute and the table speed is 12 rpm, the effective depth of cut per revolution is 0.001" (0.03 mm). If the work speed is increased to 25 rpm, which is supposed to give the wheel more work to do and break it down according to the grain depth of cut theory, the effective depth of cut is 0.0005" (0.013 mm)—which actually gives it less work, and of course, less wear. This is considered harder wheel action, not softer. (In this discussion, consider the workpiece as solid with no interruptions to eliminate any effect of impact upon the wheel.)

If the table speed is decreased to 6 rpm, the effective depth of cut at 0.012" (0.30 mm) downfeed is 0.002" (0.05 mm) per revolution. The important result is that the depth of cut per revolution of the work is changed by variations of work speed. The results, in terms of harder or softer wheel action, are contrary to the grain depth of cut theory. The stock removal rate in cubic inches per minute (cubic millimeters per minute) is not changed as long as the downfeed rate is not changed.

Cylindrical and centerless infeed grinding. With the infeed rate kept constant and the work speed in revolutions per minute changed, the depth of cut or infeed per revolution is either increased or decreased accordingly, but with a reverse in effect from predictions based on the grain depth of cut theory.

Slower work speed in an infeed cylindrical application, with all else remaining constant, removes more material per revolution and makes the wheel act softer.

Cylindrical and centerless traverse grinding. Applied to cylindrical traverse grinding, the grain depth of cut theory is correct when the change is in the traverse rate, but incorrect when the change is in the work speed, in revolutions per minute.

When work speed is constant and the traverse rate is changed, the width of cut per revolution of the workpiece is changed. A faster traverse creates a wider width of cut, more work action, and therefore more wheel wear. The result is a softer action. Conversely, a slower traverse creates a narrower width of cut, less work action, and therefore less wheel wear.

The aforementioned is in accordance with theory. However, when traverse rate is held constant, a faster work speed results in a narrower width of cut, less work action, less wheel wear, and a harder, not softer, action. A slower work speed results in a wider width of cut, more work action, more wheel wear, and a softer, not harder, action.

In centerless grinding, the width of cut is determined by the regulating wheel angle and is constant for a given work diameter, regardless of regulating wheel speed. Therefore, a change in work speed is cyclical in nature, resulting in more or less work revolutions per minute with the same width of cut per revolution. Faster regulating wheel speeds create more work and more wear, or softer wheel action. Slower regulating wheel speeds create less work and less wear, or harder wheel action.

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TABLE 11-1
Effects of Grinding Machine Manipulations

Type of Grinding	Action Resulting If Only One Movement Is Changed at a Time			
	Increase	Work	Decrease	Work
Surface—Horizontal	Crossfeed	more	Crossfeed	less
	Downfeed	more	Downfeed	less
	Traverse Speed	more	Traverse Speed	less
Surface—Vertical	Downfeed	more	Downfeed	less
	Table rpm	less	Table rpm	more
Cylindrical Infeed	Infeed	more	Infeed	less
	Work rpm	less	Work rpm	more
Centerless Infeed	Infeed	more	Infeed	less
	Work rpm (reg. wheel)	less	Work rpm (reg. wheel)	more
Cylindrical Traverse	Depth of cut/Pass	more	Depth of cut/Pass	less
	Work rpm	less	Work rpm	more
	Table Traverse	more	Table Traverse	less
Centerless Traverse	Depth of cut/Pass	more	Depth of cut/Pass	less
	Reg. Wheel rpm	more	Reg. Wheel rpm	less

* Regular wheel speed controls rpm of work and also traverse rate.

The important consideration is that downfeed, infeed, and traverse determine the amount of work done by the wheel in a unit of time, or the amount of productivity in cubic inches per minute (cubic millimeters per minute), while the speed of the work determines the conditions under which the wheel performs its work, including the pressures applied to the wheel in a unit of time.

As work speed is increased or decreased, the new infeed rate should be calculated by infeed per revolution of workpiece, not by the minute, as is usually the case. The infeed rate per minute would be determined by the work diameter as the revolutions per minute change to maintain a constant surface speed per minute (meters per second).

Traverse should be adjusted to produce the width of cut desired as a fraction of the wheel face width: wider for softer action and/or roughing; narrower for harder action and/or finishing.

To adjust infeed per revolution and width of cut, more than one machine condition has to be changed—not just one as the grain depth of cut theory suggests.

The following situations conform to the grain depth of cut theory:

Same Movements: Increased wheel speed = harder action
Decreased wheel speed = softer action

Same Work Speed: Increased traverse, crossfeed = softer action
Decreased traverse, crossfeed = harder action

Increased infeed, downfeed = softer action
Decreased infeed, downfeed = harder action

These situations do not conform to the grain depth of cut theory:

Same Infeed, Downfeed: Increased work speed = harder action
Decreased work speed = softer action

Same Traverse Speed: Increased work speed = harder action
Decreased work speed = softer action

A combination of the rate of infeed, downfeed, or traverse and the depth of cut per pass determines productivity, or the amount of work actually done in a grinding operation. A change in any of these parameters changes the rate of stock removal accordingly. Work speed determines the condition or environment in which the wheel does its work, and thereby controls the rate of wheel breakdown. Table 11-1 presents the affect on work of manipulations performed on various grinding operations.

WHEEL/WORK CONFIGURATIONS IN CYLINDRICAL GRINDING

Several quantitative relationships have been developed to describe wheel/work configurations in cylindrical grinding. Such relationships for plunge grinding and reciprocate grinding are presented in the following sections.

Plunge Grinding

The abrasive processing of workpieces may involve cylindrical and/or conical-shaped wheels fed in a radial (XFEED), axial (ZFEED), or oblique direction (VECTOR FEED) to produce external or internal diameters with or without an adjacent shoulder. Figure 11-3 illustrates four methods of producing a cylindrical surface with adjacent shoulder. The method illustrated in Fig. 11-3, *a*, is slow and results in excessive corner wheel wear. The method illustrated in Fig. 11-3, *b*, is more efficient in bringing both surfaces to size at the same time. However, thermal damage is likely to occur on the shoulder due to the large contact area between the flat side

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of the wheel and the shoulder. Figure 11-3, c, shows the wheel inclined at the angle β to provide cooler grinding action on the surface. The conformity between the abrasive and workpiece is designated as XDE and ZDE in the radial and axial direction. (Wheel/work conformity is discussed in a later section.) The vector feed direction is chosen according to the X and Z stock allowance ratio. Vector feed motions can be achieved by computer control of both X and Z slides. The method shown in Fig. 11-3, d, requires only XFEED, but results in a "size coupling" effect in which a change in ID or OD size also causes a change in shoulder dimension. A size change of either dimension can only be effected by solving the following pair of equations:

$$\Delta X = \Delta R \cos \theta + \Delta T \sin \theta \quad (6)$$

$$\Delta Z = \Delta T \cos \theta - \Delta R \sin \theta \quad (7)$$

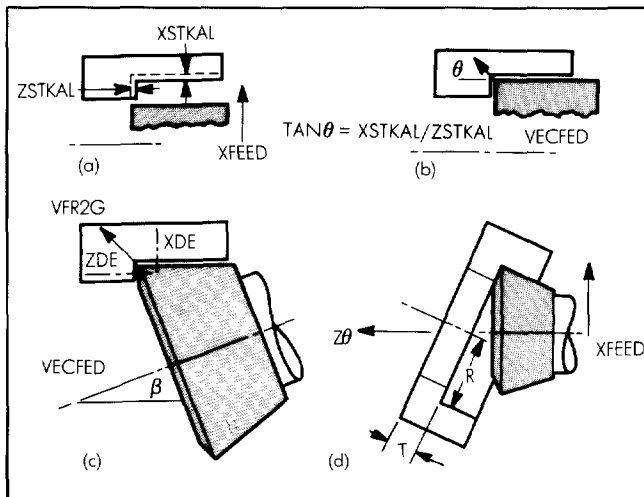


Fig. 11-3 Four methods of producing a cylindrical surface with adjacent shoulder.

Reciprocate Grinding

Long shafts or holes are ground by reciprocating the wheel in the axial direction with increments of XFEED at each end of the stroke. Under rough grinding conditions, excessive wheel wear may occur on the leading edge of the wheel if the angular stiffness of the wheel is large or the angular stiffness of the work is small. Excessive wheel wear may occur on the trailing edge of the wheel if the angular stiffness of the wheel is small, or the angular stiffness of the work is large.

The angular stiffness, K , is defined as the ratio of force to angular deflection; the lateral stiffness, K , is defined as the ratio of grinding force to radial deflection, as shown in the following equations. Figure 11-4 illustrates a cantilevered wheel grinding a long bore based on these equations.

$$K = 3EI/l_e^3 \text{ (N/}\mu\text{ m)} \quad (8)$$

$$K = 2EI/l_e^2 \text{ (N/rad)} \quad (9)$$

The normal force per unit width (normal force intensity) is high at the leading edge in the first case, and at the trailing edge in the second case. In either case, the wheel is not utilized effectively.

Another factor which makes reciprocate grinding troublesome is the fact that more rough stock may be at one end of the hole or shaft than the other. This means, in the early stages of

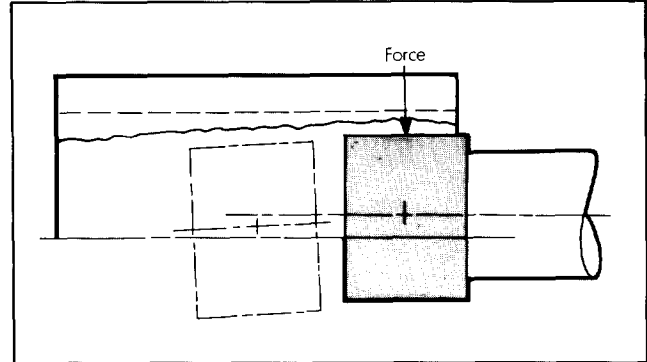


Fig. 11-4 Radial deflection in reciprocate long bore grinding.

trueing the work, that the wheel may contact the work intermittently as it is reciprocated. Again, the wheel is not being utilized efficiently.

A more efficient method of grinding long holes or shafts, which avoids the difficulties outlined previously, is to execute a series of plunge rough grinds side by side to bring the hole or shaft to "first size" and then, under smaller forces, to reciprocate finish grind to final size, thereby avoiding angular deflections and nonuniform wheelwear. Multiplunge roughing with reciprocate finish grinding can be accomplished on two-axes, computer-controlled grinding machines.

During the reciprocate finish grind, an increment, $XINK$, of XFEED is applied at each end of the stroke. The following principles may be used to establish this value:

1. The table traverse speed, V_t , should be set as high as possible to be consistent with the machine's capability to reverse.
2. A work speed, N_w , should be selected to give a lead, L , equal to about $1/2$ the width of wheel face, W , according to:

$$L = \frac{V_t}{N_w} = \frac{W}{2} \quad (10)$$

$$N_w = \frac{2V_t}{W} \quad (11)$$

3. The length of the "barber pole stripe" laid down by the wheel can be considered to be the circumference of a fictitious diameter, $DWFICT$, which determines a fictitious plunge-grind finish feed rate, v_f , and a corresponding wheel depth-of-cut, h , according to:

$$DWFICT = \frac{D_w \cdot ZSTROKE}{L} = \frac{2D_w \cdot ZSTROKE}{W} \quad (12)$$

The finish feed rate for this diameter, corresponding to the induced force intensity, F_n' , (which governs the surface finish) as given in later sections is:

$$v_f = \frac{WRP \cdot F_n'}{\pi DWFICT} = \frac{WRP \cdot F_n' \cdot W}{2\pi D_w \cdot ZSTROKE} \quad (13)$$

and the corresponding $XINK$ is:

$$XINK = \frac{v_f}{N_w} = \frac{WRP \cdot F_n' \cdot W}{2\pi N_w D_w \cdot ZSTROKE} \quad (14)$$

This increment of XFEED should be fed either at the end of each stroke or at intervals equal to the period of work

rotation, whichever is longer; i.e., if time for a stroke is greater than the time for work revolution, $XINK$ should be fed every stroke, and if time for work revolution is greater than time for a stroke, $XINK$ should be fed every revolution.

WHEEL/WORK INTERFACE

The grinding process takes place at the wheel/work interface. In cylindrical plunge grinding operations, the interface force intensity (normal force per unit width of contact) is uniformly distributed over the face of the wheel. Accordingly, plunge grinding is the simplest type of grinding, as illustrated in Fig. 11-5. The feed rate, v_f , is applied to the cross slide of the machine. At the moment the wheel contacts the workpiece, the interface force intensity is zero. As the cross slide continues to move, the springs in the system compress, generating some interface force intensity, F_n . This causes the wheel and work to mutually machine each other, the radius of the workpiece decreasing at the rate v_w , the radius of the wheel decreasing at the rate v_s , and the deflection x increasing at the rate $\dot{x}$, thus:

$$v_w + v_s + \dot{x} = v_f \quad (15)$$

The feed rate of the cross slide, v_f , only equals the plunge grinding velocity, v_w , when the wheel wear, v_s , is negligible and $\dot{x} = 0$ (the steady state).

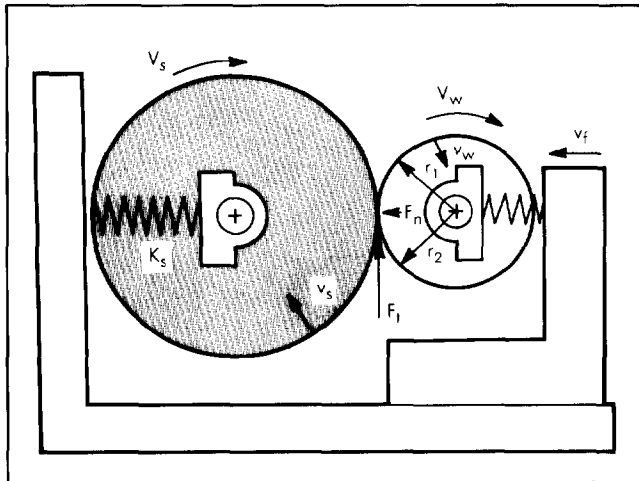


Fig. 11-5 Wheel/work grinding system.

The volumetric rates of stock removal, Z_w' , and wheel wear per unit width of contact, Z_s' , shown in the following equation are plotted against the normal interface force intensity in Fig. 11-6, resulting in a "Wheel/Work Characteristic Chart" which shows how a given wheel/work pair machine each other.

$$Z_w' = \pi D_w V_w \quad (16)$$

$$Z_s' = \pi D_s V_s \quad (17)$$

The stock removal curve, Z_w' , has a rubbing region at force intensities below F_{th}' ; the threshold force intensity; a plowing region for force intensities between F_{th}' and F_{pc}' , the "plowing/cutting transition"; and a "cutting region" above F_{pc}' .¹ In the cutting region, the abrasive grits remove chips in the usual way; in the plowing region, they remove material by causing lateral plastic flow and highly extruded ridges to be formed along each side of the scratch, with these ridges removed by subsequent

grits. The plowing region is important in obtaining good surface finish. The cutting region is important in rounding up the workpiece and in fast stock removal.

The slope of the Z_w' curve is called the "Work Removal Parameter", WRP , or sometimes λ_w and is indicative of the sharpness, S , of the grinding wheel, defined as:

$$S = \frac{WRP}{V_s} \quad (\text{m}^2/\text{N}) \quad (18)$$

This sharpness represents the cross-sectional area of a hypothetical ribbon of material being removed from the workpiece per unit of normal force. The sharpness of grinding wheels is one of the most important variables in the grinding process and is frequently most difficult to control in practical grinding operations. Its value may vary 400-500%, causing size, taper, surface finish, and surface integrity problems.

The wheel wear curve, Z_s' , illustrated in Fig. 11-6 rises gradually at low force intensity and then turns sharply upward (around 28 N/mm in this case) at the so-called breakdown force intensity, F_{bd}' . Precision grinding cycles must operate between F_{th}' and F_{bd}' . Curves for surface finish and power can also be shown on the Wheel/Work Characteristic Chart.

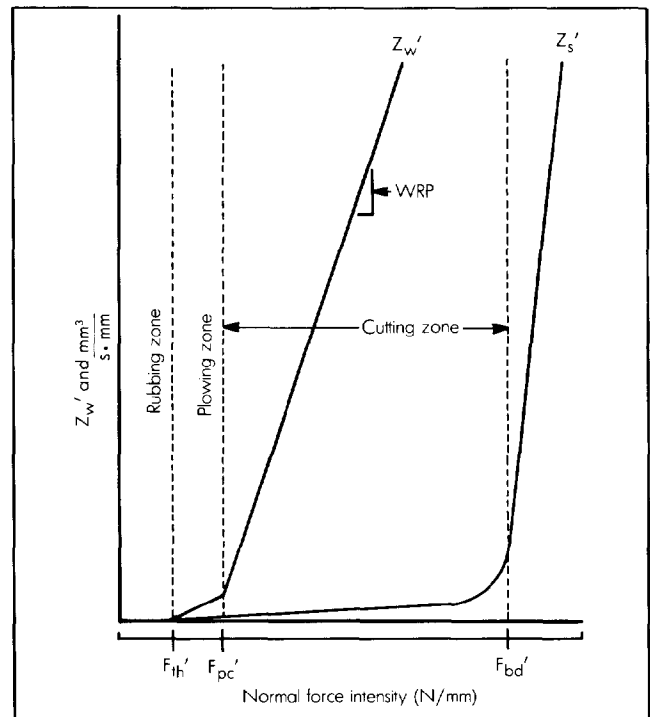


Fig. 11-6 Wheel/work characteristic chart.

WHEEL/WORK CONFORMITY

The difference in curvature of the wheel and work in the contact region has some affect on the cutting action at the wheel/work interface. The difference of curvature for internal or external grinding can be related to surface grinding by considering an equivalent diameter, D_e , of a surface grinding wheel having the same difference of curvature as the internal or external operation.

The equivalent diameter, D_e , is given by:

$$\frac{1}{D_e} = \Delta = \frac{1}{D_s} \pm \frac{1}{D_w} \quad (19)$$

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$$D_e = \frac{D_w \cdot D_s}{D_w \pm D_s} \quad (20)$$

where the + or - sign is used for external or internal grinding. With this parameter, internal, external, and surface grinding can be related. (See "Grinding Wheels" in this chapter for sample calculations in both U.S. customary and metric units.)

In grinding shoulders with wheels inclined at the angle β , the radii of curvature of the abrasive wheel in the X and Z directions shown in Fig. 11-7 are:

$$R_{sx} = \frac{D_s}{2 \cos \beta} \quad (21)$$

$$R_{sz} = \frac{D_s}{2 \sin \beta} \quad (22)$$

so that

$$XD_e = \frac{D_w \left(\frac{D_s}{\cos \beta} \right)}{D_w - \left(\frac{D_s}{\cos \beta} \right)} \quad (23)$$

$$ZD_e = \frac{D_s}{\sin \beta} \quad (24)$$

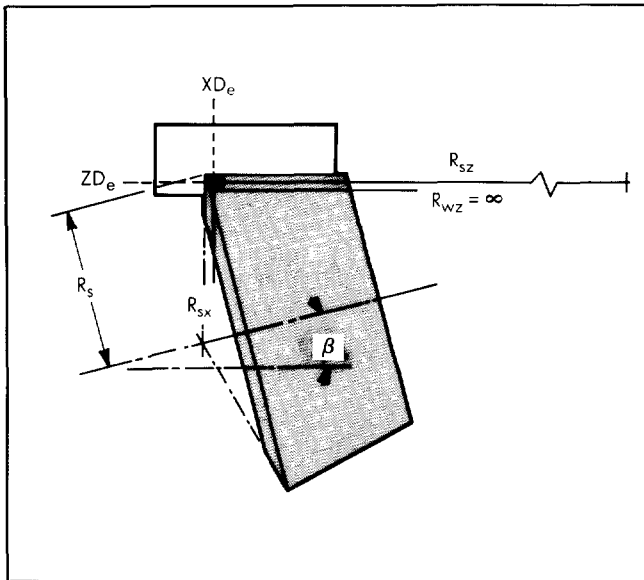


Fig. 11-7 Geometry of grinding a shoulder with wheel inclined at angle.

BASIC PLUNGE GRINDING RELATIONS

Stock removal, wheel wear, surface finish, power, and force relationships can be developed from the Wheel/Work Characteristic Chart illustrated in Fig. 11-6. Neglecting the plowing region for simplicity, the stock removal relation is:

$$Z_w' = WRP (F_n' - F_{th}) \quad (25)$$

or

$$\pi D_w v_w = WRP (F_n' - F_{th}) \quad (26)$$

or

$$v_w = \frac{WRP (F_n' - F_{th})}{\pi D_w} \quad (27)$$

Equation (27) gives the plunge grinding velocity of the normal interface force intensity. (Primed quantities signify per unit width.)

When the wheel wear rate is negligible ($v_s < v_w$) and a steady state of deflection exists ($\dot{x} = 0$), Eq. (15) becomes:

$$v_w = v_f \quad (28)$$

Equation (27) can be solved for F_n' , with v_f replacing v_w , thus:

$$F_n' = \frac{\pi D_w v_f}{WRP} + F_{th}' \quad (29)$$

This gives the induced force intensity generated by the feed rate, v_f , in the steady state when wheel wear is negligible.

The wheel wear curve Z_s' in Fig. 11-6 below F_{bd}' may be approximated according to Lindsay² by:

$$Z_s' = WWP (F_n')^2 \quad (30)$$

where:

$$WWP = (.068 \times 10^{-9}) \frac{l^2 \left(1 + \frac{c}{l} \right) N_s D_s}{\left(\frac{D_e}{2.54} \right)^{1.2/vol} (vol)^{.85}} \quad (\text{mm}^4/\text{min} \cdot \text{N}^2) \quad (31)$$

With this wheel wear parameter, WWP , wheel wear can be estimated for various grinding conditions.

The breakdown force intensity F_{bd}' in Fig. 11-6 may be estimated for Al_2O_3 vitrified wheels³ by:

$$F_{bd}' = 62.3 (vol)^{.55} (D_e)^{.25} \quad (\text{N/cm}) \quad (32)$$

Precision grinding cycles should be designed so that the induced force intensity lies below F_{bd}' .

The wheel depth-of-cut, h , advance of wheel per work revolution, is obtained by:

$$h = \frac{v_w}{N_w} \quad (\mu\text{m}) \quad (33)$$

This relation permits all the results developed for cylindrical grinding to be applied to surface grinding operations.

The work cutting stiffness, K_{cw} , (normal force required to take unit depth-of-cut) is an important quantity governing the rate of rounding up, the sparkout time, and chatter behavior when compared to the system stiffness, K_s . It is obtained by:

$$K_{cw} = \frac{F_n}{h} = \frac{V_w W}{WRP} \quad (\text{N/mm}) \quad (34)$$

The dimensionless machining-elasticity number, α , formed by the ratio:

$$\frac{K_{cw}}{K_s} = \alpha \quad (35)$$

relates elastic effects in machining or grinding operations to the stiffness of the machine tool.

The power, P , absorbed in the grinding process is:

$$P = F_t V_s \quad (\text{N} \cdot \text{m/sec}) \text{ or } (\text{watts}) \quad (36)$$

The ratio, F_t/F_n , varies between 0.3 for a dull wheel and 0.7 for a sharp wheel with an average value of 0.5. Therefore:

$$F_t = 0.5 F_n \quad (37)$$

and

$$P = \frac{1}{2} F_n V_s \quad (38)$$

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Using Eq. (29) and neglecting the threshold force, F_{th} ,

$$P = \frac{\pi D_w W V_s}{2 WRP} v_f \quad (39)$$

gives the power required for any feed rate, v_f .

The specific power P_s , using Eq. (25) and neglecting F_{th} , is:

$$P_s = \frac{P'}{Z_w} = \frac{V_s}{2 \cdot WRP} \quad (\text{J/mm}^3) \quad (40)$$

The Time Constant, τ_0 , of a grinding system governs the time required to build up grinding force or sparkout and depends upon the system stiffness, K_s , as well as on the material being ground, WRP .

$$\tau_0 = \frac{\pi D_w W}{WRP K_s} \quad (\text{sec}) \quad (41)$$

On materials exhibiting a plowing region, the time constant suddenly changes during a sparkout when the plowing region is encountered. The WRP in the plowing region is about 1/2 WRP in the cutting region.

The G ratio, giving the ratio of the volume of metal removed to the volume of abrasive consumed, is generally a variable depending upon the particular operating force intensity. It is a valid ratio only in the case where the Z_w' vs. F_n' and the Z_s' vs. F_n' relations are straight lines emanating from the origin in Fig. 11-6. Generally, this is not true.

GRINDING WHEELS AND DISCS

The proper selection of grinding wheels probably is the most important component of planning an efficient and economical grinding operation. The task of selecting the correct wheel or disc is made difficult by the fact that there are thousands of wheels and discs, each with specific characteristics. Charts and tables, such as those presented in subsequent sections of this chapter, provide guidelines for selecting a grinding wheel for the job at hand. For special applications and difficult-to-grind materials, it is best to work with the grinding wheel supplier. It is also advisable to maintain a good working relationship with the local representative to keep current with respect to new developments.

WHEEL COMPOSITION

Grinding wheels and discs are composed of selectively sized abrasive grains held together by a bonding material. Five distinct elements must be considered when selecting a wheel for a specific application. These elements are:

1. **Abrasive**—the grinding agent used in the wheel. Chemical composition, physical properties, and particle shape affect performance.
2. **Grain size**—the particle size of the abrasive grains, which influences stock removal rate and surface finish generated.
3. **Bond**—the bonding materials that hold the abrasive grains together to form a grinding wheel. Chemical composition affects strength, resilience, and other physical properties of the wheel.
4. **Grade**—the strength of the grinding wheel, usually controlled by varying amount of bonding material. This is frequently referred to as the hardness of the wheel.
5. **Structure**—the proportion and arrangement of the abrasive grains and bond. The porosity of the grinding wheel is affected by both the structure and the grade.

Abrasives

Natural abrasives. The most commonly used natural abrasives are corundum, emery, and diamond. Corundum is natural aluminum oxide containing varying amounts of impurities. Emery contains corundum mixed with varying amounts and characters of impurities. These natural abrasives, because of the varying amounts of impurities, tend to create nonuniformity in grinding wheels and in grinding performance. Their use today is

very limited. Diamond is a crystal form of carbon which varies from clear transparent stones to tinted varieties produced by slight amounts of mineral impurities. Diamond is the hardest known substance and, in the form of bonded wheels, is used for grinding very hard material such as cemented carbides, ceramics, glass, and stone.

Manufactured abrasives. Manufactured abrasives have almost totally replaced natural abrasives in grinding wheels with the single exception of diamond. Even in the case of diamond, synthesized diamonds are being increasingly applied. Manufactured abrasives in use today are silicon carbide, aluminum oxide, aluminum oxide/zirconium oxide cofusion, extruded sintered bauxite, diamond, and cubic boron nitride. These manufactured abrasives possess well-defined properties of hardness, toughness, and type of fracture.

Silicon carbide. Silicon dioxide (which is pure white quartz of the grade used in glassmaking), finely ground petroleum coke, salt, and sawdust are the raw materials used in the manufacture of silicon carbide. Silicon carbide finds its best use in grinding nonmetallics, nonferrous metals, and many cast irons. It is also used for grinding very hard and dense metals, particularly when a smooth finish is required. A relatively pure, green type of silicon carbide is more friable than a less-pure, black type.

Aluminum oxide. Bauxite is metallurgically reduced in the electric furnace to produce aluminum oxide. Aluminum oxide, which is the most popular abrasive, finds its greatest use in wheels that are used to grind steel, other ferrous alloys, and high-tensile, high-strength materials. White, nearly pure alumina abrasive is quite friable and is used when it is necessary to maintain sharp cutting points continuously through fracture of individual grits, as in dry grinding of heat-sensitive steels. More impure blue or brown "semifriable" alumina is used for general-purpose grinding, while still less-pure "regular" alumina is common in foundry snagging wheels and other heavy stock-removal operations.

Aluminum oxide/zirconium oxide cofusion. Cofusions of Al_2O_3 with ZrO_2 at levels of 10-40% have been found to provide improved durability and grinding rates compared to aluminum oxide.

Sintered bauxite. This material is usually manufactured in extruded shapes and has been found to be most effective in grinding stainless steels.

Diamond. The greatest use of manufactured diamonds has

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been in the grinding of ceramics, cemented carbides, glass, and stone. A trend in industry today is to use diamonds for difficult-to-grind steels when using other abrasives would cause them to break down too rapidly and generate high cost because of their inability to remove stock and hold geometry. Recent developments leading to controlled crystal configurations and surface coatings for manufactured diamonds have expanded the use of diamonds for ductile materials.

Cubic boron nitride (CNB). The combination of tremendous pressure with high temperatures similar to those used to produce manufactured diamonds is used for producing the diamond-like crystals of cubic boron nitride. This abrasive is finding application in wheels that are used to grind difficult-to-grind steel such as certain hard tool and die steels. Hardened steel is more suitable for grinding with this abrasive than soft steel.

The abrasive manufacturer, through his control of the production of the abrasive grain and the crushing of it afterward, is able to make available many variations of each particular basic grain. These modified forms of manufactured abrasives vary with respect to hardness, toughness, friability, and reactivity with work materials, making each particular form suitable for a specific grinding operation.

Grain Size

Abrasive grains vary in size from 6-8 grit for snagging to 1000 grit or finer for polishing and lapping. The choice of grain size is determined by the nature of the grinding operation, the material to be ground, and the relative importance of the stock removal rate and surface finish desired. Fine grain sizes are normally used for finishing; medium sizes are used for operations that require both stock removal and finish. For form-grinding, finer grit sizes are used. Hard materials generally require fine grit sizes to obtain penetration, and soft materials require coarse grit sizes. Coarse grit is broadly defined as 6 through 24, medium as 30 through 60, fine as 70 through 180, and very fine as 220 through 1000 (see Table 11-2). ANSI Standard B74.12-1977, "Specifications for Size of Abrasive Grain—Grinding Wheels, Polishing and General Industrial Uses" should be referenced for additional information.

Many other factors enter into surface finish. The method of dressing, bond type, wheel hardness and stock removal rate can have a more significant effect on surface finish than a fairly wide variation in abrasive size.

Wheel Bonds

The purpose of the bond is to hold the abrasive grains together to form a wheel. Ideally, as the abrasive grains become dull and used, the bonding material breaks away, thus permitting the dull grains either to fracture or to be torn out so that, at all times, new, sharp abrasive grains are available for grinding the workpiece. Standard grinding-wheel bonds are vitrified bond, silicate, resinoid, rubber, shellac, oxychloride, and metal.

Vitrified bond. The chief ingredients of vitrified, or ceramic, bonds are clay and flux. The majority of grinding wheels in use today are vitrified wheels. They are strong and rigid and retain high strength at elevated temperatures, with the capability to remove stock, generate accurate geometry, and produce smooth finishes. Vitrified bonds are practically unaffected by water, oils, or ordinary temperature conditions. Poor shock resistance, however, inhibits their application when mechanical impact or large temperature differentials are likely to occur.

Silicate bond. This bond is used to a very limited extent, primarily in operations in which the heat generated by grinding

TABLE 11-2
Average Particle Size of Grinding Wheels

Grain Size	Aluminum Oxide and Silicon Carbide		Diamond and Cubic Boron Nitride	
	in.	mm	in.	mm
10	0.1366	3.470	---	---
12	0.1003	2.547	---	---
14	0.0830	2.108	---	---
16	0.0655	1.664	---	---
24	0.0528	1.341	---	---
30	0.0408	1.036	---	---
36	0.0280	0.711	---	---
46	0.0200	0.508	0.1300	3.302
54	0.0170	0.432	---	---
60	0.0160	0.406	---	---
70	0.0113	0.287	---	---
80	0.0105	0.267	0.0060	0.152
90	0.0085	0.216	---	---
100	0.0068	0.172	0.0050	0.127
120	0.0056	0.142	0.0040	0.102
150	0.0048	0.122	0.0035	0.089
180	0.0034	0.086	0.0029	0.074
220	0.0026	0.066	0.0025	0.063
240	---	---	0.0021	0.053
280	---	---	0.0017	0.043
320	---	---	0.0015	0.038

must be kept to a minimum, as in grinding edged tools.

Resinoid bond. This is a synthetic-resin, organic bond mixed in powdered or liquid form with the abrasive grains. Resinoid-bonded wheels generally find their use in rough grinding and cutoff operations. They are also used in generating very fine finishes in roll grinding. Resin bonds are likely to be softened by prolonged exposure to water or water-based grinding fluids.

Rubber bond. Rubber-bond wheels are widely used in cutoff, centerless grinding, and polishing of drill flutes.

Shellac bond. Shellac is another organic bond used for wheels to produce high finishes on rolls, and for cutlery grinding.

Oxychloride bond. Magnesium oxychloride bond is used to a very limited extent in certain wheels and segments, particularly on disc grinders.

Metal bond. Metal bond is used for diamond abrasives commonly used in the grinding of ceramics. There is also a trend to use metal-bonded wheels in the grinding of carbide with a technique known as single-pass, heavy-infeed grinding. Metal bonds are also used with aluminum oxide or diamond abrasive to provide conductive wheels for electrolytic grinding.

Wheel Grade

Wheel grade is not a precisely defined term but is usually taken to be an indication of bond strength. Grade or hardness of a wheel relates to the amount of bond in the wheel, with strength being influenced by properties of the bonding agent. The greater the bond content, the "harder" the wheel. A "soft" wheel will have a small amount of bond and/or a weak bond. Some engineers specify wheels that are too hard in the mistaken belief that they are most economical because they may last longer. Actually, the grade of the wheel should be related to the productivity of the operation rather than to the life of the wheel.

Hard grades of wheels are used to remove large amounts of stock at rapid rates, to grind small areas of contact, to remove

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stock from soft materials, and to hold form on precise operations. Hard grades lend themselves to severe grinding operations.

Soft grades of wheels are used for light stock removal, to grind large areas of contact, to remove stock from hard materials and high-value parts, when grinding conditions are relatively light,

and when continuous wheel wear is necessary to maintain sharp abrasive grits and minimize metallurgical damage to heat-sensitive materials. Table 11-3 gives characteristics of soft-acting wheels. Table 11-4 gives characteristics of hard-acting wheels.

TABLE 11-3
Characteristics of Soft-Acting Wheel

Breaks down too fast. This, of course, is a relative condition but is sufficient reason to try a harder grade for better economy. The hardness should be increased one grade at a time until "hard action" is experienced. Then the next-to-last wheel tried is the most economical.

Finish gets progressively worse. After dressing, the wheel will produce the required finish, but this steadily deteriorates because the grain breaks from the wheel so rapidly that there is no chance for it to get smooth (glaze). Note: Rough finish on soft work also results from the loading of a hard acting wheel. Loading, however, is instantaneous; the above action is slower.

Cuts freely. A soft wheel has little opportunity to glaze, so there is little to retard cutting action.

Sparks out quickly. A free-cutting wheel will spark out because of low cut pressure; hence low machine distortion.

Chatter. Chatter is usually wide, and finish is poor. This is the result of a high spot, or high spots, on the wheel, making chatter spacing a function of the number of high spots, wheel speed and work speed.

Sizing difficult. A wheel that loses grain rapidly also loses its diameter at a fast rate. The coarser the grain size, the more rapid the loss in wheel diameter.

Scratches, fish tails. Grain breaks from the wheel and rolls through the cut producing scratches that are deeper than the ground surface. A wheel one grade harder will usually stop this. Dirty grinding fluid being recirculated through the lines is sometimes responsible for this condition.

(Cincinnati Milacron)

TABLE 11-4
Characteristics of Hard-Acting Wheel

Won't spark out. If the infeed of a cylindrical grinding machine is stopped and the wheel is allowed to tarry in the cut, a hard wheel will continue to cut because of the deflection in the machine elements set up as a result of high cut pressures. The machine is, in effect, a big "C spring."

Size trouble. There will be difficulty in sizing as a result of the failure to spark out. The machine cannot come to size because of high cut pressures. The amount of infeed is greater than the actual stock removed.

Heat checks. Heat checks result from hard and fine wheels and are known as grinding cracks. However, in many cases wheels are unjustly blamed, because the design, metallurgy, heat treatment of the workpiece, plus grinding fluid type and application, play an important part in this problem.

Glaze. Grain wears flat and cannot be discharged because the mechanical pressures existing in the grinding operation are insufficient to break the bond posts that hold the dull grain. The wheel looks shiny by reflected light.

Loading. The material being ground is welded into the wheel face, inhibiting the cutting action and producing poor finishes. This condition is not often found on materials over Rc55 scale. It can be an extremely troublesome condition when attempting to get good finishes on softer material. The loading may be so well distributed and so small in particle size that detection is difficult. Fine grain sizes also promote loading because they have less chip clearance and produce more heat. This heat promotes welding.

Burn. Because of flat grain (glaze) the wheel rubs the work, bringing the temperature high enough through friction to oxidize the material being ground. A glazed wheel has more grain in contact with the work. This adds to the heat buildup. Fine-grain wheels tend to burn for this same reason even though they may be acting soft.

Squeal. Hard wheels will sometimes emit a high-pitched sound called "squealing." This must not be confused with the normal grinding sound of free-cutting wheels.

Doesn't cut freely. Cut is slow, and wheel-to-work pressures are high.

Out-of-round work. Hard-acting wheels develop high cut pressures and heat that distort the workpiece and prevent the rounding action desired. In surface grinding this appears as low-center work.

Finish gets progressively better. As the grain gets smoother (glazes), the finish gets progressively better (except when there is loading) but the cutting rate gets proportionately slower.

Chatter. A hard wheel will often produce chatter that is fine and closely spaced. As the finish gets better (the result of grain getting smoother—glazed), the chatter becomes more pronounced.

(Cincinnati Milacron)

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Wheel Structure

Structure is the relative spacing of abrasive grain in a given volume. In an open-structure wheel there are fewer abrasive grains per unit volume than in a closed-structure wheel. The purpose of open structure is to provide chip clearance. Structure is designated by numbers ranging from 0-15. The lower the number, the denser the structure; and the higher the number, the more open the structure. Open-structure wheels are used in the removal of stock when chip clearance is a limiting factor. Closed-structure wheels are used for holding form.

Concentration in diamond wheels is akin to structure in other abrasive wheels in that it is a measurement of abrasives per unit volume of grinding wheel. However, concentration is a more important characteristic in diamond wheels than structure in other abrasive wheels, because the total stock which can be removed with a diamond wheel is usually directly proportional to the amount of diamond it contains. As with structure and grade, there is no published standard which establishes quantitative values to designations. However, most diamond wheel producers have adopted the convention in which 100 concentration designates 72 carats of diamond per cubic inch of wheel (0.0044 carats per cubic millimeter) and smaller concentration numbers refer to the fractional part of 100 concentration in the wheel. For example, 50 concentration designates 36 carats per cubic inch (0.0022 carats per cubic millimeter).

WHEEL SPECIFICATION

A standard marking system defined by the American National Standards Institute as ANSI Standard B74.13-1977 is used by all grinding wheel manufacturers.⁴ This marking system involves the use of letters or numbers in each of seven positions as indicated in Fig. 11-8.⁵ When necessary to show special grain combinations, manufacturers may add an additional symbol to the regular grain-size number. A similar marking system is used by most grinding wheel manufacturers to designate diamond wheels and CBN wheels.⁶ This marking system involves the use of letters or numbers in each of seven positions as indicated in Fig. 11-9. Another ANSI standard covers the specifications of shapes and sizes of grinding wheels and mounted wheels.⁷

Types of Grinding Wheels

Figure 11-10 illustrates the various shapes of standard peripheral grinding wheels in use today. Missing numbers in this list of standard shapes pertain to wheel geometries that have been dropped as standards but are usually available as specials. Grinding wheel configurations identified as specials are listed in "Grinding Wheel Specifications for Grinding Machines—1978 Supplement" (Grinding Wheel Institute, Cleveland). Figure 11-11 illustrates the various shapes of standard side or face grinding wheels in use today. Table 11-5 provides a key to letter dimensions and grinding wheel shapes to which the dimensions commonly apply.

Shapes of Grinding Wheel Faces

Figure 11-12 illustrates the various types of standard wheel faces in use today.

WHEEL INSPECTION

All new wheels should be inspected individually for chips, cracks, or other defects before they are put into service. Several methods are available for judging the soundness of a grinding wheel including the ring test and vibration test methods.

Ring Test

The ring test is a method of checking for cracks in a wheel. Small wheels can be suspended from the hole on a peg or the finger, while heavier wheels should be set on edge on a hard floor surface. With the wooden handle of a screwdriver, or a wooden or nylon mallet, the wheel is tapped lightly at a point approximately 45° away from the vertical centerline. A sound, undamaged wheel will give a clear metallic tone, whereas a cracked wheel will give "dead" tone and not ring clear. Wheels bonded with organic materials do not give the same clear metallic sound as do vitrified and silicate wheels. In this case, it is often helpful to "ring" several identical wheels for comparison, which will allow rejection of any wheel with a suspiciously different sound before use.

Certain grinding wheels cannot be tested using the ring test method because of their size or configuration. These wheels include wheels 4" (100 mm) diam or smaller, plugs and cones, mounted wheels, segments, plate-mounted wheels, and inserted-nut and projecting-stud disc wheels. In some cases, a vibration test can be used to check for cracks in these grinding wheels.

Vibration Test

As with the ring test, the vibration test should be performed immediately before mounting the grinding wheel (either new or used) because this is the last opportunity to check wheel soundness before using the wheel.

The basis of the vibration test is the way that loose sand or similar material is distributed on the side of a wheel when the wheel is vibrating. As the wheel vibrates, sand granules or other loose material will respond to the vibration energy; the granules will move away from cracks in the wheel. If the wheel is sound, the granules will remain evenly distributed over the surface of the wheel. Both sides of a wheel should be tested by placing, in horizontal position, alternate sides of the wheel on a test vibration fixture and coating the wheel with a thin layer of fine granulated material.

Any doubtful wheel should be returned to the manufacturer for another inspection and speed testing before being put into service. Should an unsound wheel be mounted without the crack or other damage being detected, it will usually break upon reaching operating speed or shortly thereafter. Therefore, it is always recommended that an operator stand aside and let the wheel run for a full minute or more (with the safety hood in place) before starting to grind.

WHEEL MOUNTING

Accident statistics show that approximately 75% of all wheel breakages in operation have been traced directly to faulty equipment and improper mounting conditions. The greatest single cause is excessive and uneven distribution of flange mounting pressures brought about by any one of a number of conditions. A few of the most common conditions are undersized or mismatched flange diameters, improper wheel mount (design and/or material), warped or sprung flanges, absence of relief area in flanges near wheel hole, excessive torque pressures (causing flange deformation), interference fit of wheels on arbors or mounting sleeves, and failure to clean the flanges.

The most critical zone in a rotating wheel is the area immediately surrounding the hole. Primary stresses are radial and tangential, with tangential accounting for the major stress. It is important to introduce flange pressures uniformly as far away as possible from the critical area surrounding the hole. This is the basis for the safety code requirement that the diameter of flanges

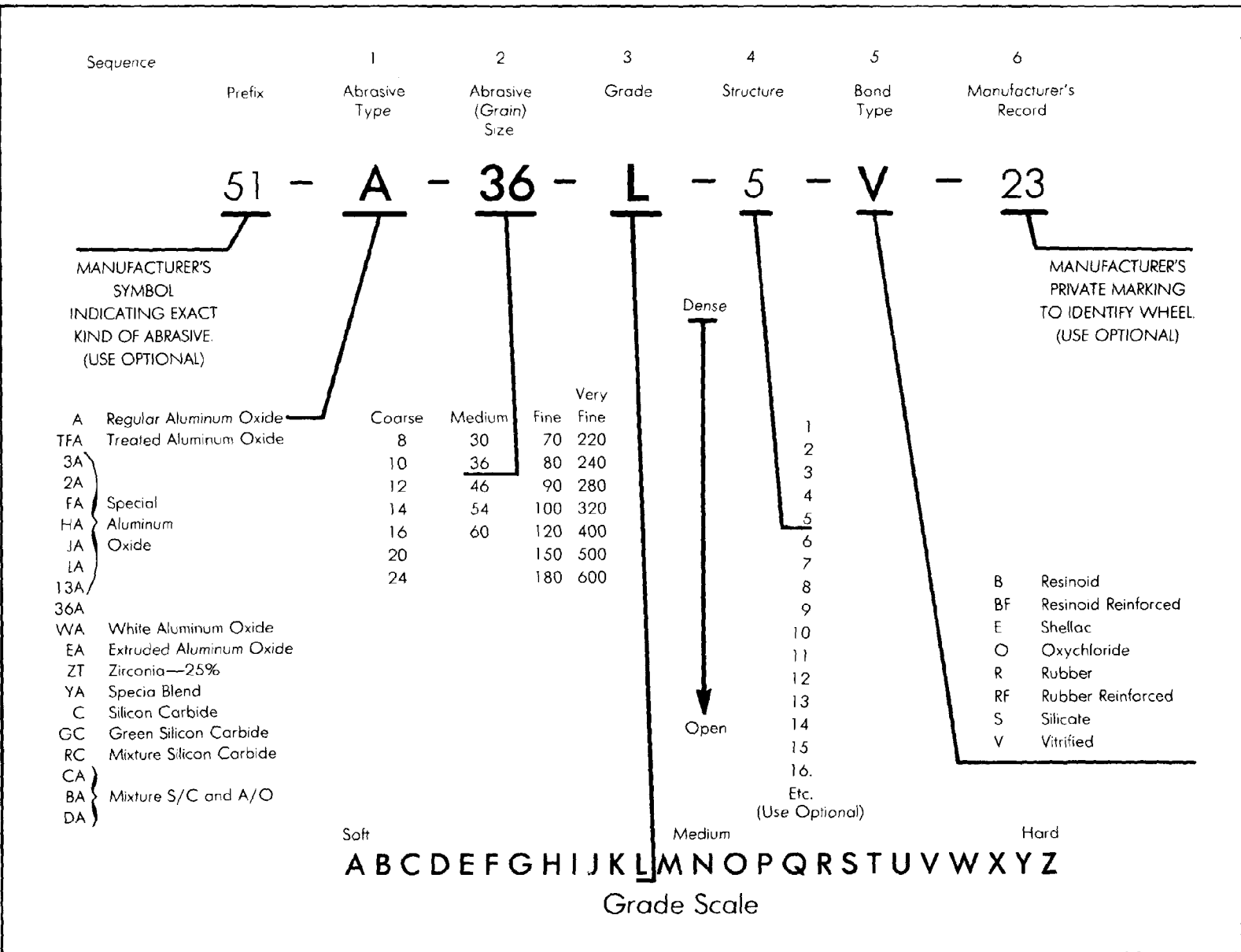


Fig. 11-8 Standard bonded-abrasive wheel-marking system (ANSI Standard B74.13-1977).

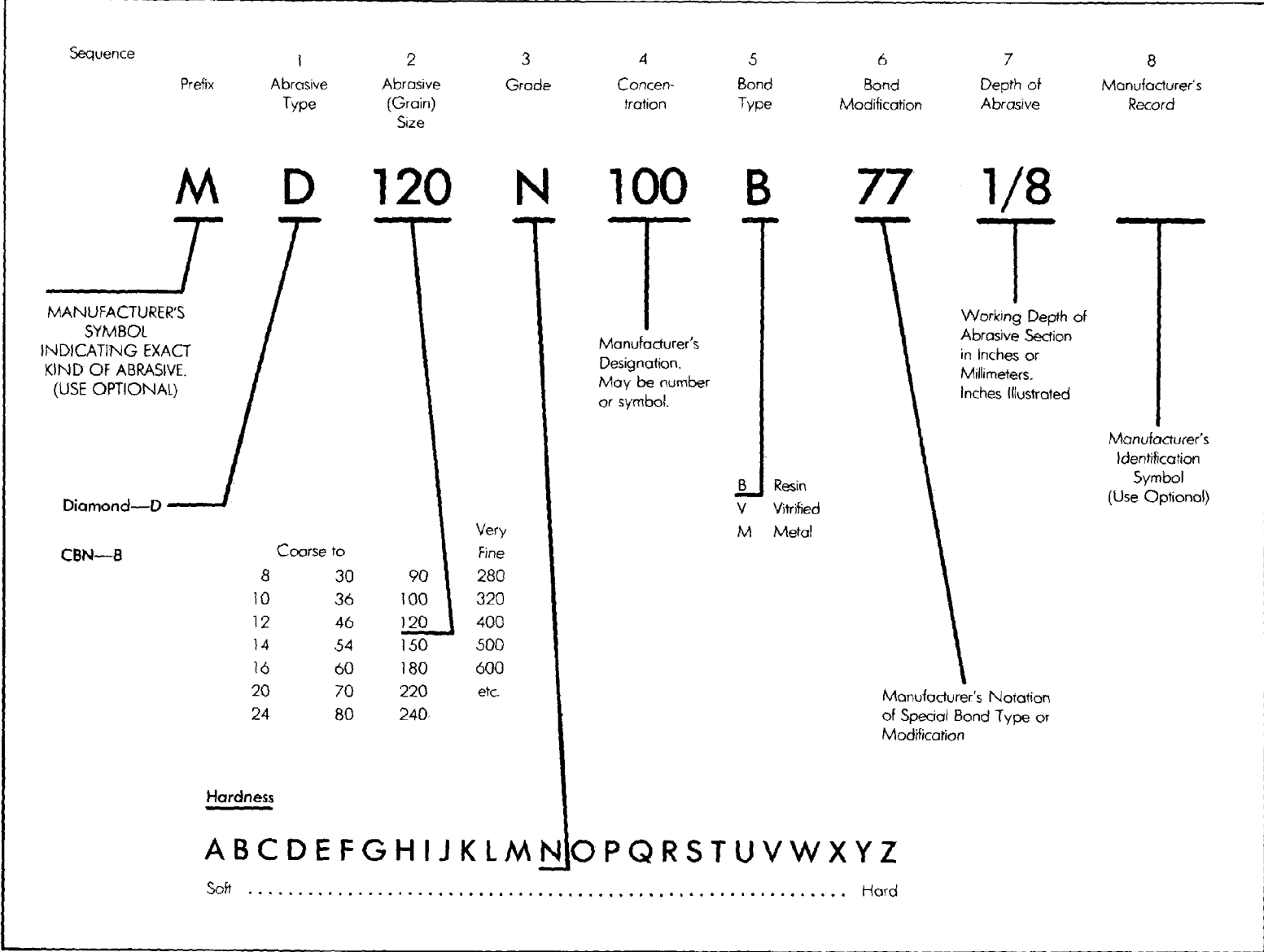


Fig. 11-9 Wheel-marking system for diamond and cubic boron nitride wheels (ANSI Standard B74.13-1977).

GRINDING WHEELS AND DISCS

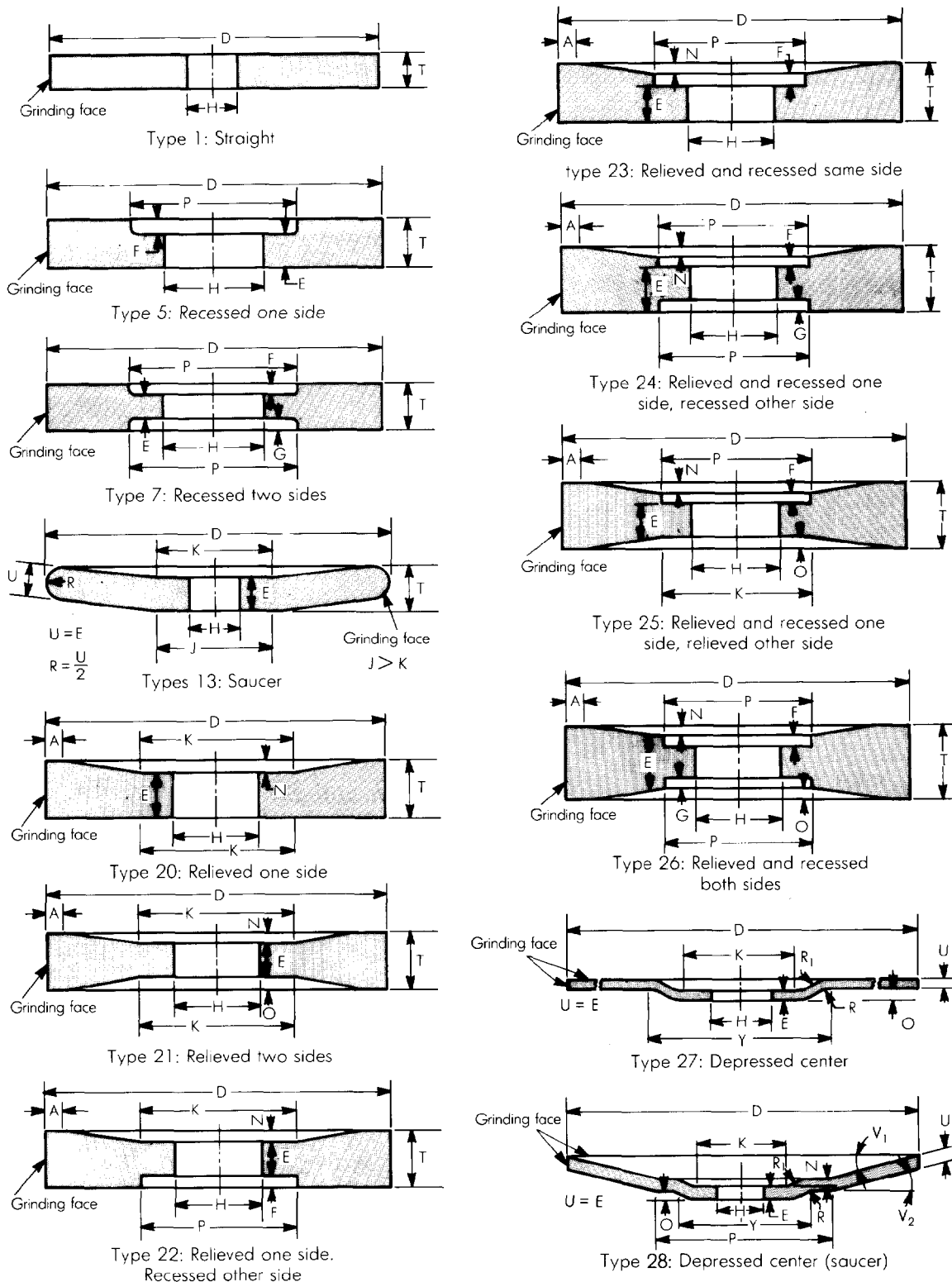


Fig. 11-10 Standard Shapes of peripheral grinding wheels. (Grinding Wheel Institute, ANSI Standard B74.2-1974).

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GRINDING WHEELS AND DISCS

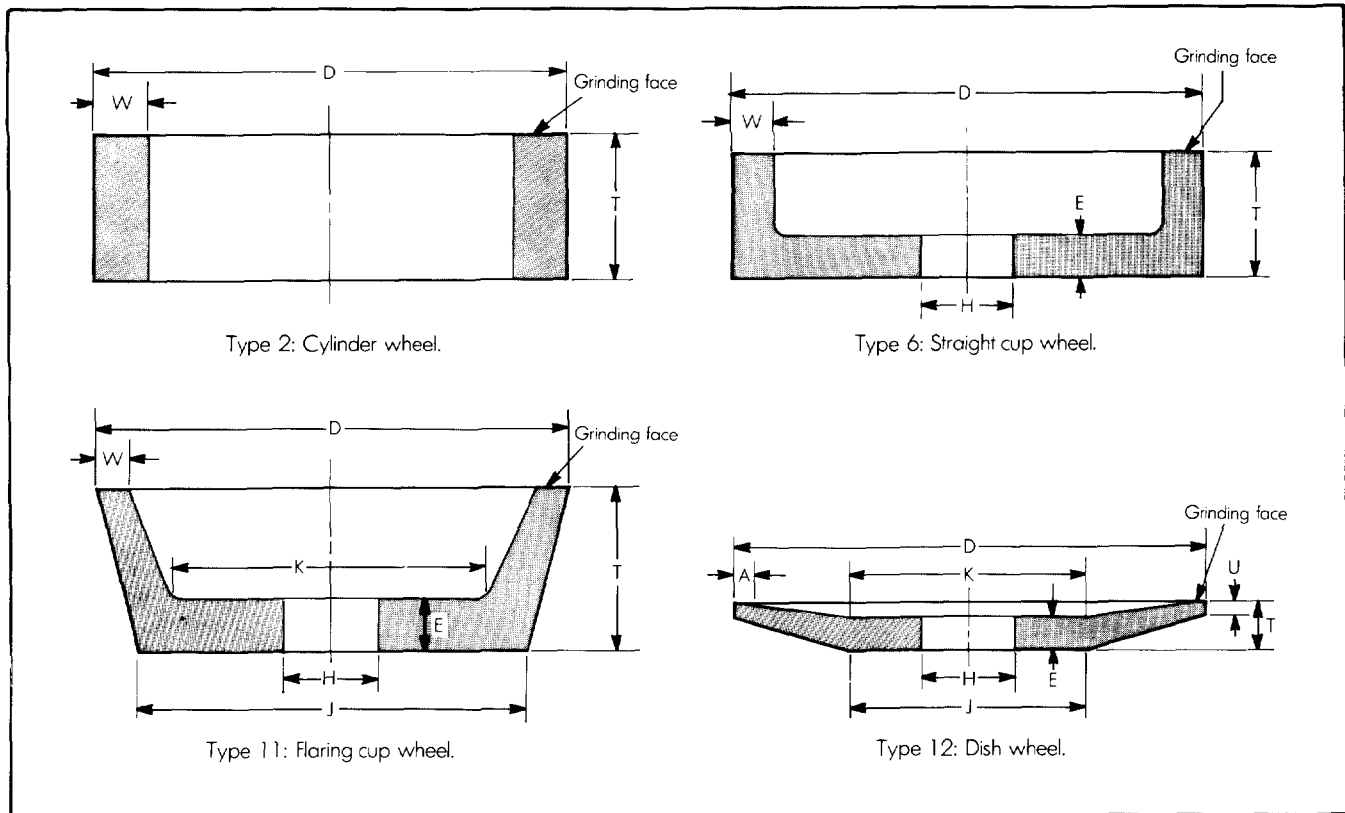


Fig. 11-11 Standard side or face grinding wheels (Grinding Wheel Institute, ANSI Standard B74.2-1974).

TABLE 11-5
Key to Letter Dimensions and Grinding Wheel Types
to Which the Dimensions Commonly Apply*

Letter Dimensions	Grinding Wheel Types
A— Radial width of flat at periphery.	Types 12, 20, 21, 22, 23, 24, 25, 26.
B— Depth of blind hole threaded bushing.	Types 16, 17, 18, 18R, 19.
D— Diameter (overall).	All types.
E— Thickness at hole.	Types 5, 6, 7, 11, 12, 13, 20, 21, 22, 23, 24, 25, 26, 27, 28.
F— Depth of recess one side.	Types 5, 7, 22, 23, 24, 25, 26.
G— Depth of recess other side.	Types 7, 24, 26.
H— Hole diameter.	All types except Type 2.
J— Diameter of outside flat.	Types 11, 12, 13, 17, 19.
K— Diameter of inside flat.	Types 11, 12, 13, 20, 21, 22, 25, 27, 28.
N— Depth of relief one side.	Types 20, 21, 22, 23, 24, 25, 26.
O— Depth of relief other side.	Types 21, 25, 26, 27, 28.
P— Diameter of recess.	Types 5, 7, 22, 23, 24, 25, 26, 28.
R— Radius.	Types 13, 16, 18R.
S— Length of cylindrical section.	Type 19.
T— Thickness (overall).	All types.
U— Width of edge.	Types 12, 13, 27, 28.
V— Face angle.	Type 1 (Faces B, C, D, E, G, H, I, and N).
V ₁ —Back angle.	Type 28.
W—Wall (rim) thickness at grinding face.	Types 2, 6, 11.
X— Face dimension.	Type 1 (Face N).
Y— Outside diameter of hub.	Types 27, 28.

(ANSI Standard B74.2-1974, published by Grinding Wheel Institute)

* See Figures 11-10, 11-11, and 11-12 for grinding wheel shapes and face specifications.

GRINDING WHEELS AND DISCS

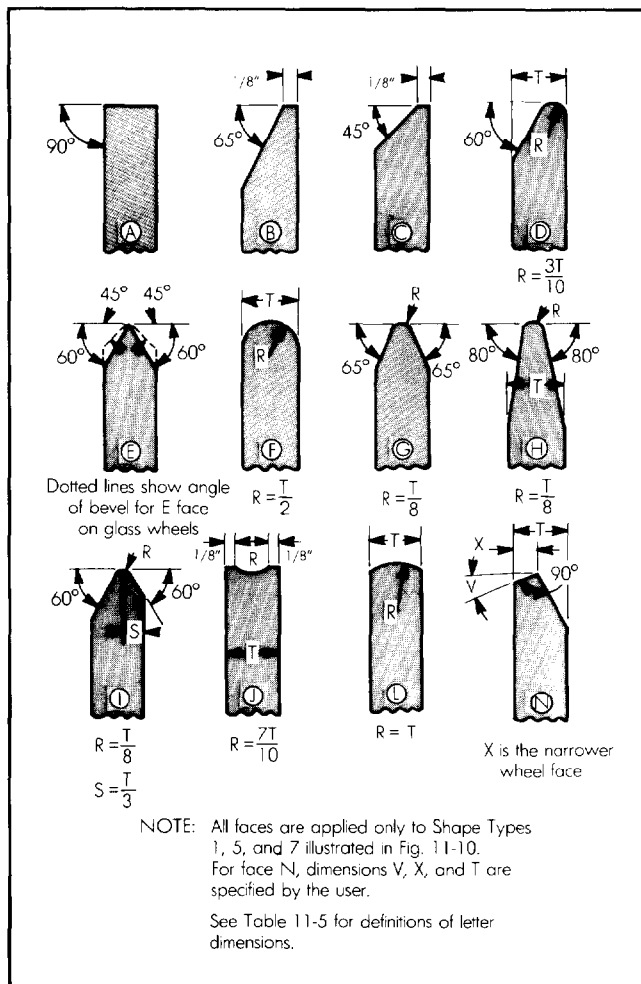


Fig. 11-12 Standard Shapes of Grinding Wheel Faces
(Grinding Wheel Institute, ANSI Standard B74.2-1974).

used to mount small-hole wheels must be not less than one-third the wheel diameter, and for large-hole wheels, approximately 2" (50 mm) larger than the hole diameter. The higher the speed of operation, the more critical these factors become, since forces increase as the square of the velocity.

Blotters of suitable compressible material and correct dimensions must always be used between flanges and abrasive wheel surfaces (except for a few specific applications) to allow uniform distribution of flange pressure. Highly compressible material, such as blotting paper (normally used), should not exceed 0.025" (0.64 mm) in thickness, and all blotters must cover the entire contact area of the mounting flanges.

Flange Tightening

Flange deformation due to overtightening is perhaps the most prevalent mounting ailment contributing to wheel breakage. The result is excessive springing of the flange so that the contact area of the flange is distorted, causing uneven distribution of mounting pressure, and a stress is introduced into the abrasive-wheel body. If severe enough, a failure (crack) in the wheel structure can occur immediately, but most commonly the strain is not relieved until other stresses from rotation, grinding heat,

and pressure come into play. The compressive strength of all grinding wheels is quite high but varies with grit size and amount and type of bond (grade of hardness).

To determine required torque pressures (or total force) on wheel/flange mounting bolts, several factors must be considered, including the size of the wheel, grinding forces, the diameter of the flanges and contact area, whether a multiple-bolt mounting or a single nut on a central arbor is involved, the available horsepower, and the required speed of operation. The flange must hold the wheel to resist both torque and grinding pressure, with friction between flange and wheel (with blotters) providing the grip. As the wheel mount warms, the metal will expand more than the abrasive wheel, thereby reducing effective tension. As a result, the mount could require retightening after a period of grinding.

Arbor Expansion

Arbor expansion, caused by hot spindle bearings or elevated grinding temperatures, is another factor often overlooked in investigating wheel failures in operation. Standard industry practice, as specified in ANSI safety codes and the OSHA Act, is to hold machine arbors to nominal diameter, +0.0001, -0.002" (+0.003, -0.05 mm). Wheel hole oversized tolerances vary depending upon the application but can range from +0.001 to +0.012" (+0.03 to +0.30 mm) or more. On precision grinding operations, the average hole is about +0.002 to +0.006" (+0.05 to +0.15 mm). The difference in the coefficient of expansion between the abrasive wheel and steel arbor is significant, with arbors expanding substantially more than wheels.

WHEEL SELECTION

Operating conditions that affect the performance of grinding wheels are wheel speed, material removal rates, normal force, material ground, area of contact, grinding fluid, the relationship between wheel and work size, vibration, truing and dressing, and power.

Abrasive Wear

The mechanism of abrasive wear has been studied by many investigators, and the present information implies that there are three major mechanisms. These mechanisms are: solution of abrasives into the workpiece material (attritious wear), chipping or fracturing of individual abrasive grains, and loss of whole grits through bond post breakage.

All three mechanisms probably occur simultaneously in most operations, but the relative importance of the mechanisms in any given application depends on operating conditions, abrasive type, bond type and amount, and work material. Tough abrasives tend to favor attritious wear and loss of whole grits; friable abrasives favor chipping or fracturing of grains; low bond strength or quality favor loss of whole grains; and abrasives with high solubility in workpiece materials favor attritious wear.

Wheel Speed

Wheel speed in grinding is measured in surface feet per minute (meters per second), rather than revolutions per minute. As wheel speed is increased, each cutting grain is called upon to do less work each time it strikes the workpiece, which results in less wheel wear. Increased wheel speed therefore results in lower abrasive cost. As the wheel speed is reduced, each cutting grain is called upon to do more work each time it strikes the workpiece, and the result is increased wheel wear (see "Principles of Grinding" in this chapter).

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Wheel speed affects the choice of the wheel bond. Vitrified-bond wheels are commonly used for speeds up to and including 8500 sfm (43.2 m/s); but speeds of 12,000 sfm (61 m/s) are also popular; and selected operations now exist in which speeds as high as 16,000 sfm (81.3 m/s) are used. Resinoid-bond grinding wheels generally operate at 9500 sfm (48.3 m/s); however, a speed of 12,500 sfm (63.5 m/s) is common in foundry floorstand grinding and steel conditioning, and speeds of 16,000 sfm (81.3 m/s) are being used for steel conditioning.

Increased wheel speeds are finding great use in producing high rates of stock removal with less tendency to distort the workpiece. High-speed grinding is discussed later in this chapter (see "Special Grinding Machines and Processes").

Work Speed

Work speed is the speed at which the workpiece traverses across the wheel face or rotates about a center. The main advantage of higher work speed is its ability to retard or prevent thermal damage to the workpiece. Metal removal rate (volume removed/unit time) may be calculated as an area being removed at a rate ($\text{in.}^2 \times \text{ipm}$ or $\text{mm}^2 \times \text{mm/s}$). When an increase in workspeed increases the metal removal rate (in reciprocating surface grinding, for example), higher forces, power, and wheel wear rates occur. When the metal removal rate is unaffected by workspeed (most cylindrical plunge-grinding operations), essentially no change occurs in forces, power, or wheel wear rates, but the surface integrity is improved by higher workspeeds.

Infeed or Downfeed

The rate at which a wheel is fed into the workpiece can cause substantial changes in wheel performance. Higher infeed rates always increase the metal removal rate (area being removed multiplied by infeed rate). This generates higher normal forces, power, and wheel wear rates. A rougher finish, poorer geometry, but higher productivity will occur. If the higher normal force is above the mechanical strength of the wheel, the wheel wear rate may be significantly higher and the new G-ratio (grinding ratio—see following section) may be much lower than the original. Reducing the infeed rate reverses all of these factors.

Traverse or Crossfeed

Traverse or crossfeed is the distance or speed at which the workpiece is moved across the wheel face; it is different from workspeed. In traverse cylindrical grinding, if the crossfeed distance is 25% or less of the wheel width, good surface finishes, but low productivity, will result. Increasing the crossfeed to 50% or more of the wheel width will produce poorer surface finish and higher productivity, but the wheel will wear evenly across its face. The workpiece surface finish depends mainly on the wheel wear rate of the center portion of the wheel (traverse cylindrical) or the exit end of the wheel (in throughfeed centerless grinding).

MATERIAL TO BE GROUND

Materials to be ground can be divided into two types: metallic or nonmetallic. Metallics can further be divided into high or low-tensile materials. The nonmetallic type can be divided into hardness ranges below or above 800 Knoop. To grind metallics, aluminum oxide grinding wheels are primarily used. In selected operations, diamond and cubic boron nitride wheels are also now being used. To grind nonmetallics, silicon carbide wheels are used if the hardness is 800 Knoop or lower; diamond wheels are used to grind the harder nonmetallics. To grind hard

materials, soft-grade, fine-grit, friable-abrasive grinding wheels are used. To grind soft materials, hard-grade, coarse-grit, tough-abrasive grinding wheels are used. To grind heat-sensitive materials, soft-grade, friable-abrasive wheels are most commonly used.

The following tables are presented as guides to wheel selection for various materials processed by various grinding operations:

- Table 11-6—Grinding Wheels for Surface Grinding
- Table 11-7—Grinding Wheels for Centerless Grinding
- Table 11-8—Grinding Wheels for Cylindrical Grinding
- Table 11-9—Grinding Wheels for Internal Grinding
- Table 11-10—Grinding Wheels for Tool Room Grinding

These tables are presented courtesy of Norton Co. and contain special designations particular to Norton products. Figures 11-8 and 11-9 can be used to identify the wheel characteristics specified in the tables. Equivalent grinding wheels are available from other suppliers.

Grinding ratio, defined as the volume of material removed from the work per unit volume of wheel wear, is a useful measurement of grindability (the ease with which a material can be ground). The higher the ratio, the easier a work material is to grind. Grinding ratio for a particular material, however, varies with different types of grinding operations and with specific conditions of the operation (speed, feed, grinding fluid, etc.).

AREAS OF CONTACT

Area of contact varies from large, as in vertical spindle/rotary table grinding, to small, as in external cylindrical grinding. Small areas of contact generate high-unit pressures (pressure is normal force divided by contact area) and require hard-grade, fine-grit wheels. Low unit pressures call for soft-grade, coarse-grit wheels. In cylindrical grinding, a parameter called the equivalent diameter, D_e , can be useful. (The relationships between D_e and other grinding process variables are discussed in "Principles of Grinding" in this chapter.) D_e can be obtained by use of the following equation:

$$D_e = \frac{\text{work diameter} \times \text{wheel diameter}}{\text{work diameter} \pm \text{wheel diameter}} \quad (42)$$

For internal grinding, the - sign is used; for external grinding, the + sign is used. The equivalent diameter, D_e , is the size of the wheel used to grind a flat surface in order to represent the fit of the wheel and work.

For example, internal grinding a 4.0" (101.6 mm) part with a 3.6" (91.4 mm):

$$D_e = \frac{(4.0)(3.6)}{4.0 - 3.6} = \frac{14.4}{0.4} = 36.0"$$

In metric:

$$D_e = \frac{(101.6)(91.4)}{101.6 - 91.4} = \frac{9286.2}{10.2} = 910.4 \text{ mm}$$

This means these two bodies fit each other like a 36.0" (910 mm) wheel would fit a flat surface. If the used wheel size is 2.88" (73.1 mm), then:

$$D_e = \frac{4.0(2.88)}{4.0 - 2.88} = \frac{11.52}{1.12} = 10.28"$$

In metric:

$$D_e = \frac{(101.6)(73.1)}{101.6 - 73.1} = \frac{7426.9}{28.5} = 260.5 \text{ mm}$$

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TABLE 11-6
Grinding Wheels for Surface Grinding

Application	Wheel Specifications	Application	Wheel Specifications
Horizontal Spindle Grinders (Straight Wheel):*		Vertical Spindle Grinders (cylinders, cups, and segments):	
Alnico	32A60-H8VBE	Aluminum	
Aluminum	37C36-J8V	plate	37C30-H8V
Brass	37C36-J8V	cast	32A30-G12VBEP
Bronze		Brass	37C24-H8V
soft	37C36-J8V	Bronze	
hard	23A36-K8VBE	soft	37C24-H8V
Cast Iron		hard	32A30-G12VBEP
ductile	32A36-J8VBE	Cast Iron	
gray	23A36-J8VBE	ductile	23A30-F12VSM
chilled	37C36-J8V	gray	23A30-F12VSM
Nihard	32A46-I8VBE	chilled	37C30-H8V
Chrome Plate	32A80-I8VBE	Nihard	32A36-F12VBEP
Die Steel		Steel	
hardened	32A60-F12VBEP	hard (broad contact)	32A36-E12VBEP
annealed	32A46-I8VBE	hard (narrow contact)	32A46-H8VBE
Steel		soft	32A24-G12VBEP
soft	32A36-K8VBE	tool and die	32A46-H8VBE
hard	32A60-G12VBEP	300 series stainless	32A46-F12VBEP
tool and high speed	32A60-F12VBEP	400 series stainless	32A24-G12VBEP
300 series stainless	32A46-J8VBE		
400 series stainless	32A46-I8VBE		
Stellite	32A46-H8VBE		
Titanium	37C60-K8V		
Tungsten	37C46-J8V		

Form Grinders:

Steel	
300 series stainless	53A60-I8VJN or 53A60-J8VJN
400 series stainless	53A60-I8VJN or 53A60-J8VJN
Heat-resistant, Nickel-based Super Alloys	
A286	53A60-I8VJN or 53A60-J8VJN
Inconel	53A60-I8VJN or 53A60-J8VJN
Rene	53A60-I8VJN or 53A60-J8VJN

(Norton Co.)

* In the wheel specifications listed for horizontal spindle grinders, the grit sizes are for wheels 14" (350 mm) diam and larger. For smaller diameter wheels, 36 and 46 grit recommendations should be changed to 46 and 60 grit respectively.

Thus, from "new" to "used" wheel, the system conformity has changed from a large area contact/low unit pressure ($D_e = 36.0"$; 910.4 mm) to a smaller area of contact/higher unit pressure ($D_e = 10.28"$; 260.5 mm).

For externally grinding a 4.0" (101.6 mm) part with a 24.0" (609.6 mm) diam wheel:

$$D_e = \frac{(4.0)(24.0)}{4.0 + 24.0} = \frac{96.0}{28.0} = 3.42"$$

In metric:

$$D_e = \frac{(101.6)(609.6)}{101.6 + 609.6} = \frac{61\,935.4}{711.2} = 87.1 \text{ mm}$$

With a used wheel, having a 16" (406.4 mm) wheel diameter:

$$D_e = \frac{(4.0)(16.0)}{4.0 + 16.0} = \frac{64.0}{20.0} = 3.20"$$

In metric:

$$D_e = \frac{(101.6)(406.4)}{101.6 + 406.4} = \frac{41\,290.2}{508} = 81.3 \text{ mm}$$

Here the conformity has hardly changed; it has remained a small area of contact/high unit pressure situation.

External grinding a 28.0" (711.2 mm) roll with a 30.0" (762 mm) diam wheel:

$$D_e = \frac{(28.0)(30.0)}{28.0 + 30.0} = \frac{840.0}{58.0} = 14.48"$$

In metric:

$$D_e = \frac{(711.6)(762)}{711.6 + 762} = \frac{542\,239}{1473.6} = 367.9 \text{ mm}$$

This is a conformity more like internal grinding (note the 10.28-36.0" [260.5-910.4 mm] range previously presented) than external grinding and is therefore a large area of contact/low unit pressure situation.

WHEEL BALANCE

Particular attention is needed to make sure that a wheel is in balance before it is used for grinding. Balance is not entirely dependent on the wheel itself, but is also affected by the machine spindle and the means of tightening the wheel on the machine. Consequently, the machine/wheel system should be in balance before the wheel is operated.

An out-of-balance wheel sets up excessive vibration, produces faster wheel breakdown, poor finishes, or chatter and can be

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dangerous. Wheels generally should be statically balanced before putting them on the machine. They then should be dressed into concentricity, taken off, rebalanced, and put on the grinder and operated. Today equipment is available that will balance the wheel while it is running on the machine.

Generally, balancing is done by shifting weights on the wheel mount. Some wheel mounts have two weights, while others have four. The following steps should be taken to balance a wheel:

1. Remove the weights from the mounting, then place the wheel on balancing ways. When the wheel is on the balancing ways, permit the heavy side of the wheel to come to rest. Place a chalk mark at the bottom (the heavy

point). Turn the wheel 90°, first to one side and then to the other side, to check the location of this heavy point. If it comes to rest at the same point, the point is properly marked.

