March 16, 1971 H. R. UHTENWOLDT ET AL 3,570,185

GRINDING MACHINE

Original Filed April 9, 1965 4 Sheets-Sheet 1

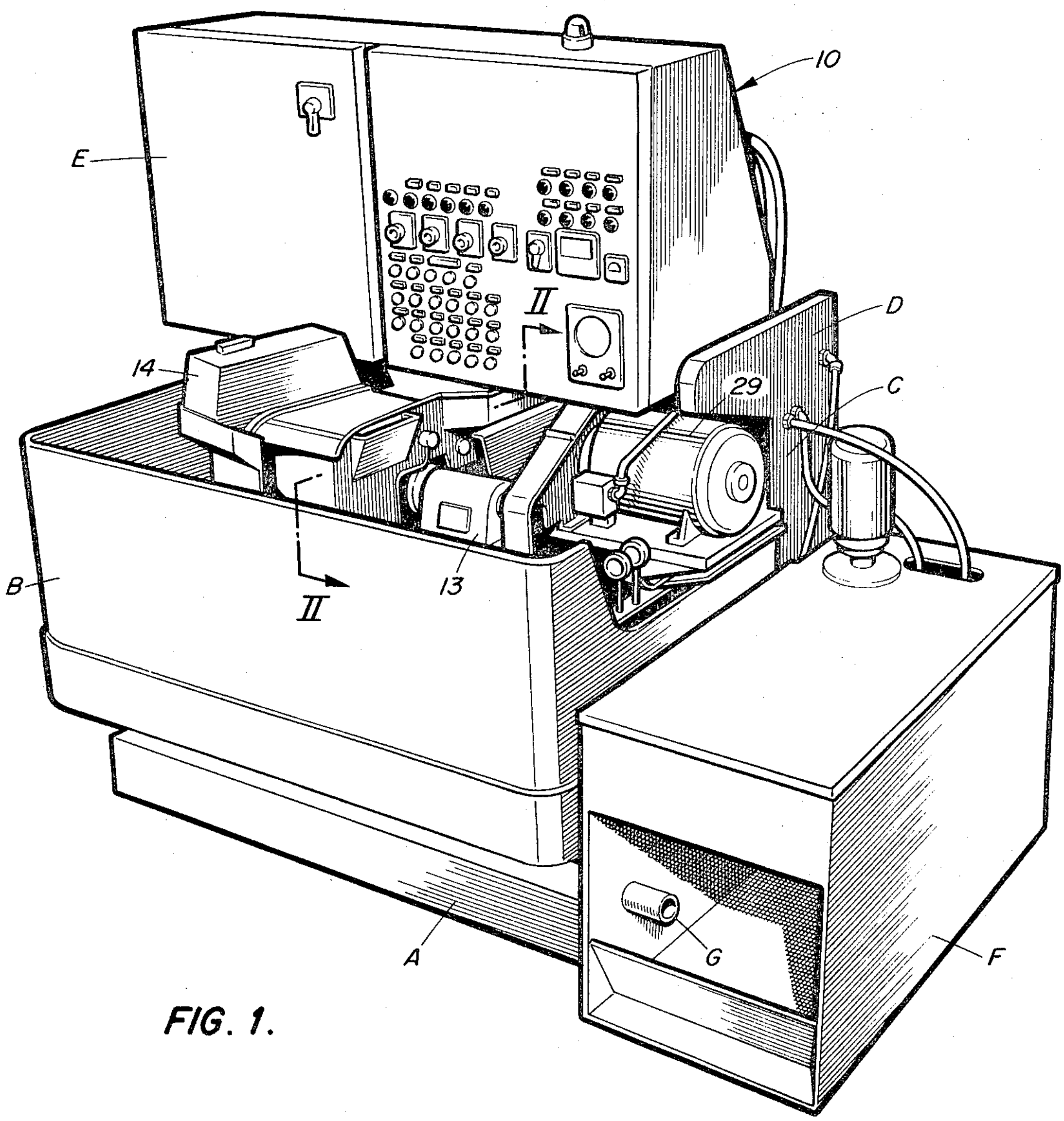

FIG. 1.

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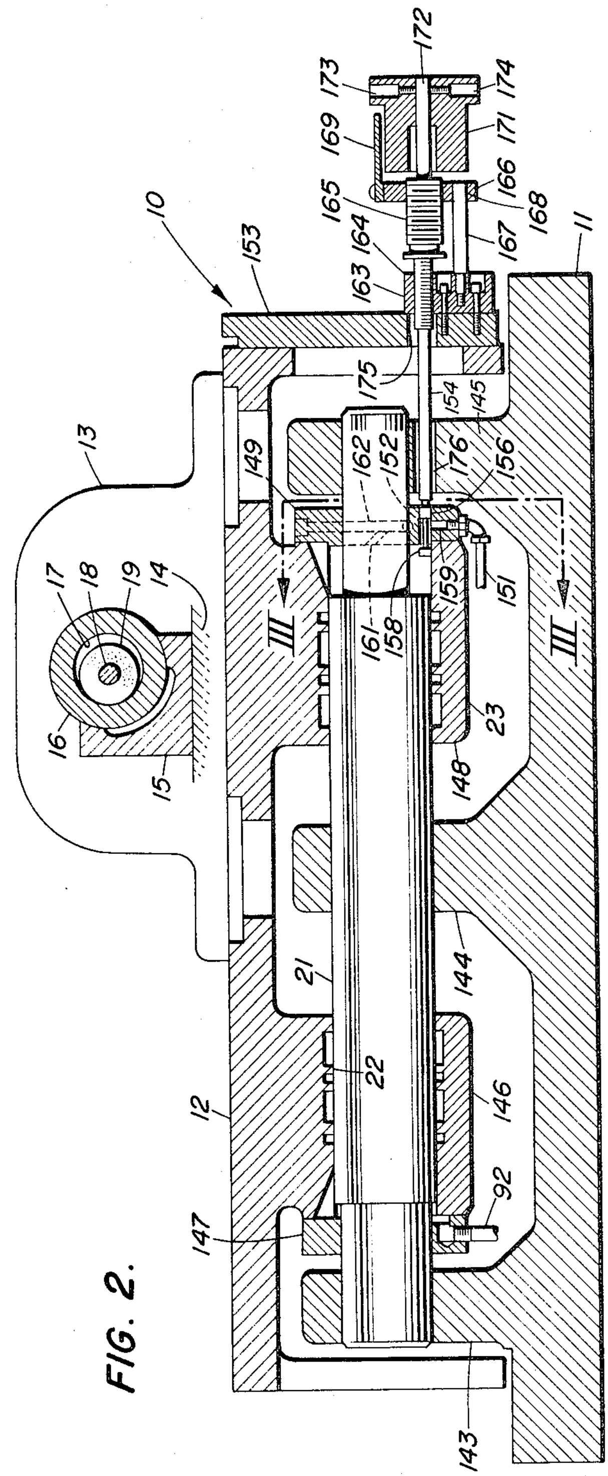

FIG. 2.

