United States Patent

Smith

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[54] **GRINDING SYSTEM**

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[52] **U.S. Cl.** ....**51/165 TW**

[51] **Int. Cl.** **B24b 49/04**

[58] **Field of Search** ....51/165.01, 165.04, 165.045, 51/165.09, 165.17, 165.18, 165.20, 165.21, 134.5, 49, 165 TW

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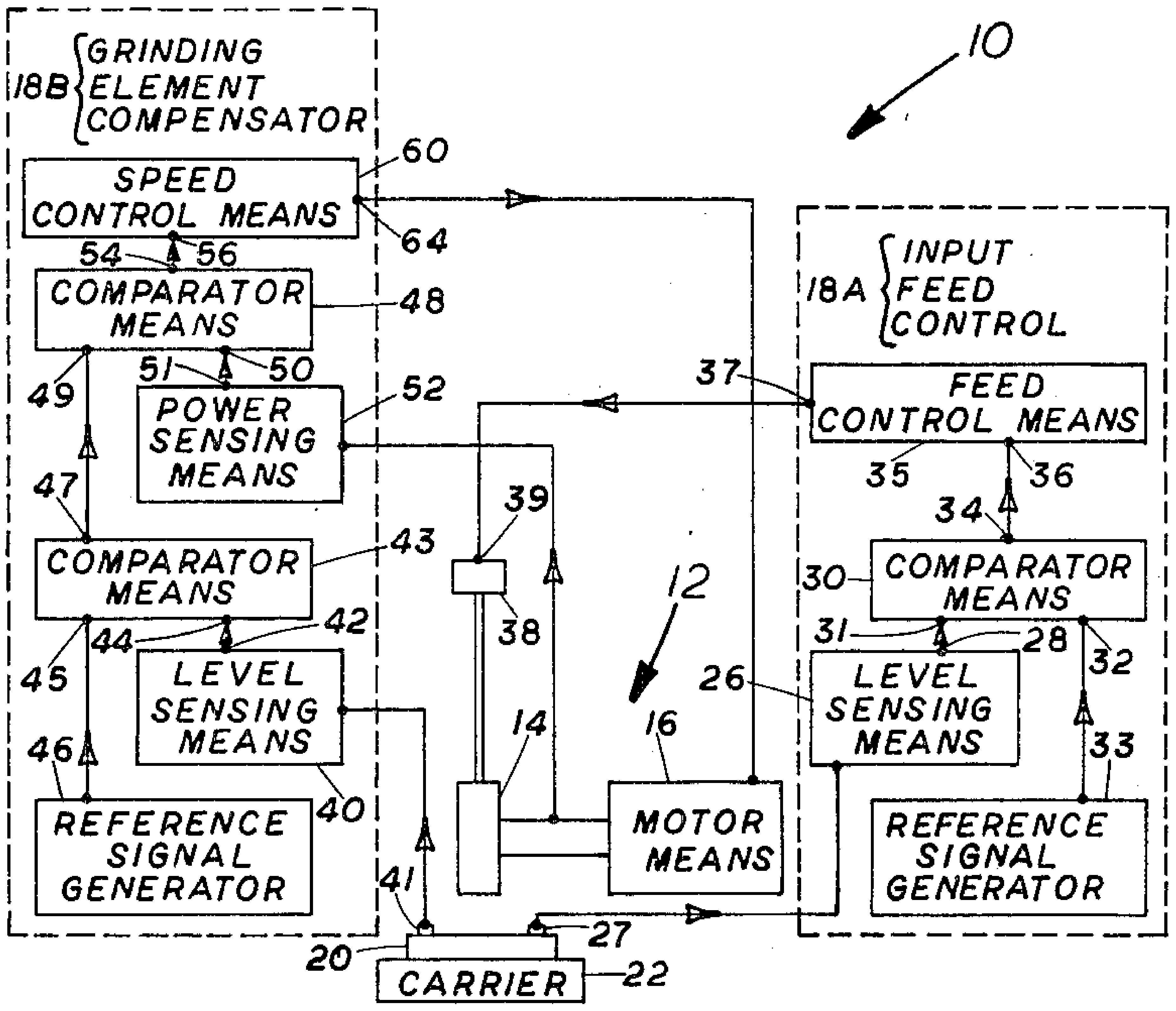
[57] **ABSTRACT**

A grinding system comprising adjustable means for controlling the after grinding size of a work piece and production rate while maintaining surface integrity and finish of the work piece substantially constant.

