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CYBERNETIC GRINDING

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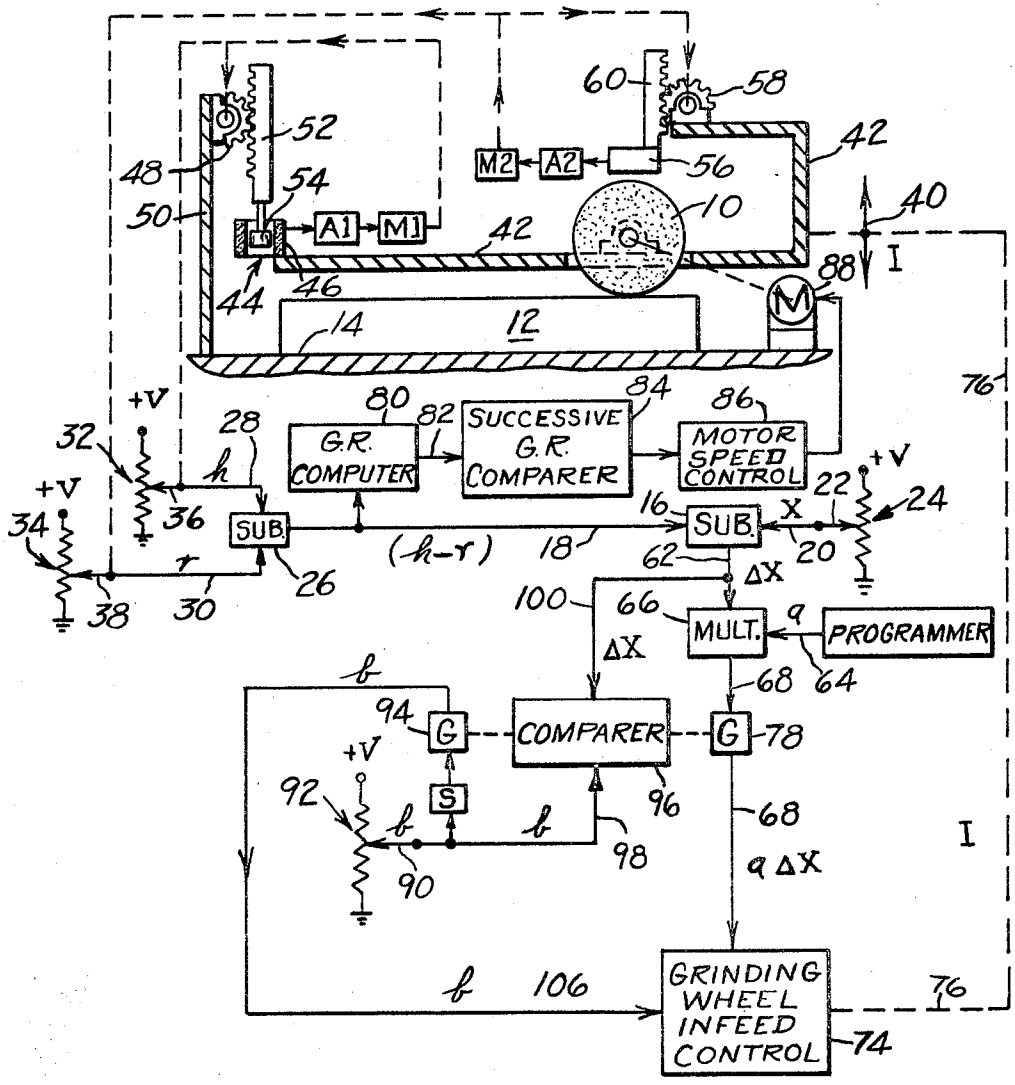
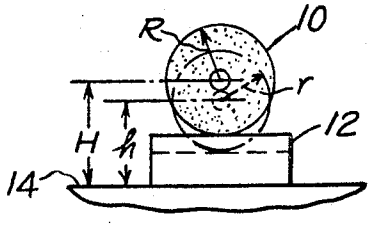


Fig. 2

Fig. 1



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CYBERNETIC GRINDING

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This application is a continuation-in-part of our applications entitled "Grinding Machine," Serial No. 253,966, filed January 25, 1963, now Patent No. 3,167,891, issued February 2, 1965 (which, in turn, is a continuation of Serial No. 163,983, filed January 3, 1962), now abandoned.

This invention relates to grinding, and more particularly, to automatic control of grinding operations.

