

United States Patent

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 Division of Ser. No. 445,298, Feb. 15, 1965,
 Pat. No. 3,431,685
 [45] Patented **Aug. 31, 1971**
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[56] **References Cited**

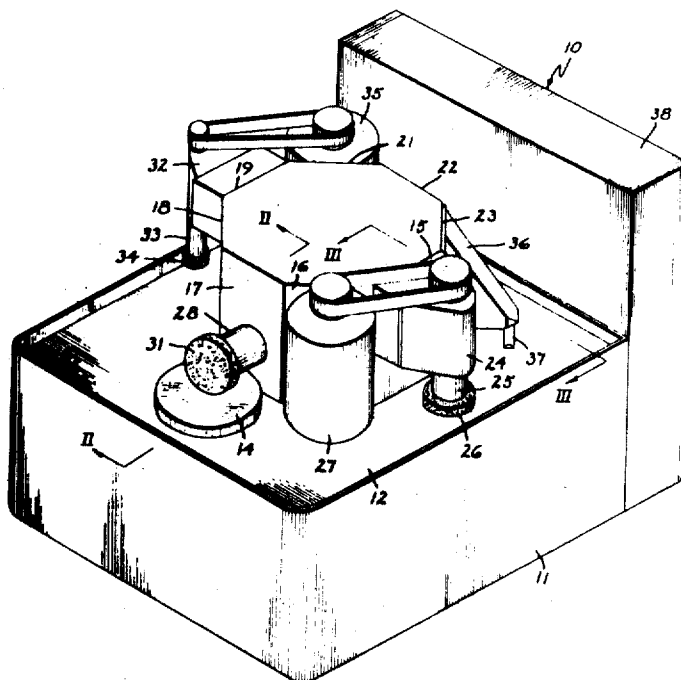
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[54] **GRINDING HIGH-TEMPERATURE ALLOYS**
 2 Claims, 24 Drawing Figs.
 [52] U.S. Cl..... **51/281**
 [51] Int. Cl..... **B24b 1/00**
 [50] Field of Search..... **51/281**

ABSTRACT: This invention relates to the grinding of high-temperature metals and, more particularly, to a method for removing stock from a workpiece by the abrasion process at an unusually rapid rate by operation in a restricted range of force intensities.



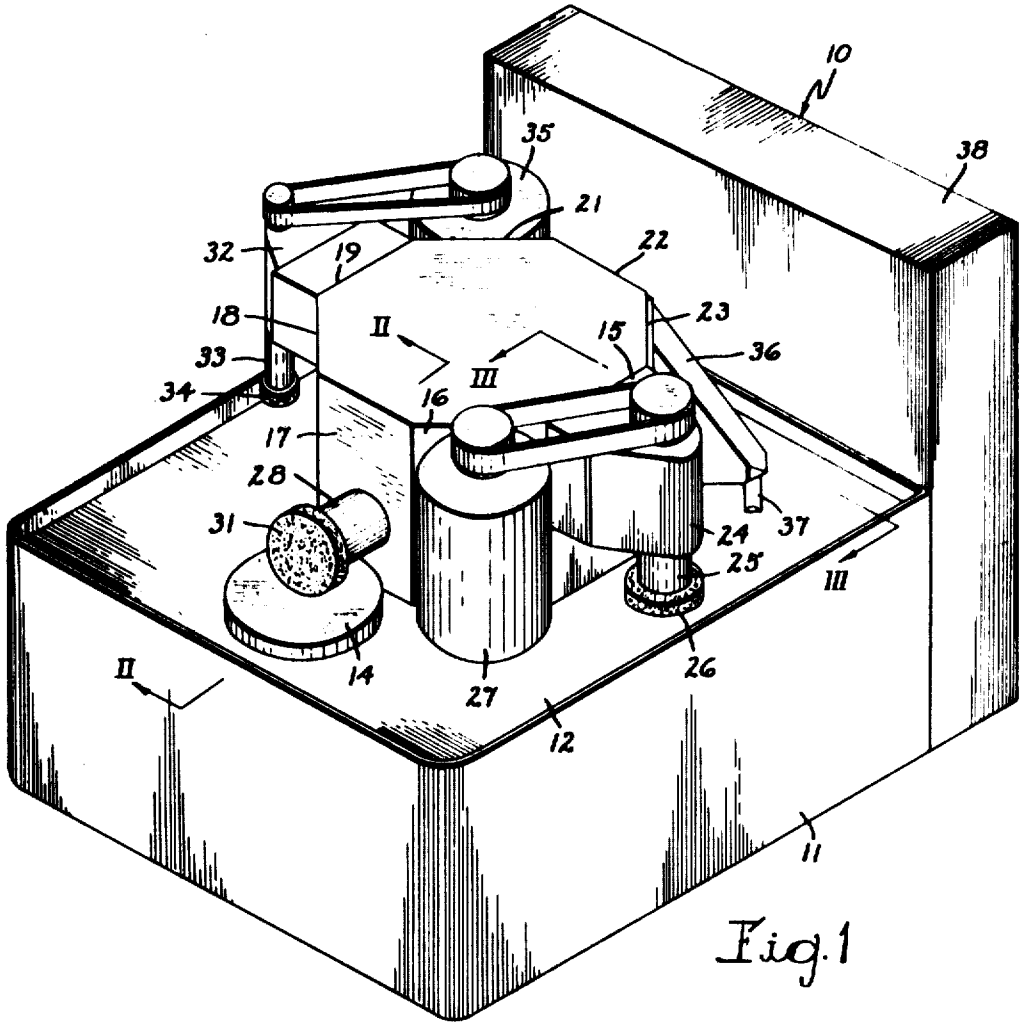


Fig. 1

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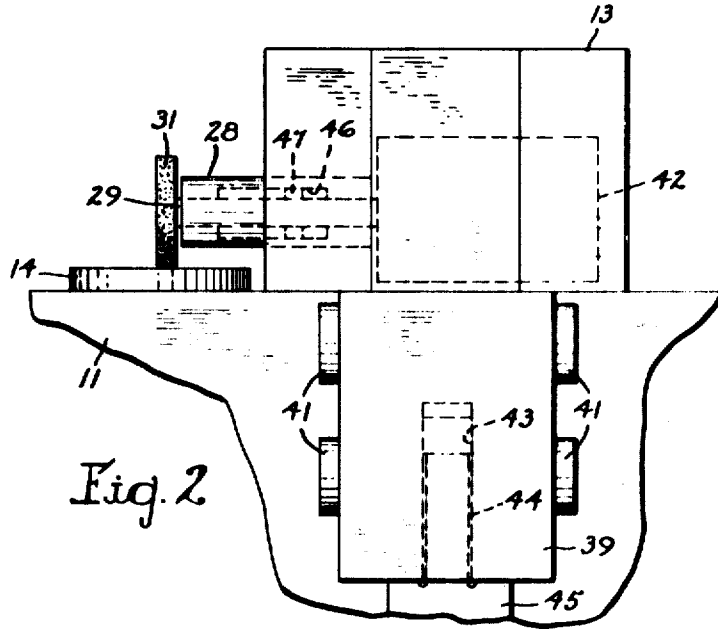