2. Draw a line horizontally through the axis on the mount or the wheel. Insert the two weights, placing them above and equidistant from the horizontal line, and repeat the operation of locating the heavy point (Fig. 11-13, *a*). If it is again at the original mark, move the two weights closer together toward the top; if it is opposite the original mark, move the weights further apart toward the horizontal axis line. At some point between the top and horizontal line, the proper balance should be found. If

TABLE 11-7
Grinding Wheels for Centerless Grinding*

Application	Wheel Specifications	Application	Wheel Specifications
Alnico	57A54-L8VCN	Carbon (hard)	37C36-NVK
Aluminum	32A46-L7VBE	Cast iron	37C46-LVK or 32A54-L5VBE
Bars**		Cemented carbides	ASD120-R50B56
hard or soft steel, 3/4" (19mm)		wheel diameter 10" (250mm)	
and smaller	23A54-SB17X344	and larger	ASD120-R50B201
hard or soft steel, 3/4 to 2 1/2"		Colmonoy	37C54-MVK or 37C60-RB17X344
(19 to 63.5mm)	23A54-RB17X344	Drills, high speed steel	57A80-M8VCN
hard or soft steel, over 2 1/2"		Fasteners (steel)	57A80-M8VCN
(63.5mm)	23A54-QB17X344	Feed wheel	
aluminum, some tool and		general usage	A80-RR51 or
stainless steels	23AC54-QB17X344	(part diameter 1/4" [6.3mm]	A80-R2R3 or
steel tubing	23A60-OB17X344	and larger with unbroken	A80-ROR30†
to achieve a commercial or		surfaces)	
better finish	23A80-QB17X344	general usage	A80-SR51 or
Bearing		(part diameter less than 1/4"	A80-T6R34
pins (straight) up to 1/8"		[63mm] or parts with broken	
(3.2mm) OD		surfaces which tend to dress	
roughing	57A80-U9BH	the wheel)	
finishing	57A100-TB17X344	heavy stock removal or abusive	A80-T6R34
pins (straight) over 1/8"		operations (Bar Grinding)	
(3.2mm) OD		Ferrite	MD120-N75M9
roughing	57A60-QB17X344	Forging	57A60-M8VCN
finishing	A100-RB17X344	General purpose grinding	57A60-L8VCN
races, OD (roughing and		Glass	A220-P8V
finishing)		Hastalloy	32A54-L5VBE
3" (76mm) diam and less	57A60-L8VCN	Inconel	57A60-K8VCN
over 3" diam	57A60-K8VCN	Inconel X	57A60-K8VCN
rollers (straight)		NOROC**	37C100-HVK or SD100-N100B
roughing	57A60-L8VCN or 57A60-P6R30 or 57A80-R4R30	Nylon	37C46-KVK or 37C36-LVK
finishing	A80-T10R34 or A120-P4R30	Pen parts	
rollers (tapered)	57A801-T10R34	rubber	37C30-JVK
Bolts		plastics	32A80-O7VBE
shoulder grinder	23A60-O6VBE	Pipe balls	A30-T5VBE
Brass	37C36-LVK	regrind	A24-Q5VBE
Bronze		Pistons	
soft	37C36-LVK	aluminum	37C46-KVK
hard	32A46-M5VBE	cast iron	37C46-KVK
Bushings			
bronze	37C46-OVK		
hardened steel	57A60-L8VCN		

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TABLE 11-7—Continued

Application	Wheel Specifications	Application	Wheel Specifications
Piston pins		Steatite ceramic	37C60-JVK
roughing	23A54-PB17X344 or 23A60-O7VBE	Steel	
semifinishing	23A60-NB17X344 or 57A100-M8VCN	hard or soft, less than 1/2"	
finishing	37C320-N8E	(12.7mm) diam	57A80-L8VCN
Piston rings		hard or soft, 3/8 to 2 1/2" (15.8 to 63.5mm) diam	57A60-L8VCN
Plasma spray (carbides, chrome)		hard or soft, over 2 1/2" (63.5mm) diam	57A60-K8VCN
roughing and finishing	39C80-H8VK	300 series stainless	32A46-K8VBE
roughing	37C60-LB17X344	400 series stainless	
Polystyrene	37C46-KVK	commercial finish	57A60-K8VCN
Porcelain	37C36-KVK or MD100S-N75M	fine finish	A120-P4R30
Regulating wheel	See feed wheel	high-speed	
Rods		commercial finish	23A60-L5VBE
miscellaneous steel	57A60-M8VCN or 23A54-QB17X344	fine finish	A120-P4R30
300 series stainless steel	37C54-NVK or 32A54-M5VBE or 23A54-RB17X344	Tappets	
nitralloy (before nitriding)	57A60-L8VCN	steel, roughing	57A60-M8VCN
solichrome steel	57A60-M8VCN or 23AC54-RB17X344	steel, finishing	57A80-M8VCN
brass and bronze	37C60-KVK	cast iron, rough	37C46-NVK
hard rubber	37C30-KVK	cast iron, finish	37C80-MVK
carbon	37C36-NVK	Titanium	37C54-LVK or 37C54-PB17X344
plastic	32A80-N7VBE	Tubing	
Rollers	57A80-L8VCN	steel	57A60-M8VCN or 23A60-OB17X344
Roller bearing cups	57A80-M8VCN	chrome nickel	57A60-L8VCN or 23AC46-QB17X344
Shafts		aluminum	37C36-KE6 or 23AC46-KB17X344
pinion	57A60-L8VCN or 23A601-QB17X344	Tungsten	37C36-KE6
spline	57A60-M8VCN	Valve stems	57A60-M8VCN
Shells (ordnance)	57A54-L8VCN	Zirconium	
Spline shafts	57A60-M8VCN	roughing	32A46-M6R52
Sprayed material	39C80-G8VK or ASD120-R75B56	finishing	37C80-M6R52
wheel diameter 10" (250mm) and larger	ASD120-R75B201		

(Norton Co.)

* For wheel speeds over 3500 sfm (43 m/s) contact grinding wheel supplier for recommendations.

**These specifications are for use on low horsepower (40 hp and less) machines.

† For wheels less than 1" (25.4mm) thick

not, that is, if both weights are opposite the "heavy mark" and touching each other, the wheel is too far out-of-balance for normal corrective measures and a third or fourth balance weight should be added (Fig. 11-13, b).

- Proceed as before to locate the heavy point of the wheel and draw the horizontal line. Place the four weights in their grooves at approximately 90° apart. Then move the two top weights closer together. If this is not sufficient, move the bottom weights upward toward the horizontal line. Turn the wheel 90° and check the location of the heavy point, which is apt to be in this case 90° away from the bottom. If this is the case, wipe off the original horizontal lines and draw a new line horizontal to the new heavy point and proceed as before to change the weights.

TRUEING AND DRESSING WHEELS

Trueing means removal of abrasive material from the cutting face of the wheel so that the OD will run concentric with the ID. It also means bringing the sides of the wheel parallel to each other and perpendicular to the spindle. Dressing means removing the glaze from a dull wheel, removing loaded material from the face, restoring a wheel to its original geometry, and conditioning the wheel to do a specific job. Grinding wheels can be made to act harder and finer, or softer and coarser, by means of wheel conditioning.

Kinds of wheel dressers available include metal cutters, abrasive sticks, abrasive wheels, single-point diamonds, single-set and matrix diamond dressers, rotary and stationary diamond rolls, and crushing rolls. Each has specific advantages in its field of usage.

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TABLE 11-8
Grinding Wheels for Cylindrical Grinding

Application	Wheel Specifications	Application	Wheel Specifications
Alnico	23A54-L5VBE	Glass	23A220-011VBE
Aluminum	32A46-I8VBE, or 37C46-KVK	Glass tubing	37C46-J5V
Aluminum oxide (ceramic)		Gun barrels (spotting and OD)	57A60-M5VBE
very hard (1A1)	SD220-J100B56	High-speed steel	see Steel (high-speed)
hard (1A1)	BMD150-N100M, or RMD120-N100V5	Molybdenum	23A60-J8VBE
Armatures (laminated)		Monel	37C60-KVK
roughing	32A100-I8VBE	Ni-Hard	23A80-K5VBE
finishing	37C320-19E	Nitr alloy	
Axles (auto and railway)	23A54-M5VBE	before nitriding	A60-K5VBE
Bolts (screws and studs)	57A60-N5VBE	after nitriding	
Boron carbide (Norbide)		commercial finish	32A60-I8VBE
roughing	ASD100-L100B56	high finish	37C100-IVK
semifinishing	ASD220-L100B56	reflective finish	37C500-I9E
finishing	SD320-L100B56	NOROC	37C100-HVK, or SD220-N100B
Brass	37C36-KVK	Norbide	see Boron carbide
Bronze		Pistons	
soft	37C36-KVK	aluminum	32A46-I8VBE
hard	23A46-M5VBE	cast iron	37C36-KVK
Bushings		Piston rods (locomotive)	A46-M5VBE
cast iron	37C46-KVK, or 32A46-J8VBE	Plastics	
hardened steel	23A60-L5VBE	Thermoplastics	
Card clothing	37C24-NVK	wet	37C46-JVK, or 32A46-I12VBEP
Carbide (nonprecision)		dry	37C36-I5B
roughing	39C60-H8VK	Thermosetting	37C30-I5B
finishing	39C100-H8VK	Porcelain	39C60-J8VK
Cast iron	37C36-JVK, or 32A46-J8VBE	Pulleys (cast iron)	37C36-JVK
Cemented carbides		Reamers	57A60-L5VBE
roughing (wet)	ASD100-R75B56	Rubber	
wheel diameter 10" (250mm)		soft	32A20-K5B7
& larger	ASD100-R75B201	hard	37C36-J5B
finishing (wet)	ASD220-R75B56	Silver	38A100-K8VBE
wheel diameter 10" (250 mm)		Spline shafts	23A60-N5VBE
& larger	ASD220-R75B201	Sprayed metal	39C60-J8VK
Chrome plating		Stainless steel	
commercial finish	32A60-J8VBE	300 series	32A46-J8VBE
high finish	A150-K5E	400 series	23A60-K5VBE
reflective finish	37C500-I9B4	Steel (high speed)	
Colmonoy	39C60-K8VK	14" (360mm) and less	32A60-L5VBE
Columbium	32A60-K8VBE	16" (410mm) and larger	32A60-K5VBE
Commutators (copper)	37C60-M4E	Steel (soft)	
Copper	37C60-KVK	less than 1" (25mm) diam	23A60-M5VBE
Drills	23A60-M5VBE	over 1" diam	23A54-L5VBE
Ferrite	MD120-N75M9, or 39C100-I8VK, or PD80-E Process	Steel (hardened)	
Ferrotic	23A60-K5VBE	less than 1" diam	23A80-L6VBE
Forgings	A46-M5VBE	over 1" diam	23A60-K5VBE
Gauges (plug)	32A80-K8VBE	Stellite	23A46-M5VBE
high finish	37C500-J9E	Tantalum	23A60-K8VBE
General purpose grinding		Tap shanks	23A80-M6VBE
best all around wheel	57A60-L5VBE	Titanium	37C60-JVK
		Tungsten	37C60-JVK
		Valve stems (automotive)	57A60-N5VBE
		Valve tappets	57A54-M5VBE
		Vitallium	32A60-J8VBE

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Metal cutters are generally used to dress wheels for roughing operations, such as those in foundries, and also on vertical-spindle surface grinding operations. Abrasive sticks are used to remove the load from diamond wheels, for wheels used in cutter-grinding operations, and to break edges on centerless grinding wheels. Abrasive wheels are used to bring diamond and cubic boron nitride wheels into concentricity and also for wheels used in rough-grinding operations. The choice of the abrasive wheel itself is determined by the operation. Fine-grit wheels are used to dress and true diamond wheels; coarse-grit wheels are used for other abrasive wheels.

Single-point diamonds are used for dressing and truing wheels for precision-type operations such as surface, cylindrical,

centerless, and internal grinding. Today, however, matrix-type diamond dressers are also being used for these same operations. When single-point diamonds are used on hard-grade, large-diameter, thick wheels, they can develop flat areas, thereby dulling the wheel in subsequent dressing operations. Multipoint diamonds will prevent this situation.

Rotary diamond wheels and formed diamond rollers are finding use on many operations, with the claimed advantage that they produce better geometry on the wheel, and consequently, on the ground workpiece. Stationary-matrix diamond dressers are used on surface-grinding operations to generate forms in the grinding wheel.

TABLE 11-9
Grinding Wheels for Internal Grinding

Application	Wheel Specifications*	Application	Wheel Specifications*
Alnico	32A60-J8VBE	Dies (blanking and drawing)	
Aluminum	37C36-K5V	carbon steel	53A60-K5VBE
Armatures (laminations)	23A46-I12VBEP, or J5VBE	high carbon, high chrome	53A80-K7VBE
Ball and roller bearing bores	23A80-K5VBE	cemented carbides	RMD180-N100V5
Ball bearing races		Ferrite	MD150-N75M9
(form grinding)	57A120-L6VBE 22 Treat	Ferrotic (annealed state)	32A80-J5VBE
(oscillating)	A1801-R8R3	Gages, Ring (steel)	
Boron carbide (Norbide)		roughing	53A60-L7VBE
roughing	ASD100-N100B56	finishing	38A100-I8VBE
finishing	ASD320-N100B56	fine finishing	37C320-J9E
Brass	37C60-L7V	Gears (hardened steel)	
Bronze		internal and face grind	19A60-K5VBE
soft	37C60-L7V	Gun barrels (37mm to 90mm)	
hard	23A60-L5VBE	grind contours of cartridge	
Bushings		chamber	53A60-L7VBE
cast iron	37C46-J5V, or	Monel metal	37C60-J8V
	32A60-K5VBE	NiHard	53A80-K7VBE
hardened steel	53A60-K5VBE	NOROC	37C100-H8V, or
Cartridge dies (tungsten			SD220-R100B56
steel)		Propeller hubs (cone seats)	
Straight and tapered bores:		rough and finish	38A60-K5VBE
roughing	SD100S-N100B69	fine finish	A120-M2R30
finishing	D20/40MIC-N100B89	Roller bearing cups	53A80-L5VBE
Cast iron	37C46-J5V, or	Rocker arm	57A60-M5VBE
	32A60-K5VBE	Sprayed metal	37C46-J5V
Cemented carbides		Steel	
roughing	RMD150-N100V5	castings and forgings	53A46-L7VBE
finishing	RMD220-N100V5	soft	57A46-M5VBE
Chrome plated parts		hardened	53A60-L8VBE
small	38A100-I8VBE	nitrided	53A80-K5VBE
large	53A80-K5VBE	stainless (nonhardenable,	
Colmonoy	37C80-I5V	300 series)	32A46-I8VBE
Connecting rods	53A80-J5VBE	stainless (hardenable,	
Cylinders (aircraft)		400 series)	23A60-K5VBE
molybdenum steel:		Titanium	39C80-K8VK
roughing	53A46-J5VBE	Valve seats (steel)	53A70-P7VBE
finishing	53A60-I5VBE	Valve lifter bodies	23A90-M6VBE
regrounding	53A54-I5VBE		
Nitrided steel:			
before nitriding	37C60-I5V		
after nitriding	53A54-J5VBE		
regrounding	37C60-J5V		

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* Specifications represent the most common specifications for production grinding.

CHAPTER 11

GRINDING WHEELS AND DISCS

TABLE 11-10
Grinding Wheels for Tool Room Grinding

Application	Wheel Specifications	Application	Wheel Specifications
Carbide Single-Point Tools (Offhand Grinding):		High-Speed Steel & Cast-Alloy Multitooth Cutters:	
Cup wheels:		Fellows Gear Shaper cutter	32A80-I8VBE
roughing (10" [250 mm] & 14" (355 mm) cups)	39C60-18VK 39C60-G+BVKP	Form cutters (circular), dish wheel	32A46-J5VBE or CB100-TBB 1/16
finishing or touching up ordinary dull tools (wet)	RMD220-P50V5 1/16 (for large, steel cutting roughing tools) 39C100-H8VK (for large, steel cutting roughing tools) MD120 or MD220-E Process GEMINI GTM 109-1/16 (General Purpose)	Hobs (Barber-Coleman hob grinder), sharpening: 7" (180 mm) wheels	32A60-I8VBE
finishing (dry)	39C100-H8VK (for large, steel cutting roughing tools)	10" (250 mm) wheels (large hobs)	23A60-J5VBE
combination roughing and finishing (wet)	RMD150-P50V5 1/16 (fast cut, long life)	Milling cutters (plain, side, face, etc.): straight wheel	32A46-K5VBE or CB100-TBB 1/16
backing off steel shank up to carbide tip	32A36-K5VBE (cup wheel)	cup wheel	32A46-K5VBE
Straight wheels:		Ingersoll Cutter Grinder	32A46-I8VBE
roughing (dry)	39C60-I8VK	Reamers:	
roughing (wet)	39C60-J8VK	cylindrical grinding	23A60-L8VBE
backing off steel shank up to carbide tip	A24-N5VBE, or General Purpose (Coarse)	backing off	32A46-K5VBE
High-Speed Steel Single-Point Tools (Offhand Grinding):		Barber-Coleman reamer sharpener	A80-I8B
Cup wheels—Type 6A2C	XB150-E Process (for roughing)	Saws (metal cutting), backing off	32A46-K5VBE or 23A46-K8VBE
6" (150 mm) & 10" (250 mm) diam, wet or dry	XB240-E Process (for finishing)	High-Speed Steel Grinding (Miscellaneous):	
Ring wheels—Type 2A2	XB150-E Process (for roughing)	Broaches, sharpening (face grinding):	
5" (130 mm) rings for use on magnetic chuck machines such as Leonard Grind-R-Lap, Kut-Kool, Kool-Karb, Eskimo or Cold Grind, wet or dry	XB240-E Process (for finishing)	dish wheel	32A60-K5VBE
High-Speed Steel & Cast-Alloy, Single-Point Tools (Offhand Grinding):		backing off, cup wheel	32A46-K8VBE
Bench and pedestal grinders:		Burrs, HSS—resharpening	38A80-HV/38A220-KV layer wheel
rough	A36-05VBE or General Purpose (Coarse)	Dies:	
finish	A60-M5VBE or General Purpose (Fine)	surface grinding—hardened dies	
combination roughing and finishing	A46-N5VBE or General Purpose (Medium)	straight wheel (dry)	32A46-H8VBE or 32A60-G12VBEP
Machine grinding:		straight wheel (wet, fast traverse)	32A60-I8VBE
15" (380 mm) diam wheels	23A36-L5VBE	cup wheel (wet)	38A46-G8VG
24" (610 mm) diam wheels	23A24-M5VBE	surface grinding—annealed dies	
cup or cylinder wheels, Gisholt	23A24-L5VBE	straight wheel (dry)	23A46-J8VBE
Wet tool grinders:		cup wheel (wet)	32A24-H8VBE
up to 20" (510 mm) wheels	A36-05VBE	cylindrical grinding (wet)	23A60-L8VBE
24" (610 mm) and larger	A24-M5VBE	internal grinding (wet)	23A60-K8VBE
		offhand grinding	
		straight wheels (coarse)	A36-05VBE
		mounted wheels (coarse)	38A60-PVM
		mounted wheels (medium)	38A90-QVM
		mounted wheels (fine)	38A120-QVM
		Drills:	
		sharpening (drill grinders)	
		drills ¼ to 1" (6.3 to 25 mm) numbered sizes	32A46-L5VBE
		point thinning	32A100-I8VBE
		cutting-off (dry)	32A60-L8VBE
		(use 1/32" [0.79 mm] thick for 6" [150 mm] diam or smaller wheel)	23A60-06B21, R sides

GRINDING WHEELS AND DISCS

TABLE 11-10—Continued

Application	Wheel Specifications	Application	Wheel Specifications
High-Speed Steel Grinding (Miscellaneous):		Miscellaneous Toolroom Grinding:	
Taps		Cutting-off tool bitstock, drills, etc.	
sharpening (tap grinders)		general use	23A60-06B21, R sides
straight wheel (small taps)	32A60-K8VBE	very hard steels (no burn permitted)	A60-M8B2 or A60-OE7
cup wheel (large taps)	23A46-M5VBE	reinforced	A60-OBNA2
touching up flutes:		Cylindrical grinding:	
large taps	32A60-K8VBE	high-speed steel	32A60-L5VBE or CB100-TBB 1/16
small taps	A60-POR30	hardened steel	23A60-K5VBE
cutting-off ends (dry)	23A60-O6B21, R sides	soft steel	23A54-L5VBE
Thread chasers:		stainless steel	
milled and tapped chasers		(No. 300 series)	32A46-J8VBE
on chaser grinder fixtures		cast iron, brass, aluminum	37C46-KVK
chamfer or throat	32A80-K8VBE	general purpose wheel	23A60-L5VBE
cutting face	32A60-J8VBE	Internal grinding:	
on geometric chaser grinders		HSS and hardened steel	32A60-L8VBE or CB120-TBB
9" (230 mm) straight wheel	32A46-K8VBE	soft steel	23A46-M5VBE
9" (230 mm) dish wheel	38A60-J8VBE	cast iron and bronze (soft)	37C46-JVK
tangent chasers		Surface grinding:	
on chaser grinder fixtures		reciprocating table (straight wheel):	
straight wheel	32A60-J8VBE	high-speed steel	32A46-H8VBE or 32A60-F12VBEP or CB100-TBB 1/16
cup wheel		hardened steel	32A60-G12VBEP
flaring	32A46-J8VBE	soft steel	32A36-K8VBE
straight	32A46-J8VBE	cast iron and bronze (soft)	37C36-J8V
on Landis chaser grinders			
straight wheel	32A60-M5VBE		
cup wheel	32A46-L5VBE		
circular chasers			
straight wheel	32A46-K8VBE		
cup wheel	32A46-K8VBE		
dish wheel	32A46-J8VBE		

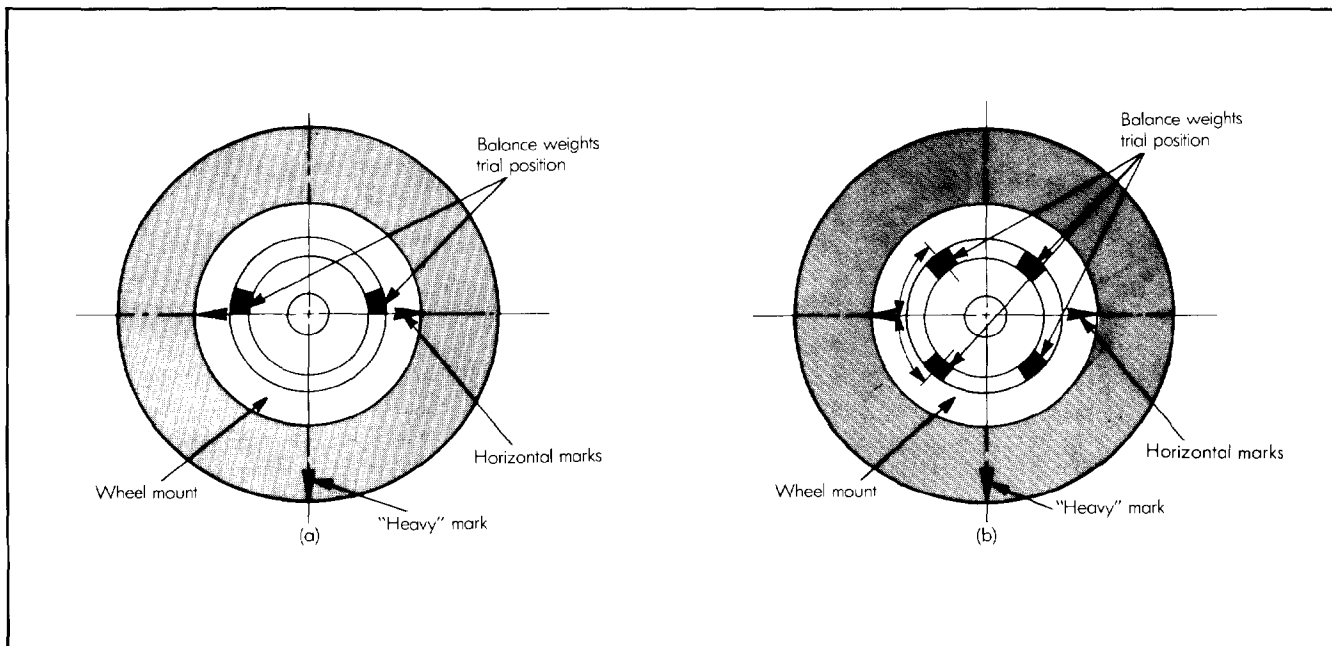


Fig. 11-13 Relative positions of balance weights on a grinding wheel: (a) two weights, (b) four weights.

GRINDING WHEELS AND DISCS

Method of Dressing

Method of dressing is important in the performance of a grinding wheel. Wheels may be dressed either wet or dry, but the operation should always be carried out under the same condition as the grinding operation. If grinding is to be done wet, then dressing should be done wet. If the dresser is permitted to become dull, the wheel will then be dressed differently than when the dresser is sharp. Consequently, grinding performance varies directly with the condition of the dressing tool. Single-point diamonds, particularly if permitted to become dull, will generate a closed surface on the grinding-wheel face which will result in poor finishes and poor geometry. Single-point diamonds should be rotated frequently about their longitudinal axis to prevent excessive flat development.

Figure 11-14 illustrates the correct positioning of a diamond dressing tool relative to the grinding wheel.

To remove stock, the wheel should be dressed openly. For example, a diamond dresser with an infeed of 0.001" (0.03 mm) per pass and a rapid traverse rate can be applied until the wheel is true or has been restored to its original geometry.

To produce a fine finish, a wheel should be given a fine dress. This can be done by using a single-point diamond with an infeed of 0.001" (0.03 mm) per pass until the wheel has been restored to its original geometry. Then two passes are taken with an infeed of 0.0005" (0.013 mm), two passes with an infeed of 0.0002" (0.005 mm), and one pass with no infeed at all.

Dressing can be compared to cutting a thread into the wheel surface. The "lead" or distance of axial motion per wheel revolution is an important variable. The traverse dressing speed is:

$$\text{Traverse speed} = (\text{Lead}) \text{ Rotary wheel speed} \quad (43)$$

For example, to dress a 0.004 ipr (0.10 mm/rev) on a wheel rotating at 1400 rpm:

$$\text{Traverse speed} = (0.004 \text{ ipr}) (1400 \text{ rpm}) = 5.60 \text{ in./min}$$

In metric:

$$\text{Traverse speed} = (0.10 \text{ mm/rev}) (1400 \text{ rpm}) = 140 \text{ mm/min}$$

A lead of 0.004 ipr (0.10 mm/rev) is generally used for precision grinding. A "fine" lead of 0.001 ipr (0.03 mm/rev) or less will produce a relatively dull wheel and, with low metal removal rates, a smooth surface finish. A lead of 0.010 ipr (0.25 mm/rev) or larger will "sharpen" a wheel, lower grinding forces, and increase wheel wear rates, but produce relatively poor surface finish and geometry.

Dressing for Form Grinding

Forming of a wheel to the reverse shape of the part to be ground can be done in a number of ways: mechanically crushing the form into the wheel by means of a roll, dressing the form using a single-point diamond with a pantograph system and template, grinding the form into the wheel using a rotary-diamond formed dresser roll, or grinding the form with a stationary-diamond formed dresser.

In crush forming, the profile desired on the workpiece is ground or machined on a metal roll having a diameter between one-third and one-fourth that of the grinding wheel and a length generally slightly greater than the width of the wheel face. This roll is rigidly mounted and placed so that the roll can be brought into contact with the grinding wheel. The technique generally is to make contact with both members while they are at rest. One of the members, either the crush roll or the grinding wheel, is then rotated slowly in the range of 150-300 sfm (0.76-1.52 m/s). The roll and the wheel are then brought together a few thousandths of an inch (about 0.07 mm) each revolution until the form has sunk deeply enough into the wheel face to have the complete contour transferred. A force of 200-600 lb/in. (35-105 N/mm) of wheel width is generally necessary to crush-form the wheel. Crush dressing only fractures the bond of the wheel, leaving the abrasive grains sharp. The time to crush-form a wheel is a matter of minutes for the initial forming and a matter of seconds for redressing the worn wheel.

Crushing rolls may be made from high-speed steel, tungsten carbide, or boron carbide; in some cases unhardened steel rolls or cast iron rolls can be used for short periods of time. Forms over 0.300" (7.6 mm) in depth generally produce high wear rates on the crush roll. It is general practice to have a master roll for

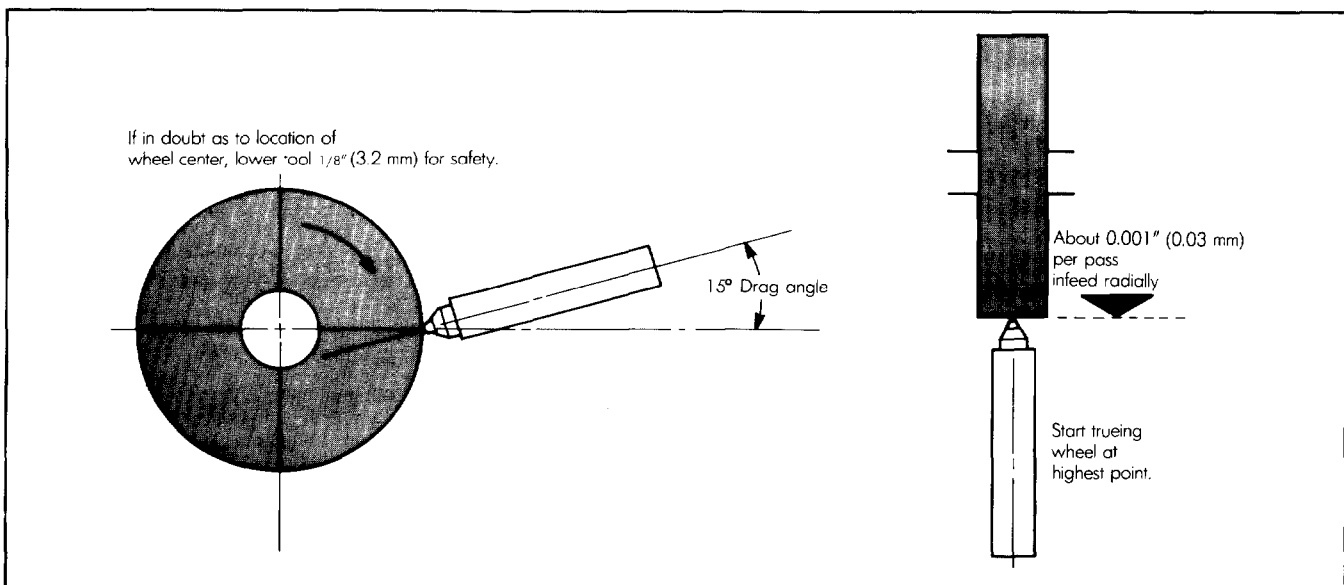


Fig. 11-14 Position of a diamond tool dresser relative to the grinding wheel.

GRINDING WHEELS AND DISCS

reference and several working rolls. On a horizontal-spindle, reciprocating-table, surface grinder, both the master roll and the working roll can be mounted on the table, one on each end. When the working roll is slightly out of true, the master roll can then crush the abrasive wheel to the true form and the wheel can be used to grind the working roll. On other machines, the crushing roll may be located above or behind the wheel. Sufficient rigidity, accuracy, and power are needed on any machine used for crush dressing.

Vitrified-bond grinding wheels are generally used in crush-forming operations, since resinoid and other bonds are not conducive to the process. Either aluminum oxide or silicon carbide wheels can be crush-formed. Some CBN wheels having relatively brittle metal bonds can also be crush-dressed.

Recommended sizes for radii at the roots of the forms together with threads per inch for wheels with various grit sizes are shown in Table 11-11. Harder and finer wheels will wear crush rolls more rapidly, since higher pressures are necessary.

Crush-formed wheels are generally free cutting and require low forces. Little heat is developed, and consequently, highly precise parts can be produced. The grinding fluid that is used almost exclusively in crush-forming operations is straight oil, but water-soluble oils can be used if mist and lack of cleanliness are problems.

Single-point diamond, pantograph-template types of dressing units can be obtained in a wide variety of styles to fit many different kinds of requirements. They are generally mounted directly on the grinding machine. The operation, the machine, the dimensions, and the form required dictate the kind of unit which will be most productive. One such unit permits dressing either a convex or a concave radius from 0.015–1.750" (0.38–44.4 mm) on a 7 or 20" (180 or 510 mm) diam wheel. It can be set to the exact radius desired; graduated stops permit dressing any desired portion of a radius. It can also be used to dress angles and tangents and can be adapted to most cylindrical and surface grinders. Accuracy is in the range of 0.0001" (2.54 μ m).

Rotary-diamond dressers are similar to crush-form dressers in that the profile desired on the workpiece is ground or machined on a metal roll and the roll is then impregnated with diamonds. This roll can be a matrix-type diamond composition,

or it can be single-set diamonds. During forming, the wheel is generally operating at conventional grinding speed. It is not necessary to reduce wheel speed in order to form. The rotary-diamond roll is rotated, and both are brought into contact with each other. Time of redressing is in the order of seconds.

Stationary-diamond dressers are used in a similar fashion on surface grinders. The dresser is profiled to the form desired, and diamonds (either in a matrix form or single set) are embedded. Then the grinding wheel is brought into contact with the dresser.

WHEEL STORAGE

All grinding wheels should be stored in proper racks or bins in a dry area in rooms not subject to extreme temperature change. Their location should be away from traffic lanes of trucks or overhead cranes. The importance of storage in a dry area cannot be overemphasized. Some bond types (especially some organic bonds) may become seriously affected by dampness, high humidity, water, etc., especially in combination with elevated temperatures; and all wheels, including vitrified, can become damaged if subjected to freezing temperatures when they have picked up moisture. Placing wheels or storage shelves adjacent to steam pipes, etc., should be avoided. Under optimum storage conditions, there should be no reason to limit the "shelf life" of a grinding wheel.

When moved from storage to the grinders, all wheels should be handled properly. Small wheels can be moved easily in cartons, boxes, etc., but larger wheels should be handled by hand or electric trucks which are equipped with padded surfaces and/or racks to protect the clean, padded floor. Also, a pad should be placed on the floor in front of racks for large wheels, so that the wheels are not subject to shock from bumping when rolled out of the racks. An inclined ramp helps prevent injury of this nature and also makes wheels easier to handle. When it is necessary to provide storage racks at the grinders, as well as in the general storage area, the same precautions apply. However, because of their proximity to the work area, additional protection for the wheels, such as doors and drop covers on the racks, may be required.

Proper handling equipment, mounting stands, lifting devices (slings, straps, frames, etc.), and hoists for large wheels should be made available at the grinders, as well as in storage areas, for handling and mounting to avoid injury to wheels, equipment, and personnel.

GRINDING WHEEL SAFETY

Grinding wheels and machines should always be used in accordance with guidelines and mandatory regulations of the Occupational Safety and Health Act of 1970. Grinding operations, which are covered in Section 1910 Subparts O and P of the act, are based on ANSI Standards B7.1-1978⁸ and B11.9-1975.⁹ These standards should be consulted for detailed recommendations not covered specifically in the act. (Grinding wheel inspection, an important aspect of safety, is covered in an earlier section of this chapter.)

Wheel Guarding

State and federal safety regulations mandate that with few exceptions, safety guards must be used on grinding machines. Surveys show unguarded grinding wheels to be the most violated safety regulation and one of OSHA's top 20 citations. Unfortunately, the numerous grinding wheel injuries

TABLE 11-11
Recommended Radii and Threads per In. (mm) for
Crush-Dressing Wheels of Different Grit Sizes

Wheel Grit Size	Min Radius of Form, in. (mm)	Max Threads per in. (mm)
500	0.001 (0.025)	100 (3.9)
320	0.002 (0.051)	36 (1.4)
280	0.003 (0.076)	24 (0.94)
220	0.004 (0.102)	16 (0.63)
180	0.005 (0.127)	10 (0.39)
120	0.007 (0.178)	8 (0.31)

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that have occurred could have been prevented had the wheel been properly guarded.

Abrasive wheels, 2" (50 mm) diam and smaller, attached to steel mandrels do not require guarding. Since the abrasive portion of the mounted wheel is basically a solid mass (except for the shallow recess in one side to accept the mandrel), the ultimate centrifugal bursting strength of the abrasive is quite high and usually exceeds the critical speed of a steel mandrel. ANSI B7.1 lists the standard mounted wheel maximum speed at 10,000 sfm (51 m/s), provided the strength of the steel shank and overhang are adequate. (See tables detailing maximum operating speed for mounted wheels presented in Section 10 of ANSI B7.1.)

Excellent reference information for proper wheel guarding can be found in ANSI Standard B7.1-1978 "Safety Requirements for the Use, Care and Protection of Abrasive Wheels"; ANSI Standard B11.9-1975 "Safety Requirements for the Construction, Care and Use of Grinding Machines"; and ANSI Standard B186.1 "Safety Code for Portable Air Tools."¹⁰

Of course, other protective equipment such as goggles, face shields, and protective clothing are positive ways to guard against flying sparks and swarf.

Wheel Speeds

Maximum operating speeds are indicated in rpm (revolutions per minute) on all grinding wheels or the cartons in which they are packed. This maximum is not the recommended speed for most efficient grinding, but rather the approved maximum safe speed dependent upon the wheel shape and strength.

Centrifugal force from rotational speed is the primary source of stress in the wheel body. It is important to recognize the relationship of these forces to the ultimate strength of the wheel being used. Centrifugal force increases as the square of the velocity; therefore, this force, which works to pull the wheel

apart, is four times greater with a wheel operating at 3,600 rpm, for example, than with the same wheel operating at 1,800 rpm.

Occasional failures of mounted abrasive wheels and points occur primarily as bending or rupturing of the steel mandrels. This is caused by deflection and whip of the mandrel due to excessive speed for the mounting conditions. For complete safety, an adequate safety factor considerably below the critical mandrel speed is desirable. Generally, a maximum recommended operating speed approximately 25% below the critical speed is followed in ANSI safety code recommendations. Factors governing maximum allowed speed are size, shape, and weight of the abrasive portion; diameter of the mandrel; and amount of overhang distance between the machine collet or chuck and the abrasive portion (exposed mandrel).

Before mounting a wheel, the spindle speed of the machine should always be checked to ensure that it does not exceed the maximum speed marked on the wheel. It should be noted, however, that the number of revolutions (rpm) may be increased as the diameter of the wheel wears smaller provided the original peripheral speed in surface feet per minute (sfm), or meters per second (m/s), is not exceeded.

Experience indicates that regular speed maintenance checks and repair programs pay dividends preventing the most serious type of grinding wheel accident—excessive overspeed breakage. Table 11-12 details the "Recommended Frequency of Speed Measurement for Various Machine Types," as printed in ANSI Standard B7.1-1978.

Should an abrasive wheel break in service, the user should immediately isolate the machine and work area and notify the wheel maker and machine builder. Corrections of adverse conditions should only be made following a complete investigation by all parties concerned. This will help determine the cause of the breakage so that a recurrence of the trouble can be prevented.

TABLE 11-12
Recommended Frequency of Speed Measurement for Various Machine Types
Measure Speeds at Time of Installation of All Machines

Machine Type	Recommended Frequency
Portable Grinders:	
Air Driven	Measure the speed of governor-controlled grinders every 20 hours of actual use or once per week, whichever comes first.
	Measure speed of all types of grinders after maintenance or repair, whenever a grinder is issued from the tool crib, and at each wheel change. Several readings should be taken.
Electric Driven (Hi-Cycle)	Measure monthly and after any maintenance or repair that could affect the speed of the machine.
All Other Grinders:	
Direct Drive (Single Speed)	Measure after any maintenance or repair that could affect the speed of the machine.
Belt Drive (Single Speed)	Measure monthly and after any maintenance or repair that could affect the speed of the machine.
Variable Speed Machines	Measure once per week and after any maintenance or repair that could affect the speed of the machine. On variable speed machines, other than semiautomatic snagging grinders, measure speed whenever a wheel change is made.

(ANSI Standard B7.1-1978)

Maximum operating speeds marked on wheels by the manufacturer are determined primarily by the known ultimate free-running bursting strength of the wheels, and should never be exceeded by the user. This bursting strength (tensile strength) varies greatly in wheels of the same size and shape, depending upon a number of factors, such as abrasive type, grit size, grade of hardness (amount of bond), structure (porosity, pores), and bond type. Coarser or softer wheels have lower bursting strengths than finer or harder wheels of the same type, thereby setting a limit on the speed of operation which can be allowed. The wheel size, shape, and kind of operation may introduce additional limitations which also affect the allowable speed of operation.

For example, Type 1 straight wheels having small arbor holes present the highest strength level, and any deviations from this base in the same grit and grade specifications usually reduce the allowable speed. These deviations may be large holes (over half the wheel diameter), deep recesses, cut and cylinder shapes, and so forth. ANSI Standard B7.1 lists standard maximum speeds in surface feet per minute (meters per second) for all types of wheels and grinding classifications: these speeds are presented in Table 11-13. Table 11-14 can be used to convert from surface feet per minute (meters per second) to revolutions per minute for a given wheel diameter.

The measurement, surface feet per minute (*sfm*) or meters per second (*m/s*), rather than revolutions per minute (*rpm*) is used universally in reference to wheel strengths, maximum speeds, and general recommendations because it is the common denominator in all types of operations, whereas revolutions per minute can be related only to a specific wheel size, operation, or machine. For determining surface feet per minute, the simple equation is:

$$sfm = \frac{\pi \times D \times rpm}{12} \quad \text{or} \quad 0.262 \times D \times rpm \quad (44)$$

where:

D = wheel diameter (in.)

An example of this equation, with D equal to 20" running at 1240 rpm, is:

$$sfm = \frac{\pi \times 20" \times 1240}{12} = 6498 \text{ sfm}$$

For determining meters per second, the equation is:

$$m/s = \frac{\pi \times D \times rpm}{1000 (60)} \quad \text{or} \quad 0.00314 \times D \times rpm$$

where:

D = wheel diameter (mm)

An example of this equation, with D equal to 508 mm running at 1240 rpm, is:

$$m/s = \frac{\pi \times 508 \text{ mm} \times 1240}{1000 \times 60} = 33.0 \text{ m/s}$$

Special Higher Speeds

In recent years, it has been demonstrated in certain types of high-production cylindrical and form-grinding applications that definite advantages are realized at surface speeds higher than standard. Very recently, speeds from 12,000-18,000 sfm have been successful on these applications with specially constructed vitrified-bond wheels on equipment specifically designed and guarded for such usage. Similar advances have also been

made with special reinforced organic-bond wheels on high-speed, floor-stand types of snagging machines in the foundry and with special high-strength, resinoid-bonded wheels on mechanical slab and billet grinders in the basic steel industry. Safety of such higher-speed operations is so dependent upon the proper combination of conditions that only wheels and machines designed and marked for such usage by the manufacturer should be used (see "Special Grinding Machines and Processes" in this chapter).

An entire section of the ANSI Standard B7.1 (Section 8) is devoted to outlining the responsibilities of the machine builder, the wheel manufacturer, and the user when operating speeds higher than standard are contemplated. One who alters an existing machine to operate at a special high speed assumes any responsibility that would normally be the machine builder's. No such modification should be attempted before consulting the machine manufacturer for his recommendations.

ABRASIVE DISCS

Discs used for disc grinding are available in a wide variety of abrasive types, grain sizes, grades, structures, bonds, mounting methods, and designs up to 53" (1346 mm) diam. Selection of the proper disc is generally more critical than for most other types of grinding because usually more area is in contact with the work. It is best to consult with a reputable abrasive disc manufacturer, specifying details of the part to be ground, material, machine to be used, amount of stock to be removed, and requirements for production rates, tolerances, and surface finishes. General recommendations for grinding disc specifications are provided in Table 11-15, presented courtesy of Norton Co. Equivalent grinding discs are offered by other abrasive manufacturers.

Abrasives

Aluminum oxide and silicon carbide are the most common abrasives for disc grinding, with aluminum oxide being used more extensively. Most disc manufacturers make several types of both abrasives; the types vary in toughness, friability, and sharpness. Some discs made from cubic boron nitride are being used to grind tool steels, and some diamond-impregnated discs are being used for carbide.

Grain Size

Grain sizes generally range from 8 (coarse) for heavy stock removal and rough surface finishes to 320 extra fine for light stock removal and finer finishes. Grades range from soft for light stock removal on hard materials to hard for heavy stock removal on soft materials. Because the surface speed of the abrasive discs and the rate of stock removal changes as the workpieces move between the discs, discs are available with harder abrasives in their outer sections and softer near their centers.

Structures

Structures range from dense for heavy-duty operations to open for lighter stock removal, smoother finishes, and grinding of harder materials. Resinoid (phenolic plastic) bond is used almost exclusively for abrasive discs, but it is sometimes modified by the addition of fillers to control breakdown and maintain sharp cutting surfaces.

Vitrified bonds are generally too strong and resist breakdown in disc grinding. The inserted-nut type of disc is by far the most popular method of mounting.

CHAPTER 11

GRINDING WHEELS AND DISCS

TABLE 11-13
Standard Maximum Speeds for Various Grinding Wheels

Classifi- cation No.	Types of Wheels	Inorganic Bonds			Organic Bonds		
		Low Strength	Medium Strength	High Strength	Low Strength	Medium Strength	High Strength
		Operating Speed, sfm (m/s), Shall Not Exceed					
1	Type 1—straight wheels, except classifications 6,7,9,10,11,12, 13, and 14 Type 4*—taper side wheels Types 5,7,20,21,22,23,24,25,26—recessed, dovetailed, and/or relieved wheels, except classification 7 and 14 Type 12—dish wheels Type 13—saucer wheels Types 16,17,18,19—cones and plugs	5500 (27.9)	6000 (30.5)	6500 (32.9)	6500 (32.9)	8000 (40.6)	9500 (48.2)
2	Type 2—cylinder wheels, including plate-mounted, inserted-nut, and projecting stud-segments	5000 (25.4)	5500 (27.9)	6000 (30.9)	5000 (25.4)	6000 (30.5)	7000 (35.5)
3	Cup-shaped tool-grinding wheels for fixed-base machines: Type 6—straight-sided cups Type 11—flaring cups	4500 (22.8)	5000 (25.4)	6000 (30.5)	6000 (30.5)	7500 (38.1)	8500 (43.1)
4	Cup-shaped snagging wheels for portable machines: Type 6—straight-sided cups Type 11—flaring cups	4500 (22.8)	5500 (27.9)	6500 (32.9)	6000 (30.5)	8000 (40.6)	9500 (48.2)
5	Abrasive disks, including plate-mounted, inserted-nut, and projecting stud either solid or segmental	5500 (27.9)	6000 (30.5)	6500 (32.9)	5500 (27.9)	7000 (35.5)	8500 (43.1)
6**	Type 1—reinforced wheels Max. diam 4" (102 mm) and a max. thickness ¼" (6.35 mm) Max. diam 10" (254 mm) and a max. thickness ½" (127 mm) All other diams and thicknesses Types 27 and 28—reinforced wheels Max. diam 9" (228 mm) and a max. thickness ⅜" (9.5 mm) Max. diam 9" (228 mm) and thickness over ⅜" (9.5 mm)	---	---	---	9500 (48.2) 9500 (48.2) 9500 (48.2) ---	12 500 (63.4) 12 500 (63.4) 12 500 (63.4) 12 500 (63.4) 9500 (48.2)	16 000 (81.2) 14 200 (72.1) 12 500 (63.4) 14 200 (72.1) 11 000 (55.8)

GRINDING WHEELS AND DISCS

TABLE 11-13—Continued

Classifi- cation No.	Types of Wheels	Inorganic Bonds			Organic Bonds		
		Low Strength	Medium Strength	High Strength	Low Strength	Medium Strength	High Strength
Operating Speed, sfm (m/s), Shall Not Exceed							
7	Type 1 for bench and pedestal grinders and Types 1 and 5 for surface grinders in following sizes only:						
	7" (178 mm) diam up to 2" (51 mm) thick and up to 2" (51 mm) hole	5500 (27.9)	6325 (32.1)	6600 (33.5)	6500 (33.0)	8000 (40.6)	9500 (48.2)
	8" (203 mm) diam up to 2" (51 mm) thick and up to 2" (51 mm) hole	5500 (27.9)	6325 (32.1)	7550 (38.3)	6500 (33.0)	8000 (40.6)	9500 (48.2)
8	Diamond and cubic boron nitride wheels	---	---	6500 (33.0)	---	---	9500 (48.2)
	Exceptions: metal bond	---	---	12 000 (60.9)	---	---	---
	steel-centered cutting-off wheels	---	---	16 000 (81.2)	---	---	16 000 (81.2)
9	Types 1 and 27A—cutting-off wheels larger than 16" (406 mm) diam, including reinforced organic	---	---	---	9500 (48.2)	12 000 (60.9)	14 200 (72.1)
10	Types 1 and 27A—cutting-off wheels 16" (406 mm) diam and smaller, including reinforced organic	---	--	---	9500 (48.2)	12 000 (60.9)	16 000 (81.2)
11	Thread and flute grinding wheels	8000 (40.6)	10 000 (50.8)	12 000 (60.9)	8000 (40.6)	10 000 (50.8)	12 000 (60.9)
12	Crankshaft and camshaft grinding wheels	5500 (27.9)	8000 (40.6)	8500 (43.1)	6500 (32.9)	8000 (40.6)	9500 (48.2)
13	Type 1—snagging wheels 16" (406 mm) diam and larger, organic bond including reinforced:						
	Used on swing-frame grinders designed for this speed	---	---	---	---	---	12 500 (63.4)
	Used on semiautomatic snagging grinders designed for this speed	---	---	---	---	---	16 500 (83.8)
14	Types 1 and 5—internal wheels max. diam 6" (152 mm)	5500 (27.9)	8000 (40.6)	8500 (43.1)	6500 (32.9)	8500 (43.1)	9500 (48.2)
15	Mounted wheels (see ANSI Standard B7.1-1978, p. 83 for limitations)	---	---	10 000 (50.8)	---	---	10 000 (50.8)

(ANSI Standard B7.1-1978)

* Nonstandard shape

** Excludes cutoff wheels

TABLE 11-14
Conversion Table—Wheel Speeds (rpm) for Various Diameters of Grinding Wheels to Give Surface Speed (sfm)

Diam. of Wheel, in. (m m)	Revolutions per Minute at the Following Surface Speeds, sfm (m/s):																		
	4,000 (20.3)	4,500 (22.8)	5,000 (25.3)	5,500 (27.9)	6,000 (30.4)	6,500 (32.9)	7,000 (35.5)	7,500 (38.1)	8,000 (40.6)	8,500 (43.1)	9,000 (45.7)	9,500 (48.2)	10,000 (50.8)	12,000 (60.9)	12,500 (63.4)	14,200 (72.1)	16,000 (81.2)	16,500 (83.9)	17,000 (86.3)
1 (25.4)	15,279	17,189	19,098	21,008	22,918	24,828	26,737	28,647	30,558	32,467	34,377	36,287	38,196	45,836	47,745	54,240	61,116	63,025	64,935
2 (50.8)	7,639	8,594	9,549	10,504	11,459	12,414	13,368	14,328	15,278	16,238	17,188	18,143	19,098	22,918	23,875	27,120	30,558	31,510	32,465
3 (76.2)	5,093	5,729	6,366	7,003	7,639	8,276	8,913	9,549	10,186	10,822	11,459	12,096	12,732	15,278	15,915	18,080	20,372	21,010	21,645
4 (101.6)	3,820	4,297	4,775	5,252	5,729	6,207	6,685	7,162	7,640	8,116	8,595	9,072	9,549	11,459	11,940	13,560	15,278	15,755	16,235
5 (127.0)	3,056	3,438	3,820	4,202	4,584	4,966	5,348	5,730	6,112	6,494	6,876	7,258	7,640	9,168	9,550	10,850	12,224	12,605	12,985
6 (152.4)	2,546	2,865	3,183	3,501	3,820	4,138	4,456	4,775	5,092	5,411	5,729	6,048	6,366	7,639	7,960	9,040	10,186	10,505	10,820
7 (177.8)	2,183	2,455	2,728	3,001	3,274	3,547	3,820	4,092	4,366	4,638	4,911	5,183	5,456	6,548	6,820	7,750	8,732	9,005	9,275
8 (203.2)	1,910	2,148	2,387	2,626	2,865	3,103	3,342	3,580	3,820	4,058	4,297	4,535	4,775	5,729	5,970	6,780	7,640	7,880	8,115
9 (228.6)	1,698	1,910	2,122	2,334	2,546	2,758	2,970	3,182	3,396	3,606	3,820	4,032	4,244	5,092	5,305	6,030	6,792	7,000	7,215
10 (254.0)	1,528	1,719	1,910	2,101	2,292	2,483	2,674	2,865	3,056	3,247	3,438	3,629	3,820	4,584	4,775	5,425	6,112	6,300	6,495
12 (304.8)	1,273	1,432	1,591	1,751	1,910	2,069	2,228	2,386	2,546	2,705	2,864	3,023	3,183	3,820	3,980	4,520	5,092	5,250	5,410
14 (355.6)	1,091	1,228	1,364	1,500	1,637	1,773	1,910	2,046	2,182	2,319	2,455	2,592	2,728	3,274	3,410	3,875	4,366	4,500	4,640
16 (406.2)	955	1,074	1,194	1,313	1,432	1,552	1,672	1,791	1,910	2,029	2,149	2,268	2,387	2,865	2,985	3,390	3,820	3,940	4,060
18 (457.2)	849	955	1,061	1,167	1,273	1,379	1,485	1,591	1,698	1,803	1,910	2,016	2,122	2,546	2,655	3,015	3,396	3,500	3,605
20 (508.0)	764	859	955	1,050	1,146	1,241	1,337	1,432	1,528	1,623	1,719	1,814	1,910	2,292	2,390	2,715	3,056	3,150	3,245
22 (558.8)	694	781	868	955	1,042	1,128	1,215	1,302	1,388	1,476	1,562	1,649	1,736	2,084	2,170	2,465	2,776	2,865	2,950
24 (609.6)	637	716	796	875	955	1,034	1,115	1,194	1,274	1,353	1,433	1,512	1,591	1,910	1,990	2,260	2,546	2,625	2,705
26 (660.4)	588	661	734	808	881	955	1,028	1,101	1,176	1,248	1,322	1,395	1,468	1,762	1,840	2,090	2,352	2,425	2,495
28 (711.2)	546	614	682	750	818	887	955	1,023	1,092	1,159	1,228	1,296	1,364	1,637	1,705	1,940	2,182	2,250	2,320
30 (762.0)	509	573	637	700	764	828	891	955	1,018	1,082	1,146	1,210	1,274	1,528	1,595	1,810	2,056	2,100	2,165
32 (812.8)	477	537	597	656	716	776	836	895	954	1,014	1,074	1,134	1,194	1,432	1,495	1,695	1,910	1,970	2,030
34 (863.6)	449	505	562	618	674	730	786	843	898	955	1,011	1,067	1,124	1,348	1,405	1,595	1,796	1,855	1,910
36 (914.4)	424	477	530	583	637	690	742	795	848	902	954	1,007	1,061	1,273	1,330	1,510	1,698	1,750	1,805
38 (965.2)	402	452	503	553	603	653	704	754	804	854	904	955	1,006	1,206	1,260	1,430	1,608	1,660	1,710
40 (1016.0)	382	430	478	525	573	620	669	716	764	812	860	908	956	1,146	1,195	1,355	1,528	1,575	1,625
42 (1066.8)	366	409	454	500	545	591	636	682	732	775	818	863	908	1,090	1,140	1,295	1,464	1,500	1,545
44 (1117.6)	347	390	434	478	521	564	608	651	694	737	780	824	868	1,042	1,085	1,235	1,388	1,432	1,475
46 (1219.2)	333	375	416	458	500	541	582	624	666	708	750	791	832	1,000	1,040	1,180	1,332	1,370	1,410
48 (1219.2)	318	358	398	438	478	517	558	597	636	676	716	756	796	956	995	1,130	1,272	1,315	1,350
53 (1346.2)	288	324	360	395	432	468	503	539	576	612	648	683	720	864	900	1,025	1,152	1,189	1,225
60 (1524.0)	255	287	319	350	387	414	446	478	510	542	574	606	638	774	795	905	1,020	1,050	1,080
72 (1828.8)	212	239	265	291	318	345	371	398	424	451	477	504	530	637	665	755	849	875	905

(ANSI Standard B7.1-1978)

GRINDING WHEELS AND DISCS

TABLE 11-15
Grinding Disc Specifications*

Application	Wheel Specifications	Application	Wheel Specifications
Alnico-Magnets	23A60-HB14	Malleable iron castings	23A16-MB14
Aluminum castings		Piston pin ends	53A60-HB14
small, light work	37C24-IB14	Piston rings	
large, heavy work	37C16-MB14	roughing	37C24-KB14
Asbestos clutch facings	37C18-JB14	semifinish	39C46-JB14
Brake linings		finish	39C80-HB14
woven	37C20-LB14	Plumbing fixtures (vitreous)	39C36-KB14
moulded commercial finish	37C16-MB14	Porcelain (finish)	37C100-JB14
moulded quality finish	37C46-KB14	Rails (surfacing)	23A16-MB14
Brass and Bronze castings		Roller bearing ends	23A100-JB14
commercial finish	37C24-JB14	Roller bearing race cage	
Brick		surfacing	57A60-HB14
squaring ends-soft	37C14-IB14	Springs	
hard	37C20-KB14	heavy wire	23A20-MB14
refractory	37C16-LB14	medium wire	23A30-MB14
Carbon	37C36-JB14	small wire	23A46-MB14
Cast iron castings		Steel-hard	
small, light work	37C24-LB14	rough	23A24-IB14
large, heavy work	37C16-LB14	finish	23A46-HB14
Chain saw blades	57A36-LB14	Steel-soft	
Clutch plates	23A36-IB14	rough	23A20-KB14
Connecting rods	57A36-HB14	finish	23A36-JB14
Copper	37C36-HB14	Steel forgings	
Dies (hardened steel)	53A60-HB14	small, light work	23A16-JB14
Ferrite	BMD100-N50M9	large, heavy work	23A30-QB14
Fibre	37C14-IB14	Tile (ceramic)	37C36-LB14
Gears (hardened steel)	57A36-HB14	Valve stem ends	57A36-KB14
Golf club heads	53A24-NB14	Wrenches	
Grey iron	37C16-OB14	roughing	53A24-IB17
Knives	57A36-HB14	finishing	53A120-IB17

(Norton Co.)

* In all types of grinding, the work area, stock removal, tolerances required and wheel speed can have a considerable effect on specification selection. This is particularly true in disc grinding. Hence, these recommendations are general in nature. For further help, contact a grinding disc supplier.

Discs are available with perforations and/or slots molded into their faces. This helps supply an ample flow of coolant to the grinding zone, remove swarf, dissipate heat, and decrease the contact area, increasing grain penetration. The results are freer and cooler cutting, and flatter disc surfaces.

Comprehensive information on handling, storing, and mounting abrasive discs, as well as safety precautions for their use, is presented in the following two publications: "Disc Grinding, Safe Rules and Methods," (Grinding Wheel Institute, Cleveland) and ANSI Standard B7.1, "Safety Code for the Use, Care, and Protection of Abrasive Wheels," (American National Standards Institute, New York).

Grinding Speeds

About 5500 sfm (27.9 m/s)—at the periphery of the disc—is generally recommended as best for all disc grinding operations. Higher speeds have not been found to increase productivity appreciably. Somewhat higher speeds, with a maximum of about 6000 sfm (30.5 m/s), may be required for some materials, while lower speeds may be necessary for grinding hard, brittle

materials such as carbide. When grinding bimetallic parts having a different material at each end, different speeds are generally used for the two abrasive discs. There are also other parts, some with different surface areas on opposite ends, that may require different disc speeds. Discs should never be rotated at speeds exceeding the manufacturers' recommendations.

Dressing and Truing

While there are some successful applications of discs that are self sharpening, others are uneconomical because of a short life resulting from high abrasive usage. Most discs which are highly efficient for a specific application will not break down at a steady rate during grinding. As a result, it is usually necessary to periodically dress discs to sharpen their faces and restore their cutting efficiencies, as well as to true them to restore their flatness.

Types of dressing tools include star-type steel cutters with sharp or flat teeth, single-point diamond nibs, cluster-type diamond nibs, and power-driven diamond rolls.

COATED ABRASIVES

Coated abrasives are versatile, multiple-point cutting tools available in sheet, disc, roll, belt, and other forms, which perform heavy-to-light stock removal, dimensioning, shaping, fitting, blending, finishing, and polishing operations (finishing and polishing operations are discussed in Volume III of this Handbook series, "Materials and Finishing"). Coated abrasives derive their versatility from design variations, which offer the user choices in flexibility ranging from very soft and conformable to extremely firm and rigid; from width variations, which range from fractions of an inch to over 100" (2.5 m); and from their adaptability to automatic, semiautomatic, in-line, and other mass-production techniques.

ELEMENTS

Modern coated abrasives are the products of an extremely technical process developed through many years of research and development. They remain, however, a product comprised of three basic elements—a flexible or semirigid backing to which abrasive grains are bonded by an adhesive. Hence, it is the selection and manufacturing of the most suitable components from the numerous elements available that produces a coated-abrasive product designed to provide the most efficient results in a particular application. Therefore, many combinations of backing, adhesive bond, and abrasive grain are required to satisfy the countless variables encountered in industry. The backings used include cloth, paper, vulcanized fiber, or a combination. Adhesives include glue and/or resin. The most common abrasives are zirconia alumina, aluminum oxide, silicon carbide, garnet, flint, emery, and crocus.

In the manufacturing process, the backing serves as the base upon which a coating of adhesive known as the "maker" coat is uniformly applied to anchor a single layer of abrasive particles (see Fig. 11-15). Individual abrasive particles are applied uniformly to the maker coat and oriented in an electrostatic field or with a mechanical process to maximize the probability that a particle will be positioned with its major, or longitudinal, axis perpendicular to the backing. The maker coat is solidified, and a second coating of adhesive known as the "sizer" coat is applied. In coated-abrasive terminology, the maker and sizer coats are often considered as a unit and are commonly referred to as an adhesive bond.

Coated abrasives are generally manufactured in two levels of abrasive grain surface density—open and closed. A closed coated abrasive is one whose backing is fully covered with mineral particles to maximize the number of cutting points

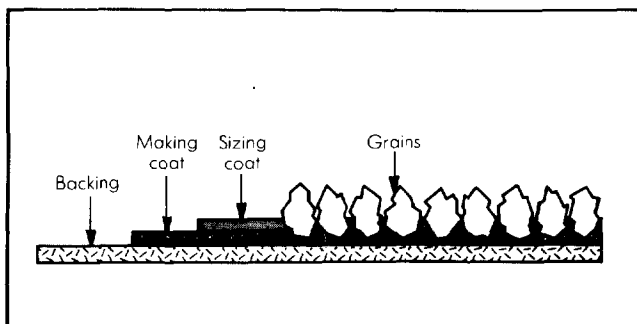


Fig. 11-15 Elements of a coated abrasive. (Norton Co.)

available and to produce a high cutting rate in a grinding operation. However, grinding operations on softer materials frequently clog or load the space between particles, rendering the coated abrasive ineffective. To combat loading, manufacturers of coated abrasives produce an open-coat construction (wider area between particles) which produces a self-cleaning action during grinding. In coated-abrasive terminology, an open-coat construction has 50-70% of its backing surface covered with mineral. Open-coat abrasives are often used to abrade softer materials such as plastics, aluminum, copper, wood, and painted surfaces.

FLEXING OF COATED ABRASIVES

Flexing is a controlled breaking of the adhesive bond that holds the abrasive grain to the backing with the aim of varying the flexibility and aggressiveness of a specific product. The direction, spacing, and severity of the breaks must be closely controlled if the product is to meet the requirements of the application for which it is intended.

Coated abrasives are normally flexed in a separate operation prior to conversion into finished form or shape. Paper-backed products tolerate only minimal flexing, whereas cloth-backed products can be subjected to heavy flexing in order to alter their grinding and polishing capabilities. Since any flexing, because it breaks the continuity of the adhesive bond, tends to decrease the durability of the product, the minimum flexing consistent with operating requirements is always the economical selection.

Flexing offers great latitude in degree of product conformability, and manufacturers of coated abrasive commonly supply several variations. As a minimum, all coated abrasives are supplied with a *modified-type single flex* to aid in handling the product during manufacturing regardless of the actual requirement in a customer's operation. *No flex* is commonly supplied on fine-grade abrasives, whose construction is inherently flexible, or on abrasives for which flexing other than a handling flex is unnecessary. *Single flex* is chosen when conformability is required in the crosswise direction, such as on drum sanders of belt operations using small-diameter contact wheels and idlers. *Single flex* should be selected for platen, aggressive-contact wheel backstands, and wide-belt operations. *Double flex* adds moderate conformability in all directions to the product. It is commonly used for abrading mildly contoured parts in slack-of-belt operations, in conjunction with soft-contact wheels, or in shaped, stationary-platen operations. *Triple flex* is chosen for maximum conformability in all directions. *Linear flex* is not as flexible as *triple flex* but will provide maximum flexibility in the lengthwise direction. *Q flex* provides a uniform flex over the entire abrasive surface in all directions. The excellent conformability of *Q flex* makes it ideal for grinding over the edges of contact rolls and for similar operations.

COATED-ABRASIVE MATERIALS

The minerals used in the manufacturing of coated abrasives are selected on the basis of their hardness, toughness, inertness, resistance to heat, fracture characteristics, and particle shape. The ability of the grain or particle to penetrate the item being abraded depends to a large extent upon the hardness and shape of the abrasive. The ability of the grain to resist breakdown and dulling under the stress of the grinding operation reflects its

toughness. The ideal abrasive grain offers maximum resistance to point wear, yet fractures before serious dulling occurs, thereby satisfying both stock removal and finishing requirements.

Selection of the proper abrasive for a given application depends not only on the grit size, but also on the correct abrasive grain for the stock being abraded. The most widely used types of coated abrasive grains fall into two general classifications: electric furnace and natural. Electric furnace types include zirconia alumina, aluminum oxide, and silicon carbide and are produced in electric furnaces. Natural abrasives include diamond, garnet, emery, crocus, and flint.

Aluminum oxide and silicon carbide have long been the mineral mainstays for the coated abrasive industry. Aluminum oxide, the mineral of choice for almost all ferrous metal applications, is generally available in several modifications depending on titania content and crystallinity. High titania content and fine crystallinity are associated with increased resistance to fracture. When the grinding application requires easy "breakdown," low titania and coarse crystalline products are recommended.

In the last decade, several additional fine crystalline synthetic oxide minerals have been introduced. Using conventional fusion furnaces, zirconia is co-fused with alumina to make an oxide "alloy." A more recently developed chemical ceramic process combines alumina with a spinel. Both of these oxide alloys are especially useful for abrasive machining of high performance metal alloys or foundry castings.

Silicon carbide remains the mineral of choice for a wide range of easier-to-grind metals and nonmetals (copper, brass, glass, painted surfaces, plastics, rubber, and ceramics). For some materials, such as titanium, the choice of oxide or silicon carbide will depend on the conditions of the grinding operation.

Aluminum Oxide

Aluminum oxide grains, brown in color, are extremely tough and wedge-shaped for high-speed penetration of tough materials without excessive fracturing or shedding. Hence, the material is particularly well adapted to grinding high-tensile materials, such as carbon steel, alloy steel, tough bronze, and hard wood. Whenever toughness (ability to resist fracturing) is the main consideration, aluminum oxide outperforms all other coated-abrasive grains.

Zirconia Alumina

Zirconia alumina grains, blue in color, have a unique self-sharpening characteristic which gives them long life when used for rugged stock removal of metals and planing of wood. This long life is due to the controlled fracturing of the grain which continuously produces sharp, new abrading points.

Zirconia alumina is a manufactured abrasive mineral. It is tougher than aluminum oxide, making it especially suitable for use when heavy grinding pressures are employed. The increased toughness retains its sharpness longer, producing longer useful life and faster cut on many operations. It is not particularly effective on steel, stainless steel, and cast iron.

Silicon Carbide

Silicon carbide grains, dark gray to black in color, are the hardest and sharpest of the minerals used in coated abrasives. Hardness and sharpness of this mineral make it the ideal abrasive for sanding nonferrous metals (aluminum, brass, bronze, magnesium, titanium, etc.), rubber, glass, plastics, fibrous woods, enamel, and other relatively soft materials.

Silicon carbide is superior to any other abrasive in its ability to penetrate and cut faster under light pressure.

Superabrasives

The superabrasives, diamond and Borazon, are available on cloth-backed products and are used for the precision grinding of ceramics, cermets, exotic alloys, and other hard, brittle materials.

Garnet

Garnet grains, red in color, are made from crushing semiprecious garnet material. Not as hard or durable as synthetic abrasives, garnet fractures along the cleavage lines of the crude crystals; hence, the resulting grains have very sharp edges. Widely used in furniture and woodworking plants, particularly in finishing operations, garnet dulls too rapidly for use in metalworking.

Emery

Emery grains, black in color, are a natural composite of corundum and iron oxide. The particles are blocky in shape and tend to cut slowly, thereby producing a polishing action on the material being abraded. They are used for general maintenance and polishing of metals and, in very fine grits, for highly technical polishing, such as preparing metallurgical specimens requiring very close tolerances.

Crocus

Crocus is essentially iron oxide particles in natural or synthetic form. Used mostly for cleaning corroded surfaces of polished metals, when a minimum of stock removal is desired, crocus is also used for polishing gold and other soft metals.

Flint

Flint grains, off-white in color, are produced by crushing flint quartz. Although flint is a sharp-edged grain, it lacks the toughness and durability of other available minerals. Hence, the use of flint is generally confined to hand sheets for general maintenance and clean-up, particularly in the home repair market. It is not recommended for production sanding.

ABRASIVE GRAIN SIZE

After the crude abrasives have been crushed, the grains are separated into standard particle sizes (grades) using screens carefully made from silk threads of exact size and number per square inch to insure extreme accuracy. The grit number (mesh number) appearing on the coated abrasive backing represents the approximate number of openings per linear inch in the final screen. Grits 240 and finer, called flours, are graded by hydraulic separators, air classifiers, and levigating tanks. These grades are regularly checked against industry standards (ANSI Standard B74.18) by testing on a series of standardized laboratory sieves and sedimentation devices.

All domestic coated abrasive manufacturers produce products that adhere to the Coated Abrasive Manufacturers Institute grading specifications, called "CAMI grades." Accurate abrasive grading practices are of vital importance in insuring absolutely uniform performance of the finished product and in eliminating random oversized grains which could damage the item being abraded.

Coated abrasives use grain sizes graded from 12-600; however, not all products are available in the complete range.

Application of coated abrasives for a given operation may involve the use of a single grit size or the use of multiple grit

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sizes. If the objective is only to remove stock with little or no concern for the finish, or to produce a specific finish with no specific stock-removal requirement, one grit size will suffice. However, when it is necessary to remove stock and develop a fine finish, a sequence of abrasive grit sizes is used. The coarsest grit size to be used in this sequence is determined by the material to be abraded and amount of stock to be removed. This initial grit size should be only as coarse as necessary to produce a practical cutting rate without producing excessively coarse scratches. The finishing grit size is determined by the specifications for the final desired finish. Selection of intermediate grit sizes is important from both quality and cost standpoints. If too few intermediate grit sizes are used, some of the coarser scratches may not be removed and optimum abrasive life may not be attained. In some cases, worn coarse-grit belts can be used for intermediate or finishing passes.

Choice of grit size, or grade, in a coated-abrasive operation depends on the amount of stock removal required, the final finish desired, and the nature of the material to be abraded. In general, the coarser the grit, the greater the rate of cut and total quantity of material removed down to a maximum grit size of 24. Grits coarser than grade 24 are used for removal of soft, tenacious materials that clog or load the abrading surface (such as paint or thermoplastic adhesives). Some very tough metals, such as titanium and nickel alloys, resist grain penetration, making finer grit sizes (as fine as grade 60) more economical to use on them for maximum stock removal.

For stripping operations (removing old finishes, rust, etc.) and for abrading materials that tend to load, grades 12, 16, or 20 are often used. For rapid, heavy stock removal and deep depths of cut, grades 24, 36, or 50 are commonly employed. Grades 60 or 80 are frequently used for medium stock removal and in progressing from rougher to smoother finishes. Light stock removal is often done with grades 100, 120, or 150; finishing (negligible stock removal), with grades 180, 220, or 240; and polishing, with grades 280 to 600. Polishing may be done in preparation for further scratch reduction through the use of buffing compounds or polishing minerals used in conjunction with buffing wheels or brushes. In progressing from a rough to smooth finish with coated abrasives, some grades can often be omitted in the sequence. In general, more grades can be omitted at the coarse end of the grade range, and fewer with the finer grades (see Volume III of the Handbook series, "Materials and Finishing").

COATED-ABRASIVE ADHESIVE BONDS

The adhesive used to bond the abrasive grain to the backing is a significant factor in the performance of the coated-abrasive product. Two types of adhesives are in use: one based on animal glue and the other based on synthetic, heat-hardenable resins. The adhesive is applied with a minimum of two bonding applications. The first, or "maker," coat adheres the abrasive grain to the backing, insuring proper anchoring and orientation. After drying or curing, the second, or "sizer," coat is applied. The sizer adhesive unites with the maker bond to provide final grain anchoring and the proper adhesive level for the finished product.

Glue Bond

In glue bond products, animal hide glue is used for both the maker and sizer adhesive coats. The glue may be used alone or with an inert filler or extender. Because animal glue has a tendency to soften from the normal heat of grinding, glue bond

products usually produce a more uniform, less-harsh finish which, in the case of fine grits, can be easily buffed out. However, although they conform well and cut soft, they lack the shed resistance, durability, and stock removal potential of resin bond products.

Resin Bond

Resins are basically liquid phenolics or ureas which can be modified for shorter or longer drying times to provide greater strength, more flexibility, or other desirable properties. In resin bond products, either pure or filled resin is used for both the maker and sizer adhesive coats. Because resins offer greater resistance to heat and are more durable in heavy stock-removal operations, resin bond products are the best all-round coated abrasives. However, they have a tendency to produce a harsher, more scratchy finish which, in the case of finer grits, is more difficult to buff out.

Resin Over Glue Bond

In resin over glue bond products, a resin sizer coat is applied over a glue coat to combine the heat resistance and aggressiveness of resin with the base flexibility of glue. This results in a product that cuts more aggressively than glue bond while producing a better final finish than resin bond.

Other Bonds

Other adhesive bonds, such as varnish and vinyl acetate, are also used in the manufacturing of coated abrasives when their particular attributes lend themselves to the desired product characteristics.

COATED-ABRASIVE BACKINGS

Whether it is paper, cloth, vulcanized fiber or a combination, the backing must be smooth enough for uniform adhesive coating, strong enough to withstand grinding pressures, and flexible enough to conform to contours (if necessary). For reasons of economy, the least expensive backing compatible with the job requirements should be selected.

Paper

The paper backings used for coated abrasives are highly specialized technical papers made to very exact specifications, thereby assuring certain essential physical properties, such as finish, strength, adhesion, flexibility, and weight. Paper weights are determined by the number of pounds in a papermaker's ream of 480 sheets, 24 x 36" (610 x 915 mm) in size.

The standard paper weights used in coated abrasives are 40, 70, 90, 130, and 165 lbs and are indicated by a letter code, from A through F, which appears immediately after the grit size on the finished product backing. Briefly stated, the lighter the backing, the greater the degree of flexibility; the heavier the backing, the greater the resistance to tearing.

A-weight (40 lbs). Light and flexible, A-weight is used primarily for hand finishing operations, both wet and dry. It serves as a backing for grits 80 and finer.

C-weight (70 lbs). Stronger and less flexible than A-weight, this backing is chosen for hand sanding, dry or wet, and for use on small portable power sanders. It is used for intermediate through fine sanding and serves as a backing for grits 60 through 180.

D-weight (90 lbs). Stronger and less flexible than C-weight, this backing is also chosen for hand sanding and for use on small portable power sanders. It is used for coarse through

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intermediate sanding and serves as a backing for grits 36 through 80.

E-weight (130 lbs). Stronger and less flexible than D-weight, this backing is used primarily on roll, belt, and disc applications for which high resistance to tearing is needed.

F-weight (165 lbs). This is the strongest, least-flexible paper backing utilized. It is used only for crankshaft lapping rolls and tannery industry belts and rolls.

Cloth

Paper-backed abrasive belts have a lower initial cost than cloth-backed belts, but cloth offers greater durability. If the severity of the operation is such that cuts, tears, nicks, etc., may be encountered, cloth should be chosen, since such damage to a paper-backed belt would cause almost immediate breakage because of tension on the belt.

Cloth backings are more durable than paper backings, offer greater resistance to tearing, and tolerate continual bending and flexing during use. The woven cotton or synthetic yarns received from the looms are treated to make them suitable for use as a coated-abrasive backing. Desizing, shrinking, drying, stretching, filling, and calendaring are all processes required to produce the desired strength, flexibility, and coating surface.

Each of the resulting backings has construction and finishing characteristics designed to make it ideally suitable for a specific product application. The standard cloth weights used in coated abrasives are indicated by a letter code, usually J, X, Y, H or S, which appears immediately after the grit size on the finished product backing.

J-weight (jeans). The lightest and most flexible cloth backing, this backing is used when finish and uniformity of the surface are more important than stock removal. It is ideal for finishing, for blending, and for use when considerable flexibility and conformity are required, such as in contour work on curved surfaces.

X-weight (drills). Stronger and relatively stiff when compared to J-weight, this backing is used on products designed for applications from coarse-grit stock removal through fine-grit finishing and polishing. Consistent productivity, relatively good finishes, and long product life are characteristic of products made with X-weight backing.

Y-weight (heavy drills). Stronger and more resistant to longitudinal splitting than regular drills cloth, Y-weight backing is used on products designed for severe applications, such as narrow-belt grinding of hand tools and wide-belt sanding of lumber and particle-board dimensioning.

H-weight (heavy duty). The strongest cloth backing utilized, this backing is used on coarse-grit products designed for extreme-pressure, heavy stock removal operations. It is used exclusively with zirconia alumina abrasive for belts having a long productive life on both wood and metal applications.