In Patent No. 3,167,891, there is described a number of ways of dressing a grinding wheel in response to the sensing of any of various conditions indicaing that the wheel needs to be dressed. For example, reduction in driving power, wheel speed, or in the grinding ratio, which is defined therein as the ratio of the volume of metal removed from the workpiece to the volume of material worn off the grinding wheel during a grinding operation, may be sensed to cause a substantial change in the speed of the grinding wheel to effect dressing thereof. In that Patent No. 3,167,891 means is provided for sensing any such reduction, and such means may be employed in the equipment of the present application to provide a signal indicative of a characteristic of the grinding operation.

It is a principal object of this invention to effect automatic programming of the infeed control to regulate the infeed of the grinding wheel into the workpiece in order to remove the maximum amount of metal from the workpiece in the fastest time to produce the desired reduction in size of the workpiece with the least damage and base finish possible in accordance with the commercial aspects of the product being worked upon.

The illustrated example of this invention provides a specific embodiment in which the grinding ratio is determined and maximized in accordance with the co-pending applications, Serial Nos. 303,305, now Patent No. 3,178,861, issued April 20, 1965, and 303,306, filed in United States Patent Office by the respective joint inventors of this application. Additionally, the instant workpiece dimension which is being changed is continuously electrically compared with the desired finish size of the workpiece and an output signal representing the difference factor taken. The difference factor is then multiplied by a predetermined instant slope factor which gives an output signal corresponding to a volumetric infeed rate which will optimize the infeed pattern until the difference factor is equal to or less than the tolerance factor of the workpiece. In fact, this invention provides for the taking into account of all of the necessary factors to increase the efficiency of the grinding operation by feeding these factors into a computing arrangement for maintaining the ultimate operative activity of the grinder. The invention provides for a rate of infeed that is programmed through a computer to accomplish a theoretical pattern of metal removal consistent of the planned utilization of the grinding wheel, and takes into consideration the particular properties of the metal being ground and all of the other factors controlling the grinding operation to obtain the most appropriate commercial operation.

Further objects of this invention are to provide for apparatus such as that described in the preceding paragraph. Still other objects and advantages of this invention will become apparent upon reading the appended claims and the following detailed description of the invention, in conjunction with a drawing, in which:

FIGURE 1 is a diagrammatic view indicating certain initial and instantaneous dimensions of a grinding wheel and workpiece; and

FIGURE 2 is a diagrammatic and schematic illustration of one embodiment of this invention in connection with the rapid and economical removal of metal by means of grinding with automatic control.

Several ways of making grinding operations more automatic are covered in our copending applications mentioned above. The way which this disclosure sets forth is one which may be designated as "Cybernetic Grinding," in which the automatic control is governed by the amount of grinding left to be done on the particular workpiece.

For example, if the finished size of a certain workpiece is to be X and the size of the piece is at any prior instant $X+\Delta X$, then the volumetric infeed rate I is equal to $a\Delta X$, wherein a is a slope factor discussed above. Under such circumstances the volumetric infeed rate is highest when the amount ΔX of grinding to be done is greatest, and it decreases when ΔX approaches a constant tolerance factor b which is determined from the tolerance of the workpiece. In a plot of the infeed rate I against the amount ΔX of material yet to be removed, the slope factor a may be a straight line intersecting the I and ΔX axes at zero when a is a constant in which case a refers to the slope of the line. This invention includes not only the use of such a constant factor a, but also the use of a variable slope factor a, for example, continuously variable in order to follow any desired curve such as a parabolic, hyperbolic, exponential, or any other configuration. Regardless of variation of constancy in factor a, the invention achieves the advantages of minimizing the extent of surface injury or the depth of metallurgical burn as the workpiece approaches finished size, and at the same time the surface finish improves to the maximum attainable for the given grinding wheel being used.

As previously indicated, these advantages and objects of this invention may be accomplished by sensing various factors of the grinding operation and correlating them to cause the infeed to be such as to effect the maximum amount of metal removal in the shortest time with the desired finish.

Reference is particularly now made to the drawing wherein FIGURE 1 shows a grinding wheel **10** operating on a workpiece **12**. The initial radius of the grinding wheel is designated as R, while its initial center height above surface **14** is designated as H. As the workpiece **12** is ground down, the grinding wheel itself reduces, and its instantaneous radius is designated as r. The instantaneous center height of the grinding wheel is accordingly designated h. It is therefore apparent that the workpiece height $X+\Delta X$ is equal to $h-r$. Recalling that X is the final height desired, and that ΔX is the amount yet to be ground off, it becomes apparent that if X is subtracted from $(h-r)$, then the quantity ΔX is made known. This is exactly what is accomplished by the subtractor **16** in FIGURE 2, which receives on its left input line **18** a signal representing the quantity $(h-r)$, and on its right hand input line **20** signal representing X. The X signal is obtained by appropriately setting arm **22** of potentiometer **24**.