Fig. 2

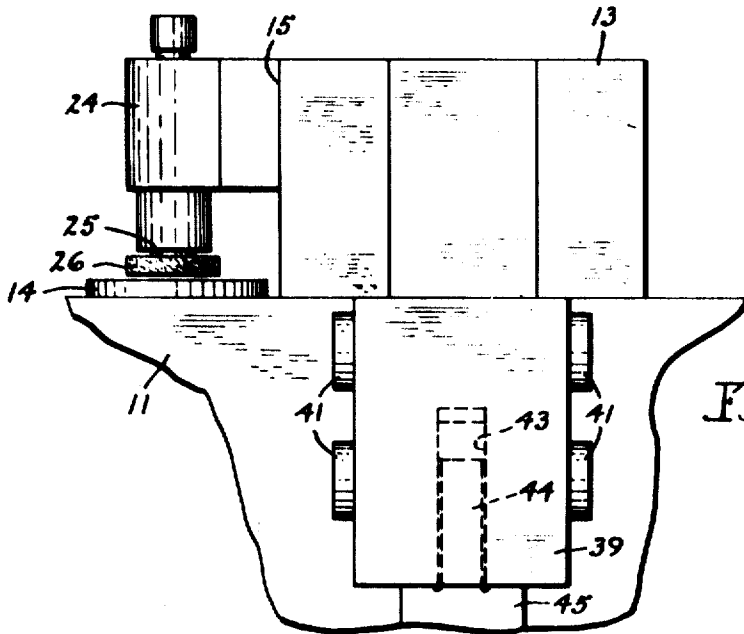
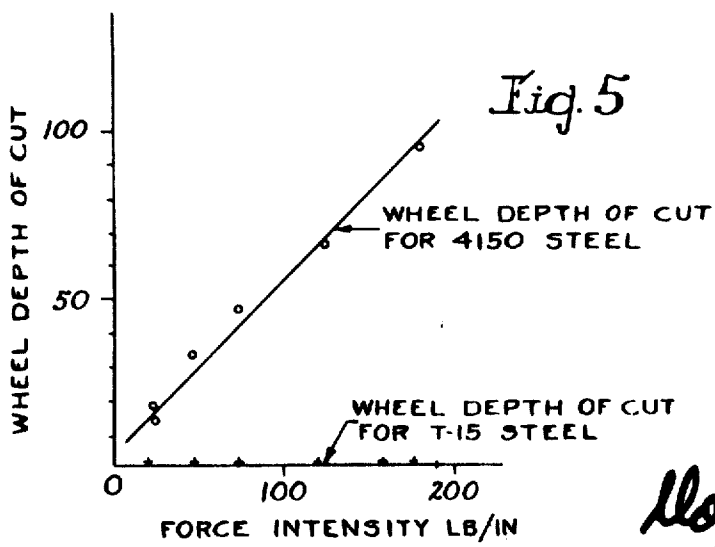
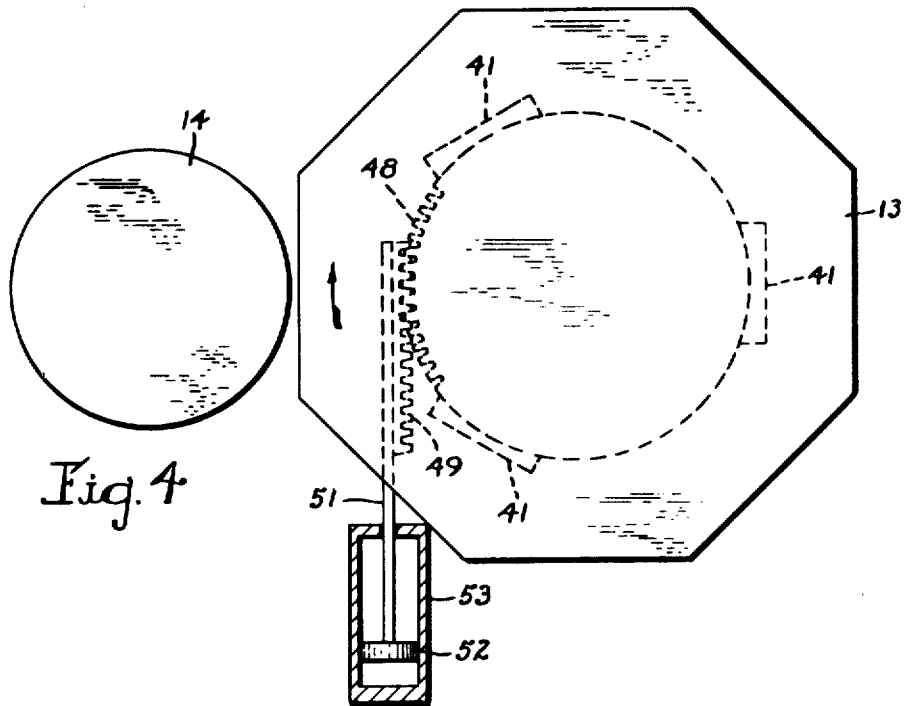


Fig. 3

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Fig. 6

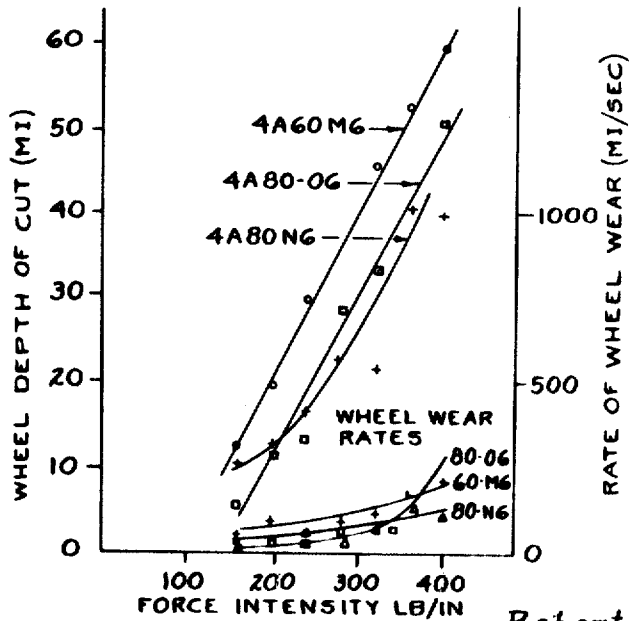
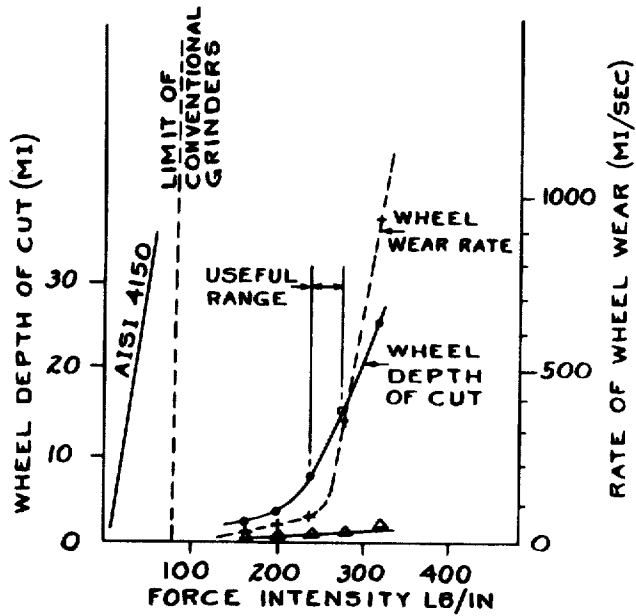


Fig. 7

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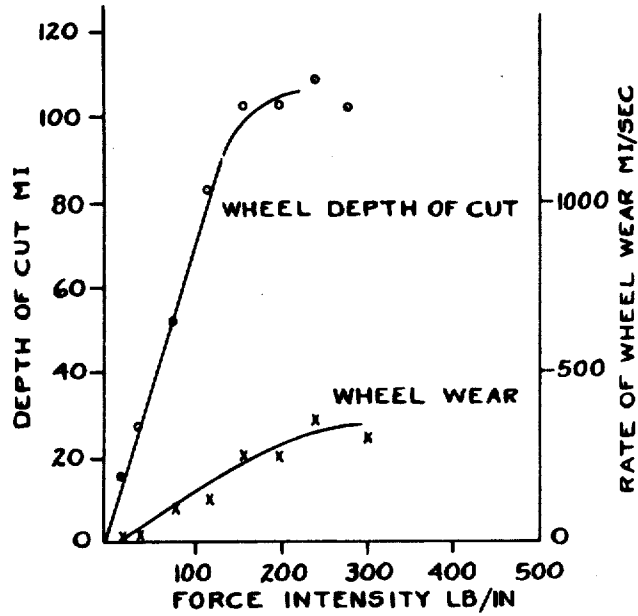