15 Claims, 10 Drawing Figures



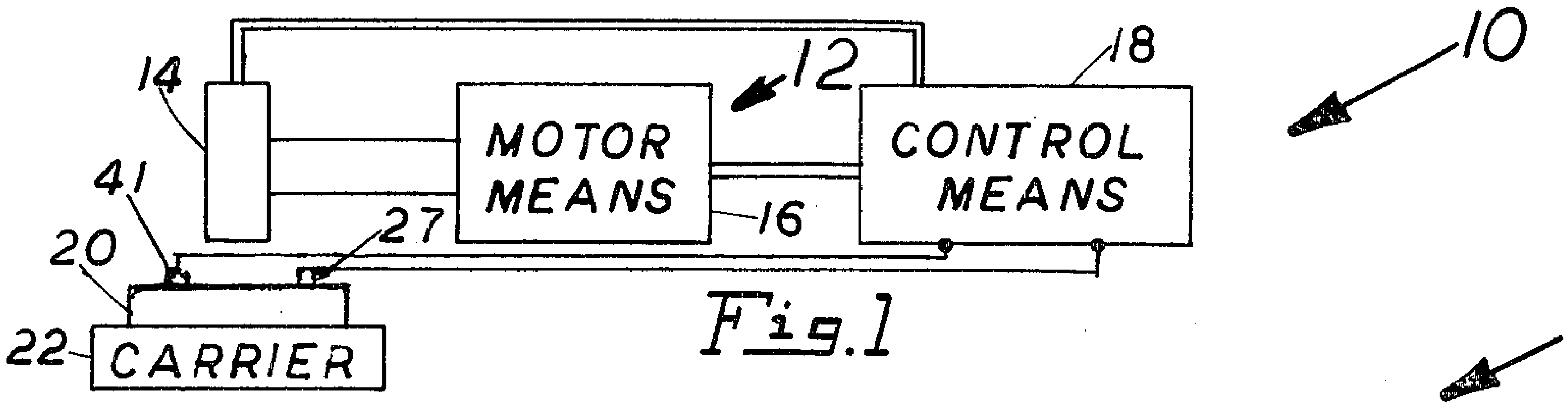


Fig.1

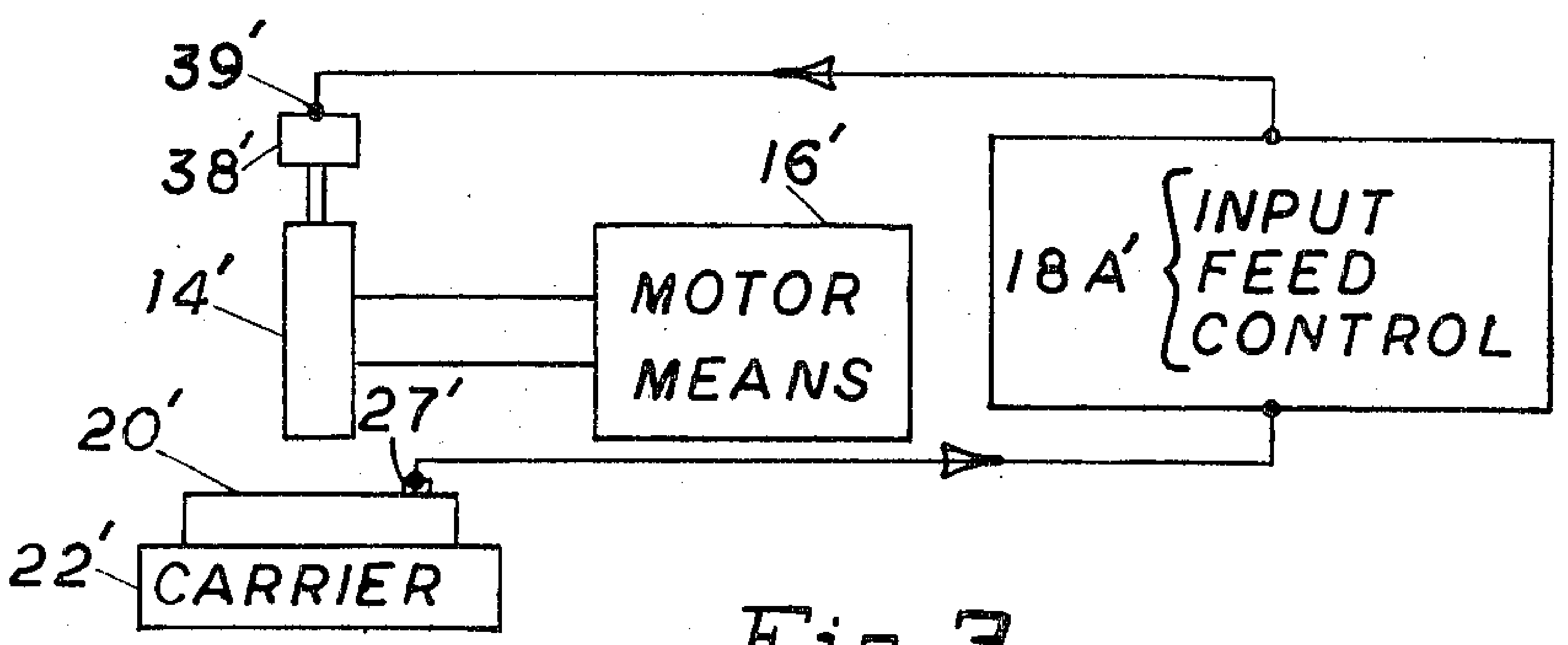


Fig.3

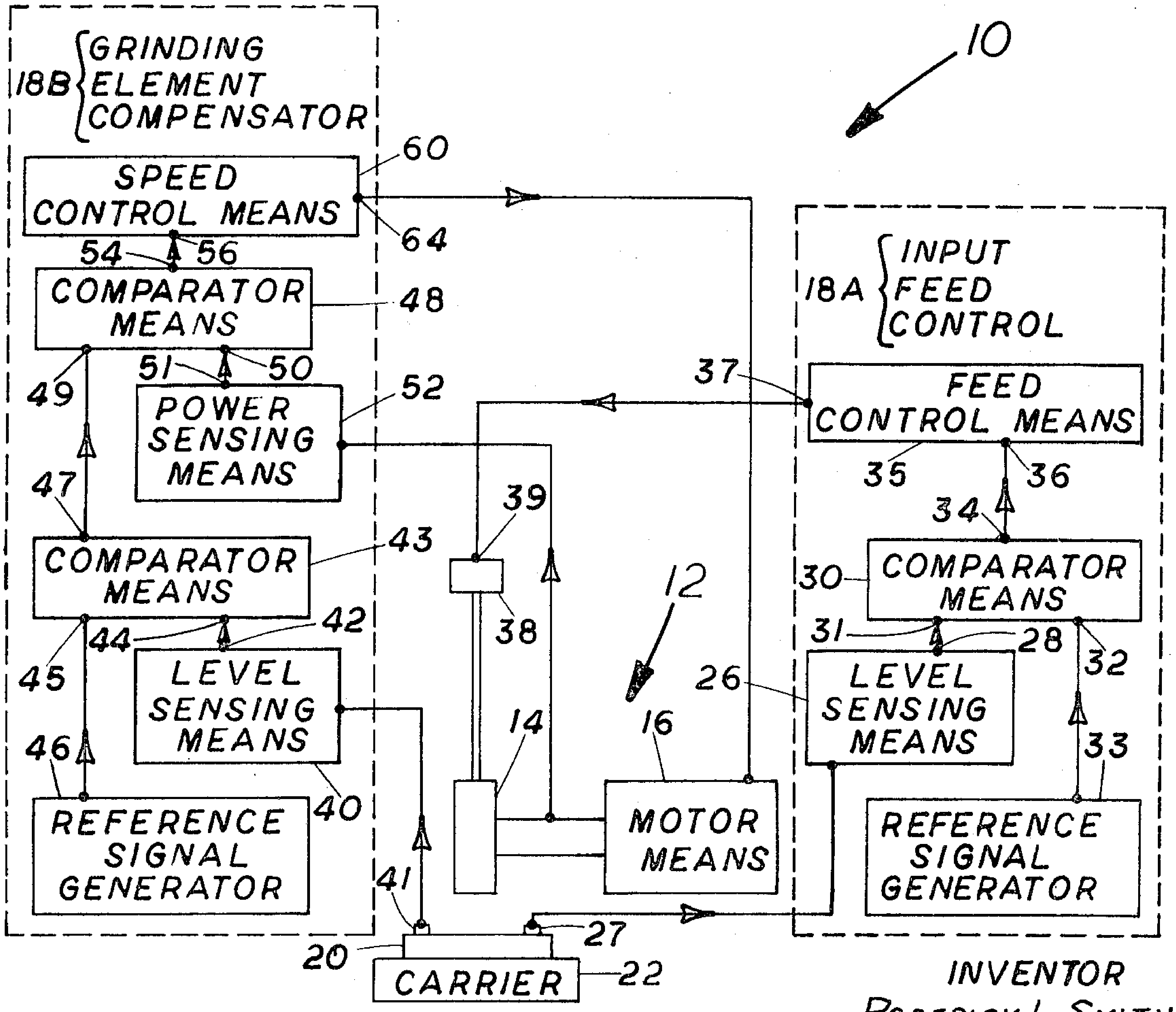


Fig.2

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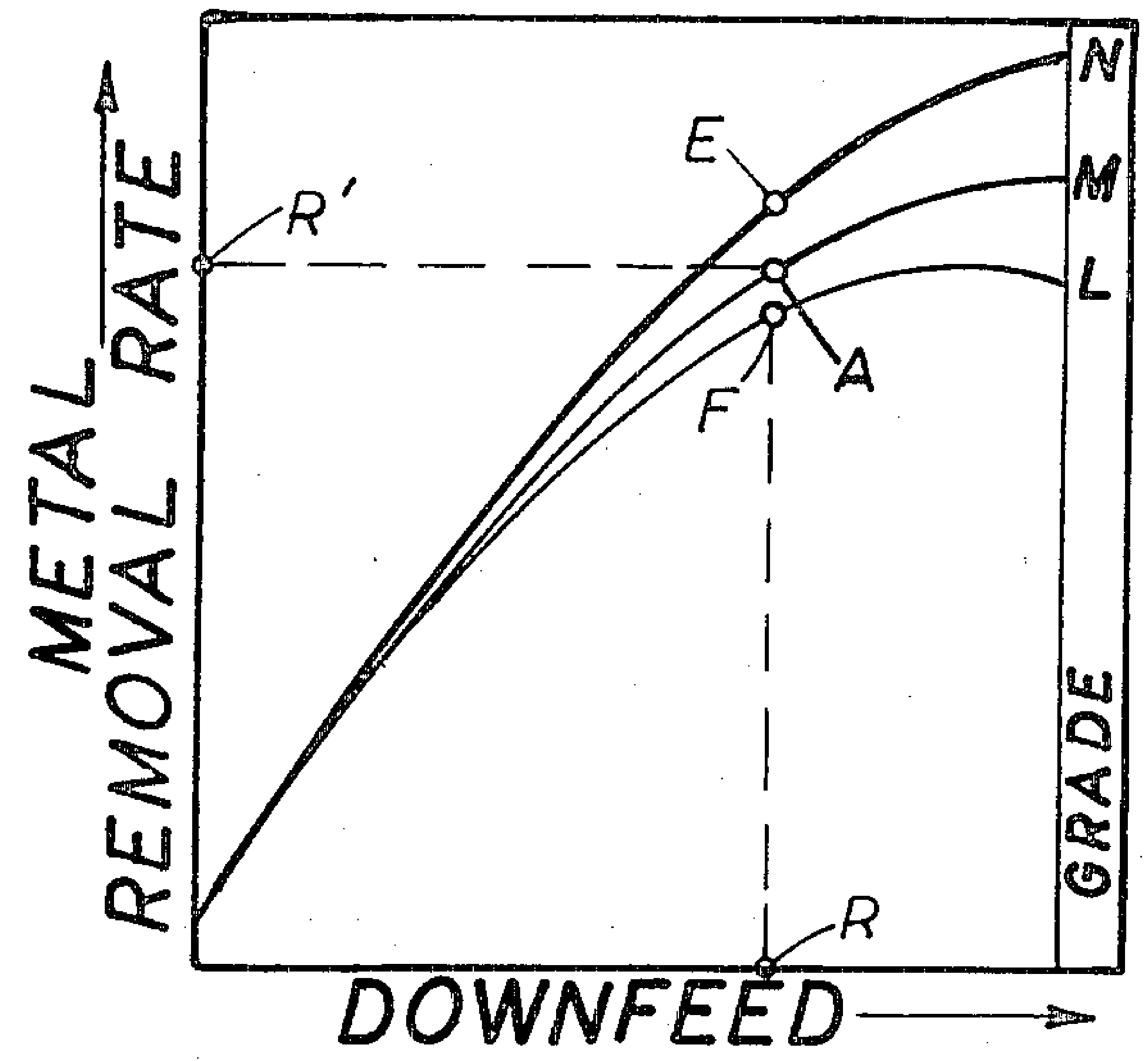