The instantaneous value $(h-r)$ designating the instant height of the workpiece **12** is obtained from subtractor **26** which has an h input signal on line **28** and an r input signal on line **30**. These two signals are, of course, variable during the grinding operation, and are obtained as voltages from the respective potentiometers **32** and **34**, the movable arms **36** and **38** of which are regulated respectively in accordance with the instant value of h and instant value of r as follows.

As indicated by arrow **40**, frame element **42** which carries grinding wheel **10**, is movable up and down, as

by the conventional infeed equipment fully disclosed in the aforementioned Patent No. 3,167,891. In order to sense the instant height *h*, a position transducer **44** is employed. As diagrammatically indicated, its pick-up coil **46** is secured to frame element **42** so as to follow the up and down movements thereof. Any such change in the frame element **42** causes the output signal coil **46** to drive servo motor M1 through an amplifier A1. The servo motor, in turn, drives a pinion gear **48**, which is secured at a predetermined height by the frame element **50**. The rotation of gear **48** moves rack **52** vertically so as to change the position of the transducer armature **54** and cause rebalance of the transducer. The rotation of motor M1 also controls the position of potentiometer arm **36**, thereby providing the voltage on line **28** which is proportional to the instantaneous height *h*.

In like manner, the instantaneous wheel radius *r* is sensed by a transducer **56** whereby decreases in the radius of the wheel are supplied as a signal to the servo motor M2 through an amplifier A2. Transducer **56** in this instance may include a magnetic or capacitance type of pick-up as indicated in the aforementioned applications. To effect rebalance, servo motor M2 rotates pinion gear **58** in a direction to change properly the position of rack **60** to the lower end of which is affixed the transducer **56**. In so doing, motor M2 also drives the potentiometer arm **38** so that between it and ground there is a voltage which is proportional to the instantaneous radius *r* of the grinding wheel.

Returning now to the subtractor **16**, it will be recalled that the difference between the input quantities $(h-r)$ and X provides an output signal ΔX on line **62**. This difference factor ΔX is multiplied by multiplier **66** with a factor *a* which appears on input line **64**. The output signal $a\Delta X$ on line **68** from multiplier **66** is a volumetric infeed rate signal I which is applied to the grinding wheel infeed control **74** to regulate the downfeed of grinding wheel **10**, by controlling the downfeed of frame element **42** as indicated by dash line **76**. This causes the infeed to be at such a rate that the grinding operation is optimized for the conditions desired.

It will now be explained how the factors *a* and *b* are obtained. First, it will be noted that the signal for factor *a* which appears on line **64**, comes from a programmer **70**.

The slope factor *a* is predetermined and will vary depending upon the characteristics of the grinding operation, especially the workpiece to be machined, such as its initial size, strength, type of material it is made of, finish size, and the desired surface finish, etc. Once the slope factor *a* is determined, it is then put into the programmer **70** which sends the proper signal to a multiplier **66** and the result is the proper infeed of the grinding wheel into the workpiece for the most efficient grinding thereof.

A method of providing a slope factor *a* for a particular workpiece could be based on such facts, for example, that the particular workpiece can initially withstand the grinding wheel pressure and heavy stock removal, because of its size, at the beginning of the grinding cycle; however, as the workpiece is reduced in size, it cannot take the same depth of cuts due to its present shape, deformation and other material characteristics, or because of some other well-proven fact. Finally, it is determined from analyzing the workpiece that the most efficient way to reduce the workpiece to the desired size and to provide the desired finish is to make the infeed rate 50% of whatever stock there is left to be removed before the desired size is reached. For example, if .032 is the amount ΔX left to be removed from the workpiece, the first depth of cut would be .016; the second depth of cut .008; the third depth of cut .004; the fourth depth of cut .002; the fifth depth of cut .001; the sixth depth of cut .0005, etc. until the size of the workpiece is within the acceptable tolerance which is the constant factor *b*. The slope factor *a* in the particular example given would be a straight line. If factor *a* is a curve, the depth of cut would not be a constant 50% of what stock there is left to be removed. It could be, for example, 50%, 30%, 20%, 10%, etc. of the stock remaining.

When the amount left to be removed from the workpiece is within the constant tolerance factor *b* of the desired size, the grinding operation may be terminated, leaving the workpiece on the larger (+) side of the desired dimension. Alternatively, the amount of the constant factor *b* may be fed to provide a final cut of the workpiece which would leave the size of the workpiece on the smaller (−) side of the desired dimension.