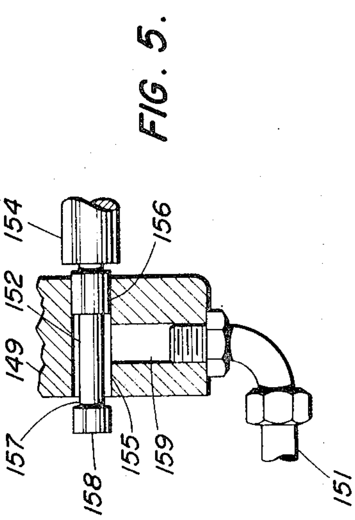

FIG. 5.

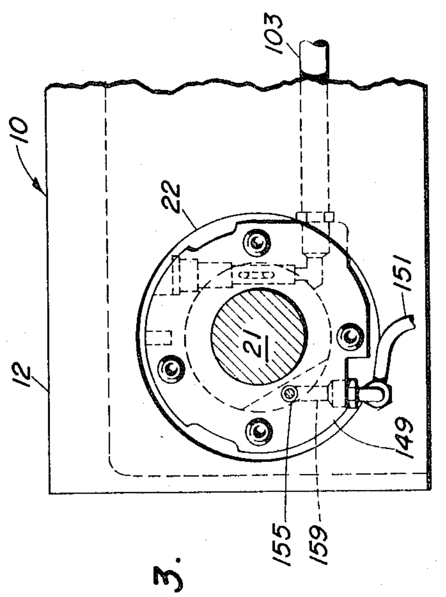

FIG. 3.

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GRINDING MACHINE

Original Filed April 9, 1965 4 Sheets-Sheet 3

FIG. 4.