Fig 4

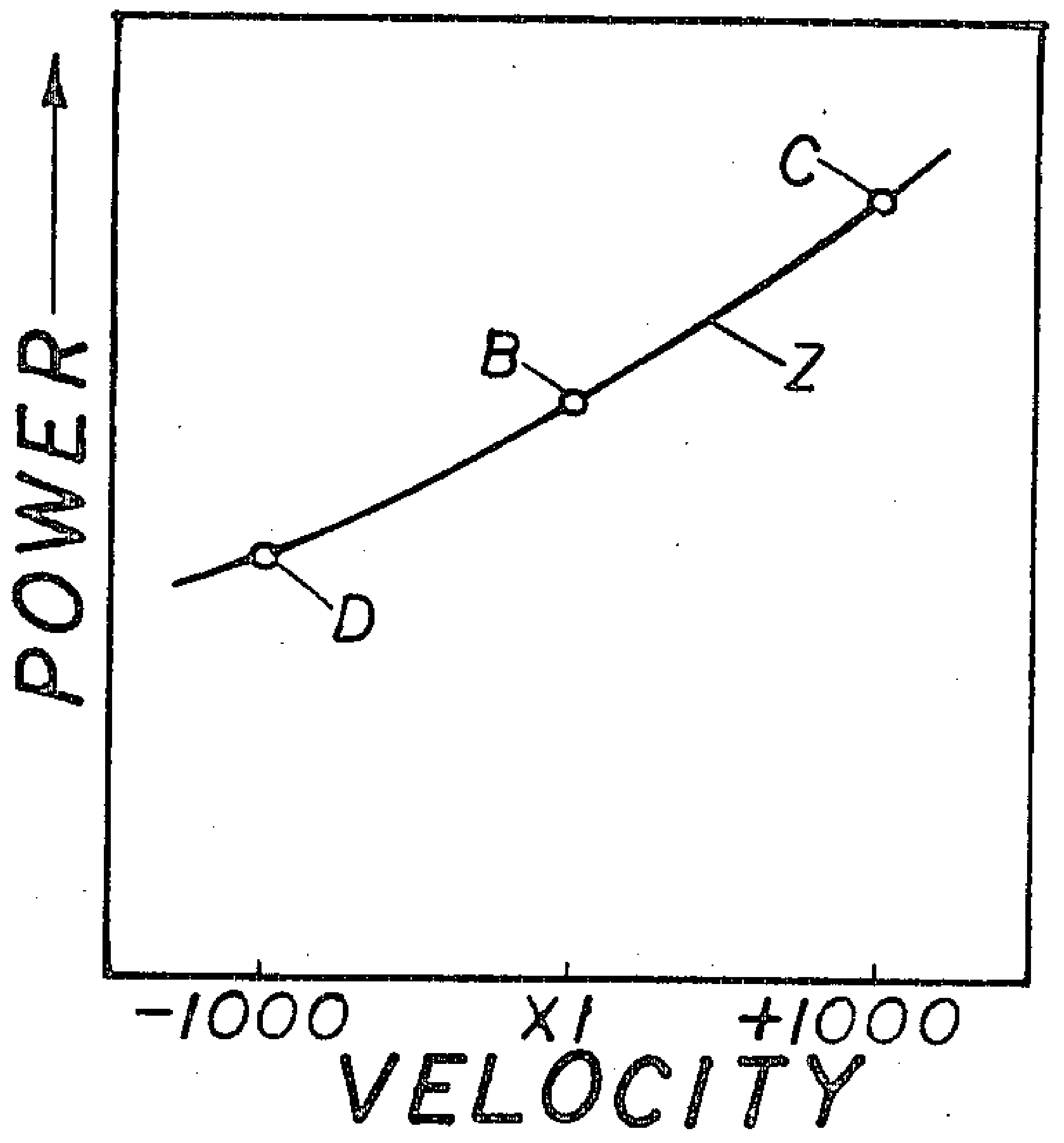

Fig. 7

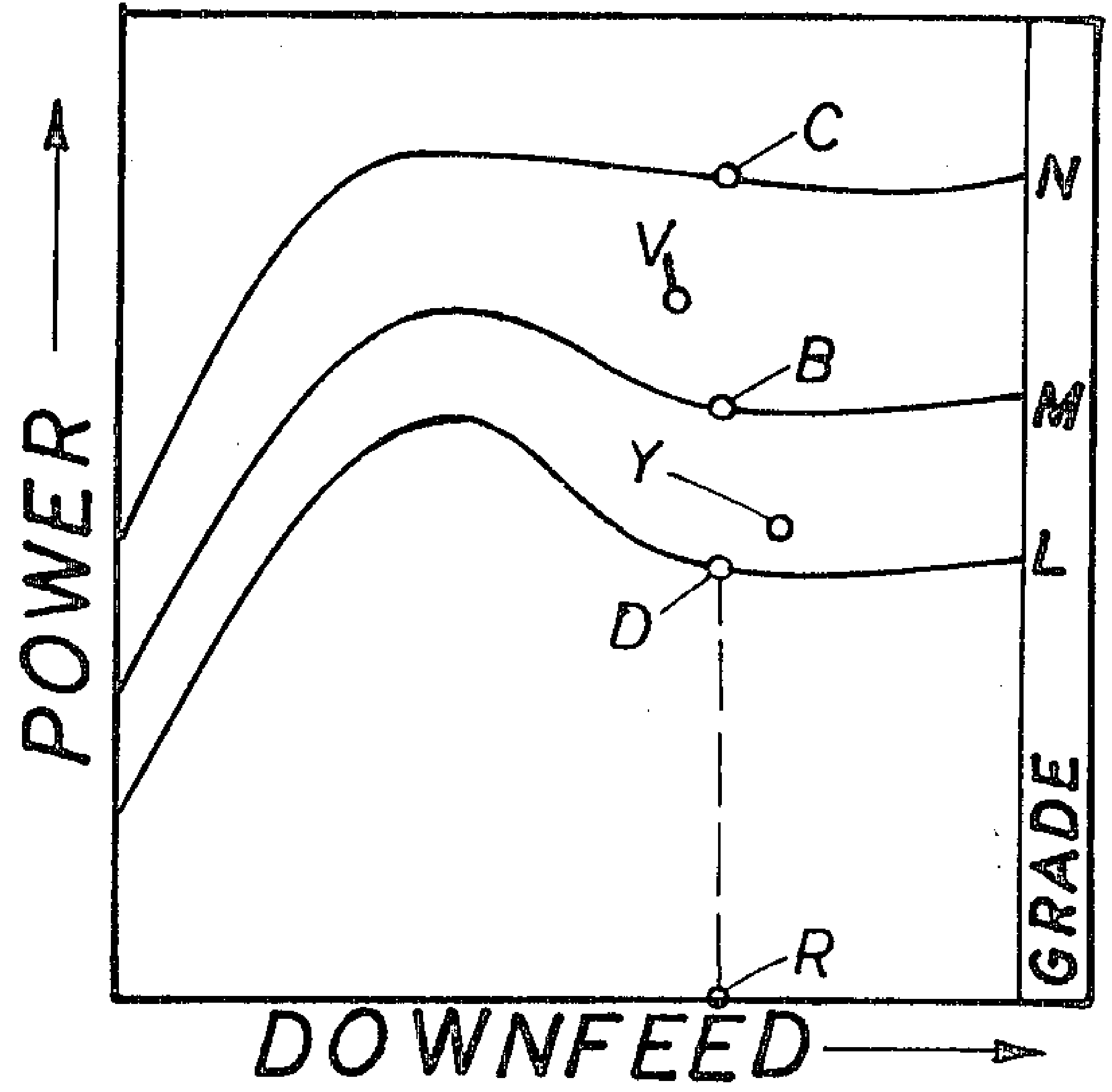

Fig. 5

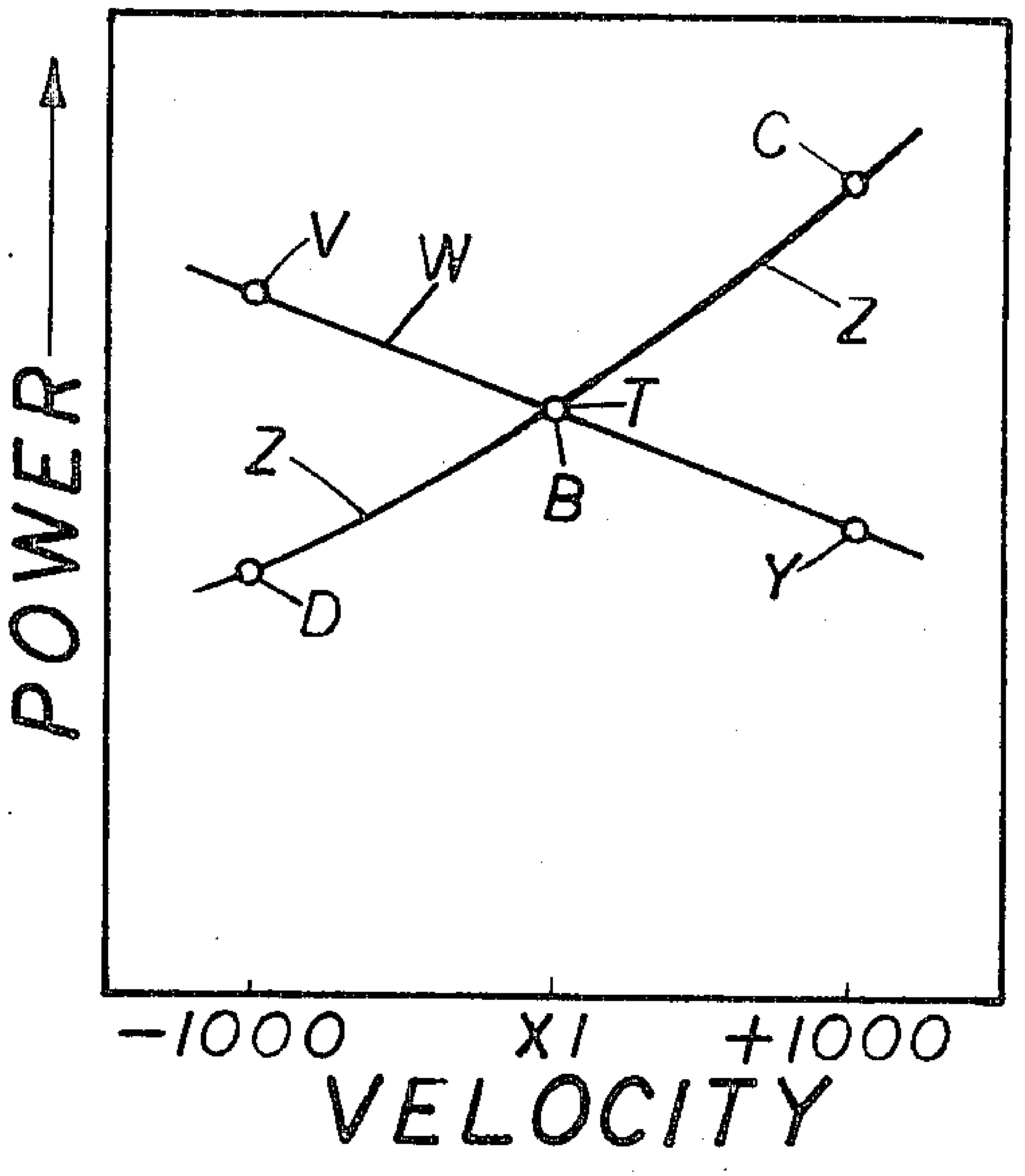