Fig. 8

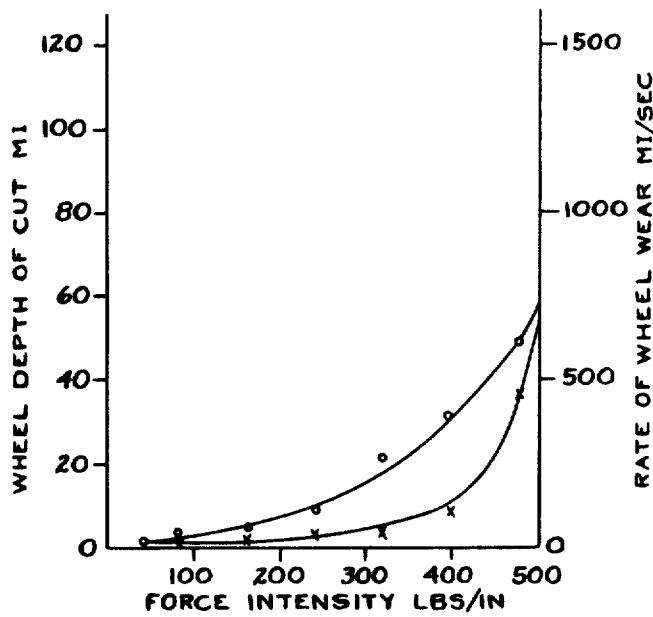


Fig. 9

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Fig. 10

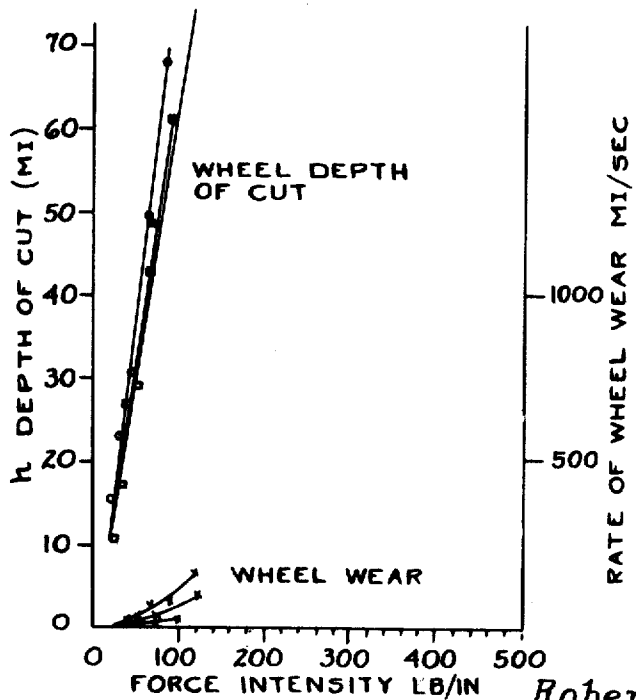
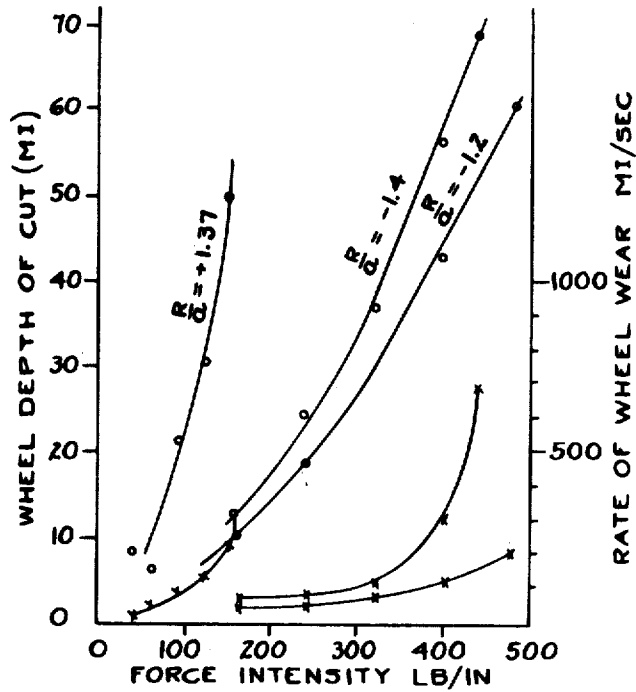


Fig. 11

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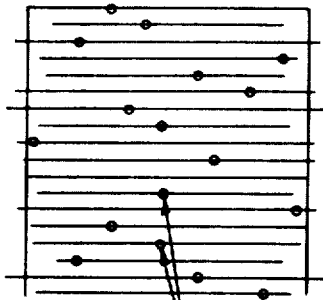


Fig. 12

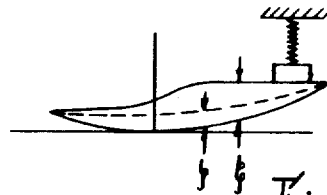


Fig. 13

ACTIVE GRAINS OR
CUTTING POINTS

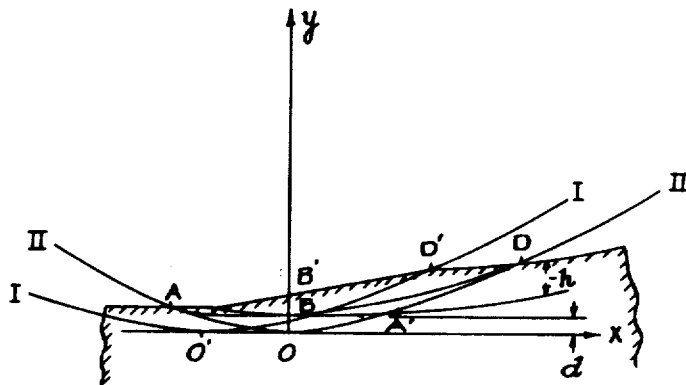
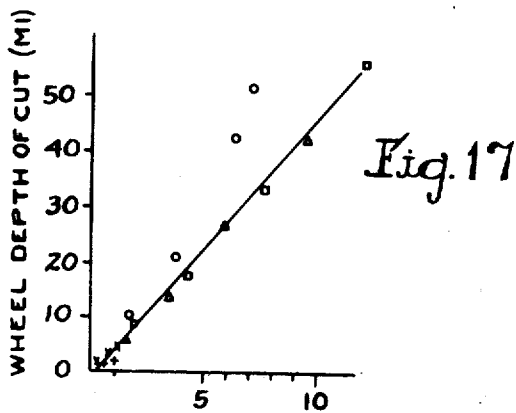
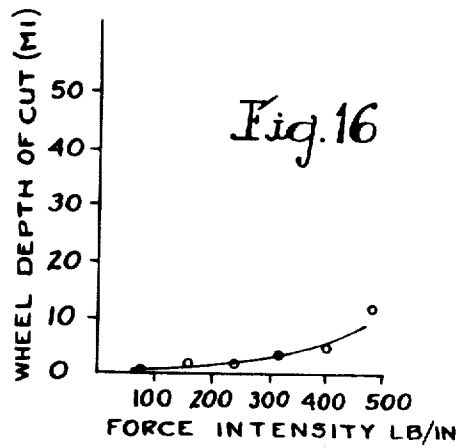
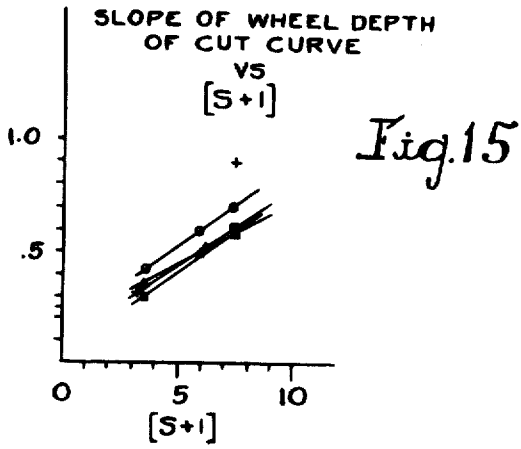
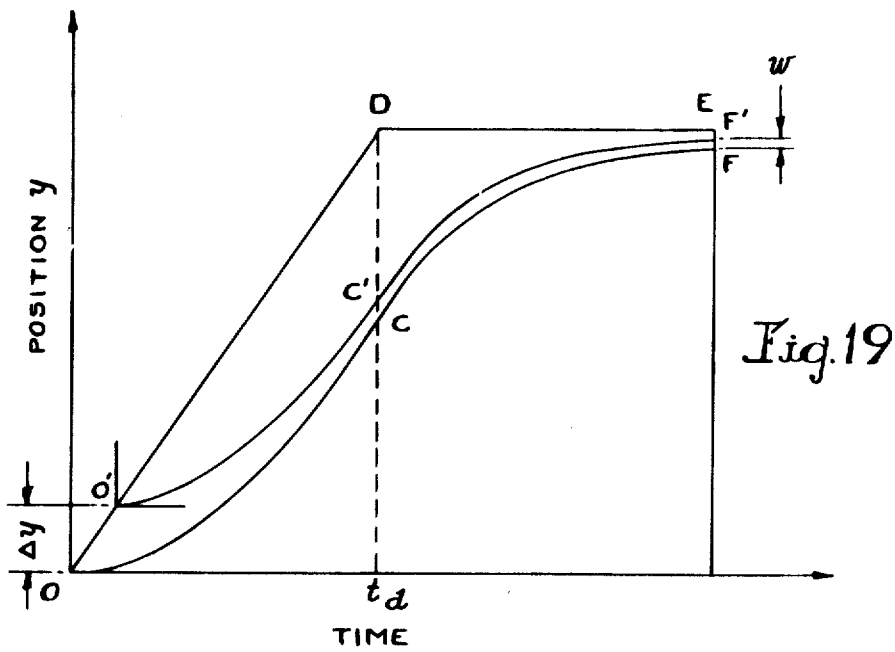
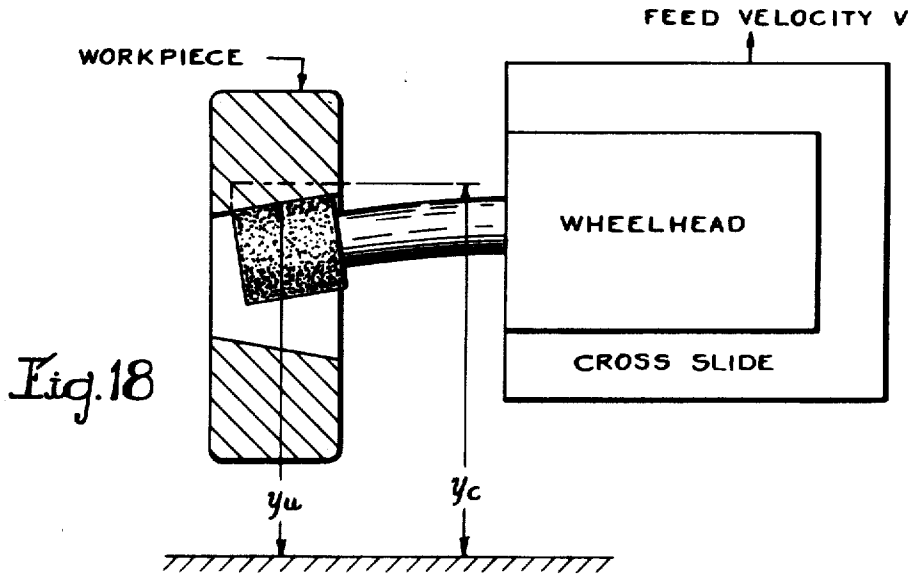