The constant factor *b* may be determined in various ways. For example, if the desired dimension of the workpiece is one inch and the tolerance plus or minus

$$.001\left(\frac{1.001}{.999}\right)$$

.001 is used as the constant *b*. If the desired dimension is one inch, plus .005 minus

$$.000\left(\frac{1.005}{1.000}\right)$$

X dimension can be 1.0025 and the tolerance .005 divided by two to provide an equal tolerance and a constant factor *b* of .0025 on either side of the dimension X and get the same results.

Likewise, if the desired dimension is one inch, plus .000 minus .005

$$\left(\frac{1.000+.000}{-.005}\right)$$

X can be .9975 and the .005 divided by two to provide equal tolerance and a constant factor *b* of .0025 and obtain the same result. If the desired dimension is one inch plus .003 minus .001

$$\left(\frac{1.003}{.999}\right)$$

X can be averaged out between the high limit 1.003 or the low limit .999 and be 1.001, and the tolerances .003 and .001 added together, divided by two to provide an equal tolerance of plus or minus .002 and a constant factor *b* of .002.

As fully explained in the aforementioned applications, the grinding ratio is the ratio of the volume of the metal removed from the work piece to the volume of material worn off the grinding wheel during a grinding operation. Those applications fully describe the manner in which computer **80**, in response to the $h-r$ subtractor **26**, delivers to output line **82** a signal which reflects the instantaneous grinding ratio. In effect, the grinding ratio is a function of the efficiency of the grinding operation, and the two later ones of those applications indicates that the speed of the grinding wheel may be changed to increase and maximize the grinding ratio and efficiency of the operation. In accordance therewith, FIGURE 2 illustrates a comparing circuit **84** which may be similar to that in Patent No. 3,178,861, for comparing successive values of the grinding ratio. As therein indicated, if the latest grinding ratio is less than the earlier one, then the direction of the speed change of the grinding wheel needs to be reversed, but if it is greater, then the present speed change direction should be continued. Accordingly, this information as determined by comparer **84** is applied to the motor speed control **86**, which, in turn, regulates the speed of the grinding wheel via motor **88**. In this manner, the efficiency of the grinding operation, as far as possible from the regulation of the grinding wheel speed, is maintained at its maximum, automatically.

There is then the further desire, as effected by this invention, to increase the efficiency of the grinding operation by regulating the infeed. This is accomplished, in the illustrated embodiment, by providing a slope factor *a* which is multiplied with ΔX and feeding the $a\Delta X$ signal through a normally open gate **78** controlled by a comparer **96** to the grinding wheel infeed control **74** until

ΔX is equal to or less than the factor b at which time the comparer **96** closes gate **78** and opens gate **94**.

The factor b is obtained, for example, as a voltage determined by the setting of arm **90** on potentiometer **92**. This voltage signal is applied through the gate **94** directly to the grinding wheel infeed control **74** provided the selector switch S is properly conditioned (closed) and the comparer **96** has opened the gate **94**.

Therefore, it is apparent that the grinding wheel infeed control **74** is operated at a rate in accordance with the factor a and ΔX, the amount of material left to be machined off the workpiece. The latter is only until ΔX decreases to or less than the value of factor b, at which time the comparer signal gate **78** is closed preventing further infeed ($I=a\Delta X$) from the multiplier **66** and opens the gate **94** which provides a way of feeding the factor b, if desired, i.e., if switch S is closed.

The equipment for selecting and effecting a cut equal to b includes the aforesaid selector switch S and comparer **96**, which receives the factors ΔX and b respectively on lines **98** and **100**. The gate **94** is normally closed, but when ΔX decreases to or less than the value of b, then the comparer opens the gate **94** allowing signal b to pass through the switch S to the grinding wheel infeed control **74**. Automatically, only one cut is accomplished when gate **94** so opens. This one cut is made the last cut in any desirable manner. For example, the comparer output to gate **94** may be made just a pulse to trigger control **74** once, or that output may be timed in comparer **96** to end at the proper time. Alternatively, control **74** may be constructed to accomplish the desired end by receiving any sort of signal on its input line **106**.

As soon as the last cut is made, the grinding wheel infeed control **74** is cut off by the comparer **96**. To recycle, the programmer is reset, in any suitable manner such as by the removal or insertion of another workpiece in the machine.

The exemplary embodiment of this invention above described is intended to be illustrative of a system which employs a predetermined constant factor a. However, as previously indicated, the factor a may be variable in accordance with any number of desired characteristics which indicate various efficiencies or the like in the grinding operation, such as the final characteristics desired for the final product.