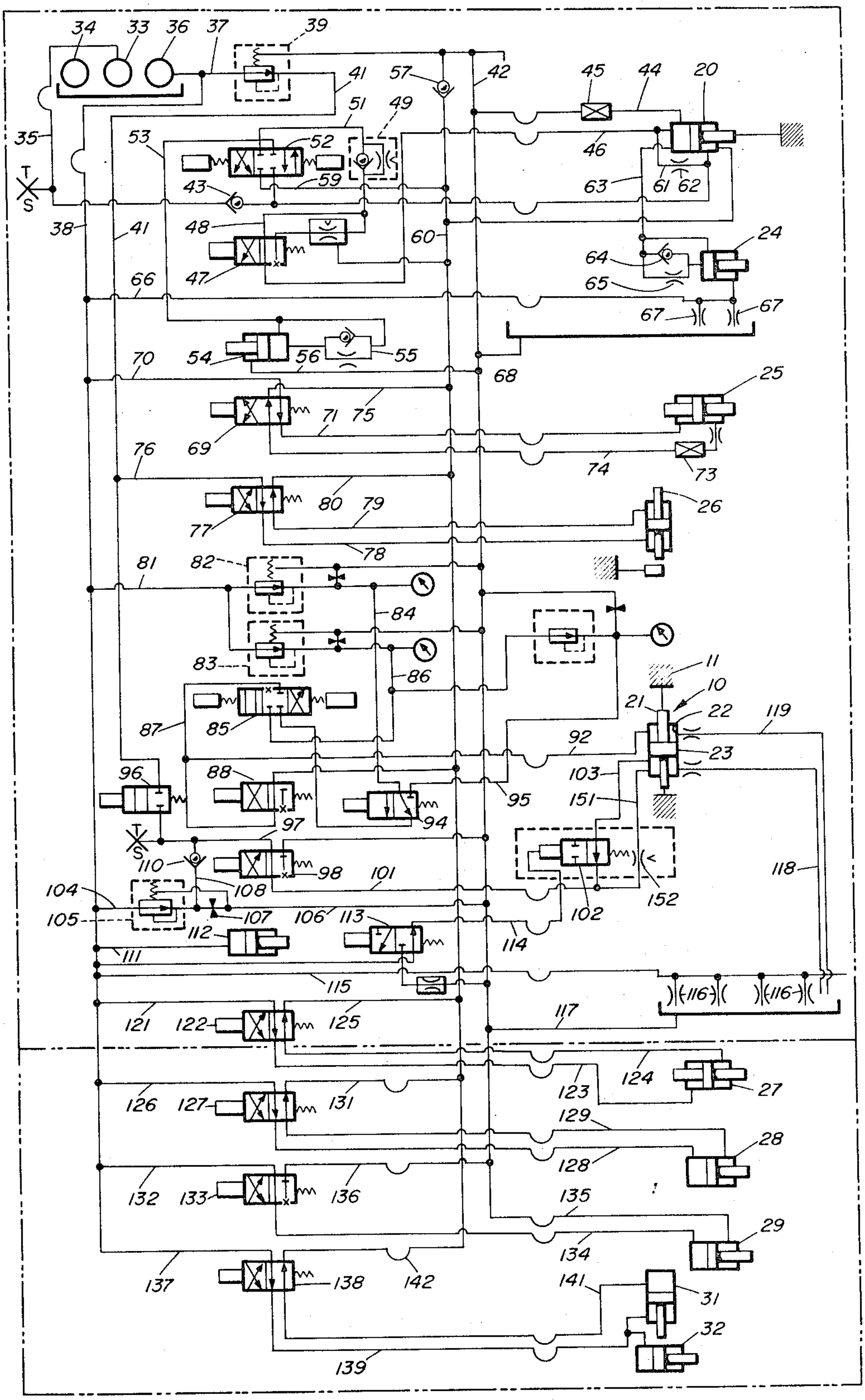


FIG. 7.
WORN (SMALL) WHEEL

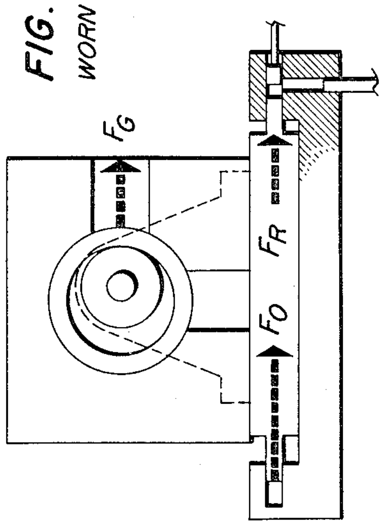


FIG. 6.
NEW (LARGE) WHEEL

$F_O - F_R = F_G$

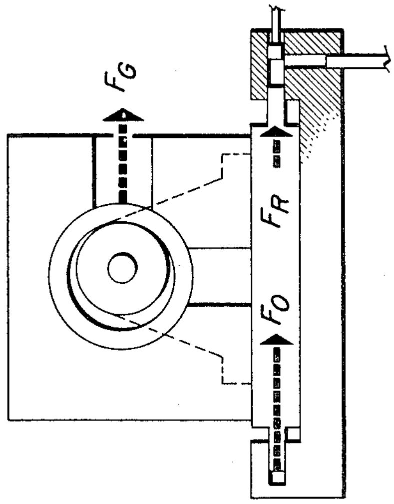
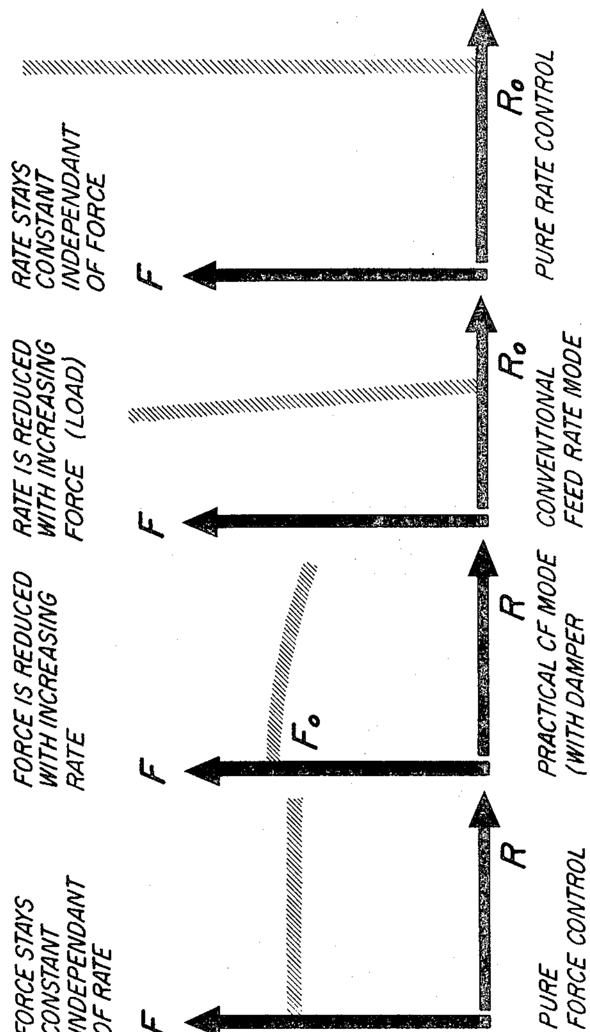


FIG. 8.



3,570,185

GRINDING MACHINE

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Continuation-in-part of application Ser. No. 759,811, Sept. 9, 1968, which is a continuation of application Ser. No. 451,712, Apr. 29, 1965. This application July 9, 1969, Ser. No. 840,324

Int. Cl. B24b 9/00, 49/00, 51/00

U.S. Cl. 51—37 3 Claims

ABSTRACT OF THE DISCLOSURE

This invention relates to a grinding machine and, more particularly, to apparatus arranged to generate a surface of revolution by the abrasive method.

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of my application Ser. No. 759,811, filed Sept. 9, 1968 which, in turn, was a continuation of my application Ser. No. 451,712, filed Apr. 29, 1965 now abandoned.

BACKGROUND OF THE INVENTION

In the grinding of workpieces, it is advantageous to feed the rotating abrasive wheel into the material of the workpiece with the greatest possible force commensurate with the strength of the wheel and the finish desired in the workpiece surface. In accordance with the controlled force method of operation, the wheel is fed into the material at a pre-determined level of force, the actual geometric movement (feed rate) between the workhead and the wheelhead of the grinding machine taking place in an uncontrolled manner. Such operation results in several definite advantages in speed of stock removal and in adequacy of the quality of the finish of the workpiece. In the past, however, some difficulty has been experienced with this method of grinding because of vibration and uneven movement of the wheel toward the workpiece. There is some reason to believe that this is due to the friction-free character of the sliding surfaces arranged to permit relative movement between the wheelhead and the workhead. Also, as the wheel becomes smaller in diameter, there is a tendency for it to cut faster; this upsets the carefully selected grinding parameters and affects the quality of the work. These and other difficulties experienced with the prior art devices have been obviated in a novel manner by the present invention.

It is, therefore, an outstanding object of the invention to provide a grinding machine using the controlled force method of grinding, which machine is free of erratic movement of the wheel toward the workpiece.

Another object of this invention is the provision of a grinding machine provided with a low friction sliding movement between the wheelhead and the workhead wherein vibration or skipping movement between the surfaces is not permitted.

A further object of the present invention is the provision of a controlled force grinding machine which is free of a tendency to produce vibratory movement between the elements.

It is another object of the instant invention to provide a grinding machine having a hydraulic system for producing controlled force operation with a reduced tendency for undesirable movement between the elements.

Another object of the invention is the provision of a grinding machine using the controlled force process, wherein reduction of wheel diameter does not affect the quality of the work.

With these and other objects in view, as will be apparent to those skilled in the art, the invention resides in the combination of parts set forth in the specification and covered by the claims appended hereto.

SUMMARY OF THE INVENTION

In general, the invention consists of a grinding machine having a base, a workpiece support mounted on the base, a wheelhead support mounted on the base, and a hydraulic actuator having a piston movable within the actuator bringing about relative feeding and retraction movement between the workpiece support and the wheelhead support. Means is provided for presenting an incompressible fluid to the actuator at one side of the piston at a controlled pressure during feeding movement. The actuator consists of a cylinder having a head at the said other side, the head being provided with a passage. A damper rod lies in the passage and is accessible from the exterior of the machine to permit regulation of the relative positions of the rod and passage and, therefore, regulation of the restriction to flow of fluid presented thereby. Means is also provided connected to the actuator at the other side of the piston to permit excape of fluid at a restricted selected rate during feeding movement and alternatively to present a fixed pressure fluid during the retraction movement. Separate sources are provided from which originate the controlled pressure fluid and the fixed pressure fluid.