S-weight (sateen). A special, heavy, stretch-resistant backing, S-weight cloth is used only in the manufacturing of sectional belts—belts with widths greater than 52" (1300 mm) for which conventional cloth backings are unsatisfactory due to the unique construction requirements of these extremely wide belts.

Additionally, several other specialized cloth constructions are utilized, such as the marquisette cloth and plain weave mesh used for backing laminates or combinations.

While stretch characteristics are not a consideration in the use of paper, fiber, or combination backings, cloth backings do elongate under tension. Of particular importance in the design of machines is the allowance of sufficient belt-tensioning

tolerances to accommodate a 3-5% stretch when cloth backings are to be used.

Fiber

Fiber backings, made of multiple layers of impregnated paper, are very hard and strong, yet provide sufficient flexibility for the intended applications.

Thirty-mil fiber. This fiber has the greatest strength of any backing used for coated abrasives. This backing is used on resin-bonded fiber discs designed for heavy-duty portable grinder applications.

Twenty-mil fiber. This fiber is used primarily as the backing material for the coarse grits of products designed for heavy drum-sanding operations.

Combination

Combination backing, constructed by laminating light cloth and 110 lb paper, is used when resistance to tearing and breaking is a requirement. It is primarily utilized on products designed for very coarse drum-cover or disc sanding.

COATED-ABRASIVE FORMS

The final step in the manufacturing process, prior to packaging, is the conversion of the coated-abrasive product into one of the shapes or forms designed for use on specific grinding, sanding or polishing equipment. Several basic categories of coated-abrasive shapes exist, including sheets, belts, discs, and specialties. The latter category consists of a number of special shapes tailored to meet industry's countless requirements.

Sheets

Sheets of coated abrasives are produced in a wide variety of sizes for use in manual operations (by hand or hand block) or on machines with straight-line or orbital action. Precut sheets are also used on a number of drum machines.

Discs

Discs are circular coated-abrasive products of varying diameters produced with or without center holes for attaching to air or electric-powered tools. Disc abrasives are used for grinding and finishing operations, particularly in difficult-to-work areas requiring portable tools. Coated abrasives converted into rolls are most commonly 50 yds (45.7 m) in length, but vary in width depending on ultimate use. Usage of rollstock varies from precision-slit abrasives used in crankshaft and bearing-polishing operations to wide rolls used on drum machines.

Belts

Abrasive belts are fabricated from lengths of roll goods made endless when joined by splices. Belts vary in width from 1/4" to over 100" (6.3-2540 mm) and can be almost any practical length. However, the Coated Abrasive Manufacturers' Institute has endorsed a program of specific belt lengths: for a length range of 12 through 36" (305 through 914 mm), belt lengths are made in 3" (76.2 mm) length increments; for a range of 42 through 168" (1067 through 4267 mm), in length increments of 6" (152 mm); and for a range of 180 through 504" (4570 through 12 801 mm), 36" (914 mm) increments.

Advancements in product and equipment technology have resulted in coated-abrasive belts becoming a recognized production tool for heavy stock removal through surface finishing and polishing. Yet, this would not have been possible if belt joint constructions had not kept pace. Belt joints, in most cases, are at

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least as strong as the coated-abrasive product itself, run smoothly, and perform as an integral part of the belt. To achieve these characteristics, while functioning on a wide range of equipment types performing a countless variety of applications, a number of belt joints are required. Basically, these joints fall into two major categories: "lap" and "butt."

Lap joints. Lap joints are formed by overlapping the two ends of the abrasive material about $3/8"$ (9.5 mm) and bonding. The abrasive grain must always be removed (skived) from the bottom lap prior to joining. The amount of grain to be removed from the top lap, if any, depends upon the grit and application. There are several types of lap joints including no top skive (NTS) and thin joint (TJ) types.

No top skive (NTS). With this type no grain is removed from the top of the joint; therefore, maximum protection is provided against wear. This type is recommended for use on the average resilient contact wheel or free-running belt operation.

Thin joint (TJ). The goal of this type is to furnish a joint no thicker than the rest of the belt. The joint surface may have all, some or none of the grain removed—full top skive (FTS), medium top skive (MTS), or no top skive (NTS)—depending upon the grit and material. This makes the belt smooth running and ideal for use with a platen, back-up plate, or hard-density contact wheel.

Lap splices are available in a variety of widths, from $1/4"$ to $3/4"$ (6.3-19.1 mm), in $1/8"$ (3.2 mm) increments. Flexibility and strength vary with the width of the splice. Splices $1/4"$ wide are most flexible and weakest, while splices $3/4"$ are strongest and least flexible. The most common splice widths are $3/8"$ (9.5 mm) and $1/2"$ (12.7 mm). The standard splice angle supplied by manufacturers of coated-abrasive belts is 55° . However, other commonly available splice angles are 30, 45, 65, and 90° . A 30° angle produces a very smooth-running belt since only a small portion of the splice is in the grinding area at a given time. At the other extreme, the entire 90° splice angle would pass the workpiece at one time and may run rougher. Shorter belts, because of the length of the splice required, may be available only with a 90° splice.

Butt joints. Butt joints are formed by butting the two ends of the abrasive material together without overlapping. A strong, thin, reinforcing patch is then bonded to the back of the joint to hold it together. As no grain is skived from the joint area, a uniform, uninterrupted abrasive surface is produced, which permits belts with butt joints to be run in either direction.

Special Forms

Special forms of coated abrasives include a large assortment of specially designed tools used for abrading relatively inaccessible areas. Cartridge rolls, cones, bands, spiral-wound strips and flaps are typical examples—all available in various sizes and configurations. Cartridge rolls are small, tightly wound rolls of

coated abrasives glued to prevent unwinding. They are press-fitted on mandrels and offer fresh abrasives as an individual winding wears away. They are utilized as deburring and polishing tools and are commonly available in end-tapered, full-tapered, and regular (untapered) shapes. Cone-shaped coated abrasives are press-fitted to a mandrel for grinding and finishing relatively inaccessible areas such as curved surfaces and punched or drilled holes. Bands are coated-abrasive materials spirally wound and glued to a similarly wound inner liner. They are fitted to a mandrel with a jam nut to expand the rubber mandrel and thereby tighten the band. Bands deburr and grind areas not reached easily by other abrasive tools. Spiral-wound strips are flexible uniform strips of abrasive wound to a specific diameter for finishing and polishing difficult-to-reach areas such as grooves, slots, flutes, threads, holes, and other small-diameter openings. Flap wheels, or polishing grinding wheels, are comprised of flaps of coated abrasives fastened radially to a core for deburring, polishing, blending, and grinding small contours, narrow openings, channels, and small-diameter tubing (see Volume III of this Handbook series, "Materials and Finishing").

CUTTING FLUIDS FOR COATED ABRASIVES

The choice as to whether a coated abrasive is to be run under wet or dry conditions is largely determined by the material to be ground and the mechanics of the grinding operation. Under dry conditions metals may discolor from localized heat. Thermoplastic materials may soften, distort, or load the abrasive, and some materials pose health or safety hazards if grinding swarf is not properly handled. On the other hand, wet operations should not be used with electrically operated portable tools or when chemical reaction occurs between the swarf and the coolant.

A detailed discussion of cutting fluids is presented in Chapter 4 of this volume, and a discussion of grinding fluids is presented in the subsequent section of this chapter. Major functions served by using grinding fluids with coated abrasives are to cool the workpiece, thus decreasing or eliminating the possibility of heat check, discoloration, melting, and warping and to reduce friction, thus decreasing grinding temperatures, permitting higher speeds, and generally improving the surface finish produced. They also reduce the tendency to load the abrasive by inhibiting the welding or bonding of swarf to the abrasive grains. This function can sometimes be accomplished in dry operations by using coated abrasives manufactured with an additional surface coating of zinc stearate to resist loading. Usually whitish in color on the mineral side, a zinc stearate oversize performs as a dry lubricant for abrading soft materials. Cutting fluids also provide chip washaway from the point of grinding to improve abrasive performance and reduce potential coarse scratches associated with agglomeration of swarf. Their use generally also results in longer abrasive life.

GRINDING FLUIDS

Many fluid formulations used to cool and lubricate cutting operations are also used to perform similar functions in grinding operations. However, the grinding process by its nature, exhibits several unique characteristics which make it significantly different from conventional cutting processes. For this reason, special considerations must be given to the

functions, selection, and use of grinding fluids. The following sections highlight several topics in fluid technology peculiar to the grinding process.

FUNCTIONS OF GRINDING FLUIDS

Grinding fluids perform virtually the same functions as

cutting fluids (described in Chapter 4 of this volume, "Cutting Fluids and Industrial Lubricants"). They lubricate the chip/grit and grit/workpiece interfaces, reducing the power required to remove a given volume of material and thereby reducing the heat generated in the grinding operation. Secondly, they cool and prevent or minimize heat buildup in the parts being ground.

In metalcutting the energy necessary to deform metal to form a chip is approximately twice that required to overcome friction between the tool/workpiece and the chip/workpiece interfaces. In grinding, the force necessary to overcome friction is approximately the same as that necessary for chip formation. Consequently, friction forces are much more important in grinding than in cutting, making lubrication in grinding critical, not only from the standpoint of power, wheel life, and surface finish, but also in relation to heat development and possible damage to the ground surface.

In single point turning it has been shown that approximately 97% of the energy required to remove metal comes "out of the system" in the form of heat, with approximately 3% of the energy left behind in the cut surface. In comparing cutting to grinding, only about 4% of the energy required to grind "leaves the system" with chips; about 12% is absorbed by the grinding grit; and the remainder, about 84%, is left behind in the ground surface. This high energy retention in the workpiece in grinding is further evidence of the need for relatively high lubrication in grinding to prevent heat generation and of the need for only enough cooling to prevent heat buildup in the part. Grinding oils do the best job of lubricating and preventing heat generation. Although this is true, parts ground with oil come out of the machine hotter to the touch than parts ground with water-miscible fluids, simply because oils do a relatively poor job of cooling.

Traditionally most centerless and cylindrical grinding operations have been performed with low-to-medium lubricity, water-miscible fluids and relatively hard, fine-grit wheels. The current trend is toward running these same operations with medium-to-high lubricity, water-miscible fluids with softer, coarser wheels. This usually results in generation of the necessary finishes and size at higher stock removal rates (higher productivity) with a reduction in overall manufacturing costs and a significant reduction in unit costs. Successful adoption of this approach to improving grinding productivity is dependent upon matching the wheel to the fluid, not the more traditional approach of matching the fluid to the wheel.

Grinding fluids are generally formulated the same way as fluids used in cutting and are compositionally described by types in Chapter 4 of this volume, "Cutting Fluids and Industrial Lubricants." For further information, refer to Chapter 4 or to *Cutting and Grinding Fluids: Selection and Application*.¹¹

SELECTION OF GRINDING FLUIDS

As noted earlier, grinding oils, while unquestionably providing the greatest degree of lubricity of any available grinding fluid, are generally avoided whenever possible because of high cost, danger from fire, and potential operator health problems. Today, grinding with nonemulsifiable oils is generally restricted to use on materials of low grindability and to form-grinding from the solid. However, even in these two areas, heavy-duty, water-miscible fluids used at high concentrations (10-20%) with properly matched wheels are making inroads against these oils.

Regulating Lubricating Properties

In general, there are two approaches to regulating the lubricating properties of water-miscible grinding fluids:

1. To incorporate lubricating elements such as fats or fat-like materials, chlorine, sulfur, and phosphorus organic compounds, alone or in combination, into the grinding fluid concentrate.
2. To regulate the ratio of the concentrate to the water. A large percentage of the concentrate and small quantity of water (for example, 1 part concentrate to 10 parts water) will impart high lubricity. A large quantity of water and small quantity of concentrate will provide more cooling.

Area of Contact

Not only must the combinations of the grinding wheel and workpiece be considered in making a choice of grinding fluid, but the type of grinding must also be considered from the standpoint of grinding wheel/workpiece unit pressure. Cylindrical and centerless grinding are almost line contact; consequently, high unit pressures exist between the wheel and the workpieces. In these applications, usually a relatively hard wheel with a high-lubricity fluid gives longest wheel life, takes less power, and gives best finish. A reciprocating surface or rotary surface grinder will have a greater area of contact than cylindrical or centerless grinder, and a slightly softer grinding wheel and a fluid with somewhat less lubricity can be used.

An internal grinder will have a still greater area of contact between wheel and workpiece so that unit pressures are still lower. In these applications, an even softer wheel is usually used and an even lighter duty oil can be used if the metal removal rate is not so high as to cause excessive heat buildup in the workpiece. Ordinarily, a moderate-duty, water-miscible fluid must be matched with the wheel/workpiece combination.

Vertical spindle surface grinding involves the greatest area of contact with the work, and high heat is involved. In these applications, soft, coarse wheels are usually used with a low-lubricity, high-heat conducting, rust-inhibiting type of water-miscible fluids. Sometimes small amounts of water-miscible fluids of fairly high lubricating effect can be added to the regular fluid to improve finish and wheel life. If this is done, it must be carefully controlled.

Grinding Tests

Before grinding tests are performed to determine the relative value of various fluids, the machine must be thoroughly cleaned if one fluid is to be replaced by another (see "Maintenance of Cutting Fluids" in Chapter 4 of this volume, "Cutting Fluids and Industrial Lubricants"). The same wheel may not be best for all fluids tested. A wheel that is too hard for one fluid may be just right for another. This does not mean that the second fluid is necessarily superior; it may simply be compensating for the hardness of the wheel. For a significant comparison of several grinding fluids, it may be necessary to evaluate them on the basis of power consumption, grinding ratio, or a combination of variables.

Care should be taken to keep all other conditions unchanged while the fluids are being tested. When the ground parts are to be subjected to high stresses in actual service, as in jet engines,

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GRINDING FLUIDS

factors such as surface finish and residual grinding stresses may also have to be considered in the evaluation of the fluids.

Types Of Grinding Fluids

Categorizing grinding fluids is extremely difficult due to the largely proprietary formulations of the fluid manufacturers and the lack of agreement among those manufacturers as to what exactly comprises a light-duty, general-purpose, or heavy-duty fluid (see "Types of Cutting Fluids" in Chapter 4 of this volume). As a result, probably the most expeditious solution to any given grinding problem is to call for the assistance of capable abrasive engineers and reputable grinding fluid suppliers who usually have both the experience and products to be of assistance. Table 11-16 provides general recommendations for selecting a grinding fluid for specific workpiece materials.

A current trend in manufacturing is to attempt to minimize the number of fluids in use in a plant. This is normally done by

selecting heavy-duty fluids which have broad-range capabilities; i.e., they are compatible with many work materials. When used at low concentrations (2-4%), they function as light-duty fluids; at medium concentrations (4-8%), the same fluids function as general-purpose fluids; and at high concentrations (10-20%), they function as heavy-duty fluids. The advantages of using one or two fluids in this manner is obvious: fewer materials need to be purchased and fewer inventory, control, and waste-treatment disposal procedures need to be developed. Finally, with this approach, there is less likelihood of inadvertently mixing fluids and suffering the problems which arise should the mixed fluids prove to be incompatible.

GRINDING FLUID APPLICATION

The most effective fluids available will do very little good in providing the lubricity necessary in grinding if the fluid is not applied so that it will penetrate into the grinding zone. Some

TABLE 11-16
Grinding Fluid Recommendations*

Work Materials	Thread, Gear, Form Grind	Centerless, Cylindrical	Internal	Surface	Abrasive Cutoff	Hone**
Free-Machining Steel (low-medium carbon)	MD oil, HD water	LD oil, M-HD water miscible	GP water miscible	LD-GP water miscible	Water miscible	LD oil, spec. fluids
Low-Alloy Structural Steel (martensitic)	HD oil, HD water miscible	HE oil, HD water miscible	LD oil, water miscible	GP water miscible	Water miscible	LD oil, spec. fluids
Hot-Work Die Steels (martensitic) Stainless Steels (austenitic, martensitic, precipitation hardening) maraging steels nickel & cobalt alloys	HD oil, HD water miscible	HD water miscible	GP oil, GP water miscible	HD water miscible	Water miscible	LD oil, spec. fluids
Cast Iron	HD water miscible	GP water miscible	GP water miscible	GP water miscible	Water miscible	LD oil, spec. fluids
Magnesium & Alloys	LD oil, spec. fluids	LD oil, spec. fluids	LD oil, spec. fluids	LD oil, spec. fluids	LD oil, spec. fluids	LD oil, spec. fluids
Aluminum & Alloys	HD water miscible	HD water miscible	HD water miscible	HD water miscible	HD water miscible	LD oil, spec. fluids
Copper & Alloys	HD water, miscible	LD oil, HD water miscible	LD oil, HD water miscible	LD oil, HD water miscible	HD water miscible	LD oil, spec. fluids
Titanium & Alloys	HD water miscible	HD water miscible	HD water miscible	HD water miscible	HD water miscible	LD oil, spec. fluids
Beryllium & Alloys	HD water miscible	HD water miscible, spec. fluids	HD water miscible, spec. fluids	HD water miscible, spec. fluids	Water miscible	LD oil, spec. fluids
Refractories	HD oil	HD oil, HD water miscible	HD oil, HD water miscible	HD oil, HD water miscible	HD oil, HD water miscible	LD oil

* HD = Heavy-duty; GP = General-purpose; LD = Light-duty; MD = Medium-duty.

** Some honing is now being successfully done using heavy-duty, water-miscible fluids and honing stones specifically designed for use with water which incorporate cubic boron nitride abrasives. This application is so sufficiently new that general recommendations can not yet be made.

experts believe that the high wheel speeds normally associated with commercial grinding (6500 sfm, 33 m/s) result in an air layer surrounding the wheel that is of such intensity that it is difficult to force the fluid through the air layer and into the grinding zone.

Traditionally, the concept of an "air cushion" around the grinding wheel has been accepted as a reasonable explanation of the observed effects of grinding wheel/fluid interaction. Recently, however, some researchers have cast doubt on the air cushion mechanism. Werner and Lauer-Schmaltz state:¹²

"... If the laminar stream of fluid has a much lower or much higher speed than the disk, i.e., the grinding wheel, then the fluid forms turbulences and bounces off. As a matter of fact, this would happen in a vacuum, too. Consequently, the mechanical principle behind the effect cannot be an air cushion, but rather energetic effects, which cause the laminar fluid to form turbulences. If on the other hand the velocities of the fluid and the wheel are approximately equivalent, then the laminar stream follows the wheel contour due to adhesive forces for a certain length without forming turbulences, and is finally leaving the wheel surface due to centrifugal forces.

"In most application cases, especially in high-speed/high-efficiency grinding, the coolant velocity is not high enough to meet the wheel speed. At conventional coolant pressures of 10 to 15 psi [69-103 kPa] the coolant speed reaches values of 10 to 20 m/s [about 1970 to 3940 sfm] only. For high-efficiency grinding operations at increased wheel speeds, the coolant pressure should be in the range of 100 psi [689 kPa] and above.

"The turbulent bouncing of the coolant in case of too low coolant velocity can easily be observed, and it has falsely been interpreted as the effect of an air cushion. The counter-measures, however, which were taken on the grounds of the misinterpreted observations led in the right direction: In order to penetrate the imaginary air layer, the coolant pressure was increased, and as a matter of fact, improved grinding results could be observed. The real reason for this improvement, however, was that together with the increased coolant pressure its speed was increased, and as a consequence the laminar stream of coolant was most efficiently dragged into the wheel-work contact zone."

To counter these effects, numerous techniques have been tried with varying degrees of success. Some of these techniques are:

1. Flooding—the most common application technique for grinding. A large volume of grinding fluid is applied at low pressure (10-25 psi, 69-172 kPa) in an attempt to submerge the wheel and workpiece in fluid. Flooding generally gives acceptable results in surface grinding of all types.
2. In jet application, high-pressure fluid (25-50 psi, 172-345 kPa) applied through directed nozzles positioned closely to the wheel and workpiece with the fluid flowing in the direction of wheel rotation. Jet applications are common in groove, form, gear, and thread grinding and are frequently used in abrasive cutoff applications. They are occasionally combined with conventional flooding.
3. Applying fluid through the wheel by making use of voids present in vitrified wheels. This technique has been shown to be very effective in getting fluid to the grinding

zone and thereby lowering friction and removing the heat that is generated. The fluid is normally applied to the wheel either through the spindle or by means of cupped flanges on the wheel. Very fine, positive filtration is required with this type of application; because of this, applying fluid through the wheel is not widely used.

4. Air-deflector flood nozzles, sometimes called chamber-type nozzles. These nozzles are being used increasingly in the low-pressure application of grinding fluids on horizontal spindle surface grinders, high-speed grinders, and centerless and other types of cylindrical grinders. Although some controversy exists as to the mechanism by which these devices work, air-deflector flood nozzles have proven effective in getting the grinding fluid into the grinding zone, and they can be retrofitted to existing machines equipped with conventional low-pressure systems.

Figure 11-16 illustrates the configuration of a typical air-deflector nozzle. Some experts believe such an air deflector nozzle removes the air cushion from the wheel and thereby generates a low-pressure area immediately ahead of the grinding zone. This low-pressure area is said to pull the fluid from the nozzle into the wheel face, which carries the fluid into the grinding zone.

Other experts claim that the so-called air cushion has little effect on the grinding operation and that the positive effects of a so-called air-deflector nozzle are actually caused by a different mechanism. Werner and Lauer-Schmaltz state:¹³

"... The widely open mouth of a chamber-type nozzle covers a larger section of the wheel surface. As a result, the fluid near to the wheel surface is accelerated by the wheel itself, such that a laminar stream of coolant is in contact with the wheel. As it has exactly the speed of the grinding wheel, the exiting stream of coolant adheres to the wheel surface and gets into the wheel-work contact area most effectively."

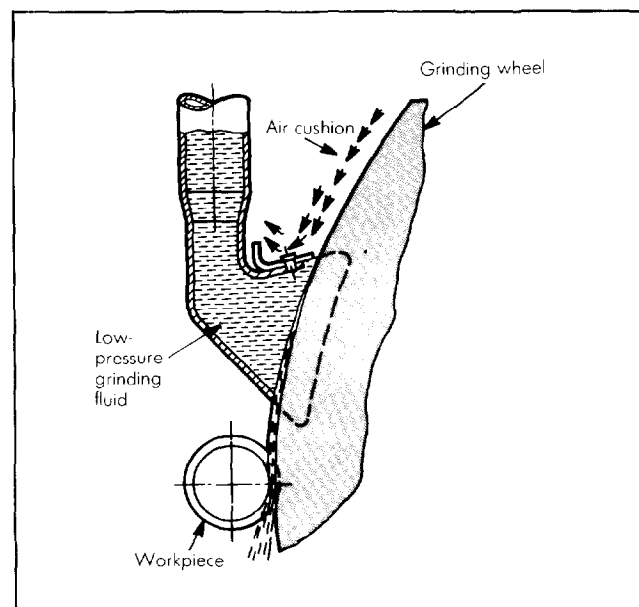


Fig. 11-16 Air deflector nozzle or chamber-type nozzle used to increase grinding fluid accessibility in the grinding zone.

GRINDING FLUIDS

Internal grinding is probably the most difficult type of grinding on which to obtain an adequate supply of fluid. The relatively limited space through which fluid lines must run makes it imperative that the lines be directed with the wheel's direction of rotation and that fluid pressure and flow be kept as high as possible. On parts with "through holes," fluid should be supplied as described previously in conjunction with fluid supplied through the work spindle.

GRINDING FLUID FILTRATION METHODS

A general discussion of filtration methods for cutting fluids is presented in Chapter 4 of this volume, "Cutting Fluids and Industrial Lubricants." Topics peculiar to the grinding process are presented in the following sections.

Settling Tanks

Gravity settling is the simplest means of cleaning fluids. Its efficiency can be greatly improved by the use of weirs, baffles, and dragout bars. Generally, settling tanks should be sized to contain enough fluid for a minimum of 10 and preferably 20 minutes of retention time.

Multiple Weirs

With the folded or multiple-weir clarifier, the length of the wall over which the fluid flows is greatly increased. Dragout bars and surface skimmers remove the swarf from the bottom and skim off floating contaminants. The multiple-weir clarifier is efficient at settling fine grit and swarf such as cast iron, molybdenum, glass, and other grinding swarf that pack so tightly that they clog positive-media filters. Tanks should be designed for a minimum of 10 minutes of retention time.

Centrifuges

Centrifuging is an accelerated settling process in which centrifugal force is used to replace the force of gravity to speed up the process. Centrifuges for grinding fluids are subdivided into the following categories for two widely different purposes.

Basket-bowl centrifuges. These centrifuges are low-speed (800-3500 rpm) machines designed for the removal of solid particles from grinding oil or water-miscible grinding fluids. They are very effective in small-particle, low-volume swarf applications such as carbide grinding.

Disc-bowl centrifuges. These are high-speed (6000-10,000 rpm) machines designed to remove both free and emulsified tramp oil from water-miscible fluids or water from grinding oil. Disc-bowl machines are generally not intended for solid-from-liquid (clarifying) applications.

Cyclones

An adaption of an old concept, the cyclone separator is a relative newcomer to cutting fluid clarification. Among the major advantages is the fact that no moving parts exist in the cyclone itself. Cyclone systems must have pumps that will be rugged enough to handle chips and swarf and must also be designed so that large particles of shop debris will not plug the underflow orifice. If the system is designed improperly, this orifice will wear and require both frequent adjustment of back pressure for proper operation and periodic replacement of the orifice. Operation at flows in excess of rated capacity will cause a dramatic decrease in solids removal.

Flotation

The flotation unit combines settling and the principle of

flotation to clarify the fluid. In selecting a grinding fluid for use in a flotation unit, it is important to select a fluid that will provide a sufficient amount of foam. These units are limited to soluble oil emulsions and cannot be used with chemical or semichemical fluids. Very fine particle separation generally cannot be achieved with these units.

Magnetic Separators

Magnetic separators remove swarf from the cutting fluid as it passes over a magnetic drum. Magnetic separators usually find their applications with individual grinding machines or in small systems in combinations with positive filters. Advantages are the relatively little floor space required and the low initial cost. They will not work with nonmagnetic (nonferrous) work materials.

Positive Filters

In positive filtration, used grinding fluid passes through a porous filter medium, such as cloth, paper, or wire screen, by means of gravity, pressure, or vacuum. Swarf is deposited on the filter medium, and the clarified fluid then returns to a clean tank.

Based on the many variables in the design and operation of positive filters, more than a hundred practical combinations can be made using the following categories of design parameters. (Design parameters are listed in order of popularity under each category.)

1. Propelling force:
 - a. Vacuum
 - b. Pressure
 - c. Gravity
2. Medium composition:
 - a. Paper
 - b. Cloth
 - 1) Woven
 - 2) Nonwoven
 - c. Wire screen
 - d. String
 - e. Precoat combination, i.e., diatomaceous earth and cloth
3. Medium forms
 - a. Flat sheet
 - b. Tube
 - c. Leaf
 - d. Cartridge
 - e. Bag
4. Medium life:
 - a. Disposable
 - b. Permanent
5. Method of swarf removal:
 - a. Scrape off
 - b. Convey with medium
 - c. Backflush

The acceptance of pressure and vacuum-type positive filters has been greater than that of the gravity type because they are more efficient and require less floor space.

Vacuum Filters

In these units, the fluid enters the grinding fluid tank and passes through the filter medium by means of a vacuum to the clean tank. The medium can be disposable paper or cloth, permanent cloth, or wire screen. The swarf can be removed by

GRINDING MACHINES AND FIXTURES

indexing the medium, by dragout bars, or by backflushing. These units are extremely effective in most types of steel-grinding and machining installations. Insoluble hard-water soaps and scums will clog or "blind" positive-media filters; therefore, in hard-water areas, the fluid must be mixed with demineralized (deionized, not softened) water and must not contain anionic wetting agents.

Pressure Filters

In these units, the dirty fluid is forced through the medium, generally paper or cloth, rather than being pulled through by means of a vacuum. At a predetermined point, regulated by the amount of swarf on the filter medium, the pressure shuts off, and the medium is indexed to a clean portion. Fluids for use in these systems must be stable and nonscumming and must have low foaming tendencies.

Tube and leaf filters, working on a pressure or vacuum principle and utilizing a precoat, are often used in filtration of honing and grinding oils when separation of fine particles (under $5 \mu\text{m}$, $196 \mu\text{in.}$) is needed. Care should be taken in considering a precoat filter for use with water-miscible fluids, since the precoat may adversely affect the emulsion.

It is strongly recommended in selecting a filtration system that the following points be kept in mind:

1. It is very unwise to combine grinding of dissimilar metals in one system:
 - a. Cast iron should be kept to itself.
 - b. Copper and its alloys should be kept to themselves.
 - c. Aluminum and its alloys should be kept to themselves.
 - d. Widely different steels should be segregated. Low-carbon steels and stainless steels should not be ground on the same system.
2. It is equally unwise to combine dissimilar grinding operations or to combine cutting with grinding.
 - a. Frequently, cylindrical and centerless grinding can be combined, but not always.
 - b. Internal grinding should be kept to itself.
 - c. Surface grinding should be kept to itself.
3. Fluids used to grind cast iron
 - a. Should be chemical or semichemical in nature. Soluble oils should not be used.
 - b. Are best clarified by multiple-weir settling systems.
 - c. Can be clarified by pressure or vacuum positive-media filters, but not inexpensively; free graphite from the iron tends to blind positive media and increase its usage. Tramp oil contamination of the fluid in excess of 2% increases media consumption dramatically.
4. Central filtration systems for grinding should be designed as a total system, and they should be designed by experts in consultation with the fluid supplier. If increases in capacity requirements are anticipated for the near future, they should be designed into the system initially.
5. Competitive bidding on a system automatically increases the tendency for system suppliers to undersize in order to hold costs down. Therefore, it is wise to establish system performance specifications in addition to mechanical, electrical, and other specifications against which suppliers must bid; the successful bidder should be held accountable for meeting the performance specifications.
6. The capability of removing tramp oil should be designed into all central systems. High-speed, disc-bowl centrifuges, properly sized, have proven to be the most effective devices developed to date for removing both free and emulsified tramp oil.

GRINDING MACHINES AND FIXTURES

Many modern grinding machines feature greater mass due to thicker bed wall sections, longer bed lengths, and heavier columns. Increased rigidity and stability of this latest generation of grinding machines make it possible to grind with higher horsepower and to perform heavier grinding operations. For example, one newly developed vertical-spindle surface grinder equipped with a reciprocating table features a large 150 hp (112 kW) motor and can remove stock at the rate of over 40 in.³/min (11 000 mm³/s).

One line of precision surface grinders uses a combined concrete and steel/iron construction for bases, columns, and other structural members. These grinders not only cost less than conventional machines but provide greater stability. This static and dynamic stiffness is essential for minimizing deflection, vibration, chatter, and backlash, and for improving accuracy and finish.

The introduction of more rigid machines makes it possible to use bonded abrasive wheels as well as abrasive belts for heavy stock removal and to use more than one spindle for simultaneous grinding of two or more surfaces. Machines are also available with self-supporting bases and leveling systems which minimize the need for special foundations.

Modular design concepts used today allow machine builders to provide custom-made machines at lower costs and in a wider

variety of configurations. These modular grinding machines permit the use of more than one wheelhead for a combined rough and finish grinding operation that would normally require two or more operations performed on more than one machine.

The use of hydrodynamic spindle bearings on grinding wheel heads provides higher accuracy, increased life expectancy, heavier load capacity, and higher speeds. With hydrodynamic spindle bearings, a high-pressure oil film supports the load and keeps runout to a minimum. The increased spindle diameters made possible with this design allow up to 100% increase in horsepower (kilowatt) capacity of new grinding machines. Hydrostatic bearings, although more costly and complex, provide even greater stiffness and increased accuracy for heavier operations, without significant spindle wear.

A major factor in the metal removal performance of the latest generation of grinders is the trend toward increased grinding wheel peripheral speeds. This development has made possible significant improvements in productivity, with reductions in machining costs.

Over the past decade, grinding machine builders have introduced a wide variety of new machine control features aimed at boosting the operating performance and overall productivity of new grinders. These new control features are

SURFACE GRINDING

generally classified as one of two different types: (1) machine controls designed to control grinding process variables, such as speed, infeed pressure or workspeed, in response to changes in the grinding operation and (2) machine controls designed to control positioning or "tool path."

By far, the use of NC or CNC has excelled in tool path control but, to date, has not been as widely used for adaptive control of grinding process variables. Adaptive control of the complex relationships in grinding, and other machining processes for that matter, has lagged behind applications of tool path control, probably because adaptive control is significantly more complicated and is less easily developed for general use.

On modern grinders, position control or tool path control is characterized by the widespread use of manual data input (MDI), allowing the operator to program the grinder on the shop floor without the assistance of specially trained NC programmers. On many new machines, a variety of program storage methods are available, such as tape cassettes, floppy disks, and traditional paper tape, to facilitate increased flexibility in programming and changeover.

The latest generation of electronically controlled grinders feature "canned cycles" to assist in programming—a convenience that speeds programming and helps eliminate costly programming errors.

In the future, grinding machines will feature increased capability due to still more sophisticated controls. Advances are expected to be made in both tool positioning and the controlling of the physical process of grinding. It is expected that control capabilities now found only on NC lathes, machining centers, and sophisticated milling machines will carry over and be available on grinders as well. This phenomenon is evidenced by the fact that some machine builders are now offering equivalent grinding machines that closely resemble, with respect to controls, certain machining centers and turning machines in their product line.

For example, toolchangers have been standard equipment on CNC and NC machining centers for many years, and some observers believe that features such as these (namely, wheel changers) will be developed for automated grinders in the future. This trend is now evidenced by a number of grinding machines that are sold with an auxiliary wheel arbor as standard equipment. This second wheel can be mounted, balanced, and dressed off the machine while the grinder is in operation. When a wheel change is required, the second wheel is ready for installation with minimum downtime. An automated wheel-changing feature would be particularly effective in speeding changeover in job-shop grinding operations.

The control of grinding process variables through the use of adaptive control will come more slowly than more sophisticated positioning controls. The largest stumbling block appears to be a lack of consensus among developers as to which grinding process variables should be controlled. Another obvious problem in such work is the development of reliable hardware that will function well in production and will be maintainable over an extended period (see "Adaptive Control" in Chapter 5 of this volume).

SURFACE GRINDING

Introduced initially as an alternative to filing for producing flat surfaces, surface grinders were first used in the United States around 1876. Today the surface grinder is an indispensable metalworking tool used in all phases of toolroom and production parts manufacturing.

Surface grinders are used to produce high-quality flat surfaces on workpieces. Peripheral surface grinders with horizontal spindles use the periphery of the grinding wheel to impart a flat surface to the workpiece. Vertical-spindle grinders use the face of cup, cylinder, disc, or segmental wheels to produce a flat surface. Workpiece motion relative to the grinding wheel during the grinding process on horizontal-spindle (peripheral) surface grinders and vertical-spindle (wheel-face) grinders can be either traverse or rotary, as illustrated in Fig. 11-17.

Disc grinding is often thought of as a special type of wheel-face grinding that utilizes a broad contact of the face area of the wheel during grinding. As illustrated in Fig. 11-18, in disc grinding, the contact area between the grinding disc and workpiece is relatively large in comparison with conventional wheel-face grinding in which the contact area is significantly less.

In general, peripheral grinders are used in high-precision operations in which control of size and geometry is more important than heavy stock removal. The fine, straight-line pattern produced by peripheral grinding is desirable for certain products, such as sliding bearing parts. Some newer peripheral grinders equipped with grinding wheels from 32-36" (810-915 mm) diam and drive motors up to 125 hp (93 kW) can be used to effect stock removal rates comparable to those of high-performance wheel-face grinders.

With vertical-spindle grinders, wheels with coarse grains, relatively soft bonding, and open structure are normally employed to achieve heavy stock removal. Such operations are ideal for grinding interrupted surfaces, and the scratch patterns produced in this type of grinding are a series of overlapping curves, which are desirable for many bearing surfaces. Vertical-spindle grinding typically has been used for operations in which highly accurate size control and high-quality surface finish have not been of primary importance. However, improvements in machine construction, workpiece loading, and holding devices have broadened the utility of vertical-spindle grinders to workpieces requiring greater control of size and surface finish.

Horizontal-Spindle Surface Grinders (Peripheral)

Typical applications for horizontal-spindle surface grinders include:

- Plain, flat surfaces—continuous or interrupted.
- Taper grinding—workpiece supported at an angle to produce an inclined flat surface.
- Angular grinding—parallel flat surfaces at different angles of inclination.
- Slots in a common plane.
- Flat surfaces next to a shoulder.
- Flat surfaces positioned around the periphery of a workpiece.
- Flat, recessed surfaces in different orientations on the face of the part.
- Straight surfaces with several cross-sectional elements of regular form.
- Straight, flat surfaces with special profiles.
- Single-plane, flat surfaces in controlled locations.
- Flat surfaces in several parallel or related planes.

Generally, there are five basic configurations of horizontal-spindle surface grinders:

1. Compound table with vertical column adjustment. This

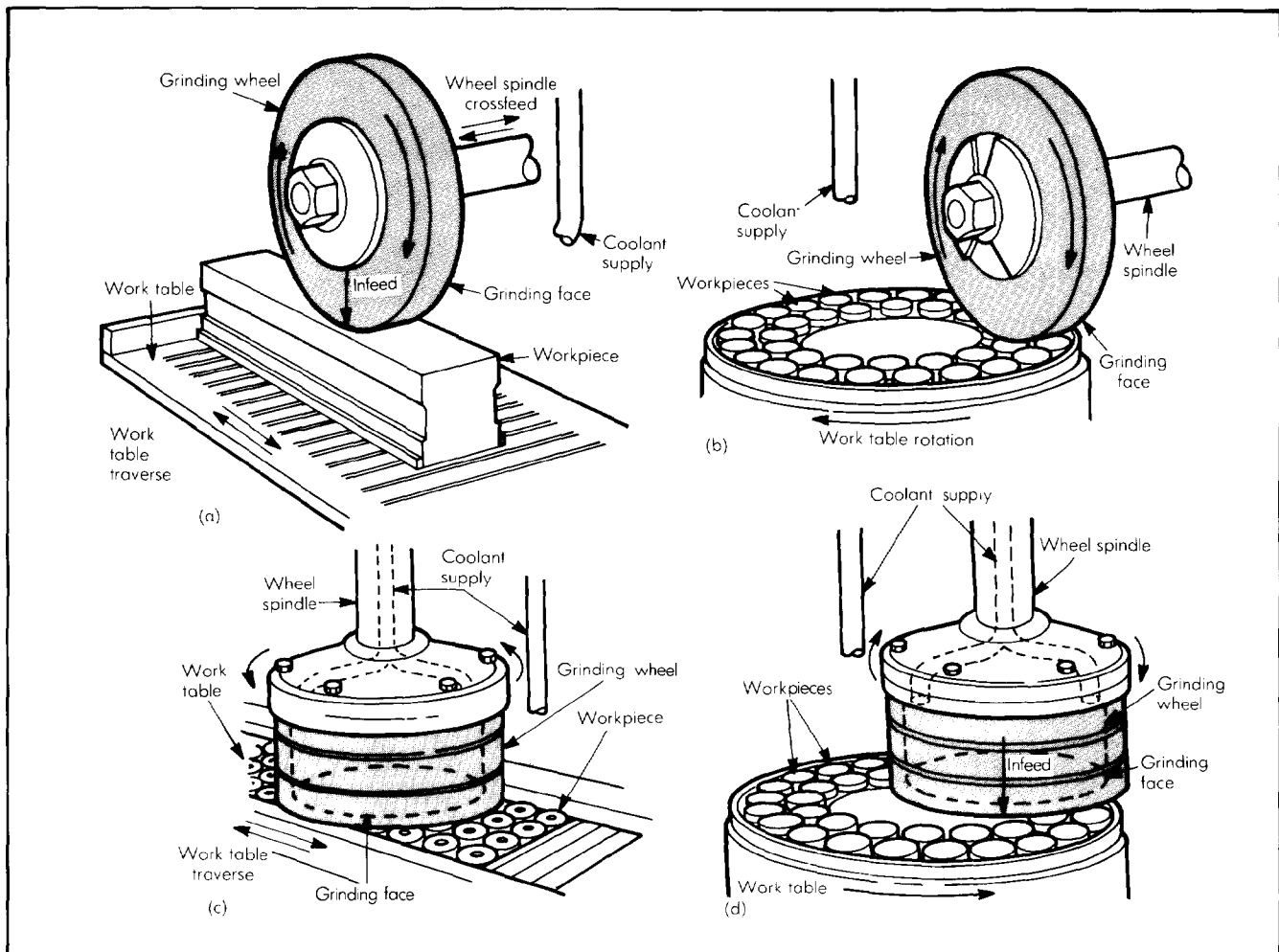


Fig. 11-17 (a) Periphery grinding—traverse workpiece motion, (b) Periphery grinding—rotary workpiece motion, (c) Wheel-face grinding—traverse workpiece motion, (d) Wheel-face grinding—rotary workpiece motion.

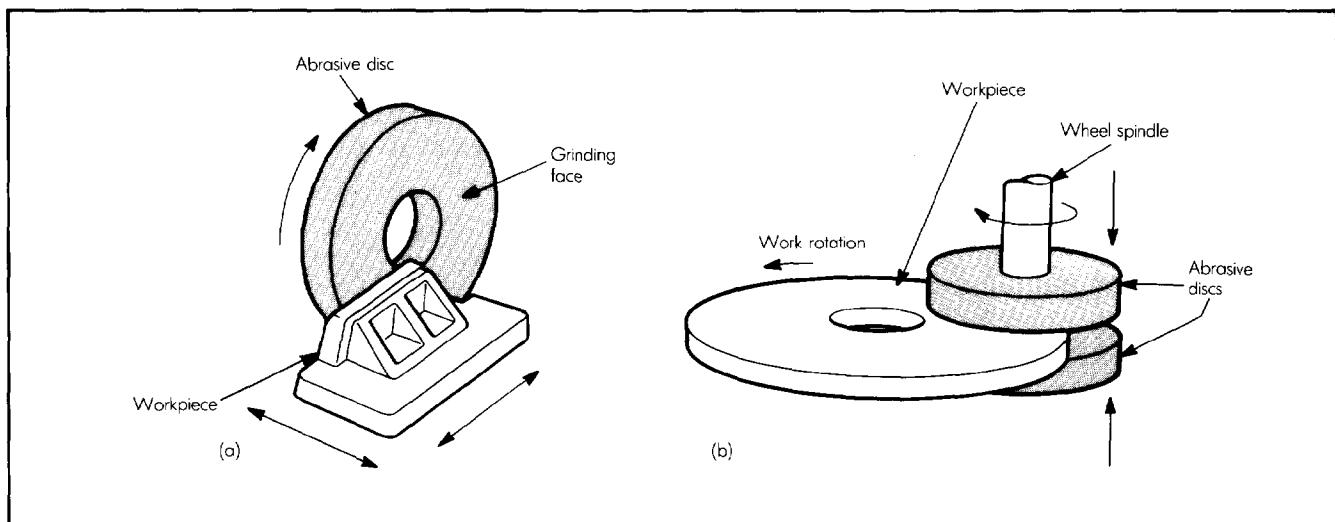


Fig. 11-18 (a) Single-disc grinding, (b) Double-disc grinding.

SURFACE GRINDING

configuration is often used for universal tool grinders in light applications for which the combined weight of the wheel head and arm can be held to a minimum to maintain sensitive vertical adjustment.

2. Compound table and vertical wheelhead adjustment. This configuration is often used for small and medium-sized machines, including toolroom grinders. The machine base and column are usually a single casting, assuring a close relationship between the table and vertically adjustable wheelheads.
3. Plain reciprocating table and traverse column base. This configuration uses a traversing column coupled with vertical wheelhead adjustment. Used for light and medium-heavy grinders, this configuration is like the preceding type except that the saddle guideways for the table are directly in the base as are the guideways for the column.
4. Plain reciprocating table and compound saddle for the wheelhead. With this configuration the column supports and provides guideways for vertical adjustment of the wheel-head saddle, which has horizontal guideways for the adjustment of the wheelhead slide. Usually used for medium and heavy-duty machines, this configuration normally employs a single casting for the base and column of the machine to assure a close relationship between the wheelhead saddle and table.
5. Rotary table. This configuration of a horizontal-spindle surface grinder may be equipped with either a reciprocating ram or reciprocating rotary table to effect traverse motion. Downfeed is accomplished with either table or wheelhead adjustment. Rotary-table, horizontal-spindle grinders are available in a wide variety of light, medium, and heavy machines.

The following sections present descriptions of the various types of horizontal-spindle surface grinders in common use today. Included are both reciprocating-table and rotary-table types.

Light-duty, horizontal-spindle surface grinders. Many light-duty horizontal-spindle surface grinders are well suited for both toolroom and production applications. Within this class of grinders, numerous accessories are available to provide increased versatility required for toolroom and production jobs.

Light-duty, horizontal-spindle surface grinders are available in a variety of configurations, including hand feed, single axis with powered longitudinal table, two axis with powered longitudinal table and crossfeed, and three axis with powered longitudinal table, crossfeed, and downfeed.

Although relatively simple in design, sometimes only with manual crossfeed, these relatively inexpensive surface grinders typically exhibit a size control of 0.0002" (0.005 mm) or less—in slot or sidewheel grinding, size control is within 0.0001" (0.003 mm). With the proper grinding wheel specification, these grinders will produce good surface finish (5 μ in., 0.1 μ m rms). Table capacities usually are on the order of 6 x 12" (150 x 305 mm) to 6 x 18" (150 x 460 mm), and maximum work height is usually about 12" (305 mm). Wheel capacities of 8" (200 mm) diam with widths up to 1 1/4" (3.2 mm) are used. Spindle horsepower of 1-2 hp (0.75-1.5 kW) is common.

The light-duty, horizontal-spindle surface grinder illustrated in Fig. 11-19 features the common solid upright column and base design. While cross and vertical movements of the saddle and column are flat and "V" ways, the table moves longi-

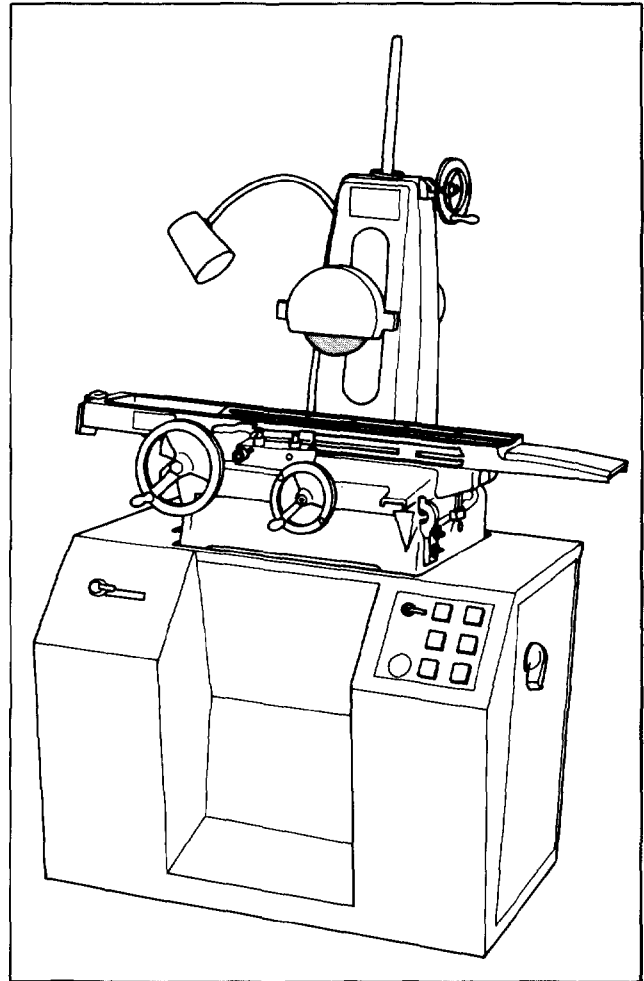


Fig. 11-19 Light-duty, horizontal-spindle surface grinder for the shop and tool room. (Bridgeport/Harig)

tudinally on precision ball bearings which contribute to more effortless hand feeding and accurate machine life.

A grinder of similar design which is particularly well-suited to toolroom work is illustrated in Fig. 11-20. Accuracy of the machine is on the order of 0.0001" (0.003 mm), with the capability of producing surface finish to 5 μ in. (0.1 μ m) rms. Table capacities for this machine range from 6 x 18" (150 x 460 mm) to 8 x 18" (200 x 460 mm), with a maximum work height of about 15" (380 mm). The machine may be equipped with manual reciprocating and crossfeed movements, hydraulic longitudinal movement coupled with manual crossfeed, or hydraulic drive of both movements.

Medium-duty, horizontal-spindle surface grinders. Production grinders of this class are used to grind a wide variety of workpiece sizes. Figure 11-21 illustrates a machine which is typical of the medium-duty, horizontal-spindle surface grinder in use today for production applications.

Within this class of grinders, worktable capacities usually range between 12-24" (300-610 mm) in width, 40-170" (1.02-4.31 m) in length, and 16-36" (400-910 mm) in table height. Grinding wheels up to about 20" (510 mm) diam, varying in widths from 3-6" (75-150 mm), are used on these machines.

SURFACE GRINDING

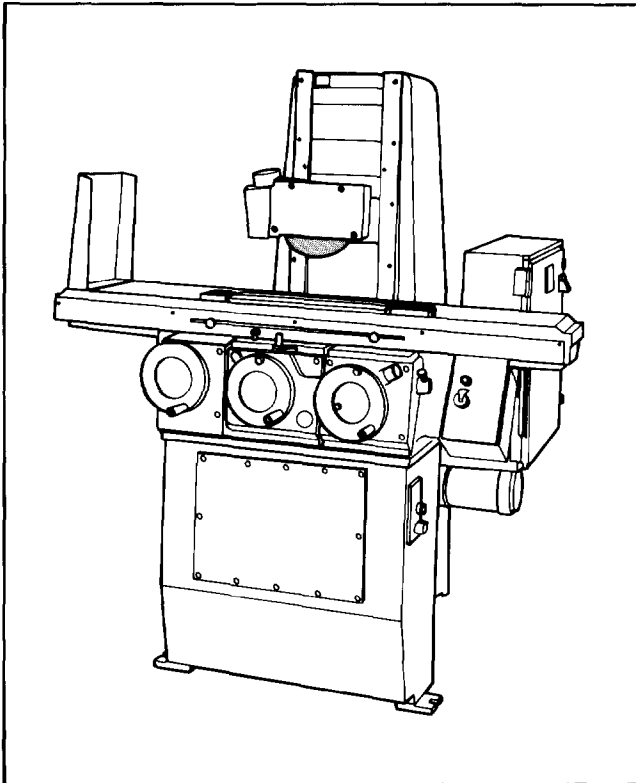


Fig. 11-20 Light-duty, horizontal-spindle surface grinder for toolroom and production is particularly well suited to toolroom applications. (*Brown & Sharpe Manufacturing Co.*)

Horsepower usually is in the 10-15 hp (7.5-11 kW) range.

Heavy-duty, horizontal-spindle surface grinders. Peripheral surface grinders within this class are used to grind large workpieces that require significant stock removal with high accuracy and good surface finish. Table capacities of these machines range from 24 x 60" (610 x 1520 mm) to 36 x 120" (910 x 3050 mm), and height capacities range between 25-36" (630-910 mm). Horsepower of these machines is usually between 30-50 hp (22-37 kW).

The largest horizontal-spindle surface grinders in common use are equipped with tables up to 42 x 240" (1 x 6 m) in capacity, and height capacities to 40" (about 1 m) or more in some cases.

Figure 11-22 illustrates a heavy-duty, horizontal-spindle, openside surface grinder for grinding ways, shear blades, die blocks, machine tool components, and other large workpieces. Table capacity on this machine is 36 x 144" (910 x 3660 mm); a 40 hp (30 kW) motor drives a 36" (910 mm) diam wheel. Nominal surface-finish capability is about 15 μ in. (0.38 μ m) rms.

Rotary-table, horizontal-spindle surface grinders. Rotary-table, horizontal-spindle surface grinders are generally used for precision grinding of small to medium-sized workpieces. The grinding wheel rotates about a horizontal axis while the workpiece(s) is revolved about a vertical axis. The grinding wheel spindle is on a wheel slide which is traversed across the work. Metal removal rate is established by the amount of downfeed of the wheel per revolution of the table. Some machines can be set up to change downfeed increments

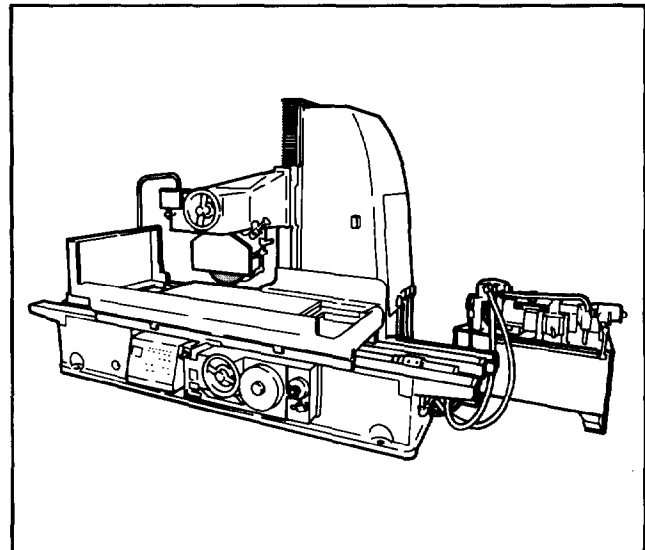


Fig. 11-21 Medium-duty, horizontal-spindle surface grinder for production. (*Hill Acme Co.*)

automatically from rough to fine feed at a point between 0.001-0.005" (0.03-0.13 mm) from finish size.

Wide-angle corner or concave-conical surfaces can be generated on rotary-table, horizontal-spindle surface grinders by swiveling the workpiece chuck about a horizontal axis which is tangent to the table. Figure 11-23 shows how these surfaces are generated.

Rotary-table surface grinding is used in a variety of applications including:

- Round thin parts with flat surfaces.
- Round thin parts, such as saw blades, that must be ground with slight concavity to relieve the center of the tool from the cutting periphery.
- Annular shoulders around an extending hub.
- Medium-sized workpieces in batched production.

Typical of rotary-table, horizontal-spindle surface grinders for precision grinding of small workpieces is the machine illustrated in Fig. 11-24. The vertical-column type of machine is available with power capabilities to 5 hp (3.7 kW) and is equipped with an 8" (200 mm) diam chuck with about a 6" (150 mm) vertical capacity when a 7" (180 mm) diam grinding wheel is used. Manual models of this machine employ a large handwheel for table reciprocation. Automatic models provide either manual or hydraulic reciprocation, with wheel feed automatically advanced a small increment at each stroke.

Other rotary-table surface grinders of this type are available in larger configurations. These larger machines (15 hp, 11 kW) typically feature chuck sizes between 16-30" (400-760 mm) diam and grinding wheels between 9-12" (230-300 mm).

Vertical-Spindle Surface Grinders (Wheel Face)

Surface grinding on a vertical-spindle machine (wheel-face grinding) is accomplished by grinding with the face of a cup, cylinder, or segmental-shaped wheel. Grinding machines of this type are available in a wide range of sizes and configurations to suit surface grinding requirements of nearly any small to

SURFACE GRINDING

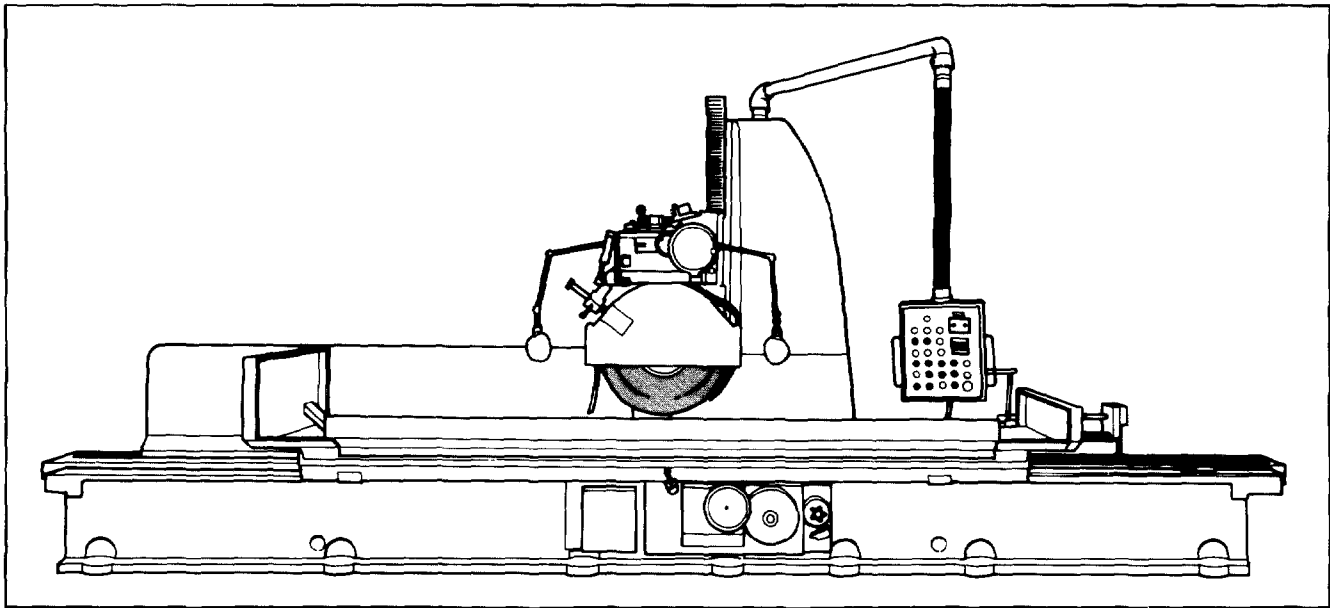


Fig. 11-22 Heavy-duty, horizontal-spindle surface grinder— openside type. (Hill Acme Co.)

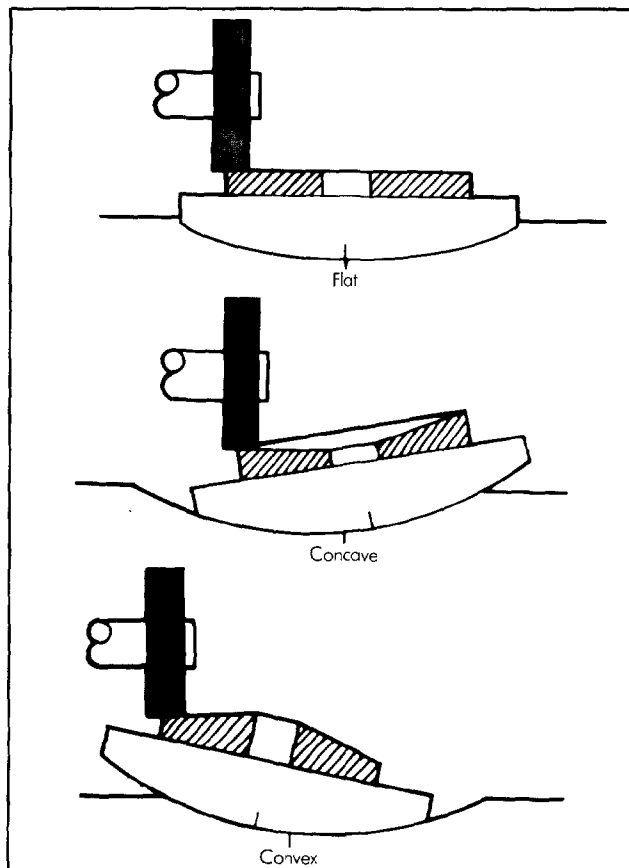


Fig. 11-23 Flat, concave, or corner surfaces generated on a rotary-table, horizontal-spindle surface grinder by tilting the workpiece fixture relative to the table. (Heald Machine Div., Cincinnati Milacron, Inc.)

moderately large workpiece. The following sections discuss some of the more common types of wheel-face surface grinders.

Vertical-spindle surface grinders with reciprocating tables. The self-dressing characteristics inherent in vertical-spindle grinding, coupled with the consistent cross-hatch pattern produced by the grinder, make this method of grinding desirable for flat grinding certain high-precision workpieces. Although highly accurate size control and high-quality surface finish are not usually the primary objective of most vertical-spindle surface grinders, some are designed for unusually close-tolerance work for which surface finish and flatness are highly critical. These high-precision surface grinders are normally employed in the processing of relatively small workpieces and may be equipped with either a rotary table or reciprocating table.

One model of precision vertical-spindle surface grinders uses cup wheels from 2-10" (50-250 mm) diam and features a reciprocating table with a magnetic chuck capacity of about 7 x 18" (180-460 mm). The speed of the table is infinitely variable to 400 ipm (10 m/min), and fine table speeds are featured for "creepfeed" grinding (see "Special Grinding Machines and Processes" in this chapter).

These types of precision surface grinders can often be programmed for a completely automatic cycle, including roughing, finishing, and sparkout using an electronic contact gage.

Other reciprocating-table, vertical-spindle surface grinders are used to grind larger workpieces. Figure 11-25 illustrates a vertical-spindle, openside grinder with a 24 x 72" (610 x 1830 mm) table capacity for grinding flat surfaces for which high stock removal is required. Nominal surface finish on machines of this type is usually about 32 μ in. (0.81 μ m) rms. Other machines are available with table capacities ranging from 18 x 36" (460 x 910 mm) to 60 x 240" (1.5-6.1 m), with wheel clearances of 18-36" (460-910 mm) and horsepower ratings of 40-250 hp (30-186 kW).

Rotary-table, vertical-spindle surface grinders. Normally, grinding machines of this class are used in production appli-

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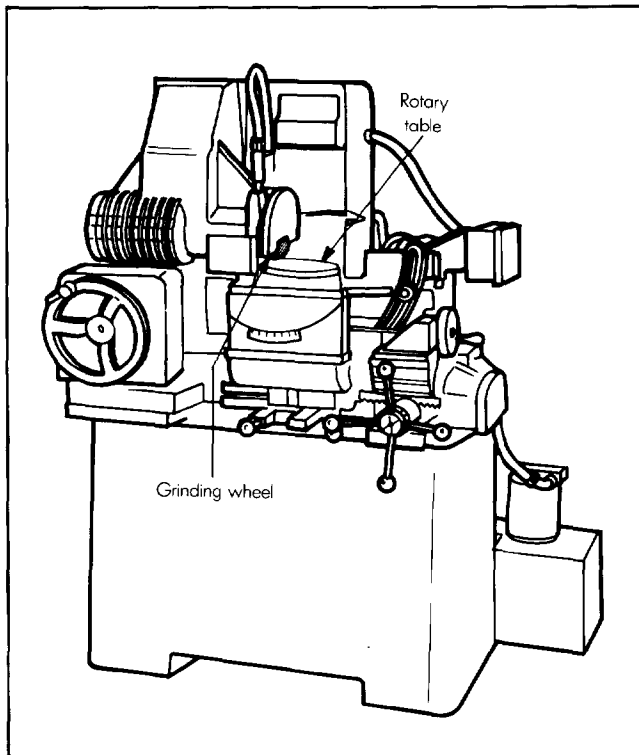


Fig. 11-24 Rotary-table, horizontal-spindle surface grinding machine. (Heald Div., Cincinnati Milacron, Inc.)

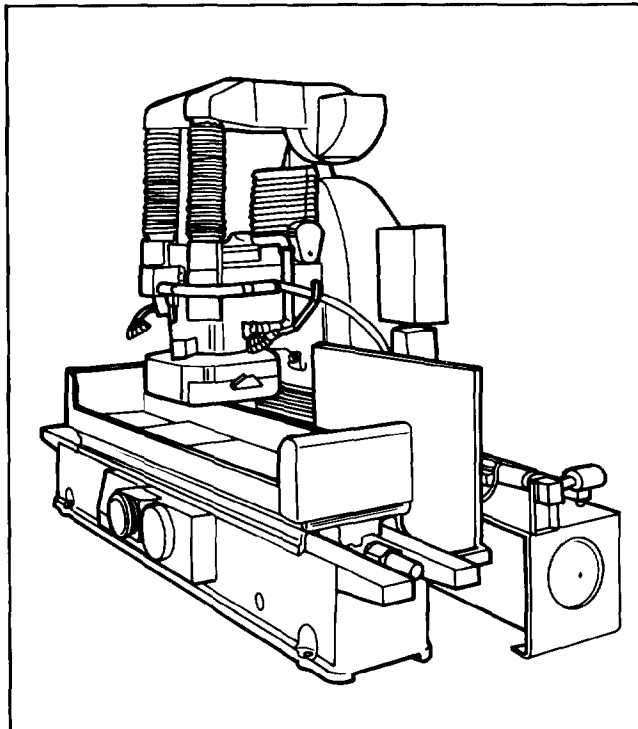


Fig. 11-25 Vertical-spindle, openside grinder for grinding flat surfaces when high stock removal is required. (Hill Acme Co.)

cations involving significant stock removal. Some large machines can remove 0.25-0.5" (6.3-12.7 mm) of metal from castings in a single pass. The machines are available in a wide range of sizes and are equipped with cylinder or segmental wheels. Flatness and parallelism is obtainable to 0.0002" (0.005 mm) depending upon the size and rigidity of the machine. Size-holding capability is usually on the order of 0.0005-0.001" (0.013-0.03 mm).

Small to medium-sized machines in this class usually feature table sizes of about 16-60" (410-1520 mm) and use wheels from 11-32" (280-810 mm) diam. Figure 11-26 illustrates this class of grinder.

Heavy-duty, rotary-table, vertical-spindle surface grinders feature table sizes of 72-120" (1.8-3.0 m) diam and use segmental wheels of 36-60" (910-1514 mm) diam. These machines are typically powered by 150-300 hp (112-225 kW) motors. Some large machines feature table sizes up to 160" (4.1 m) diam, are equipped with 80" (2.03 m) diam wheels, and are powered by 300 hp (225 kW) motors. These extraordinarily large machines are used in special applications such as grinding large steam-turbine components.

A variation of the basic rotary-table, vertical-spindle surface grinder is the rotary-duplex machine, which uses a single wheel spindle but features two rotary tables mounted on a traversing bed to facilitate loading and unloading. With this configuration, one workpiece can be ground while another is being set up.

Multiple-head, rotary-table, vertical-spindle surface grinders. Machines of this class are similar to machines discussed in the previous section except that they are equipped with two, three, four, or five vertical spindles. On most two-spindle models, the spindles are mounted on peripheral columns; three, four, and five-spindle models usually are equipped with the spindle mounted on a center column. Sequential rough grinding, intermediate grinding, and finish grinding operations can be performed on a single machine equipped with wheels of various

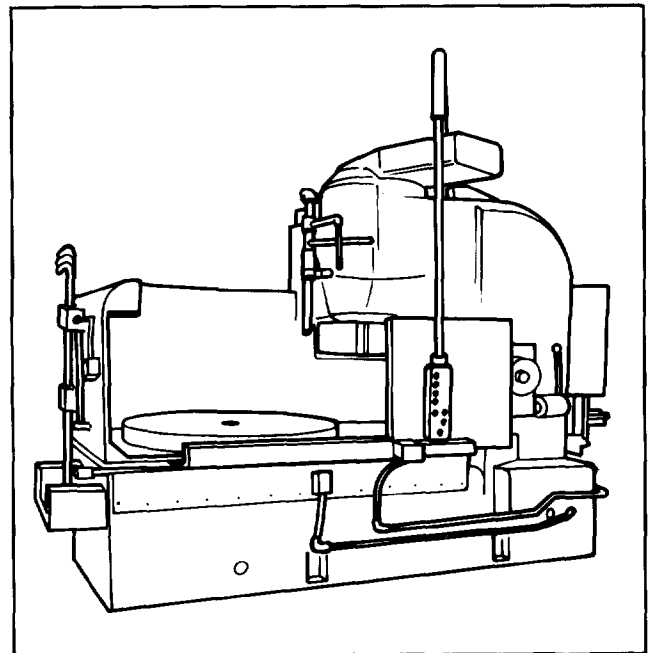


Fig. 11-26 Rotary-table, vertical-spindle, wheel-face grinder. (Cone-Blanchard)

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sizes and grades operating at various speeds. Figure 11-27 illustrates an example of this class of grinder—a five-spindle, rotary-table surface grinder for the processing of small to moderate-sized workpieces.

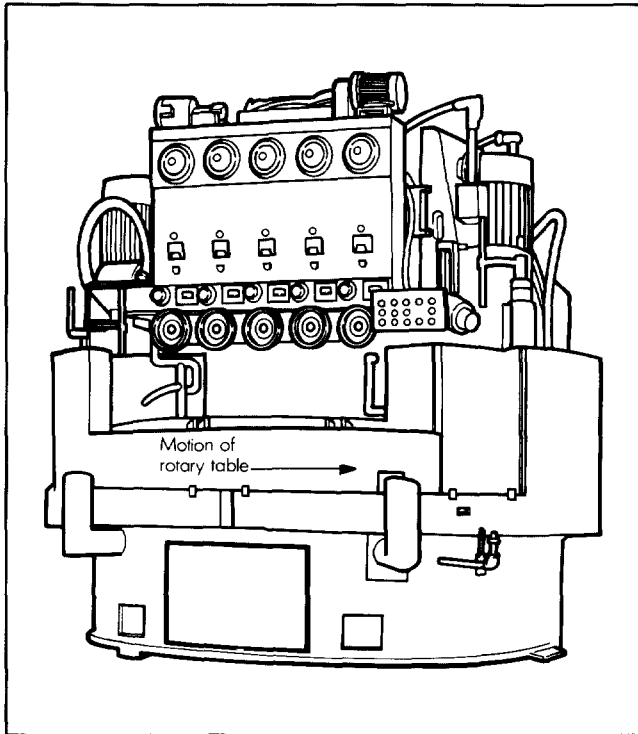


Fig. 11-27 Five-spindle, rotary-table surface grinder.

Multiple-head, index-table surface grinders. In contrast to rotary-table grinders which operate with continuous rotating table motion, index-table grinders feature multiple indexing positions, usually four positions 90° apart, that allow one station to be loaded and unloaded while the remaining stations are used to perform various sequential grinding operations. This machine design is particularly effective for production grinding of parts which require more unloading and loading time than available with continuous rotary-table machines.

The machine illustrated in Fig. 11-28 is typical of the indexing-type, rotary-table, vertical-spindle surface grinder in use today. The index table is available with either four or eight workholding spindles that can handle small or medium-sized workpieces. Spindles are mounted on either two or three columns, usually with one or two spindles per column. Turning, boring, or honing can be performed by substituting special tool heads for grinding heads at one or more stations. Unless the work configuration restricts the size of the wheel, a 6" (150 mm) diam, type 6, straight cup wheel is used on the 3600 rpm motorized spindles. If smaller diameter wheels must be used to grind recessed faces, belt-driven spindles or high-frequency spindles are used to obtain appropriate grinding speeds.

Oscillating-wheel surface grinders. A variation of the vertical-spindle surface grinder, somewhat like a reciprocating-table grinder in function, is the oscillating-wheel surface grinder. Machines of this class differ from reciprocating-table, vertical-spindle grinders in that relative motion between the grinding wheel and workpiece is along a circular arc instead of a straight

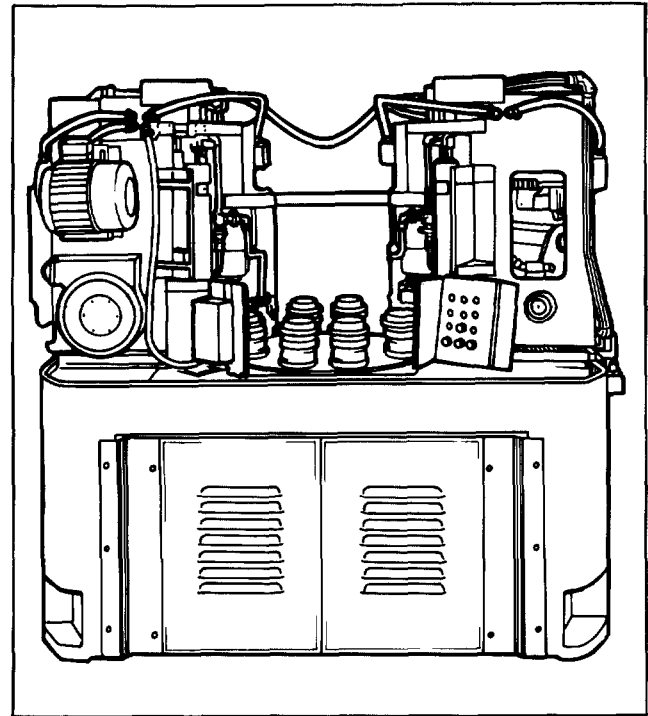


Fig. 11-28 Multiple-head, index-table surface grinder. (New Britain Machine Div., Litton Industries)

line and relative motion between the grinding wheel and workpiece is brought about by the oscillation of the wheelhead column about a fixed vertical axis. In this way, the work remains stationary while the grinding wheel is traversed across the workpiece along a circular path. These machines are usually less costly than reciprocating-table, vertical-spindle surface grinders of comparable capacity. The machines are normally used to grind small to moderate batch sizes of relatively small workpieces.

Horizontal-spindle, wheel-face surface grinders. Machines of this type are similar to horizontal-spindle milling machines in the way in which the wheel is traversed across the workpiece. These machines use either a reciprocating table or a traveling wheelhead configuration to effect relative motion between the wheel and workpiece. Horizontal-spindle machines are used to grind workpieces that are more easily handled and are less prone to deflection when fixtured on a vertical table. Often very large, difficult-to-handle workpieces are ground in this way.

Reciprocating-table machines with horizontal spindles are available in a wide range of table capacities up to about 240" (6096 mm) in length. Larger machines are typically of the traveling wheelhead configuration to conserve space.

Throughfeed wheel-face grinders. A relatively new variation of wheel-face grinders, throughfeed grinders use continuous conveyor feed in the surface grinding of relatively small workpieces. As shown in Fig. 11-29, the typical throughfeed grinding system consists of a vertical-spindle grinding wheel mounted over a continuous-feeding conveyor belt. A variable-power, electromagnetic table serves as the machine table, magnetic chuck, and locating surface. A conveyor belt supported by the electromagnetic table is used to transport workpieces under the grinding wheel. Adjustable guide rails

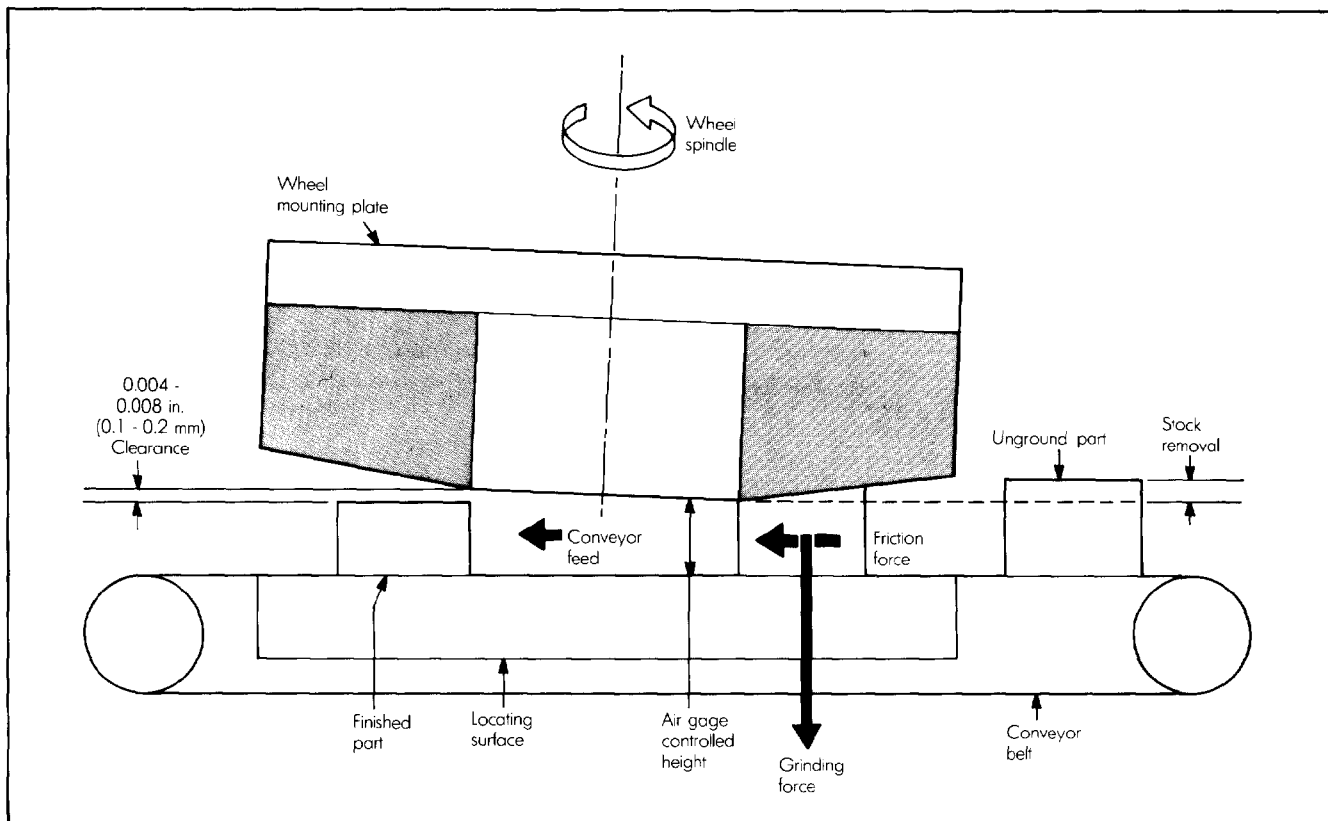


Fig. 11-29 The concept of throughfeed grinding. (Speedfam)

position parts on the conveyor and absorb the horizontal force, or side thrust, created by the grinding action. Air gages compensate for wheel wear.