Fig. 14

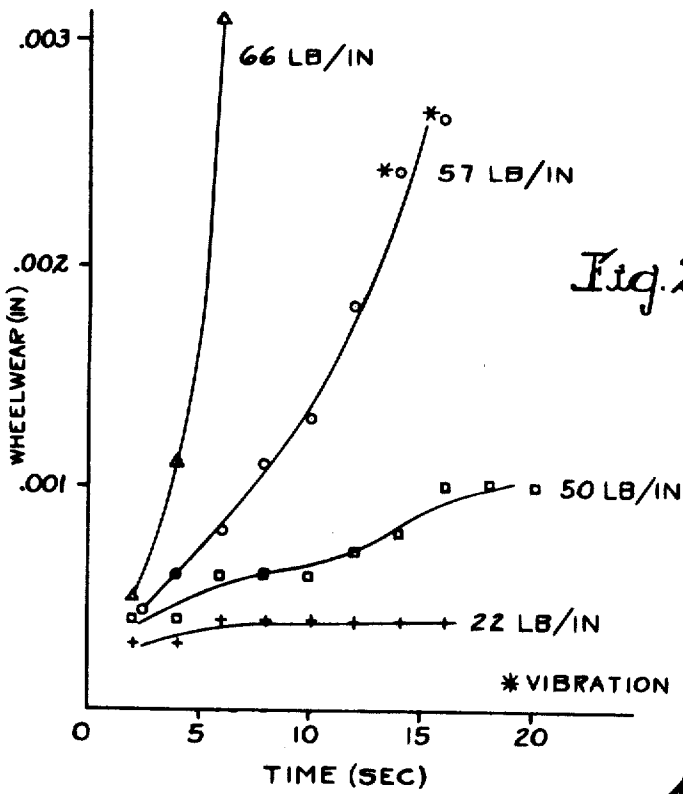
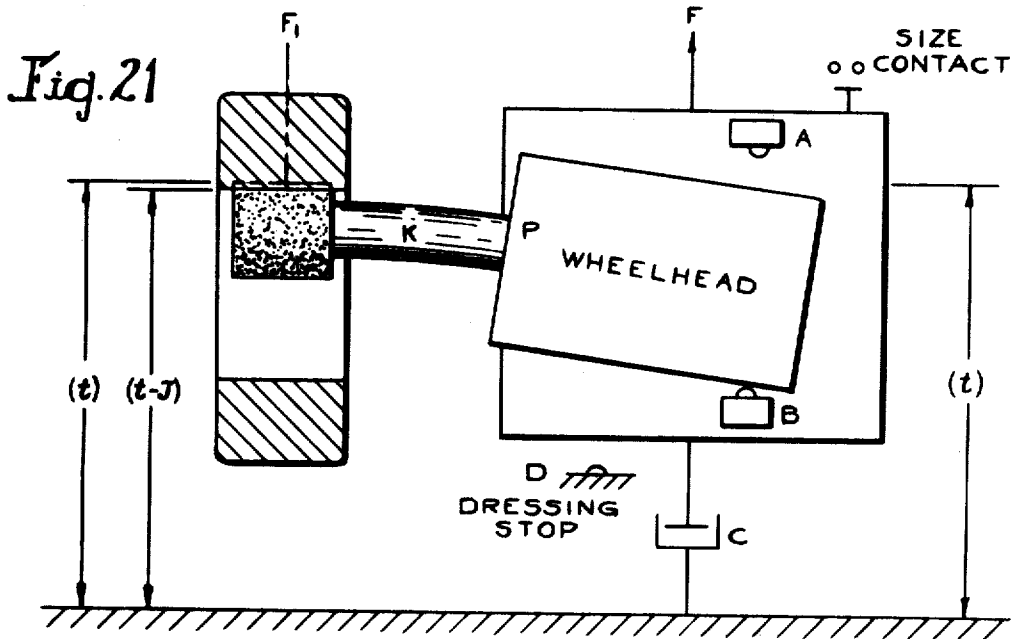
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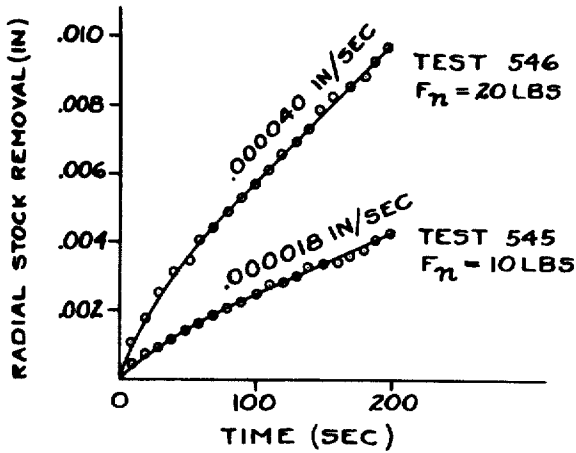


Fig. 22

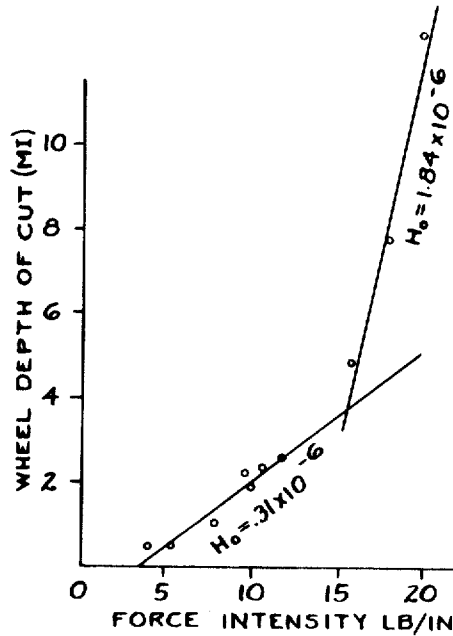


Fig. 23

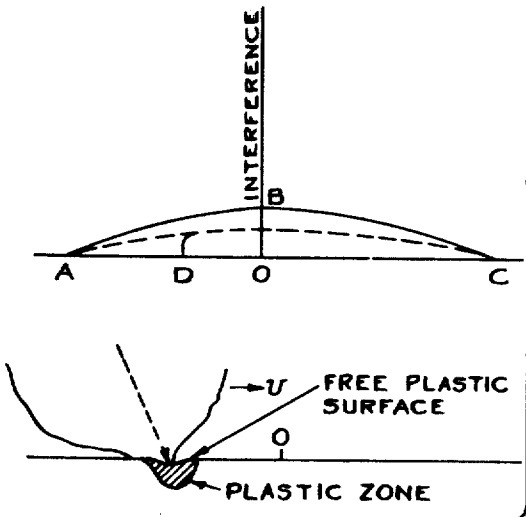


Fig. 24

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GRINDING HIGH-TEMPERATURE ALLOYS

CROSS-REFERENCE TO RELATED APPLICATION

This application is a division of the patent application of Robert S. Hahn, Ser. No. 445,298, filed Feb. 15, 1965 for Grinding High-temperature Alloys, now U.S. Pat. No. 3,431,685 dated Mar. 11, 1969.