BRIEF DESCRIPTION OF THE DRAWINGS

The character of the invention, however, may be best understood by reference to one of its structural forms, as illustrated by the accompanying drawings, in which:

FIG. 1 is a perspective view of a grinding machine embodying the principles of the present invention,

FIG. 2 is a sectional view of the apparatus taken on the line II—II of FIG. 1,

FIG. 3 is a sectional view taken on the line III—III of FIG. 2,

FIG. 4 is a schematic diagram of hydraulic apparatus used in the invention,

FIG. 5 is an enlarged view of a portion of the apparatus,

FIGS. 6 and 7 are schematic views of the elements of the grinding machine, and

FIG. 8 is a graphic representation of force-rate relationships.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring first to FIG. 1, it can be seen that the grinding machine, indicated generally by the reference numeral **10**, is of the type shown and described in the patent of Hohler et al., No. 3,197,921 which issued on Aug. 3, 1965. It is provided with a lower base A on which is mounted a workhead **14** and a wheelhead **13**. Around the front of the base extends a splash guard B which is readily removable. Extending upwardly from the rear of the base A is a superstructure C having two arms similar to the arm D which extend forwardly from the ends of the base. Mounted between the arms is a control cabinet E. At one end of the machine is located a coolant tank F receiving coolant returned from the machine through a pipe G.

Referring next to FIGS. 2 and 3, it can be seen that the grinding machine **10** also has a base **11** on which is mounted a wheelhead table **12** carrying the wheelhead **13**. The base **11** also carries the workhead **14** which has shoes **15** for supporting and rotating a workpiece **16**. The workpiece is shown, for the purposes of illustration, as a ball bearing race having an internal surface of revolution, such as a bore **17** whose surface is to be finished.

The wheel head **13** carries a rotatable spindle **18** on which is mounted an abrasive wheel **19**, means being provided to rotate the spindle and wheel. The base **11** carries a piston **21** slidable in a longitudinal bore **22**, those elements serving to define a FEED cylinder **23**.

Referring next to FIG. 4, which shows the hydraulic apparatus, the grinding machine is provided, as has been stated, with a table cylinder **20** which operates to move the workhead **14** axially toward and away from the wheel **19**, a TABLE IN dashpot **24**, a loading cylinder **25** (which serves to load and unload workpieces from the machine) and, of course, the feed cylinder **23**, which has been described. The machine is also provided with a compensation cylinder **26**, which is connected to a compensating arrangement (not shown) and to the base **11** in such a way as to compensate for removal of stock from the abrasive wheel **19** during dressing by a diamond. The machine is also provided with a WHEELHEAD SWIVEL cylinder **27** and with GAGE-IN cylinders **28** and **29**. The machine is also provided with DIAMOND TURNER cylinders **31** and **32** serving to rotate and to advance the dressing diamond from time to time. It should be noted that the hydraulic circuitry is shown, in accordance with the J.I.C. Standards for industrial equipment. Pressure hydraulic fluid is furnished by a pump **33** driven by an electric motor **34**. From the pump extends a 500 p.s.i. unfiltered line **35**. Another ouput of the pump is connected to a filter **36** from which extends a line **37** and a line **38**. The line **38** is at 500 p.s.i. filtered, while the line **37** operates through a pressure-reducing valve **39** from which extends a line **41** carrying hydraulic fluid at approximately 125 p.s.i. Extending through the circuitry is a drain line **42** which returns all fluid to the sump.

The line **35** is connected through a check valve **43** to the table cylinder **20**, while the other side of the cylinder is connected by a line **44** to the drain line **42** through a manual shut-off valve **45**. The same side of the cylinder **20** which is connected to the line **44** is also joined to a line **46** which is joined to a solenoid valve **47**, the other side of which is connected by a line **48** to a flow control valve **49**, the other side of which is attached by a line **51** to a TABLE INDEX valve **52**.

Also connected to the TABLE INDEX solenoid valve **52** is a line **53** leading to a TABLE OUT dashpot **54** whose hydraulic side is connected in a closed circuit through a flow control valve **55**. The other side of the dashpot **54** is attached by a line **56** to the drain line **42**. Extending through the hydraulic circuitry is a 5 p.s.i. line **60** which is joined through a check valve **57** to the drain line **42**. The TABLE INDEX valve **52** is attached by a line **58** to the line **35** and the valve is also connected by a line **59** to the 5 p.s.i. line **60**. The line **46** is connected around the cylinder **20** to the line **35** by a line **61** containing a throttle **62**. The same end of the cylinder **20** that is joined to the lines **44** and **46** is also attached by a line **63** to the TABLE IN dashpot **24**. Connected to the end of the dashpot in the usual way is a check-valve **64** and a throttle **65**. The 500 p.s.i. filtered line **38** is joined by a line **66** to table hydrostatic control pockets **67** which drain through a line **68** into the drain line **42**.

The 500 p.s.i. line **38** is joined by a line **70** to a load valve **69** which, in turn, is connected by a line **71** to one side of the load cylinder **25**. The other side of the cylinder is connected through a valve **73** by a line **74** back to the valve **69** whose drain side is joined by a line **75** to the 5 p.s.i. line **60**. The 125 p.s.i. line **41** is attached by a line **76** to the CROSS-SLIDE COMPENSATION valve **77**, the other side of which is joined by a line **78** to the COMPENSATING cylinder **26**. The other side of the COMPENSATING cylinder is connected by a line **79** to the valve **77** whose drain side is connected by a line **80** to the 5 p.s.i. line **60**.

The 500 p.s.i. line **38** is connected by a line **81** to a LOW-FORCE pressure regulating valve **82** and also to a HIGH-FORCE pressure regulating valve **83**. The output side of the valve **82** is joined by a line **84** through valve **94** to the CROSS-SLIDE valve **85**, while the valve **83** is similarly connected to a valve **85** by a line **86**. The valve **85** is joined by a line **87** to the CROSS-SLIDE FEED valve **88**, the other side of which is connected by a line **89** to the 5 p.s.i. line **60**. The line **87** is also connected by a line **92** to the FEED cylinder **23**. The 125 p.s.i. line **41** is connected to a backoff high pressure valve **96**, the other side of which is connected by a line **97** to a backoff valve **98**, the other side of which is connected to a line **101**. The line **101** is connected to a cross-slide damper **102**, the other side of which is connected to a line **103**. The line **92** is connected to the outer end of the cylinder **23**, while the line **103** is connected to one end of the FEED cylinder **23**.