Stock removal capacity is on the order of 0.100" (2.54 mm) or more per pass on some materials. Tolerance-holding capability is about ± 0.001 " (0.03 mm) with relatively low horsepower drives, 15-25 hp (12-19 kW).

One machine of this class handles parts up to 6" (150 mm) wide and 6" in height.

Nonmagnetic workpieces can sometimes be processed without special fixtures with the use of pad rollers to hold the workpiece down as it passes under the grinding wheel.

Disc Grinders

A simple description of disc surface grinding is grinding with the face of an abrasive disc. Single-spindle disc grinders and double-spindle disc grinders (see Fig. 11-18) are manufactured in vertical and horizontal types. Special machines have been built with three or four spindles. Some machines are manufactured with the head and related disc mounted on an adjustment device, enabling the head attitude to be varied to meet special requirements.

Modern disc grinders are among the most efficient machines available for generating flat surfaces to close tolerances and fine finishes at high production rates. Thousands of abrasive grains contact the work simultaneously, thus rapidly developing the entire surface to the size and finish required. Flat surfaces generated by disc grinding are generally flatter than those produced by the periphery of a wheel and often eliminate or

minimize the need for subsequent lapping. Many surfaces ground in this way do not require gaskets or sealants between mating surfaces to prevent leaks.

For parts with opposed flat surfaces, double-disc grinders provide the best and most economical method of grinding flat, smooth surfaces to precise tolerances with respect to parallelism and overall size (thickness or length). Grinding two sides of a part simultaneously also results in profitable production because of the low cost per part. This method eliminates the need for inverting a part several times to obtain the required flatness, as is often required on vertical-spindle, single-disc machines equipped with magnetic chucks, which can cause warpage or distortion. Heat buildup and stress relieving during double-disc grinding are generally equally divided on opposite sides of the workpiece, thus contributing to the ability to produce flat and parallel surfaces.

Recent advances in double-spindle disc grinding machines and their controls make it possible to hold flatness and parallelism on some parts to as close as 0.00005" (0.0013 mm). Overall size (thickness) can be maintained to 0.0001" (0.003 mm), and surface finishes of 6 μ in. (0.15 μ m) or less can sometimes be produced.

Powerful machines, available with up to 150 hp (112 kW) drive motors on each spindle, permit a total stock removal of 1/4" (6.4 mm)—1/8" (3.2 mm) per side—or more in a single operation.

While many disc grinders utilize abrasives having a relatively wide face width, a substantial number of machines are produced that use abrasives having very narrow faces. The face width of

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the disc is determined by subtracting the center hole diameter from the diameter of the disc and dividing by two. For example, a 30" (760 mm) disc with an 8" (200 mm) center hole would have an 11" (280 mm) face width. By the same token, a 30" (760 mm) diam disc having a 28" (710 mm) center hole, would have a 1" (25.4 mm) face width. In those cases in which a narrow face width is involved, the name "disc" becomes somewhat misleading and the abrasives are probably better described as ring-wheel types.

Feeding principles. Different methods of grinding with double-disc machines are shear, progressive, and face or plunge grinding, and combinations of these methods.

Shear grinding is the removal of all or most of the stock as the workpiece makes initial contact with the abrasive discs, with the discs set parallel to each other. Full shear grinding is generally restricted to applications in which the workpieces are rigidly clamped.

Progressive grinding, as the name implies, involves progressively removing stock as the workpieces pass between the abrasive discs, with the discs set at an angle to each other. This method can be used for grinding parts that are either clamped or floating in the openings of the work carrier.

Face cutting or plunge grinding involves placing the part or parts to be ground between the discs, with little or no contact with the abrasive; subsequently feeding the discs together until the parts are to finished size; and then retracting the discs and withdrawing the parts. This method is frequently used for heavy stock removal from fragile parts and for grinding parts with light stock removal to very close tolerance. Systems are available to rapidly feed the discs together a predetermined

amount, then advance them with a preset, slower infeed, and finally allow them to dwell for sparkout before rapidly retracting them.

There are many applications in which some shear grinding is combined with either progressive grinding or face cut or plunge grinding with good results. In some cases, about half of the stock removal is done by shear grinding, and the remainder by progressive grinding. This avoids having to set the discs at too great an angle with respect to each other, which makes it difficult to obtain close tolerances on flatness.

Major factors influencing the selection of the type of work carrier or tooling to be used with double-disc grinders include production requirements; the size, shape, and material of the parts to be ground; stock removal; and tolerances required.

In the past it has generally been accepted that three basic feeding principles are used in either single-disc or double-disc grinding. One principle is applied with the oscillating or reciprocating type of fixture; another with the rotary type of fixture, and still another with the throughfeed type of fixture. Figure 11-30 illustrates the application of these principles. Indexing, rotating fixtures are now used on some machines.

Vertical-spindle, single-disc grinders. Currently the indexing, rotating fixture is used exclusively on vertical-spindle, single-disc machines. This tooling concept has proved extremely successful on applications in which relatively high production is involved and optimum flatness on the surface being ground is an important criteria.

A number of variations on the basic principle have been used. One system involves a basic indexing table that is equipped with 2-4 rotating stations. The indexing table places one rotating

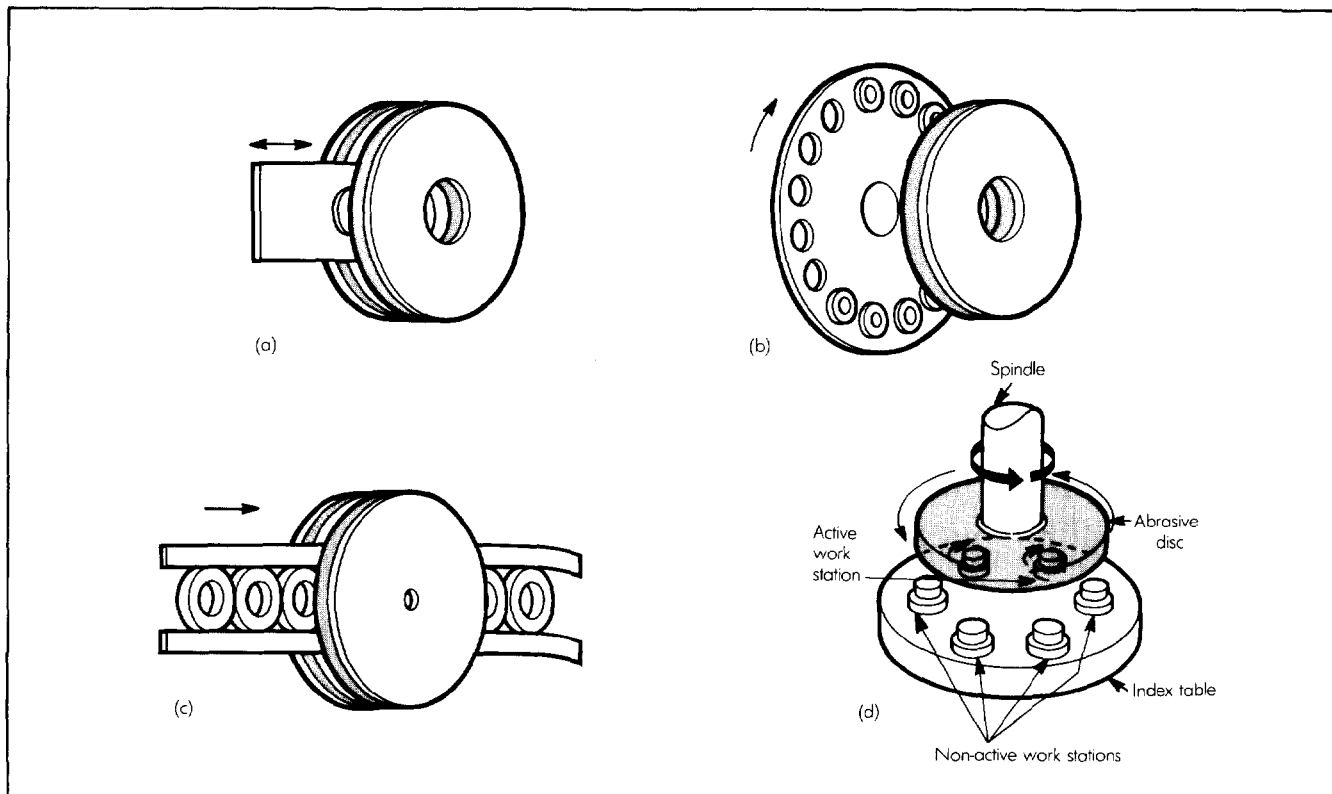


Fig. 11-30 Feeding principles used in disc grinding as applied by (a) reciprocating fixture, (b) rotary fixture, (c) throughfeed fixture, (d) indexing, rotating fixture. (Gardner Machine Co.)

station directly under the ring-type abrasive being used. The rotating station, appropriately tooled to accept the part being ground, commences rotation after being indexed in place as the abrasive progressively downfeeds on the part being ground. The workpiece is generally rotated on its own axis. A variation of this same principle involves fixturing multiple parts on a common rotating station. In another variation, the same technique is used with the exception that two stations are indexed under the abrasive at approximately 11 o'clock and 1 o'clock (see Fig. 11-30, *d*). Here again the stations may accommodate one workpiece that is rotated on its own axis or may involve multiple workpieces mounted on the common rotating station. The size of the workpieces being ground determines to a large extent the type of tooling that will be used.

The fixtures used on these machines have generally involved strategic rest points, drive members, and part retainers. In some cases magnetic tables and chucks are used.

Double-disc grinders. A simple description of double-disc grinding is the grinding of two surfaces at the same time in one machine. On double-spindle machines, the two abrasive discs are opposed and the workpieces are fed between the discs to grind parallel surfaces simultaneously. Double-disc grinders are manufactured in both vertical and horizontal types. As in the case of single-disc machines, double-disc machines are also manufactured with the heads either set at a prescribed angle or mounted on adjustable devices allowing them to be inclined as required (see Fig. 11-31). Double-disc grinders are also provided with the heads offset. The degree of offset involved varies according to the type of work being delivered to the machine. In general, the majority of double-disc grinders are involved with workpieces for which equal or semiequal metal removal is required on two parallel, external surfaces. Figure 11-32 illustrates a typical horizontal-spindle, double-disc grinder.

The three basic feed principles referred to earlier are generally used in double-disc grinding. These are used in the oscillating or reciprocating type of fixture, the rotary type of fixture, and the throughfeed type of fixture. An alternate principle used is to mechanically rotate the workpiece,

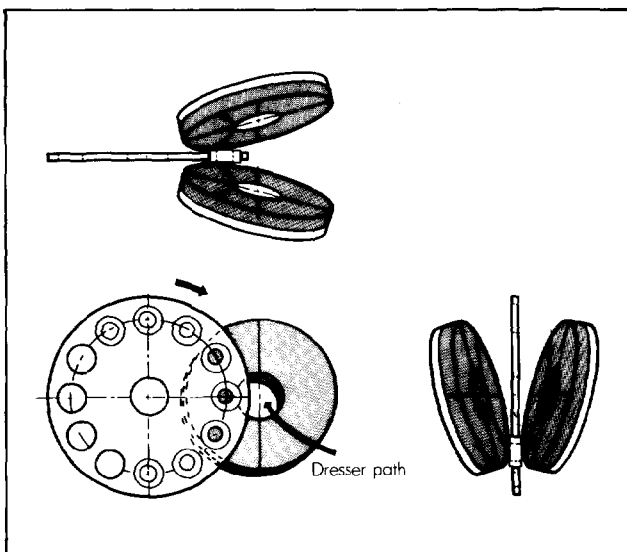


Fig. 11-31 Compound head setting for progressive grinding with a rotary carrier consisting of tilting discs together at their front and bottom edges. (Gardner Machine Co.)

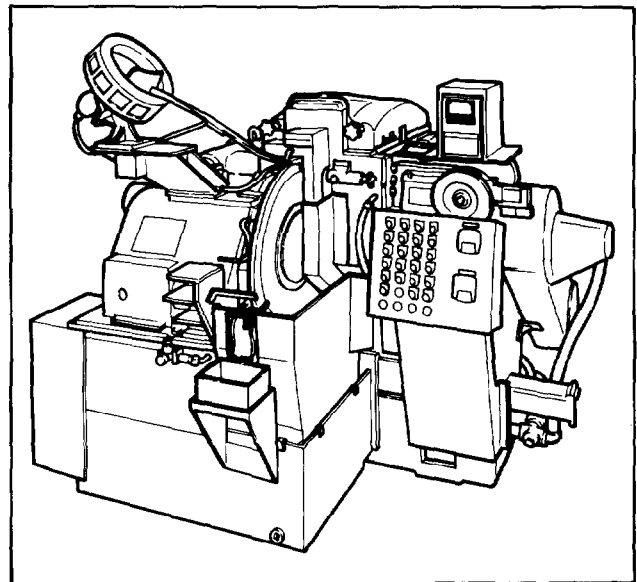


Fig. 11-32 Horizontal-spindle, double-disc grinder equipped with powered rotary-type fixture for grinding the parallel ends, edges, and faces of workpieces. (Bendix)

after it has been inserted in the grinding zone, while both abrasive discs progressively close on the part piece and grind it to the desired size.

Components such as disc brake rotors, clutch discs, and large rings are frequently ground using this alternate principle. Viewed strictly from a workpiece-per-hour standpoint, production on a fixture using this feeding principle or on the oscillating or reciprocating type of fixture is generally substantially lower than that obtained on either the rotary or throughfeed types of machines. The type of work being delivered to these machines frequently cannot be done any other way. An exception to this statement would involve the oscillating or reciprocating type of fixture which, in many cases, is considered desirable by users because of its versatility and its capability of tooling inexpensively.

Additionally, these machines are capable of very close tolerance work. On the oscillating or reciprocating type of machines, a blade or workholding fixture either oscillates in an arc or reciprocates in a straight line, carrying the work between the abrasive discs. Oscillation or reciprocation can be either manually operated or power operated.

On those machines equipped with fixtures rotating the workpiece while the abrasives close on it, a sliding-table, swinging-arm type of fixture with appropriate tooling is used. The sliding-table or swinging-arm fixture, in operation, retracts to a load/unload position. The workpiece is manually loaded into the workholding fixture. The workholding fixture may incorporate a rotating arbor or retractable power-driven clamping rolls. When the cycle start button is pressed by the operator, it causes the fixture to move forward, inserting approximately 50% of the area of the part being ground between the abrasives (generally ring-wheel type). If power-driven clamping rolls have been provided, these rolls clamp the part and start the part rotating. In those cases in which a mandrel is used, the mandrel would of course begin rotating the part.

Once the part has commenced rotation, the abrasives then

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close on the work as previously described, grinding the work to size. When finish size has been obtained, the abrasive rapidly retracts, the rotation of the part ceases, and the sliding table or swinging arm retracts the part to the unload/load position.

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Magnetic chucks, vacuum chucks, and vises are commonly used workholding devices for surface grinding operations. In addition, special surface grinding fixtures which may or may not include a magnetic chuck or vacuum chuck as a major component are sometimes used to hold nonmagnetic workpieces or irregularly shaped parts. Many high-speed, high-production operations require specially designed surface grinding fixtures such as these.

Magnetic Chucks

The most commonly used workholding device for general purpose surface grinding is the magnetic chuck. In practice, the workpiece simply is positioned on the chuck face; the magnet is energized holding the part flat against the chuck surface throughout the grinding operation.

For horizontal-spindle surface grinders and some vertical-spindle surface grinders, magnetic chucks are usually rectangular in configuration and are available in a wide variety of standard and special sizes up to about 3.5 x 8 ft (1 x 2.5 m). Circular magnetic chucks are used on many rotary-table, vertical and horizontal surface grinders. V-block chucks and other magnetic chucks with special shapes are used in some applications.

Types of magnetic chucks. There are three basic types of magnetic chucks: electromagnetic, permanent magnet, and electrically energized permanent magnet chucks.

Electromagnetic chucks. Most magnetic chucks are electromagnetic. Electric power, usually d-c, is supplied to the chuck during the grinding operation, then switched off to release the workpiece for unloading.

Permanent magnet chucks. Magnetic chucks of permanent magnet design are heavily used and are available in small and medium sizes. Available as a solid base or swivel design, these chucks operate without electric supply and are turned "off" and "on" through use of a manually operated mechanical switching device.

Electrically energized permanent magnet chucks. A variation of magnetic chucks combines the electromagnet and permanent magnet. This hybrid design requires an initial pulse of current to activate the permanent magnet and a current impulse of opposite polarity to deactivate the chuck. The advantage of this type of chuck is that a loss of electrical power to the chuck during grinding will not cause loss of holding power.

Maintenance of magnetic chucks. To ensure proper performance and long life, magnetic chucks should be kept clean and should be well oiled when not in use. Cleanliness in operation is particularly important because grinding swarf tends to form ridges that can harden on the face of the chuck. Periodic cleaning will help avoid this problem.

If the chuck surface develops flaws, hand stoning with a medium India oilstone will clean off light burrs. More serious flaws may be removed by grinding with a soft-grade, free-cutting wheel. The removal of 0.001-0.002" (0.03-0.05 mm) from the face of the chuck should clean it and restore its accuracy. This operation should involve light cuts with plenty of grinding fluid.

Demagnetizers. Generally, workpieces held by magnetic chucks during grinding are demagnetized after grinding is complete. Portable demagnetizers are used for heavy, large workpieces that are difficult to move. Plate demagnetizers are used for small and medium-sized workpieces. To demagnetize the part, the operator manually passes the workpiece along the surface of the demagnetizing plate. Aperture-type demagnetizers are employed to remove magnetic fields of small workpieces, usually in automatic grinding operations. Workpieces pass through the frame-like demagnetizer unit as they are ejected from the grinding operation. Usually, in an automatic setup such as this, the aperture-type demagnetizer is positioned in line with the unload chute of the grinding operation.

Vacuum Chucks

A vacuum chuck is similar in configuration to a magnetic chuck except that the holding force is developed by a vacuum instead of magnetic attraction. Vacuum chucks are used to hold magnetic or nonmagnetic, small to medium-sized workpieces.

The principle operation of a vacuum chuck is simple. The face of the chuck is constructed with multiple air-entry ports (holes or porous material), and a vacuum pump is used to suck air through these ports. When a workpiece is placed on the face of the chuck, atmospheric pressure on the workpiece holds the part firmly against the chuck face. Usually, a vacuum chuck develops about 12 psi (83 kPa) of effective holding pressure. Portions of the chuck face not covered by the workpiece are masked with rubber, plastic sheet, or sheet metal to eliminate leakage. The masking material also serves to hold the workpiece against lateral movement during the grinding operation. On some vacuum chucks, masking is not needed because the port holes are tapped for set screws that can be inserted in areas of the chuck face not covered by the workpiece.

Vacuum chucks are available in standard rectangular sizes up to about 1 x 4 ft (0.3 x 1.2 m). Round chucks and rotary vacuum chucks are also available.

Pin-hole chucks. These vacuum chucks are the simplest in design—a metal box with a pattern of small drilled holes in the top plate.

Grooved-plate chucks. Usually used for round vacuum chucks, this design employs a series of concentric grooves on the face of the chuck. Each groove features at least one porthole to the vacuum chamber.

Porous-plate chucks. Some very thin or extremely fragile workpieces tend to deform when held on a conventional pin-hole vacuum chuck; the workpiece material is pulled into the portholes. Also, some very small workpieces may cock or be otherwise dislocated by grooves or portholes in the face of a conventional vacuum chuck. In these cases, a vacuum chuck equipped with a porous ceramic chuck face can be used. However, experience has shown that some special masking problems can develop when using porous-plate chucks.

Rotary chucks. Rotary vacuum chucks are used for workholding in both rotary-table surface grinding and cylindrical grinding applications. These chucks may be designed with pin-hole plates, porous plates, grooved plates, or other configurations. (In cylindrical grinding, these chucks are used as faceplate holding fixtures.) In horizontal surface grinding, rotary chucks are used on Blanchard-type machines for multiple part grinding.

Special vacuum chucks. When extremely thin workpieces are to be ground, vacuum chucks with specially designed faceplates are used. The faceplate of the chuck usually features recessed

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areas that fit exactly the contour of the workpieces. Often, these special vacuum chucks use porous ceramic inserts in the counterbores to provide the vacuum surface for holding. Parts as thin as 0.007" (0.18 mm) have been ground in this way. These special vacuum chucks are mounted on reciprocating-table and rotary-table, horizontal and vertical surface grinders.

Precision Grinding Vises

Special vises used for workholding of relatively small workpieces feature accuracy to about 0.0002" (0.005 mm) in parallelism and squareness of the holding surfaces. These special vises, called grinding vises, may feature a swivel base or tilt adjustment. Some special fixtures used for surface grinding employ modified standard vises as components. These are discussed later in this chapter.

Special Fixtures for Surface Grinding

Fixtures used for surface grinding are generally classified and identified by the type of operation they perform. For the purpose of this discussion the examples cited are classified in the same manner.

A few important points to be kept in mind when any fixture for surface grinding is designed are (1) the type of machine to be used and (2) the method to be used to mount and hold the fixture. The most common types of surface grinders found in many shops are the reciprocating-table, horizontal-spindle type and the rotary-table, vertical-spindle type. Fixtures designed on the appropriate type of machine can save countless hours of wasted machine time. For example, if several small pieces require grinding, the fastest method is generally to fixture the rotary-table machine; however, if the parts are long, the reciprocating-table model may work better.

The method used to mount and secure the fixture can also have a direct bearing on how the fixture is designed and built. Whenever possible, a magnetic table should be used as part of the fixture. If, however, the part to be ground is made of a nonferrous or nonmetallic material, a vacuum chuck can be used.

In either case, the magnetic or vacuum chuck saves elaborate fixturing by simply incorporating its holding power into the function of the fixture. In those cases in which the design of the part does not permit the use of the chuck, a special mechanical holding device must be used. The fixture itself, however, must be held by the chuck. Therefore, to ensure proper mounting, it is imperative that the fixture and chuck have the proper orientation device.

Simple retaining fixtures. Retaining fixtures are those that are intended to confine rather than clamp workpieces during a surface grinding operation. The principle advantages of using these fixtures are their low cost and ease of fabrication. Illustrated in Fig. 11-33 is a fixture used to confine parts. As illustrated, the fixture acts as packing to prevent the lateral movement of the parts during grinding. Both the fixture and workpieces are held by the chuck during the grinding cycle. Another simple variation of the principle is shown in Fig. 11-34. Though these two fixtures are intended for use on a rotary-table grinder, similar fixturing can be used with a reciprocating-table grinder as shown in Fig. 11-35.

Simple clamping fixtures. Simple clamping fixtures are the most common form of workholders used for surface grinding. These fixtures are used to position and hold an almost infinite variety of parts. A few examples of simple clamping fixtures include vise-jaw, right-angle, and indexing fixtures.

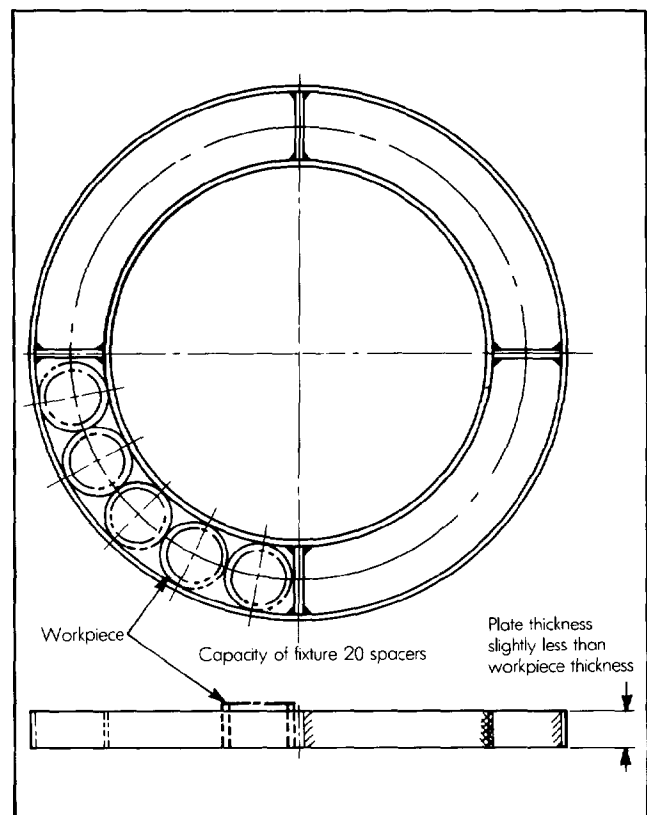


Fig. 11-33 Simple retaining fixture for a rotary-table surface grinder.

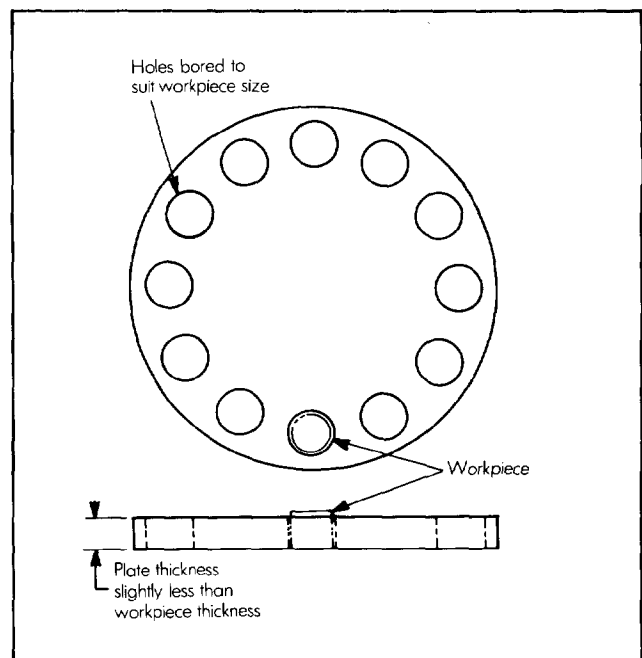


Fig. 11-34 Retaining fixture for rotary-table surface grinder designed to prevent lateral movement of parts during grinding.

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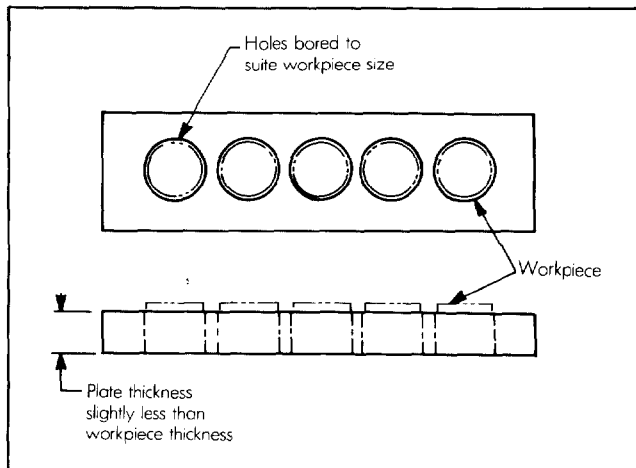


Fig. 11-35 Retaining fixture for reciprocating-table surface grinder.

The fixture illustrated in Fig. 11-36 is a simple device used to hold the parts shown. Here, the main requirement is that the edges of raw stock be ground perpendicular to the sides. This fixture is capable of holding 25 parts; in practice, four fixtures are mounted on a rotary-table grinder to grind 100 parts per setup.

Another variation of this principle is shown in Fig. 11-37. In this case, the die inserts shown must be ground on two surfaces. In operation, the smaller surface is ground first and the larger surface second. As the second surface is ground, the shoulder is also ground. The main clamp in the fixture applies pressure from the side forcing the inserts together. The other clamp is used to hold the inserts against the fixture to ensure squareness. This clamp uses a nylon (or similar material) pad to compensate for any minor surface irregularities in the parts.

Vise-jaw fixtures. Another common method of fixturing parts for surface grinding is the vise-jaw fixture. Vise-jaw fixtures are extremely versatile and can be adapted to suit a wide variety of parts.

The fixture shown in Fig. 11-38 illustrates a typical example of an instance when a vise-jaw fixture is well suited. Here, the part, a piercing punch, must be end ground square to the sides. The ground mounting notches on each side of the part provide an excellent locating surface. As shown, the fixture has a hardened shelf that fits the notch in the punch. The movable jaw element has a nylon pad that is used to equalize the pressure and to compensate for slight differences in part sizes. The part is held square by the solid jaw element and the dowel pins, as shown. Additional clamping is provided by a small thumbscrew placed at the end of the solid jaw element. The thumbscrew is used to hold the punches against the dowel pins; the main clamping is performed by the vise.

Another form of vise-jaw fixture is shown in Fig. 11-39. Here, the fixture is required to hold four cylindrical bushings. As shown, another form of equalizer device is used to compensate for differences in part sizes. In this case, the parts are mounted in the slot with their flat side against the solid jaw element. The movable jaw has four plungers that contact the parts forcing them against the locator. The upper locator plate is cut to the shape of the bushings and serves to nest the parts. The plungers are backed by urethane pads inserted in the cavity below the plungers.

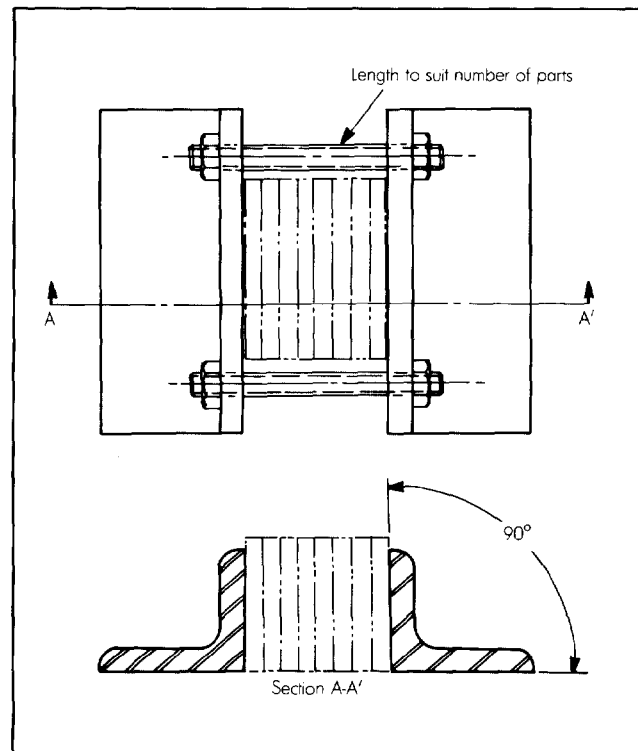


Fig. 11-36 Clamping fixture that holds 25 parts. Four fixtures are used per setup.

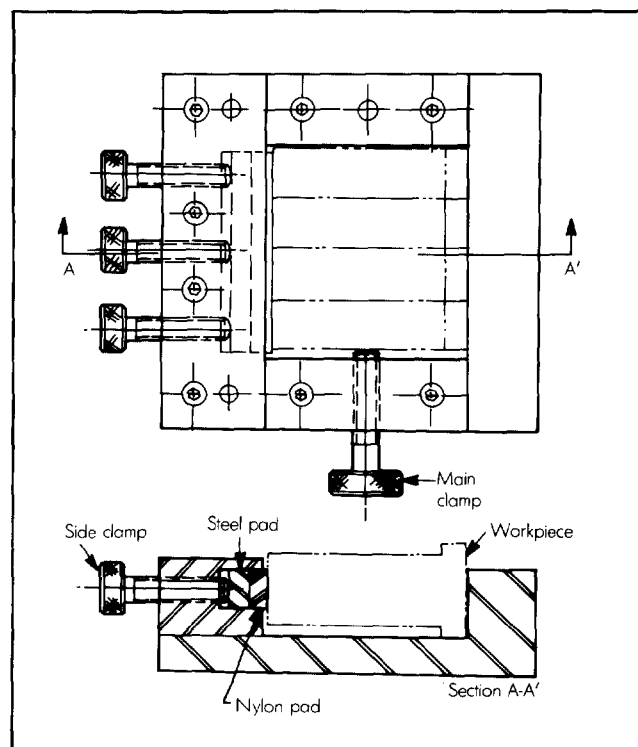


Fig. 11-37 Clamping fixture ensures squareness between locating and work surfaces.

WORKHOLDING METHODS IN SURFACE GRINDING

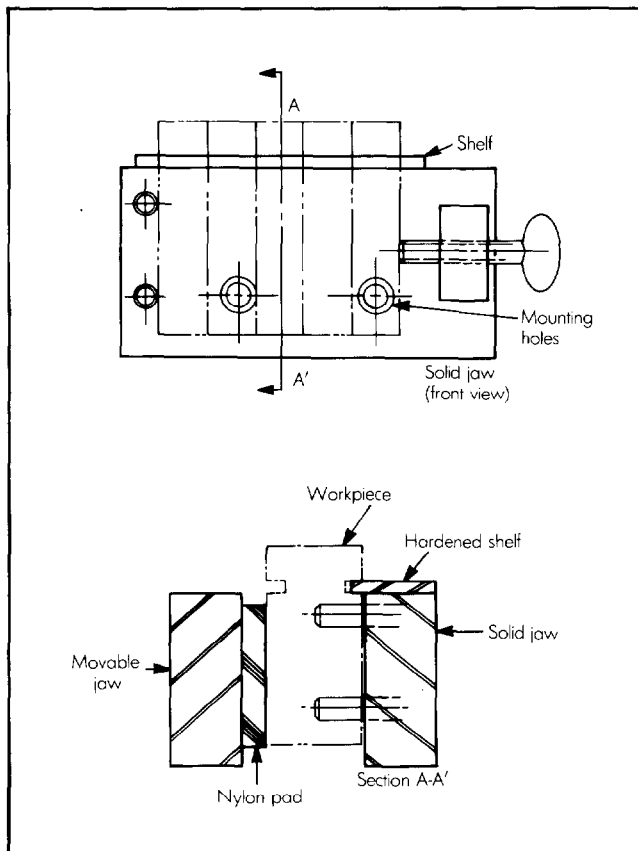


Fig. 11-38 Vise-jaw fixture modified from a standard grinding vise.

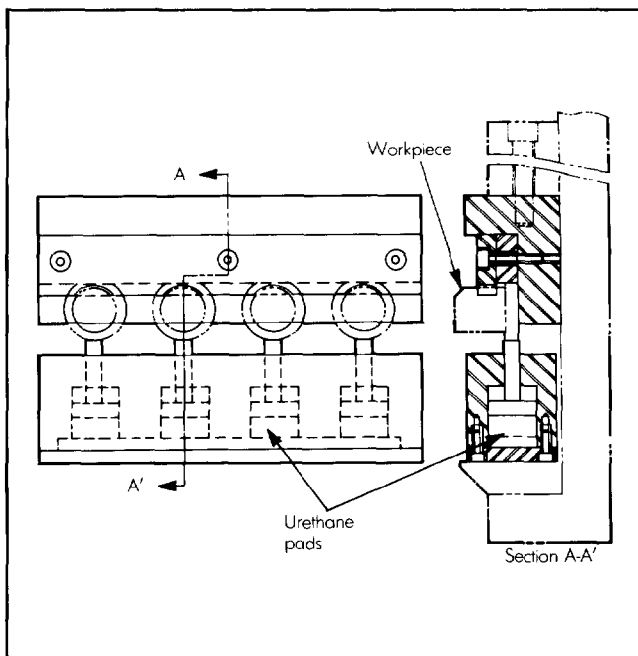


Fig. 11-39 Vise-jaw fixture for cylindrical workpieces.

Right-angle fixtures. Right-angle fixtures are very useful for grinding surfaces that must be perpendicular to the sides of the part. A typical right-angle fixture is shown in Fig. 11-40. Here, the part to be ground is a tri-square. In practice, a pin mounted in a spring-loaded plunger holds the edge of the square against the locating block until the hook clamps are tightened with wing nuts. An additional feature of this fixture is that it is adjustable. When the fixture is set up, a master square is positioned in the fixture and checked with an indicator. Adjustments, if required, are made by tightening or loosening the adjusting screw on the locator block.

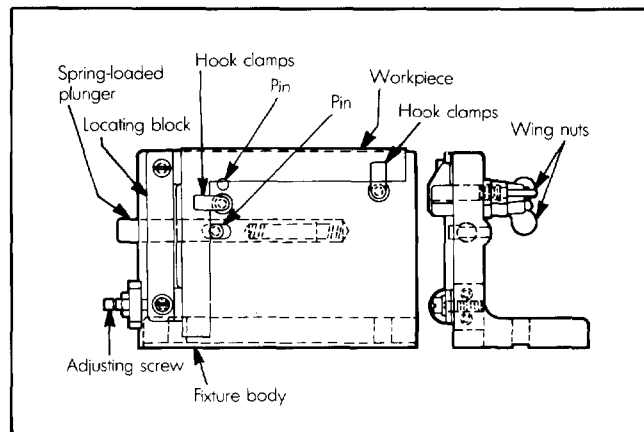


Fig. 11-40 Right-angle fixture for grinding a T-square. (L.S. Starret Co.)

Another type of angle plate fixture is shown in Fig. 11-41. This type of fixture is very useful for a wide range of special grinding operations. As shown, the T-shaped base contains 15 evenly spaced holes that are used to mount eccentric studs. A toggle clamp or similar device is used to hold the part to the fixture. In use, the eccentric studs are positioned to locate the workpiece in the desired position. The part is then mounted and clamped. The number of possible positions this fixture is capable of locating is almost limitless.

Indexing fixtures. Frequently, parts mounted in a surface grinder must be ground on several surfaces around the periphery of the part. In these cases, an indexing fixture can greatly reduce the set-up time required for each part.

The fixture shown in Fig. 11-42 features a standard indexing head mounted on a base with a tailstock. The base can be made in-house from almost any available ferrous material. The exact size of the base can be determined by the size of the indexing head and the magnetic table on the surface grinder. This type of fixture is of universal design since the movement of the tailstock in the center slot can accommodate almost any size of part within its range.

Another variation of the principle is shown in Fig. 11-43. Here, the centers are mounted in a vise-jaw fixture. This fixture is well suited for smaller parts and those that require a flat ground the complete length of the part. The principle disadvantage to this type of fixture is its inability to accurately index the part for multiple flats. If this is a requirement, then an indexing arrangement can be positioned behind the solid jaw end of the fixture. Depending upon the application, either a special dog or a standard grinding dog can be used to secure the workpiece.

WORKHOLDING METHODS IN SURFACE GRINDING

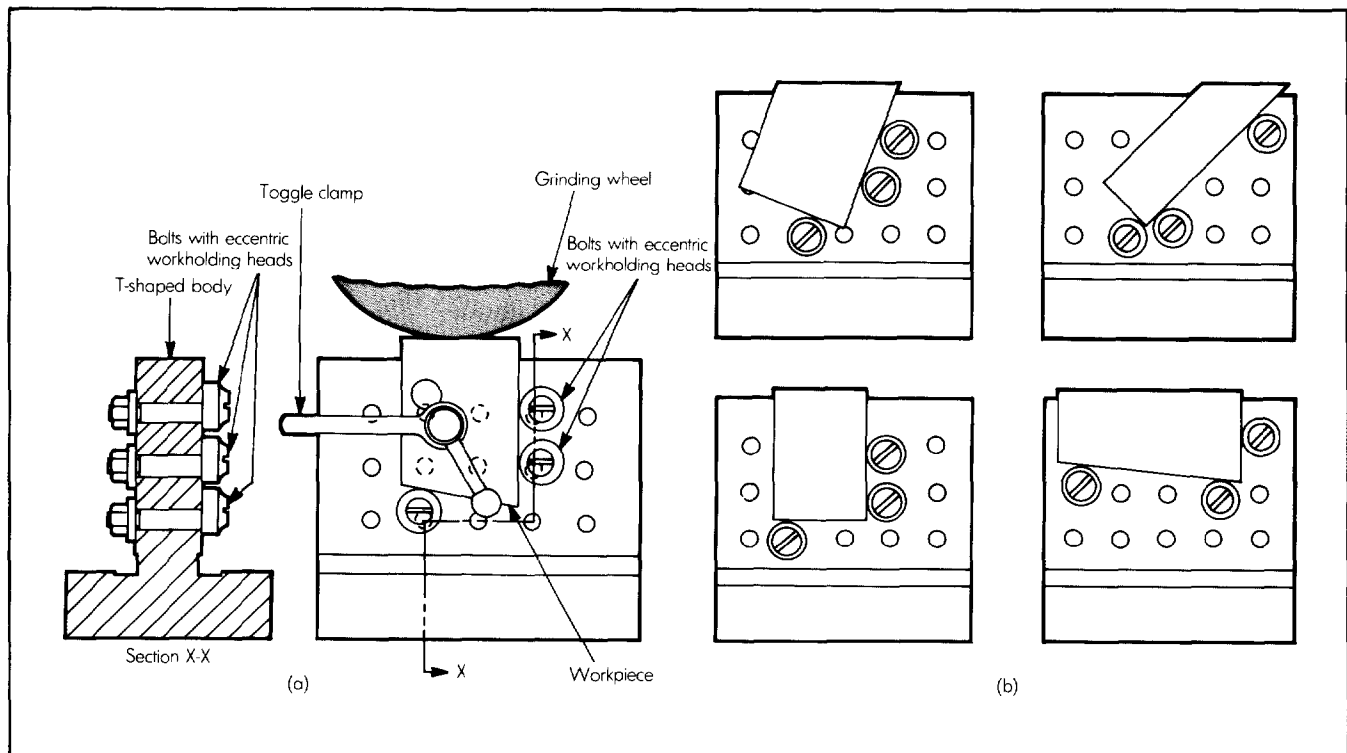


Fig. 11-41 (a) grinding fixture for holding workpieces at various angles, (b) four typical setups.

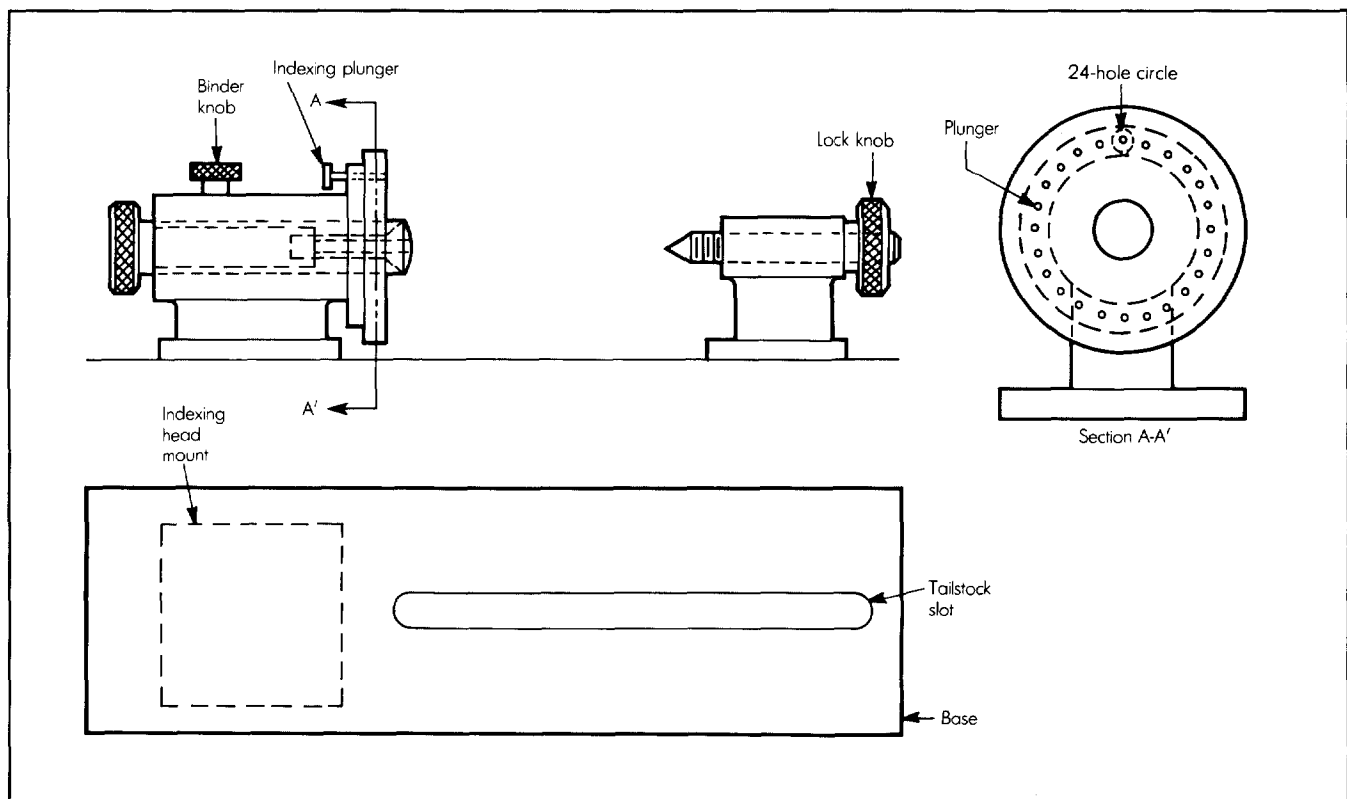
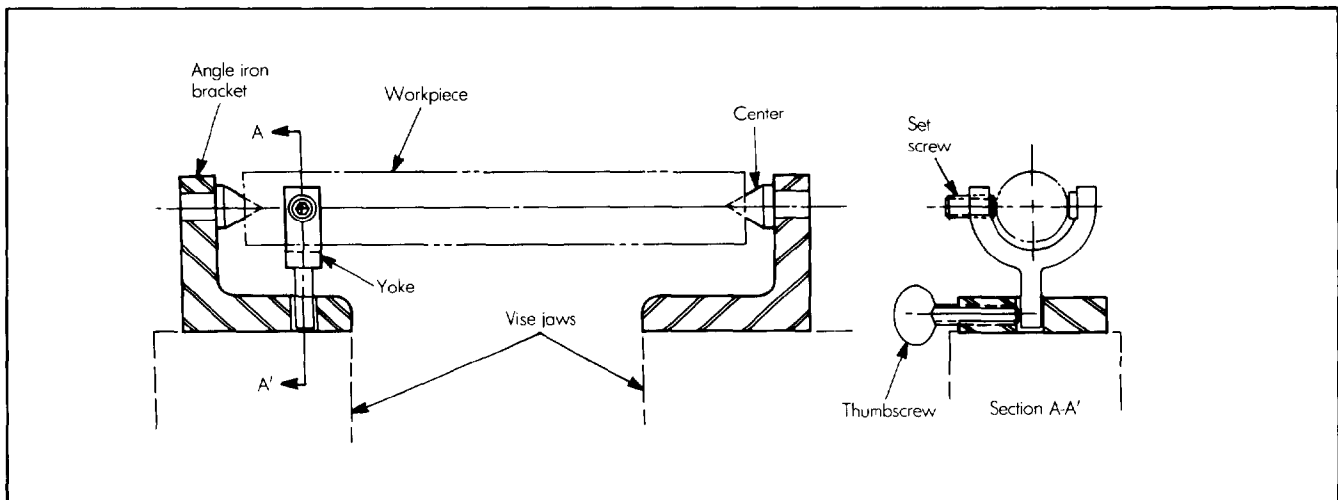


Fig. 11-42 Indexing fixture for grinding flats around the periphery of a cylindrical workpiece.

CYLINDRICAL GRINDING



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Cylindrical grinding is performed to remove stock, create precise geometry, and obtain desired surface finishes on external or internal surfaces of round workpieces. The term cylindrical grinding generally refers to outside diameter (OD) grinding. Internal grinding generally is the term used to refer to the grinding of the internal surfaces, or internal diameter (ID), of workpieces. These surfaces (OD or ID) are usually cylinders, shoulders, or tapers, but they may include fillets, grooves, or other formed surfaces of revolution. This section describes the various types of internal and external cylindrical grinders used in metalworking today.

A special type of external cylindrical grinder, the thread grinder (discussed in Chapter 12), produces precise helical surfaces. Another special grinder called a roll grinder (discussed in a subsequent section of this chapter) produces crowned cylinders with mirror finishes.

Manual vs. Automatic Grinding

Manually operated machines will not move or perform their various functions unless the operator moves each machine unit. Even if some type of mechanical or hydraulic servomechanism is supplied for the wheelhead infeed or power-table traverse, the machine is still considered a manual machine.

Semiautomatic machines will perform one complete cycle of operation automatically and then stop. This means that the machine must still be operator attended, with the operator responsible for each cycle of operation. However, in order for the machine to cycle independently, it must be equipped with some type of automatic infeed mechanism. Single or multiple rates of infeed can be obtained. When units such as these are supplied, the wheelhead will also rapidly traverse to and from the workpiece. Some manufacturers also supply an incrementalizing feed mechanism for extremely accurate wheelhead movement. Certain grinding machine manufacturers also supply supplementary equipment which can further reduce the time required per cycle. One of these mechanisms is a wheelhead rapid-advance unit for getting the grinding wheel to the rough-stock diameter on the workpiece faster.

Many advantages can be gained by using a semiautomatic machine in place of a hand-operated or manual machine. An

individual operator can sometimes attend two or more machines at once. Semiautomatic machines, particularly the ones with automatic gage sizing, eliminate human error. Small items such as "dogging time" for the workpiece need not be charged against a semiautomatic machine, since dogs can be applied to the work while the machine is cycling.

Gage sizing on semiautomatic machines generally consists of a hand-caliper type of gage or a jump-on gage. This means the operator must snap the caliper on and off every workpiece before and after it is ground. The use of gage sizing means that the semiautomatic machine should be more consistently accurate than a machine without it.

Automatic machines are similar to semiautomatic machines with a few exceptions. To be fully automatic, the machine must have some type of automatic device to load the workpiece, and if gage sizing is used, then an automatic jump-on gage must replace the hand-caliper gage. Limit switches and detection devices are used on automatic machine setups to determine the location of parts to be ground in relation to the grinding wheel area.

Fully automatic machines require no permanent operator attendance. They are capable of handling parts as they come to the machining area, orienting these parts if necessary, automatically loading them into the machine, grinding them to size, and unloading them. Machines such as these also stop cycling if no parts are present in the loading chutes, or if the unloading chutes are jammed.

Automation usually refers to a machine or a line of machines performing an operation or a series of operations on a given part. A line of equipment such as this not only grinds the work but in some cases also checks each individual operation performed against a master gage (see "Gaging for Grinding Operations" in this chapter). Information is fed back to the machine in such a way that the machine performing the operation is automatically corrected for any errors which have occurred in the last machined part. The work is gaged while in process, and sometimes immediately after processing. Sometimes automated lines such as these also completely check all operations performed on the parts at the end of the line. All parts handling, checking workpieces, wheel dressing, and size compensating are completely automatic.

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Traverse vs. Plunge Grinding

In cylindrical grinding, the grinding wheel can feed into the workpiece using one of several techniques. A comparison of plunge and traverse grinding is illustrated in Fig. 11-44. Traverse grinding up to a shoulder or other obstruction, as shown in views *a* and *b*, produces a series of reverse arcs or cross-hatch patterns, as in view *c*, which could be objectionable, for example, on a thrust-bearing surface. An improvement would be to use a dished wheel or a wheelhead set at an angle, as shown in view *d*. A still better method is to plunge grind the journal and face simultaneously, as shown in view *e*, having the wheel set at an angle of 20-30°.

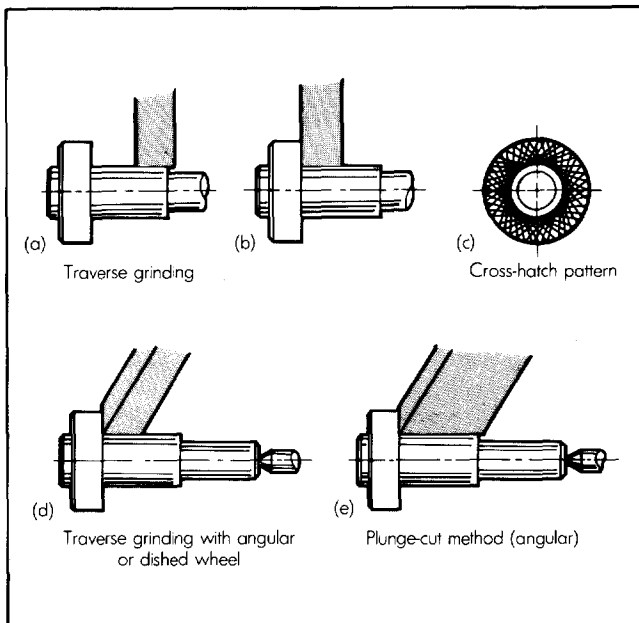


Fig. 11-44 Comparison of traverse and plunge grinding.

External Cylindrical Grinders (OD Grinders)

External cylindrical-grinding techniques. There are three principal external cylindrical-grinding techniques. In the first technique, the part is captured between two centers as the grinding wheel removes stock. This technique is called center-type cylindrical or OD grinding. In the second technique, the workpiece is held securely in a fixture mounted on a rotating spindle in a workhead; this technique is called chuck grinding. In the third technique, the work is ground while it is supported on shoes or a fixed blade and regulating wheel. Since no centers are required in this process, it is called centerless grinding. Specialized machines using each of these techniques are available for mass-production operations. Included are the multiple-wheel center-type grinders for crankshaft and camshaft bearings, the crankpin grinder (which has two chucking heads), and the shoe-type machines used for finishing precision antifriction bearing races. Conventional centerless grinders with blades and regulating wheels are used for throughfeed grinding of straight pins, shafts, or bars; for infeed grinding of countoured pins, shafts, or bars; and for infeed grinding of valves and other shouldered or stepped-diameter parts.

The three techniques cited are distinguished by the method in which the workpiece is constrained. In operational parameters, such as wheel speed, work speed, feed rates, and fluid

application, the methods are quite similar. Conceptual views of the various types of external cylindrical-grinding methods are presented in Fig. 11-45. Table 11-17 lists general tolerance-holding capabilities of cylindrical grinders.

In the selection of external cylindrical-grinding methods, the following guidelines should be considered:

1. Center-type grinding is used for single or multiple-diameter shafts and machines, especially when concentricity must be held between diameters ground in separate operations.
2. Chucking grinders are used for mass production of short parts workpieces that do not lend themselves to center-type grinding. These grinders are ideal in applications in which the ground surfaces must be concentric with a diameter that can be held in the chuck.
3. Throughfeed centerless grinding is used for continuous surfaces on either long or short pieces. It is effective on parts which cannot accept centers or be held in a chuck. Infeed centerless grinding produces concentricity on multiple diameters when they are ground simultaneously.

Selecting center-type or centerless grinding. The several different methods of center-type and centerless grinding must be considered in choosing between the two. Center-type grinding methods include plunge and traverse grinding, while centerless grinding methods include infeed and throughfeed grinding. Throughfeed grinding on a centerless machine is not quite the same as traverse grinding on a center-type machine. In throughfeed grinding on a centerless machine, the length of

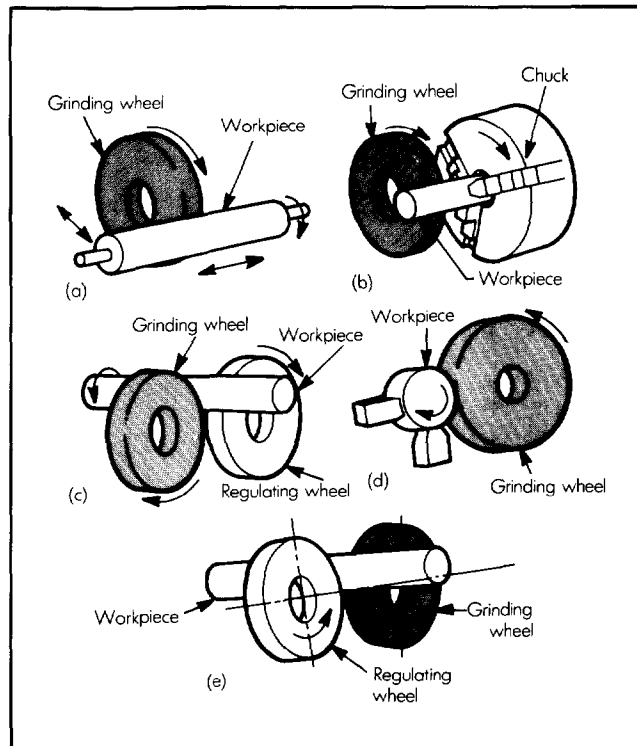


Fig. 11-45 Cylindrical grinding: (a) between centers, (b) chucking type, (c) centerless, (d) shoe-type centerless, (e) through-feed centerless (Reprinted with modifications from *Metalcutting: Today's Techniques for Engineers and Shop Personnel*, McGraw-Hill Publications Co., 1979, p. 164.)

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TABLE 11-17
Capabilities of Cylindrical Grinding

Dimensional Characteristics	Optimum Tolerance Limits, μ in. (μ m)		
	Regular Cylindrical Grinding	Precision Cylindrical Grinding	High-Precision Cylindrical Grinding
Size holding (diameter)	50 (1.27)	25 (0.635)	10 (0.25)
Geometric accuracy (straightness, roundness, etc.)	75 (1.9)	25 (0.635)	6-10 (0.15-0.25)
Surface finish, AA (R_A)	8 (0.2)	2-4 (0.05-0.1)	1-2 (0.025-0.05)

Source: Francis T. Farago, *Abrasive Engineering Methods*, Vol. I, (New York: Industrial Press Inc., 1976).

surface to be ground can be shorter or longer than the width of the grinding wheel on the machine.

There are advantages to both center-type and centerless grinding. The first decision in the selection of either method is based on whether or not the workpiece should have center holes. To the process engineer or the engineer who is designing the part, this may be a rather costly decision. In many cases, the design of the part determines whether or not it can be ground on a center-type or centerless machine. If the workpiece has a square notch or slot cut through the end of it, and if the size of the slot is of major proportion in width to the diameter of the workpiece, it is impossible to put a center hole in the end of a round workpiece. Also, some heat-treating situations on the workpiece determine whether or not center holes can be placed in the end of the part.

If a part is of such a configuration that an inside diameter must be ground concentric with the outside diameter, it may have to be mounted on a mandrel. In this case, no center holes are required in the workpiece. However, the center-type grinding method must still be used.

Volume of parts to be produced is another consideration. If only a few parts are going to be produced, it is much easier (if the part will allow) to produce center holes and grind the parts on a center-type machine. This is because the cost of setting up a center-type grinder is generally much less than the cost of setting up a centerless machine. Even though the time required to grind a workpiece may be slightly more on a center-type grinder, this situation would still favor center-type grinding.

In the case of multiple-diameter work to be ground on the centerless machines, it is rather expensive to produce a work blade with the exact step relationship required. In addition, the regulating and grinding wheels must have the proper step relationship in order to match the workpiece. If a small number of multiple-diameter parts are to be ground, they are generally less expensive to grind on a center-type machine, even when it is possible to do only one diameter at a time.

It is evident that cost is generally the most important consideration in the selection of the proper grinding method. This is assuming that the configuration of the part permits a selection. In the case of single-diameter straight pins, it is obvious that the fastest method is throughfeed centerless grinding. However, in the case of a pump pinion, the fastest method is between centers on an angular wheel-slide grinding machine.

In the case of multiple-diameter, high-production work in

which gear teeth or spline shafts may have to be cut on a particular surface of the workpiece, a center-type grinding method must be used. Even though only one diameter can be ground at a time, the area of the splines or gear teeth to be cut must be concentric with the other diameters that are ground.

Considering the case of a multiple-diameter shaft for which all diameters are to be ground in a finishing operation, the obvious solution, provided the length of the workpiece does not exceed the length of the grinding wheel and production requirements permit, is centerless grinding. Here again, however, a special blade must be ground and special cams and form wheels must be made, thus adding to the cost. However, for high-production runs, savings can be large. Long bars, assuming their diameters are large enough to support the bar weight, can generally be ground more economically on a center-type machine if only one or a few pieces are required. If a large number of bars are required, however, the throughfeed centerless-grinding method should be considered.

Many other factors too numerous to mention also determine whether or not a part should be ground by the center-type or centerless method. The following is a list of items which should be considered during the selection of a method:

1. Less grinding stock is required for the centerless method.
2. Less loading time is required for the centerless method.
3. Heavier cuts may be taken using the centerless method.
4. The centerless method grinds long, slender shafts more easily.
5. The centerless method grinds parts which cannot be centered.
6. No centering is required when using the centerless method.
7. No driving dogs are necessary when using the centerless method.
8. Straight and multiple-diameter shafts up to 8" (200 mm) long, and often longer, may be plunge-ground with the centerless method, sometimes from the solid.
9. The diamonds are always in position for dressing both wheels in the centerless method.
10. The workpiece need not be balanced during centerless grinding.

Center-type cylindrical grinders. Center-type grinders are machines on which the workpiece is rotated between centers, on backrests, steadyrests, or journal rests, or held in some type of

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clamping device. These machines consist primarily of a bed, a wheelhead (which may or may not swivel), a workhead (which also may or may not swivel), and a tailstock mounted on a swivel table which in turn is mounted on a sliding table.

As shown in Fig. 11-46, center-type grinding machines are characterized by the workpiece being held between centers. On these machines, externally ground work can be no more accurate than the location and geometry of the work centers of both the workpiece and the machine. Stress in the machine and machine alignment also play important roles in accuracy. The center holes in the work and the work centers of the machine must be round and ground or lapped to the correct angle to produce accurate work. The center holes in the work should always have a relief at the bottom to clear the point of the work center. If the point of the work center touches the bottom of the center hole, the work will revolve on the point instead of bearing on the angle, and the shaft (workpiece) will wobble causing out-of-round work. Special center-hole grinders are used to generate work centers, as discussed in the section of this chapter entitled, "Special Grinding Machines and Processes."

One of the most important applications of center-type cylindrical grinding is the creation of bearing surfaces on spindles and shafts. These surfaces may actually become the bearing element of a fluid-lubricated bearing system, or they may be the mounting surfaces for antifriction bearings of all kinds. In either case, precise size, roundness, concentricity with other bearing surfaces on the same part, and smooth finish are essential. The cylindrical surfaces must be straight, free of taper, and square with adjacent shoulders. Fillets must be free of scratches and large enough to avoid undue stress concentration, yet small enough to avoid interference with the fit of the bearing.

On these same parts there are usually other diameters to grind for finish and concentricity with the bearings. Friction-seal surfaces, gear and rotor-fit surfaces, labyrinths, and running clearances are examples. Sometimes they can be done in the same setup, but often the part must be transferred to another machine or turned end for end. Here, center-type grinding is especially effective because all the surfaces are referenced to the center holes in the part and excellent concentricity can be maintained.

Typical applications of center-type cylindrical grinders include machine spindles, transmission shafts, automobile rear axles, crankshaft and camshaft bearings, cam lobes, rotary cutting tools, and numerous other round parts. Workpiece materials include almost every metal and nonmetal of commercial importance, but the largest volume of work is done on steel bars, extrusions, forgings, and castings of all types.

Traverse speed. Traverse speed is limited by the width of the wheel and the finish required. Traverse should never be greater than approximately 75% of wheel thickness per revolution of the work for rough grinding. In addition, it should be reduced to the speed necessary to produce the finish desired when finish grinding. The length of traverse should never extend beyond the work. In general, the work rpm and the traverse rate can be regulated to make a wheel act softer or harder as needed. If the work rpm is increased, the wheel will act softer; conversely, if the work rpm is decreased, the wheel will act harder. If the traverse rate is increased, the wheel will act softer; if the traverse rate is reduced, the wheel will act harder (see "Principles of Grinding" in this chapter). In general, as the traverse rate or work rpm is increased, more work is presented to the wheel in the same amount of time. This creates more mechanical stress

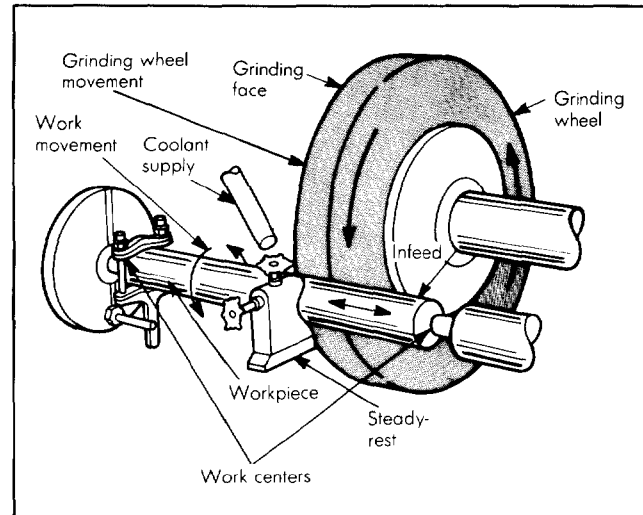


Fig. 11-46 Machine and work movements in OD, center-type cylindrical grinding.

on the grains of the wheel, causing the wheel to break down faster or act softer. If the traverse rate or rpm is reduced, less work is presented to the wheel in same amount of time. This puts less stress on the grain of the wheel, causing the wheel to break down more slowly or act harder.

Grinding Fluid. To prevent damage to the work and reduce the heat of the grinding operation, most work on center-type machines is ground wet. To get the full benefit from a grinding fluid, it is necessary to keep a good volume of fluid on the work during grinding, with the nozzle adjusted to force the fluid between the wheel and the work (see "Grinding Fluids" in this chapter).

Shoulder Grinding. In center-type cylindrical grinding many jobs involve grinding a diameter and shoulder, holding a radius or fillet to close tolerances, or grinding a flange face with the side of the wheel. Recessing and dishing the side of the wheel reduces the contact area between the wheel and the work, giving a cooler and freer cut than possible when using a straight-side wheel.

On a machine on which the wheelhead can be swiveled or on a plain machine with a 30° or 45° angle, this type of operation can be done with an E-face or an N-face wheel. Grinding both the diameter and face (shoulder) with the periphery of the wheel gives a freer cut and better finish with less heat damage to hardened parts than possible when grinding with the side of a wheel.

Steadyrests. Steadyrests are necessary when grinding long, small-diameter parts that will be sprung or deflected from revolving on their true axes by the pressure of the cut. They help prevent chatter and make it possible to take deeper cuts. The number of steadyrests required depends upon the length and diameter of the part. If more than one steadyrest is used, they are generally spaced longitudinally along the axis of the part at a distance between each steadyrest of 6-10 times the diameter of the workpiece. When the steadyrests are set, one should be located in the approximate center of the work; if more are needed, they should be equally spaced on each side of the center.

Both workpiece and wheel balance are necessary for accurate work on the center-type grinder, particularly when the workpiece cannot be held rigidly in the machine.

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Work speed. The speed of the work is generally from 50-100 sfm (0.25-0.50 m/s); however, on some work that is badly out of balance, lower speed is necessary to get a round part. Soft metals and nonferrous alloys grind better at higher work speeds, up to 200 sfm (1.0 m/s) when shape and design of work permit.

Wheel grade. Selection of the wheel grade depends on the kind of material (hard or soft), stock removal, finish required, form to hold, fillet or radii, and tolerance. Generally, small-diameter work permits use of harder wheels; hardened material requires finer grain and softer wheels. Soft, ductile metals, heavy stock removal, and unhardened metals (green grind) require coarse grain sizes. The same wheel can be used to rough and finish by changing dressing techniques. For free cutting or roughing, a fast pass with a diamond dressing tool across the wheel face approximately 0.001" (0.03 mm) deep will open up the wheel face or cut grooves in it, making the wheel act coarse and giving good stock removal but poor finish (see "Grinding Wheels and Discs" in this chapter).

Wheel dressing. If several slow passes are made across the wheel face with the diamond dressing tool with very little infeed, the wheel face will become closed up or glazed and the wheel will finish in the same way a wheel several grit sizes finer would finish. However, a wheel in this condition does not remove much stock and can develop chatter if glazed too much. In production quantities of work requiring better than commercial finish and heavy stock removal, it is better to rough with a coarse-grit wheel and finish with a fine-grit wheel than it is to control finish by dressing.

Two general types of center-type cylindrical grinding machines exist: plain and universal. Plain center-type machines are designed for plain cylindrical work, are good production machines, and are not readily adaptable to other types of work. The wheel slide is 90° to the table travel on these machines, and neither the wheel slide nor the workhead can be swiveled. The wheel slide and workhead of a universal machine can be swiveled in relation to the table travel. A universal machine, consequently, can be readily adapted to perform a variety of grinding jobs.

Plain, OD, center-type cylindrical grinders. Plain, OD, center-type machines that permit traverse grinding are usually thought of as high-production machines, because they are not as versatile as universal machines. Angular-wheel-slide and straight-plunge machines also fall into the high-production category. Both of these types are basically plunge-grinding machines, meaning that the wheel is plunged into the work at a predetermined feed rate and is withdrawn at the time the workpiece reaches correct size. The majority of plain OD grinders and practically all angle-head and plunge grinders have wheelhead-mounted dressing devices, usually with automatic units that reposition the wheelhead to compensate for reduction of the wheel diameter due to dressing and cycle counter to dress the wheel after a preset number of pieces have been ground.

Plain, OD, center-type cylindrical grinders are available in a variety of sizes to accommodate a wide range of workpiece sizes and configurations. High-precision grinders of this type are designed for extremely small workpieces that require unusual tolerance and finish control. Typically, this type of grinder features a work swing capacity of about 4" (100 mm) and a distance between centers of about 5" (130 mm). Often these versatile machines are constructed to accommodate interchangeable components such as workheads and tailstocks. It is not unusual for these machines to accept an attachment for

internal grinding. Chucking attachments and collet attachments provide the means to accommodate work other than center-type work. One manufacturer of equipment of this type claims that size (diameter) can be held on center-type work to 4 μ in. (0.0001 mm) and on collet work to 12 μ in. (0.0003 mm).

OD, center-type cylindrical grinders are also available for production applications on small workpieces requiring close tolerance control. Usually these grinders feature work swing capacity to about 5" (130 mm) and a distance between centers of about 10-20" (250-500 mm). Machines of this type are sometimes equipped with interchangeable quills for grinding between centers, grinding with a collet, or grinding with a three-jaw chuck. Representative models of this class of grinder are often equipped with interchangeable workhead bases that allow swivel adjustment for angular-grinding applications. Taper-grinding attachments are also available.

Larger OD production grinders of the center-type feature work swing capacities ranging from 6-24" (150-600 mm) and accept work between centers from 20-120" (500-3000 mm). These medium-sized production grinders are usually powered by motors up to about 25 hp (19 kW). This class of grinder is specifically designed for production work, and the emphasis in machine design is on production efficiency for repetitive work rather than versatility. However, many machine builders supply a large number of optional configurations in machine design which allows the user to customize a machine for his particular requirements. One manufacturer of production grinders of this class offers 50 different combinations of swing, center distance, horsepower (kilowatt) ranges, wheel diameters, and wheel widths.

Typical of this class of plain, OD, center-type grinder is the machine illustrated in Fig. 11-47. The machine is equipped with a programmable controller, which allows pushbutton programming of production cycles, and is offered with an optional tape cassette to store programs. Among the many optional features are electric in-process gaging, taper correction unit, gap eliminator, quill tailstock, U-frame automatic loaders, and indexing automatic loaders to facilitate large-volume runs. Figure 11-48 illustrates a plunge, center-type grinder for production applications.

Universal, OD, center-type cylindrical grinders. Universal, OD, center-type grinders are primarily manually operated, toolroom machines for grinding close-tolerance workpieces

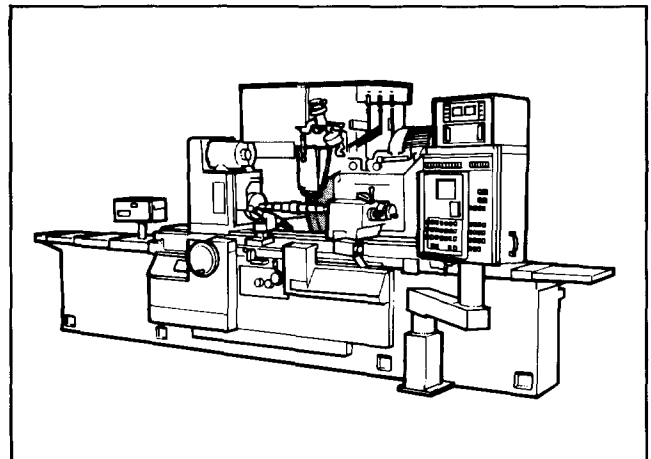


Fig. 11-47 Plain, OD, center-type cylindrical grinder for production applications. (Cincinnati Milacron)

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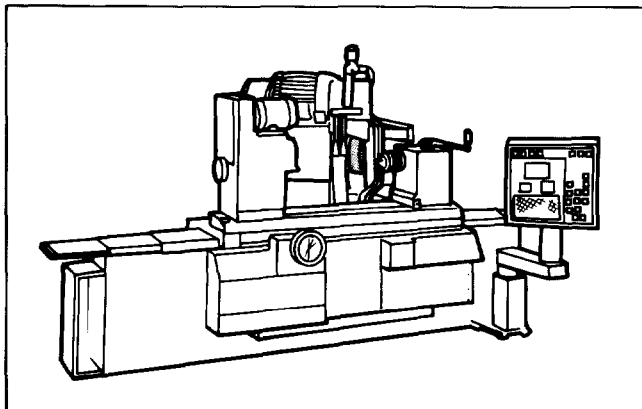


Fig. 11-48 Plunge, OD, center-type cylindrical grinder for production applications. (*Cincinnati Milacron*)

such as gage and fixture details. Machines such as these are capable of grinding a variety of parts with a wide range of configurations. More and more, these machines are equipped with semiautomatic features.

The distinguishing characteristic of this class of grinder is versatility. Often, work accuracy is considered more important than stock removal rate. This is evidenced by the small wheel widths, usually less than 2" (50 mm), featured on most universal grinding machines.

The typical universal grinder features a workhead that can be swiveled about its base and adjusted to different positions along the table. Also, most workheads on these machines can be converted easily from dead center to rotating live center, thereby accommodating varying workpiece requirements. Universal grinders can be used as internal toolroom grinding machines when equipped with an internal grinding attachment.

Figure 11-49 illustrates a typical universal grinder for grinding workpieces up to 8" (210 mm) diam and cylindrical work up to 15" (380 mm) in length. Figure 11-50 illustrates a universal grinder for work up to 14" (360 mm) diam and cylindrical work up to 40" (1020 mm) in length. The latter machine is a member of a family of universal grinders that are provided in a range of precision classes, the most accurate of which can hold size tolerance to ± 0.00001 " (0.0003 mm) and surface roughness to 3μ in. (0.076 μ m).

Roll grinders. Roll grinders are a special class of extra-heavy, plain, center-type cylindrical grinding machines used for accurate external grinding of large workpieces such as steel mill rolls which require crowning.

There are two distinct requirements for roll-grinding machines, one for manufacturing and the other for maintenance. Manufacturers grind few duplicate sizes of rolls at any one time and must grind the necks and journals of rolls. They require machines that are versatile, easily adjusted, and equipped with a full range of attachments. Maintenance shops, on the other hand, usually grind a narrow range of roll sizes and many duplicate sizes; they seldom have to do taper-journal grinding. They may require less-sophisticated machines with fewer special attachments. Roll-grinding machines of any type must have the capability to rough and finish-grind rolls, with a surface finish free from defects of chatter and traverse marks. Manually operated machines, which require operator manipulation and control of functions, can produce extremely accurate rolls to close tolerances and exceptional finishes by using

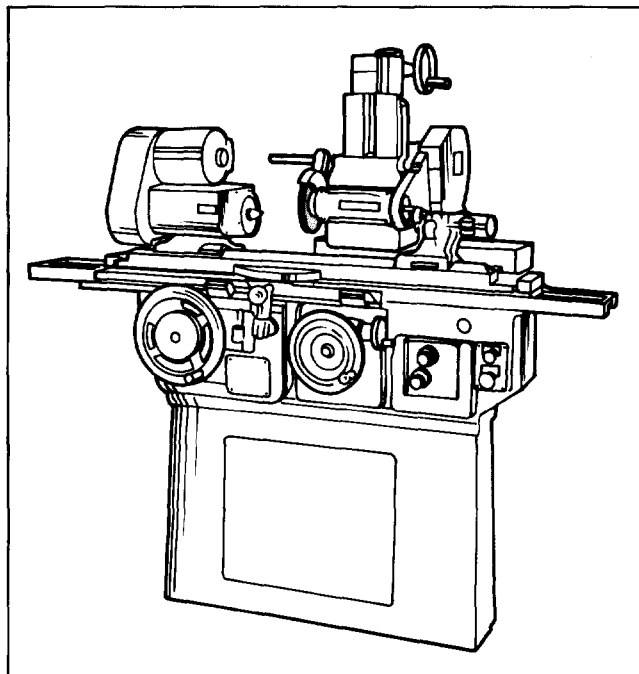


Fig. 11-49 Universal and tool grinding machine for relatively small workpieces. (*Brown & Sharpe Manufacturing Co.*)

proper techniques and equipment combined with good workmanship and skill.