Fig. 8

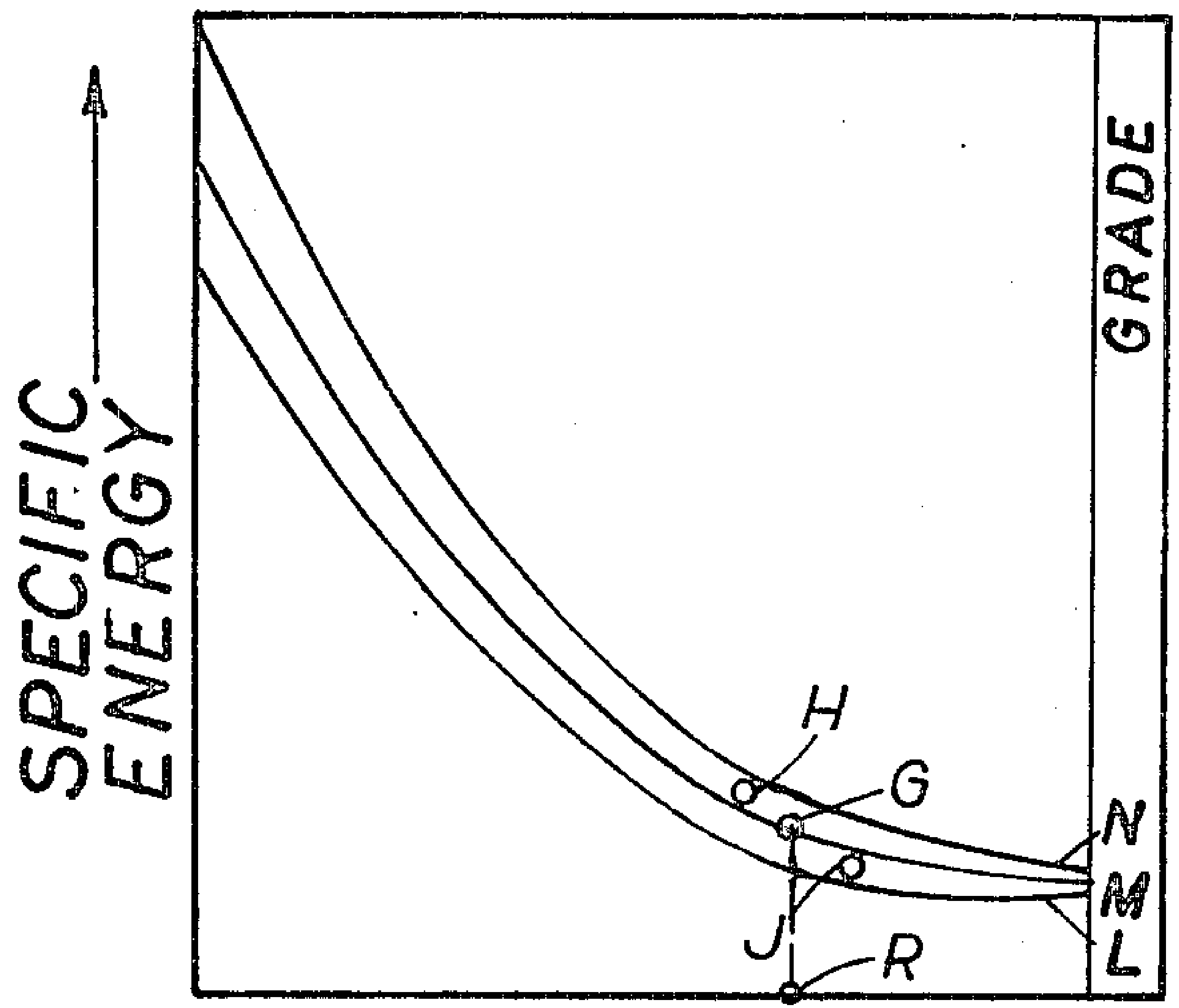

Fig. 6

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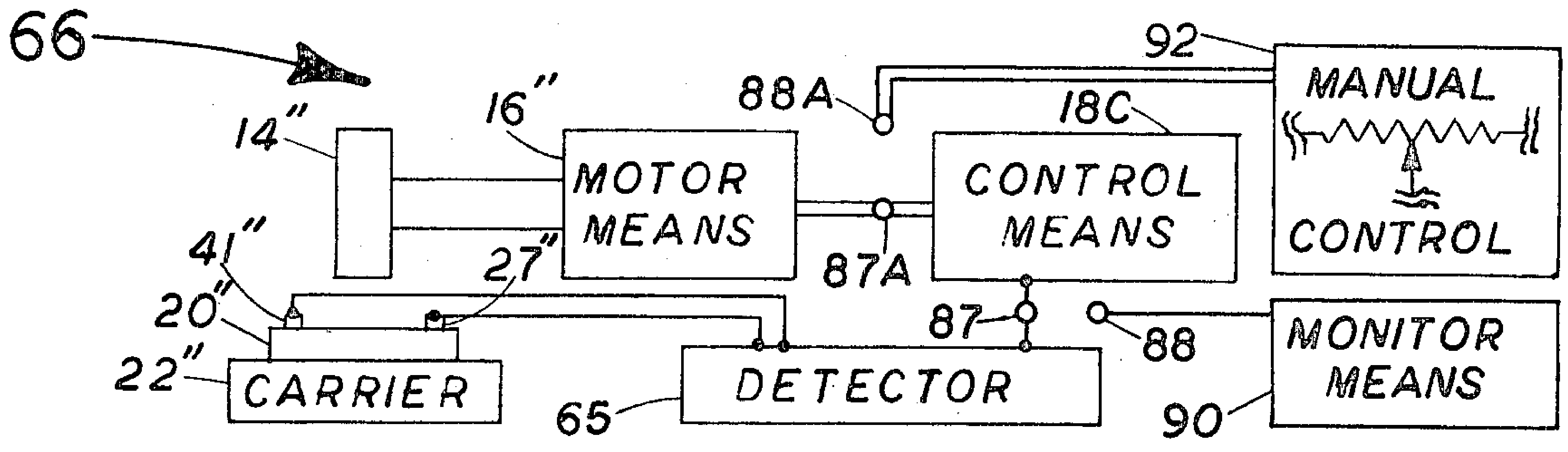