BACKGROUND OF THE INVENTION

In the machining of metal parts, considerable use has been made recently of the so-called "abrasive machining" concept. According to this machining method, the old procedure of performing rough machining operations by use of single point cutting tools in lathes and planers and milling machines and then merely finishing or removing a slight amount of the surface by the abrasive process has been abandoned. This is because machine shops have come to realize that, among other things, a considerable amount of labor and time is consumed in moving the workpiece from the conventional machine tool to the abrasive tool in performing the two operations. It is quite clear that in many instances the abrasive process can be used both for the rough cutting and for the finishing, thus removing the necessity of providing for two operations on two separate machine tools. When one attempts to apply this concept, however, to the new high-temperature alloys, such as T-15, which are capable of maintaining their strength even at high temperatures, it has been found that with the known machines and methods, it is impossible not only to perform abrasive machining but to even, in many cases, perform the finish grinding which gives the product its smooth finish. It has been necessary to machine these alloys, therefore, by very expensive and time-consuming alternative methods. 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 method for effectively machining high-temperature alloys.

Another object of this invention is the provision of a method of removing stock from workpieces formed of very tough alloys by the abrasive process.

A further object of the present invention is the provision of a grinding method for rapidly and accurately machining tough alloys.

It is another object of the instant invention to provide a grinding method capable of a machining operation at very high force intensity and with the absorption of large amounts of horsepower.

A still further object of this invention is the provision of a method for grinding which incorporates a novel discovery in the theory of grinding and which permits the removal of large amounts of stock from very tough alloys in a minimum amount of time.

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.

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 vertical sectional view of the grinding machine taken on the line II—II of FIG. 1;

FIG. 3 is a vertical sectional view of the machine taken on the line III—III of FIG. 1;

FIG. 4 is a somewhat schematic plan view of the machine;

FIG. 5 is a graph showing wheel depth of cut plotted against force intensity of grinding for two types of steel using a conventional grinding machine;

FIG. 6 shows wheel depth of cut versus force intensity as well as a curve of wheel wear when a force intensity is used which is much greater than conventional intensities;

FIG. 7 shows graphs of depth of cut and wheel wear rates versus force intensity for three conventional grinding wheels;

FIG. 8 is a graph of wheel depth of cut and wheel wear plotted against force intensity;

FIG. 9 is a graph of wheel depth of cut and rate of heel wear plotted against force intensity;

FIG. 10 is another graph of wheel depth of cut and rate of wheel wear plotted against force intensity;

FIG. 11 is a graph of depth of cut and wheel wear plotted against force intensity;

FIG. 12 is a somewhat schematic view of an abrasive wheel surface showing the manner of dispersion of the individual abrasive particles;

FIG. 13 is a somewhat schematic view showing the relationship of a grinding wheel and the surface of the workpiece during grinding;

FIG. 14 is a geometric diagram showing the relationship between an abrasive wheel and the workpiece surface during grinding;

FIGS. 15 and 16 are graphs of the slope of the wheel depth of cut curve versus force intensity plus 1 in certain test relationships;

FIG. 17 is a graph of wheel depth of cut versus a certain mathematical factor as produced in various tests;

FIG. 18 is a somewhat schematic view of a conventional feed rate grinding machine;

FIG. 19 is a graph showing various positional relationships during the operation of the conventional machine shown in FIG. 18;

FIG. 20 shows graphically various relationships inherent in the machine shown in FIG. 18;

FIG. 21 is a somewhat schematic view of a grinding machine using the controlled force principle of grinding;

FIG. 22 is a graphical representation of certain relationships making use of the apparatus shown in FIG. 21;

FIG. 23 is a graphical relationship of heel depth of cut versus force intensity making use of the apparatus of FIG. 21; and

FIG. 24 is a somewhat schematic representation of an abrasive particle as it operates to remove stock from a workpiece.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring first to FIG. 1, wherein are best shown the general features of the invention the grinding machine, indicated generally by the reference numeral 10, is shown as having a base 11 with a horizontal upper surface 12. Located centrally of the base and overlying the surface 12 is a turret head 13 adapted to be rotated on occasion about a vertical axis. Adjacent the turret head and adapted to be rotated about a vertical axis spaced from and parallel to the axis of the turret head is a work table 14. The turret head 13 is octagonal in shape and is provided with eight vertical plane faces 15, 16, 17, 18, 19, 21, 22, and 23. On these faces are mounted various machining implements. Mounted on the face 15 is a wheelhead 24 carrying a vertical spindle 25 on the lower end of which is mounted an abrasive wheel 26. The spindle is driven by a 40-horsepower electric motor 27 mounted on the face 16. Mounted on the face 17 is a wheelhead 28 carrying a horizontal spindle 29 (see FIG. 2), on the outer end of which is carried an abrasive wheel 31. Mounted on the face 19 is a wheelhead 32 in which is mounted a vertical spindle 33 carrying at its lower end an abrasive wheel 34. A 40-horsepower electric motor 35 is mounted on the face 21 and is connected to the spindle 33 for the driving thereof. Mounted on the face 23 is a boring head 36 carrying a boring tool 37.

The electrical and hydraulic controls for the machine are mounted in a hollow abutment 38 extending from the base above the upper surface 12. In FIG. 2, it can be seen that the turret head 13 is fastened to the upper end of a vertical post 39 of cylindrical form which is mounted in the base 11 for rotation in hydrostatic bearings 41. These bearings are of the well-

known type for resisting radial forces and are spaced not only circumferentially around the post 39 but longitudinally thereof to resist large bending moments in the turret head 13. Within the turret head is a 40-horsepower electric motor 42 which is connected to the spindle 29 for the driving thereof. Extending into the bottom of the post 39 is a bore 43 in which is slidably carried an elongated piston 44 whose lower end is attached in a fixed portion 45 on the base 11. The assemblage of the bore 43 and the piston 44 form a hydraulic linear actuator for producing traverse motion as well as reciprocatory motion of the turret head relative to the work table 14.

Extending through the wheelhead 28 concentrically of the spindle 29 is a bore 46 in which is slidably carried a piston 47, the piston and bore cooperating as a hydraulic linear actuator to produce reciprocation of the spindle 29 and the abrasive wheel 31 over the surface of the table 14, there being a suitable sliding connection built into the spindle 29 to permit it to be continuously connected to the motor 42, despite the reciprocatory motion of the spindle.

FIG. 3 shows another view of the arrangement of the vertical spindle 25, the abrasive wheel 26, and associated equipment. The spindle 25 and the wheel 26 are intended for use with the table 14 in grinding external surfaces of revolution, while the spindle 33 and the abrasive wheel 34 are intended for grinding internal surfaces of revolution. Similarly, the spindle 29 and the abrasive wheel 31 are provided to produce flat surfaces.

Referring to FIG. 4, means is shown whereby the turret head 12 may be reciprocated in increments of 45° about its axis relative to the table 14. The post 39 is provided with a ring gear 48 which is engaged by a rack 49 fastened to the opposite end of a piston rod 51. The piston rod is connected to a piston 52 which is slidably carried in a cylinder 53, the piston 52 and the cylinder 53 forming a hydraulic linear actuator suitably controlled to produce reciprocation of the rack and one-way rotational operation of the turret head 12. This figure also shows the hydrostatic bearings 41 located 120° apart about the post 39.

The operation of the grinding machine 10 will now be readily understood in view of the above description. The operation is performed by rotating the turret head 13 until the proper face 15, 16, 17, 18, 19, 21, 22 or 23 is located beside the work table 14. This rotation is brought about by use of the cylinder 53 operating through the rack 49 and the ring gear 48 to rotate the post 39. Surface grinding is brought about by using the abrasive wheel 31 and the spindle 29 driven by the 40-horsepower motor 42. The wheel is traversed across the work as it is rotated on the table 14 by means of the piston 47 sliding in the bore 46. Internal grinding takes place by using the abrasive wheel 34 on the spindle 33 as rotated by the 40-horsepower motor 35. Traverse motion in to the bore and out again is produced by the post 39 and its bore 43 sliding over the piston 44. The slight axial reciprocation of the wheel which is used in internal grinding can be produced with this same cylinder using suitable hydraulic valving and controls. When an external surface of revolution is to be ground the abrasive wheel 26 is used rotated by the spindle 25 which receives its power from the 40-horsepower motor 27. Here again, axial movement of the wheel relative to the surface is brought about by the sliding of the post 39 over the piston 44 under the impetus of controlled hydraulic flow to and from the bore 43. It can be seen, therefore, that abrasive operations can be carried on with the present machine using very large force intensities between the wheel and the workpiece and using very large amounts of power without affecting the accuracy of the operation and without detriment to the machine. This is because of the peculiar construction of a large vertical cantilevered beam that is supported almost entirely along its length by the hydrostatic bearings 41. The bending force is applied to the large post in a fairly short, unsupported portion thereof.