Types of roll-grinding machines. To meet the many procedures and wide range of roll lengths and diameters, roll-grinding machines are made in several types. One type has a traveling table and a stationary, single-wheel, grinding head. The table carries the roll and the roll-driving and supporting equipment. This type of machine is generally used for small-diameter and short-length rolls and is somewhat similar to a conventional cylindrical grinder.

A second type of machine, the most commonly used, has a traveling single wheel, with the roll and roll-driving and supporting equipment on a stationary bed. The grinding wheel is supported on a carriage that travels on a separate bed, usually attached to the roll bed. This type of grinding machine is classified by the maximum-diameter roll accepted, usually 24-60" (610-1520 mm) and larger.

A third type, which has been used almost exclusively to regrind paper-mill rolls, is a single-bed machine with two opposed wheels mounted on a traveling carriage. This type of machine is made in two sizes, the smaller for rolls up to 32" (810 mm) diam and the larger for rolls up to 44" (1120 mm) diam. Either size can be made to grind rolls with larger diameters by the addition of auxiliary equipment to raise the roll centerline and, at the same time, raise and separate the opposed wheels. While this is possible, a sacrifice is made in the rigidity of the machine, which may affect the metal-removal capacity and surface-finishing ability.

Workhead and drive. With the exception of two-wheel, roll-grinding machines (which use a retractable or a universal-joint driving bar), roll-turning workheads are equipped with an equalizing wobbler mounted on the faceplate and used for accurate roll driving and to minimize minor errors in roll settings. To prevent lifting, the wobbler (with the two driving

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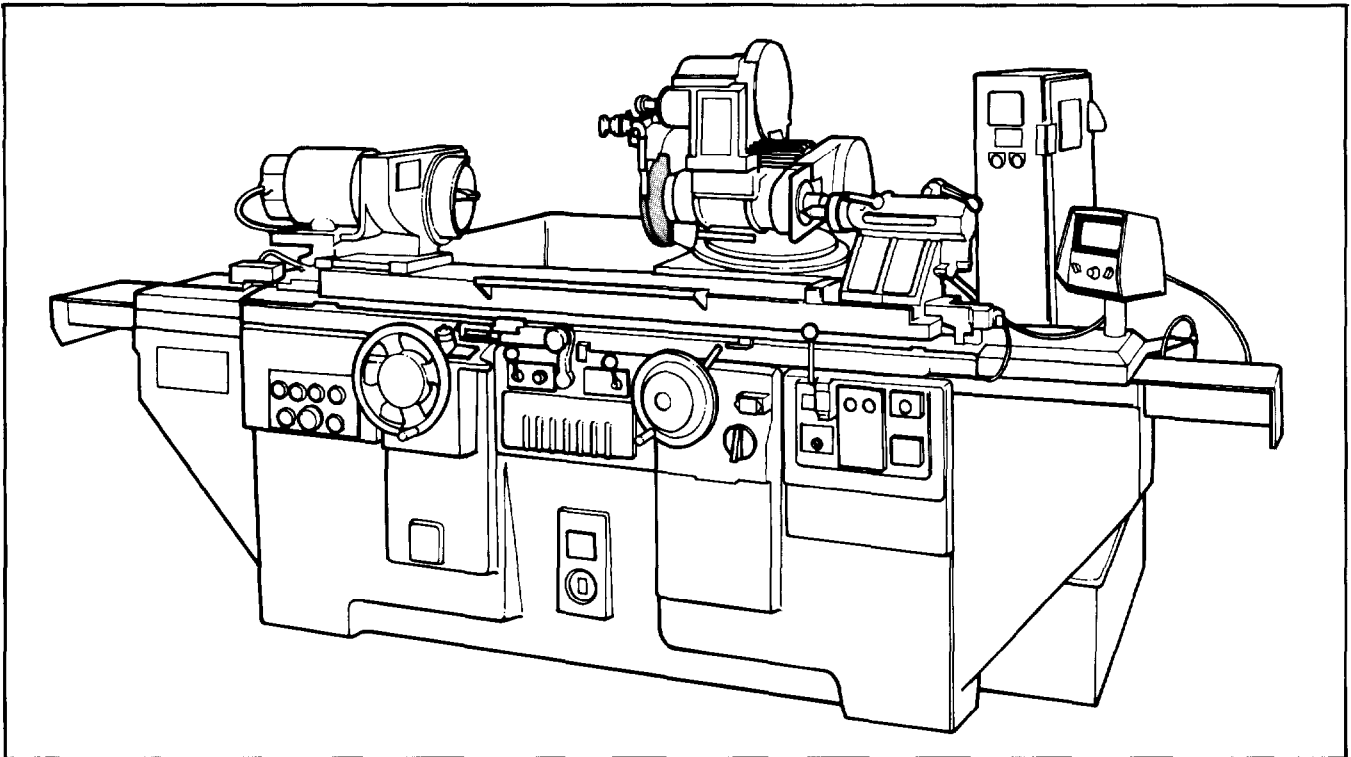


Fig. 11-50 Universal grinding machine for large workpiece applications in the toolroom. (Brown & Sharpe Manufacturing Co.)

rollers) should be pulled by the pivots in the direction of roll rotation.

Workhead centers can be either live or dead center, depending upon preference. Auxiliary controls mounted on the workhead, such as start, stop, and jog, are necessary to control roll rotation for setup and removal purposes. Workhead roll-driving horsepower and rotational speeds vary with the maximum weight and diameter of the roll to be ground. Roll-speed variation by field and voltage control through direct-current motors is generally more acceptable than the limitations of speed by field control only.

Tailstocks for roll grinders. With the exception of the two-wheel roll-grinding machine, a tailstock is furnished with longitudinal adjustment on the roll bed to accommodate a range of roll lengths. Adjustment is made manually or by an optional motor drive. When in position, rigid locking prevents slippage. Tailstocks are usually made in two sections so that the upper section can be transversely adjusted for alignment of its center with the workhead center. The spindle-mounted center may be either a dead or a live center.

Roll supports. Roll-supporting equipment is of two types. Two-wheel, paper-mill, roll-grinding machines use two cradle-type neck rests or journal supports, one under each roll neck. Each of these supports uses either two or three bearing blocks, two at equal angles below the horizontal centerline and, when three are used, the third one at the bottom of the vertical centerline. Supports are located on the centerline of the single bed and are manually adjusted longitudinally to accommodate various roll lengths. Journals and necks cannot be ground with this supporting equipment.

Single-wheel roll-grinding machines make use of two double-bearing neck rests. One bearing block is located 12-15° from the

vertical centerline (toward the wheel), and the other is on, or slightly below, the horizontal centerline at the back, thus opposing wheel pressure. The supports are manually adjusted on the roll bed to accommodate rolls of various lengths. Journals and necks can be ground with this supporting equipment.

One set of neck rests of either type provides for a wide range of roll neck diameters. Bearing blocks for either type have babbitted bearing surfaces bored to give uniform bearing along the roll necks and are adjustable for roll-alignment purposes. Lubrication of the roll journals is through pads applied directly on the journal over the bearing blocks. The pads are fed by a drip system adjusted with a needle valve.

Crowning mechanism. Equipment for crowning or concaving roll bodies is, with few exceptions, built into the roll-grinding machine. This equipment is adjustable for both magnitude and contour of the crown. The grinding wheel is pivoted at the front (under the wheel) on a horizontal trunnion. Raising or lowering the back of the wheelhead (by means of an eccentric) swings the wheel into or away from the work. The magnitude of the crown or concavity is determined by the adjustment of the eccentric setting. Contour of the curve (symmetrical on both halves of the roll) is related to the roll-face length by change gears or other devices.

Taper attachment. Taper-journal grinding is usually confined to roll manufacturing and is infrequently required by processing or maintenance shops. Roll-grinding machines of the traveling-table and fixed-wheel types can be made with a split table that will permit setting the entire roll and drive equipment to the desired taper. Roll beds on some traveling-wheel roll-grinding machines can be split and adjusted similarly.

Taper grinding on larger traveling-wheel roll-grinding

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machines can be accomplished using several methods. One method is to place a separate compound-slide grinding unit on the carriage-bed ways; another is to furnish a split carriage with short slide ways that are adjustable to permit the grinding wheel to travel parallel to the taper. Still another method is to use a geared screw-feed, cross-travel mechanism that cuts in one direction only with the lead screw determining the accuracy of the taper.

Foundations for roll grinders. To minimize vibrations from within, grinding-machine components are usually made from cast iron because of its damping characteristics. To minimize vibration from outside sources, the machine must be stable on its foundation. This can be accomplished with an inertia block of concrete that is wider and longer than the machine and usually 5-8 ft (1.5-2.4 m) deep, depending upon the machine length and weight. The concrete block must be separate from all footings and floors and must be insulated from the soil at the bottom and all sides by a pad of hard-packed, round-grit sand. The sand should be sealed to prevent water seepage from sources below ground level and from external flooding and grinding coolant at ground level. Another method of vibration control is to suspend the machine and inertia block on a series of heavy, nested, low-frequency springs. With either foundation, periodic alignment is required to maintain accuracy.

Roll mounting. Rolls, because of their size and weight, are generally supported on neck rests and bearing pads. These pads are often small in width, with insufficient bearing surface. This may generate heat in the roll neck and expand the end of the roll body, which is then overground. When the roll cools, the ends contract and become undersized. This can be partially corrected by applying a small stream of cold water to the neck, between the bearing pad and the end of the roll face.

The best and most generally used bearing-pad lubrication is oil-soaked felt pads held at the top of the bearing surface and fed by a drip-regulated system. This provides an oil film thick enough to reduce friction, but not fluid enough to be unstable when grinding.

Roll speeds. Roll speeds can best be determined after preliminary trials. High roll speed may give good grinding conditions, but may introduce vibration in the roll and excessive heat at the bearing pads. A good speed to start with is 100-120 sfm (0.51-0.61 m/s) for chilled-iron rolls and from 120-135 (0.61-0.68 m/s) for steel rolls. Speeds can then be adjusted to obtain optimum conditions. Slight differences in roll diameters and densities may cause vibration at various speeds, making adjustment necessary from roll to roll.

Finish-grinding passes on roll bodies demand that wheel traverse per revolution of the roll be small. High roll speeds reduce the ratio of traverse to roll speed and are desirable if vibration is not introduced. Small-diameter rolls with long bodies have a tendency to whip and cause chatter marks at fast speeds.

Traverse of wheels. The full width of the wheel must never travel off the face of the roll. One-quarter to one-half of the wheel-face width is the usual maximum amount of overtravel for good grinding practice. More than this increases the unit pressure of the individual wheel grains left in contact with the roll, causing greater grain penetration and subsequent marking, and also grinding the roll ends undersize.

Traverse speeds for roughing, semifinishing, and finishing are all variable for different roll materials and finishes. For roughing, one-half to two-thirds travel of the wheel width per revolution of the roll is generally satisfactory. For semifinishing,

one-third to one-half travel of the wheel width is satisfactory, and for finishing, one-quarter to one-half travel of the wheel width can be used.

Multiple-wheel grinding. High-production, OD, cylindrical grinding is normally done in a plunge-grinding cycle. Frequently, more than one surface on the workpiece must be ground at a time. Multiple-wheel mounts are used on both center-type and centerless plunge grinders for this purpose. On longer shafts with wide spreads of cylindrical surfaces that require finishing, a machine specifically designed for multiple-wheel mounting is desirable. Center-type cylindrical grinders of this type are now available with up to about 30" (762 mm) of wheel span. Figure 11-51 illustrates a typical multiple-wheel machine. One operation that requires a multiple-wheel machine, and is common to both crankshafts and camshafts, is the grinding of main bearings.

Equipment used on the worktable of multiple-wheel machines is identical to that used on an external cylindrical grinder. Workpieces are held on centers and are supported with one or more steadyrests. A small amount of axial movement of the work must be provided to align the bearing surfaces with the grinding wheels. This axial shift or endwise location is provided by a sliding-spindle workhead, a sliding worktable, or axial motion of the wheel-spindle assembly.

Gaging is used to control the work size on these machines. Two gages are normally supplied, one at each end of the shaft. In addition, these gages are employed in logic circuits to sequence the machine cycle and promote better work straightness.

Wheel slides on multiple-wheel grinders have a spindle with bearings at the ends to carry the heavy weight of the grinding-wheel spindles and wheels. In addition to one wheel for each main bearing on a crankshaft, wheels are provided for other concentric surfaces such as the oil seal and pulley mount. Thus, six to nine wheels, each 42" (1070 mm) in diam, may be mounted on a single spindle. The wheel-drive motor is also carried on the wheel slide.

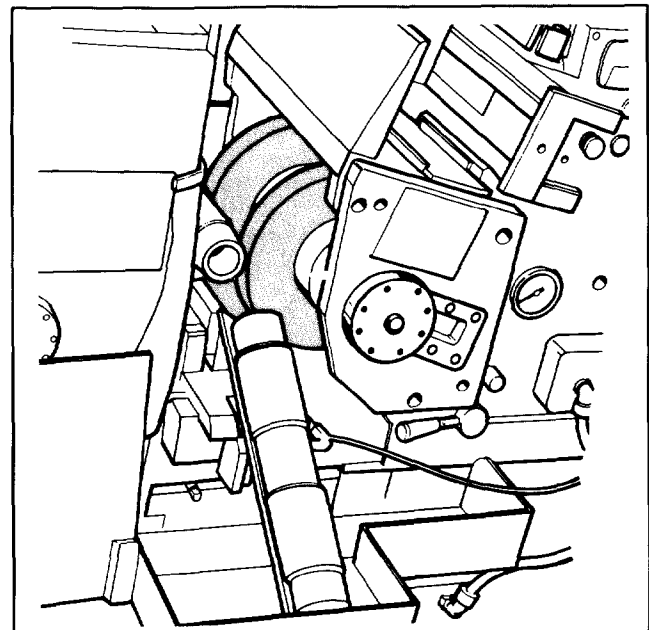


Fig. 11-51 Typical OD, multiple-wheel grinding machine. (Bryant)

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Because the multiple-wheel grinder is a specialized machine for high production, it includes in its standard equipment an automatic wheel-truing mechanism. This may include a truing head for each wheel, or it may be arranged with a single truing head that traverses the entire span of wheels. In the latter case, the truing device is typically a roll with inset diamonds. As the truing head traverses the wheels, it may be called upon to dress radii on the wheel corners as well as the straight faces. This requires a complex form bar which must have accurate contour, steps, and spacing for the wheels.

Machine cycles involve unloading and loading the work, endwise location, and then a plunge cycle in which the wheel is fed into the workpiece. Feed cycles are broken down into rapid approach, rough grind, fine grind, and sparkout, and are terminated by a signal from an in-process gage. On some machines, wheel-feed control systems use solid-state circuitry and have a crystal-controlled oscillator to control feed rates and timing dwells precisely. Grinding wheels used on multiple wheel bearing grinding are of medium grit size (54) and hardness (N). Variations in wheel grade from this starting point are based on several factors including whether the machine is roughing or finishing and whether it is new or worn. The wheels are mounted on the spindle and separated by rings to create the desired spacing. Wheel-spindle assemblies are generally of cartridge design and are brought to the machine with the full complement of wheels in place.

On a crankshaft-bearing grinder, the wheels are first side-dressed to make the width of each wheel equal to that of the bearing. The faces and radii of the wheels are trued, and then the machine is ready for operation. Automatic loaders, fed by in-plant conveyor systems, are often used with these machines. This permits a single operator to oversee a group of multiple-wheel grinders (see "Special Chucking-Type External Grinders—Crank Pin Grinders" in this chapter).

Camshaft-bearing grinding operations are not as critical as crankshaft-bearing operations because there are no shoulders or fillets to be ground. Wheels are trued with straight faces, and because they do not remove as much metal as a crankshaft wheel, they are dressed less frequently and thus last much longer.

Cam grinding. Large numbers of cams in almost limitless configurations are required in modern industrial equipment. To reduce wear on these cams, their surfaces are often hardened and then ground. Grinding is used to finish such parts as the distributor cams for internal-combustion engines. Also, pistons in an internal-combustion engine, although not cams, are oval in shape and are therefore finished by a cam-grinding technique. The most important high-production application of cam grinding is the finishing of the contours on the lobes of camshafts of automobile engines.

Cam grinders are themselves cam actuated. One problem that is encountered as a result of this involves the geometrical design of the master cam and follower to create the proper contour on the product cam. Another problem involves accommodating the peculiarities in the grinding process that are associated with the generation of the contour. A third problem involves modifying the tooling to compensate for the effects of the grinding process.

Cams are generated by a grinding wheel of fairly large radius, but the cams actuate tappets that have a curvature quite different. This difference must be accommodated in the master-cam contour. Tappets in automobile engines move linearly, while the cam contour is created by a rocking motion.

Geometric conversion of this lift data is required. The desired contour may require high accelerations and steep rates of change of acceleration. Cam-grinder generating mechanisms must be capable of responding to such contours.

For convenience, the camshaft is rotated at constant angular velocity while the cams are being generated. This causes varying work speed around the cam, which in turn affects the grinding action. Also, at constant rotation speed, the flank sweeps by the grinding wheel in a very short time. For example, the flank, which may represent one-fourth or one-fifth of the periphery of the cam, may be in contact with the wheel only 3-5% of the time. If the flank is flat, the grinding time approaches zero. Grinding may be done on center, about center, or below center. This affects the grinding action and the forces imposed on the cam-grinding mechanism. Some machines are available with variable workhead rotational speed. Using preprogrammed input to a servomotor driving the workhead, the rotational speed varies within the revolution of the camshaft in order to distribute the grinding forces evenly along the cam profile. This feature reduces potential grinding burns and enhances the profile accuracy of the cam. Wheel wear results in changes in contour and in grinding action. For example, 2" (50 mm) of diametral wheel wear causes the flank of the cam to be "fat" by about 0.002" (0.05 mm). To improve the cam accuracy and the inherent profile variation caused by the excessive change in grinding wheel diameter, specially built cam grinders equipped to properly true and dress cubic boron nitride are commercially available. The minor changes in diameter from a new to worn cubic boron nitride grinding wheel provides more consistent cam profile throughout the useable life of the wheel. These major factors, plus many other variables in the process, make tooling of a cam grinder a highly specialized engineering technique.

An automatic cam-grinding machine is similar to an external cylindrical grinder except that the table is equipped with a rock-bar mechanism which allows the work to move toward and away from the wheel with each revolution of the work. The work-supporting centers and the steadyrest are mounted on the rocker bar. The rocking motion permits generation of the cam contour.

Inside the workhead, the work spindle carries master cams, one for each lobe on the camshaft being ground. A master-cam roller is brought in contact with the appropriate master cam. After one lobe is ground, the table traverses to bring the next lobe in front of the wheel. At the same time, the master-cam roller is indexed to the next master cam. Thus, the cam lobes are ground consecutively down the shaft.

In addition to contour generation, cam grinders are usually required to produce a slight axial taper (an angle of a few minutes) on the cams. The taper may be in alternate directions on successive lobes. This is accomplished by swiveling the wheel slide back and forth relative to the base with each index of the table.

Camshafts are mounted on centers in the machine and are driven by dogs. A steadyrest is set up on the middle bearing, which is usually ground in a prior operation. Sometimes two steadyrests are employed on long shafts. Work speeds are relatively low (80-160 rpm for roughing, 20-50 rpm for finishing) because of the accelerations imposed by the contour.

Grinding wheels must be unusually versatile to remove large amounts of stock, finish all portions of the cam to accurate dimension, and produce low surface roughness. Demands for higher productivity have led to machines that rough and finish

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in the same setup, with only a dressing operation to convert the grinding wheel from an abrasive machining tool to a finishing wheel capable of holding surface roughness under 20μ in. (0.5μ m) rms. Average stock removal is about 0.150" (3.8 mm) in roughing, and 0.008-0.010" (0.2-0.25 mm) in finishing. For typical hardened, cast iron camshafts, the wheel selected would have about 80-size grit and M bond hardness. Wheel speeds of 6,500 sfm (33 m/s) are regularly employed, but wheel speeds of 12,000 sfm (61 m/s) are being used to increase productivity. On some machines, the drive motor automatically changes wheel speed after roughing and before finishing.

In cam grinding, critical dimensions are the lift and the rate of change of lift with angular rotation. The work size (base-circle diameter) is not critical; size is controlled simply by feeding the wheel slide to a positive stop. For greater accuracy, grinders are equipped with automatic size control; however, due to the complexity of the gaging and the response time of the machine controls, a slight loss of productivity can be anticipated. Wheel wear from cam to cam is accommodated by swiveling the worktable slightly, and then the total effect of the wheel worn and dressed away is compensated after each truing. The master cam and the characteristics of the grinder determine the contour that will be obtained. Tolerances are in the order of a few ten-thousandths of an inch (about 0.006 mm), and each inlet and each exhaust cam must be like the others. This requires good repeatability in the master cams, the machine, and the grinding process.

One of the causes of lack of repeatability in the contour is the increasing curvature of the wheel as it wears. This effect is so critical in some cases that only 1" (25.4 mm) of wheel wear radially is permissible on a 24" (610 mm) diameter wheel. To extend the useful life of the wheel, or to make further improvements in contour repeatability, an additional set of master cams may be supplied in the workhead. For example, camshafts for V-8 engines have 16 lobes, and the cam grinder is normally provided with 16 master cams. As an option, a master-cam spindle with 32 cams can be provided. Sixteen of these are ground to the correct contour with a full-sized wheel; the other 16 generate the proper shape when the wheel is partially worn. The master-cam roller is shifted from one set of master cams to the other when the wheel has served half its useful life.

Automatic camshaft grinders can grind a camshaft for a V-8 automobile engine (from cast lobes to finished contours) in less than 5 minutes. These machines are specialized in their application and are tooled for one particular camshaft. Prototype camshafts have been made on numerically controlled grinders, and numerical control has also been applied in the manufacturing operation for the master cam.

Chucking-type cylindrical grinders. Chucking grinders hold workpieces in a fixture (usually a chuck) mounted on a rotating spindle in a workhead. This type of cylindrical grinder is almost exactly the same as the shoe-type centerless machine (discussed later in this chapter) except that a collet, diaphragm, gear chuck, or other workholding device is mounted on the workhead instead of a magnetic chuck, drive-plate adapter, and shoe-support assembly. This basic difference makes the chucking grinder more versatile since it can accommodate a wide variety of part configurations. However, both chucking and shoe-type centerless work can be done on the same machine provided both sets of tooling are supplied.

General-purpose chucking-type grinders. Chucking grinders are widely used to finish external cylindrical surfaces on relatively short parts having no convenient surface for driving.

They are also widely used when providing center holes in the part is impractical or impossible. When the machine is provided with automatic chucks and loaders, it becomes an extremely productive cylindrical grinder ideally suited to the finishing of screw machine parts as well as to the grinding of automobile engine valve seats.

One limitation of chuck grinding is that the workpiece must be relatively short. In some cases, this can be overcome by a combination chucking and center-type grinder in which a tail-stock is provided to support the outboard end of the workpiece. Another consideration with chucking grinders is that the roundness of the workpiece is inherently limited by the quality of the workhead spindle bearings. Hydrostatic workheads, advanced-design, plain workheads, and high-quality antifriction-bearing workheads can minimize this problem.

One feature of chucking grinders is their ability to grind surfaces concentric with the diameter which is held in the jaws of the chuck. An application of this type is grinding the tips of the blades on a stage of an aircraft gas-turbine engine. This operation requires a chucking grinder with a very large swing capacity. Another use of chucking grinders is to generate a cylindrical surface with a closely held eccentricity from the surface which is held in the chuck. This is the requirement for grinding the pins on crankshafts. Figure 11-52 illustrates the types of part configurations usually ground using a chucking grinder.

Figure 11-53 illustrates a chucking-type grinder that handles workpieces from 2-10" (50-250 mm) diam. This machine is typical of the heavy, rigid, external chucking grinders available today for performing a variety of production grinding operations on workpieces not suited for center-type or centerless grinding. Equipped with a workhead that features variable angle settings, the machine permits accurate taper grinding, simultaneous OD grinding, and shoulder grinding. Machines of this class are typically equipped with a programmable controller that allows direct programming in U.S. customary or metric units, and with built-in and optional diagnostic packages to help pinpoint control or machine malfunctions.

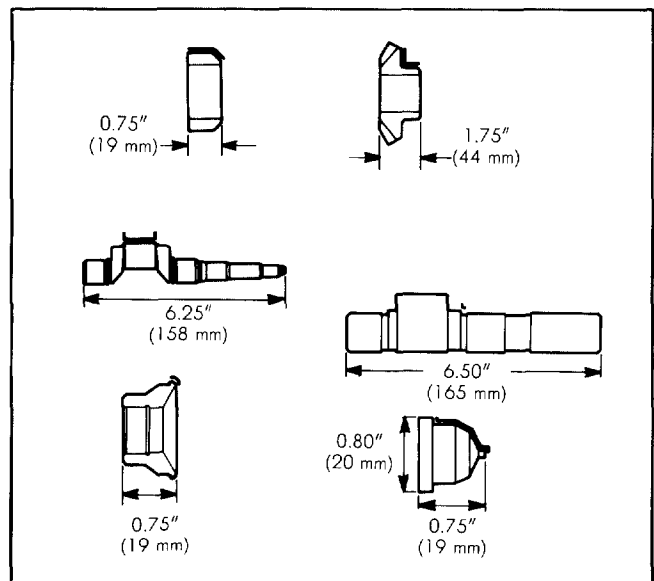


Fig. 11-52 Various workpiece configurations ground using chucking-type grinders. (Cincinnati Milacron)

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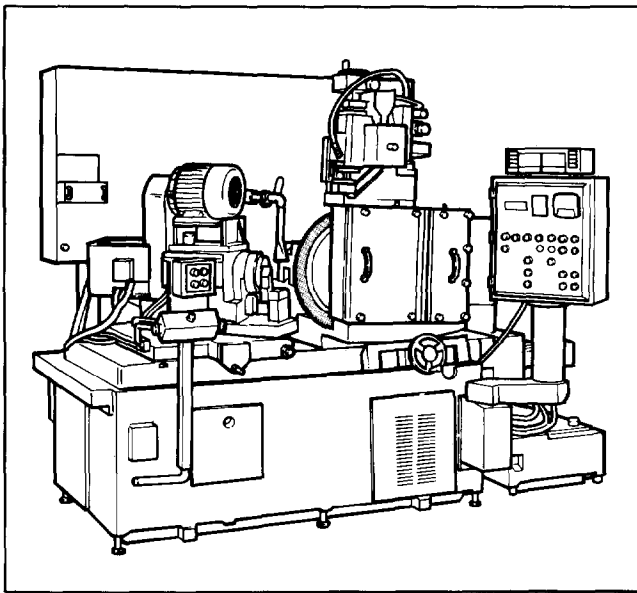


Fig. 11-53 Chucking-type grinder. (Cincinnati Milacron)

As mentioned earlier, many chucking grinders for external work can be equipped for shoe-type centerless grinding. A wide selection of interchangeable tooling, combined with a variety of wheel dressers; automatic workhandling; and gaging options make machines of this class extremely versatile for high-production applications.

Special chucking-type external cylindrical grinders—crankpin grinders. A major finishing operation on crankshafts is the external cylindrical grinding of crankpins. Pins on crankshafts are a series of short cylindrical bearing surfaces which are eccentric from the centerline of the shaft. They are angularly displaced from each other to create a series of throws for the attachment of connecting rods, which are pinned to the pistons in a reciprocating engine or compressor. Crankpins, therefore, are bearing surfaces which must have precisely controlled geometry in order to operate with a long life, at high speeds, and under rapidly fluctuating heavy loads.

Size tolerance on crankpins is usually within 0.0001" (0.003 mm) on diameter. Machine capability must be well within this tolerance, so in-process gages are used for size control. Characteristics of the gage, and response of the grinding machine to the command signal from the gage, determine the size of the crankpin. Crankpins must also be truly cylindrical, without concavity, barrel shape, or taper. Alignment of the machine components and of the form bar in the wheel dressing device combines with the machine cycle to influence the cylindricity of the pin.

Because crankpins are critical bearing surfaces, they must be held to extremely close roundness. The machine cycle and steadyrest setup influence the roundness. Vibration caused by machine resonance, grinding-wheel imbalance, or transmission from nearby equipment can also influence the ability of the machine to generate a round crankpin. The amount of eccentricity of the pins from the main bearings is called the "throw." It is determined by the eccentricity of the chuck jaws from the center of the workheads. Angular displacement of each successive pin from the first is determined primarily by the indexing mechanism in the workhead. This mechanism includes

an index plate with holes or slots that are precisely located. The pin which is inserted into the index plate and the locating pin which mates with a premachined surface on the crankshaft must be capable of engaging with good repeatability in order to hold close angularity of the pins. In addition, the jaws of the chucks must open and close without disturbing the angular orientation of the shaft that has been achieved by the indexing mechanism.

The axial length of the crankpin is determined by the width of the grinding wheel. This in turn depends upon the dressing device, including the form bar, which is used to generate the proper shape on the wheel. Axial spacing of crankpins along the shaft is not a precisely prescribed dimension. Rather, the crankpin is ground after centering the roughed-out pin in front of the grinding wheel. Thus, the crankpin lathe used in a preceding operation controls the axial location of pins. Crankpin grinding includes the grinding of sidewalls and fillets, as well as the cylindrical portion of the pins. This is a critical operation because incorrect fillet size will reduce the fatigue life of the crankshaft. The truing device of the crankpin grinder must have the ability to generate the correct radius on the corners of the grinding wheel to produce the desired fillets.

Crankpin grinders have two major slides. One is the table that carries the workheads which hold the crankshaft, and the other is the wheel slide that supports the grinding wheel on its spindle. A feed mechanism is provided to move the wheel slide toward the table to create interference between the grinding wheel and the crankshaft while the grinding wheel itself eliminates the interference by the removal of stock. In addition to the wheel, the wheel slide carries the truing device.

Crankshafts are held by their two end bearings in chucks, which are fitted to the workhead spindles. These spindles must be carefully aligned with each other and are driven through a mechanism which ensures their rotary synchronization. Workheads are mounted on a table which is moved in the direction of the crankshaft axis to bring the successive crankpins in front of the grinding wheel.

Before coming to the machine, the main bearings of the crankshaft are ground to serve as the reference surfaces for grinding the crankpins. As the crankshaft arrives at the loading station, the indexing mechanism is in the correct position for the first pin and the worktable is situated so that the first pin is in front of the grinding wheel. The jaws of the chuck are opened and the crankshaft is laid in place. A hole or slot in a flange on the crankshaft must be engaged with a locating pin to line up the shaft properly with the plate of the index mechanism. Then the crankshaft is shifted axially a small amount to align the pin and the wheel, so that the same amount of stock will be taken off each sidewall. The workpiece can then be clamped, and the grinding cycle can commence.

Initiation of the grinding cycle turns on the work drive and grinding fluid and begins the feed sequence. First, the wheel slide traverses rapidly to bring the wheel close to the surface to be ground. Next, the slide is advanced at a slower rate while stock is removed from the shoulders. As the wheel approaches the cylindrical portion of the pin, the feed rate is slowed further to provide the proper conditions for the heavy removal of stock from the pin. When grinding has progressed to the point at which the pin has been cleaned up by the wheel, the steadyrest on the front of the machine moves forward to support the crankshaft for the remainder of the operation.

The wheel slide continues to advance until the diameter of the crankpin is close to final size. An in-process gage, which is brought into position shortly after the steadyrest moves

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forward, signals when final diameter size is approaching. The feed rate is reduced to a level appropriate for the sizing operation, and grinding continues until the crankpin diameter is within a few ten-thousandths of an inch (about 0.007 mm) of size. Again, a gage signal is produced, and the wheel slide is stopped. As the pressure between the wheel and workpiece that was built up during grinding is relaxed, a small amount of stock is removed and the correct size is achieved. A final trip point on the gage senses this and causes the wheel slide to be withdrawn and reset for the next cycle.

After the first pin is ground, the steadyrest is withdrawn and the work rotation stopped. The table is indexed to bring the second pin in front of the grinding wheel. The jaws of the chucks are opened, and the crankshaft is rotated automatically or manually for the angular position of the second pin. The indexing mechanism is locked, the endwise location of the crankshaft is effected, and the chucks' jaws are closed. The second crankpin is then ground through a feeding cycle similar to the one employed for the previous pin.

Repetition of the positioning, indexing, and feed cycling permits the remainder of the crankpins to be ground. When the last pin is finished, the crankshaft is removed from the machine and the machine mechanisms are returned to their starting condition. Typically, the wheel is dressed at this time, although more or less frequent dressing may be dictated by the operating conditions.

The degree of automation employed in crankpin grinding depends on the lot size of shafts to be produced. Small lots are usually ground on semiautomatic machines on which the operator controls the table and angular indexing motions, while the cycling of the wheel slide is done automatically. For mass production, fully automatic crankpin grinders are used. On these machines, the operator merely loads and unloads the machine; the table position and angular indexing are accomplished with powered mechanisms cycled in with the wheel feed. If automatic loaders and unloaders are added, a group of crankgrinders can be overseen by a single operator.

Wheel-infeed functions for the various amounts of feed, stock-removal rates, and dwells can be set on some machines through numbered thumb-wheel switches, or they can be controlled by hard-wired circuit boards. Wheel-feed movement is by a stepping motor connected to the feed screw. For precise control of feed rates and dwell timing, the solid-state control uses a crystal-controlled oscillator. Radial indexing of crankshafts "on the fly" (while the shafts are being automatically moved laterally to grind subsequent crankpins) is also available.

Centerless cylindrical grinders. Centerless grinding is different from center-type grinding in that the workpiece is not held physically in place while it is being ground. Instead, it rests on a workrest blade and is backed up by a regulating wheel. Machines such as these consist primarily of a bed, a wheelhead, upper and lower slides, and a regulating wheel housing. Centerless machines are built in various sizes; however, unlike the center-type machines, they all operate the same way. Also, they all can be used for either toolroom or high-production grinding.

Centerless grinding eliminates the need for workpiece center holes, drivers, or workhead fixtures that are required in the other two cylindrical-grinding methods—center-type and chucking-type. Much of the tooling for the job is accomplished in the truing of the grinding and regulating wheels, and some capability exists for additional fixturing in the steadyrest geometry and the work stops and supports.

In centerless grinding, the grinding wheel drives the workpiece while the regulating wheel controls the work speed. The regulating wheel must have sufficient friction to prevent the workpiece from running away with the grinding wheel. The grinding wheel, regulating wheel, and work rest are placed in a way so that the workpiece is constrained at all times. In the axial direction, the work is held by special stops, by an adjacent workpiece, or by friction in the axial direction produced by the regulating wheel. This makes centerless grinding amenable to both long bars and short cylindrical pieces which can be stacked next to each other. Examples of the former are ground bar stock and tubing; examples of the latter are ball-bearing races and automobile engine piston pins.

Theory of centerless grinding. The three elements of a centerless grinder—the grinding wheel, regulating wheel, and workrest—are illustrated in Fig. 11-54.

The work lies between the two wheels—a grinding wheel of the correct size to fit the machine and of specifications appropriate to the material and nature of the work and a regulating wheel. The regulating wheel serves as both a driving wheel and a brake, rotating the work at a constant surface speed equal to that of the regulating wheel.

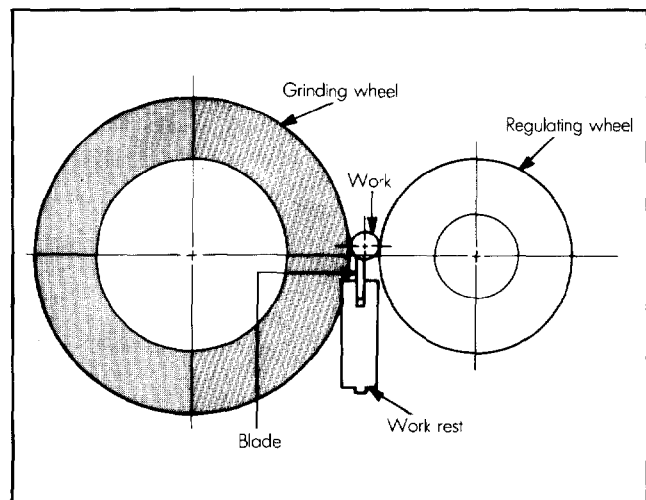


Fig. 11-54 Wheel and work movements in centerless cylindrical grinding.

The workrest blade, which supports the work between the two wheels, is adjustable to raise or lower the center of the work in relation to the centerline of the grinding wheel and the regulating wheel. When the work is to be ground cylindrically, the workrest blade height is usually adjusted to raise the center of the work above the centerline of the wheels an amount equal to 50% of the work diameter on small-diameter parts and to 1/2" (12.7 mm) maximum for work over 1" (25.4 mm) diam. The distance between the grinding wheel and the regulating wheel controls the diameter of the work; the height of the center of the work in relation to the centerline of the wheels controls the roundness of the work. Figure 11-55 illustrates this phenomenon. This setup shows the center of the work in line with the centerline of the wheels and a flat-top blade. The surface of the wheels contacting the work and the flat-top blade form three sides of a square. As the work is rotated, any high spot coming in contact with the regulating wheel pushes the work into the grinding wheel, causing a diametrically opposite

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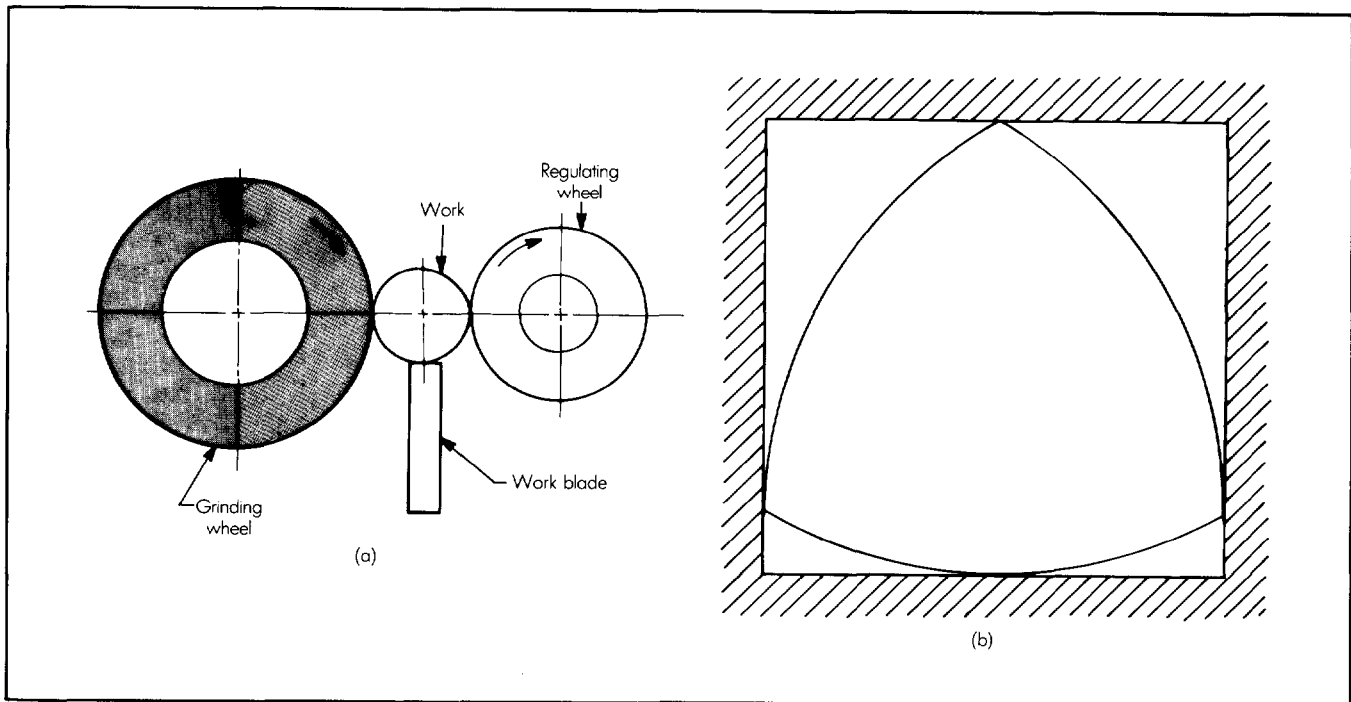


Fig. 11-55 (a) Effect of out-of-round work resting on flat top blade, with work on center. (b) Exaggerated shape generated by such a setup.

low spot. With this setup, the work is not ground round, although it gages perfectly. This setup creates a shape like a rounded 120° triangle.

When work is to be checked for this out-of-round shape, it must be put in a 120° V block and rotated with an indicator in contact with it. When checked in a 90° V block, with micrometers or by snap gages, this defect in geometry is not detected.

When the center of the work is raised above the centerline of the wheels by raising the workrest blade; any high spot on the work coming in contact with the regulating wheel pushes the work into the grinding wheel, creating a low, but not diametrically opposite, spot. As the work is rotated, the high and low spots do not occur opposite each other as they do when the center of the work is on the centerline of the wheels. Instead, a gradual rounding takes place. Maximum rounding action occurs when an angled blade is used, as shown in Fig. 11-56.

The higher the work is positioned above centerline of the wheels, the quicker the rounding action. However, if the work is too high, chatter develops from the work being squeezed up from between the wheels or raised off the blade and dropped back on it rapidly. Since the height of the center of the work above the centerline of the wheels controls roundness, it may be necessary to set the blade extra high to grind a particular part within a specified tolerance. When this condition exists, an extra soft grade of wheel will help to prevent chatter that results when the work is too high above the centerline of the wheels. The soft wheel reduces the contact pressure, which reduces the tendency to lift the work from the blade.

When long work such as steel bars or tubing that is not straight is ground, the workpiece will whip and chatter. Better results can be obtained by lowering the blade to position the center of the work below the centerline of the wheels for the first pass and then raising to put the center of the work above the

centerline of the wheels for additional passes to round up the work and grind it to size. When ground below the centerline of the wheels, the work is held down firmly against the blade by the wheels, thus the tendency of the bar to whip and chatter is reduced. If straight bars are required, they must be straightened before being ground since bent or crooked bars cannot be corrected by a centerless grinder.

In general with respect to workrest blade material, it is advisable to start with a hard material like sintered carbide and, if it shows any tendency to "pick up" and score the work, to compromise on the hardness gradually by using a softer blade material. Sintered-carbide and hard-bronze blades usually give

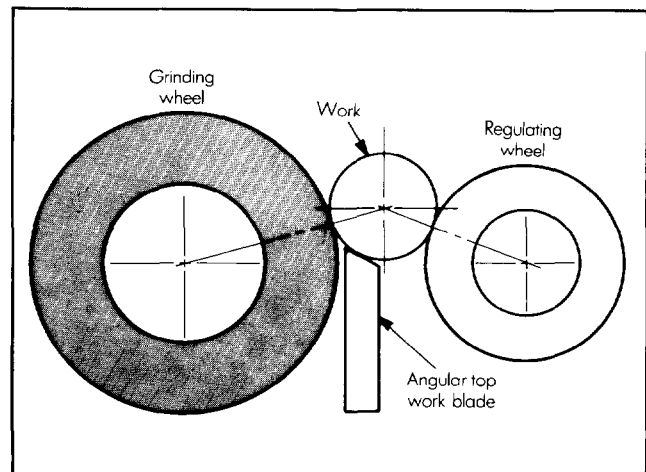


Fig. 11-56 Centerless grinding setup that produces maximum corrective rounding action.

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good results when used in grinding stainless steel. High-speed steel blades are well suited for nonferrous metals, for parts which vary in hardness from one end to the other, and for very small diameter parts. Meehanite and cast iron blades are sometimes used for soft-steel work.

Most centerless grinding is done with an angled-top blade. The angle of the blade should be varied to match the diameter of the work. The larger the work diameter or the longer the blade, the flatter the blade angle. Smaller diameter work requires a steeper blade angle. By using the steeper blade angle, more pressure is put on the regulating wheel, giving it more control of the rotating speed of the work. This prevents the work from picking up the speed of the grinding wheel. However, this also increases the side pressure on the workrest blade, and especially on narrow workrest blades. Too steep an angle can cause the blade to deflect under the pressure, thus developing chatter. For work 1/2" (13 mm) diam or larger, a blade angle of 20-30° is generally satisfactory.

Throughfeed grinding. Throughfeed grinding is performed by passing the workpiece between the grinding wheel and the regulating wheel, with a lateral or axial movement of the work past the grinding wheel as shown in Fig. 11-57. The speed,

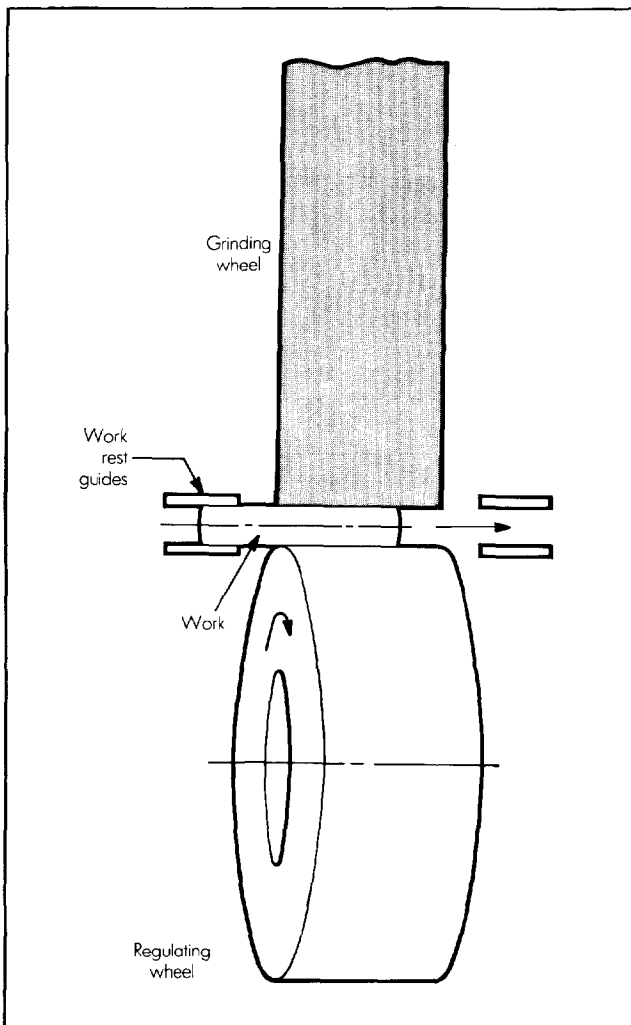


Fig. 11-57 Top view of throughfeed centerless grinding setup.

diameter, and angle of inclination of the regulating wheel determine the work traverse rate. This traverse rate can be approximated by multiplying the diameter of the regulating wheel by 3.14 times the rpm of the feed wheel, times the sine of the angle of inclination of the feed wheel (angle α in Fig. 11-58). For the fastest and smoothest roughing, a slow regulating-wheel speed with a large angle of inclination is used. In finish grinding, the angle of inclination should be reduced and the regulating wheel speeded up to give the wheel more time to cut the material and longer sparkout time to produce better finishes.

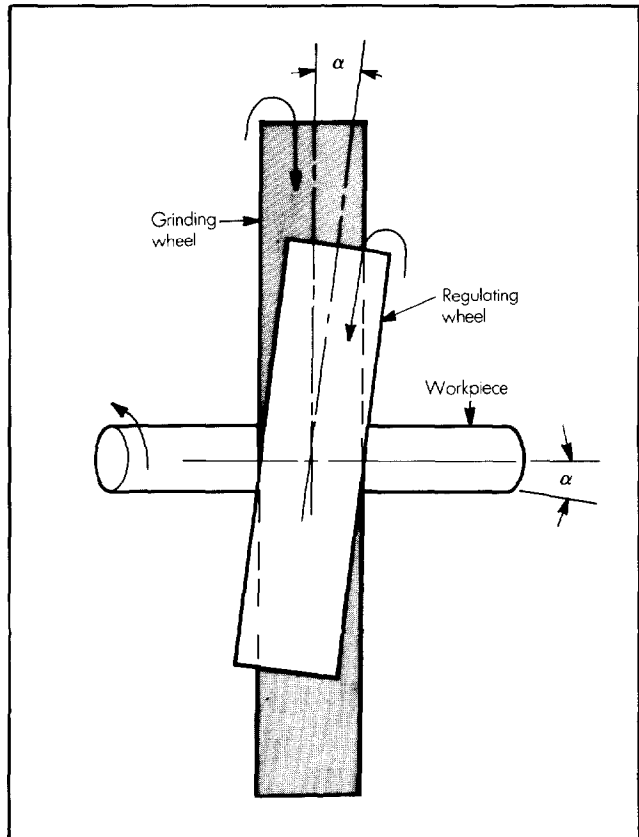


Fig. 11-58 The angle of inclination, α , the speed, and the diameter of the regulating wheel determine the traverse rate of the workpiece in throughfeed centerless grinding.

The α angle can be varied from 2° below to approximately 8° above a line relative to the axis of the grinding-wheel spindle. It is often necessary to pass work between the wheels more than once to remove the stock and get the straightness, roundness, and finish required. The throughfeed workrest holds the work blade and has adjustable guides at both the front and rear of the wheels to direct the work in a straight line into and from the wheels.

General-purpose regulating wheels, 2A80-R-BR, have proved satisfactory for most throughfeed work. Harder grades and finer grain sizes are available for special application when needed. The harder grades are used when the regulating wheels must be very thin and when the general-purpose grade deflects under the pressure of the grind. Harder grades offer some advantage when work must be ground to very close tolerances.

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They also are advantageous if the regulating wheel wears excessively when two or more diameters are ground and one is much larger than the other. In this case, the difference in sfm (m/s) causes one of the diameters to slip or skid in contact with the wheel. The general-purpose grade gives a better drive or braking action and resists spinning more than the finer, harder wheels on average work. The average starting speed of the regulating wheel is 22-39 rpm, and for general-purpose work the angle of inclination of 3° is recommended as a starting point.

However, both the angle and wheel speed can be changed to suit specific conditions. The steeper the angle, the faster the traverse rate; the flatter the angle, the slower the traverse rate. The wheel speed also affects the traverse rate. The faster the wheel speed, the faster the traverse rate; conversely, the slower the wheel speed, the slower the traverse rate. For work that is warped from hardening or machining, the best straightening effect can be obtained by using a high traverse rate or by increasing the angle of the regulating wheel. For work that is straight, but out-of-round, a faster rounding-up action can be obtained by using a higher regulating wheel speed and a flatter angle. This does not necessarily mean less production from the machine, because increasing the wheel rpm and reducing the angle of the regulating wheel could give approximately the same traverse rate.

Taper on the front end of the workpiece in throughfeed operations generally results from the work guides on the entrance side being deflected toward the regulating wheel. Taper on the rear end of the workpiece is usually caused by the guides on the exit side being deflected toward the regulating wheel. If both the entrance and exit-side work guides are deflected toward the grinding wheel, concaved or hollow-shaped work is produced. Improper truing of the regulating wheel is another cause of tapered or concaved work. Faulty truing in turn can usually be traced to improper setting of the truing fixture.

Work guides must be properly adjusted to obtain good results in throughfeed grinding. For all throughfeed work, the bearing surface of the workrest guides on the regulating wheel side should be set parallel and in line with the face of the regulating wheel. To accurately set the regulating wheel guides (front and rear), use an aligning bar or other shaft that is straight within 0.0001" (0.003 mm), approximately the same diameter as the workpiece, and as long as the width of the regulating wheel plus the length of the front and rear guides should be used.

To set up the machine to grind the workpiece, the following steps are taken. The blade is set for height above the centerline of the wheels, the regulating wheel housing is set to the feed angle to be used, and the regulating wheel is timed. The regulating wheel guides are then backed off, and the aligning bar placed on the blade. The regulating wheel is adjusted to support the aligning bar so that it does not contact the grinding wheel.

Two small wooden wedges are placed between the grinding wheel and the bar to hold the aligning bar against the face of the regulating wheel. The regulating wheel guides are then brought forward until they lightly contact the aligning bar. A feeler gage should be used to determine if a full line contact is obtained between the workrest guides and the alignment bar. The workrest guides on the grinding wheel side are adjusted to 1/64 to 1/32" (0.4 to 0.8 mm) clearance since the work does not contact these guides, as shown in Fig. 11-59.

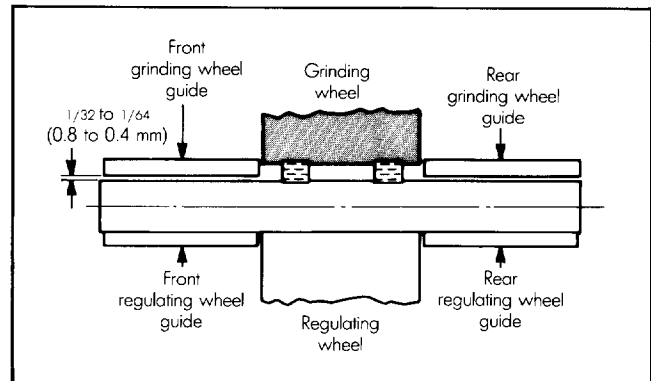


Fig. 11-59 Setup for adjusting work guides in throughfeed centerless grinding.

The regulating wheel must be trued to a special shape so that the work, while passing between the wheels, makes a straight-line contact with the wheel face. Four factors must be considered for the truing unit to be set to form this shape:

1. Angle of inclination of the regulating wheel.
2. Location of the center of the work with respect to the centerline of the grinding and regulating wheels.
3. The angle to which the regulating wheel truing slide is swiveled.
4. The amount the diamond holder is set over.

The third and fourth factors listed are based on the ratio of the diameter of the regulating wheel and the diameter of the workpiece. The ratio is determined by dividing the diameter of the regulating wheel by the diameter of the workpiece. After this ratio is established, Table 11-18 should be referenced to determine the correct truing angle for the truing slide and the correct diamond holder setting for dressing the special shape required on the regulating wheel.

For example, in using the chart for a setup with a 3° angle of inclination, 2" (50.8 mm) work diameter, 1/2" (12.7 mm) height above center, and 12" (305 mm) diam regulating wheel, the ratio is determined by dividing the diameter of the regulating wheel by the diameter of the work ($12 \div 2 = 6$ ratio). In referencing Table 11-18, the ratio of 6 should be noted. Reading up on the chart to the line extending from 3° in the leftmost column, the angle to the swivel truing slide would be $2^\circ 50'$. The diamond holder setting is determined by reading down on the chart from ratio 6 to the line extending from the 1/2" (12.7 mm) work height above center. The diamond holder setting would be 15/32" (11.9 mm) above center, as shown in Fig. 11-60.

The rate of travel of the truing tool to dress the regulating wheel is approximately 1-2 ipm (25.4-50.8 mm/min). The highest regulating wheel speed should be used when truing.

Infeed grinding. This method, similar to plunge grinding on a center-type grinder, is usually employed when grinding work that has a shoulder, head, or some portion larger than the ground diameter. It is also used when grinding work with multiple diameters, taper, any irregular profile, or groove requirements. There is no relative axial movement of the work, and the length of the grind is limited to the width of the grinding wheel. If the grind length is longer than the width of the wheels and the work must be ground only a short distance from each end, one end of the work is supported by the workrest blade; the other end rests on an outboard roller support.

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TABLE 11-18
Trueing Angles and Heights Above Center for Regulating Wheel Trueing

Work Feed Angle	Trueing Angle Setting									
	7°	6° 10'	6° 10'	6° 20'	6° 25'	6° 30'	6° 35'	6° 45'	6° 50'	6° 55'
6°	5° 15'	5° 15'	5° 15'	5° 25'	5° 30'	5° 35'	5° 40'	5° 45'	5° 55'	5° 55'
5°	4° 20'	4° 25'	4° 30'	4° 35'	4° 40'	4° 40'	4° 50'	4° 55'	5°	5°
4°	3° 30'	3° 30'	3° 35'	3° 40'	3° 45'	3° 45'	3° 50'	3° 55'	4°	4°
3°	2° 35'	2° 40'	2° 40'	2° 45'	2° 50'	2° 50'	2° 55'	2° 55'	3°	3°
2°	1° 45'	1° 45'	1° 50'	1° 50'	1° 50'	1° 55'	1° 55'	2°	2°	2°
1°	50'	50'	55'	55'	55'	55'	55'	1°	1°	1°
Ratio D/d	3	3.5	4	5	6	7	12	18	24	48
Work Height Above Center	1/8 (3.2)	7/64 (2.8)	7/64 (2.8)	7/64 (2.8)	7/64 (2.8)	7/64 (2.8)	1/8 (3.2)	1/8 (3.2)	1/8 (3.2)	1/8 (3.2)
	1/4 (6.3)	7/32 (5.5)	7/32 (5.5)	7/32 (5.5)	15/64 (5.9)	15/64 (5.9)	15/64 (5.9)	15/64 (5.9)	1/4 (6.3)	1/4 (6.3)
	3/8 (9.5)	21/64 (8.3)	21/64 (8.3)	11/32 (8.7)	11/32 (8.7)	11/32 (8.7)	23/64 (9.1)	23/64 (9.1)	23/64 (9.1)	3/8 (9.5)
	1/2 (12.7)	7/16 (11.1)	7/16 (11.1)	29/64 (11.5)	29/64 (11.5)	15/32 (11.9)	15/32 (11.9)	31/64 (12.3)	31/64 (12.3)	1/2 (12.7)
	5/8 (15.8)	35/64 (13.9)	35/64 (13.9)	9/16 (14.3)	37/64 (14.7)	37/64 (14.7)	19/32 (15.1)	19/32 (15.1)	39/64 (15.4)	5/8 (15.8)
	3/4 (19.0)	21/32 (16.6)	21/32 (16.6)	43/64 (17.0)	11/16 (17.4)	45/64 (17.8)	45/64 (17.8)	23/32 (18.2)	47/64 (18.6)	47/64 (18.6)
	7/8 (22.2)	3/4 (19.0)	49/64 (19.4)	25/32 (19.8)	51/64 (20.2)	13/16 (20.6)	53/64 (21.0)	27/32 (21.4)	55/64 (21.8)	55/64 (21.8)
	1 (25.4)	55/64 (21.8)	7/8 (22.2)	29/32 (23.0)	59/64 (23.4)	15/16 (23.8)	15/16 (23.8)	61/64 (24.2)	63/64 (25.0)	63/64 (25.0)
Diamond Holder Setting										

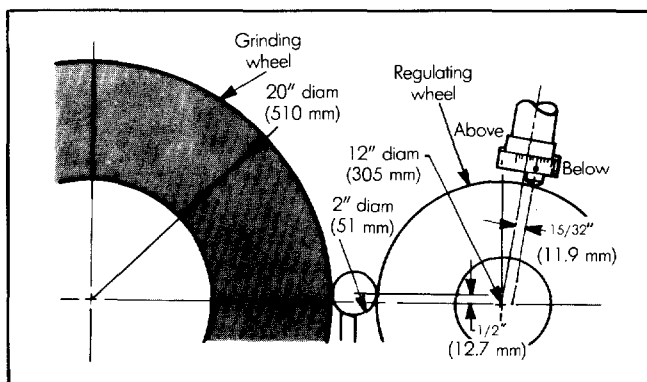


Fig. 11-60 Setup for trueing the regulating wheel in through-feed centerless grinding.

In infeed grinding, the wheel is dressed to match the form of the part. Because the work does not traverse across the wheel face, the regulating wheel is set with only a slight angle to keep the work against the end stop. The part is laid on the work

blade and regulating wheel and against the end stop, either manually or mechanically, and advanced into the grinding wheel (see Fig. 11-61).

When the work is ground to size, the regulating wheel is moved back away from the grinding wheel; either a manual or automatic ejector kicks the work out from between the wheels. Then the operator or an automated loading device places another piece in position.

End feed grinding. This method is used on tapered or straight work. The grinding wheel, regulating wheel, and workrest blade are set in fixed relation to each other, and the work is fed from the front, either manually or mechanically, to a fixed end stop. The grinding wheel or the regulating wheel, or both, must be trued to the proper taper (see Fig. 11-62).

Combination infeed and throughfeed grinding. In some applications, the infeed and throughfeed grinding methods can be combined to achieve increased production efficiency. This relatively special technique is sometimes used for:

1. Parts that are more conveniently ground in a single pass, but require too large a stock removal for conventional throughfeed grinding.

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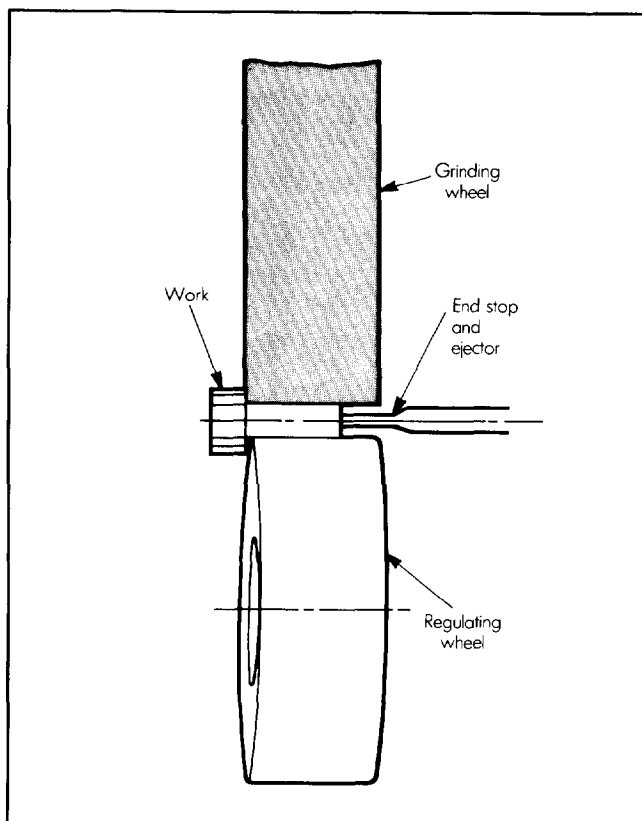


Fig. 11-61 Top view of infeed centerless grinding.

2. Parts that have two diameters. Combination grinding is used to process the smaller diameter on such parts, where the portion to be ground exceeds the width of the grinding wheel (see Fig. 11-63).
3. Parts that are warped, in cases where the warpage or bow does not exceed the total stock removal, and the length of the part is less than the width of the wheels.

General-purpose centerless grinders. The centerless grinder illustrated in Fig. 11-64 is typical of the general-purpose centerless grinder in use today. Machines of this type, sometimes called universal centerless grinders, can grind a wide variety of workpieces, using either infeed and throughfeed methods. Typically, machines of this class are not designed for high-production, automatic operation, but are characterized by versatility. The machines are designed for relatively quick set-up changes, even when the new setup requires a different grinding wheel, regulating wheel, or truing cam.

Production-type centerless grinders. The vast majority of centerless grinders in use today are of the type illustrated in Fig. 11-65. Machines of this class are specifically designed for high productivity grinding, featuring automatic loading and unloading devices, special wheel dressing techniques, automatic gaging, etc. In recent years, production-type centerless grinders have been introduced with wider wheels, larger diameter wheels, and higher horsepower capacity to handle larger stock-removal requirements.

Figure 11-66 illustrates a production-type, heavy-duty centerless grinder featuring an angular bed design. This distinguishing characteristic provides greater contact pressure between the

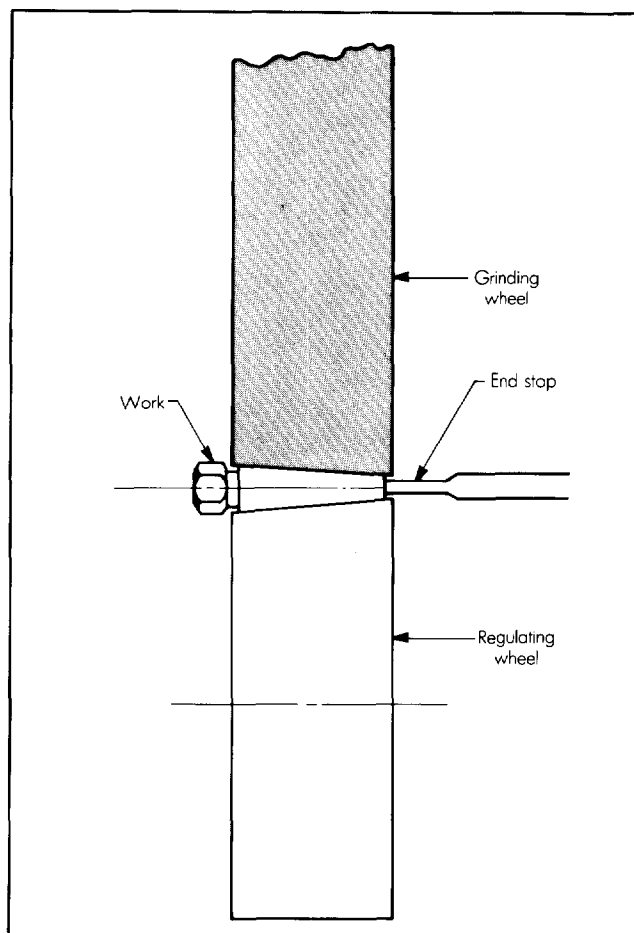


Fig. 11-62 Top view of endfeed centerless grinding.

work and the regulating wheel which assures positive braking action for heavy cuts. Typically, machines of this design are used to grind large, heavy workpieces or thin-walled rings and cylinders.

Shoe-type centerless grinders. Special machines called shoe-type centerless grinders, sometimes called external form grinders, have been developed primarily for the bearing industry. The grinding principle is the same as in centerless grinding, but the workpiece is supported on two shoes and is driven by a magnetic chuck. These machines are high-production units, with tooling designed to handle a specific part such as bearing races. Applications are limited as to the size and configuration of parts that can be ground. Machines such as these consist of a bed, tilting wheelhead, and workhead unit for holding the parts to be ground (see Fig. 11-67).

In shoe-type centerless grinding, the work is offset from the center of the driver; thus, the work constantly slips on the driver face and is forced against the shoes. The drive may also be a roller, as when grinding stainless steel races. Supporting shoes may be located outside, or in the case of delicate parts, inside the part and directly opposite the grinding force.

Many production grinders of this class can easily be converted from chucking-type operation to shoe-type operation with a simple change in tooling. These machines are used for the grinding of single, or double-row ball tracks, thrust bearing

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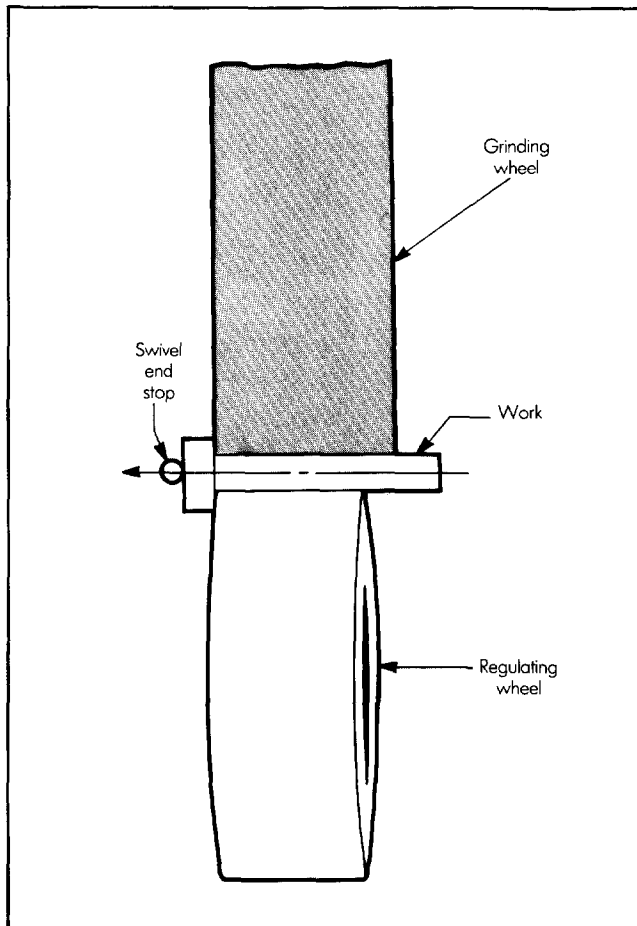


Fig. 11-63 Top view of combination infeed and throughfeed grinding.

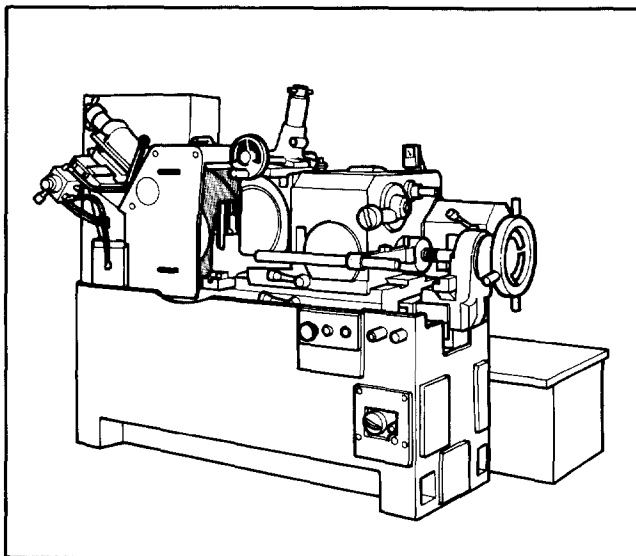


Fig. 11-64 General-purpose centerless grinding machine that can be changed over from infeed grinding to throughfeed grinding. (Cincinnati Milacron)

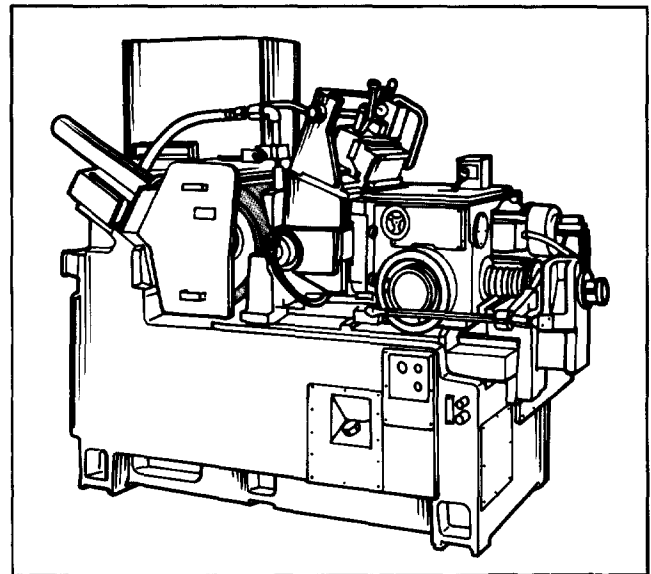


Fig. 11-65 Production-type centerless grinder for high volume, high-productivity applications. (Cincinnati Milacron)

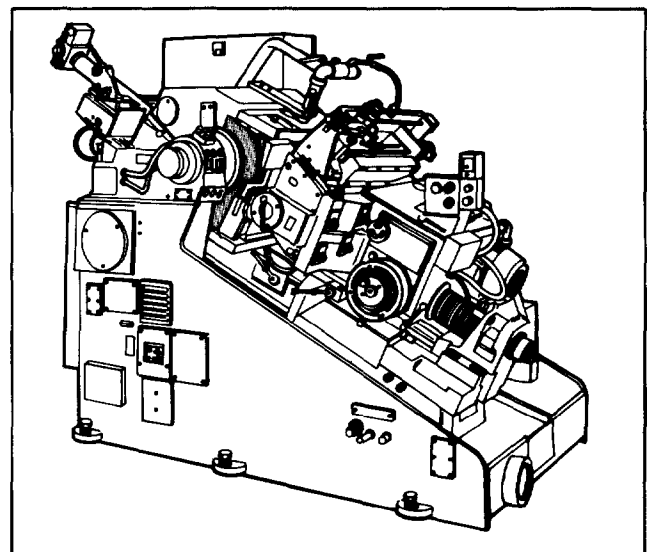


Fig. 11-66 Production-type centerless grinder with angular bed design for heavy, large workpieces. (Cincinnati Milacron)

raceways, cylindrical roller-bearing inner races, the lip and track on tapered bearing cones, and spherical or other contoured shapes.

Internal Grinders

Internal grinding is generally used to produce precision holes in workpieces. Straight or tapered, blind or through holes are produced by the process. Also, internal grinders are used to produce holes with multiple IDs, internal shapes, contours, and flat sections. Often, internal grinding is applied to bring holes to final shape and surface finish, correcting variations in geometry caused by previous operations.

The internal grinding process is conventionally used to grind hardened workpieces. Holes in hardened parts can also be

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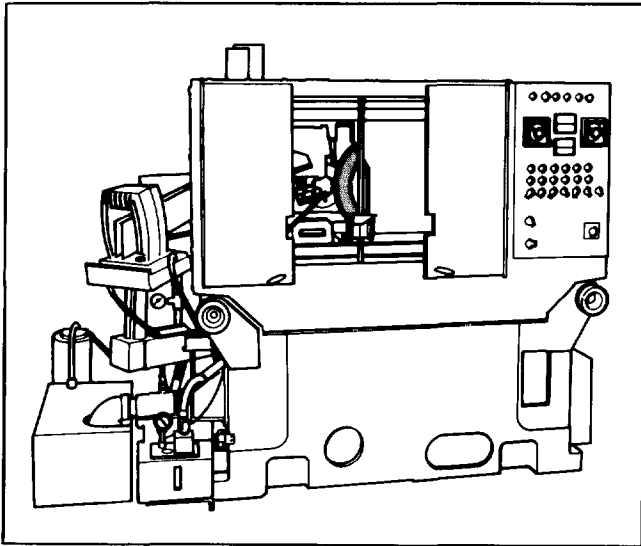


Fig. 11-67 Shoe-type centerless grinder. (Bryant)

finished by honing or lapping, but neither of these processes correct significant errors in bore geometry or location (see Volume III of this Handbook series, "Materials and Finishing"). With internal grinding, stock removal rates are greater than the stock removal rates possible with either honing or lapping; for this reason, grinding is often preferred when applicable.

Stock removal. Amount of stock left in a hole for grinding is a function of several variables including the size, length, and out-of-roundness of the unground holes, distortion from heat treatment, and depth of decarburization. To minimize grinding costs, the amount of stock is selected just large enough to ensure a clean grind. (A method of determining stock removal allowances in relation to tolerance stack-ups on a workpiece is presented in Chapter 2 of this volume, "Tolerance Control.")

Generally, longer bores require more stock allowance as do holes which are out-of-round or have to be held closely with respect to location or concentricity to other axes or surfaces on the workpiece. For a bore-length ratio of up to 2, mean values for diametral grinding stock allowance are usually 0.010" (0.25 mm) for 1" (25.4 mm) diam holes, 0.020" (0.51 mm) for 5" (127 mm) diam holes, and 0.030" (0.76 mm) for 8" (203 mm) diam holes.

A typical grinding cycle is to rough grind, at a penetration rate of 0.001-0.002 ips (0.03-0.05 mm/s) to within 0.002" (0.05 mm) of final diametral size, dress the wheel, finish the hole at a radial feed rate of 0.0004-0.0001 ips (0.010-0.0025 mm/s) and spark out for about 1 second or more (depending upon finish or taper tolerance).

On hard-to-grind materials or when stock removal is heavy, it is often necessary to dress more frequently than once per workpiece. Each dressing of the wheel necessitates compensation by moving the wheel toward the dressing tool an amount equal to the amount the wheel was worn during grinding plus the amount to be dressed off the wheel—usually 0.0002-0.001" (0.005-0.03 mm). With easy-to-grind materials, when the stock removal is low and the tolerances liberal, interrupting grinding to dress the wheel may not be necessary. Instead, the wheel can be dressed before the grinding cycle starts. It may even be possible, as in external grinding, to grind a number of parts before the wheel has to be dressed.

With suitable rigid workpieces and holes over 1.5" (38 mm) diam, abrasive machining (heavy stock removal) can also be applied to internal grinding. Larger amounts of stock, for example, 0.250" (6.35 mm), can be plunge-ground economically at penetration rates of 0.005-0.010 ips (0.13-0.25 mm/s), in many cases eliminating prior turning operations. With diamond roll dressing, complicated contours such as ball tracks in bearing races and seal grooves can be plunge-ground from straight bushings.

Surface finish. In most production-type internal-grinding applications, surface finishes of 8-15 μ in. (0.20 to 0.38 μ m) rms are commonly obtained. Surface finishes as fine as 2-3 μ in. (0.05-0.08 μ m) rms can be obtained.

Although internal grinding traditionally has been considered a precision operation, newer internal grinders are characterized by the ability to achieve required close surface finishes in shorter cycle times.

Types of internal grinders. Conventional internal grinders have a horizontal workhead spindle located on the left side of the machine (viewed by the operator) and a wheelhead, which accepts and drives the grinding wheel, on the right side of the machine. On universal-type internal grinders, a longitudinal slide generally moves the wheel axially and a cross slide moves the wheel radially with respect to the work. Both slides are mounted under the wheelhead. Other internal-grinding machines, especially production-type units, may have the longitudinal slide (table) or the cross slide (feed slide) under the workhead.

Degree of sophistication on internal-grinding machines varies from the simplest hand-operated type (toolroom and universal units) to the completely automatic cycling type for high-production grinding, in which feeding, dressing, gaging, and work loading are automatic.