It is therefore apparent that this invention has provided for the objects and advantages herein stated. Other objects and advantages, and even further modification of the invention, will become apparent to those of ordinary skill in the art upon reading this disclosure. However, it is to be understood that this disclosure is illustrative of the invention defined by the scope of the following claims.

What is claimed is:

1. Apparatus for automatically increasing the efficiency of a grinding operation by a grinding wheel on a work piece, comprising:

means for determining the difference factor ΔX between the instant size of said work piece and a desired size thereof, and

means for computing an infeed I equal to a function of ΔX, wherein I is less than ΔX.

2. Apparatus for automatically increasing the efficiency of a grinding operation by a grinding wheel on a work piece, comprising:

means for determining the difference factor ΔX between the instant size of said work piece and a desired size thereof,

means for providing a factor a relating to at least one characteristic of said grinding operation including said workpiece,

means for combining said factors to determine and provide infeed rate signal I equal to $a\Delta X$, and

means responsive to said signal I for controlling the relative infeed of said grinding wheel and work piece.

3. Apparatus as in claim **2** and further including

means for providing a factor b relating to the allowable tolerance of said desired size of said work piece, and

means for providing a given output signal when factor ΔX becomes equal to or less than factor b to terminate grinding of the work piece.

4. Apparatus as in claim **2** and further including

means for continuously determining when the factor ΔX decreases to a value equal to or less than factor b for providing a predetermined output signal, and

means responsive to that signal causing said infeed rate signal I then to be equal to b and the final cut by said grinding wheel of said work piece.

5. Apparatus for automatically increasing the efficiency of a grinding operation by a grinding wheel on a work piece, comprising:

means for determining the difference factor ΔX between the instant size of said work piece and a desired size thereof,

means for providing a predetermined slope factor a,

means for providing a factor b relating to the allowable tolerance of said desired size,

means including a multiplier for multiplying the factor a by ΔX to determine an infeed rate signal I,

means responsive to said signal I for controlling the relative infeed of said grinding wheel and work piece,

means for providing a predetermined output signal when ΔX becomes less than or equal to b,

means responsive to said given signal for causing the said infeed rate signal I then to be equal to b, and

means in said infeed controlling means responsive to said given signal for stopping the grinding action following the final cut determined by the last mentioned infeed rate signal.

6. Apparatus for automatically increasing the efficiency of a grinding operation by a grinding wheel on a work piece, comprising:

means for determining the difference factor ΔX between the instant size of said work piece and a desired size thereof,

means for providing a factor a relating to at least one characteristic of the grinding operation including said work piece,

means for combining said factors to determine an infeed rate signal I equal to $a\Delta X$,

means for providing a factor signal b relating to the allowable tolerance of said desired size, and

means responsive to said signals I and b for controlling the relative infeed of said grinding wheel and work piece.

7. Apparatus as in claim **6** and further including

means for providing a given output signal when ΔX becomes less than b, and

means responsive to said output signal for causing the said infeed rate signal to be terminated.

8. Apparatus as in claim **6** and further including

means for computing the grinding ratio of said grinding operation, and

means responsive to the output of said grinding ratio computing means for controlling the speed of said grinding wheel to maximize the grinding ratio and increase the efficiency of said grinding operation.

9. Apparatus as in claim **8** and further including

means for continuously determining when the factor ΔX decreases to the value of factor b for providing a predetermined output signal, and

means responsive to that signal for causing the final cut to be made by said grinding wheel on said work piece.

10. Apparatus for automatically increasing the efficiency of a grinding operation by a grinding wheel on a work piece, comprising:

means for determining the difference factor ΔX between the instant size of said work piece and a desired size thereof,

means for continuously computing the grinding ratio of said grinding operation,

means responsive to the output of said computing means for controlling the speed of said grinding wheel to cause the grinding ratio to increase and maximize,

means for providing a factor *b* relating to the allowable tolerance of said desired size,

means including a multiplier for multiplying a predetermined slope factor *a* by ΔX to determine an infeed rate signal I,

means responsive to said signal I for controlling the relative infeed of said grinding wheel and work piece,

means for providing a predetermined output signal when ΔX becomes less than *b*, and

means responsive to said output signal for causing the

said infeed rate signal to terminate and cause a final cut to be made on said work piece in accordance with said factor *b*.

References Cited by the Examiner

UNITED STATES PATENTS

1,534,302	4/1925	Conradson et al.	51—165 X
2,946,161	7/1960	Schultze et al.	51—165
3,056,240	10/1962	Morgan et al.	51—165
3,167,891	2/1965	Coes et al.	51—165
3,178,861	4/1965	Milias	51—165

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