In considering the advantages and the operation of the machine described above, it is clear that the value of a machine tool must be evaluated in terms of its output versus

its cost. In the present case, by taking advantage of recent developments in grinding technology and making use of the unique properties of hydrastatic bearings, an interesting machine tool configuration has been evolved. The present machine is capable of rotary surface grinding, O.D. grinding, bore grinding, boring, turning, and facing with single point tools. The workpiece is mounted on a rotary table, while the surface grinding head as well as the other grinding heads and tooling are mounted on a large turret head which is capable of vertical feed and of indexing motions as well as rotary feed and rotary indexing motions. These rotary and axial motions are accomplished by means of the large hydrostatic bearings operating on the cylindrical post of the turret head. The reciprocating motion of the rotary surface grinding wheel is accomplished by the axial motion of the head in a hydrostatic sleeve by a feedout motion of the hydrostatic spindle itself. The vertical feed and indexing motion are accomplished by the cylinder shown, while the O.D. and I.D. grinding are accomplished, as has been described. The rotary feed of the turret along with a vertical reciprocating stroke is accomplished by moving the turret post in the large hydrostatic bearings. This machine can be applied to various classes of workpieces, taking advantage of the economic advantage available by the use of abrasive machining. Recent developments in abrasive wheels indicate that metal can be removed quite rapidly by abrasive machining and, in this category, would fall all sorts of vertical turret lathe work. Cast iron, as well as steel forgings can be machined by abrasive wheels and, in the present case, single point tools could be applied, also, when desired on one of the turret head stations.

As an example, a clutch plate which needed to be machined to a 32 r.m.s. finish. It is well known that it is difficult to get decent finishes on cast iron steel and, especially, alloy steel by turning. Furthermore, if an alloy steel is to be machined, the surface speed must be kept low, thus requiring considerable time to generate the surface. By abrasive machining, a 20 r.m.s. finish can readily be obtained. The volume of metal to be removed from the particular clutch plate was about 1.5 cu.in. The rate of metal removed in grinding often runs about 5 horsepower per cu.in. per min. Assuming a 40-horsepower drive, this gives a metal removal capability of 8 cu.in. per min. as calculated according to the procedures set forth in The Tool & Manufacturing Engineer for Feb., 1961 at page 111. This means that the 1.5 cu.in. can be removed in about 11 seconds. If this particular clutch plate were generated by a single point tool cutting at 400 feet per min. (138 r.p.m.) on 4150 steel with 0.045 radius and 0.006 lead (required to give 60 r.m.s. finish) a cutting time of 216 seconds is required. Consequently, the clutch plate could be machined in one-twentieth of time with abrasive machining as would be required by the single point tool. Obviously, as the amount of stock to be removed is increased, the abrasive machining time will increase and, finally, will equal the single point tool machining time. However this break even point may often be well above the stock allowances on castings and forgings. Recent developments have also been made in fiberglass reinforced grinding wheels (as described in Grinding and Finishing Magazine for July, 1962 at page 40), whereby operation is permitted at 12,500 feet per min. and forces of 1,000 lbs. for snagging operation. This results in high stock removal rates.

By using the cutting tools and abrasive heels in various combinations, many parts, such as clutch plates, gear blanks, brake drums, and so on could be machined. Drilling and tapping units could also be incorporated on one of the turret faces, although it would then be necessary to angularly position the rotary table during the drilling operation. Antifriction bearing races of the larger sizes can also be ground with the machine giving excellent concentricity. Furthermore, the machine can be used for generating general solids of revolution, such as paraboloids, ellipsoids, and so forth. These surfaces can be generated by numerical control applied simultaneously to the vertical and rotary movements of the turret.

It is well known that the missile and space industry has encountered severe problems in machining high-temperature alloys. Grinding of these materials has been found to be nearly impossible except by the so-called "hot machining" techniques. It would appear to be a distinct advantage of the present machine to be able to machine these alloys without the use of hot machining, which is expensive and presents certain problems of warpage and so on in the finishing of the machine. In order to understand how this may be done, it is necessary to consider some of the discoveries made as part of the present invention.

In FIG. 5 is plotted the wheel depth of cut against force intensity in grinding a 4150 steel and also in grinding a high-temperature alloy T-15. It should be noted that the T-15T—curve proceeds along the abscissa axis and no material was removed. This is an experimental curve obtained by using a grinding machine with conventional grinding force intensities. Although, when extremely high force intensities were attempted, the curves shown in FIG. 6 resulted, wherein the heel depth of cut and wear are plotted against the force intensity. It can be seen that, as marked on the graph, a very useful area is obtained when force intensities between 240 and 280 lbs. per in. are used. When force intensity is too low, no cutting took place (as was shown in FIG. 5). When the force intensity was too high, of course, the wheel broke down. Obviously, when conventional feed rate reciprocating grinders are used, it is impossible to operate them in this range of force intensity. In FIG. 7 are plotted wheel depth of cut versus force intensity as well as wheel wear rates for three different grinding wheels operating on T-15, thus indicating that in grinding T-15 with a 1-inch wide wheel a force of 400 lbs. and a power requirement of 40-horsepower is necessary. Present grinding machines will not operate in these values. Therefore, by providing a machine particularly adapted for these forces and power, it is possible readily to grind high-temperature alloys, not merely for finishing these alloys but also for doing the general machining of such workpieces.

To properly understand the manner in which the present methods and machine operate to permit the grinding of high-temperature alloys, it is necessary to go into the theoretical aspects of grinding in general. In this discussion the following nomenclature is used: ξ =thickness of interference zone

ξ =effective grain deflection

κg =effective rigidity of grain

Y_g =grain metal removal parameter (grain depth of cut per unit force)

\mathcal{R} =volumetric rate of metal removal

N =wheel speed

n =work speed

α =wheel radius

R =work radius

γ =axially condensed grain density (grains/unit length)

b_e =effective width of grain

$$X_A = \text{coordinate of } A = \sqrt{\frac{\alpha}{I - \frac{1}{2\rho}}} \cdot \sqrt{d}$$

$$X_D = \text{coordinate of } D = \sqrt{\frac{\alpha}{I - \frac{1}{2\rho}}} \cdot \sqrt{d+h}$$

d =effective elastic flattening of wheel and work

h =wheel depth of cut

I =trochoidal locus factor

$$= \frac{\left(1 + \frac{N}{n}\right)^2 - \left(1 + \frac{R}{\alpha}\right)}{2\left(\frac{R}{\alpha} + \frac{N}{n}\right)^2} \quad (\text{for external})$$

$$= \frac{\left(1 + \frac{N}{n}\right)^2 - \left(1 - \frac{R}{\alpha}\right)}{2\left(\frac{R}{\alpha} + \frac{N}{n}\right)^2} \quad (\text{for internal})$$

$$= \frac{S^2}{2(1+S)^2} \quad (\text{for surface})$$

S =ratio of wheel surface speed to work surface speed

λ =effective peripheral grain spacing

W =axial width of wheel-work contact

E_n =normal grinding force

F_t =tangential grinding force

$\mu = (E_t/F_n)$

HP_w =horsepower to work

P =force intensity, force per unit length of contact

$C = (1/a) + (1/R)$, the conformity factor

$\epsilon = (1/E_1) + (1/E_2)$, the elasticity factor

E_1 =Modulus of elasticity of wheel

E_2 =Modulus of elasticity of work

HP_n =horsepower to wheel

From experimental work on grinding, it has been found that work materials may roughly be divided into two categories. In one case a linear behavior of the heel depth of cut occurs, while in the other a more complex situation exists. These cases are described below, and the technical factors relating to them are discussed. This work forms the basis for predicting metal removal rates in abrasive machining of conventional as well as high-temperature alloys.

Grinding tests have been made, using the controlled force technique. In these tests the wheel depth of cut is measured for various normal force intensities. FIG. 8 shows a typical plot of wheel depth of cut vs. force intensity for a conventional AISI 4150 Steel. The data plots essentially as a straight line which goes through the origin, with perhaps a little concavity downward due to loading of the wheel. Many material behave in this way. Some materials, on the other hand, have the characteristic shown in FIG. 9 where the curve emerges from the origin horizontally and is generally concave upward. It may or may not intersect the Force Intensity axis at some positive value. The cause of this behavior is considered to be due to considerable rubbing of the abrasive grain on the workpiece. As the force intensity is increased to higher values, more grains begin to cut, causing the curve to be concave upward. This type of behavior is exemplified by many high temperature alloys as illustrated by T-15.