Typical of the smaller type of internal grinders available is the grinder illustrated in Fig. 11-68. The machine features swing over table capacity of about 12" (305 mm) and can be equipped

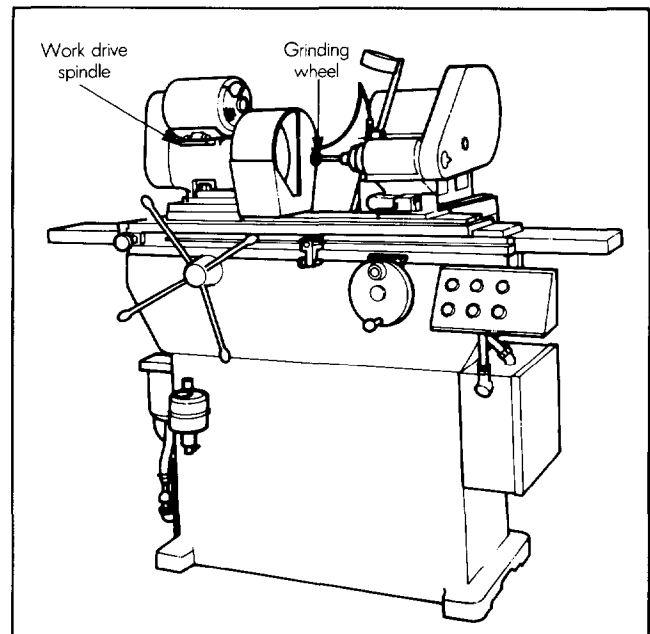


Fig. 11-68 Manual-feed internal grinder for small-size workpiece production in the toolroom or shop. (Parker-Majestic)

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with multiple-jaw chucks; magnetic, diaphragm, or spline chucks; or collets. The spindle drive motor is rated at 1.5 hp (1.1 kW) at 3600 rpm; the workhead motor is rated at 0.25 hp (0.18 kW) at 900 rpm. Machines of this type are particularly effective for grinding small to medium-sized workpieces in small lots.

The semiautomatic internal grinder illustrated in Fig. 11-69 features an automatic swing unit which is cam actuated. The grinder features a 16" (406 mm) table travel with power feed and a 0-3" (76 mm) table reciprocating mechanism; it employs a 1.5 hp (1.1 kW) spindle drive motor. Swing over table capacity is 12" (305 mm).

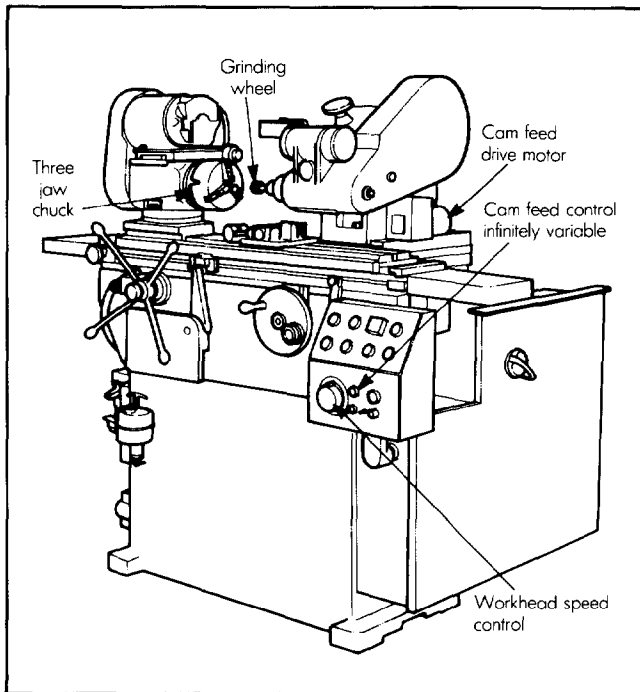


Fig. 11-69 Cam-actuated sizing control on this internal grinder speeds semiautomatic operation. (*Parker-Majestic*)

The internal grinder illustrated in Fig. 11-70 is a semi-automatic grinder which is used for both toolroom and production work. The distinguishing characteristic of this rather special internal grinder is that it can grind bores up to 12" (305 mm) in depth in long parts such as machine-tool work spindles. The work table is designed so that long parts may be held either in the standard hollow work spindle and steadyrest or in a special fixture arranged so that a machine-tool work spindle can be assembled to rotate in its own bearings while the bore is being ground. The work table may be adjusted longitudinally to meet the requirements of the work being ground. For this reason the machine is adaptable not only for grinding long work, but with the workhead moved forward toward the wheel, it can also perform the work of a standard internal grinder. The workhead base may be pivoted to provide for grinding a taper up to a 30° included angle. A facing stop makes possible the grinding of a face during the same chucking as that used for grinding the bore.

The universal internal grinder is used for toolroom and high-production applications in which quick setup and large machine capacity covering a wide range of workpiece types and sizes is required. Machines of this type can grind straight and tapered

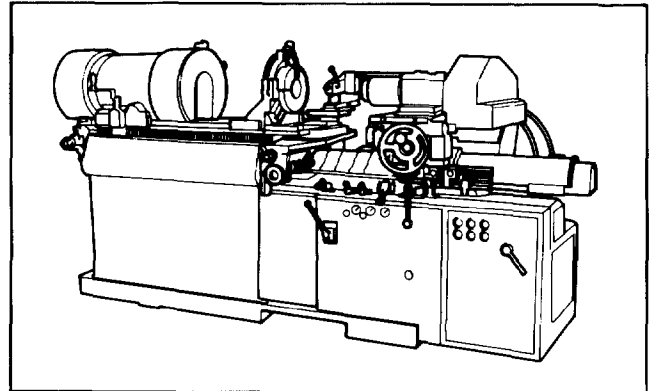


Fig. 11-70 Internal grinder for grinding bores up to 12" (305 mm) long. (*Bryant*)

bores, external diameters, and internal and external faces. In addition, rotary face grinding can also be accomplished. Figure 11-71 illustrates the many configurations available in a line of universal grinders featuring CNC.

For grinding large-diameter workpieces up to 100" (about 2.5 m) and more, the vertical universal type of grinder is particularly well suited because it provides a rotary table with a vertical work spindle (Fig. 11-72). The rotary table may be the faceplate type with radial T-slots or a magnetic surface for holding a variety of parts. Fixtures designed for selected work may be utilized under higher production situations. Typical parts that these machines are designed to grind are gears, sheaves, rings, bearings, spacers, hydraulic cylinders, jet engine parts, and other circular and irregular shapes.

Opposing the vertical work spindle is the vertical grinding spindle and corresponding slide that may be swiveled up to 45° left or right from the vertical position. Tapered holes, mating parts, shoulders, offsets, and undercuts can be ground to high accuracies.

The vertical grinding spindle and slide are, in turn, mounted on a horizontal rail to provide horizontal feeding and positioning. In certain models the horizontal rail is adjustable vertically for additional vertical-grinding capacity.

Vertical internal grinders. The primary advantage of the vertical internal grinder is that it is capable of grinding contoured bores with simple, cam-operated fixtures. Large swing (above 24", 610 mm) and heavy workpiece capabilities are additional advantages for grinding cam rings and crown gears. Loading and positioning of unwieldy parts is easier on this type of machine, and the weight of the work adds to the holding force on the rotary table or magnetic chuck. Vertical internal grinders can also be set up to perform taper, face, OD, and contour grinding.

One of the larger multispindle verticle grinders can be set up to grind parts up to 64" (1625 mm) diam and up to 36" (915 mm) or 52" (1320 mm) work height, depending upon machine arrangement and part configuration. Equipped with two vertical grinding wheel spindles, the machine can process inside and outside work surfaces, faces, grooves, and tapers and can be set up to grind two surfaces simultaneously. One of the grinding spindles can be replaced by a machining compound for boring, facing, turning, chamfering, or grooving. The machining compound can be equipped with a five-tool turret to extend machining versatility. The machine can also be equipped with a horizontal side-head grinding spindle.

CYLINDRICAL GRINDING

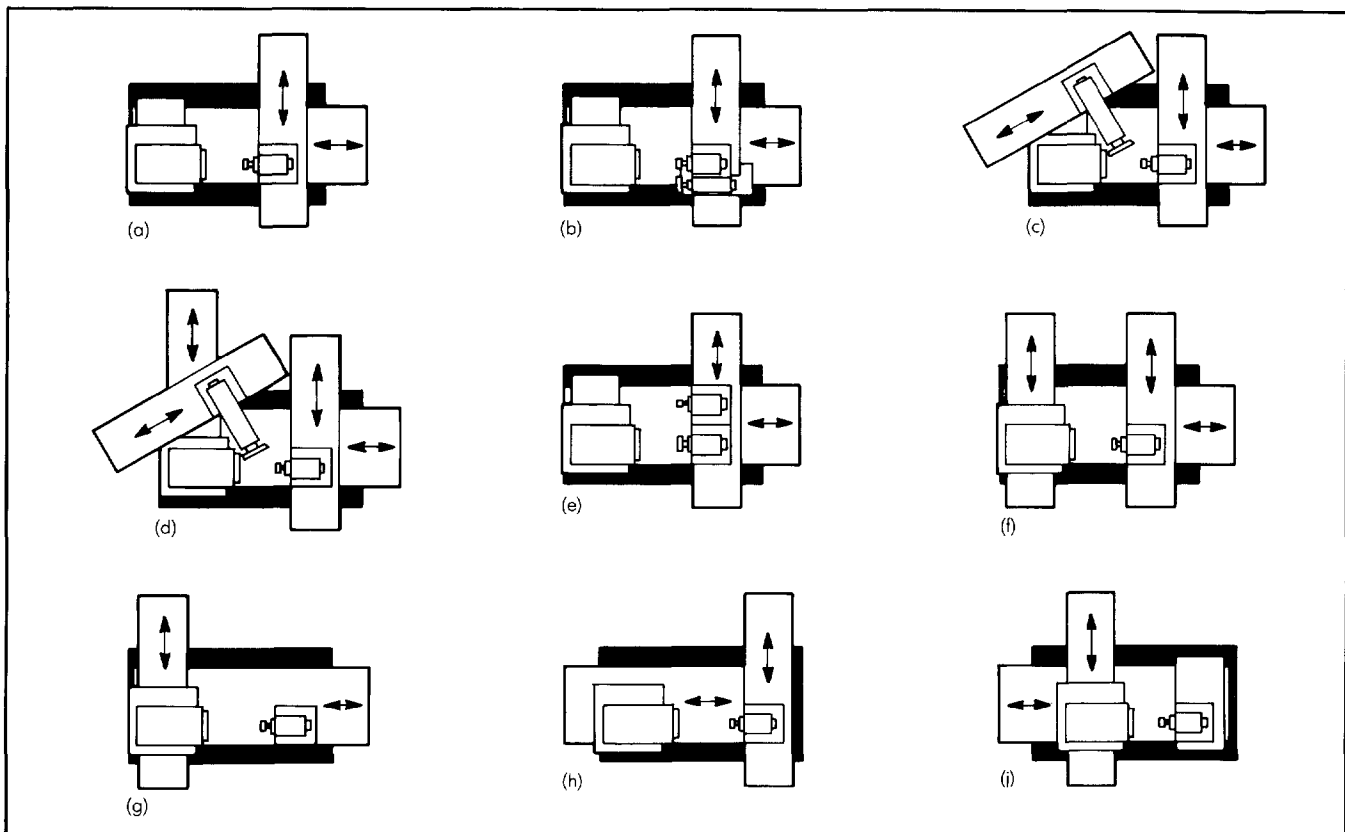


Fig. 11-71 Universal, CNC grinders are available in a wide variety of configurations. One model featuring modular components can provide (a) compound slide under wheel, (b) compound slide under wheel with front facing attachment, (c) compound slide under wheel with rear facing attachment, (d) compound slide under both bore and facing wheels (4 axes), (e) compound slide under two-spindle arrangement, (f) compound slide under wheel with workhead cross slide (3 axes), (g) longitudinal slide under wheel and cross slide under work, (h) cross slide under wheel and longitudinal slide under work or, (i) compound slide under work. (Bryant)

Planetary internal grinders. Internal grinders of the planetary type are generally used for operations in which it is impractical to rotate the workpiece and for jig grinding. On these machines, the wheel describes a planetary motion and is fed radially into the work. An eccentric mechanism increases the orbiting diameter of the wheel to grind the hole to finish size.

The planetary internal grinder illustrated in Fig. 11-73 is typical of the class of grinder used for large workpieces. The machine table reciprocates hydraulically with the length of stroke, and table reversal is automatically controlled by adjustable table dogs. Table speed is infinitely variable up to 14 fpm (4.26 m/min). The cross slide mounted on the table serves as a base for the planetary wheelhead. It provides 36" (915 mm) of travel for horizontal positioning. The outer eccentric of the spindle is positioned for grinding within a 7" (180 mm) vertical range. The machine can be equipped to grind bores from 1 1/4" (31.8 mm) diam to 14 1/2" (370 mm) diam, with maximum hole lengths up to 34" (865 mm), depending upon bore diameter.

Chucking-type vs. centerless internal grinding. Types of devices used for locating, orienting, holding, and driving workpieces are normally dictated by the job. There are two basic workholding principles used in internal grinding. One is the chucking type, in which the workpiece is held rigidly in a fixture on the spindle and is rotated against the grinding wheel.

This is called conventional internal grinding (Fig. 11-74). The other is the centerless type, in which the work center is not coincident with the workhead spindle axis. On this type the work center is determined by the V-block effect of the shoes or rolls which support the part on its OD; work direction is the same as that of the wheel. This is called climb grinding (Fig. 11-75).

Chucking-type internal grinding. For toolroom jobs, faceplates, manually operated three or four-jaw chucks, or collets are generally used. For production jobs, power-operated (hydraulic or air) diaphragm chucks or pullback-finger (axial-clamp) chucks are used. Besides these standard chucks, many special workholding devices, such as balloon, pot, grease, and gear chucks, are available.

Centerless internal grinding. When OD to ID concentricity is critical, for example, in grinding antifriction-bearing races, centerless internal grinding is generally used. If the workpiece is relatively short and the faces are ground, shoe-type tooling, as shown in Fig. 11-75, is used. A magnetic chuck or a faceplate (with axial pressure or roll clamping) drives the workpiece, which is supported on shoes.

Roll tooling is used for internal centerless grinding of relatively long parts, such as bushings, engine-cylinder liners, needle bearings, and workpieces in which faces are not ground. The "on-center" roll centerless principle is illustrated in

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Fig. 11-76. Here the grinding wheel feeds along a common centerline between the work and the regulating roll. Since the workpiece is directly supported by the regulating roll at the line of wheel contact, thin-wall parts can be ground with minimum distortion. However, OD size or shape errors are duplicated in the hole, because this arrangement produces uniform wall thickness. With the "above-center" roll arrangement (Fig. 11-77) wheel and work centers are considerably above the regulating roll center. Here OD size errors and waviness are not directly reproduced in the hole.

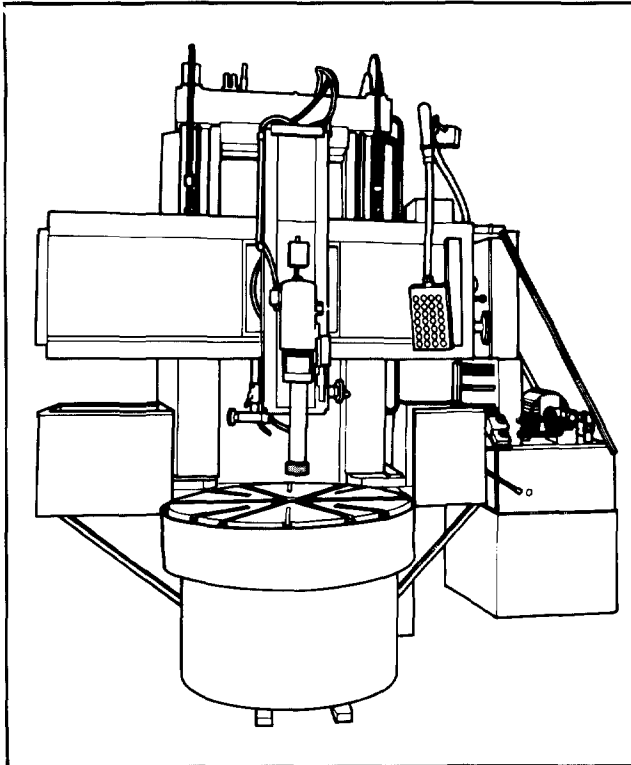


Fig. 11-72 Vertical, universal grinder for large workpieces. (Cone-Blanchard)

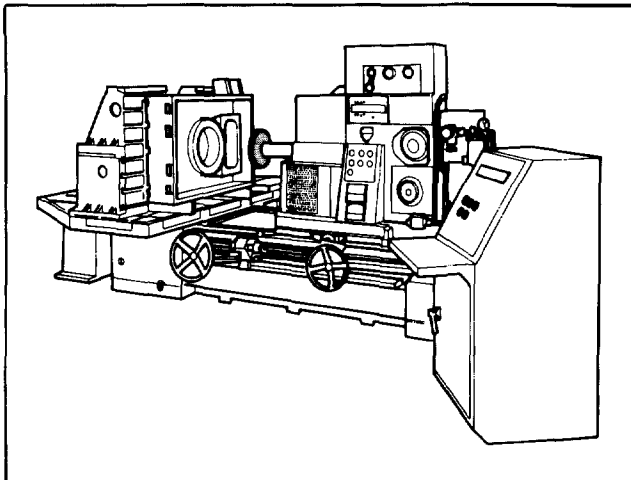


Fig. 11-73 Planetary internal grinder. (Heald)

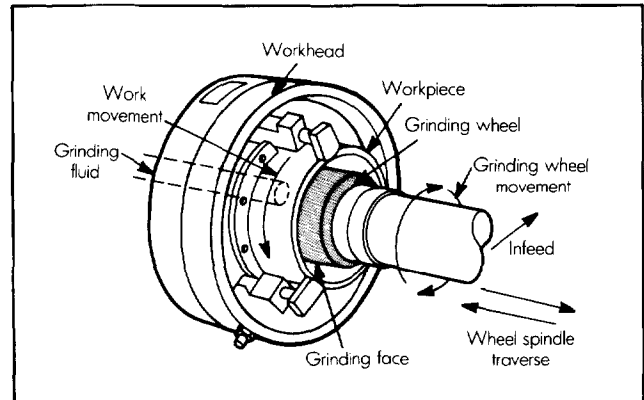


Fig. 11-74 Motions of wheel and work in conventional internal grinding.

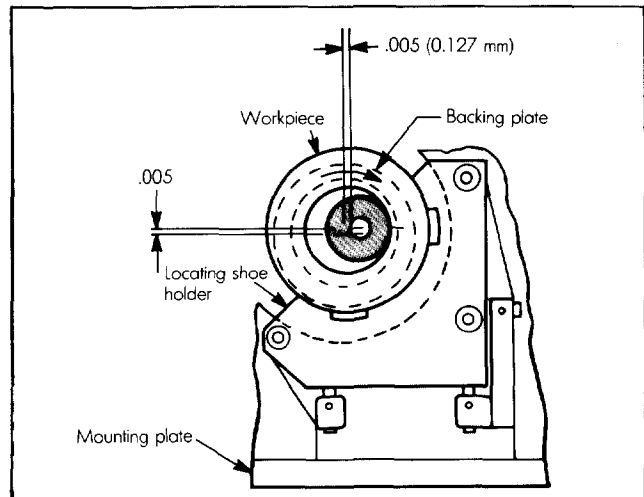


Fig. 11-75 Centerless internal climb grinding in which work center (in relation to workhead spindle) is determined by V-block effect of work-supporting shoes.

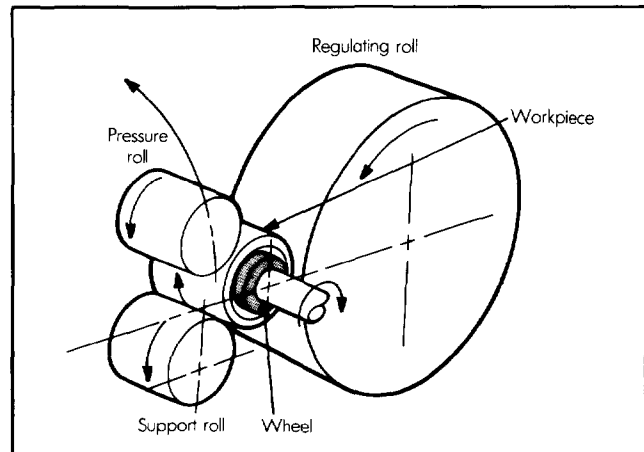


Fig. 11-76 On-center type of internal centerless grinding, which minimizes distortion in finishing thin-wall workpieces.

WORKHOLDING METHODS IN CYLINDRICAL GRINDING

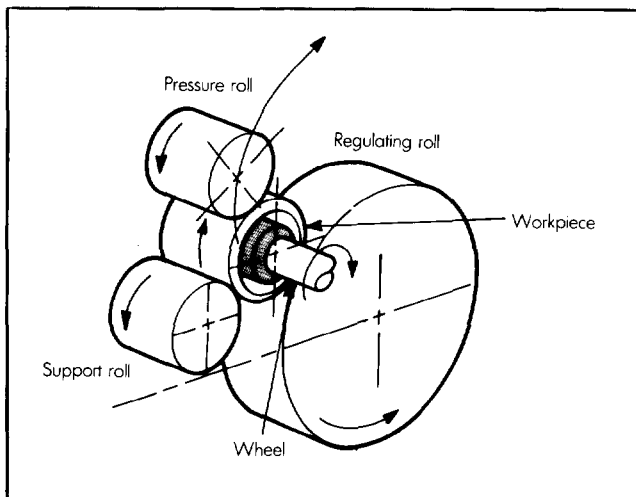


Fig. 11-77 Above-center type of internal centerless grinding, which eliminates direct reproduction of hole-size errors and waviness.

WORKHOLDING METHODS IN CYLINDRICAL GRINDING

The most commonly used workholding devices for general-purpose cylindrical grinding are centers, chucks, mandrels, collets, and faceplates.

Cylindrical grinding fixtures are similar in design to lathe turning fixtures (see "Turning and Boring," Chapter 8 in this volume). There are, however, several unique features of grinding that must be considered when designing a cylindrical grinding fixture. These considerations include the following:

1. Since grinding is essentially a finishing operation when dimensions are held to very close tolerances, accuracy of the fixture is a prime concern.
2. In most cases only a relatively small amount of material is removed; consequently, grinding fixtures do not require the bulk characteristics of machining fixtures.
3. Locating parts properly is very important. However, since most parts to be ground have already been machined, a relatively accurate surface should be available to hold and locate the part.
4. Thin workpieces cannot be permitted to deflect during grinding. If necessary, auxiliary work supports (steady-rests, etc.) must sometimes be used in addition to the fixture to prevent distortion.
5. Heat build-up should be controlled with a proper application of fluid.
6. Grinding fluid nozzles should be selected to deliver a large volume of fluid with minimum pressure. The contact line between wheel and work must be well flooded with fluid.
7. Fixtures must be designed to permit easy removal of fluid and sludge. All pockets in which these materials can accumulate must be eliminated or the balance of the fixture could easily be affected.
8. Fluid nozzles should never inhibit the movement or operation of the fixture.
9. Wheel dressing and truing should be performed without removing the fixture or without seriously reducing the grinding time.

10. Fixtures that are intended to rotate must be balanced. If the fixture cannot be balanced internally, an auxiliary counterweight must be selected and positioned to ensure dynamic balance.

Fixtures used for cylindrical grinding are normally classified by the grinding process they perform or by the type of grinding machine with which they are used. In addition, fixtures may also be classified by their basic construction characteristics. For the purpose of this discussion, the latter method of identification is used to distinguish these fixtures.

Centers

The most common type of workholding device used on cylindrical grinding machines is the center. In practice, the work is actually mounted between centers on the center points (see "Special Grinding Machines and Processes" in this chapter). Centers generally have a 60° point on the workholding end and a taper on the other end which goes into the footstock or headstock. Points on these centers may be either high-speed steel or tungsten carbide. High-speed steel or carbide grinding centers should have some type of lubricant between the center and the workpiece. In some cases, special centers are used in the headstock for driving the workpiece as well as for holding it in position. This can be done only when a live-spindle headstock has been supplied with the machine. This technique eliminates the need for driving dogs or pins.

On all center-type grinding machines, the workpiece and wheel have a negative contact between one another. Viewing the workpiece and grinding wheel from the headstock end of the machine, both the workpiece and wheel would be revolving in a clockwise direction. At the point of contact between the workpiece and wheel, the workpiece would be traveling in one direction and the grinding wheel in the opposite direction. These directions of rotation are maintained to provide solid contact between the dog clamped on the workpiece and the driving pin which sticks out of the headstock. If the headstock rotates in the opposite direction, it would act as a brake to stop the workpiece from rotating. These directions of rotation are useful when grinding is done between centers, since the work is simply supported by the centers (without being actually clamped in place). They are all that gives the work positive drive with the headstock.

Chucks, Collets and Faceplates

Chucks, collets, and faceplates are workholding devices which are sometimes used for fixturing parts that must be cylindrically ground. In most cases the fixtures designed to be used in these workholders are very similar to turning fixtures (see "Workholding for Turning" in Chapter 8, "Turning and Boring" in this volume). The principle difference between these fixtures and turning fixtures is their closer attention to tolerance and balance.

Before chucks can be used in grinding, a live-spindle headstock (workhead) is needed. This means that chucks can be used only on universal center-type grinders or plain grinders with live-spindle headstocks. A four-jaw independent chuck is useful when odd-shaped work must be ground and there are no center holes. When this type of chuck is used, the work must be indicated and each jaw adjusted separately so that the surface to be ground rotates concentrically with the axis of rotation of the headstock spindle. When using a chuck to grind work, the runout in the headstock spindle must also be taken into consideration. As a matter of fact, anytime a live spindle is used,

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the runout in the headstock spindle determines the roundness of the workpiece.

Illustrated in Fig. 11-78 is an example of a fixture designed to be used in either a four-jaw chuck or collet. With this fixture, the part is designed to be mounted between the tailstock center and the center in the fixture. The three set screws are then tightened to provide a positive drive. Fixtures like this are frequently used to hold parts that have only one center hole.

Another fixture of similar design used to hold a punch is shown in Fig. 11-79. Here the part is held on the diameter below the head. This diameter is the critical size. The diameter of the head is relatively unimportant and has a tolerance of $\pm 0.010"$ (0.25 mm). When mounting the part, the upper cap is removed and the punch inserted. The cap is then reinstalled and tightened. The positive drive is accomplished by inserting the punch locator in the fixture.

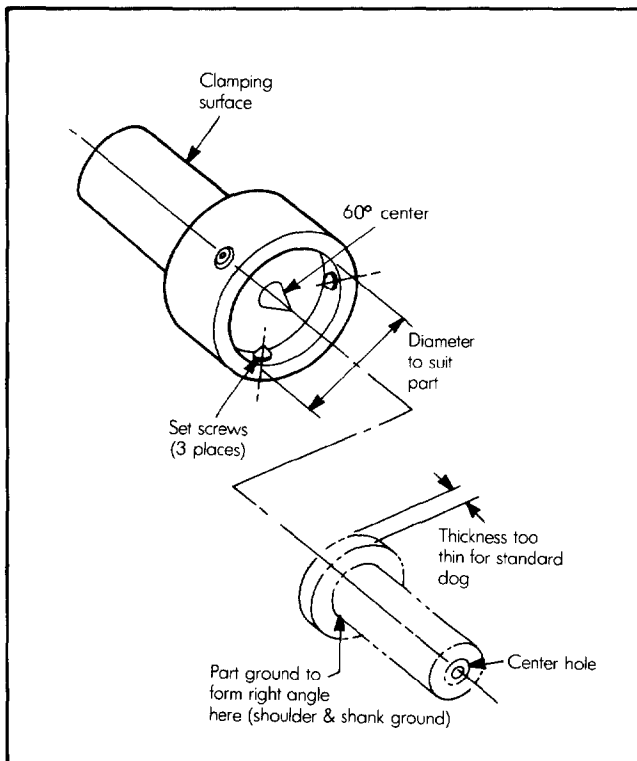


Fig. 11-78 Grinding fixture for parts to be mounted between the workhead center and the center in the fixture.

Mandrels

Mandrels are commonly used for locating and driving workpieces in grinding operations. In addition to providing excellent fixturing, mandrels also provide an accurate method to ensure concentricity between the OD and ID of the workpiece. The principle variations of mandrels commonly used for fixturing are: solid mandrels, expansion mandrels, nut mandrels, and special-purpose mandrels.

Solid mandrels. Solid mandrels are generally used for close tolerance concentric grinding. These mandrels are normally made of tool steel and are hardened and ground with lapped center holes. The gripping area of these mandrels generally has a taper ground to match the tolerance of the part. In cases in which the OD must be concentric to the ID and square to the

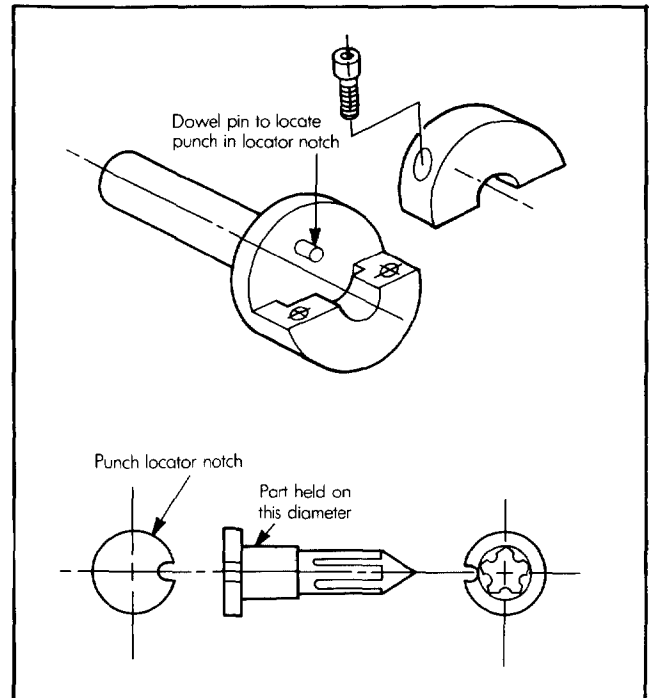


Fig. 11-79 Grinding fixture—cap is removed, the part is installed, and the cap is replaced and tightened to provide location and drive of the workpiece.

sides, a fixture such as that shown in Fig. 11-80 can be used. Here the mandrel is used to mount and drive the part. The sliding sleeve is used to ensure the squareness of the part on the mandrel.

Expansion mandrels. Expansion mandrels are normally used for parts that have a larger tolerance on the ID of the workpiece or for parts that do not have an extremely close concentricity tolerance. Expansion mandrels are capable of tolerances in the range of 0.0003-0.001" (0.008-0.03 mm) TIR. As shown in Fig. 11-81, expansion mandrels are rather simple in design. In Fig. 11-81, the fixture body is made of tool steel and is hardened and ground with ground and lapped center holes. In use, the part is mounted and the set screw is tightened against the rod which exerts pressure against the ball, expanding the mandrel.

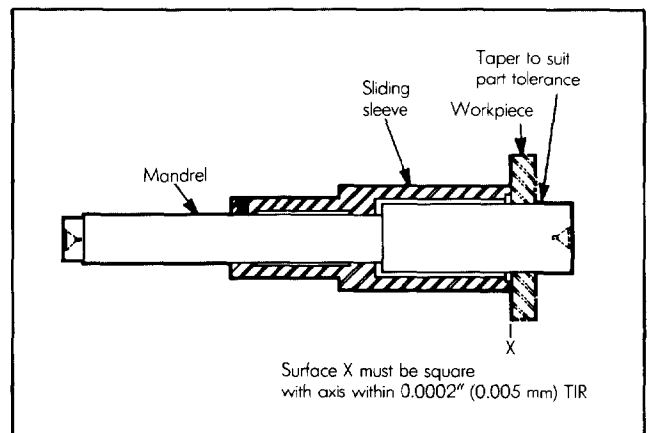


Fig. 11-80 Solid mandrel.

WORKHOLDING METHODS IN CYLINDRICAL GRINDING

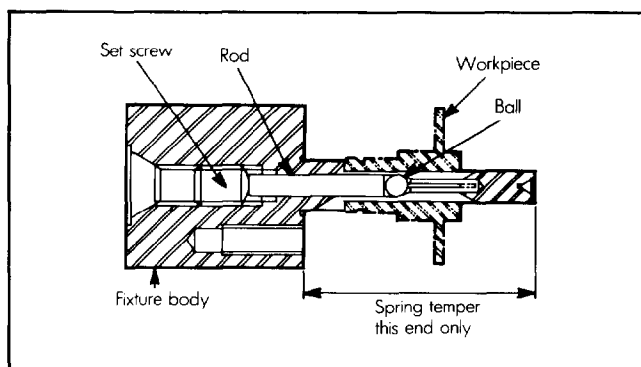


Fig. 11-81 Expanding mandrel.

Another variation of this principle is shown in Fig. 11-82. The mandrel in Fig. 11-82 is activated by a set screw which applies pressure against wedge rods to expand the mandrel. This type of expanding mandrel is normally mounted on a faceplate or in a chuck. In this application the fixture is not removed from the machine to change parts.

Another form of expansion mandrel is shown in Fig. 11-83. This type of expansion mandrel is designed to be used in either a chuck or a collet. To use this type of expansion mandrel, the mandrel OD is first machined to a size slightly larger than the part. The mandrel is mounted in the grinder and expanded. Then the mandrel OD is ground to approximately 0.001" (0.03mm) greater than the workpiece ID. The expansion screw is loosened, and the part is mounted. The screw is then tightened to the proper tension. The principle advantage to using this type of expansion mandrel is cost. These mandrels are made to be thrown away after a single job or are machined to fit a workpiece with a smaller ID.

Nut mandrels. Nut mandrels are similar in design to solid mandrels, the principle difference being the method used to secure the part. Nut mandrels use pressure from either a screw or nut rather than wedge action of a taper, to secure the part to the mandrel. As shown in Fig. 11-84, the basic nut mandrel holds a workpiece by simply applying force to one end of the part and binding it against the opposite side of the mandrel.

A variation of this principle is shown in Fig. 11-85. Here the part is thin walled and could bend or distort from end pressure. In this case a Neoprene bushing is used to hold the part by being compressed by a socket-head cap screw. The important points to remember here are that the bearing surface must be long enough to ensure accurate seating and the washer must be smaller than the ID of the part.

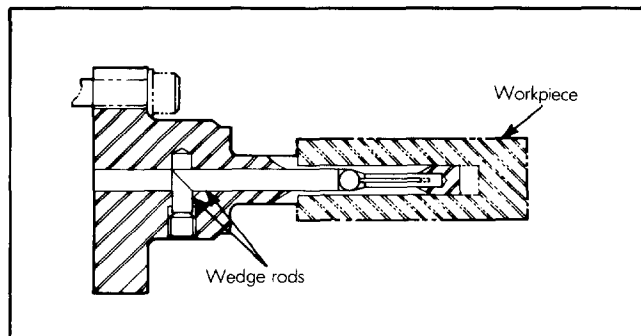


Fig. 11-82 Faceplate expansion mandrel.

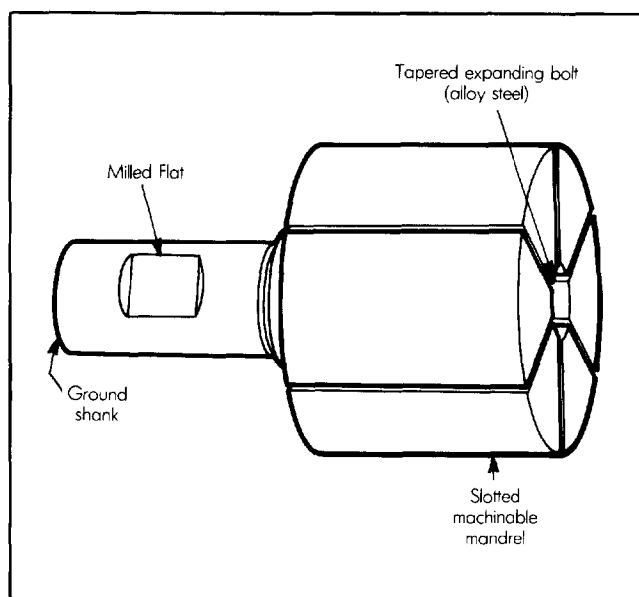


Fig. 11-83 Expansion mandrel for use in either a chuck or collet.

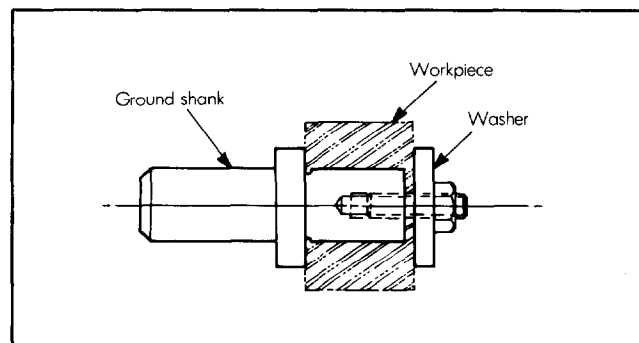


Fig. 11-84 Nut mandrel.

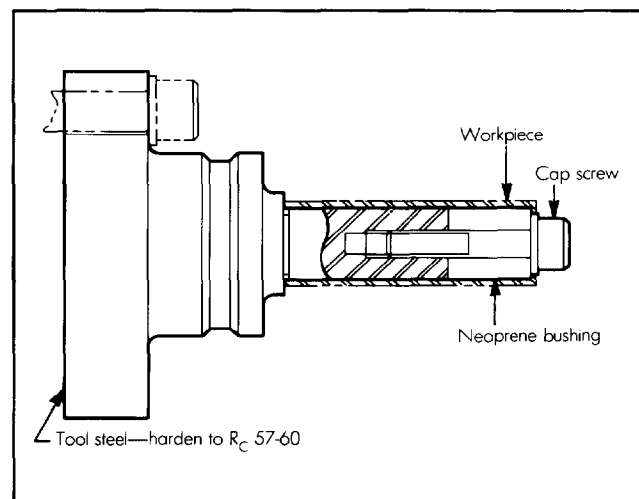


Fig. 11-85 Nut mandrel for thin-walled workpieces.

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Another form of nut mandrel is shown in Fig. 11-86. Here the workpiece OD must be held concentric to the ID to within 0.00025" (0.0064 mm) TIR. The surface Y is previously ground square to the bore and is used to establish the required squareness. The ground and lapped center holes in the mandrel ensure the concentricity of the mandrel. The sleeve is pressed on the mandrel and has three equally spaced pins that maintain the squareness of the part by contacting surface Y. The spring-loaded centralizer establishes the position of the center hole and is held in place by the cover. The clamping pressure is applied by a spherically seated hand knob which forces the washer against the part.

Special mandrels. Special mandrels are those that are not easily classified by any standard term. These mandrels include those designed to hold parts with odd, or irregular, internal details or those that combine features of the standard form of mandrels. The mandrel shown in Fig. 11-87 is specially designed to hold the part shown. With this mandrel, the bearing surface has a pentagonal form to match the internal detail of the die insert. These inserts must be ground concentric to the pentagon to within 0.0005" (0.013 mm) TIR. To accomplish this, the mandrel is made to a size that permits a slight interference fit in the broached inserts. The washer and the socket-head cap screw are included to prevent lateral movement of the workpiece during grinding. The concentricity of the mandrel is ensured by ground and lapped center holes in the hardened-tool-steel mandrel body.

Another type of special mandrel is shown in Fig. 11-88. This mandrel is used for mounting threaded parts that must be ground concentric to the threaded ID. The mandrel shown is made of hardened and ground tool steel with ground and

lapped center holes. The area of the mandrel where the part is mounted is cut to the diameter and pitch of the required thread, and the second thread is cut larger and left hand. This second thread is used to lock the part on the mandrel. When the mounting threads of the part are cut, great care must be used to ensure that the pitch diameter is correct. When parts like this must be concentric to a thread, both the part and mandrel pitch diameters must be closely controlled.

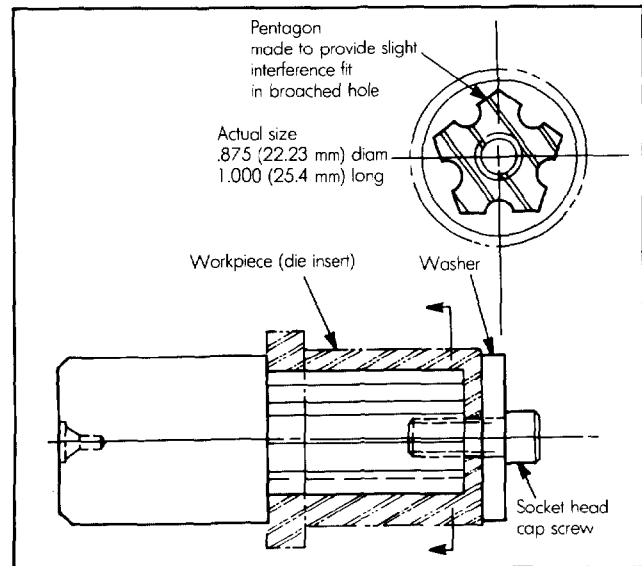


Fig. 11-87 Special mandrel for grinding of die insert.

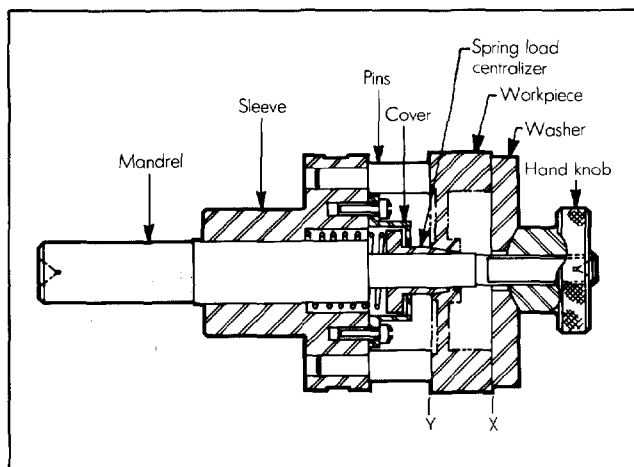


Fig. 11-86 Nut mandrel for parts requiring close concentricity between OD and ID.

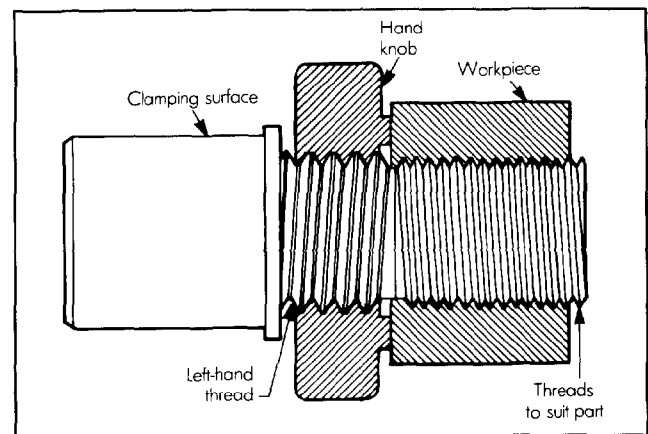


Fig. 11-88 Special mandrel for mounting threaded workpieces that must be ground concentric to the threaded ID.

SPECIAL GRINDING PROCESSES

Grinding, as a class of metalworking operation, includes many processes, methods, and techniques not easily classified by conventional means. The purpose of this section is to present a compilation of discussions relating to some of these processes—center hole grinding, deep and creep-feed grinding, and high-speed grinding—and to present discussions of special

grinding machines such as toolroom grinders and jig grinders.

CENTER HOLE GRINDING

The accuracy of center-type turning and grinding operations is heavily dependent upon the accuracy of the workpiece centers. Rough machining or grinding operations in which

CENTER HOLE GRINDING

accuracy is not particularly critical may require only drilled center holes. (Special center hole drills are covered in Chapter 9 of this volume, "Drilling.") However, in precision operations, center holes must be ground accurately. For example, grinding of center holes may be required after heat treating because heat treating of workpieces may seriously distort center holes and the resulting oxidation and scale may create location problems in precision operations.

Properly ground centers must be round and ground at the precise angle. A true conical form must be generated, and the surfaces of the center hole must be free of ridges for proper location. In addition, concentricity is an important consideration.

Common Errors in Center Holes

Figure 11-89 illustrates common errors found in center holes. These errors must be avoided because no amount of lapping or polishing can correct these geometric variances.

Roundness of center holes is particularly important because work produced can be no more accurate than the roundness of the centers supporting the work.

Concentricity of center holes effects the center of gravity of the rotating workpiece, and accurate concentricity ensures that the center of gravity is on the axis of rotation. Lack of concentricity results in unbalance of the workpiece—a frequent cause of vibration and chatter in grinding of rotating parts. In addition, controlled concentricity of center holes permits minimum stock removal, resulting in efficient production and a reduction of scrap.

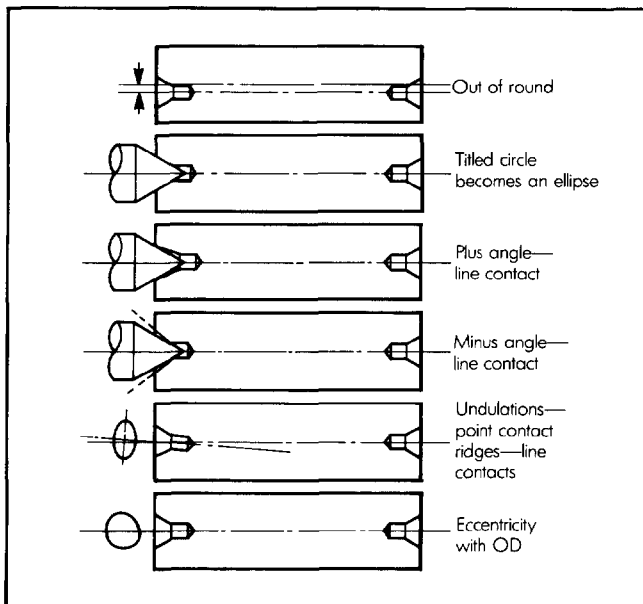


Fig. 11-89 Common errors in center holes which effect accuracy of finished workpieces.

Center Hole Grinders

Precision center holes can be ground using several grinding techniques, including plunge grinding and generation. Simple plunge grinding is effective for many applications, but when particularly close control of roundness and concentricity is required, center holes may be ground with a generation-type process, as illustrated in Fig. 11-90. This principle for generating

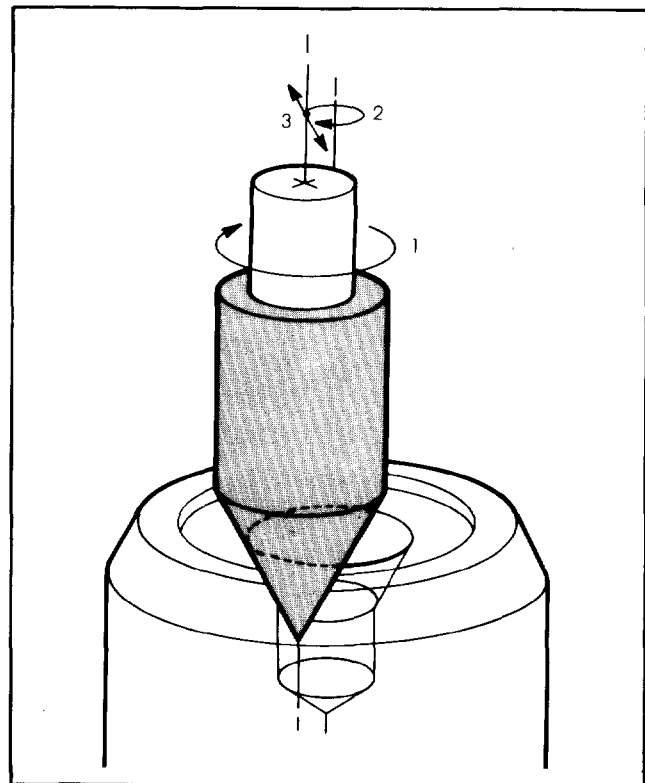


Fig. 11-90 Center holes ground on generation-type grinders are produced with three simultaneous grinding motions.

center holes is used on the center hole grinder illustrated in Fig. 11-91. The machine imparts three simultaneous grinding motions to the cone-shaped grinding wheel:

1. Rotary motion of the grinding cone about its spindle axis.
2. Planetary motion of the grinding cone about the work axis.
3. Reciprocating motion of the grinding cone along a line 30° from the work axis, thereby enabling the grinding wheel to make only line contact with the center hole surface.

The center hole grinder illustrated in Fig. 11-91 produces 60° centers up to 2" (50 mm) diam in workpieces up to 6" (152 mm) diam and 2-42" (50-1070 mm) long. Optional models are available for workpieces up to 110" (2795 mm) long.

TOOL GRINDING

The purpose of this section is to provide an overview of the many types of grinders available for reconditioning cutting tools. Geometries of specific tools are presented in the following individual chapters of this volume:

- Chapter 6—Sawing
- Chapter 7—Broaching, Planing, Shaping and Slotting
- Chapter 8—Turning and Boring
- Chapter 9—Drilling, Reaming and Related Processes
- Chapter 10—Milling
- Chapter 12—Threading
- Chapter 13—Gear and Spline Production

TOOL GRINDING

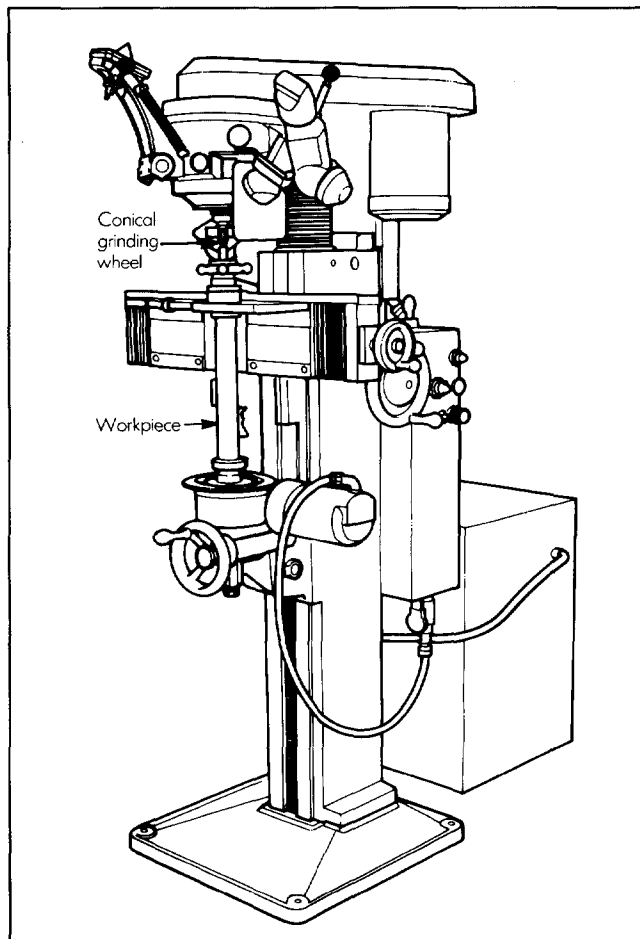


Fig. 11-91 Center hole grinder for generating precision center holes. (Bryant)

The sharpening of tools and cutters covers a wide range of styles and types of tools; consequently, the purchase of a single machine to achieve the desired reconditioning is impossible. As an example, a tool and cutter grinder can grind many cutting tools, but it is not a satisfactory machine for repointing of twist drills. The types of machines to be considered must be consistent with the volume of tools to be sharpened and any special manufacturing conditions that exist.

Standard Tool and Cutter Grinders

The general-purpose tool and cutter grinder is the most popular of all the tool-grinding machines because of its capacity and capabilities. Using various attachments, this class of grinder can be used to sharpen most types of cutting tools. These machines can also be used to perform most internal, cylindrical, and form-grinding operations.

Standard tool and cutter grinders are manufactured in two basic styles. The horizontal-spindle type (Fig. 11-92) resharps cutters and permits some cylindrical grinding. The vertical-spindle tool and cutter type is simply built for cutting tool reconditioning or metal removal and is somewhat simpler to operate. The vertical-spindle type of machine is generally available in both manual and automatic styles.

Standard cutter grinders recondition a wide range of cutting

tools, including milling cutters, end mills, reamers, saws, spot facers, counterbores, countersinks, form tools, etc.

Workholding methods. Tools are generally held in one of two ways on cutter grinders. They can be held in a work spindle having a tapered opening, or they can be placed between centers. When a work spindle is employed, the taper in the tooling should be checked to make certain the cutter grinding equipment is compatible. When the work is to be held between centers, it is advisable to check not only the distance between centers but also the swing dimension. Many combinations of center-to-center distance and swing dimensions are available in cutter grinding machines.

Straight shank tools are usually held in collets which in turn are held by collet drawbar assemblies. Special-purpose collets are also available and care should be taken to make certain the shank of the holder corresponds with the taper in the work spindle. Also, the addition of holding devices used in conjunction with the standard cutter and tool grinding equipment will subtract from the overall length capability. It may become necessary to provide extra length capacity on the tool and cutter grinder to accept the tools which are under consideration for resharpening purposes.

Generating radii. Radius work is one of the most difficult areas of all cutter grinding. It is usually handled either by use of attachments or by means of a special-purpose tool and cutter grinder. Usually, the grinding is accomplished either by using a traveling lip rest or finger or by simply swinging or pivoting the tool. If the tool involved has a rake angle or helix angle, the pivoting method would be disadvantageous in some instances because a true radius would not be developed.

Optical Projection Form Grinders

Optical-projection grinders are machines with built-in optical comparators. They are used for accurate grinding of small profiled shapes, such as flat and circular form tools, templates, carbide cutter tips, profiling masters, lamination dies, and similar parts. An image of the work being ground is projected from 5-100 magnifications onto a glass screen on which the desired form has been drawn at an equal magnification. Alternatively, a large-scale master drawing can be placed behind the viewing screen, as seen in Fig. 11-93.

The operator simply actuates the machine controls while watching the magnified wheel and work contact each other, then grinds the workpiece until it conforms with the drawing. Operations are usually done dry so that the grinding fluid does not impair the vision of the operator. Soft-grade and friable wheels are generally used so that a minimum of heat is generated and accurate forms and finishes can be produced. Tolerances of $\pm 0.0001"$ (0.003 mm) can be maintained in this way.

Single-Purpose Cutter Grinders

If the quantity of tools of a particular type is large enough, specialized single-purpose grinding machines can be purchased to give superior results for tool life, surface finish, production rates, etc. Machine tools of this type are hob sharpeners, face mill grinders, broach sharpeners, gear cutter grinding machines, etc. There are many instances when, even if the number of cutters of a particular type to be sharpened is limited, the purchase of the single-purpose grinder would be easily justified because of unusual hardness of material which makes unusual geometry necessary or creates the need for critical surface-finish requirements, etc.

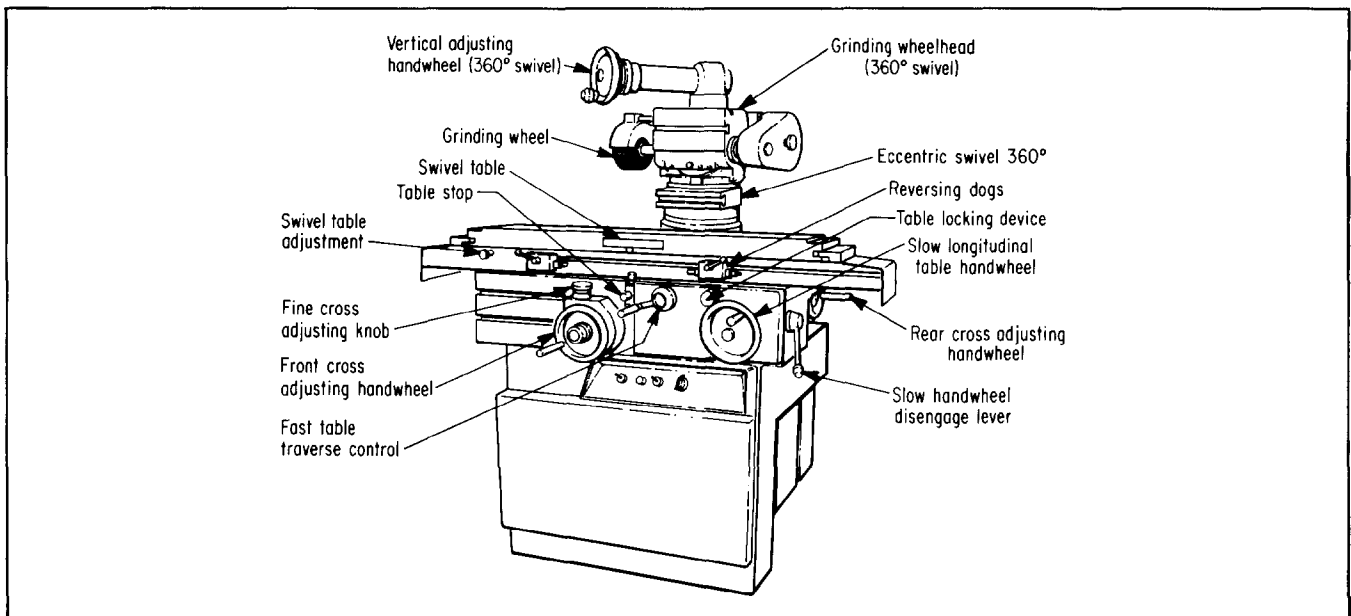


Fig. 11-92 Tool and cutter grinder has wide range of cutter sharpening capabilities.

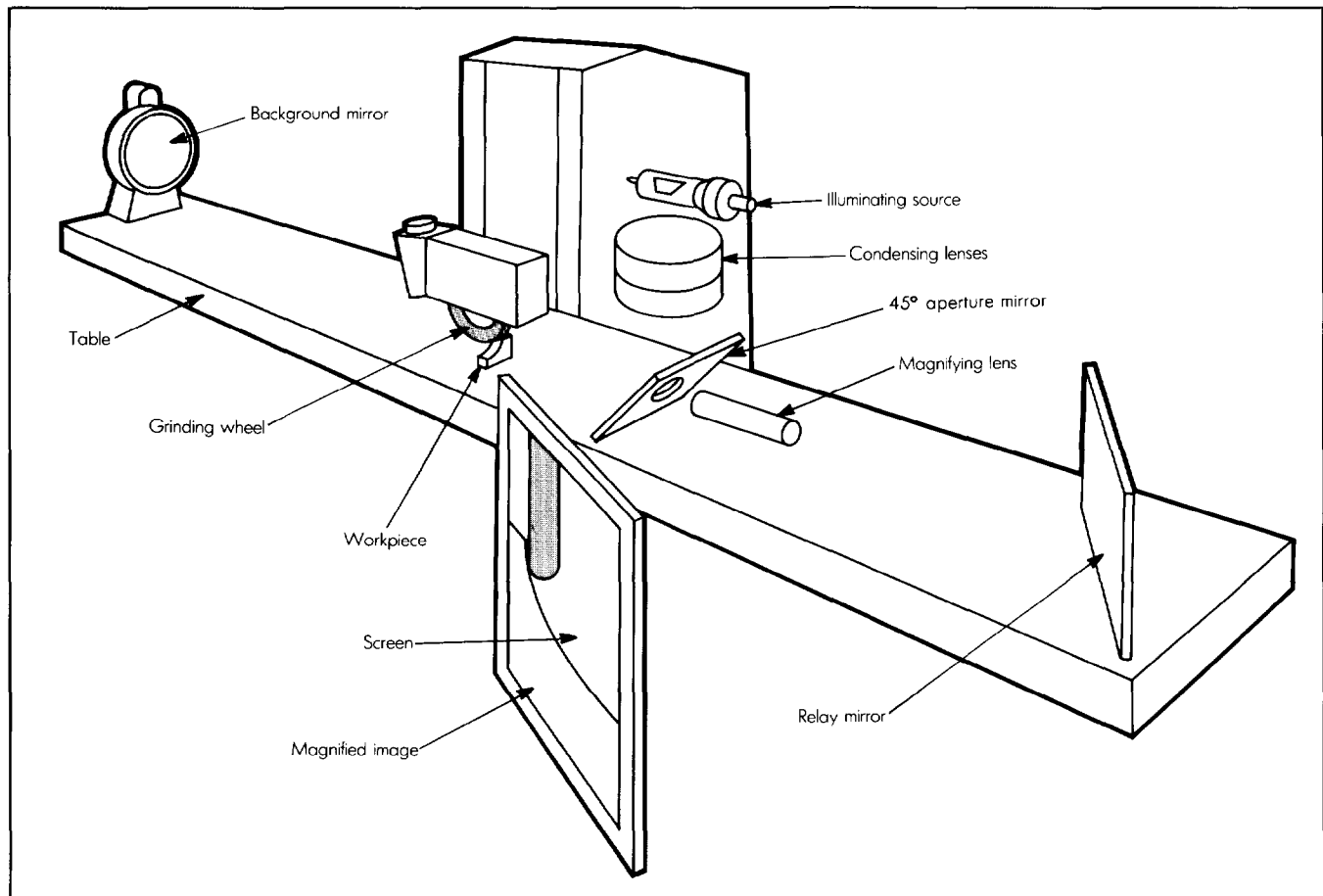


Fig. 11-93 Optical projection form grinding setup. (Brown & Sharpe Manufacturing Co.)

TOOL GRINDING

Drill grinders. Drill grinders are usually available as floor-type machines (Fig. 11-94) for large drills and bench or pedestal-type machines (Fig. 11-95) for small-sized drills. They range in style from automatic machines for production runs to automatic machines for sharpening on an individual basis and finally to manually operated grinders. The machine illustrated in Fig. 11-95 can also be used for web thinning (see next section).

The type of drill points available vary from the constant clearance or swing-type grinding drill point to the generated drill point which reduces torque and thrust requirements and thus improves production possibilities. Generally, it is not feasible to expect to sharpen small drills on a large, floor-type machine or, conversely, a large drill on a small machine. It is, therefore, usually a good investment to have two different drill grinders on the floor.

Care should be taken to make certain that any drill grinder considered has the capability to give a range of included point angles and variable clearance or lip relief angle capability. This consideration is necessary so that the proper geometry can be obtained for the material being drilled.

Numerically controlled drill grinding operations are much more prevalent. Some of the more sophisticated drill grinders can produce a self-centering type of drill point which enhances the opportunity of improving hole location and hole size. In some instances, eliminating center drilling operations is possible.

Step drills and sub-land drills generally cannot be handled on most drill grinders. These drills are usually sharpened on a single-purpose machine designed to permit the sharpening of the minor diameter and the shoulder angle between the minor and major diameter. Some machines are capable of regrinding the pilot and adding the necessary relief to the pilot diameter.

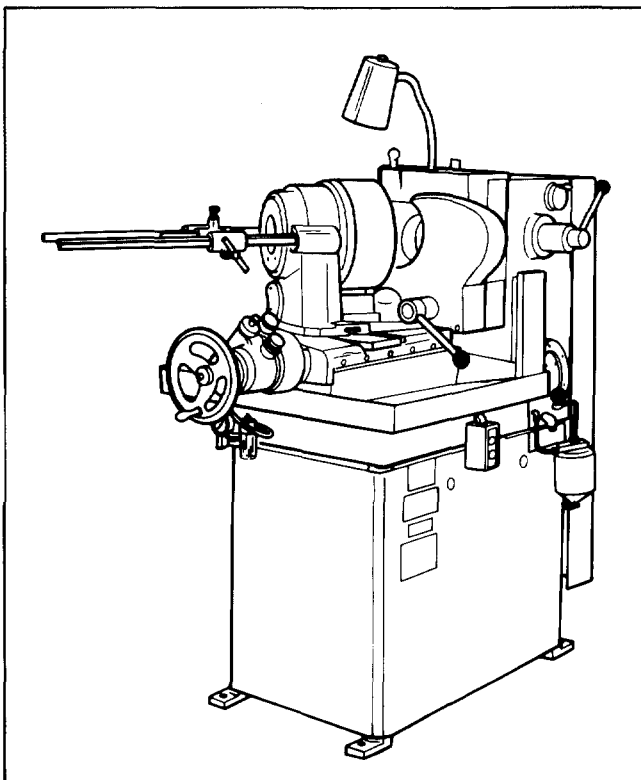


Fig. 11-94 Floor-type drill grinder. (Black & Webster)

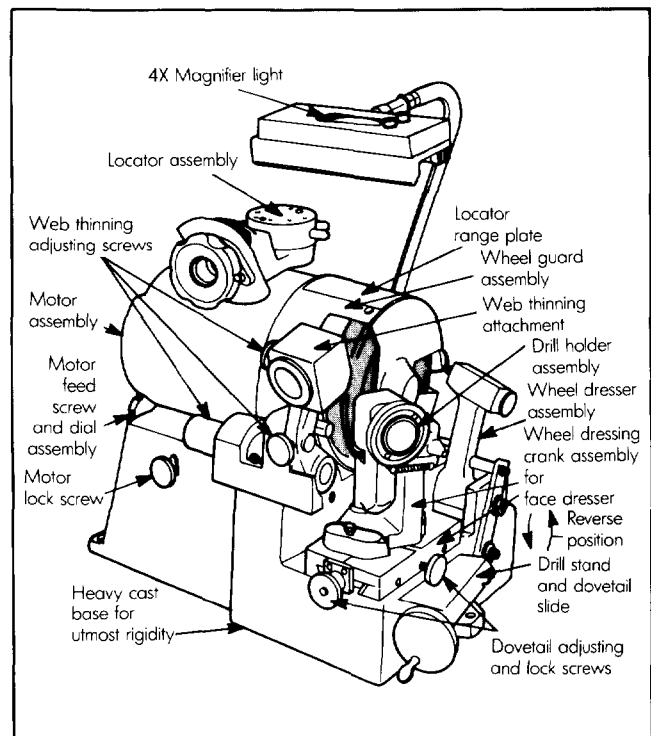


Fig. 11-95 Bench-type drill grinder. (Black & Webster)

Drill-point web-thinning machines. The web of a drill becomes thicker as the tool is used and repointed. Obviously, when the web becomes too thick, the thrust required for penetration increases considerably. Therefore, proper web thinning becomes almost as important as good drill-point sharpening.

If drill-point web-thinning needs are minimal, a simple attachment can do the job. However, this attachment is usually limited to vertical or horizontal movement only and satisfactory geometry usually cannot be produced.

When larger drills are involved or when the job dictates a need for better quality, a drill-point web-thinning machine (Fig. 11-96) that is a single-purpose machine should be considered. This type of unit has the capability to cope with different flute shapes, different helix angles, etc. Drill-point web-thinning machines can also provide the proper hook angles plus the necessary contours for proper chip flow. These machines are usually capable of adding chipbreakers and correcting flute spacing. (The machine illustrated in Fig. 11-95 can also be used for drill web thinning.)

Face-mill grinders. Face-mill grinders are available in both manual and automatic styles. The machine selected should be capable of producing minimum runout on the face of the tooth since this is the area that controls the type of finish that is produced on the material being milled. Manual machines should be capable of grinding the OD, lead angle, face, and dish.

Automatic face-mill grinders (Fig. 11-97) have three advantages: (1) they are generally operator free after the setup has been completed; (2) they are capable of adding a corner radius instead of a bevel, which adds considerably to cutter life; and (3) they can produce a large radius on the face of the tooth, which compensates for any spindle tilt on the milling machine

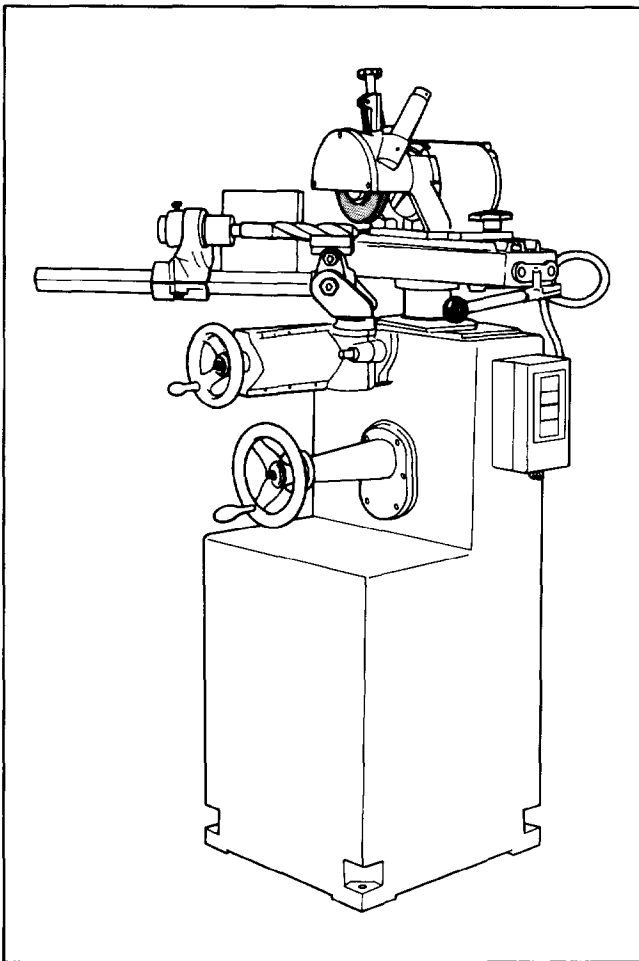


Fig. 11-96 Drill web thinning grinder. (Oliver Instrument Co.)

and aids in obtaining a better surface finish on the material being milled.

End-mill grinders. End mills can be ground on a variety of tool-grinding equipment. One of the more recent advances in end-mill grinding (from blank or resharpening) is the introduction of an 8-axis, CNC, end-mill grinder (Fig. 11-98). Five of the numerically controlled axes are linear, and three are rotary. Resolution of the axes is 0.0001" (0.003 mm), with feed rates from 0-100 ipm (0-42 mm/s), and each axis is programmable in inches per minute. Rotary axes resolution is 0.01°, and rotary feed rates are programmable from 0-25,000 ipm (0-10.6 m/s).

By using eight numerically controlled axes, the CNC end-mill grinder, consisting of one program and one setup, can grind the inside surfaces of the flute; gash the end teeth; relieve the primary and secondary angles on the end teeth and OD; grind corner radii, grind chamfers, and complete ball nose geometry.

Gear cutter sharpening machines. Most gears are cut with hobs, helical gear cutters, or spur gear cutters. Hobs are used for the cutting of involute gears in most instances and are generally reconditioned on a single-purpose, automatic hob-sharpening machine. The machine should be capable of handling both a spiral gash and a straight gash. It is important that the original lead be maintained and that the original rake angle be duplicated in order to produce the proper gear tooth profile.

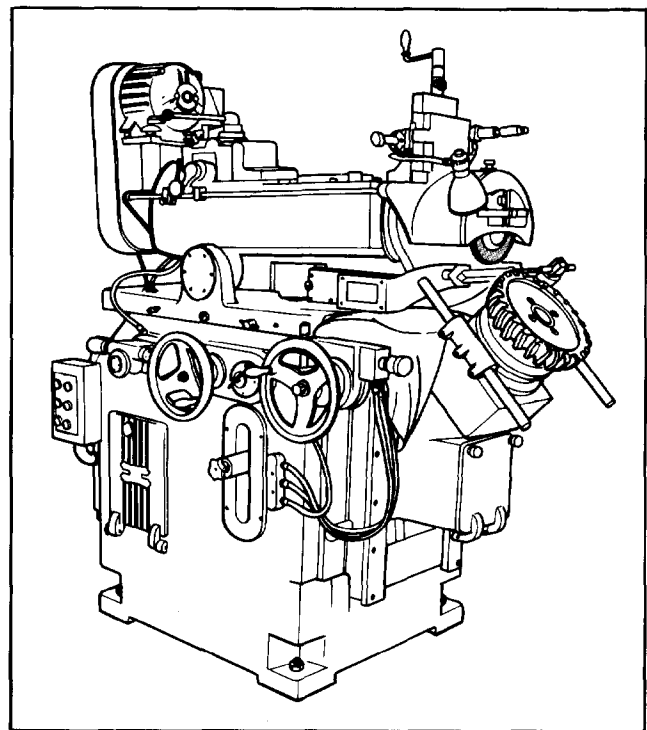


Fig. 11-97 Automatic face-mill grinder. (Oliver Instrument Co.)

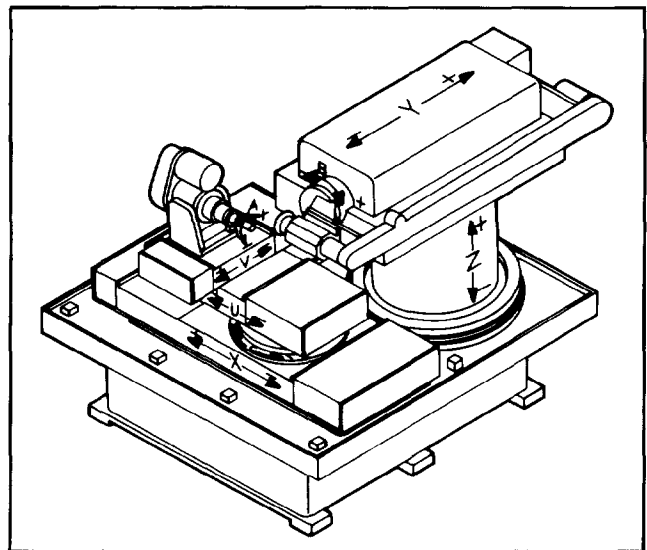


Fig. 11-98 Motions of an 8-axis, CNC, end mill grinder. (S.E. Huffman Corp.)

Helical gear cutter grinders. Helical gear cutters are best sharpened on an automatic cutter grinder (Fig. 11-99) that provides the ability to produce the correct face angle and angle of dish. A machine such as this is complete with automatic indexing and automatic stock-removal sequences. Accuracy of grind and a superior finish on the tooth sharpened are of utmost importance.

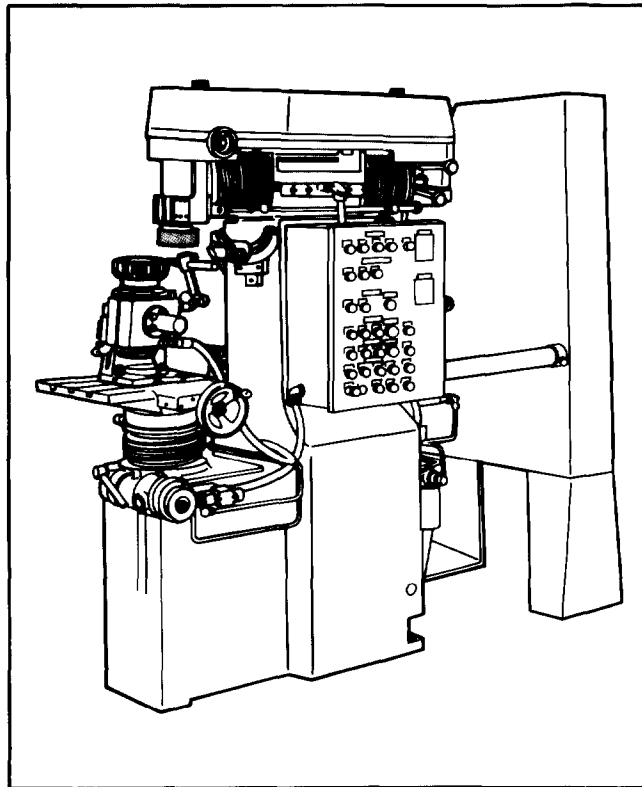


Fig. 11-99 Automatic helical gear cutter grinder. (Oliver Instrument Co.)

Spur gear cutter grinders. Spur gear cutters are sharpened by simply spinning the cutter in a rotary fashion. The cutter is set up on an angle to permit the grinding of the inward dish during the rotary grinding sequence. Several different styles of machines are available for this type of grinding.

Tap grinders. Tap regrinding can be handled on a standard tool and cutter grinder or on a specialized tap grinder (Fig. 11-100). The latter is much more efficient. The chamfered end of the tap is normally the only surface that requires sharpening. A tap grinder machine permits the addition of eccentric or radial relief. Normal practice is to grind away one or two threads from the end of the tool and then duplicate the original chamfer angle and length of chamfer. Occasionally, tap flutes require grinding to resharpen the cutting edges.

Broach grinders. Broach grinding can be accomplished by the use of specialized broach grinders or by the use of attachments for tool and cutter grinders. Single-purpose machines are rather costly, and a rather large resharpener volume is required to justify these units.

Most broaches are flat, round, or contoured. Flat broaches can be sharpened either by top grinding or face grinding. Obviously, continuous top grinding causes loss of chip room area. If face grinding is used continually, the tooth is weakened. The machine involved should be capable of doing both top grinding and face grinding so that the user can top grind three or four times, then face grind one time, etc. Round broaches and contoured broaches can only be sharpened on the face. In particular, the grinder should be capable of producing a minimum runout on the finishing teeth in order to provide a good broach surface finish.