Fig. 9

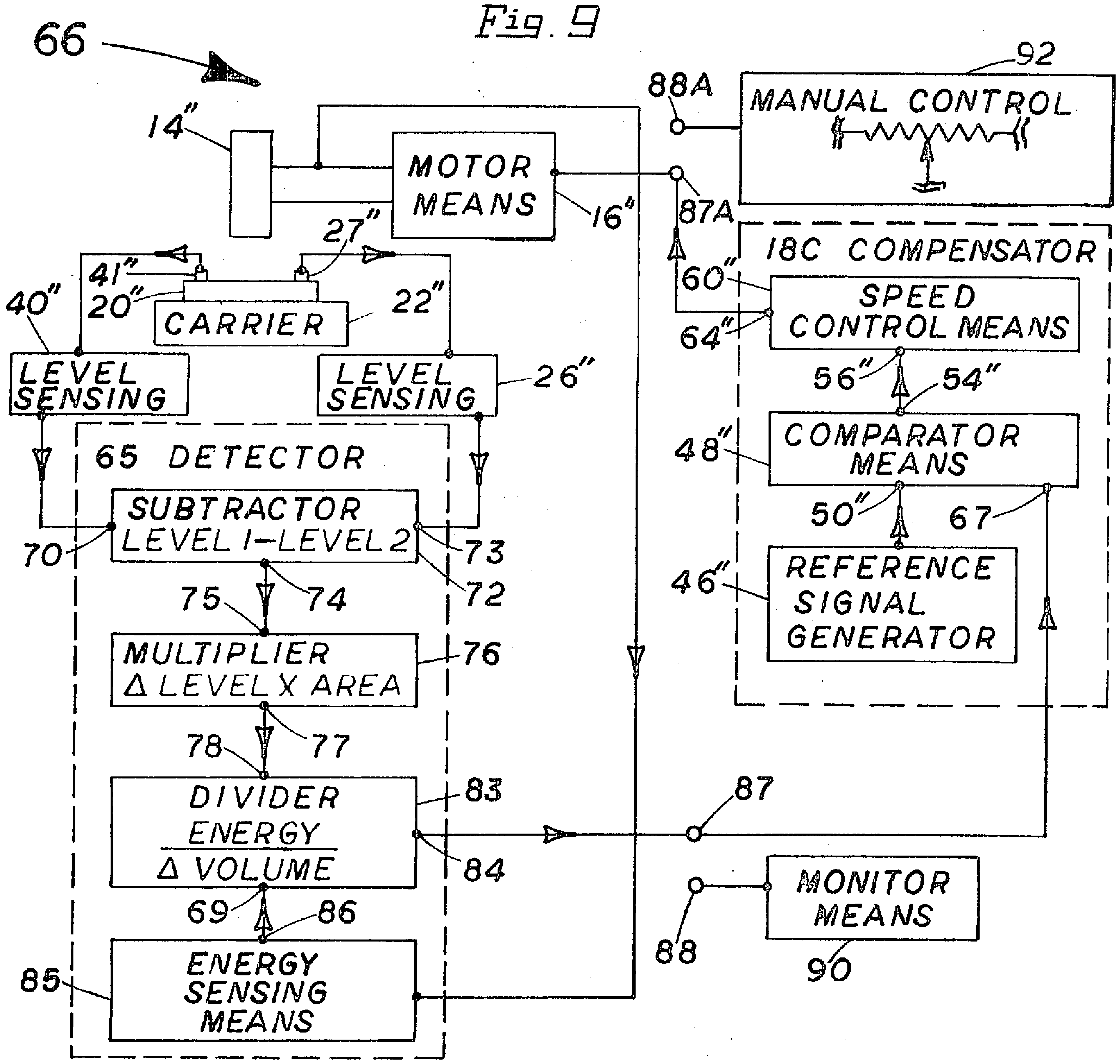

Fig. 10

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GRINDING SYSTEM

BACKGROUND OF THE INVENTION

This invention relates generally to grinding machines, and more particularly, relates to a grinding system comprising automatic adjustable means for controlling grinding operations.

The grinding machines generally used for removing material from a work piece may be characterized either as controlled force grinding machines or controlled feed grinding machines. The subject invention is particularly suitable to provide controlled feed grinding.

In order to accomplish removal of material, the controlled feed grinding systems were generally designed in accordance with the concept that the material removed from the work piece depends upon the wear of the grinding element and the feed or relative forced interference of the work piece with the grinding element.

A typical controlled feed grinding system comprises a grinding wheel powered by a motor driving a belt sheave arrangement. The work piece is mounted on a carrier which is moved toward the grinding wheel at a controlled rate of speed, and the carrier may move under the wheel in continuous backward and forward cycles. Means are provided to move the rotating grinding wheel into the work piece at a controlled downward movement. A cross-feed mechanism may be provided to move the work piece transversely relative to the grinding wheel.

The great majority of the conventional industrial general purpose and special purpose machines use grinding wheels in their grinding systems (refer to Marks Mechanical Engineers Handbook, 6th Edition 1968, pp. 13–97 ff.) Many grinding systems may, however, also use elongated, tapered, scaled down or various other shapes of grinding elements.

The main objectives of controlled feed grinding machines are (1) to remove material from a work piece to a predetermined desired size (2) in a substantially predictable time (3) while maintaining the surface integrity of the work piece and (4) developing the desired surface finish. Surface integrity and surface finish are referred to hereinafter as work piece quality.

Generally with present-day general purpose grinding machines, the work piece size attained after a given period of grinding time is variable and relatively unpredictable. This is primarily due to the unpredictability and instability of grinding element wear which causes variation in the amount of material removed.

With present-day grinding machines, the initial satisfactory surface quality of the work piece generally cannot be maintained after repetitive grinding operations. In time, symptoms of poor surface quality develops, such as chatter marks, grinding burn and grinding cracks.

Prior to an initial grinding operation, the abrasive cutting grains of a grinding element are in a sharp condition. With continued grinding, the grinding element becomes dull. Therefore, external sharpening of the grinding element called dressing is usually required from time to time to prevent poor surface quality.

The proper selection of the correct grinding element for a specific grinding job is a highly skilled art and is generally achieved by a trial and error process. The most important variable of the grinding element specification is hardness, which indicates the relative wear resistance of the grinding element. Grinding elements are manufactured in a range of grades, with soft to hard grades designated by the letters A through Z respectively.

The general practice is to make adjustments of the grinding performance of the grinding system by varying the volume rate of interference of the work piece with the grinding element, and thereby alter the performance of the particular grade of hardness of the grinding element. In this manner, a particular grinding element grade may actually perform in the system as a softer or harder grade grinding element. However, although this method affords some control over grinding performance it is unable to provide a constant work piece size in a given predictable time, nor is it able to provide freedom from poor work piece surface quality.

To provide a more predictable and constant grinding rate, grinding systems have been devised with open and closed loop feedback compensating circuits. These prior feedback compensating circuits were capable of providing some control over work piece quality and size but afforded very little control over the predictability of work piece size and grinding time. Furthermore, many of these type systems required excessive diamond sharpening of the grinding element.

Some of the prior feedback systems, by selectively using soft grinding element grades, achieved a fairly stable work piece quality due to the continual wearing away of the dull surface of the grinding element. However, an undesirable feature of these systems was the greater expense incurred for frequent replacement of grinding elements. Also, they did not achieve a predictable and constant after grinding part size within normal finish grinding tolerance. In other systems, multistation grinding means were used. The last station generally removed very little material and functioned primarily to provide the desired final work size and surface finish. The initial high cost of such multistation systems limited their use to high volume production, and also abrasive cost was unusually high, due to necessity of using soft grinding element grades.

Grinding machines have also been used comprising means such as a diamond dresser which automatically sharpens the grinding element after each grinding operation. The desired work piece quality and work piece size were maintained relatively constant due to the grinding element being in a constant sharpened state, and the element wear for each operation being less than finish part size tolerance. However, the greater expense incurred for frequent grinding element replacements and the substantial cost for replacement of diamond dressers contributed appreciably to the cost of production when these machines were used.

In virtually all the present day controlled feed grinding systems, the point of system operation is determined by some combination of volume rate of interference and grinding element wear resistance. Whenever the work piece configuration and/or work piece material is changed, a new combination of volume rate of interference and grinding element grade must be used. This means non-productive interrupting. In addition, a large variety of different grade grinding elements must be stocked by the user, who must have the skill to know the proper grinding element to use. The subject invention overcomes this by providing means which enables the same grinding element to be utilized for wide variation in the strength or configuration of the material to be ground.

SUMMARY OF THE INVENTION

The grinding system of the subject invention comprises means for controlling the work piece size and grinding time, means for adjusting effective grinding grade action of the grinding element, and a means for maintaining the desired work piece quality.

The grinding system of the invention includes compensator means responsive to variations in final work piece size from an original reference work piece size. When the compensator means responds to a sensing signal corresponding to a variation in final work piece size, the relative position of the grinding element is automatically adjusted to maintain final work piece size substantially constant. Within the limits of variation in work piece size before grinding, the compensator means also serves to maintain the material removed from the work piece substantially constant.

The grinding system of the subject invention further includes means to control grinding time by varying the speed of movement of the work piece or grinding element through the grinding zone. By providing means to control the amount of material removed from the work piece and means to control grinding time, control of material removal rate is thereby achieved. Thus, with material removal per unit time held constant, any changes in grinding element motor torque or power are caused by changes occurring in the specific grinding energy, the grinding fluid, the physical properties of the work piece material, the volume rate of interference, and other such grinding system variables.

The grinding system of the subject invention also includes means for automatically adjusting the effective grinding grade action of the grinding element by varying the surface velocity of the grinding element to achieve a desired specific grinding energy level. Thus, if the horsepower or torque required varies from a predetermined normal level, the surface velocity of the grinding element varies in response thereto to bring the grinding performance back to the original level. Therefore, an initial setting of the operating point with respect to a horsepower or work level per unit time is maintained without sacrificing work piece surface quality.

Moreover, the grinding system of the subject invention includes compensator means responsive to variations in specific grinding energy from an initial preset level. When the compensator responds to a sensing signal representing a variation of grinding element torque or power from a normal or preset magnitude, the speed of the grinding element is varied in response thereto, to bring the system back to the original level. This maintains the specific energy and work piece quality substantially constant.

Accordingly, a primary object of the invention is to provide an automatically controlled grinding system that maintains the final size or level of material removal with respect to a reference substantially constant.

Another object is to provide an automatically controlled grinding system which maintains the rate of producing finished parts substantially constant.

Another object is to provide a grinding system substantially independent of variations in the abrasive surface of the grinding element within a particular range of abrasive grade variations.

Another object is to provide a controlled feed type grinding system that automatically maintains operation at substantially a particular specific energy point regardless of variation in the surface of the grinding element, variations in the properties of the work piece material, variations in the amount of material to be removed from the work piece, and variations in the volume rate of interference.

Another object is to provide a grinding system which varies the surface velocity of the grinding element in response to variations in specific grinding energy.

Another object is to reduce the problem of multiple and complex grinding element selection and stocking problems by providing a grinding system that may be adjusted to obtain a plurality of grinding grade actions from one particular grinding element grade.

Another object is to provide a grinding system that can be set to operate automatically at a minimum specific grinding energy so as to maximize removal rate and productivity from a given power machine.

These and other objects and advantages of the invention will become apparent from the illustrations in the accompanying drawings and the following specification and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring to the drawings in which the same characters of reference are employed to indicate corresponding or similar parts throughout the several figures of the drawings.