Since rubbing of the grain can be favored or discouraged by the geometry of the grinding operation, tests were run by grinding with three different conformities, i.e., by grinding on an OD, by internal grinding with a heel of moderate size, and with a wheel which nearly filled the hole. FIG. 11 shows the results for AISI 4150 and FIG. 10 for the high-temperature alloy T-15. It will be noted that on the 4150, where negligible rubbing occurs, the conformity makes little difference. On the other hand, when grinding T-15, there is a very large effect of conformity. From this we must recognize two categories, one in which rubbing is essentially absent and one in which considerable rubbing takes place.

In order to analyze the effects of wheel size, work size and other geometrical effects, it is necessary to consider the interference zone. The locus of a point on the wheel relative to the workpiece is a trochoidal curve as given previously in The Effect of Wheel-Work Conformity in Precision Grinding, R S. Hahn - Trans. ASME Vol. 17 No. 8, Nov. 1955-1325-1329. The loci of two peripherally adjacent acting grits I and II are shown in FIG. 14. Due to deflections of the grit and the workpiece, grit I does not sweep out the locus O'D'. Instead, it sweeps out and generates the surface AB'D'. The interference zone presented to the grit II is thus AB'D'DA'OA. Here, the wheel depth of cut is designated by h , and the effective elastic flattening of the wheel-work combination by d . It is clear that the two parameters d and h are independent, since in grinding some materials, h may even be zero, although the elastic flattening d may be finite. Under some grinding conditions h is negligibly small compared to d and the interference zone becomes symmetric

At any instant there are a number of active grains in contact with the workpiece as represented in FIG. 12. These grains will have a uniform probability distribution along their respective interference zones. Therefore, for the purposes of this analysis it is permissible to transfer all active points or grains onto one average interference zone and to consider it to be uniformly populated with active points.

Next, if one assumes the grain depth of cut ($\xi-\zeta$) to be proportional to the force $\kappa_n \zeta$, there results

1. $(\xi-\zeta) = \Gamma_g \kappa_n \zeta$

The instantaneous rate of metal removal \mathcal{R} for m grains is

$$(2) \quad \mathcal{R} = \sum_{r=1}^{l=m} (\xi-\zeta) \cdot b_0 (2\pi N_n \pm 2\pi NR)$$

where b_0 is an effective width of the grains.

The plus sign is used for conventional grinding, the minus sign for climb grinding.

By solving Equation (1) for ζ and using the result, the grain depth of cut may be written as

$$(3) \quad (\xi-\zeta) = \xi - \frac{\xi}{1 + \Gamma_g K_g} = \frac{\Gamma_g K_g}{1 + \Gamma_g K_g} \xi$$

Introducing the grain density γ (grains/unit length) and replacing the summation in Eq (2) by integration and using Eq (3) gives

$$(4) \quad \mathcal{R} = \frac{\Gamma_g K_g}{1 + \Gamma_g K_g} \gamma b_0 (2\pi N_n \pm 2\pi NR) \int_{X_A}^{X_D} X_D \xi dx$$

where

$$X_A = \sqrt{\frac{a}{I - \frac{1}{2\rho}} \sqrt{d}}$$

$$X_D = \sqrt{\frac{a}{I - \frac{1}{2\rho}} \sqrt{d+h}}$$

Since the rate of metal removal is also given independently by

$$(5) \quad \mathcal{R} = hw2\pi R_n$$

Equation (4) becomes:

$$h = \frac{\gamma b_0 (S \pm 1) \Gamma_g K_g}{W (1 + \Gamma_g K_g)} \int_{X_A}^{X_D} X_D \xi dx$$

Equation (6) is of the form $t(d,h)=0$ and relates to the metal removal.

The grinding force, on the other hand is given by

$$(7) \quad F_n = \frac{\nu K}{1 + \Gamma K} \int_{X_A}^{X_D} X_D \xi dx$$

which is of the form $t(F_n, d, h)=0$

Equations (6) and (7) are independent equations containing d . In principal, d can be eliminated from these giving a relation between F_n and h . However, by virtue of the assumed linear grain depth of cut relation Eq. 3, both Eq. (6) and (7) contain the interference zone integral. This integral can be immediately eliminated from Eq. (6) and (7) giving

$$(8) \quad h = \frac{(S+1)(b_0 \Gamma_g)}{w} F_n$$

or

$$\frac{h}{F_n/w} = (S+1)(b_0 \Gamma_g)$$

which represents the slope of the h vs. force intensity graphs. It should be noted that Γ_g may possibly be a function of speed and geometry. The quantity $(b_0 \Gamma_g)$ is the area swept out per unit force and represents a basic metal removal parameter.

Equation (8) may be rewritten, with the aid of Eq. (5) in the following form

$$(9) \quad \mathcal{R} = 396,000 \left(\frac{b_0 \Gamma_g}{\mu} \right) [HP_h + HP_w]$$

From Eq. (8) we see that as long as there is no rubbing and a linear grain depth of cut relation holds, the geometry of the interference zone completely drops out. Secondly, the slope

($h/F_{n/w}$), of the force intensity graph is a linear function of the surface speed ratio S .

The above theoretically derived results may be compared with experiment. In order to do this, a set of four different wheels were tested at three different surface speed ratios. FIG. 8 shows a typical test curve. The slope of the wheel depth of cut curve (in this case 0.70×10^{16}) was measured for each surface speed ratio and the results of these tests were summarized. It was seen that the slope of the wheel depth of cut curves does increase with surface speed and, in fact, is a linear function of $(S+1)$ as shown in FIG. 15, as predicted by the theory. Also, the computed values of $(b_0 \Gamma_g)$ for each wheel appeared to be reasonably constant and unaffected by surface speed. It is interesting to note that the average value of $(b_0 \Gamma_g)$ for the 60 and 70 grit wheels is greater than that for the 46 grit wheels.

From Eq. (9) it is seen that the rate of metal removal depends on the total horsepower. This is in agreement with data of a commercial grinding machine company who have found the following horsepower requirements:

0.25 in. ³ /min.	17 hp./in. ³ /min.
0.50 in. ³ /min.	10.5 hp./in. ³ /min.
1.00 in. ³ /min.	7.75 hp./in. ³ /min.
2.00 in. ³ /min.	5.3 hp./in. ³ /min.
3.00 in. ³ /min.	4.4 hp./in. ³ /min.

Using the value of $(b_0 \Gamma_g)$ of 0.102×10^{16} in Eq. (9), one obtains 12.4 HP/in.³/min. which is in reasonable agreement with the commercial data. It should be noted that the commercial data refers to large surface grinding machines, while the present data refers to small grinding wheels.

In the case where considerable rubbing predominates, as inferred in FIG. 9, the theory presented above does not hold. The data shown on FIG. 10 for the OD tests and the ID tests indicates that the conformity or the geometry of the interference zone plays a very important part. Another test which reveals the nature of high temperature alloy grinding is presented in FIG. 16. Here a wheel having a synthetic resin bond was used to grind T-15. By comparing FIG. 16 with FIG. 10, it is clear that the "soft," more elastic resin bond wheel, cut much slower than the "hard," vitreous bonded wheel under these conditions.

The above observations suggest that the contact stress is important. For the same force intensity the Polybond wheel does not generate as much stress as the harder vitreous bonded wheels do. Also, for the same force intensity, more stress is developed for the OD conformation than for ID. The problem is to discover what quantity will rectify the OD and ID conformity data as well as the data for the Polybond wheel.

The three sets of data on FIG. 10 and the data on FIG. 16 for the Polybond wheel have been replotted on FIG. 17 against the quantity

$$P^2 \left(\frac{C}{\epsilon} \right)^{\frac{1}{2}}$$

where P , C , and ϵ are the force intensity, the conformity factor and the elasticity factor, respectively. This quantity is proportional to the product of contact width and the square of the maximum stress. It will be referred to as the stress-width factor. It may be seen that, to a rough approximation, all data points fall on a single straight line. This quantity then, in a general way, governs the grinding of high-temperature alloys.