The 500 p.s.i. line **38** is connected by a line **104** to a backoff pressure-regulating valve **105** whose output is connected by a line **106** to the drain line **42** through a backoff pressure orifice **107**. Between the orifice **107** and the valve **105** is connected a line **108** leading through a check-valve **110** to the line **97**.

The 500 p.s.i. line **38** is also joined by a line **111** directly to a COMPENSATION SLIDE PRE-LOAD cylinder **112**. The 500 p.s.i. line **38** is also joined by a line to a damper bypass valve **113** whose output is joined by a line **114** through the hydraulic control end of the damper **102**. The line **38** is also joined by a line **115** to the cross-slide hydrostatic control pockets **116**. These pockets are joined by a line **117** to the drain line **42**. The line **117** also receives fluid arriving in a line **118** originating in the ends of the FEED cylinder **23** and carrying leakage and from a throttle line **119** originating in the end of the cylinder **23** to which the line **92** is attached. The 500 p.s.i. line **38** is joined by a line **121** to the WHEELHEAD SWIVEL valve **122** which in turn, is joined by a line **123** to the WHEELHEAD SWIVEL cylinder **27**. The other side of the WHEELHEAD SWIVEL cylinder is connected by a line **124** back to the valve **122** whose drain side is connected by a line **125** to the 5 p.s.i. line **60**. The 500 p.s.i. line **38** is connected by a line **126** to a SINGLE-JET GAGE valve **127** which, in turn, is connected by a line **128** to the GAGE IN cylinder **28**. The other side of the cylinder **28** is connected back to the valve **127** whose drain is joined by a line **131** to the 5 p.s.i. line **60**. The 500 p.s.i. line **38** is attached by a line **132** to a DOUBLE-JET GAGE valve **133**, the other side of which is connected by a line **134** to the GAGE IN cylinder **29**. The other side of the cylinder **29** is joined by a line **135** directly to the drain line **42** and the drain side of the solenoid valve **133** is also joined by a line **136** to the drain line **42**.

The 500 p.s.i. line **38** is attached by a line **137** to a DIAMOND TURNER valve **138**, the other side of which is joined by a line **139** to the DIAMOND TURNER cylinders **31** and **32**. The other side of the cylinder **31** is joined by a line **141** back to the valve **138** whose drain is attached by a line **142** to the 5 p.s.i. line **60**.

Returning now to FIGS. 2 and 3, it can be seen that the base **11** is provided with three spaced vertical abutments **143**, **144**, and **145** and that the piston **21** is fixedly mounted in them and extends horizontally through them. The piston **21** has an enlarged central portion and two reduced end portions, the end portions being mounted in the abutments **143** and **145** and the enlarged portion extending through the abutment **144**. The end that appears in the left in FIG. 2 would normally be at the rear of the grinding machine and resides in an abutment **146** which extends downwardly from the lower surface of the wheelhead table **12**. The abutment **146** is provided with a portion of the bore **22** and a head **147** overlying the bore. Extending through the head and into the bore is the line **92**. The other end of the piston **21** resides in an abutment **148** which extends downwardly from the table **12**, this abutment being provided with another portion of the bore **22** and also being provided with a head **149**. Extending into the head are a line **103** and a line **151**, the latter including a throttle **152**. Extending downwardly from the front of the table **12** is an apron **153**. Carried by the apron is a throttle rod **154** which extends into the head **149**. As is evident in FIG. 4, the head carries a bore **155** and the rod is provided with a portion **156** which fits this bore exactly. Next to the portion **156** is a reduced portion **157**, while the extreme end of the rod carries an enlarged portion **158**, the enlarged portion **158** being not quite as large as the bore **155**, however. It will be understood, of course, that the portions shown in the drawing of the bore **155** and the portions **156**, **152**, and **158** of the rod **154** are drawn out of proportion for clarity of description. As a practical matter, however, the difference between the diameter of the reduced portion **157** and the diameter of the bore **155** is quite small and is sufficient to present considerable viscous friction or throttling to the flow of fluid. Extending from the central portion of the bore **155** is a passage **159** leading to the line **151**. Also extending from the chamber formed by the piston **21**, the bore **22**, and the head **149** is a passage **161** leading to a vertical passage **162** (see FIG. 2) formed in the head and leading to the line **103**.

Mounted on the forward surface of the apron **153** is a block **163** having a threaded bore through which extends a similarly threaded portion **164** of the rod **154**. The rod is formed with a much larger threaded portion **165** at its outer end, which threaded portion has a nut **166** mounted on it. A rod **167** is carried in the block **163** and extends into an aperture **168** formed in the nut **166**. Extending from the nut **166** is an indicator **169** which is generally coextensive with a knob **171** which is fastened to an outer reduced portion **172** of the throttle rod **154**. The knob **171** is locked in place by set screws **173** and **174** extending into the knob **171**.

The apron **153** is formed with an aperture **175** which is much larger than the threaded portion **164** of the rod so that it does not interfere with movement of the rod. A similar bore **176** extends through the abutment **145** of the base **11** to permit free relative movement of the rod **154**.