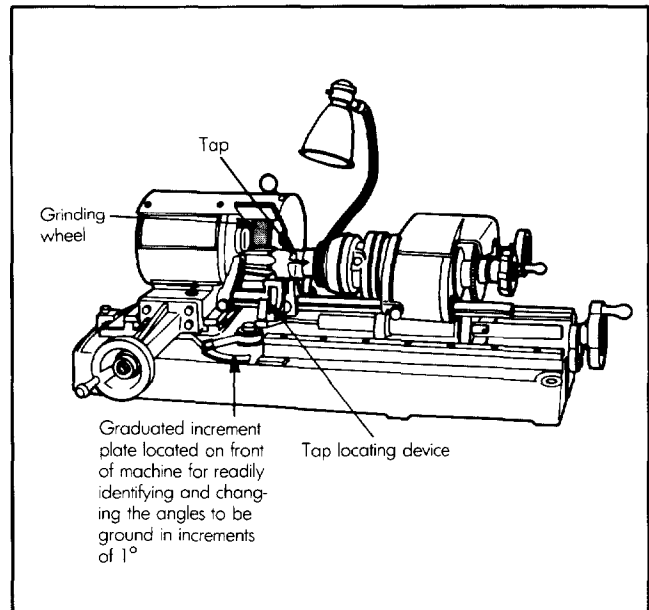


Fig. 11-100 Tap chamfer grinder. (Black & Webster)

JIG GRINDING

Jig grinding machines (Figs. 11-101 and 11-102) were originally designed to grind holes accurately to size and to coordinate location in hardened steel, as required for the manufacturing of press tools. These machines utilize the same principles of rectilinear-positioning control employed in jig borers. They are commonly used as companion machines to the jig borer. Modern jig grinders can generate vertical surfaces contoured in the X-Y plane as well as internal and external diameters.

Data presented in the section on jig borers in Chapter 8, "Turning and Boring," applies equally to the jig grinder. Topics covered in Chapter 8 include basic design of the measuring system, accessories and requirements for setting up the workpiece, requirements for the environment, machine maintenance, and the effect of machine geometry on linear accuracy.

Jig grinding machines differ from jig borers in that the machine spindle is replaced by a more complex unit offering the following capabilities:

1. Means for adjusting the radial offset of the grinding spindle to accommodate various diameters or radii.
2. Provisions to drive the grinding spindle in a planetary orbit at controlled speeds.
3. Fine adjustment of the radial offset engineered to function while the main machine spindle is operating.
4. An automatic vertical reciprocating feed motion for the grinding spindle with provisions for control of its rate and traverse range.
5. Means for generating the vertical surfaces of workpieces at set angles, producing tapered diameters and contoured surfaces as required for clearance in press tools.
6. Provisions for controlling the angular direction of the planetary offset for the grinding spindle relative to the machine's slide motion.
7. An engineered system for transmitting and controlling power to the machine spindle and the grinding wheel, both simultaneously and independently.

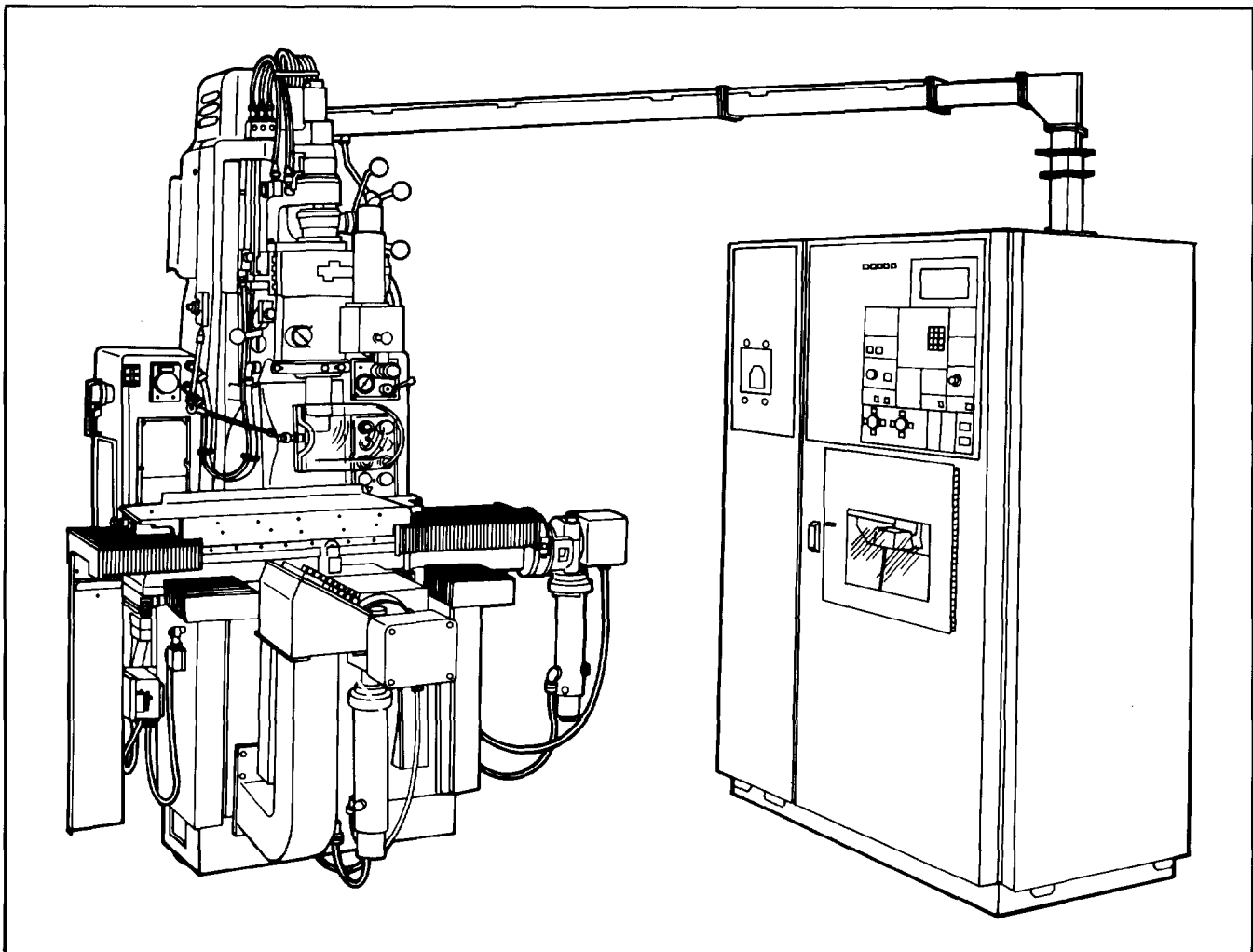


Fig. 11-101 Open side-type jig grinding machine, numerically controlled. (Moore Special Tool Co., Inc.)

8. Provisions for interchanging a variety of grinding spindles as required for universal application.

Particular attention is given in the design of the jig grinder to provide protection for the vital components of the machine from the harmful effects of abrasive particles produced while operating.

Jig Grinder Applications

The jig grinder is essential to the tool and die industry for the manufacturing of press tools. The functional details of die components are ground to specifications after hardening, thus eliminating inaccuracies resulting from distortion produced by heat-treating. The integrity of wear surfaces and the precise control of clearance between punch and die is assured. Precise dimensional control allows the fabrication of interchangeable die components. Die parts can be stocked for quick replacement in press tools. Hand fitting and adjustment of matching die components is eliminated.

The application of the jig grinder is extended into other areas of manufacturing. Examples are found in the machine-tool, aerospace, and instrument-manufacturing industries. These

include gearboxes or bearing plates having hardened inserts requiring precise location, parts that are too large or asymmetrical for conventional internal grinding, keyslots or other rectilinear details, and curvilinear forms in cams used for mechanical control of instruments or other devices. Numerically controlled jig grinders effectively accommodate the complex dimensional detail of these parts (Fig. 11-103). The operator is relieved from the responsibilities of controlling and monitoring numerous coordinate settings and various other control devices.

Accessories for the Jig Grinder

Information on accessories for setting up the workpiece is presented in the section on jig boring (Chapter 8, "Turning and Boring"). This information applies equally to jig grinding machines.

Spindle accessories, specifically designed for use on the jig grinder, include the following:

1. Vertical-axis grinding spindles designed for interchangeable mounting on the main spindle of the machine. These grinding spindles, or heads, provide appropriate speed

JIG GRINDING

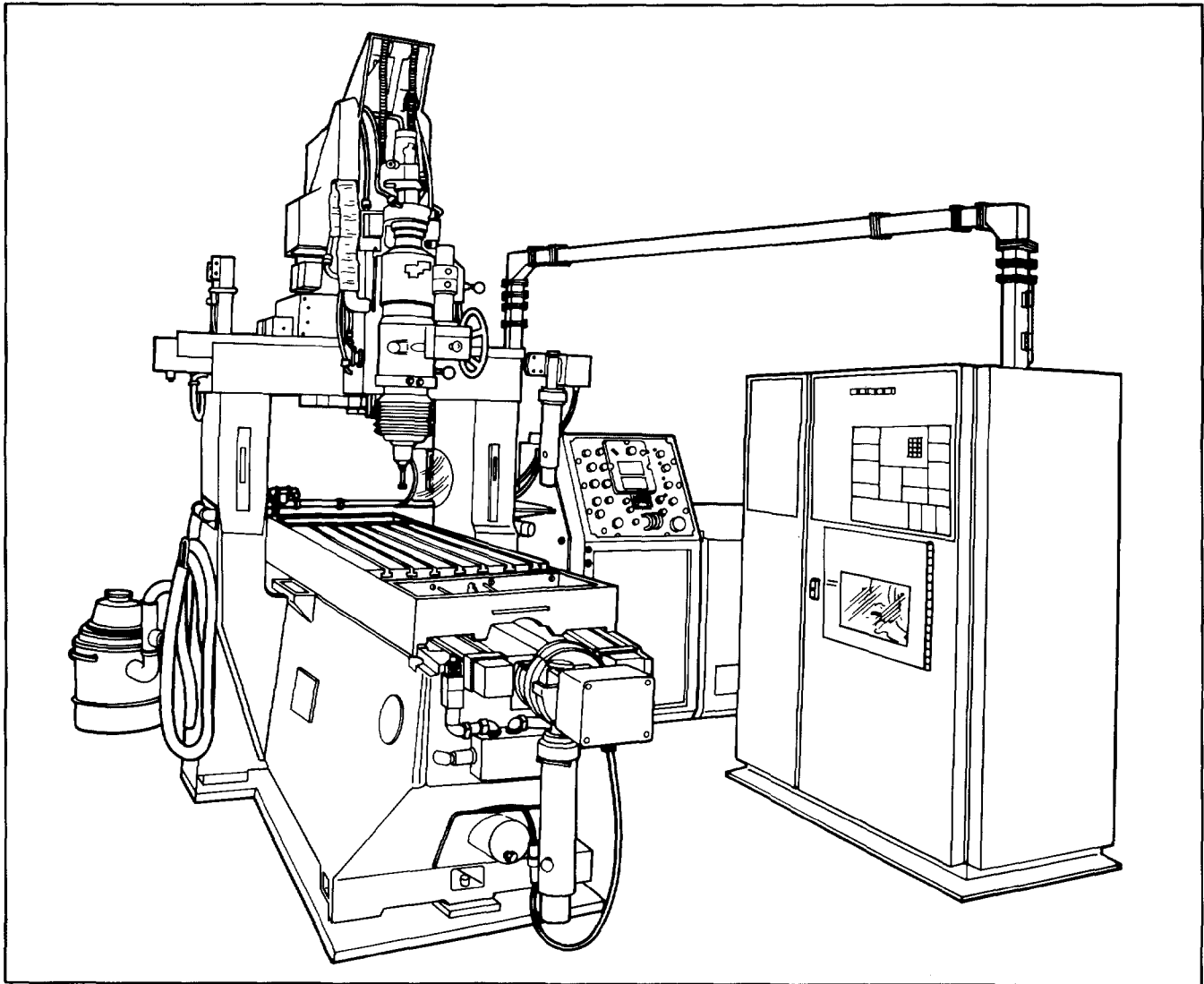


Fig. 11-102 Fixed bridge-type jig grinding machine, numerically controlled. (Moore Special Tool Co., Inc.)

and power for wheels from 0.020" (0.5 mm) to approximately 3.0" (76.2 mm) diam.

2. Horizontal-axis spindle (slot grinder) unit with interchangeable spindles for wheels from approximately 0.75" (19.0 mm) to 3.0" (76.2 mm) diam.
3. Adapters for the grinding spindles extending the range of diameters and depths for grinding.
4. A 45° angle spindle-mounting adapter used when generating concave spherical forms.
5. A wheel dresser (Fig. 11-104) used for dressing grinding wheels that require frequent dressing or conditioning to restore their cutting properties and geometry which normally deteriorate with use. This reconditioning is commonly done using a diamond-tipped dressing tool supported on the machine table. Dressing devices specially designed for use on the jig grinder serve to control the dressing of abrasive wheels, providing improved efficiency for a variety of dressing requirements (Fig. 11-105).

Flexibility and low-cost jig grinding capability can be added to the tool spindle of any precision machine, such as a jig borer, boring machine, or milling machine, with the use of an air-operated jig grinding attachment. The result is a dual-purpose machine capable of precision jig grinding hole sizes from 0.020-8.000" (0.51-203 mm) diam. The basic jig grinding attachment consists of a spindle adapter, an adjustable offset head, an airmotor capable of delivering the optimum surface feet per minute, an arbor, and a grinding wheel. Air motors are available with from 4500-300,000 rpm. Spindle adapters are available for hundreds of common machine tools.

Wheels for Jig Grinding

Grinding wheels used in the jig grinder include the following types:

1. Mounted wheels with abrasive material bonded to steel or tungsten carbide shanks.

JIG GRINDING

2. Wheels designed for mounting in arbors or directly on the spindle end of the grinding head.
3. Wheels designed for use in the horizontal-axis spindle of the slot grinder.

A variety of abrasive materials are used in the jig grinder. They are selected to accommodate various engineering materials (see also "Grinding Wheels" in this chapter).

Aluminum oxide. Used for hardened and unhardened ferrous materials, wheels made of aluminum oxide can be dressed and shaped for form grinding using diamond dressing tools.

Silicon carbide. This abrasive is used for grinding wear-resistant tool steels and other tough hardened materials. Like aluminum oxide, silicon carbide can be dressed using diamond dressing tools.

Diamond. Bonded in metallic, resin, or ceramic material, diamond abrasive is used for grinding tungsten carbide and

ceramic materials. Diamond wheels are molded close to the desired form when manufactured and, with specially designed truing devices, shaped to finished size.

Cubic boron nitride (CBN) or amber boron nitride (ABN). Used for grinding virtually all ferrous materials in their hardened state, CBN grinding wheels are fabricated in the same manner as those made with diamond abrasive. Because of the cool, free-cutting, and low-wear characteristics of CBN, it is particularly well suited for use with numerically controlled jig grinders.

Cutters or burrs made of tungsten carbide. These tools are effectively used for machining unhardened or nonferrous materials. Since these tools cannot be trued in the spindle, as conventional abrasive wheels would be, care must be taken to ensure that the cutting edges are concentric with the grinding spindle. Because of the comparatively high speed of the grinding spindle, the diameter of carbide cutters or burrs should not exceed 0.4" (10 mm) diam.

Operating Practices

Instructions in the operation of jig grinding machines are provided by the manufacturer. Procedures used vary to some degree and are determined by the operating features engineered for the machine.

Machine slide position and other machine functions are controlled employing the following features provided for the jig grinder:

1. Control of coordinate settings. Commonly used devices include micrometer dials, precision end standards, precision scales fitted with a system of optics, or a digital readout displaying the numerical value of the respective slide position.
2. Automatic positioning. Automatic positioning is accomplished from data set up by the operator using dial setting or keyboard input.
3. Positioning and other machine functions. These functions are controlled by programmed tape command or by data stored in the control memory.
4. Contouring. This function is accomplished by coordinated movement of the X and Y axes integrated with other machine functions controlled by the NC or CNC system.

Operation of the machine spindle is accomplished in several ways:

1. Machine spindle power rotation for starting, stopping, and controlling the rate of speed by manual control or programmed command.
2. Infeed/outfeed of the grinding spindle from the main spindle of the machine by manual control or programmed command.
3. Vertical feed travel limits and speed rate for the grinding spindle, controlled by manual setting of devices on the machine. Feed is initiated and halted by operator control or program command.
4. Grinding spindle power rotation start/stop, controlled by the operator and/or programmed command. The range of the grinding spindle speed is determined by the spindle selected and the power, compressed air or electric current, supplied to the spindle motor.
5. Controlled hand rotation of the machine spindle to predetermined angular limits, employed when arcs are generated using the coordinate layout method for

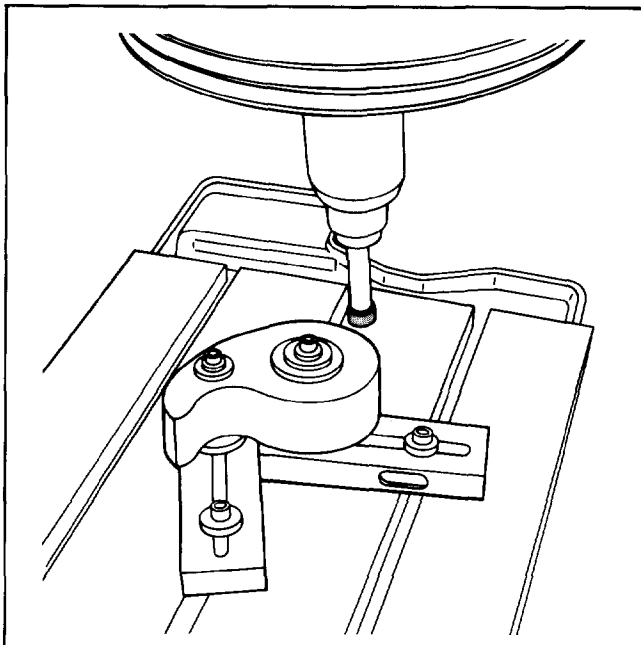


Fig. 11-103 Contour grinding with a numerically controlled jig grinder. (Moore Special Tool Co., Inc.)

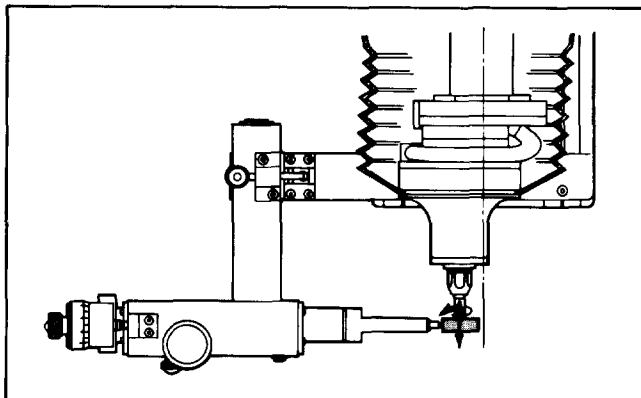


Fig. 11-104 Wheel dresser for the jig grinder. (Moore Special Tool Co., Inc.)

JIG GRINDING

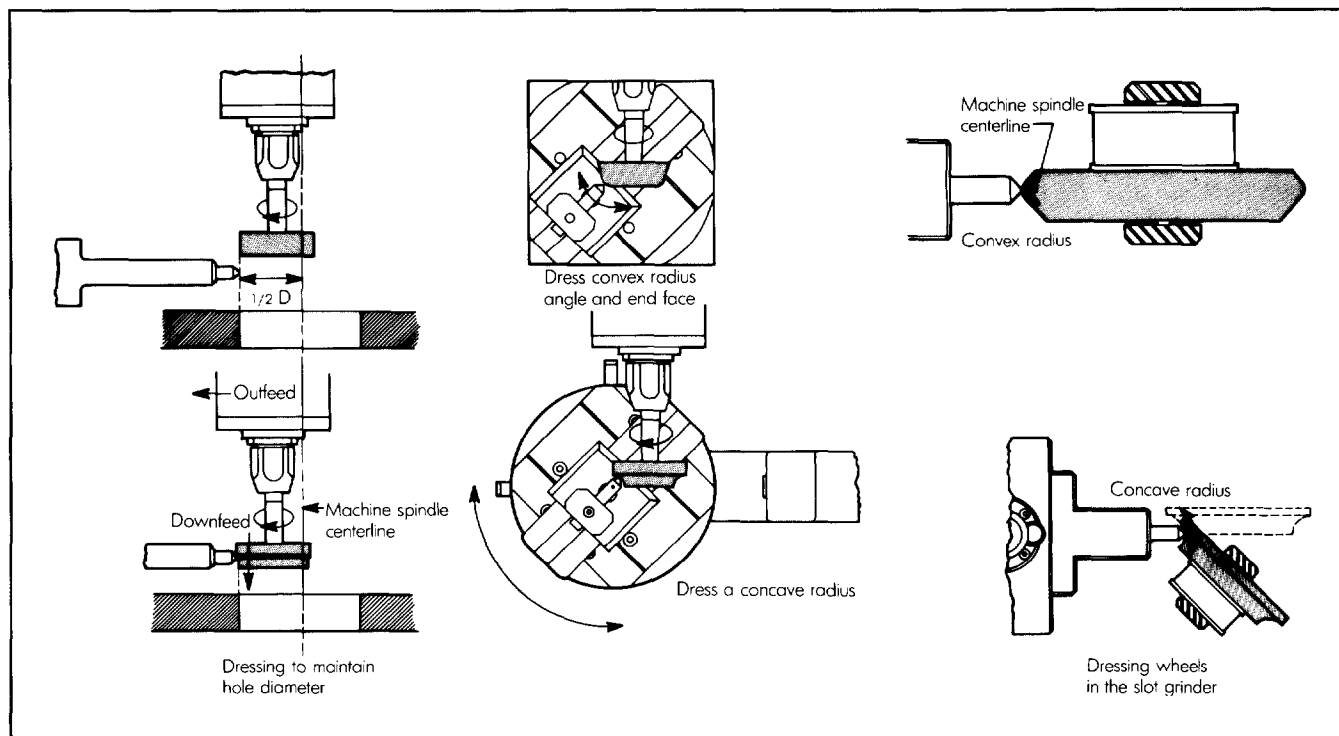


Fig. 11-105 Examples showing the universal application of a wheel-dressing system engineered for the jig grinder. Procedures used when dressing the wheel involve machine and/or dresser motions. In all cases the dressed surface of the wheel is established at a predetermined distance from the machine spindle centerline.

contour grinding (Fig. 11-106). Machines equipped with indexing controls for contouring are manually programmed using angular values dialed in the controller.

6. Grinding tapers. There are two systems engineered for grinding tapers, as shown in Fig. 11-107. In view *a*, the vertical motion of the grinding wheel is inclined from the vertical, while the main spindle is rotating, thus generating a tapered or conical hole. The system shown in view *b* combines the vertical and outfeed motion at a fixed ratio when generating tapers.

Jig Grinding with Numerical Control

Jig grinding machines with numerical control, NC or CNC, are designed to operate automatically, performing the functions for positioning control, spindle start and stop, vertical feed motion, and linear feed rates for contouring in the X-Y plane.

The procedures used for generating contours with numerically controlled jig grinders differs from those employed with manually operated jig grinders. When contours are ground on numerically controlled continuous path jig grinders, they are generated by the continuous synchronized motion of the X and Y axes slides of the machine.

The contoured path, representing the part edge, is programmed directly to its dimensional specifications or to a cutter center-line path programmed to generate the contour at a selected distance from the part edge.

Part edge programming requires the employment of a controlled C axis as shown in Fig. 11-108 *a* and *b*. This rotary axis controls the angular direction of the grinding wheel planetary offset from the main spindle centerline so that the angular attitude of the wheel spindle offset and its point of

interception with the workpiece is maintained normally to the contoured part edge as it is generated. The contour is controlled for size by adjustment of the planetary offset or by the use of subroutine calls programmed to produce an effective infeed/outfeed.

Jig grinders using cutter diameter compensation generate the contoured path at a fixed or variable distance from the part edge contour. This requires the use of a continuous orbiting motion of the grinding wheel. Infeed for material removal is made by adjustment of the planetary offset or by the use of subroutine calls.

HIGH-SPEED GRINDING

The theory of high-speed grinding, a relative newcomer to metalworking, suggests that, under certain conditions, grinding wheel speeds can be increased significantly beyond normal wheel speeds to effect proportional increases in material removal rates without significant changes in chip geometry, grinding forces, energy required per unit volume of material removed, surface finish, or residual stresses in the workpiece. The theory of high-speed grinding dictates that dressing the grinding wheel can be used to control normal grinding force, surface finish, and wheel wear.

Although widespread application of high-speed grinding is yet to materialize, experiments at General Motors Corp. and other companies have confirmed the technical feasibility of the process.¹⁴ At GM, a plunge-type OD grinder with angular wheelhead was modified to achieve wheel speeds up to 35,400 sfm (180 m/s) using a special segmental wheel with an AISI 4140 steel hub. Results of the experiments are presented in Fig. 11-109.

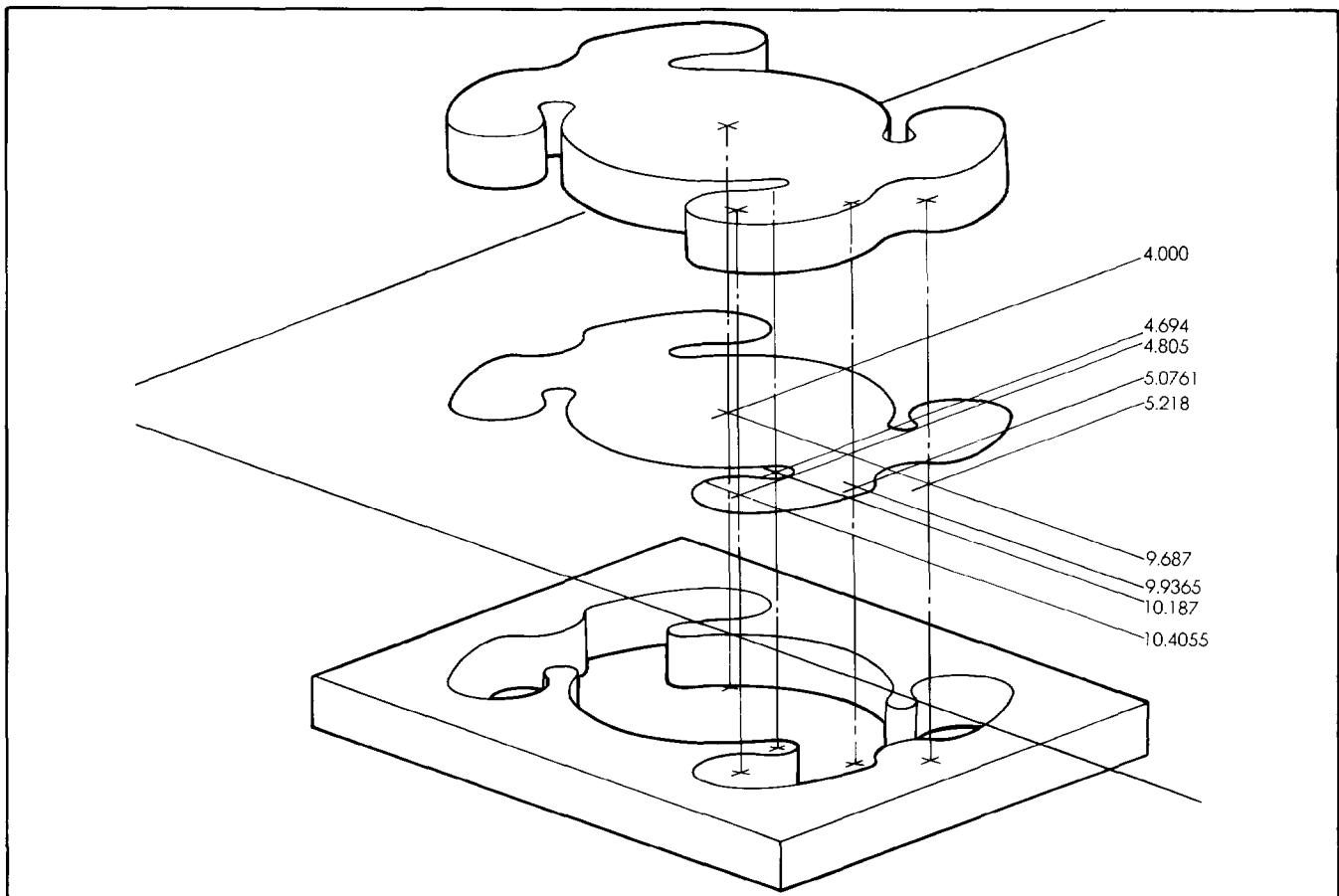


Fig. 11-106 Coordinate layout of a contoured shape to be produced by jig grinding (metric conversions omitted for clarity).

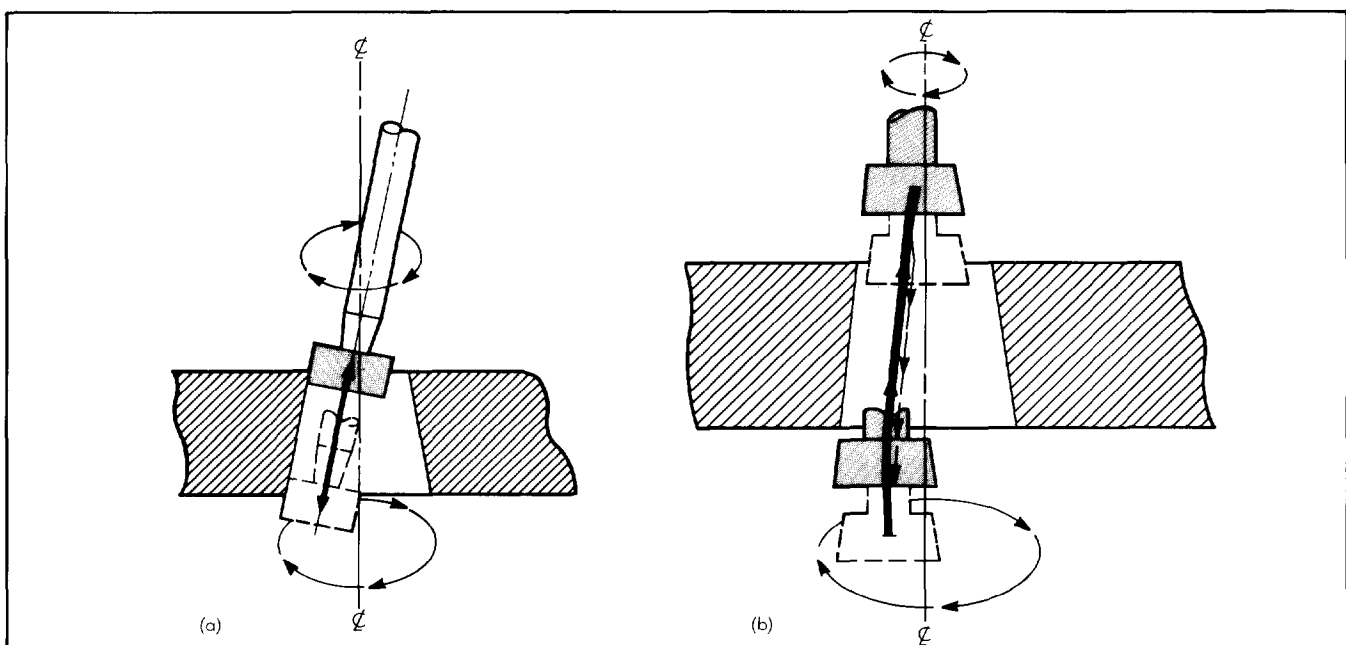


Fig. 11-107 Two methods of grinding a taper using a jig grinder.

CHAPTER 11

HIGH-SPEED GRINDING

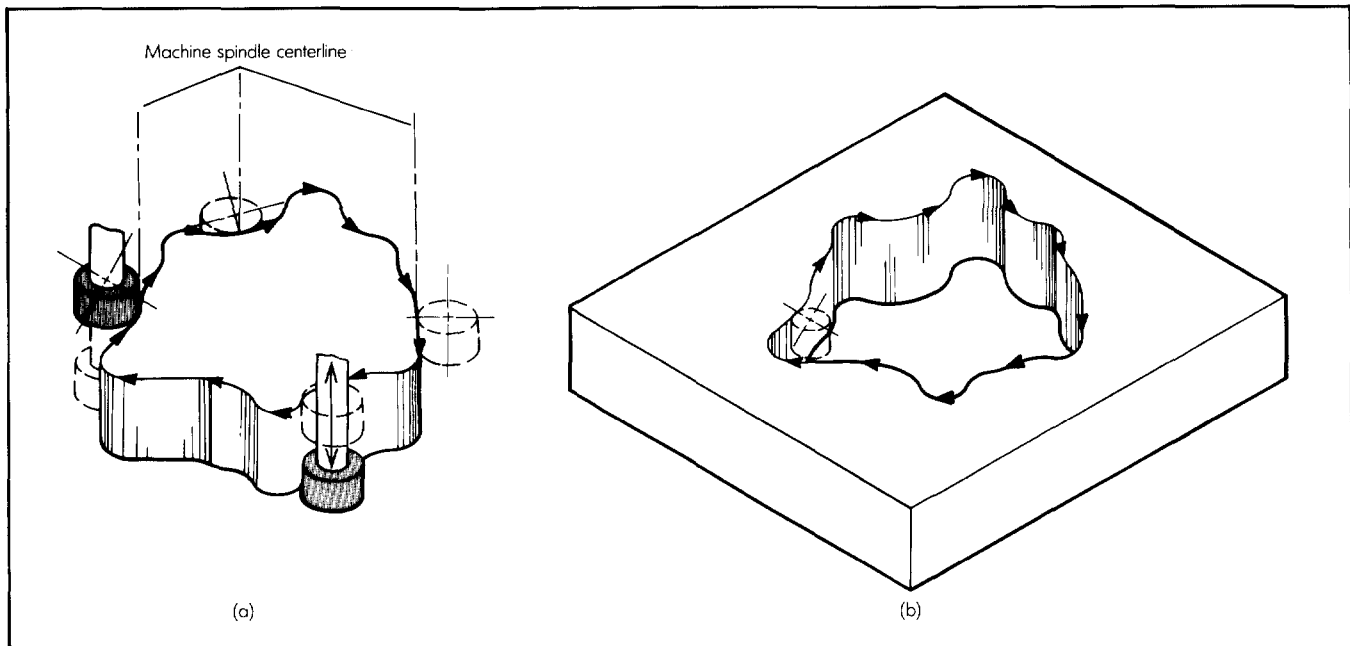


Fig. 11-108 (a) Contour grinding with numerical control: movement of the X and Y-axis slides causes the part edge to pass under the machine's main spindle centerline. In this illustration it appears as though the grinding wheel is moving along the contoured part edge. In reality, the part moves with its programmed path (part edge) passing under the machine spindle, while the wheel's offset direction is controlled outside the workpiece. (b) The mating part is contoured using the same program, but with the wheel-offset direction reversed.

To date, however, most production applications of high-speed grinding are limited to wheel speeds of less than 16,000 sfm (81 m/s). Some successful applications of the process are the grinding of crankshafts, automotive front wheel spindles, end mills, transmissions parts, and piston rings.

As mentioned earlier, the application of high-speed grinding has not been widely accepted. Several reasons are cited as obstacles to increased use of the process. In the early evolution of the process, some grinding experts believed that high-speed grinding might be developed sufficiently to compete effectively with single-point machining operations in heavy stock-removal applications. However, the potential relative advantages of high-speed grinding declined throughout the 1970's due to advances in cutting tools (materials and applications) and significant improvements in the design and construction of lathes and chucks. Consequently, high-speed grinding is now applied mostly in groove grinding and processing of exotic metals which sometimes are not well suited to single-point machining. Production of small parts using high-speed centerless grinders is another successful application.

Safety considerations have proved to be a major obstacle in the application of high-speed grinding. For example, to be competitive on a material removal basis with a single-point machining operation using coated carbides, a high-speed grinder might require up to 250 hp (186 kW) and might need to be operated at speeds well in excess of 12,000 sfm (61 m/s).

Containing broken wheel fragments can be a significant problem in high-speed grinding although some advances have been made in wheel guard design. More serious sometimes is the containment of unrestrained energy released when a wheel breaks at high speed. Special high-speed grinders under development by German machine tool builders feature an

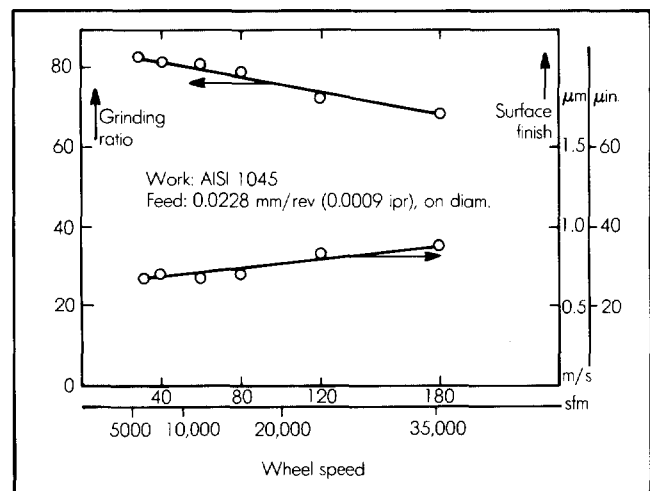


Fig. 11-109 Grinding ratio and surface finish variations with various wheel speeds in special high-speed grinding experiments on parts made of AISI 1045 steel.

integral wheelhead and base. This design is aimed at avoiding having the wheelhead fly off the machine base when a wheel breaks.

These and other safety considerations dictate that high-speed grinding should be performed only on equipment specifically designed for the purpose.

Another obstacle in the application of high-speed grinding is surface finish control. Experience has shown that, contrary to high-speed grinding theory, it is extremely difficult to

DEEP AND CREEP-FEED GRINDING

reduce the diameter of a workpiece by about 0.25" (6.3 mm) at 15,000 sfm (76 m/s) while maintaining acceptable surface finish without excessive wheel dressing. The most successful applications of high-speed grinding have been performed at about 8500 sfm (43 m/s) in removing about 0.010-0.025" (0.25-0.63 mm) from heat-treated parts.

Further experience has shown that high-speed grinding at 15,000 sfm (76 m/s) often results in disproportionate diamond wear and higher truing costs. Tradeoffs of additional costs to provide higher grinding speeds (special wheels, special machines, etc.) may not justify the incremental benefits except in isolated cases. For these reasons, high-speed grinding must be applied very selectively.

DEEP AND CREEP-FEED GRINDING

Creep-feed grinding originated in Europe in about 1958, when the first prototype creep-feed grinder was developed by ELB-Schliff of West Germany.¹⁵ Within five years, several production-type creep-feed grinding applications surfaced. Today, several machine tool builders, both domestic and overseas, offer special creep-feed grinding machines. Particular interest recently has been centered around creep-feed machines which feature both conventional grinding and creep-feed capabilities.

Process Characteristics

Creep-feed grinding is generally used to describe a surface grinding operation performed in a single pass with an unusually large depth of cut. The term deep grinding is used in Europe to describe creep-feed operations in external cylindrical grinding such as tool, thread, and gear grinding.

Generally, the creep-feed grinding process is marked by a special mode of operation. As illustrated in Fig. 11-110, in contrast to the conventional grinding technique, the depth of cut per pass or revolution is increased 1000-10,000 times and the work speed is decreased in the same proportion. Thus, it is possible to grind profiles with a depth of 1.0-30.0 mm (0.04-1.2") or more in one pass, using work speeds from 0.25-0.75 m/min (9.8-30 ipm), and to reduce machining times 50-80%. Figure 11-110 illustrates the difference between the two modes of operation in surface grinding. At creep-feed conditions, the multiple initial wheel/work contacts, typical for conventional operation, are avoided. As a consequence, the profile stability of the grinding wheel is improved considerably. On the other hand, the stroke length is increased at creep-feed conditions due to the extended contact length of the wheel and workpiece.

Compared with conventional grinding processes at the same metal removal rates, deep or creep-feed operations are characterized by the following technological features.¹⁶

- Increased total grinding forces.
- Reduced average force per individual grit.
- Increased temperature in the wheel/work contact zone.
- Reduced temperatures in the newly generated work surface.

These features can be viewed as direct causes of typical characteristics of creep-feed grinding systems. Due to the significantly higher grinding forces, creep-feed grinders must have increased static and dynamic stability, as well as accordingly increased power. At the same time, the grinding wheel must be a softer grade, since the average forces per cutting edge are reduced. Due to increased contact temperatures and the related dangers of wear and loading of the grinding wheel, a

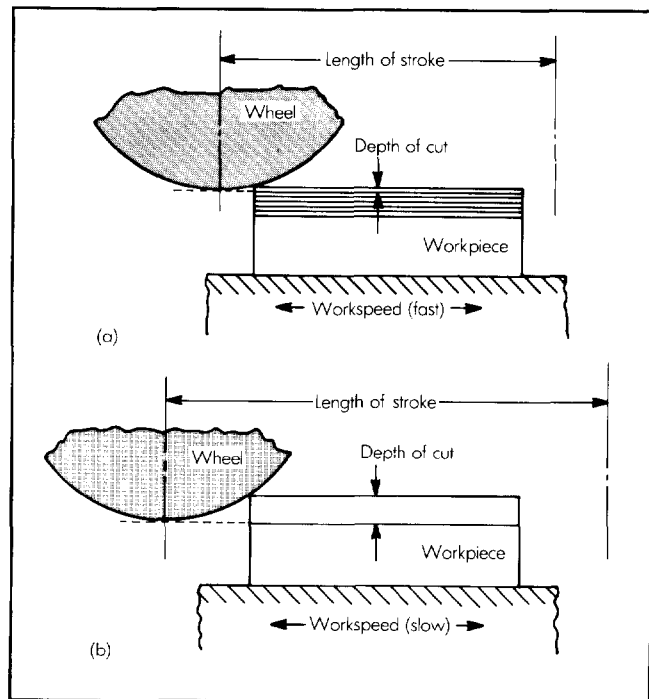


Fig. 11-110 Feed, length of stroke, and depth of cut for (a) conventional surface grinding and (b) creep-feed grinding.

high-efficiency grinding fluid system is required. On the other hand, the work surface temperatures under creep-feed conditions can be significantly lower than those under conventional grinding conditions. This is one of the most important advantages of the creep-feed process.

To make full use of the economic and technological advantages of this high-efficiency, high-precision manufacturing process, the application of specially developed and constructed machine tools, grinding wheels, dressing methods, and controlling techniques is essential. A manufacturing system such as this should provide the following features:¹⁷

- High static and dynamic stability of the machine tool.
- High-accuracy, stick-slip free slides with favorable damping characteristics.
- Considerably increased spindle power (2-3 times higher than in conventional surface grinding).
- Infinitely variable spindle speed.
- Highly balanced and directly connected motor-spindle system with high-accuracy/high-performance ball bearings.
- Nonhydraulic, single-unit, table drive covering the whole area from the creep-feed to the conventional region, with infinitely variable speed.
- Consistent table speed, especially in the lower speed range.
- High-pressure cooling and cleaning system.
- Integrated dressing devices.
- Integrated controlling systems.
- Pertinent grinding wheels.
- Updated process know-how.

An absolute prerequisite for successful application of the creep-feed method is the use of machines and tools that are

DEEP AND CREEP-FEED GRINDING

specially designed for the purpose of creep-feed grinding and fully meet the above standards.

Surface Grinding Applications

Generally, two classes of applications exist for creep-feed surface grinding. The first class is the grinding of deep slots with parallel sides; the second class is the grinding of profiles, including especially those applications featuring high depth to width ratios and those with profiles to be ground in difficult-to-grind materials.

The following workpieces, representing the first class of application, have been successfully processed using creep-feed grinding:

- Racks of chuck jaws.
- Locating slots in connecting rods.
- Cavities in mould inserts.
- Slot-type ways in chucks.
- Cutting teeth on straight jaws.
- Complete profiles of small racks.
- Keyseats in rotors of hydraulic motors.
- Gear elements on automobile steering parts.
- Keyseats in gear bodies.
- Profiles in coupling parts.
- Slot-type ways in textile machine parts.

Turbine blades made of superalloys are an important application of creep-feed grinding of profiles. Usually profiles (blade roots, for example) are ground in one or two roughing passes and a single finishing pass, using creep-feed conditions throughout.

Cylindrical Deep-Grinding Applications

An advantage of cylindrical deep grinding is that the contact zone in deep grinding is significantly less than in creep-feed surface grinding. This results in grinding forces up to three times smaller than creep-feed surface grinding at the same removal rate. A disadvantage exists, however, in external deep grinding. The process involves the grind wheel plunging down into the workpiece first, then performing the creep-feed operation by a full revolution of the workpiece, and finally retracting the wheel without leaving a mark on the ground work surface.

Often this deep-grinding operation is carried out by simultaneously performing the plunge and creep-feed motion and finishing the operation in more than one workpiece revolution.

Actually, the external deep-grinding process has an older tradition than creep-feed surface grinding. Precision threads, for example, have been produced by so-called full-infeed grinding for several decades.

The most impressive example of the potential of the creep-feed method in general is the deep grinding of twist drill flutes with a maximum depth of cut of 0.68" (17.3 mm) and with wheel speeds up to 20,000 sfm (100 m/s). In this application, the flutes are ground to full depth in a single pass from the solid by special resin-bonded, high-speed wheels. Material removal rates reach maximum values of 1 in.³/s (16 387 mm³/s) which is 50-100 times higher than the maximum values in creep-feed surface grinding and up to 20 times higher than attainable by conventional flute form milling. In the case of small and medium-sized drilling tools, the operation is performed in hardened high-speed steel. Drilling tools larger than about 0.59" (15 mm) diam are hardened after deep grinding to ensure a constant hardness over the total work cross section.

LOW-STRESS GRINDING

Low-stress grinding, a somewhat nontraditional use of the conventional surface grinding process, leaves a low-magnitude, residual stress in the workpiece surface, thus increasing fatigue strength and improving end product durability and reliability.¹⁸ Typically, low-stress grinding is used on workpieces that will be subjected to high stress or stress corrosion environments. Usually, the process is applied as a finishing operation, with conventional grinding techniques used for roughing and semifinishing operations.

Typical applications for low-stress grinding are found in the processing of turbine blades and in the preparation of test specimens for evaluation of material properties.

Effects of Stress

The effect of high-stress, conventional, and low-stress grinding on the fatigue-endurance limit of various materials, including steel, titanium, and nickel-based alloys, is shown in Fig. 11-111. High-stress grinding refers to an inadvertent "accident" during grinding—for example, grinding dry due to a plugged lubricant nozzle or grinding with an excessively hard wheel that was not changed from a previous operation.

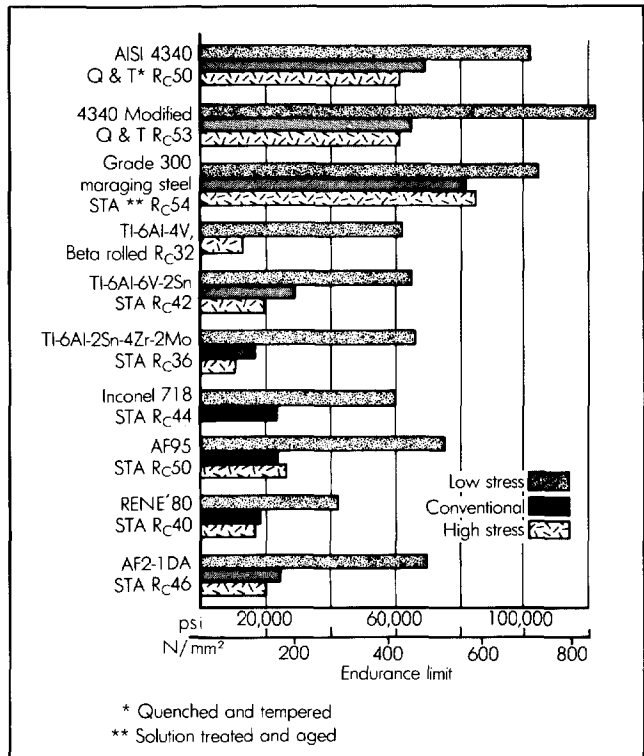


Fig. 11-111 High cycle fatigue response of various materials created with low-stress, conventional, and high-stress grinding.

Control of residual stress is critical in areas requiring close dimensional control for mating parts or in critical stress areas. A high-stress pattern, tensile or compression, can result in distortion of the part. The curves in Fig. 11-112 show that conventional grinding can produce a relatively shallow but rather high tensile stress. The low-stress technique produces a surface with a low-level stress pattern which is generally compressive in nature.

LOW-STRESS GRINDING

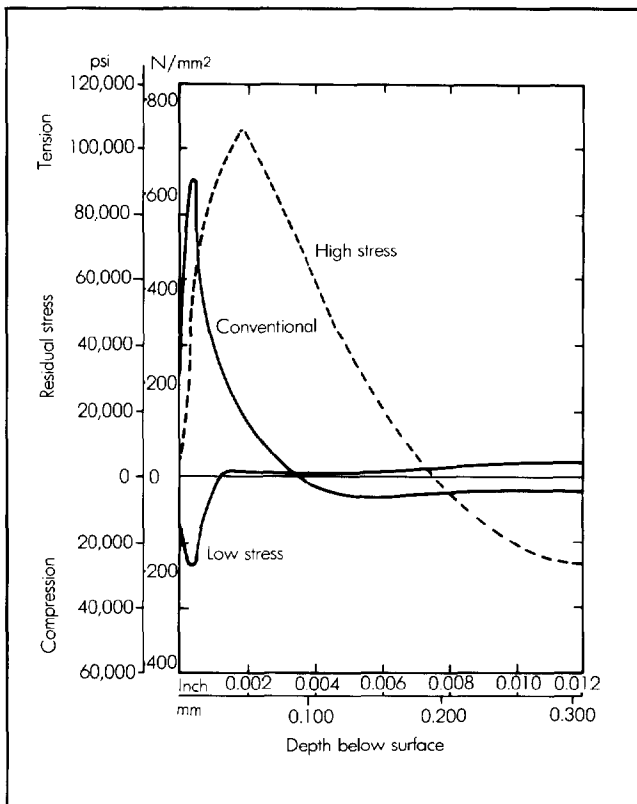


Fig. 11-112 The nature of high-stress, conventional, and low-stress at various depths below the surface of a workpiece.

Figure 11-112 shows the residual stress profile produced by three different sets of grinding conditions on a part made of AISI 4340 steel quenched and tempered R_{C50} . Low-stress grinding was done with an A46HV wheel, a sulfurized oil as the grinding fluid, a wheel speed of 2000 sfm (10 m/ms), and an infeed of 0.0002-0.0005" (0.005-0.013 mm) per pass. For conventional grinding, an A46KV wheel and 1:20 soluble oil were used, with a wheel speed of 6000 sfm (30 m/ms) and an infeed of 0.001" (0.03 mm) per pass. The high-stress condition involved an A46MV wheel running dry at 6000 sfm (30 m/ms), with an infeed of 0.002" (0.05 mm) per pass.

TABLE 11-19
Low-Stress Grinding Parameters and Values

Parameter	Value
Wheel speed	Under 3500 sfm (18 m/s)
Infeed rate	0.0002-0.0005" (0.005-0.013 mm) per pass
Wheel grade	Soft and open (G, H, I)
Dressing	Frequent and coarse to maintain sharpness
Grinding fluid	Oil base (not water)
Table speed	50 sfm (15.2 m/min) and up

Low-Stress Grinding Parameters

Conventional surface grinding typically involves wheel speeds of about 6000 sfm (30 m/s), an infeed of about 0.001-0.003" (0.03-0.08 mm) per pass, and a water-based fluid.

In low-stress grinding, the wheel is soft and is run at a much slower speed, which tends to make the wheel act as if it were softer. Infeed is very light, usually about 0.0002" (0.005 mm) per pass. It is decreased progressively as grinding approaches the finished dimension. Typical statistics are 0.0005" (0.013 mm) per pass for the first 0.009" (0.23 mm) and 0.0002" (0.005 mm) per pass for the last 0.001" (0.025 mm).

Low-stress grinding does not require the use of special equipment, but rather adjustments or modifications of various grinding parameters. Infeed rate and wheel speed are normally limited by the grinding machine. If the proper levels of the other parameters are selected, a ground surface of acceptable quality can be obtained on almost any traditional grinder.

The parameters which provide low-stress grinding are shown in Table 11-19. The major parameters are seen to be wheel speed, infeed, wheel grade, wheel dressing, grinding fluid, and table or work speed. The conditions which result in low stress also tend to minimize surface alterations in the material and promote high fatigue strength of a component.

Infeed rate is the only parameter that directly affects production output. Wheel dressing and grinding speed, although having a more dramatic effect on quality, do not directly affect production rates. Thus, they can be adjusted for a higher quality product without sacrificing production.

CONTROL GAGING FOR GRINDING OPERATIONS

Machine control gaging can be used to automate and simplify the operation of almost any grinding process. These gaging systems can vary from complex microprocessor-based systems, which can be programmed to control the execution of an exact taper grind, to a simple comparator stand checking parts after they have been produced.

The greatest returns on a gaging investment are seen on machines that are designed for rapid and continuous production. Among these are the centerless, internal, single-disc, double-disc, and center-type grinders. The end results of fitting one of these machines with the proper control gaging system include reduction of scrap, reduction of costs, improved

quality, increased abrasive life, and dramatic increases in overall production.

When more "intelligence" is built into the basic grinding machine, the machine operator is able to make more efficient use of his time. Operator skill and attention requirements are reduced. Most effective gaging systems have the ability to control the entire grinding process. In the bearing industry, in which the use of automatic gaging is quite prevalent, it is common to see one person operating as many as four machines. These machines incorporate control gaging to monitor part size, position grinding wheels when size corrections are necessary, dress grinding wheels automatically, and shut down

CONTROL GAGING FOR GRINDING OPERATIONS

the machining process in the event of an emergency. These capabilities reduce operator requirements extensively, making proper machine and gage setup the operator's primary function. As with most manufacturing aids, gaging can do more harm than good if it is not maintained or if it is set up incorrectly. If an incorrect gage setup is made and not noticed, an entire production run could be ground to the wrong size.

Most new high-production grinders are equipped with some type of control gaging system installed as original equipment. Gaging can also be easily retrofitted to older machines that were originally designed for manual operation. It may be more cost effective to increase productivity on an older machine than it would be to purchase a new machine to do the same job. Careful consideration must be placed upon tolerance requirements and the overall condition and capability of the existing grinder before this decision can be made. As a general rule of thumb, if a skilled operator can maintain proper size manually and if the machine has the necessary rigidity and accuracy, the machine can be controlled with a gaging system.

There are four categories that control gaging systems fall into when applied to abrasive operations. These are referred to as pre-process gaging, in-process gaging, post-process gaging, and match gaging. The first three are widely used, with each having its own distinct advantages and disadvantages that should be given proper attention when a decision is made as to which type would best suit a particular grinding process. The fourth, match gaging, is more specialized and only used in limited applications.

PRE-PROCESS GAGING

Pre-process gaging is used when overall work size must be consistent before entering a manufacturing process. It is commonly used when finishing parts on throughfeed centerless grinders or lappers. Better tolerances on size and surface finish can be maintained on these machines when the parts entering them are consistent.

This type of gaging is also useful when odd-sized workpieces entering a process may cause extensive damage to a machine or may destroy an elaborate setup. These workpieces can be detected and segregated from the work flow.

IN-PROCESS GAGING

In-process gaging is the most common type of machine control and can be applied to most grinding operations. This technique monitors the part size while machining is taking place. On center-type or internal grinders, an in-process gaging system controls the complete grinding cycle (see "Gaging for Internal Grinding" in this chapter). The gage tells the wheelhead when to rapid infeed, when to initiate the wheel dressing, when to slow infeed, when to spark out, and when desired size is achieved.

When using in-process gaging on center-type or centerless infeed grinders, the response time of the control becomes critical. Parts will be ground undersize if the gage does not keep up with the infeed rate of the wheel.

When positive-stop, OD grinding is used, final size is directly related to the condition of the grinding wheel. When freshly dressed, a wheel is free cutting and lower forces are required to remove the same amount of stock. As the wheel becomes glazed or loaded, these forces become higher, and since the grinding cycle is constant, more deflection is built up in the machine and part. This causes a greater oversize condition than would occur with a freshly dressed wheel. When the wheel breaks down, giving a freer cutting condition, part size will constantly become

larger unless manual compensation is made on the machine. When the machine is controlled with a gage, this oversize trend due to wheel breakdown can be eliminated. The gage, if properly designed, will retract the wheelhead when the part comes to size, regardless of wheel breakdown.

Taper is a machine alignment and deflection function and cannot be eliminated by a gage. In some applications, however, it can be controlled so that a part with one end ground undersized does not have to be scrapped. This is accomplished by putting a gage on both ends of the part; whichever gage indicates size first will retract the wheelhead. If taper exists, the small end will be to size and the other end will be oversize.

Roundness is a direct function of workholding conditions such as center holes and rate of feed per revolution of the workpiece at wheelhead retraction. If the feed rate is 0.00005 ipr (0.0013 mm/rev) at finish size, it is unlikely the part will be better than 0.00005" (0.0013 mm) roundness. The roundness can be improved by introducing a dwell or spark-out near finish size, which essentially represents an extra-fine feed. This will greatly affect size on a machine that is not gage controlled, because of the unequal cutting forces due to the wheel condition. However, on a machine that is gage controlled an electrical contact in the control unit can be set to block the feed rate a few ten-thousandths of an inch (about 0.007 mm) from size. This will provide a controlled dwell until the part reaches the size limit on the gage. It also gives an extra-fine feed rate that is not based on time, thus providing roundness and size control.

Time to reach final size is often variable depending upon the deflection force present at the time feed is stopped. Some controls allow for the restoring of feed after a set time interval.

Surface finish produced is controlled entirely by a combination of wheel grading, wheel condition, feed rate or force at finish size, and cleanliness of the cutting fluid. A gage may help in achieving the proper finish during production runs by introducing a controlled dwell to more or less burnish the workpiece to size.

TREND GAGING

Trend gaging is a form of in-process gaging that is normally used for continuous applications such as throughfeed centerless grinding. On this type of operation, the part size remains fairly consistent from one piece to the next. They are so consistent, in fact, that some systems are unable to detect any differences at all. This enables the gage to maintain tolerance requirements without having to check every piece. Circuit designs let the gage overlook sporadic readings that may be caused by dirt or sludge.

On some applications in which the parts to be gaged are subjected to extreme contamination or vibration, sensing the position of the wheel may be more advantageous than actually gaging the part during machining. This is a method of in-process gaging that is used successfully on infeed centerless grinding. Because of the ease of setup, wheel position gaging is often used when one machine is employed to grind a variety of different parts.

POST-PROCESS GAGING

Post-process gaging is used to measure part size after machining has been completed and parts have left the machine. The gaging area can be located some distance from the operation; however, for best results as a machine control, the part should be gaged as quickly as possible. This enables size corrections to be made on the machine before the desired

CONTROL GAGING FOR GRINDING OPERATIONS

tolerance is exceeded.

This type of gaging interfaces well with CNC equipment, such as the type used to grind multiple diameters with a single grinding wheel. After being ground, the part goes to an inspection station, which analyzes all dimensions and sends information back to the controller so that any size corrections can be made on the next piece.

With the coming of age of microprocessor technology, some post-process gages feed information back to the in-process gage to determine the final-size kick-out point on a grinder. For instance, it is an easy task for the post-process gage with a computer to perform a running statistical analysis of any desired parameter on parts exiting a grinding machine. Using this information, a normal curve can be constructed. The center of distribution of this curve can be determined, limits set for its drift, and the information used to control the final-size point on the in-process gage which will keep the distribution within the predetermined limits. The computer can also automatically compare the statistical distribution with the norm and indicate when the machine is going out of control.

Optical gages are also used in a post-process mode to monitor the surface finish condition enabling the operator to determine if dressing the wheel is necessary.

MATCH GAGING

Match gaging is a system which enables an operator to grind pieces to size, using a previously manufactured part as the gaging standard. Clearances between the mating parts can be set in the gaging system and maintained regardless of the variations in the previously machined part. This type of gaging is most frequently used in applications in which a cylindrical part is inserted in a bore, such as a valve body and spool configuration.

CONTACT GAGING

All types of control gaging must sense the size of the parts either directly or indirectly. Gaging systems that make mechanical contact with the workpiece tend to be the most accurate and are used when tight tolerance requirements are to be maintained. Gage contacts must be made of high wear-resistant material, such as diamond or carbide, and arms and holders must be rigid enough not to deflect or distort when part contact is made. Thermal deflection of gage elements is an important consideration.

When using contact gaging for in-process systems, it is important to electrically or mechanically overlook false part-size readings, which may be caused by dirt or sludge passing between the piece and the gage tip. This is when trend gaging becomes most beneficial.

Contacting-type gages have the ability to snap on a workpiece, even when considerable stock has to be removed. In most cases, this overtravel can be in excess of 0.080" (2.03 mm). This type of gage also has the ability to span interrupted work, such as a keyway or even a spline. A contacting-type gage can be used in conjunction with an air or electronic cartridge, which is easily calibrated without the need for minimum or maximum setting masters. It is usually easy to design in adjustability to cover an even wider range of part sizes.

Contacting gages do, however, have a few characteristics that could be troublesome, but most of these can be overcome by good design. Wear on the contact points is constantly present, but this condition can be tolerated by manual adjustment of the gage box. Proper selection of materials, such as ceramics,

epoxy, or the proper grade of carbide contact tips, can minimize this wear.

For automated installations, a post-process gage located in a more suitable atmosphere can be used to check the finished parts and feed back any size variation to the in-process gage. Contact-type gages, with their moving parts, are more susceptible to contamination present during grinding, and dirt and grit can easily jam the moving parts. To avoid these problems, the pivot joints and fragile air cartridges can be encased in their housings and pressurized to ensure cleanliness.

New design concepts in contact gage fixtures and improved electronic controllers have reduced the actual pressure exerted on the piece part from the gage to about 1.7 oz (50 g). This light contact pressure is essential on throughfeed centerless machines, because any back pressure can affect finish and final size of parts.

NONCONTACT GAGING

Although contact gaging systems are by far the most common, they may not be practical on some processes. When this happens, the use of a noncontact type of gaging system may be necessary. The most widely used form of noncontact gaging is employed with pneumatics. The biggest advantage that air gaging has over the other forms of noncontact gaging is that it can be used in highly contaminated environments due to the emission of air forcing contamination away from the surface during gaging.

Noncontacting or open-orifice gages have no wear characteristics to speak of. There are no moving parts; therefore, dirt is of no major concern to their reliability. Also, they cannot cause chatter or burnish marks on the workpiece, because of the absence of physical contact. However, large stock removal cannot be tolerated because of the fixed gap between the gage orifice and finished workpieces.

The limitation caused by excessive stock removal can be overcome by spring loading the orifices against a fixed stop. When an oversized piece comes between the orifices, they are opened to allow the piece through and then closed against the fixed stops. By using an air-to-electronic pressure transducer and the proper electronic circuit, air gaging can be used to check parts that have interrupted surfaces.

If the metallic structure of the parts being ground remains constant and tolerance requirements are not excessively tight, systems using capacitance or inductive pick-up heads can be used.

Other forms of noncontact gaging incorporate electronic proximity sensors, and still others use scanning lasers against photosensitive backgrounds.

New designs in scanning lasers have resolutions down to 10 millionths of an inch ($0.25 \mu\text{m}$) and can check a number of parameters on the same piece. Accuracy of laser gaging is greatly dependent upon a clean environment. This, along with its bulky components, makes it impractical in most in-process gaging applications.

GAGE CONTROL UNITS

There are three different ways a control system can interpret information from a sensing unit. It can interpret using all electronics, all pneumatics, or a combination of the two. The all electronics and combination types are by far the most widely used in industry today. When using pneumatic control, an open orifice or air cartridge, whichever is used in the gage tooling, sends a signal to the control unit in the form of either an

CONTROL GAGING FOR GRINDING OPERATIONS

increasing or decreasing back pressure. This back pressure is used in two ways. It is fed into a pressure dial, which is calibrated in inches or millimeters rather than pounds per square inch, or Pascals, to offer a visual indication of how far the part is from the finished size. It is also simultaneously fed into a number of pneumatic pressure switches that are preset to actuate at a specific pressure, which in turn represent a definite part size. The resulting electrical signals are used to control the machine, such as reducing the feed rate or retracting the wheelhead when finished size is reached.

For most in-process applications, linearity and amplification are not too important. The most important thing is a consistent firing point when finished size is reached. However, for throughfeed centerless or matched-hole gaging, amplification, linearity, and the absence of hysteresis are of prime importance.

In the combination of an air and electronic gage system, the back pressure from the air orifice being used is changed to an analog electronic signal before it reaches the control console. This signal is then processed electronically and displayed on a meter. With this system, one achieves the advantages of a self-cleaning air gage and the accuracy, versatility, and dependability of an electronic control console.

An all-electronic gage system is the most accurate and simplest type to use and maintain. As with the air-electronic system, the control console is all solid state and can be made without any moving or mechanical parts. This is done through the use of LED displays and solid state relay outputs.

SELECTING A GAGING SYSTEM

With all these different varieties of machine control gaging systems available, it becomes necessary to consider some important points when choosing which system would best suit a particular process. These are maintenance, ease of setup, stability, accuracy required, and the condition of the machine.

Any initial gains in machine efficiency achieved through the use of gaging can easily be lost at a later date if the system cannot easily be maintained. Simplicity and quick replacement of primary components are important design features. Production can also be lost if the gage set-up procedure is difficult or takes a great amount of time to execute properly. A system of this type would be extremely impractical for shorter production runs.

Overall stability in any type of gaging system is essential. Gage fixtures must be well designed and free from mechanical hysteresis or twist; electronic controls must be accurate and consistent. Rapid heat buildup can adversely affect the performance of a gaging system. A brief warm-up period of the machine may be necessary in order for the process to thermally stabilize.

The condition of the grinding machine must be taken into account when it is being considered for use with a gaging system. Any machine condition which produces erratic or uncontrollable situations will make it more difficult to maintain tolerances regardless of the gaging system being used. It is important for the machine slides to be free to move. Spindles and spindle bearings must be in good shape, and lead screws should be free of backlash.

Every good machine control gaging system should come complete with protection circuitry to shut down gage function in the event of failure. For example, when a machine is dependent upon a signal from a gage before executing a different function and that signal never arrives, extensive machine damage could result. These fail-safe control features

can be incorporated through the use of load meters, which sense how hard the grinding wheel motors are working, or through the use of timers, which can automatically shut the machine down if a proper signal is not sensed within a reasonable amount of time. The same features can be used to provide better process control over variables.

Fail-safe features should also be designed into the mechanical tooling of the gage fixtures themselves. For instance, as a machine process begins and a gage is improperly adjusted, it would be more economical to shear off a gage contact than to freeze up a precision machine slide. It also protects the more complicated inner tooling of the gages if the contacts are the first component to break. It usually requires very little down time to replace broken contact arms.

Progressive gaging companies are expanding their product lines to include special grinding fixtures that are used to upgrade old, worn-out grinders to match or better the performance of a new machine. For example, an old centerless grinder with worn slides can be used as a precision infeed grinder providing the spindles are still good. This is done with the use of a fixture to convert the machine from normal operation to a tangential grind.

GAGING FOR INTERNAL GRINDING

For the toolroom or for low-production internal operations, holes are generally gaged manually. This is done by manually interrupting the finish grind or spark-out cycle and checking the hole with a go-no-go plug, dial-bore, gage, air gage, or electronic gage. On high-production internal grinders, gaging is generally automatic. The most common and least costly approach is the diamond sizing method shown in Fig. 11-113. Here the dressing tool (diamond) serves as a reference point. After the wheel is dressed, it is fed a constant amount (0.001", 0.03 mm is typical). The bore radius will be equal to the fixed distance, D , that the diamond is set from the center of the work, plus the amount, F , that the wheel is fed after dressing. With this method, sizing accuracy is 0.001-0.003" (0.003-0.076 mm), depending upon variation in wheel wear after dressing, diamond wear, slide repeatability, system deflection, and thermal drift.

To maintain closer bore tolerances (0.0001-0.0004", 0.003-0.010 mm) on high-production internal grinders, and to eliminate the effect of OD size variation in centerless grinding,

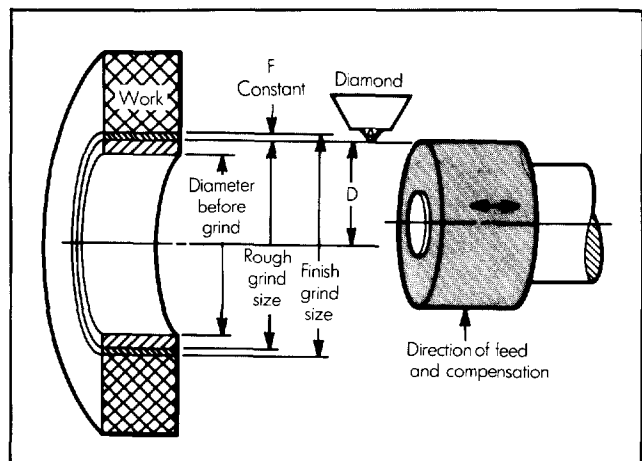


Fig. 11-113 Most common and least costly method of automatically gaging internal grinding operations is diamond sizing.

CONTROL GAGING FOR GRINDING OPERATIONS

in-process gaging is used. A solid or spidered plug gage is urged against the back of the bore whenever the reciprocating wheel is withdrawn, as shown in Fig. 11-114. When the plug enters the hole, a switch is made in the plug gaging mechanism, thus signaling the machine that final size is reached. Plug sizing is limited to straight bores, and sizing accuracy is influenced by variations of chamfer on the end of the bore, wear of the plug, and rate of stock removal per wheel reciprocation.

In contrast to plug gaging (which is intermittent) continuous gaging uses one or two probes (fingers or forks), which continually measure the hole being ground. The finger may be a diamond-tipped stylus operating an electronic transducer or an air jet operating a pneumatic amplifier, as shown in Fig. 11-115. Continuous in-process gaging produces close hole-size tolerances and is influenced more by thermal distortion of the gage

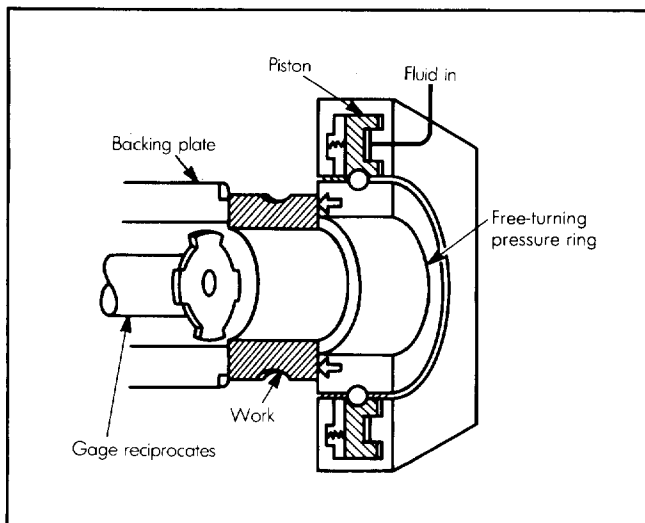


Fig. 11-114 Reciprocating plug is used for in-process gaging on high-production internal grinders.

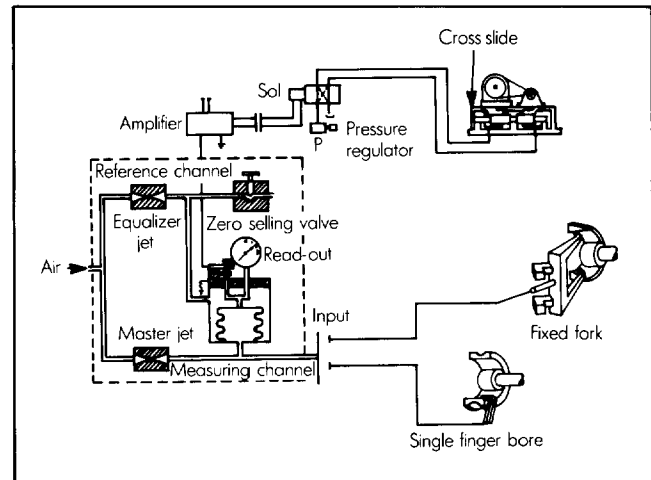


Fig. 11-115 Continuous in-process gaging of internal grinding operations uses a single finger or two probes on a fork to measure hole being ground.

mechanism, stylus wear, and grinding-rate variation (coupled with machine response time) than by gage transducer resolution or amplifier drift.

Modern automatic internal grinders not only use in-process gages to signal final size and retract the wheel, but they also can change feed forces or feed rates as the hole approaches final size, initiate dressing, and detect and correct for diamond wear and thermal drift. This will keep either amount of finishing time, finishing stock, or size point for gage release within preselected limits. These gages may also be used as post-process gages when holes are too small or unsuitably shaped for in-process gaging. By measuring the workpiece after it is ground, a post-process gage will improve the accuracy of a diamond sizing unit by detecting thermal drift or diamond wear, and feed corrections to the feed stop or diamond position.

TROUBLESHOOTING GRINDING OPERATIONS

The purpose of this section is to present a compilation of troubleshooting guidelines for various grinding processes. An exhaustive study of all the cause and effect relationships between variables in all grinding processes is beyond the scope of this presentation because such a wide variety of factors influence the performance of any grinding operation. As aids to troubleshooting, Table 11-20 presents hints for correcting cylindrical grinding operations; Table 11-21 presents similar material for correcting errors in surface grinding; and Table 11-22 pinpoints troubleshooting guidelines for double-disc grinding.

Of the many problems experienced in grinding, chatter in cylindrical grinding and surface grinding, and feedlines and out-of-round work in cylindrical grinding, are often most troublesome. These common difficulties are highlighted in the following discussion presented courtesy of Cincinnati Milacron.

CHATTER

Chatter can originate from any or all of five sources: (1) the machine, (2) the method, (3) the wheel, (4) the workpiece, or

(5) other equipment nearby or even at a considerable distance. Part of the solution is to find the point, or points, of origin; this must be done largely by trial and error.

The Machine

Of the several methods used to locate the vibration in machine elements that causes chatter, the dial indicator method is the most economical one currently available. The "feel" method is questionable. Electronic equipment may be used if it has reasonably good amplitude fidelity at frequencies less than 100 cps. This is the range most troublesome in heavy equipment.

When using dial indicators, it is wise to have several indicators of different manufacturers to be sure that the natural resonant frequency of a single-dial indicator is not giving a false amplitude picture. Since it is not well known how much vibration, or what frequencies can be permitted in a grinding structure, it is best to reduce all amplitudes to a practical minimum. Remember that the best place to reduce vibration is at its source.

Motors. Motors on precision grinders require balancing to

CHAPTER 11

TROUBLESHOOTING GRINDING OPERATIONS

TABLE 11-20
Causes and Corrections of Cylindrical Grinding Problems

Complaint	Causes	How to Correct
Chatter on workpiece	Out-of-balance wheel	Rebalance on mounting before and after dressing. Run wheel without fluid to remove excess water. Store a removed wheel on its side to keep retained water from causing a false heavy side. Tighten wheel mounting flanges. Make sure wheel center fits spindle.
	Wheel out of round	True before and after balancing. True sides to face.
	Wheel too hard	Use coarser grit, softer grade, more open bond.
	Improper dressing	Use sharp diamond and hold rigidly close to the wheel. It must not overhang too far. Check diamond in mounting for rigidity.
	Faulty work support or rotation	Use sufficient number of work rests, one every 9" (230 mm) of work length, and adjust them more carefully. Use proper angles in work centers. Clean dirt from footstock spindle and be sure spindle is tight. Make certain that work centers fit properly in spindles.
	Improper operation	Reduce rate of wheel feed.
	Work vibration	Reduce work speed. Check workpiece for balance.
	Outside vibration transmitted to machine	Check to make sure that machine is level and sitting solidly on foundation. Isolate machine or foundation.
	Interference	Check all guards for clearance.
	Wheelhead	Check spindle-bearing clearance. Use belts of equal lengths or uniform cross section on motor drive. Check drive motor for imbalance. Check balance and fit of pulleys. Check wheel-feed mechanism to see that all parts are tight.
Spirals (traverse lines) on workpiece, with same lead as rate of traverse	Headstock	Incorrect work speeds. Check drive motor for imbalance. Make certain that headstock spindle is not loose. Check work-center fit in spindle. Check wear of faceplate and jackshaft bearings.
	Machine parts out of line	Check wheelhead, headstock, and footstock for proper alignment.
Check marks on workpiece	Truing	Point truing tool down 3° at the work/wheel contact edges. Make edges of face round.
	Improper operation	Do not force wheel into work. Use greater volume of fluid and a more even flow. Affirm the correct positioning of fluid nozzles to direct a copious flow of fluid to the work/wheel interface.
	Improper wheel	Make wheel act softer. Use softer grade wheel. Review the grain size and type of abrasive. A finer grit or more friable abrasive, or both, may be necessary.
	Improper dressing	Make sure diamond is a sharp, good quality and well set. Increase speed of the dressing cycle. Make sure diamond is not cracked.