FIG. 1 is a basic block diagram of the grinding system embodying the principles of the invention;

FIG. 2 is a detailed schematic block diagram of the control means of the grinding system in FIG. 1;

FIG. 3 illustrates another preferred embodiment of the invention which utilizes a particular motor load-speed characteristic for controlling the operating point of the system;

FIGS. 4 through 8 illustrate typical data of a conventional surface grinder system;

FIG. 4 illustrates the relationship of metal removal rate and downfeed for various grinding wheel hardness grades;

FIG. 5 illustrates the power used to obtain the metal removal rate in FIG. 4;

FIG. 6 illustrates the relationship of specific energy and downfeed for the same wheel hardness grades as FIG. 4;

FIG. 7 illustrates horsepower versus surface velocity for an M-grade grinding element;

FIG. 8 illustrates horsepower versus surface velocity curves respectively for a motor means and a grinding element driven by said motor means, (of FIG. 3 system);

FIG. 9 illustrates another preferred embodiment of the invention embodying the principles of the invention, which includes means for maintaining the specific energy of the grinding operation substantially constant; and

FIG. 10 illustrates a more detailed block diagram of the invention in FIG. 9.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to FIGS. 1 and 2 of the drawing, the reference numeral 10 indicates generally a controlled feed grinding system embodying the principles of the invention. As shown in FIG. 1, the grinding system 10 includes a grinding means indicated generally by the reference numeral 12 comprising a grinding element or wheel 14 driven by a motor means 16. A control means indicated generally by the reference numeral 18 automatically controls the operation of system 10. Control means 18 comprises an input feed control 18A and a grinding element compensator 18B which will be more fully described below.

A work piece 20 is supported on a carrier 22. The carrier 22 feeds the work piece to the grinding wheel. In the illustrative embodiment it is contemplated that the relative interference of the grinding element 14 and work piece 20 is controlled primarily by varying or changing downfeed, infeed or transverse feed of the grinding element 14, and/or longitudinal transverse feed of the carrier 22.

Turning now particularly to FIG. 2, the control means 18 will be described. The input feed control 18A controls the position of the grinding element 14 and the grinding element compensator 18B varies the speed of rotation of the grinding element in response to variations in the specific grinding energy. Specific grinding energy defines the grinding action of the grinding element, the grinding fluid, the physical properties of the work piece material and the volume rate of interference between the grinding element and the work piece and other such grinding system variables.

The input feed control 18A comprises an after grinding level sensing means 26 having an outer pressure sensitive pick-up needle 27 to contact work piece 20 and sense the size or level of the work piece after a grinding operation, with respect to the top of the carrier or other fixed reference level. The level sensing means 26 converts variations in level of the work piece into electrical signals to provide a sensing signal at output 28. The needle 27 is stationary as the work piece is fed to the grinding element 14.

Sensing means 26 may comprise a suitable transformer means such as a transducer means for converting level variations occurring at the surface contacting pick-up needle 27 into electrical signals at output 28. Alternatively, instead of the pick-up needle, an air or fluid gauge, or inductive pick-up, may be used to provide sensing signals corresponding to level variations.

A comparator means 30 receives the sensing signal from the after-grinding level sensing means 26 at input 31 and compares it with a preset reference signal impressed at input 32 from a reference signal generator 33. A variation or difference between the relative magnitudes of the sensing signal and reference signal is translated into an error signal at output 34 of comparator means 30.

A feed control means 35 receives the error signal at input 36 from output 34 of comparator means 30 and converts it into a drive signal at output 37. A positioning means 38 receives the drive signal at input 39 and in response provides a mechanical force for varying the interference position of the grinding element 14 from a normal preset interference position. Thus, if the size or level of a ground work piece is too high after grinding, the error signal at output 34 causes the grinding element 14 to move to a lower position. If the level of the finished work is too low, the error signal at output 34 causes the grinding element to move to a higher position.

The grinding element compensator 18B comprises a pre-grinding level sensing means 40 having an outer pick-up needle 41 to contact work piece 20 and sense the level or size of the work piece before removal of material. Level sensing means 40 converts variations in level into electrical signals to provide a sensing signal at output 42. Sensing means 40 may, similar to sensing means 26, comprise a transducer means for converting level variations into electrical signals.

A comparator means 43 receives the sensing signal at input 44 from output 42 of level sensing means 40 and a reference signal at input 45 from reference signal generator 46. The signal from reference signal means 46 is preset to a predetermined level. A variation or difference between the relative magnitudes of the sensing signal and reference signal is translated into an error signal at output 47 of comparator means 43.

A comparator means 48 receives the error signal at input 49 from output 47 of comparator means 43 and a load sensing signal at input 50 from output 51 of a power sensing means 52. The power sensing means 52 may comprise a transducer means for converting variations in motor torque to electrical signals at output 51. Alternatively, power sensing means 52 may monitor input electrical power of the motor means 16.

The comparator means 48 provides a drive signal at output 54 when the torque of the motor means 16 increases from a normal point and the size or level of the work piece just prior to grinding does not exceed a predetermined normal level, and the input feed control 18A is functioning to maintain the level of the surface of the work piece after grinding substantially constant (which in effect maintains the grinding surface of the grinding element at the same relative preset position). Under these conditions, variation in torque is due essentially to changes in frictional losses caused by variations in the grinding surface of the grinding element or variations in the material of the work piece. On the other hand, if torque increased and the specific grinding energy (frictional losses mentioned above) has not increased, the increased torque would be due primarily to an oversize of the work piece and a motor drive signal would not be generated at output 54. This would be due to the sensing signal at input 50 indicating increased torque cancelling the effect of the error signal at input 49; and any change in torque or power not attributed to frictional losses caused from variations in the grinding surface and work piece surface or variation in the position of the grinding element, is caused essentially from oversize of the work piece before grinding.

Thus, the error signal at input 49 due to an oversize work piece cancels the sensing signal appearing at input 50 for increased torque.

The output 54 of comparator 48 is connected to an input 56 of speed control means 60. The drive signal at input 56 is converted into a speed control signal at output 64. The speed control signal varies with the magnitude of the drive signal at output 54. Thus, for example, if the normal specific grinding energy increases due to variations in the grinding action, a drive signal is developed causing the speed control means 60 to generate a speed control signal for decreasing the speed of the grinding element, and if the normal specific grinding energy decreases the speed control means causes the speed of the grinding element to increase. This automatic adjustment maintains specific energy substantially constant irrespective of normal variations in the grinding element, grinding material and other grinding operation variables.

Referring now specifically to FIGS. 3, 7 and 8, another preferred embodiment of the invention will be described. Similar parts to those in FIGS. 1 and 2 are designated by the same numeral and a prime (') suffix. The control system in FIG. 3 is indicated generally by the reference numeral 10'. An input feed control 18A', controls the position of the grinding element 14' and is similar to the input feed control 18A in FIG. 2. Motor 16' is preselected to provide a specific load-speed characteristic curve such as curve W shown in FIG. 8. The load-speed characteristic curve W may be obtained from many types of motors, such as the conventional DC series, AC induction motor Nema Class D, AC wound rotor with resistance, and DC shunt with resistance in the armature. Curve Z in FIGS. 7 and 8 illustrates the relationship of power to surface velocity for a grinding element driven at various speeds. The desired operation for drive system 10' is to automatically cause the surface velocity of the grinding element to decrease when a change in load occurs due to an increased change in grinding grade action as indicated by increase in specific energy; and the surface velocity to increase upon a decreased change in the grinding grade action as indicated by a decrease in specific energy. The change in grinding grade action may be due to a change in the work piece material, the grinding element, etc.

Turning now specifically to FIG. 8, when the load increases, the motor operating point tends to move from an operating point T of the system 10' towards point V, and the surface velocity of the grinding element automatically decreases because of the operating curve W of the motor. Due to the decreased surface velocity, the grinding element decreases its required power in accordance with curve Z and returns the system operation back to operating point T. Similarly, if the load decreases due to a change in grinding grade action and the motor operating point tends to move from a point T toward a point Y, the surface velocity increases in accordance with curve W and system performance returns to point T, due to the action of the grinding element according to curve Z.

Depending upon the disturbance causing the change in grinding grade, the system may or may not return to point T. For instance, if the grinding grade action when the system was previously operating at point T cannot be repeated by a change in the surface velocity of the grinding element, a slightly new operating point would be established. This would be the case when the change in grinding grade action was caused by the grinding element grade varying with wear or the physical characteristic of the work piece had changed. However, if a change in the grinding grade action occurred due to dulling of the grinding element, the system operation would tend to be maintained at point T (FIG. 8). Dulling of the wheel increases removal rate of material which increases the load toward the point V of curve W. Increased load along the curve W decreases the surface velocity of the grinding element and the motor operation returns to point T.

The input feed control 18A' of system 10' (FIG. 3) functions identically to the input feed control 18A in FIG. 2 to provide substantially constant surface level after grinding with respect to a reference, by varying the position or downfeed of the grinding element into the work piece. Hence, by controlling the downfeed, the grinding element wear is compensated for and thereby maintains after grinding level substantially constant. Thus, since the level after grinding is held constant, any change in horsepower is attributed to variation in specific energy caused by a change in the grinding element material, the work piece material, or other frictional variable provided the size or level of the work prior to grinding remains unchanged. Without the grinding element compensator 18B, the operating point of the system may shift if the level of the work piece prior to grinding varies from a normal level which would thereby vary horsepower.

In setting the proper parameters for the operation of the grinding system 10, grinding data charts such as those illustrated in FIGS. 4 through 7 may be utilized. FIG. 4 shows the relationship of metal removal rate and downfeed for grinding grade hardness values L, M and N for the grinding element.

Points E, A and F indicate metal removal rates respectively for grinding grades N, M and L at a downfeed of R. For greater downfeeds, a noticeable increase in the metal removal rate is shown for higher hardness grades.