The operation of the apparatus will now be readily understood, in view of the above description. The cycle of the machine is controlled by the solenoid valves **47**, **52**, **69**, **77**, **85**, **88**, **94**, **98**, **113**, **122**, **127**, **133**, **138**, **96**, and **102** which, in turn, are regulated by electrical controls operating on the coils of the solenoids. The electrical control apparatus is of the conventional type and is well known in this art. At a certain part of the cycle, it is necessary to withdraw the abrasive wheel **15** from the bore in the workpiece. For that purpose, the TABLE cylinder **20** is actuated and the abrasive wheel **19** is withdrawn from the workpiece and moves axially. Before the wheel passes over a diamond for dressing, the table **12** carrying the abrasive wheel **19** is moved transversely into backoff position. The 500 p.s.i. pressure output of the valve **105** passes through the line **108** and the check-valve **110** and through the line **97** and the solenoid valve **98**. This fluid pressure operates on the cylinder **23** and moves the table forwardly (to the right in FIG. 1) which moves the wheel **19** away from the surface of the workpiece into a backoff position at which time it moves axially and moves past the diamond and dressing takes place. The backoff position is located so that the diamond removes the slight amount of surface from the abrasive wheel. The wheel moves longitudinally outwardly to the end of its retracted position and the TABLE cylinder **20** is reversed by means of the TABLE INDEX valve **52**. The abrasive wheel **19** returns along the same path toward the workpiece bore **17**. The oil passing through the line **92** to the cylinder **22** for the grinding operation is shut on and off by the solenoid valve **85**. However, the particular pressure involved is determined by the pressure regulating valves **82** and **83** in the usual manner to provide a pre-determined oil pressure in the cylinder during feeding. When feeding takes place, oil is pressed from the other end of the cylinder. Since the valve **102** is closed, the oil is forced to flow through the throttle **152**. This throttle is made up of the portions of the throttle rod **154** and the bore **155** and, of course, is adjustable. The valve **102** is hydraulically operated and this operation is determined by the valve **113**. Oil which is pressed out of the cylinder chamber through the throttle **152** by the movement of the piston passes through the valve **113** and goes to the drain line **42** through the valve **98**. When it is desirable to move the wheel **19** away from the workpiece surface for dressing or for loading of a workpiece or the like, it is only necessary to operate the valve **113** to remove the pressure oil from the hydraulic actuator portion of the valve **102** and to connect that portion to drain. Then, the valve opens and oil is admitted to the forward end of the cylinder **22**. It enters the cylinder through the passage **161**. The oil which is delivered to the passage **161** through the line **103** in this stage of the operation originates in the line **41**.

It can be seen then that, during the grinding operation, while the wheel **19** is being pressed into the surface of the workpiece by the oil originating in the line **92**, oil is being pressed out of the other end of the cylinder and its only means of escape is through the line **151** and the throttle **152**. The throttle is set to very accurate adjustment for regulating the resistance to flow. Now, the table **12** moves relative to the base **11** on friction-free guides, as is the usual method, so that very accurate determination of pressure in the line **22** results in very accurate determination of the pressure between the wheel **19** and the workpiece **16**. This is in accordance with the so-called "controlled-force" method of grinding. However, it has been found in the past that this arrangement in itself can result in somewhat erratic feeding of the wheel into the workpiece surface. This is possibly caused by vibration; the system is a friction-free sliding system with a spring in the form of the spindle on which the wheel is mounted. Such a system has a high degree of resilience and a low amount of damping and lends itself to vibration. Vibration of extremely large displacement may take place, particularly when there is introduced into the system an impulse close to its natural frequency as would be true in "rounding up" a bore. Also, there is a tendency in sliding guides to produce a stick-and-release action in which sliding does not take place for a short period of time and then, suddenly, a hydrodynamic film builds up and release of the holding takes place, so that the wheel jumps forwardly. Both of these motions is obviated by the present invention. The result of providing a throttle in the system in the manner suggested by the applicant is that a viscous resistance is introduced into the spring system. Any attempt for the elements to move more rapidly than a predetermined speed will encounter extreme resistance because it is necessary for fluid to flow into the chamber of the piston cylinder arrangement in order for such action to take place. This type of damping is time-oriented to prevent suddent movements between the elements. Since the valve **102** is closed during feeding operation, the only way fluid can move in and out of the chamber is through the throttle **152**. The throttle, therefore, has the effect of damping any extraneous vibrations or erratic movements. The advantage of this viscous damping is that the amount of resistance is proportional to velocity, so that extreme variations of table movement will result in large compensating resistance to such movement.

The engagement of the threaded portion **164** of the block **163** results in advance and retraction of the rod and in adjustment of the passage between the rod and the bore **155** in the head **149**. The rotation of the rod to produce this adjustment is produced by rotating the knob **171**. Now, the rotation of the rod also cooperates through the rod **167** and the nut **166** to advance or retract the nut **166** relative to the knob **171**. The finely-threaded portion **164** and the coarsely-threaded portion **165** provide a differential movement, permitting very accurate adjustment. Since the indicator **169** and the surface of the knob **171** are provided with indicia, this results in the production of a micrometer indicator which can be calibrated to show various settings of the throttle **152** and, possibly, be calibrated in terms of rate of flow of fluid.

To thoroughly understand the advantages of the present invention, it is necessary to review the art of "controlled force" grinding. To begin with, practice has proven that internal controlled force grinding leads the field in obtaining the most work and economy from an abrasive wheel. Grinding machine users and builders continue to find new benefits and capabiilties for improving production and quality with this revolutionary grinding method. One of the more common internal grinding operations is that of precision finishing the track of a ball bearing outer race. The size tolerances and geometrical shape requirements provide grinding machine designers with one of their most challenging problems. For example, the cross track curvature must not vary from a true radius by more than .000020 to .000040 of an inch and a .0001 to .0002 size envelope must be maintained. This has to be accomplished with stock removal conditions that can change .025″ piece to piece and workholding locating surface dimension variations that actually exceed that of the ball track tolerance requirements.

The machine system devices involved in this grinding process are: the grinding machine with its wheel dressing device, the coolant and, of course, the grinding wheel. In the past, with rate feed mechanism it was customary, while maintaining this degree of quality, to grind from 200 to 300 parts with one wheel in the 6 to 8000 s.f.p.m. The wheel then had to be changed. In some cases, it could be used again on subsequent operations with smaller bores, but more often, the wheel had served its purpose and had to be thrown away. Today, using the controlled force internal grinding system together with multi-wheel quill arrangements, never before possible with feed rate grinding, the same wheel can produce ten times as many workpieces with improved quality. Controlled force internal grinding has proven that a vitrified abrasive wheel is a tool with capabilities far exceeding the work to which it is currently being applied and that the controlled force grinding system is a way to obtain many additional benefits.

To review the controlled force grinding system, a common nomenclature must be established. Prior to 1963, all grinding machines, both internal and external, were built with "feed rate" infeed devices. That is, the grinding wheel was advanced into the workpiece at a preset rate which involved much art or guess work. On automatic machines, it was an estimate of stock variation, the grade wheel available and the type of coolant to be used that determined the rate setting. The grinding machines went through the motions of a given cycle in exactly the same time, but as inspection proves, not all the workpieces came out of the machines to the same size or finish. When this dilemma was recognized as limiting the precision capabilities of feed rate grinding, particularly on internal grinding machines, thoughts could be channeled into the developments of a new grinding system. The outcome of much engineering effort, time and dollars, was the controlled force grinding system applied to an internal grinding machine.