TROUBLESHOOTING GRINDING OPERATIONS

TABLE 11-20—Continued

Complaint	Causes	How to Correct
Isolated deep scratches on work	Improper wheel	Use finer wheel and consider a change in abrasive type.
	Improper fluid and/or fluid filter	Use grinding fluid that settles chips. Check fluid filter.
Fine spiral or thread scratches on work	Improper operation	Reduce wheel pressure. Use more work rests. Reduce traverse with respect to work rotation. Use different traverse rates to break up pattern when making numerous passes. Keep edge of wheel from penetrating by dressing wheel face parallel to work.
	Faulty wheel dressing	Use slower or more even dressing traverse. Set dressing tool at least 3° down and 30° to the side from time to time. Tighten holder. Do not take too deep a cut. Round off wheel edges. Starting dressing cut from wheel edge may help.
Narrow and deep regular marks	Wheel too coarse	Use finer grain size.
Wide irregular marks of varying depth	Wheel too soft	Use harder grade.
Widely spaced spots on work	Oil spots or glazed areas on face	Balance and true wheel. Keep oil from wheel face.
Irregular "fishtail" marks of varying lengths and widths	Dirty grinding fluid	Clean tank frequently. Use filter for fine-finish grinding. Flush wheel guards after dressing or when changing to finer wheel.
Wavy traverse lines	Wheel edges	Round off wheel edges with abrasive stick. Check for loose thrust on spindle and correct if necessary.
Irregular marks	Loose dirt	Keep machine clean.
Deep irregular marks	Loose wheel flanges	Tighten wheel flanges, being sure to use blotters.
Isolated deep marks	Grain pulls out	Change pH value of grinding fluid.
	Coarse grains or foreign matter in wheel face	Dress out.
Grain marks	Improper dressing	Use sharper dressing tool. Brush wheel after dressing with stiff-bristle brush.
	Improper finishing cut	Start with high work and traverse speeds; finish with high work speed and slow traverse, letting wheel spark out completely.
	Grain sizes of roughing and finishing wheels differ too much	Finish out better with roughing wheel or use finer roughing wheel.
	Dressing too coarse	Use shallower and slower cut.
Work out of round, out of parallel, or tapered	Wheel too coarse or too soft	Use finer grain size or harder grade wheel.
	Misalignment of machine parts	Check headstock and footstock for alignment and proper clamping. Check table setting and adjustments for straightness. Check headstock bearings.

TROUBLESHOOTING GRINDING OPERATIONS

TABLE 11-20—Continued

Complaint	Causes	How to Correct
When wheel is fed to same position, it grinds one piece to correct size, another oversize, and still another undersize	Work centers	Centers in work must be deep enough to clear center point. Keep work centers clean and lubricated. Check footstock spindle shake. See that footstock spindle is clean and tightly seated. Regrind work center if worn. Work centers must fit taper of workcenter holes. Footstock must be checked for proper tension.
	Improper operation	Do not let wheel traverse beyond end of work. Decrease wheel pressure so work will not spring. Use harder wheel or change feeds and speeds to make wheel act harder. Allow work to spark out. Decrease feed rate. Use proper number of work rests. Allow proper amount of tarry. Workpiece must be balanced if odd shape.
	Grinding fluid	Use greater volume of grinding fluid.
	Wheel	Rebalance wheel on mounting before and after truing. Wheel must be properly dressed and free-cutting.
	Improper dressing	Use same positions and machine conditions for dressing as in grinding.
	Spindle bearings	Check clearance.
	Work	Work must come to machine in reasonably accurate form.
	Improper work support or rotation	Keep work centers clean and lubricated. Regrind work-center tips to proper angle. Be sure footstock spindle is tight. Use sufficient work rests, properly spaced.
	Wheel out of balance	Balance wheel on mounting before and after truing.
	Loaded wheel	Use softer grade wheel.
	Improper infeed	Check forward stops of rapid feed and slow feed. When readjusting position of wheelhead by means of the fine feed, move the wheelhead back after making the adjustment and then bring it forward again to take up the backlash and relieve strain in feed parts. Check wheel spindle bearings. Do not let excessive lubrication of wheelhead slide cause floating. Check and tighten wheel-feed mechanism. Check parts for wear. Check pressure in hydraulic system. Check infeed cushion. Check pistons to see that they are not sticking. Check positive stop for position.
	Improper traverse	Check traverse hydraulic system and the operating pressure. Prevent excessive lubrication of carriage ways with resultant floating condition. Check to see if carriage traverse piston rods are binding. Carriage rack and driving gear must not bind. Change length of tarry period.
	Grinding fluid	Use greater volume of clean fluid.
	Misalignment	Check level and alignment of machine.
	Work	Workpieces may vary too much in length, permitting uneven center pressure.

TROUBLESHOOTING GRINDING OPERATIONS

TABLE 11-20—Continued

Complaint	Causes	How to Correct
Glazing; some loading; lack of cut; chatter; burning of work	Wheel acting too hard	Increase work and traverse speeds as well as rate of infeed. Decrease wheel speed, diameter, or width. Dress more sharply. Use thinner grinding fluid. Do not tarry at end of traverse. Select softer wheel grade and coarser grain size. Avoid gummy grinding fluid. On hardened work, select finer grit, more fragile abrasive, or both, to get penetration. Use softer grade.
Wheel marks; tapered work; short wheel life; not holding cut	Wheel acting too soft	Decrease work and traverse speeds as well as rate of infeed. Increase wheel speed, diameter, or width. Dress with little infeed and slow traverse. Use heavier grinding fluid. Do not let wheel run off work end of traverse. Select harder grade wheel or less fragile grain or both.
Loaded wheel has metal lodged on grains or in wheel pores; glazed wheel has shiny appearance and slick feel	Incorrect wheel	Use coarser grain size, more open bond, or softer grade.
	Improper dressing	Keep wheel sharp with sharp dresser. Clean wheel after dressing. Use faster dressing traverse, deeper dressing cut.
	Faulty operation	Control speeds to soften action of wheel. Use less infeed to prevent loading, more infeed to stop glazing.
	Faulty grinding fluid	Use more, cleaner, less oily, and thinner fluid.

limits that are much closer than ordinary commercial tolerance. Antifriction bearings wear out and require replacement, and antifriction bearings cannot be much better for roundness, and hence for life, than the holes they are pushed into or the shafts they support.

Motors running with no load may seem to be operating smoothly; but, with load, they can be a real source of heavy vibration. This is particularly true of sleeve-bearing machines on which bearings are worn or shaft-bearing surfaces are out-of-round. Clear, light oil is a must on grinding wheel motors with sleeve bearings.

Drive sheaves out-of-round or out-of-balance. It is common to find V-belt sheaves running out-of-round (pitch lines not concentric with the axis of rotation).

Wheel collet is poor fit on the spindle. Occurring more commonly than is generally believed, this is not an easy condition to check. The key must be removed from the spindle and the taper coated with a very thin film of Prussian blue. The collet should be stripped of the wheel, flange, belts and spacers, if any, to make it as light as possible for handling. The taper bore of the collet should be lightly polished with about 80-grit paper to remove rust and leave a bright surface for bearing indicator contrast. The bore should be thinly coated with red lead paste (machine oil vehicle). Then the keyways should be lined up (no key, however) and the collet carefully pushed home on the spindle. The collet must be held firmly and rotated back and forth several times about 5°. It should then be carefully removed, and the bearing should be carefully inspected. Any drag marks that were made in getting the collet on and off the spindle should be discounted, and any high spots carefully removed with a half round scraper. Particular attention should be paid to the edges of the keyway.

Recheck the collet bearing. If the collet shows about 85% of well-distributed bearing, it is ready for use. The key should be installed with no more than a light tap fit, or the spindle will be distorted. If there is less than 85% bearing, extensive scraping on the bore of the collet should not be attempted unless the spindle is removed from the machine and mounted vertically in the collet to check the bearing.

Wheel balance. The lighter the machine structure the better the balance must be. Large wheels should not be balanced on disc-type stands because their accuracy falls off rapidly with weight. The most satisfactory static balancer is the straight way stand if it is kept level.

Poor wheelhead fit on the ways. During scraping, the wheelhead bearing should be relieved on both vee and flat to prevent rocking of the wheelhead on the base.

Loose spindle. Bearings are usually egg shaped unless they are the hydrodynamic or advanced hydrostatic type, in which case they can be adjusted.

Machine should be leveled. Center-types should be checked for bow. All leveling screws should be snug.

Dull diamonds will glaze wheels causing chatter and burning. Cluster diamonds will produce this effect much more rapidly unless dressing speeds are increased. Too slow a dressing rate will produce glazing with any diamond. An inadequate supply of grinding fluid will give burn. This may glaze the wheel and may produce uneven breakdown with coarse chatter.

The Wheel

Too hard a wheel will glaze, skid on the surface, and produce a fine closely spaced chatter. The finish on the part will be good. Too soft a wheel will break down and produce a widely spaced, rough chatter. The finish on the part will be quite poor.

TABLE 11-21
Causes of Surface Grinding Problems

Causes	Problems								
	Burning or Checking	Burnishing of Work	Chatter Marks	Scratches on Work	Wheel Glazing	Wheel Loading	Work Not Flat	Work Out of Parallel	Work Sliding on Chuck
Machine Operation									
Dirty coolant				•		•			
Insufficient coolant	•						•	•	
Wrong coolant					•	•			
Dirty or burred chuck				•			•	•	
Inadequate blocking									•
Poor chuck loading							•	•	•
Sliding work off chuck				•					
Dull diamond					•				
Too fine dress	•				•	•	•		
Too long a grinding stroke								•	
Loose dirt under guard				•					
Grinding Wheel									
Too fine grain size	•				•	•			
Too dense structure					•	•			
Too hard grade	•	•	•		•	•	•		
Too soft grade			•	•					
Machine Adjustment									
Chuck out of line								•	
Loose or cracked diamond				•			•	•	
No magnetism									•
Vibration			•						
Condition of work									
Heat treat stresses							•		
Thin							•		

(DoALL Co.)

TROUBLESHOOTING GRINDING OPERATIONS

TABLE 11-22
Methods to Prevent or Correct Double-Disc Grinding Problems

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- A good practice is to warm up the machine prior to starting the production run.
 - Specifications of the abrasive discs must be correct.
 - The abrasives must be properly dressed to produce flat and parallel work.
 - The workpieces must be correct for the type of tooling used.
 - The work stations or fixtures should be in alignment in order to properly present the work to the abrasive discs.
 - The workpieces being ground should be uniform in size as they come to the machine. A wide variation in the stock removal affects the accuracy of the finish ground work.
 - Gages used to check finished parts should be carefully checked to make certain they are giving the correct reading.
 - If size cannot be held on finished ground parts, the grinding fluid may be too strong or too hot or there may be excessive stock removal, too fast a feed rate, abrasives out-of-flat, or dull.
 - If the ground workpieces are not parallel, the abrasives should be checked for glazing. If glazed, the abrasives should be dressed or changed to a different specification.
 - If the ground workpieces are not as flat as required, the abrasive discs should be checked for flatness.
 - Out-of-flat parts can be caused by the abrasive not breaking down uniformly across the face. Too high or too low in the center affects the flatness.
 - Out-of-flat parts can be caused by the part pieces not breaking into the centerhole properly. The workpiece—on a rotary—should break into the centerhole approximately 1/4 to 1/3 the part around the center hole; if it breaks into the center hole too much, the abrasives will wear low around the center hole.
 - A poor finish is often caused by dirty grinding fluid, fluid too strong, rate of feed too slow or too fast, excessive stock removal, or machine vibration.
 - If the parts are burned or distorted, the abrasives may be too hard, too fine—or both; abrasives may be dull; there may be insufficient fluid, fluid too hot, feed rate too fast, or excessive stock removal.
 - The grinding fluid may not be properly directed to the surface being ground.
 - There should be a sufficient volume of grinding fluid; excess flooding is far better than not enough fluid. Increasing the volume tends to flush away the abrasive grit and grinding residue.
 - It is important to have uniform grinding fluid temperature. Too hot fluid affects accuracy. To reduce the temperature, the volume of the fluid tank should be increased, refrigerated fluid should be used, air should be introduced into the fluid lines, the abrasives should be dressed, or a freer cutting abrasive should be used. Excess stock removal produces heat, and in turn nonaccurate workpieces. Fluid that is too hot affects the wear of the abrasive disc, producing off tolerance workpieces.
 - The grinding fluid must be kept clean; dirty fluid causes scratches on the work glazing of the abrasives and heating up of the fluid.
 - The fluid should be mixed properly and accurately to the ratios recommended by the manufacturer, too rich a mixture can cause loading of the abrasives.
 - The machine must be level and securely fastened to the foundation. In some cases, special heavy foundations are recommended.
 - The fixturing, abrasive disc misalignment, and the dresser must be properly aligned with each other. For close tolerance work, extra care should be taken in alignment.
 - Machine vibration can be caused by:
 1. Out-of-balance abrasives caused by:
 - a) Out-of-flat abrasive discs.
 - b) If the grinding fluid is permitted to flow on a stationary abrasive, an out-of-balance condition is caused by absorbing the fluid in one area. It is good practice to let the spindles run with the fluid flow shut off to permit the fluid to be thrown off, avoiding an out-of-balance condition.
 2. Worn spindle bearings.
 3. Poor foundation.
 4. Out-of-balance motor sheaves, and/or spindle, and/or poor motor V-belts.
-

(Bendix Besley)

TROUBLESHOOTING GRINDING OPERATIONS

The Workpiece

Chatter in thin-wall tubing can sometimes be reduced by partially filling the tube with lead or steel shot. Some parts have natural bell shapes that promote chatter. It often helps to wrap an unground section of the part with a turn or two of friction tape or rubber to damp vibration.

Other Sources

Reciprocating machinery (shapers, planers, slotters, prime movers, forge hammers, cold headers, etc.) are often responsible for low-frequency, high-amplitude vibrations that can be transmitted for long distances.

Rotating machinery. Lathes, mills, other grinders, ventilating fans, etc., can also be responsible for chatter.

Insulating pads. Caution should be used in placing insulating pads under precision machinery. It may be difficult to hold the beds in alignment. Most such pads are of little value since they do not ordinarily absorb the low frequencies that are the most troublesome.

Chatter on Centerless Grinders

The following potential causes of chatter should be checked:

- Work too high above center.
- Too steep an angle on the blade (20-30° is about standard).
- Too thin a blade. The thickest possible blade should always be used.
- Warped blade.
- Too heavy a cut. If the blade vibrates sideways, chatter will result.
- Worn out drive chain or sprockets on regulating wheel; worn parts or belt slip.
- Improper contact of work and regulating wheel. If the regulating wheel is too large in the center, the work will tend to rock over this point, especially during infeed grinding. The angle of the regulating wheel truing slide should be increased by small increments, and the wheel should be retuned for each trial increase.

Chatter on Center-Type Grinders

The following potential causes should be checked:

- Improperly ground or loose centers.
- Machine centers bottoming in work centers.
- Loose tailstock spindle (also results in taper).
- Too much pressure on work centers.
- Footstock or headstock worn barrel-shaped on the bottom surfaces that contact the swivel table.
- Headstock driving arm improperly contacting work dog, tending to force work off center.
- Interference between headstock drive plate and headstock casting.
- Worn or unmatched V-belts.
- Long thin work that is supported only by centers and may require backrests.
- On large roll grinders on which chatter occurs on rolls of certain sizes, but not on others, the natural frequency of the machine and roll may be too close together. It may be necessary to install vibration dampers or large fixed masses to the wheelhead.

Chatter on Surface Grinders

The following potential causes should be checked:

- Too heavy a cut. Wheel rides up on the work and cannot grind itself clear.
- Loose head gib.
- Out-of-round spindle.
- Bent spindle (result of wrecks).
- Work not firmly held on the chuck. The work often will bow up or bridge from the heat of the cut. On cooling this will show as low center in the work.

Chatter on Internal Grinders

The following potential causes should be checked:

- Too thin a quill for the size of wheel and cut (too much overhang).
- Wheelhead vibrating. Because of the high spindle speed, the wheelhead must be in good mechanical condition.

The following procedures can be used to eliminate chatter in internal grinding operations:

1. Count the number of chatter marks around the workpiece ID. If the marks are not uniformly spaced, include the count marks which should be there to make the spacing uniform.
2. Increase or decrease the workspeed by at least 10%. If the number of marks remains the same, the chatter problem is caused by chuck-jaw distortion, worn work spindle bearings, etc. If the number of marks increases proportionately with decreased workspeed or decreases proportionately with increased workspeed, the chatter is not caused by the chuck jaws or work spindle bearing.
3. If the chatter problem is not caused by chuck-jaw distortion or worn work spindle bearings, it may be caused by a wheel problem. Multiply the number of chatter marks by the workspeed (rpm). The result of this calculation is the frequency of vibration. If the frequency of vibration is close to the wheel speed, and if the number of chatter marks increases or decreases proportionately with changes in wheel speed (use at least $\pm 10\%$ for checking purposes), then the chatter is caused by poor wheel balance or poor wheel spindle balance, a poorly dressed wheel, or a nonuniform wheel. Worn wheel spindle bearings may also cause chatter.
4. If the frequency of vibration is not close to the wheel speed (spm), check the correlation between the frequency and speed of the motor used on the machines (1200, 1800, or 3600 rpm, for example). In some cases, the source of chatter can be traced by comparing the frequency of vibration to a multiple of the number of vanes of pistons in a faulty hydraulic pump.
5. If none of the previously mentioned procedures apply, increase or decrease the wheel speed (rpm) 10%. If the number of chatter marks does not change with changes in wheel speed (rpm), and no motor or pump can be pinpointed as a problem, vibration is probably self-excited by the grinding process itself. Try a more rigid quill, a more free-cutting wheel, a faster dress, a sharper diamond, a shorter wheel, or a different sparkout period.

FEED LINES

Feed lines are particularly troublesome in precision work and can be caused by a variety of factors. The following sections indicate possible causes of feedlines for center-type and centerless grinding operations.

TROUBLESHOOTING GRINDING OPERATIONS

Feed Lines—General

The following potential causes should be checked:

- Too hard a wheel. This will sometimes result in a “burned” feed line.
- Improper dressing. The diamond should contact the wheel at exactly the wheel/work contact point. Using a dull diamond dresser should be avoided. A dull diamond (or a cluster diamond) will produce a glaze that will result in a feed line as well as chatter. Dressing too slowly will also produce a glazed wheel. Diamond wear, even in dressing narrow wheels, will produce a tapered wheel.
- Too fine a wheel (will also produce burn).
- Too heavy a cut.
- Too great a traverse rate for rpm of work.

Feed Lines on Center-Type Grinders

The following potential causes should be checked:

- The major source of feed lines in center-type machines can be found in warped beds. Any out-of-parallelism between vee and flat ways of the table and bed will certainly result in feed lines and taper in the workpiece. One of the best ways to check this is to place a straight plug gage in the vee way at one end of the bed. This gage should be large enough in diameter to extend about the rails, etc. A machinist’s level should be placed on the plug gage, and build up should take place from the flat way with Jo blocks until a level reading is obtained. The entire system should be moved to the other end of the bed. If the readings are not the same, the bed is twisted. Releveling may correct this; if not, hold down bolts must be installed. Note: It is not important that the machine lie in a flat horizontal plane. It can be high or low, end-to-end, front-to-back—but it must not be twisted.
- Spindle of machine not parallel with vee way of bed in all planes. This is a common source of trouble with universal machines, on which the wheelhead can be swiveled. The effect of this error can be cancelled by dressing the wheel on the same line at which it contacts the work.
- The swivel table can be a prime source of trouble on center-type machines. When swivel is repositioned, both clamps must be loose or bending stress will be set up in the sliding table, which will prevent its tracking properly in the vee way. The swivel table should be removed at least twice a year and cleaned; the surface in contact with the sliding table should be coated with waterproof grease. Machines with capacities greater than 36” (910 mm) between centers should have 0.0001” (0.003 mm) indicators (or metric indicators of accuracies to about 0.003 mm) on both ends of the swivel to make sure movements are equal. Before the indicators are set, the clamps should be loosened and the contact between the tables should be broken with a pinch bar to relieve any bending due to frictional drag.
- In center-type grinding, especially roll grinding, a feed line will usually be found in the rough and semifinish operations. Here feed lines can be used to interpret the progress of grinding. If the finishing is proceeding satisfactorily, a feed line will be wiped out on the return pass and a new one of the opposite hand (helix) laid down. It will grow fainter with each pass and finally disappear. An experienced operator can detect out-of-

roundness, low or high spots, taper, etc., by observing the feed lines.

Feed Lines on Centerless Grinders

The following potential causes should be checked:

- Grinding wheel not relieved on the exit side.
- Work guides not in proper alignment with the regulating wheel.
- The finishing portion of grinding wheel not parallel with the regulating wheel.
- The concavity of the regulating wheel not correct for a given angular setting of the regulating wheel. The regulating wheel truing slide should be readjusted, and the wheel should be redressed. The most practical procedure is to make an aligning bar 2” (51 mm) longer than the distance over the outguides and to the finished size of the part to be ground. The bar should then be coated with a thin coat of red lead paste, placed in the machine, and turned through a small arc (5°). The marks on the bar will show the necessary corrections.
- In long bar fixtures, outboard rollers with excessive pressure due to misalignment which stripe the work, giving the appearance of a wheel feed line.
- Metal accumulation on the blade which sometimes stripes or scores the work, giving the impression of a feed line. This metal accumulation is metal from the part being ground that is welded to the blade. Three basic interrelated conditions are responsible for this.
 1. High heat caused by:
 - a. Work speed too fast.
 - b. Part temperature too high. Use a high velocity nozzle or the equivalent.
 2. High pressure caused by:
 - a. High spot on the blade.
 - b. Cut too heavy.
 - c. Too little lubricity in the grinding fluid.
 3. Molecular affinity of metals. Some metals and alloys will weld at low temperatures and pressures, and cannot be used together. Assuming that the high heat and pressure (a and b above) have been reduced to a minimum, the following list of blade materials should be tried in the order shown:
 - a. Tungsten carbide.
 - b. High-speed steel.
 - c. Bronze. Ampco 18 through 25 or the equivalent.
 - d. Meehanite cast iron.

Feed Lines on Internal Grinders

The following potential causes should be checked:

- If the wheel tends to cut heavier at one end of the hole than the other, the leveling and the alignment of the machine.
- The wheel spindle and the workhead for relative alignments.
- Spindle deflection which often results in a feed line.

OUT-OF-ROUND WORK

The following sections provide possible causes of out-of-round work in various grinding operations.

TROUBLESHOOTING GRINDING OPERATIONS

Out-of-Round Work—General

The following potential causes should be checked:

- The heat of the cut which can result in distortion of parts with thin or unequal cross sections.
- Interrupted cuts over keyways, oil grooves, valve parts, etc.
- Out-of-balance work.
- Distortion of part through improper clamping in chucks and fixtures.
- Wheel too hard or too fine.
- Not enough tarry when work has reached size.
- Insufficient grinding fluid directed into the cut and over the part.
- Lack of rigidity in machine elements or fixtures.

Out-of-Round Work on Center-Type Grinders

See "Chatter on Center-Type Grinders"—most listed potential causes of chatter also can cause out-of-round work.

Out-of-Round Work on Centerless Grinders

The following potential causes should be checked:

- Regulating wheel speed too slow.
- Workpiece not high enough above center.

- Blade angle not steep enough.
- Loose or worn regulating wheel bearings.
- Worn out drive chain or sprockets on regulating wheel drive.
- Not enough stock to round up.
- Regulating wheel loose on collet.
- Regulating wheel spindle bent from unequal torquing of screws. Two 0.001" indicators (or metric indicators with accuracies to about 0.01 mm) should be used, one on the top and one on the side (90°) of the spindle. They should be set to zero when the wheel is loose. The spindle should be returned to a zero setting by torquing the screws. Before the wheel is mounted, the blotters should be dampened.

Out-of-Round Work on Internal Grinders

The following potential causes should be checked:

- Workpiece may be distorted in clamping. This may be checked by indicating the ground hole before and after releasing the clamps.
- When workpieces have bell-mouth holes, the wheel may have overtraveled the hole too far. Also, alignments of the workhead, wheel spindle, and diamond truing line should be checked.

ABRASIVE-BELT MACHINING

Abrasive belts, which used to be applied primarily for light stock removal and polishing operations, are being increasingly employed for heavier stock removal. The purpose of this section is to provide a general discussion of abrasive-belt grinding as used for general-purpose stock removal. Abrasive-belt grinding used primarily for finishing, polishing, etc., is covered in Volume III of this Handbook series, "Materials and Finishing."

The capability of abrasive-belt machining to remove metal at high stock removal rates is the result of availability of stronger, tougher, and sharper grains; better bonds; and stronger backings, as well as the development of machines for optimum use of the improved belts (see "Coated Abrasives" in this chapter). Versatility is a major advantage, since machines can be quickly converted from heavy stock removal to finishing operations, or for grinding different materials or parts, by simply changing the belts, and/or contact wheels. Most materials can be ground with abrasive belts, but the harder the material, the more difficult the operation.

STOCK REMOVAL RATES

Stock removal rates are proportional to pressure applied, depending upon the coated abrasive, cutting fluid, surface finish required, and workpiece material. A stock removal rate as high as 30 in.³/min/in. (322 mm³/s/mm) of belt width is practical with standard belts. By gradually increasing the pressure, it is possible to obtain a nearly constant cutting rate for the life of the belt. When using contact wheels, grinding pressure is often expressed as the horsepower (watts) available per inch (millimeter) of belt width for driving the contact wheel. This can vary from 1/2 hp/in. (14.7 W/mm) for light stock removal to 30 hp/in. (881 W/mm) of belt width for heavy stock removal.

BELT SPEEDS

Belt speeds of 5000-9000 sfm (25.4-45.7 m/s) are generally the most satisfactory for grinding ferrous and nonferrous metals. Toughness of the material to be ground is more critical than hardness, and some materials such as titanium are best ground at belt speeds in the 1500-3000 sfm (7.6-15.2 m/s) range.

CONTACT WHEELS, ROLLS AND PLATENS

Contact wheels, rolls, or platens are necessary as a backup support behind the abrasive belt when pressure is applied for most grinding operations. Contact wheels are usually made of cloth or rubber, but special compositions or metal are sometimes used. Hardness or density of the contact wheel affects stock removal and the finish produced. The harder the wheel, the greater the stock removal and the coarser the finish. Decreasing the diameter of the wheel has an effect similar to that of increasing the hardness. Serrated or slotted wheels increase the unit pressures applied, improve the cutting action, and prolong belt life.

Belt tension usually varies from about 4-40 lb/in. (0.7-7.0 N/mm) of belt width. Low tension is desirable with soft-contact wheels operating at reduced speeds to obtain maximum flexibility and resilience for contour grinding. High tension should be used when contact wheels are hard and heavy pressure is applied, particularly when the area of contact is small. In all cases, tensions should not exceed that required to prevent slippage and keep the belt tracked. Tension is usually applied by suspended weights, springs, or air cylinders.

Platens are often used for support behind abrasive belts, but they are not as effective as contact wheels in increasing unit pressure or controlling breakdown of the abrasive. Platens are usually flat, but are sometimes shaped to conform with

ABRASIVE-BELT MACHINING

workpiece contour. Most platens are smooth, but they can be serrated to increase their aggressiveness. Cooling is sometimes done by circulating water through the platen; in other cases, jets of water or air are applied between the belt and platen. Graphite lubricants are also used sometimes to decrease friction between the platen and belt. Carbide inserts or facings can also be employed to lengthen platen life and maintain flatness.

In addition to imparting tension to the belts, idler pulleys also serve to keep the belts centered on the contact wheels by having crowned peripheries. No crown is provided on wider pulleys, and automatic tracking devices are generally employed.

TYPES OF ABRASIVE-BELT MACHINES

Abrasive-belt machines are available in a wide variety of types to suit specific applications, as shown in Fig. 11-116. Most of them can be arranged for manual, semiautomatic, or fully automatic operation.

Backstand Grinders

Backstand grinders are some of the simplest, lowest cost, and most versatile abrasive-belt machines (see Fig. 11-116, *a*). They are basically conversions of polishing lathes to abrasive-belt use by the addition of backstand idlers. Workpieces can be held against the belt manually or with semiautomatic workholding devices, as shown, for faster production. Longer belts can be used without sacrificing floor space by using two idler pulleys, or the idler can be mounted above the contact wheel or on the wall to conserve floor space.

Arm attachments with the belt spring loaded between a contact wheel and an idler pulley are also available for installation on polishing or buffing lathes to permit abrasive-belt grinding operations on existing equipment. Backstand grinders or lathes with abrasive-belt arm attachments can be arranged along work-indexing or conveying semiautomatic machines to perform any number of operations, including, through the use of different belts on successive heads, roughing and finishing operations in a single pass. Figure 11-116, *b*, shows a straight-line machine with two backstand grinders for finishing two opposed sides of workpieces. Contact wheels can be contoured or straight depending upon the surfaces required. Such machines are made in a wide variety of sizes and configurations, including straight-line, rectangular, and rotary. A semiautomatic rotary-type abrasive-belt grinder is shown schematically in Fig. 11-116, *c*.

Swing-Frame Grinders

Swing-frame abrasive-belt grinders (Fig. 11-116, *d*) are generally used on large and heavy parts when tolerance is not critical. They can be suspended from overhead for removing weld beads, mounted on wheels for cleaning large plates, or rigidly mounted to a carriage for grinding odd-shaped parts. The angle between the workpiece and belt (where it leaves the contact wheel) is important in swing-frame grinding and should be about 20° for easy operator control. Operator control is accomplished with handle bars, with which the operator can apply pressure where and when he wants it. On most grinders, the operator can twist or rotate the handle bars to swivel the grinder so that areas at a right angle to flat planes can be ground. Power is transmitted through the abrasive belt, and grinding should always be done on the tight side of the belt. Smooth finishes can be obtained with swing grinders, depending on the type of belt used. Also, polishing on the slack

of the belt just behind the contact wheel can be done on cylindrical parts. Swing grinders are effective on all materials except gray-iron and steel castings, where high pressures and belt speeds are necessary. For removing weld beads, a rule of thumb is to use a swing grinder having 1 hp per 1/8" (235 W/mm) thickness of material.

Free Belt Roll Grinders

In finish grinding or polishing, the work need not necessarily be applied to the belt at the wheel. It may be "strapped" against the unsupported belt or against a belt made firmer by a parallel backup or saddle belt of leather, rubber, or canvas, as shown in Fig. 11-116, *e*. Machining of this sort, which forces the belt to conform to the workpiece, requires a guide yoke or deeply flanged pulley to keep the belt tracking properly. Abrasive-belt attachments such as these are available for cylindrical grinding on center-type machines such as roll grinders and lathes. Some are bolted to the cross slides of lathes.

With stroke-type finishing machines, workpiece contact is made by stroking the back of a moving abrasive belt with hand blocks, a hand lever with pressure pad, or an automatic traveling head. These machines usually have two or more pulleys over which the belt travels and a movable workholding table. Another stroke machine is an automatic-gantry type on which the machine rides on crane rails and traverses stationary workpieces and a contact roll head strokes the belt against the work.

Vertical Grinders

Vertical abrasive-belt grinders are used in several ways, with workpieces generally being supported on tables. Work can be applied against a section of unsupported belt, a platen (Fig. 11-116, *f*) or contact wheel behind the belt, or a section of belt between two rollers (Fig. 11-116, *g*). The roller arrangement is useful for grinding radii on the edges of workpieces. Belts can be arranged to operate vertically, horizontally, or at an angle, and the worktable can be adjusted to various angular settings on most machines. Oscillation of the work across the face of the belt is desirable for uniform belt wear and surface finish. Cutting rates can be controlled by hand, air, mechanical means, or hydraulic power.

Vertical-head contact-wheel surface grinders can be of either the reciprocating-bed (or table) type or the continuous-throughfeed type with workholding conveyor. Many continuous-feed contact-wheel surface grinders are made with two or more belt heads (Fig. 11-116, *h*) and a common conveyor belt to carry workpieces under the belts. By varying the grit sizes on successive belts, parts can be rough and finish-ground in a single pass. Close tolerances can be held on flatness, parallelism, and thickness with these machines.

Multiple floating-type abrasive-belt heads can be used to rough and finish-grind contoured parts in one pass. Each head floats independently, with rise and fall controlled by the workpiece contour, a cam, or a template. Continuous or reciprocating conveyors can be used to move parts beneath the heads.

Centerless Grinders

Abrasive-belt machines are also available for centerless grinding cylindrical-shaped parts, tubing, rod, and bar stock. These machines are widely used for throughfeeding of parts requiring grinding of only one external diametral surface. Parts are fed across a steadyrest between an abrasive belt (running

ABRASIVE-BELT MACHINING

over an idler and contact wheel) and a regulating wheel (Fig. 11-116, j) or another abrasive belt (Fig. 11-116, k).

Existing centerless grinding machines can be converted for the use of abrasive belts by providing a contact wheel, idler, and belt. Some machines are equipped for reciprocating feed for heavier stock removal. Reciprocating feed can be done automatically by reversing the rotating direction of the regulating wheel (abrasive regulating belt) or repositioning the wheel of the feed belt at the end of each stroke. Multiple-pass centerless grinding for heavier stock removal or smoother

finishing can be done with several heads or machines arranged in tandem.

Sheet and Strip Grinders

Corrective grinding, polishing, or cleaning of metals in strip form, such as titanium, stainless steel, bimetal products, carbon steel, and exotic metals, is performed using specially designed abrasive-belt grinders. These special sheet and strip grinders are discussed in Volume III of this Handbook series, "Materials and Finishing."

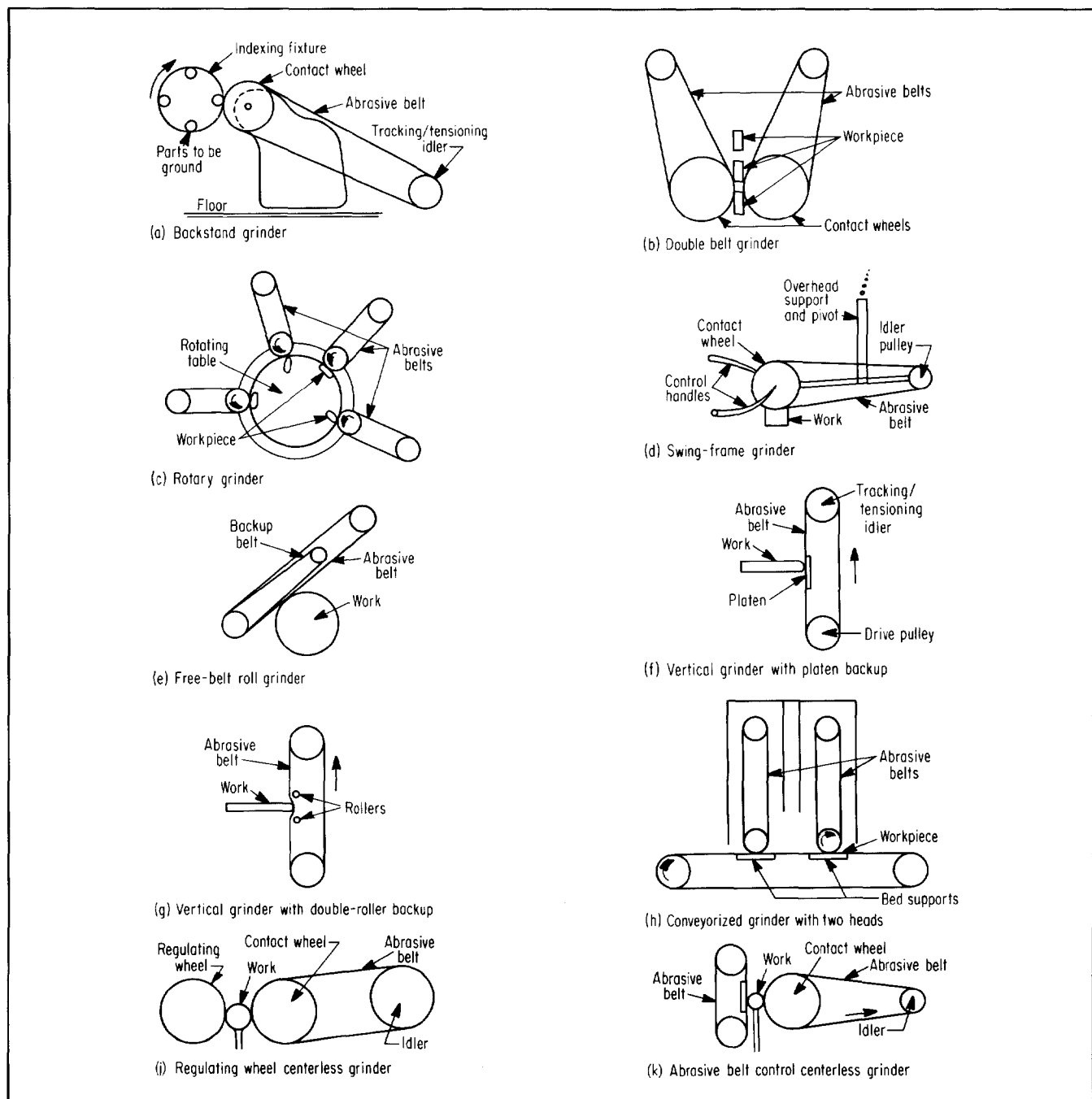


Fig. 11-116 Typical configurations and applications of abrasive-belt machining.

ABRASIVE CUTOFF

Abrasive cutoff differs from most conventional grinding operations (in which flat, cylindrical, or contoured surfaces are finished) in that abrasive cutoff uses thin, bonded abrasive wheels to sever billets, bars, castings, forgings, extrusions, or other shapes for subsequent processing.

As a class of operation, cutoff is also performed on lathe-type cutoff machines with single-point tools. This cutoff method is discussed in this volume in Chapter 8, "Turning and Boring." Sawing processes are also used for cutoff operations as discussed in Chapter 6 of this volume, "Sawing."

Cost per cut in abrasive cutoff can be relatively high because of high power requirements, limited wheel life, and material losses in the kerf, but in many cases it is more economical than other cutoff methods, especially for materials having higher strengths, temperature resistance, and hardness.

Recent advances in abrasive cutoff technology have resulted in more efficient, economical, and accurate abrasive cutoff than was possible previously. Abrasive cutoff wheels can remove stock at a rate of 20 in.³/min (5460 mm³/s) and even faster when cutting hot metals such as billets. Wet-abrasive cutoff machines with 100 hp (75 kW) motors and 48" (1220 mm) diam wheels rotating at 12,500 sfm (63 m/s) can remove 25 in.³/min (6830 mm³/s) of Inco 901 alloy without difficulty. Even larger machines up to 150 hp (112 kW) and with 72" (1830 mm) diam wheels have been built.

ABRASIVE CUTOFF WHEELS

Cutoff operations are performed either wet or dry, depending upon the workpiece material, cutoff machine setup, and other parameters. Specific recommendations to be used in initial selection of wheels for cutting different materials are given in Table 11-23. In the table, soft, medium, and hard designations are used instead of letter grades.

The following guidelines are presented as an aid to selecting abrasive cutoff wheels:

1. The horsepower (kilowatts) of the machine should be matched to the grade of wheel.
 - a. The hard grade of wheel should be used if the ratio of machine horsepower to wheel diameter (in inches) is about 1:1 or greater (i.e., a 20 hp machine with a 20" diam cutoff wheel). In metric, the hard grade of wheel should be used if the ratio of machine kilowatts to wheel diameter (in millimeters) is about 0.029 or greater (i.e., a 15 kW machine with a 510 mm diam cutoff wheel).
 - b. The medium grade of wheel should be used if the ratio of machine horsepower to wheel diameter (in inches) is about 3:4. In metric, the medium grade of wheel should be used if the ratio of machine kilowatts to wheel diameter (in millimeters) is about 0.022.
 - c. The soft grade of wheel should be used if the ratio of machine horsepower to wheel diameter (in inches) is about 1:2. In metric, the soft grade of wheel should be used if the ratio of machine kilowatts to wheel diameter (in millimeters) is about 0.014.
2. Cutting should be done at the proper feed, about 3–4 s/in.² of workpiece material. In metric, the proper feed is about 0.46–0.62 s/cm² of workpiece material (see the section "Wheel Speed and Feed Rates" in this chapter).

- a. If the cut cannot be made this fast for some reason, the next softer grade should be used to prevent wheel glazing.
 - b. If the cut can be made faster for some reason, the next harder grade should be used to extend wheel life.
3. A determination should be made as to whether the job requires a reinforced or nonreinforced cutoff wheel. The following facts should be considered:
 - a. Reinforced wheels resist breakage, and are particularly well suited for older or worn cutoff machines.
 - b. When a variety of operators use a particular cutoff machine and safety is of special concern, reinforced wheels should generally be used.
 - c. It is usually best to use a reinforced wheel for cutting irregular workpieces that are difficult to clamp.

Dry Cutting

Dry cutting is the simplest and fastest method of abrasive cutting. It is generally used when quality of the surface finish produced is not of primary importance. Dry-abrasive cutoff is usually done with a resinoid-bonded wheel of rather coarse grit size and with relatively hard grades for soft materials and soft grades for hard materials. Aluminum oxide abrasive is generally used to cut most metals, and silicon carbide for nonmetallics.

Coarse-grit, hard, resinoid-bond wheels may produce burrs, discoloration, and some surface hardening in parts being dry-cut. Changing to a finer grain and/or a softer grade wheel may eliminate these conditions, but more rapid wheel wear will usually result.

Wet Cutting

Wet cutting was previously performed almost exclusively with calendered rubber wheels. These wheels minimize burning, burr formation, and possible workpiece damage and produce smooth surface finishes. High-speed wet cutting is now possible with so-called rubber-resin or pressed-rubber bonds. These wheels have high strength and can be easily reinforced with fiberglass materials.

Fluid penetration of the peripheral boundary layer of air that travels with the wheel at high speed can be done in the same way it is done for high-speed cylindrical grinding (a controversy exists as to the true effect of the "air cushion"—see "Grinding Fluids" in this chapter). The fluid should also be equally distributed on both sides of the wheel. By directing the fluid at the sides of the wheel, centrifugal force throws it to the cutting edge. A fluid supply of 1 gpm for each horsepower (2.8 L/min for each kilowatt) consumed is generally adequate for high-speed cutting. Filtration is recommended, and refrigeration may be necessary. Wheel costs can increase when the fluid temperature rises. A fluid used for most materials with good results is plain water with a small amount of chemically active additive (see "Cutting Fluids and Industrial Lubricants," Chapter 4 in this volume).

Wheel Speed and Feed Rates

If the feed rate, d , at which a wheel is fed radially into the work is increased with the wheel peripheral speed, V , so that the ratio, d/V , is held constant, the efficiency of cutting increases. In other words, the rate of cutting will increase while wheel wear remains substantially the same.

TABLE 11-23
Selection of Abrasive Cutting Wheels*

Wet Cutting						Dry Cutting						
Soft		Medium		Hard		Material to be Cut	Soft		Medium		Hard	
Size of Grain	Type of Bond	Size of Grain	Type of Bond	Size of Grain	Type of Bond		Size of Grain	Type of Bond	Size of Grain	Type of Bond	Size of Grain	Type of Bond
A120	R	A80	R	A80	R	Alnico	A60	B	A46	B	A36	B
A46	R	A46	RB	A24	RB	Aluminum (hard): Bar Tubing	A46	B	A36	B	A36	B
A120	R	A90	R	A80	R		A90	R	A90	RB	A90	B
						Asbestos products (molded)	C36	B	C30	B	C24	B
C120	R	C90	R	C60	R	Beryllium						
						Bits (mine or drill)	A46	B	A36	B	A30	B
A90	R	A46	R	A46	R	Brass and bronze (hard): Bar Tubing	A60	B	A46	B	A36	B
A120	R	A90	R	A80	R		A90	R	A90	RB	A90	B
						Brick: Common Face	C20	B	C20	B	C20	B
							C24	B	C20	B	C20	B
A120	R	A90	R	A46	RB	Cable (steel)	A90	R	A46	B	A30	B
						Carbon	C60	B	C46	B	C36	B
						A46	R	A24	RB	Cast-iron pipe	A36	B
A90	R	A46	R	A24	RB	Channel Iron	A36	B	A30	B	A24	B
						C24	B	C24	B	Concrete and cinder block	C20	B
A90	R	A46	R	A46	R	Copper (hard): Bar Tubing	A60	B	A46	B	A36	B
A120	R	A90	R	A80	R		A90	R	A90	RB	A90	B
A80	R	A46	R	A46	R	Drill rod	A60	B	A46	B	A36	B
A60	R	A46	R	A46	R	Drills, twist	A46	B	A36	B	A36	B
						Fiber: Tubing Solids	C60	B	C46	B	C36	B
C60	R	C60	R	C60	R		C60	B	C46	B	C36	B
						Gates and risers: Steel Brass and bronze			A30	B	A24	B
									A30	B	A24	B
C120	R	C120 C240	R R	C120 C180	R R	Germanium: Large sections Small sections						
C120	R	C90 C120 C120	R R R	C120 C120	R R	Glass: Solids and heavy wall Tubing and thin wall Pyrex and Vycor						
A46	R	A60	R	A46	R	High-temperature alloys			A30	B	A24	B
						Investment castings			A46	B	A30	B
A60	R	A80	R	A60	R	Knives (machine)	A46	B	A36	B	A30	B

TABLE 11-23—Continued

Wet Cutting						Dry Cutting						
Soft		Medium		Hard		Material to be Cut	Soft		Medium		Hard	
Size of Grain	Type of Bond	Size of Grain	Type of Bond	Size of Grain	Type of Bond		Size of Grain	Type of Bond	Size of Grain	Type of Bond	Size of Grain	Type of Bond
A60	RB	A90	R	A60	R	Metallographic specimens:						
A120	R	A90	R	A80	R	Large sections			A60	B		
						Small sections						
A90	R	A46	R	A46	R	Molybdenum						
A46	R	A46	R	A36	R	Nickel alloys			A36	B	A30	B
A46	R	A46	R	A36	R	Nickel anodes	A36	B	A30	B	A24	B
A320	R	A240	R	A220	R	Pen points			A240	R		
A46	RB	A46	RB	A24	RB	Pipe (steel)	A36	RB	A30	B	A24	B
		C80	R	C60	R	Plastics (thermosetting)	C46	B	C36	B	C30	B
		C90	R	C60	R	Porcelain	C60	B	C46	B	C36	B
		C24	B			Refractory brick	C20	B	C20	B	C20	B
		C60	R	C46	R	Rubber (hard)	C36	B	C30	B	C24	B
A46	R	A46	R	A46	RB	Steel: Carbon bars	A36	B	A30	B	A24	B
A60	R	A46	R	A46	R	Alloys and tool bars	A46	B	A36	B	A30	B
A46	R	A46	RB	A46	RB	Plate	A24	RB	A24	RB	A24	B
A120	R	A90	R	A60	R	Tubing (including flexible)	A90	B	A60	B	A46	B
						Tubing (capillary)			A240	R	A180	R
A46	R	A46	R	A36	R	Stainless steel: Bars	A36	B	A30	B	A24	B
A120	R	A90	R	A60	R	Tubing (including flexible)	A120	B	A90	B	A60	B
A60	R	A46	RB	A46	RB	Stellite			A30	B	A24	B
		C24	B			Tile	C24	B	C24	B	C24	B
C120	R	C60	R	C46	RB	Titanium: Large sections						
C240	R	C120	R	C120	R	Small sections						
A90	R	A60	R	A60	R	Tools (salvage)			A36	B	A36	B
A60	R	A46	R	A46	R	Transformer cores						
A180	R	A180	R	A120	R	Tungsten: Rod						
C120	R	C120	R	C120	R	Large sections (high density)						
C120	R	C90	R	C46	RB	Uranium						
		A46	R	A46	R	Valve stems			A36	B	A30	B
C120	R	C60	R	C46	RB	Zirconium						

* Find the material you wish to cut, read to the left if it is to be cut wet, to the right if dry. The selection from the three columns on either side should be based on the following general rules: (1) Soft wheels give highest quality, fastest cutting, and may be required to cut the harder varieties of some materials. (2) Medium wheels are for the average job, giving a good compromise of quality, speed of cut, and economy. (3) Hard wheels give longer wheel life where quality requirements are less exacting and will give excellent results on the softer variations of some materials. Code: Abrasive type: A, aluminum oxide; C, silicon carbide. Bond type: R, rubber; B, resinoid; RB, rubber-resin.

ABRASIVE CUTOFF

Increased wheel speed without a corresponding increase in feed rate will make the wheel act harder. Also, if the feed rate is increased while the wheel speed is held constant, the wheel will act softer. If the feed rate is increased too much, the wheel will break. With the ratio, d/V , held constant, the same wheel grade range used for cutting at lower rates can be used for fast cutting. Since higher wheel speeds induce higher strains, however, stiffer wheels are required.

Normally, in wet cutting, rubber-bonded wheels should be operated at speeds ranging from 7500-9500 sfm (38.1-48.3 m/s). However, slower speeds in most wet cutoff operations will yield better quality without significant reduction of cutting rates.

In dry cutting, a fast rate of cutoff is essential for efficient operation. When cutting dry, wheel speed is generally higher than that used in wet cutting; speeds from 12,000-16,000 sfm (60.9-81.3 m/s) are suggested.

Inspection of Cutting Edge

Observation of wheel edges after cutting can give an indication of whether the proper wheel has been selected and whether the proper fluid is being used in wet cutoff operations. Figure 11-117 illustrates the most common cutting edge geometries after cutting. The significance of these geometries to the cutoff operation is detailed in the caption of Fig. 11-117.

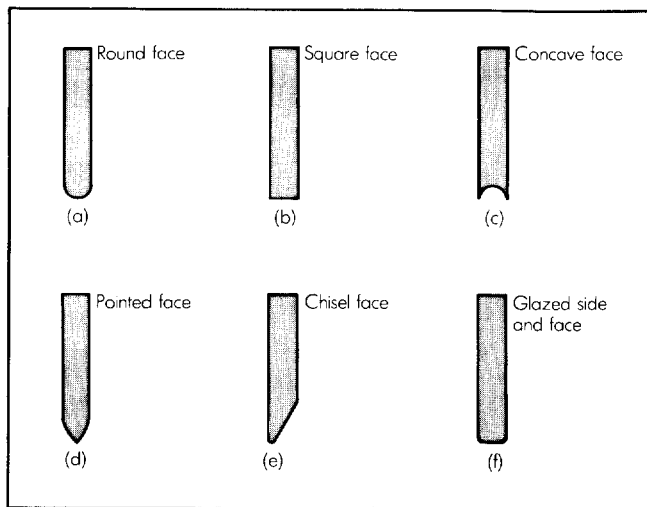


Fig. 11-117 Common cutoff wheel geometries: (a) Round face—normal when using proper wheel to cut large solids. (b) Square face—normal when using proper wheel to cut small solids, structurals, medium-wall pipe and tubing. (c) Concave face—normal when using proper wheel to cut tubing and thin wall sections. (d) Pointed face—means wall is too hard. May cause binding, breakage, and excessive burns on the cut. (e) Chisel face—wet cutting problem. Normally indicates wrong applications of fluid. May cause breakage and crooked cuts. (f) Glazed side and face—means wheel is too hard or cutting too slowly. Requires excessive pressure and power to cut. Causes breakage, excessive burr, and burn. (Continental Machine Tool Co.)

ABRASIVE CUTOFF MACHINES

There are four basic types of abrasive cutoff machines: chopstroke, oscillating, horizontal, and rotary, as shown in Fig. 11-118. Each type is available for manual, semiautomatic, or fully automatic operation. All machines must be rigidly

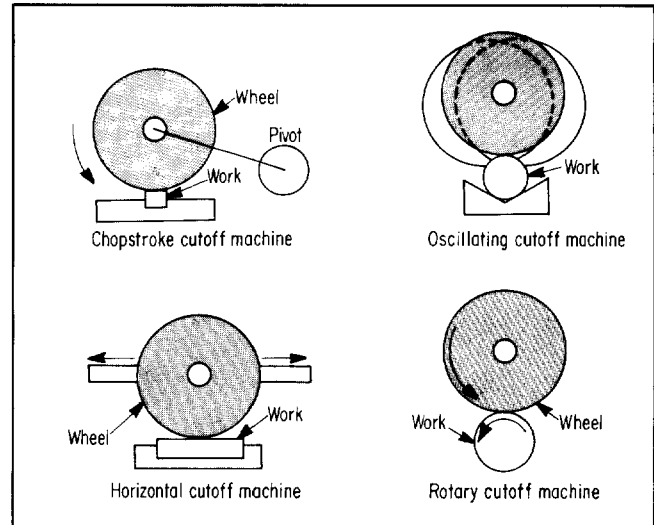


Fig. 11-118 Four basic types of abrasive cutoff machines. Each type is available for manual, semiautomatic, or fully automatic operation.

designed to minimize vibration and must have sufficient horsepower for fast wheel speeds and fast cutting rates. Large cylinders are needed to feed the wheels at fast rates into the work.

An adaptive control unit is available on some abrasive cutoff machines to show total cost per cut. A computer is used to automatically control the feed rate at which the machine operates to obtain the conditions for the lowest cost per cut. Programmed into the computer are direct labor costs, variable and fixed costs related to the machine, and cost of the wheel. Cost of each cut is computed and reflected in both a visual and a printed readout. This information is stored in the computer memory and compared with subsequent cuts made with different feed rates. The computer then makes a decision to either increase or decrease the feed rate as it seeks the optimum feed rate that will give minimum cost per cut.

Chopstroke Machines

Chopstroke machines are the simplest and generally are used for cutting bars or tubes from 2-4" (51-102 mm) diam. Workpieces are held in a fixed position, and a pivoted wheel, up to about 26" (660 mm) diam, cuts down through the work. Workpiece capacity is dependent upon the wheel diameter and horsepower of the wheel drive motor. The longest cross-sectional dimension of the work should be placed parallel to the direction in which the wheel is fed to minimize the length of chip produced. Fast feeds minimize burning of the work. Coarse, hard wheels are more efficient. Fine, soft wheels minimize burrs, but wear faster.

Oscillating Machines

Oscillating abrasive cutoff machines simulate a sawing action and can handle larger sections—up to 12" (305 mm) round or square. Newer machines of this type are designed so that the amplitude of oscillation of the wheel remains the same over the entire vertical distance it travels, thus increasing cutting efficiency. Most modern machines are also equipped so that both amplitude and frequency of oscillation may be varied over a wide range.

HONING FOR HEAVY STOCK REMOVAL

Horizontal-Traverse Machines

Horizontal-traverse machines have either a wheel that moves horizontally across the work (traversing wheel) or a fixed wheel against which the work is moved (fixed spindle). Traversing-wheel machines are used for cutting medium or large plates and slabs several inches (about 75 mm) thick, while fixed-spindle machines are employed to cut glass and nonmetallic materials such as brick, tile, and refractories.

Rotary Machines

Rotary machines have both the wheel and work rotating, making it possible to cut solid round stock of twice the diameter that could be cut if the work were stationary. This method is recommended for cutting bars over 8" (203 mm) diam. Wheels can be worn to a smaller diameter, thus reducing cost per cut. Rotary chucks for these machines which open for easy loading

from the top are now available. Higher grinding ratios (volume of metal removed to volume of wheel used) are generally obtained with this type of machine. Feed of the wheel into the work should be increased as penetration is made into the work to avoid producing smaller chips and causing burning toward the center of the cut and to obtain full power of utilization. This can be done manually or with automatic controls. Wheel guides, provided on some machines, are very useful in rotary cutoff. They keep the wheel from skidding over the surface before penetration is made, reducing scoring time (time during which the wheel is fed slowly into the work until it touches around the entire periphery of the bar), and also hold the wheel in proper alignment for straight cutting. Some machines combine oscillation and controlled vibration of the wheel to provide chip clearance and to cool cutting edges.

HONING FOR HEAVY STOCK REMOVAL

Honing is an abrasive machining operation in which heavy stock can be removed from the wall of a bore by the shearing action of abrasive grains. The purpose of this section is to present a discussion of honing as a heavy stock removal process. Honing used primarily for finishing is covered in Volume III of this Handbook series, "Materials and Finishing."

In honing, abrasive stones are normally spaced at regular intervals around the periphery of a honing tool head and the head is attached to a driving shaft. (Some manufacturers produce honing tools with irregular stone spacing. In some cases, such design is said to improve accuracy and reduce noise.) A reciprocating and rotating action is transmitted to the stones through a positive pressure system. The bonded abrasive grains of the honing stones act as tiny cutters to remove stock from the surface being honed. Although the amount removed by each cutting edge is very small, the combined action of the many cutting edges working simultaneously can provide a fast, accurate, heavy stock removal.

The amount of stock and the rate of removal depends upon the physical characteristics of the workpiece combined with the balancing of the controllable factors of the honing process. It is not unusual to remove 0.070" (1.78 mm) stock from cold drawn steel tubing, and larger amounts up to 0.250" (6.35 mm) on diameter have been removed economically.

The honing operation is actually the only production stock removal process that can be used on any length of bore without loss of accuracy. The accuracy of the honing operation is not dependent upon the alignment or rigidity of the honing tool. Inaccuracies of previous operations are overcome. Axial straightness is generated through the length of the stones. This extra length assures stock removal on the high spots first. Diametric roundness is generated by the rotary motion of the tool and its freedom to center itself with the neutral axis of the bore. Diametric straightness (freedom of taper) is generated by the reciprocation of the tool and the maintenance of a constant pressure throughout the stone area. Cutting pressure is equal at all points of the stone surface since the honing stones stabilize the center of rotation on the neutral axis of the bore.

HEAVY STOCK REMOVAL

Since the honing operation is the only type of machining that

is suitable for certain types of parts, it must also be used for heavy stock removal operations. The term heavy stock removal is sometimes a little misleading since an automotive cylinder bore with 0.006-0.008" (0.15-0.20 mm) stock would be heavy while a steel cylinder tube with this amount of stock would be rather light.

Parts with hardness of Rc60-64 are successfully being honed, removing up to 0.050" (1.27 mm) stock on diameter on parts ranging up to approximately 8" (203 mm) ID x 30" (760 mm) long. In addition to the heavy stock, these parts are generally badly distorted but require a very close tolerance on completion. Honing is the only machining operation that can successfully remove the stock and generate the bore accuracy and still maintain an economical production operation. The following requirements are necessary for a heavy stock removal application:

- The honing machine must be of the most rugged spindle and head construction available.
- The horsepower of both the spindle and the hydraulic reciprocation must be greater than the horsepower of standard machines.
- Monitors should be employed on motors to check power consumption.
- A heavy-duty hone expansion system must be used to give the maximum cutting action to the stones.
- The fixtures must be of an extremely rigid construction to resist both the up and down thrust of the tool, hold the torque, and at the same time prevent distortion of the part.
- Sufficient honing fluid must be supplied at all times to flush away the metal and grit. Traditionally, the honing fluid is cooled to control heat buildup in the workpiece. However, tests have shown that heated honing oil sometimes contributes to faster cutting action.
- The basic honing tool carrying the stones must be of a heavy-duty type including both the upper and lower universal joints.

BORE FINISH CONTROL

Surface finish refers to the roughness of the surface and is

HONING FOR HEAVY STOCK REMOVAL

precisely measured with various types of instruments. Surface finish measurement is covered in Volume IV of this Handbook series, "Assembly, Testing, and Quality Control." The degree of finish can be accurately controlled through varying the speed of rotation, the honing stones, rate of stone expansion, and the honing fluid mixture. A fine stone with a tight, hard bond will produce a fine finish. Fast reciprocation speed removes stock rapidly and generally produces a coarse finish. Stones tend to break down quickly with fast reciprocation. Fast rotation does not cause fast stone wear.

The important factor in heavy stock removal honing operations is that it is impossible to hone large amounts of stock from the bore at a good production rate and at the same time obtain a good surface finish. Heavy stock removal applications require the use of relatively coarse grits in the honing stones, and these stones must operate under extreme force against the wall of the bore; they thereby inherently cause the finish to be rough. From this point, if a fine finish is required, fine-grit stones must be used and a second honing operation applied. On this type of operation, small amounts of stock are removed at a slower rate and the proper finish is obtained.

Steel Tubing

An example of this type of operation is honing of seamless steel tubing used primarily in the manufacture of hydraulic cylinders. The honing of this soft tubing is a large honing application, and in most cases, requires heavy stock removal with a fine finish.

Steel tubing today is being honed without the benefit of any previous operation on the part. Stock removals will vary from 0.020" (0.51 mm) on diameter to 0.060" (1.52 mm) on an average, and have also been known to be as high as 0.125" (3.17 mm). This application requires a coarse-grit aluminum oxide stone (120 grit) to remove the stock at a rapid production rate. The rate of removal of the metal can vary from 0.8 in.³/min (218 mm³/s) on smaller diameters to over 2.0 in.³/min (546 mm³/s) on larger diameters. However, with this fast rate and the coarse stones, the bore finish will be in the range of 60-70 μ in. (1.5-1.8 μ m).

Most hydraulic cylinder tubes require a finish below 20 μ in. (0.51 μ m). Several procedures can be taken after rough honing to accomplish this finishing technique. After rough honing, it is common practice to either reduce the hone pressure or merely allow the tool to "run out" for a few minutes in the bore. Generally, run out in a steel-tube bore will drop the 70 μ in. (1.8 μ m) rms finish down to 35 μ in. (0.89 μ m) before it is removed from the machine. To obtain a finer bore finish, the part then must be either polished with fine-grit stones or an abrasive cloth. In some instances a roller burnishing tool is pushed through the bore after rough honing to obtain an extremely fine finish 8 μ in. (0.20 μ m) rms.

Hardened Steel Parts

Obtaining a fine finish on hardened steel parts is not as difficult as on softer parts since the grits cannot penetrate the surface of the bore as easily. When honing heavy stock in hardened steel, a lower viscosity honing fluid is used and relatively softer stones are employed for the cutting action. The basic problem in honing hard steel is not obtaining the finish but actually removing the metal. On this type of operation, the speeds are reduced to allow penetration, and pressure of the stones on the wall of the bore must be increased. This pressure must stay constant throughout the cycle since any relaxation

will immediately cause the stones to "glaze." Reduction of rotational speed will help only if the stone acts too hard. In such a case, a more suitable stone should be chosen and/or the reciprocating speed increased. With a properly chosen stone, increasing rotational speed will increase stock removal speed.

Glazing

When glazing occurs on the stones, a general practice is to reverse the spindle rotation if the design of the honing tool permits. This reversing of the spindle will generally open new grits in the stones and allow the cutting action to start again. If, at that time, cutting does not take place, the tool must be withdrawn from the bore and the individual stones dressed off manually with either a file or another stone. It should be remembered that when this glazing takes place, the wall of the bore has also taken on an extremely fine finish which makes any grit penetration very difficult. In most applications on hard steel, the removal of stock is primary since the grit size of the stones can be in a relatively wide range and maintain a fine finish. Rough finishes are more difficult to obtain in honing hard steel than are any of the finishes in the finer ranges.

HONING FLUIDS

Careful selection of honing fluids with filtration and refrigeration have proven very beneficial when honing extremely close tolerances and when fine finishes are required. Other factors, such as work characteristics, material, and stock removal may also demand that proper fluid selection, fluid filtration, and refrigeration be employed.

The fluid in honing operations has two major roles: (1) it keeps abrasive elements clean and lubricated and (2) it carries away the heat and sludge generated by the cutting action. Fluid cleanliness will result in fewer rejects, and increased efficiency is realized in that the honing stones do not become loaded with waste particles. The load-free fluid flush minimizes abrasive deposits on the machine surfaces, fixtures, tables, and critical working parts of the honing machine.

The primary function of refrigerated honing fluid is to remove the heat energy created by the work being done. Heavy stock removal applications in which high removal rates are employed will produce temperatures in excess of 150° F (65° C). Unless this heat is removed in some manner, the results are poor tolerance control, decreased stone life, inefficiency of fluid, and less production.

During the past thirty years very little change has been made in fluid types used for honing, although today, considerable testing is being done on various types of water-soluble mixtures. Conventional honing fluids are still kerosene and mineral seal oil which are sometimes used with a sulfur-based oil as an additive. Due to extreme fire hazard, many plants today will not allow kerosene. Honing fluid mixtures for various metals are presented in Table 11-24.

Most materials can be honed with either the mixtures as noted in Table 11-24 or some slight variation. If a fine finish is required, the chemical activity of the honing fluid should be increased by the addition of the sulfur-based oil; however, in some cases, the cutting will be somewhat retarded. Conversely, a low-activity fluid (kerosene) is very aggressive in the honing of soft steel and, in some instances, will tend to tear the bore, so the fluid must always be dampened with some sulfur-based oil.

Fluids for the honing of aluminum are also somewhat critical since aluminum tends to load the stones and retard the cutting. Because aluminum is rather soft, an aggressive stone and fluid

HONING FOR HEAVY STOCK REMOVAL

TABLE 11-24
Honing Fluid Formulations for Various Materials

Material	Honing Fluid Formulation
Cast iron	100% kerosene or mineral seal oil, or 90% kerosene or mineral seal with 10% sulphur base oil.
Soft steel	75-80% kerosene or mineral seal with 20-25% sulphur base oil.
Hard steel	100% kerosene or mineral seal oil, or 95% kerosene or mineral seal with 5% sulphur base oil.

will tear the bore, so both the fluid and the grit and grade of the stones are somewhat more critical. Although the fluids mentioned in Table 11-24 will work satisfactorily, it has been found that a fluid with lard-oil base is best for honing aluminum. (Cutting fluids are discussed in detail in Chapter 4 of this volume, "Cutting Fluids and Industrial Lubricants." Grinding fluids are discussed in the section "Grinding Fluids" in this chapter.)

SPECIAL FEATURES

In several instances, it has been mentioned that the stone pressure against the wall of the bore is greater in heavy stock removal applications than in other types of honing. This pressure system is designed into the reciprocating head of the machine and, through a push rod in the tool, forces the stones out against the wall of the bore during the honing cycle. This pressure or force can be remotely controlled from the operator's control station and can be varied to give the best cutting action for the various types of abrasive.

The push rod pressure can be developed by one of several different methods; the most common method is a hydraulic cylinder giving a direct pressure to the push rod. This system will vary somewhat on the different machines. Many machines are designed with direct pressure and some have the added features of a controlled expansion so that at no time will the stones expand into a taper in the bore. In other words, the stones are always under control. Pulsating-type expansions can also be used wherein the pulsating of the push rod may tend to clear the stones of grit and swarf.

A method now being used on heavy stock removal operations is the electric type of expansion. This system employs a screw drive to apply the force to the push rod, and the screw is driven by a dual electric motor drive. The one motor is an a-c rapid expansion and collapse motor; the second motor is a d-c variable-speed motor. In this system, the a-c motor will rapidly expand the honing stones to the wall of the bore and, upon contact of the wall, will stop; the d-c motor, with varying control, will continue to expand the stones at the desired rate until final size has been reached (see Fig. 11-119). This system offers the following advantages:

- Optimum expansion rate for a fast honing cycle.
- Greater abrasive life with instantaneous adjustments to surface characteristics preventing crushing or breaking of the stones as well as eliminating glazing.

Although the honing tools for these heavy-duty applications carry the standard tool design, they must be strengthened throughout to carry excess loads; their primary strength is

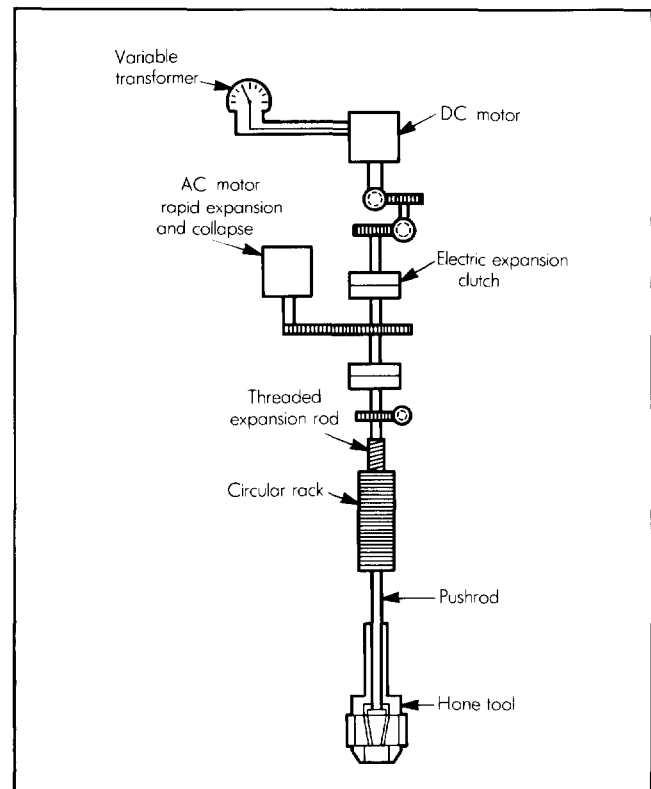


Fig. 11-119 Schematic of electric hone expansion. (Barnes Drill Co.)

designed into the universal joint and into the long push rod. Since the push rod passes down through the driveshaft tube, support must be given throughout its length to prevent any bending under the extreme force of the expansion system. The newer tools are now being designed with a square push rod inside the round tool driveshaft. This gives four lines of support through the full length and prevents any friction binding due to bending, as shown in Fig. 11-120.

One honing machine manufacturer supplies standard honing machines equipped with a self-monitoring electrical circuit to control abrasive penetration into the work. The technique is called plateau honing.

As shown in Fig. 11-121, in plateau honing, a combination rough and finish honing tool assembly is used. The honing tools used are of the pull-cone design. The pull-cone concept lends itself to a definite two-directional-cut hone pattern which is a prerequisite for a good functional bore surface. This two-directional cut is insured with the pull-cone design in that the tool and driveshaft universal joints and internal moving parts are in compression at all times, thereby reducing the normal relaxing of these components on the upward stroke of the tool, which is inherent with a push-type cone.

The stone expansion system used to plateau hone is a special, programmed hydraulic pressure system. An individual hydraulic cylinder works directly on the cone rod in the honing tool. There are no clutches, linkages, or switches in the system; thus, the possibility of loss of control of the honing abrasives due to wear and slippage and downtime for maintenance is eliminated. The adaptive controls automatically program the pressures to the feed cylinder to provide the sequences of rapid

HONING FOR HEAVY STOCK REMOVAL

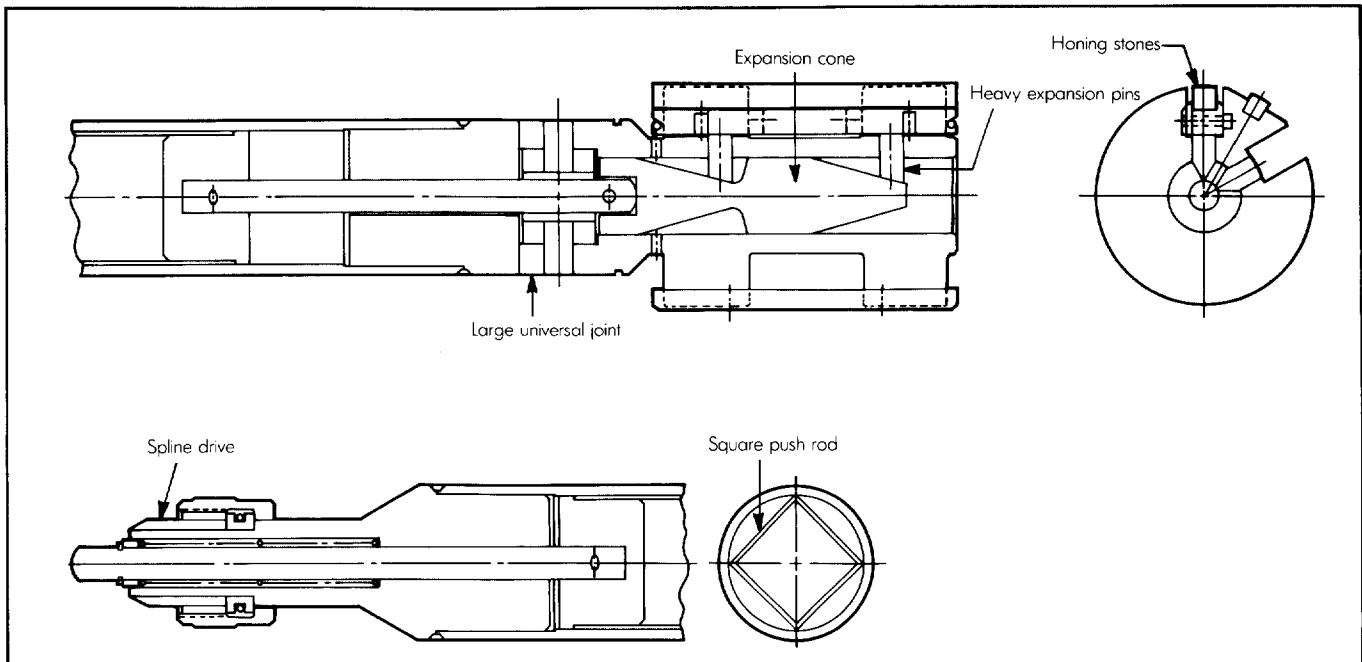


Fig. 11-120 Square push rod inside round tool driveshaft provides extra support for heavy stock removal honing applications.

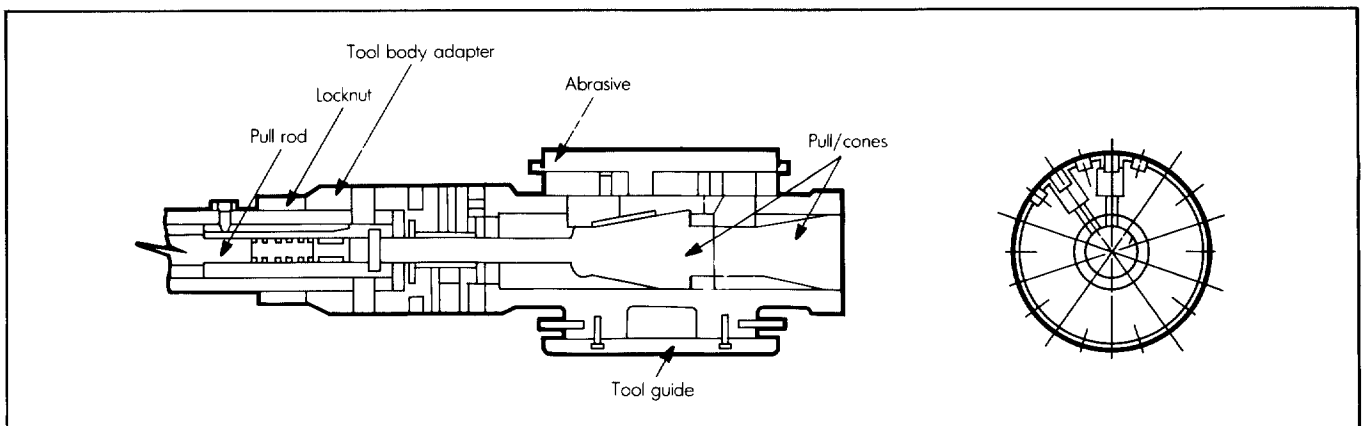


Fig. 11-121 Combination rough and finish tool assembly—6 roughing stones and 4 finishing stones. (Ex-Cell-O Corp.)

approach to bore contact, controlled pressure to keep the abrasives cutting at their most efficient honing rate during the stock removal portion of the honing cycle, and controlled pressure for the finishing portion of the cycle. Distortion of the bore and tool “wind-up” are avoided because only enough pressure is applied to remove stock efficiently during the rough and finish cutting phase of the cycle.

A special honing tool is used which contains both roughing and finishing abrasive sticks, designed so that only one set is expanded at a time. The expansion from rough to finish abrasive sticks is accomplished by a reverse direction of spindle rotation. The change in tool rotation direction presses a mechanism in the tool so that the finishing stones are expanded as the feed rate is applied. As bore size is reached, the finishing stones collapse. When all tools complete the sequence, the finishing stones are expanded for a short runout cycle, after which the tools lift out of the bore.

The following are some advantages in using the rough and finish tool with programmed hydraulic feed. (The first six are accomplished by controlled feed-out pressures and by the use of optimum abrasive.)

1. Definite two-directional cut.
2. Closer size control.
3. Improved bore roundness and straightness.
4. Reduced heat distortion.
5. Controlled surface finish.
6. Longer stone life (the stock removal to stone wear factor is improved 20%).
7. Elimination of double handling and/or locating workpiece.
8. Elimination of the need for additional machine and operator.
9. Conservation of floor space.

10. Higher production rates.
11. Fast and simple stone changing.

ABRASIVE ADVANCEMENTS

Two of the most recent advancements in heavy stock removal honing is in the use of metal bonded diamond stones, and a more recent development—cubic boron nitride (CBN). Both of these abrasive elements are now termed super-abrasives and in many instances offer many advantages over a vitrified bonded aluminum oxide stone.

The operating parameters for Borazon CBN are considerably different than the parameters for conventional abrasives. When honing with CBN, both the speed of reciprocation and the spindle speed are about double the conventional speed; so in many instances, modifications have to be made to conventional machines to obtain the best cutting action.

The stone width of the CBN is approximately 0.125" (3.18 mm) wide as compared to an aluminum oxide width of 0.375-0.500" (9.52-12.70 mm). The narrow width is necessary to achieve the proper chip clearance. However, this narrower stone usually takes less pressure to obtain good penetration into the workpiece.

Testing is still continuing with CBN, and many installations have placed the abrasive in production with excellent results. The advantages claimed are as follows:

- Stones will hone at high rates of removal with very low stone wear.
- Stones are freer cutting and require less machine pressure.
- Less heat is generated at high stock removal rates.
- Stones hone uniformly, and hone time is predictable because cutting action is consistent from stone to stone.
- Stones hone quietly, and geometry of the workpiece is generally improved.
- All of the basic fluids mentioned in Table 11-24, with the necessary additives, will work well with CBN stones.

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