FIG. 5 shows that a greater horsepower is used for the harder grades of the grinding element at the same level of downfeed. Power levels at points C, B and D, in FIG. 5 provide respectively the material removal rates at points E, A and F for grinding elements N, M and L at an R downfeed.

FIG. 6 indicates the specific energy curves for grinding grades N, M and L. Specific energy is the horsepower minutes per cubic inch of grinding. Point G designates the specific energy for an M-grade grinding element at a downfeed of R. Point H designates the specific energy when the M-grade grinding element acts as an N-grade at a power level of V (FIGS. 5 and 8) and point J designates the specific energy when the M-grade grinding element acts as an L-grade at a power level Y (FIGS. 5 and 8).

The curve Z in FIGS. 7 and 8 shows the horsepower increasing as the surface velocity of the grinding element increases and the horsepower decreasing as the surface velocity decreases.

Thus, if the surface velocity of an M-grade wheel providing a removal rate R′ at point A in FIG. 4 is decreased approximately 1,000 sfpm, the grinding grade action shifts to an L-grade and the removal rate decreases to the level at point F. If, on the other hand, the surface velocity of the M-grade providing the removal rate R′ at point A is increased approximately 1,000 sfpm, the grinding grade action shifts to an N-grade and the removal rate of the material increases to the level at point E (FIG. 4).

Curve Z in FIGS. 7 and 8 illustrates power variation of an M grinding element for corresponding variation in velocity. The power value for an M-grade grinding wheel at 1,000 sfpm higher than a predetermined normal (X1) is substantially equivalent to the power value of an N-grade wheel at said normal velocity and is designated as the power point C in FIGS. 4, 7 and 8. The power value for an M-grade wheel at 1,000 sfpm lower than normal velocity is equivalent to the power value of an L-grade wheel at normal velocity and is designated point D in FIGS. 5, 7 and 8.

Grinding grade action is a result of the material of the work piece, the material of the grinding wheel, and the operation of the grinding system which controls downfeed and the surface velocity of the grinding element. The grinding grade action is most clearly represented by the specific energy. Poor work piece quality is characterized by high values of specific energy, which gradually become higher and higher as grinding proceeds. As may be seen from FIGS. 4, 5 and 6, the condition of harder grinding element grades and lower downfeed, leads to higher specific energy values. Metals exhibiting high specific energy values are difficult to grind and easy to injure. Therefore, by controlling the surface velocity of the grinding element with the grinding element compensator 18B, a desired specific energy point may be maintained and thereby provide a consistently high work piece quality.

For maintaining the work piece size constant, the level of the surface after grinding is sensed by the sensor 27 in FIG. 2, or sensor 27′ in FIG. 3. The deviation from a normal is transmitted through the associated circuitry of the input feed control 18A or 18A′ to activate the positioning means 38 and 38′, and cause the grinding element to move toward the work piece, thereby compensating for the wear of the abrasive material of the grinding element. If the initial size or level of the work piece remains the same prior to grinding, the amount of material removed from the work piece is substantially constant.

Therefore, if the transverse speed of carrier 22 of FIGS. 1 and 2 and carrier 22′ of FIG. 3 through the grinding zone and the level after grinding are maintained relatively constant, the amount of material removed from the work piece per unit time or material removal rate is substantially constant provided there is no appreciable variation in the work piece size or level prior to grinding.

In FIG. 4, point A provides, for purposes of example, a typical desired constant metal removal rate for a grinding element of M-grade. Point B in FIG. 5 is the associated power level point for the A removal rate and point G in FIG. 6 is the associated specific energy point.

If the grinding element grade increases from M to N and the material removal rate increases from point A toward E (FIG. 4), sensor 27 senses the increases in the material removal. The input feed control 18A, responsive to the sensing signal from sensor 27, causes the grinding element 14 to be moved away from the work piece and hence decreasing the downfeed with respect to the work piece. This action causes the material removal rate to decrease back to point A.

In FIG. 6, H designates the specific energy point for an N-grade grinding element to provide an A metal removal rate (FIG. 4). As may be seen, the effective downfeed for the N-grade element at a specific energy of H is less than the effective downfeed rate for the M-grade at G (FIG. 6). This is due to the N-grade wearing less than the M-grade. If on the other hand, the grinding grade decreases from M-grade to L-grade and the material removal rate decreases from point A toward point F in FIG. 4, sensor 27 senses the decrease in material removal. The input feed control 18A, responsive to the sensing signal from sensor 27, causes the grinding element 14 to be moved inward toward the work piece and hence increasing the downfeed; thus compensating for grinding element wear. This action causes the material removal rate to increase back to point A.

Referring to FIGS. 5 and 8, power levels at Y and V of motor curve W of the preselected motor means 16′ are sufficient to enable respectively a harder or softer grade change in the grinding action by causing a plus or minus 1,000 sfpm change to occur in the grinding wheel velocity. Thus, if the grinding action changes from an M- to an N-grade, the increased load of power exhibited at point V decreases the velocity of the grinding element 1,000 sfpm. The increase in power from point T in FIG. 8 to point V of the motor curve W causing a drop in velocity of 1,000 sfpm is less than the decrease in power required by the grinding element at 1,000 sfpm, lower velocity, as the velocity decreases from points B to D along curve Z in FIGS. 7 and 8. If the grinding action changes from an M to an L, the power level exhibited at point Y increases the velocity of the grinding element. The decrease in motor power from point T in FIG. 8 to point Y of motor curve W causing an increase in velocity of 1,000 sfpm is less than the increase in power required by the grinding element at 1,000 sfpm higher velocity, as the velocity increases from points B to C of curve Z in FIGS. 7 and 8. With such a relationship between the motor and grinding element, the operation is stable and capable of returning to point T (FIG. 8) in the event of an increase or decrease in velocity of the grinding element from the desired point T.

From FIG. 6, it can be seen that the grinding energy points H, G and J for power levels V, T and Y (FIG. 8) are substantially the same. Therefore, the compensation of the system to increase and decrease the velocity of the grinding element for corresponding increases and decreases of the grinding grade action has very little, if any, effect upon grinding quality, since there is very little change in the grinding energy.

The work piece size is maintained substantially constant by the input feed control 18A of system 10 and 18A′ of system 10′. Surface integrity and finish, herein defined as work piece quality, is maintained relatively constant by the action of the grinding element compensator 18B which senses variations of grinding energy as reflected by increased motor torque or power.

Alternatively, as pointed out previously, the desired work piece quality may be maintained by the preselection of the motor means 16′ whose load-speed characteristic curve enables it to self-compensate for variations in grinding grade energy. Thus, the preselected motor means 16′ cooperating with the grinding element 14′ maintains the operation of the grinding system at a desired load-speed operating point. However, it should be noted that system 10′ reacts to torque or power variations caused by variations in size of the work piece prior to grinding. Therefore, system 10 (having the grinding element compensator 18B which reacts only to variations in specific energy of the grinding operation and not to load changes due to variation in work piece size prior to grinding) more precisely controls work piece quality than system 10'.

Referring now specifically to FIGS. 9 and 10, another preferred system of the subject invention indicated generally by reference numeral 66 will be described. Similar parts to those in the other figures are designated by the same numeral and a double prime suffix (''). The system 66 in FIGS. 9 and 10 provides control of grinding grade action and work piece quality. System 66 is particularly suitable when a high degree of preciseness of size control is not necessary and manual adjustment of the downfeed of the grinding element is acceptable for compensating for wheel wear.

System 66 comprises a specific energy detector means 65 which detects variation of the specific energy, from a predetermined normal specific energy to produce an error signal. The error signal is fed to the grinding element compensator 18C which varies the surface velocity of the grinding element 14'' in response to said error signal; thereby maintaining the specific energy rate and work piece quality substantially constant.

Turning now to FIG. 10, System 66 will be described with greater detail. A pick-up needle 27'' sensing the level or size of the work piece after grinding is connected to an after grinding level sensing means 26'' and the pick-up needle 41'' sensing the size or level of the work piece prior to grinding is connected to a pre-grinding level sensing means 40. Sensing means 26'' and 40'' are transducer means which convert size or level variations into electrical signals. The outputs from sensing means 26'' and 40'' are connected respectively to inputs 70 and 73 of a subtractor means 72.

The difference between the signals at inputs 70 and 73 generates a difference signal at the output 74 of subtractor 72 which in turn is impressed at input 75 of a multiplier 76. The difference signal is multiplied by a preset signal proportional to the work piece area. The signal appearing at the output 77 is substantially proportional to the volume of the material ground off the work piece 20''. Output 77 is connected to the input 78 of a divider means indicated generally by the reference numeral 83. An output 86 from an energy sensing means 85 is connected to a second input 69 to the divider means 83.

The energy sensing means 85 monitors electrical energy used by the motor and converts it to an electrical drive signal at the output 86. The divider means 83 includes means for diving the energy signal from input 69 by the volume signal at input 78 to provide a signal proportional to specific energy or horsepower minutes per unit volume of material removed at its output 84. The output 84 as shown, is connected to an input 67 of comparator means 48'' through a point 87.

A preset signal generated from the reference signal generator 46'' is connected to input 50''. If a variation exits between the signals at input 50'' and 67, a drive signal appears at output 54'' which is connected to speed control means 60''. The output 64'' of the speed control means 60'' is connected through point 87A to the motor means 16''. An increase in specific energy indicated by the signal at output 54'' causes a decrease in speed of the grinding element, and a decrease in specific energy causes an increase in speed of the grinding element. By this action, the specific en ergy is maintained substantially constant, and thereby providing control of the quality of the surface being ground. The level of the ground surface of the work piece, however, may not remain constant in system 66, as is the case with systems 10 and 10' which include the input feed control 18A and 18A'.