The first consideration when comparing grinding systems is the force between the work and the wheel. Laboratory tests prove that there is a particular force with a given workpiece, coolant and grinding wheel combination where the fastest stock removal will take place without damaging the wheel. This is true with both external and internal grinding. With internal grinding and the wheel mounted on a cantilever beam, there is an additional problem. As the force between the work and the wheel changes, so does the deflection of the quill. This, of course, causes

changes in size and taper. Even with sparkout, in-process gaging and other cycle accessories, there is a limit to the precision that can be obtained. In the simplest terms, with the controlled force grinding system, the pressure between the work and the wheel is preset to suit known conditions that prevail. The rough grind cycle time will vary somewhat with significant changes in stock conditions, but the workpiece size and conditions of the wheel for grinding action will remain constant.

In most instances a new machine with advanced capabilities means more sophistication. However, this is not true with the automatic internal controlled force grinder shown in the present case, where a simple hydrostatic way system and a hydraulic force piston provide the basic feed mechanism; this replaces the old complex feed box and lead screw.

Any controlled force feed slide must be frictionless. In technical terms, Coulomb friction must be eliminated. Since a controlled force feed slide is not anchored to a screw, it is free to move backward as well as forward in the feed direction. Here, an apparent road block in the design concept of a controlled force grinding machine has been used to great advantage. By providing a hydraulic damper with controllable shock absorbing characteristics in the hydraulic force feed system, a controlled force machine can be adjusted to provide the fastest possible "rounding up" of the eccentric surface conditions of the usual rough workpiece. In effect, when the wheel first contacts the work, it will contact the high spots of an irregular surface with more force than on the low zones. For example, this allows an "out of round" rough bore to be "rounded up," with the entire surface clean ground, much earlier in the cycle than would be possible with a feed rate grinding system. This complements the ability of maintaining a more precise amount of finishing stock just prior to final size.

Now let us consider the grinding force control in a little more detail. When we talk about controlled force, it is in relative terms. Just as there is not a "pure feed rate," there is also not a "pure controlled force." We have a force-rate spectrum as shown in FIG. 8. Controlled force is closer to the pure force end of the spectrum and controlled rate closer to the pure rate end of the spectrum.

Due to the required viscous damping in the controlled force slide as described before, the grinding force will decrease with increased grinding rate. This is very desirable, since it will regulate the grinding process. When the penetration rate of the wheel decreases, due to dulling, the force between wheel and will slowly build up causing the wheel to self-sharpen, which in turn, makes the wheel cut faster. Again the regulating process takes over. The faster grinding rate due to rate sensitive damping causes the force between wheel and work to reduce slowly, which prevents loading of the wheel, burning, and high micro.

However, with controlled force, the change in the force of the wheel against the work is more subtle and smaller than with feed rate. It is limited to a maximum force which is preselected for a given wheel and length of part such that the wheel will self dress when the penetration rate slows down due to dulling and continues cutting with its highest efficiency. On a controlled force machine with the input force preselected at, say, 150 lbs., the force of the wheel against the work cannot exceed 150 lbs., whereas, on a feed rate machine due to the mechanical advantage, forces of 1,000 lbs. and more can develop, thus damaging wheels, quills, and bearings.

Controlled force grinding normally requires that the wheel be as wide as the work surface to be ground. However, with high damper strength and a feed stop control, long bores can be ground with narrow wheels.

The controlled force grinding system with its advanced capabilities offered opportunities to develop new control devices to get even greater precision for size holding, finish and geometry with a completely automatic cycle. These controls complement the cutting action of the wheel and the finish potential as well.

During the life of an internal grinding wheel, for instance, it becomes smaller in diameter with each subsequent dress, and this changes the grinding conditions. As the wheel O.D. is reduced, the surface speed changes, the wheel-work contact area is reduced. This, in turn, results in a gradually increasing RMS finish. A retracting stop in the cross slide unit is frequently used to monitor the final .001 of stock removal to insure that, just prior to finish size, a given wheel will be cutting under exactly the same conditions regardless of wheel size and thus insure greater finish consistency. This escapement rate feed, at the last instant of the I.D. grinding cycle, is adjustable and can be set to suit a given machine setup. This retracting stop is really another force regulating mechanism. It reduces the applied force even further than the damper, or can stop the slide entirely for final sparkout. In other terms, the retracting stop acts as a force divider. The input force minus the force against the retracting stop is equal to the wheel force against the work.

To review again, the controlled force grinding system gives the best wheel/coolant grinding performance without wheel damage for variable stock removal conditions. The retracting stop provides additional control for low finish requirements as the wheel size changes.

At the present time, there is much development work with high wheel surface speeds. High speed grinding tends to produce heat which, if not controlled, will cause workpiece surface damage. The controlled force grinding system complements high speed grinding by being able to provide optimum forces. In many cases, significantly faster cycles can be obtained without damaging the wheel or burning the work surface.

Adaptive controls are also a part of the controlled force equipment. When specifications demand the ultimate in short cycle time, above average geometrical requirements or rough stock conditions are present that hinder the grinding process, machine component operational variations can be monitored and signals "fed back" to make desirable cycle changes automatically.

A typical control system for maintaining a low micro finish and accurate size is the so-called automatic drift control. Here the machine constantly senses the amount of finish stock and the time required for the final grind. The length of finish grind is affected by diamond wear or thermal changes in the machine. If the finishing time becomes short, let's say due to diamond wear, the micro could exceed the specified tolerance. However, if the finish time becomes too long, the finish would have a low micro reading, the cycle time would be longer. Certain limits for the amount and time for the finish portion of a cycle are pre-set. When the machine senses a change from this reference, it will automatically adjust for diamond wear and the effects of thermal drift. This maintains constant finish grind parameters.

Ammeter monitoring of the wheel drive motor is a common adaptive control and can be used on controlled force machines. It can give an electrical signal to control the final portion of a cycle in terms of finish and taper relative to the current load (e.g. in long bores on internal grinders).

Machine cycle combinations with controlled force grinding are numerous and different from feed rate cycles. The controlled force slide "in feed" rate is, of course, determined by the force at which a particular wheel with a given coolant can grind into the workpiece material. The best force to use is easily determined. This is accomplished quickly by starting with a conservative pressure setting and recording the time necessary for a particular wheel to remove a given amount of material. The force can then be increased in convenient increments until an increase in force does not produce a reduction in time. When the proper force is determined, then appropriate cycles can be developed for either single or multiple wheel applications.

The most common cycle is the so-called "interrupt for dress." Frequently, because of pure controlled force performance or the ability to use several wheels on a single quill, as a side benefit of controlled force, "dress at load cycles" can be used. This type of time saving cycle might not have been possible with feed rate grinding.

Other cycle comparisons include skip dressing and multi dressing. Skip dressing has always been used with feed rate internal grinding for ball bearing ball tracks in outer races. The controlled force system can generally skip twice as many cycles as the feed rate system before a dress is necessary on this type of work.

Without adding sophisticated and costly controls to a feed mechanism, the basic controlled force system allows for an unlimited number of interruptions for dress which are necessary for grinding modern exotic materials.

Multi wheel applications with controlled force gives one of the newest and most interesting cycle innovations. The best possible wheel grade and force can be determined for roughing with an equivalent selection for finishing. No longer is a compromise wheel grade selection necessary to complement two objectives. Most of the time on feed rate grinders, the finish requirements dictated the wheel grade and cycle at the expense of the stock removal ability. The newest application of controlled foced multiwheel grinding is true abrasive machining.

Several controlled force machines are now in production which grind the complete internal contour of a bearing outer race from a solid blank bushing. A #210 ball bearing outer race with an O.D. of 3½" and a width of ¾" can be form ground in one chuckling, removing half a cubic inch of 52100 steel in approximately one minute. This single operation replaces six separate I.D. grinding operations previously used. It produces a finished ball track, a rib diameter, two chamfers plus a tapered surface adjacent to the (angular contact) ball track. With a two wheel quill, a driven diamond wheel dresser forms the contour on the outboard wheel, and a radius dress provides the geometry on the second ball track finishing wheel. The ball raceway is semi-finished by the first wheel. Oil coolant is required on this type of abrasive machining.

FIGS. 6 and 7 illustrate how the viscous throttling used in the present invention is helpful in controlled force grinding. The force arrows are drawn to indicate their relative sizes under various conditions. The equation $F_o - F_r = F_g$ indicates that the total force, F_o, available due to oil pressure in the cylinder is divided between the grinding force, F_g, and the force F_r, absorbed by the resistance to flow of the fluid through the throttle. When the wheel is new and is large compared to the bore, as shown in FIG. 6, the piston is allowed to move slowly, due to the advance of the wheel in grinding its way into the surface of the workpiece. After a large number of workpieces have been ground in the automatic grinding machine, the diameter of the wheel is reduced in size by wear and by dressing, as shown in FIG. 7, so that it is relatively much smaller than the bore. It then cuts much more rapidly and, if the grinding force, F_g, were to remain the same, the qualities of the finished workpiece would suffer. For one thing, the rate of movement of the abrasive wheel into the workpiece material would increase substantially, resulting in a deterioration in the fineness of surface finish. With the present invention, however, the start of such a rapid movement is immediately counteracted by a similar increase in the viscous force, F_r, with an attendant decrease in the grinding force, F_g. The decrease in grinding force will slow down the progress of the wheel through the workpiece material, thus restoring most grinding parameters to the conditions prevailing at set-up time (FIG. 6).

Another situation that arises frequently in automatic grinding machines has to do with wheel dulling. As grinding progresses (between dresses), the wheel becomes duller. In a feed-rate machine, when the wheel gets duller, it is pressed onward into the material, nevertheless, so that the force increases greatly; eventually, the surface of the wheel breaks down under this great pressure, new grains of abrasive are exposed, and grinding begins to speed up. In the past, this "automatic dressing" of dull wheels was not available in controlled force machines, because the force could not go up when the wheel became dull.

With the present invention, however, when the wheel becomes dull, the rate of grinding decreases, and the velocity of the wheelhead table also decreases. With the viscous damping, the decrease in table velocity means less resistance to fluid flow and a decrease in F_r. Thus, more force from F_o is available for grinding (F_g); this increase in F_g causes the wheel surface to break down, exposing new grains of abrasive, and speeding up the grinding process again. This returns the grinding parameters to their original values and helps to maintain the quality of the finished workpiece surface to the original predetermined values.

It is obvious that minor changes may be made in the form and construction of the invention without departing from the material spirit thereof. It is not, however, desired to confine the invention to the exact form herein shown and described, but it is desired to include all such as properly come within the scope claimed.

The invention having been thus described, what is claimed as new and desired to secure by Letters Patent is:

1. A grinding machine, comprising
(a) a base,
(b) a workpiece support mounted on the base,
(c) a wheelhead support adapted to carry a grinding wheel and mounted on the base,
(d) a hydraulic actuator having a piston movable within the actuator connected to one of the supports for bringing about relative feeding and retractive movement between the workpiece support and the wheelhead support,
(e) means for presenting an incompressible fluid to the actuator at one side of the piston at a controlled pressure during feeding movement, the actuator consisting of a cylinder having a head at the other side of the piston, the head being provided with a passage, and a damper rod lying in the passage accessible from the exterior of the machine to permit regulation of the relative positions of the rod and passage and, therefore, regulation of the restriction to flow of fluid presented thereby,
(f) means connected to the actuator at the said other side of the piston to permit escape of fluid at a restricted selected rate during feeding movement and alternatively to present a fixed pressure fluid during the retractive movement, and
(g) separate sources from which originate the controlled pressure fluid and the fixed pressure fluid.

2. A grinding machine as recited in claim 1, wherein the last-named means consists of an adjustable restriction and a valve connected in parallel with each other, the restriction and the valve being connected on one side to the actuator and at the other side to a selector valve which is, in turn, connected to a source of pressure fluid and a sump.

3. A grinding machine, comprising
(a) a controlled force feed mechanism,
(b) a source of controlled pressure fluid connected to a first portion of the mechanism during feed movement,
(c) an adjustable flow restrictor connecting a second portion of the mechanism to a return line during feed movement,
(d) a source of fixed pressure fluid connected by a path independent of the restrictor to the second portion of the mechanism during retraction movement, and
(e) means connecting the first portion of the mechanism to a return line during retraction movement, the restrictor presenting viscous resistance to the flow of fluid during the feed movement, so that the total resistance to movement provided by the restrictor is proportional to the velocity of movement.

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