As shown in FIG. 10, output 84 for the divider means 83 is connected to point 87 (FIG. 10). Alternatively, output 84 may be disconnected from point 87 and the compensator 18C, and connected instead to an input point 88 for a monitor means 90 which monitors specific energy. In such an arrangement, the motor means 16'' must be disconnected from point 87A and connected instead to point 88A of a manual control means 92. Control means 92 enables the operator to vary motor speed in accordance with the information provided by the monitor means 90, which in turn varies the surface velocity of the grinding element.

The description of the preferred embodiments of this invention are intended merely as illustrative of this invention, the scope and limits of which are set forth in the following claims.

I claim:

1. In a grinding system having a movable grinding element, a power means driving said grinding element for removing material from the work piece and a grinding element compensator, said grinding element compensator comprising:

a load sensing means generating detector signals in response to variations in load on the grinding element from a predetermined reference load;

comparator means associated with the load sensing means to provide a drive signal in response to said detector signal, said comparator means including means for cancelling any part of said detector signal caused by a variation of the pre-grinding level of the work piece with respect to a reference level; and

speed control means associated with said comparator means and said power means, said drive signal causing said speed control means to decrease the surface velocity of the grinding element when said load increases and to increase the surface velocity of the grinding element when said load decreases.

2. In a grinding system having a movable grinding element, a power means driving said grinding element for removing material from the work piece and a grinding element compensator, said compensator comprising:

a load sensing means generating a detector signal in response to variations in load on the grinding element from a predetermined load;

a pre-grinding level sensing means associated with the work piece to provide a sensing signal indicating variations in the level of the work piece prior to grinding with respect to a fixed reference level;

means for receiving said detector signal and said sensing signal to provide a drive signal when the magnitude of said detector signal is greater than the sensing signal; and

speed control means associated with said last-mentioned means and said power means, said drive signal causing said speed control means to decrease the surface velocity of the grinding element when said load increases and to increase the surface velocity of the grinding element when said load decreases.

3. The grinding system of claim 2, wherein said means for receiving said detector and said sensing signals comprises:

a comparator means having a first input for receiving said detector signal and a second input for receiving said sensing signal, said comparator means providing said drive signal when the magnitude of said detector signal is greater than the sensing signal.

4. The grinding system of claim 1, including an input feed control means comprising:

an after grinding level sensor means associated with the work piece to provide a sensing signal indicating variations in surface level from a predetermined normal level;

a positioning means associated with the grinding element for varying the position of the element with respect to the work piece; and

a second comparator means associated with the positioning means and said after grinding sensor means, the second comparator means providing a drive signal in response to said sensing signal indicating variations in said surface level after grinding, to cause the positioning means to vary the position of the grinding element and thereby maintain the level of the work piece after grinding substantially constant.

5. In a grinding system having a movable grinding element, a power means driving said grinding element for removing material from the work piece and a grinding element compensator, said compensator comprising:

a load sensing means generating a detector signal in response to variations in load on the grinding element from a predetermined load;

a pre-grinding level sensing means associated with the work piece to provide a sensing signal indicating variations in the level of the work piece prior to grinding with respect to a fixed reference level;

means for receiving said detector signal and said sensing signal to provide a drive signal when the magnitude of said detector signal is greater than the sensing signal;

speed control means associated with said last-mentioned means and said power means, said drive signal causing the speed control means to decrease the surface velocity of the grinding element when said load increases and to increase the surface velocity of the grinding element when said load decreases;

an after grinding level sensor means associated with the work piece to provide a sensing signal indicating variations in surface level from a predetermined level;

a positioning means associated with the grinding element for varying the position of the element with respect to the work piece; and

means associated with the positioning means and said after grinding sensor means, said last-mentioned means providing a drive signal in response to said sensing signal indicating variations in said surface level after grinding, to cause the positioning means to vary the position of the grinding element and thereby maintain the level of the work piece after grinding substantially constant.

6. The grinding system of claim **5** wherein:

said pre-grinding level sensing means comprises a pressure sensitive needle to contact the work piece and sense the level of the work piece prior to grinding, and transducer means associated with said needle to convert level variations at said needle into electrical sensing signals;

a first comparator means associated with the transducer means for receiving said electrical sensing signals for comparison with a reference electrical signal, a variation between magnitudes of the sensing signal and reference signal provides an error signal at the output of the first comparator means;

a second comparator means associated with the first comparator means, said second comparator means including a first input for receiving said error signal and a second input for receiving said detector signals indicating variations in load on the grinding element, a variation between magnitudes of the sensing signal and reference signal providing said drive signal for driving said speed control means.

7. The grinding system of claim **6** wherein:

said after grinding level sensing means comprises a pressure sensitive needle to contact the work piece and sense the level of the work piece after grinding, and transducer means associated with said needle to convert level variations at said needle into electrical sensing signals; and

said means associated with said positioning means comprises a third comparator means associated with the transducer means for receiving said electrical sensing signals for comparison with a reference electrical signal, a variation between magnitudes of the last-mentioned sensing signal and reference signal providing an error signal at the output of the third comparator means for driving said positioning means.

8. In a grinding system having a movable grinding element, a power means driving said grinding element for removing material from the work piece and an input feed control means, said input feed control means comprising:

an after grinding sensor means associated with the work piece to provide a sensing signal indicating variations in the level of the work piece after grinding from a predetermined level;

a positioning means for controlling the interference between the element and the work piece;

a comparator means associated with the positioning means and said after grinding sensing means, said comparator means providing a drive signal in response to said sensing signal to cause the positioning means to increase the interference between the grinding element and the work piece when the level after grinding exceeds said predetermined level and to decrease said interference when the level after grinding is below said predetermined level; and

a compensating-drive means associated with the grinding element for varying the speed of the grinding element responsive to load variations acting on the grinding element other than load changes due to variations of the pre-grinding level of the work piece with respect to a reference, whereby an increase of said load from a predetermined reference load causes a decrease in the surface velocity of the grinding element and a decrease in load variation from said reference load causes an increase in the surface velocity of the grinding element, the cooperation of the compensating-drive means, the positioning means driven by the compensator means and the grinding element causing the metal removal rate to be substantially constant.

9. The grinding system of claim **8**, wherein:

said compensating-drive means is a motor means which increases in speed for a decrease in load and decreases in speed for an increase in load.

10. The grinding system of claim **9**, wherein the load-speed characteristic curve of said motor means is substantially inversely proportional to the load-surface velocity characteristic curve of the grinding element, whereby the load on the grinding element increases with an increase in the surface velocity of the element and the load decreases with a decrease in the surface velocity of the element and said motor means increases in speed with a decrease in load and decreases in speed with an increase in load.

11. In a grinding system having a movable grinding element, a power means driving said grinding element for removing material from the work piece, a control means for controlling said grinding element, said control means comprising:

an input feed control means for maintaining the level of the work piece after grinding substantially constant;

a pre-grinding level sensing means associated with the work piece to provide a sensing signal indicating variations in the level of the work piece prior to grinding with respect to a fixed reference level;

a load sensing means generating a detector signal in response to variations in load on the grinding element from a predetermined load;

means for receiving said detector signal and said sensing signal to provide a drive signal when the magnitude of the detector signal is greater than the sensing signal; and

speed control means associated with said last-mentioned means and said power means, said drive signal causing said speed control means to decrease the surface velocity of the grinding element when said load increases and to increase the surface velocity of the grinding element when said load decreases.

12. In a grinding system having a movable grinding element, a motor means driving said grinding element for removing material from the work piece and means for maintaining the specific energy substantially constant, said last-mentioned means comprising:

a volume sensor means for sensing material removal and providing a volume sensing signal;

an energy sensor means for sensing energy used for said material removal and providing an energy sensing signal;

a converter means associated with said volume sensor means and said energy sensor means, said converter means including input means for receiving said volume sensing signal and said energy sensing signal, whereby said converter means converts said signals into a specific energy signal; and speed control means to enable the velocity of the grinding element to be varied in accordance with the magnitude of the specific energy signal, for maintaining the specific energy at substantially a predetermined level.

13. The grinding system of claim 12 wherein said volume sensor means comprises:

a pre-grinding sensor means for sensing the level of the work piece prior to grinding and providing a first signal;

an after grinding sensor means for sensing the level of the work piece after grinding and providing a second signal;

a subtractor means associated with the pre-grinding sensor means and the after grinding sensor means to provide a difference signal of first and second signal; and

a multiplier means associated with the subtractor means for multiplying said difference signal by a preset signal corresponding to a predetermined area of said work piece to provide said volume signal.

14. The grinding system of claim 12 wherein:

a comparator means is associated with the speed control means and said converter means;

a reference signal means is associated with the comparator means and providing a preset signal, said comparator means including input means to receive the signal from the reference signal means and the specific energy signal whereby said comparator means provides an error signal when the specific energy signal varies from the magnitude of the preset signal, said speed control means receiving said error signal to cause the velocity of the grinding element to increase when the specific energy decreases and the velocity of the grinding element to decrease when the specific energy increases.

15. The grinding system of claim 12 wherein said converter means is connected to a monitor means, said monitor means providing indication of the magnitude of the specific energy signal, said speed control means including manual adjust means for varying the speed of the motor means to control the magnitude of said specific energy signal.

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