It is interesting to determine the maximum attainable value of

$$P^2 \left(\frac{C}{\epsilon} \right)^{\frac{1}{2}}$$

on present day grinding machines. It can readily be shown that the force intensity is related to the Horsepower per unit of wheel face by

$$P = \frac{33000 \mu}{\text{s.f.p.m.}} \frac{HP}{W}$$

Using this formula, and collecting data on conventional internal, external and large surface grinders, the following TABLE was obtained:

	Heald 273A Internal	Cincinnati 6'x30" Center Type	Thompson 5ft. x 14ft. Surface Grinder
Wheel width	1.0 in.	2%	6
Wheel dia.	1.5	24	24
Work dia.	-.3	+1.5	00
HP	5	7.5	40
C	0.67	1.41	0.083
E	0.158x10 ¹⁴	0.158x10 ¹⁴	0.158x10 ¹⁴
F _{max}	13.8	7.8	18.4
$\frac{F_{max}}{P_{max}}(Cl_e)^{1/2}$	0.105	0.066x10 ⁶	0.57x10 ⁶

From this, the Heald Internal has the capability of producing the highest stress-width factor of the group. However, the magnitude of these factors, as found on the above machines, are completely inadequate for abrasive machining high-temperature alloys. These valves all fall very close to the origin on FIG. 17.

The following discussion is also offered for an understanding of the reasons for the unobvious results obtained and advantages available by the use of the methods of invention.

The difficulty of machining high temperature and exotic alloys is well known. The development of techniques to machine these alloys efficiently will undoubtedly reduce manufacturing costs of many space and military devices. Recent research and development work in connection with the grinding or abrasive machining of these materials indicates that considerable improvement can be made in processing these materials, by a new technique called "Controlled Force Abrasive Machining." The type of machining operations to be considered are those of turning, boring, and the facing of solids of revolution such as are commonly carried out on vertical turret lathes. Parts with simple as well as fairly complex cross sections consisting of grooves, shoulder, and contours such as jet engine parts, are to be considered. Drilling and tapping operations are to be excluded. On difficult-to-machine materials, where the cutting speed is low and tool life short, the abrasive machining of these parts becomes very advantageous. However, excessive residual stress and thermal damage to the workpiece must be avoided. This appears to be possible by Controlled Force Abrasive Machining at high work speeds as will be discussed.

Before discussing controlled force abrasive machining it is important to understand certain characteristics of the conventional feed rate grinding process. In present grinding machines it is customary to feed the wheel into the work at given feed rate v and then to provide a dwell or spark-out time. FIG. 18 illustrates the basic elements of an internal grinder where the spindle is relatively flexible. Although the considerations to follow relate to internal grinding, they apply equally well to external and rotary surface grinding, since some flexibility is always present. The line OD in FIG. 19 illustrates the cross slide position during feed and DE during the dwell. The line OCF represents the instantaneous position of the grinding wheel itself, which differs from the cross slide position because of elastic deflections. The instantaneous grinding force induced between wheel and work is proportional to the vertical difference between the two curves in FIG. 19. It has been shown (in an article entitled "Controlled Force Grinding—A New Technique For Precision Internal Grinding" by R. S. Hahn, presented before the ASME Winter Meeting, Nov. 17 through 22, 1963) that this force is given by:

$$F_u = \frac{V}{\Gamma_n} [1 - C - \Gamma \kappa_n t]$$

where:

F_u = normal grinding force

V = feed rate

Γ = metal removal parameter i.e., the wheel depth of cut per unit normal force

n = work speed

κ = system static stiffness, includes flexibility of work support, bearings, etc.

M = cross-slide mass

h = wheel depth of cut

μ 32 ratio of tangential force to normal force Here (V/Γ_n) is the steady state grinding force and $(1/\Gamma \kappa_n)$ is the time constant of the wheel-work-machine system. From Eq. (A) it can be seen that the instantaneous grinding force depends upon the feed rate V , the metal removal parameter Γ pertaining to the wheel-work combination, and the effective rigidity κ of the machine too.

The grinding action of an abrasive wheel depends directly on the grinding force. If the force is small, the wheel tends to dull, if too high, the wheel breaks down at an excessive rate. FIG. 20 shows wheel wear vs. time for several levels of force intensity (force per unit width of wheel-work contact). At 22 lb./in. the wheel is not wearing and becomes dull and glazed. At 66 lb./in. wheel wear is excessive.

In view of the above and the fact that the grinding force depends on the feed rate V , the metal removal parameter Γ and the static machine tool stiffness κ , it is easy to understand why grinding is an art and how a machine operator has to manipulate grinding conditions until satisfactory results occur. On difficult to grind materials he may never attain these conditions. Moreover, a further variation in grinding force occurs as a result of stock variations from piece to piece. Consequently, it is clear that in feed rate grinding, the grinding force and thus the grinding action are complicated functions of several variables.

The recently developed controlled force method of grinding combined with the present invention eliminates these difficulties. In this method, the wheel is pressed against the workpiece with a prescribed force, and the feeding velocity of the cross-slide becomes the dependent variable. FIG. 21 shows the controlled force method applied to internal grinding. The wheelhead is mounted on a frictionless cross-slide of mass M . A force F is applied to the frictionless cross slide which causes a reaction F_r between the wheel and workpiece. The wheel then grinds under this force according to its ability to remove stock. The progressive forward displacement of the cross-slide indicates the stock removal. The wheelhead may be swiveled to compensate for angular deflection. The cross-slide is retracted to the dressing stop D for wheel dressing or unloading the workpiece. The dressing stop and size contact are moved periodically to compensate for wheel wear.

The cross slide mass M and the spindle spring constant κ constitute a vibratory system. Although FIG. 21, depicts a flexible internal grinding spindle, κ represents the overall system static stiffness and thus accommodates flexibility in the work supporting device and the machine in general. Moreover, this same system in effect, applies to external, and rotary surface grinding as well as internal grinding.

The stability of this κ - M vibratory system has been studied and it has been shown that, if the work rotational speed is above a certain critical value, a rounding up action will take place, i.e., an initially out of round workpiece will become round and consequently controlled force grinding is possible. At low workspeeds the system is unstable and violent vibrations may build up.

From the above it can be seen that controlled force grinding results in efficient stock removal, control of the self-dressing effect and wheel sharpness, and a simplification of the grinding process. The grinding force is no longer dependent on many variables.

The metal removal characteristics of grinding wheels can be readily measured using the controlled force method. FIG. 22

shows a typical result where the radial stock removed is plotted against time. The slope of the curve is the rate of radial advance. The wheel depth of cut or radial advance per revolution of the work is obtained by dividing the rate of radial advance by the work speed

Three types of abrasive action have been observed. FIG. 23 shows wheel depth of cut vs. force intensity. Under the conditions of the test only rubbing occurred below 4 lb./in. From 4 to about 16 lb./in. ploughing occurred and above 16 lb./in. cutting occurred. The ploughing process is one where the abrasive grain plastically plows a groove with the metal extruding sideways into ridges along the side of the groove. These highly extruded ridges may be removed by other grains or fragments may break off. In ploughing no chip is formed ahead of the grain. In the cutting process chips actually form ahead of the abrasive grain in the usual way.

The key to understanding the grinding behavior of many high temperature alloys is best explained in terms of the "free plastic surface" (See the booklet entitled "On The Nature Of The Grinding Process" by R. S. Hahn in the Proceedings of The Third International Machines Tool and Research Conference at the University of Birmingham, England, Sept., 1962, published by the Pergamon Press). In FIG. 24 a plastically deformed zone is illustrated under the leading edge of the abrasive grain. If a fracture of the "free plastic surface" occurs before the grain reaches the point O, a chip will be formed and flow up the rake surface of the grain, otherwise only ploughing or rubbing will take place. This accounts for the tremendous difference in grindability of various materials. FIG. 5 shows the wheel depth of cut curves for AISI 4150 and a high vanadium high speed steel T-15 both heat treated to the same hardness. The tremendous difference in grindability is obvious. In grinding the AISI 4150 sample, the grain forms a chip readily and little or no rubbing or ploughing takes place, whereas with T-15 many of the grains rub or plough until very high force intensities are reached.

In general, then two extremes of grinding behavior occurs. When little or no rubbing or ploughing takes place, the wheel depth of cut curve is a straight line through the origin as shown in FIG. 8. When the work material refuses to fracture in the "free plastic surface" excessive rubbing takes place and the wheel depth of cut curve emerges from the origin in a horizontal direction like a parabola and only at high force intensities does it turn upward as shown in FIG. 9. Curves for Rene 41, Inconel X, 17-7PH, Thermold J have been determined and lie intermediate to those in FIG. 8 and FIG. 9.

The significance of controlling the force intensity becomes apparent from FIG. 6, which shows that there is only a narrow range of force intensity within which successful operation can

be achieved. If the force intensity is too low, no metal removal takes place; if it is too high, the wheel wear rate is excessive. From this it is easy to understand how the grinder operator, using the conventional feed rate method, must cut and try many combinations and even then may not find successful conditions. Furthermore, the force intensities required for grinding some of the high temperature alloys lie outside the capabilities of present day grinding machines. FIG. 6 also shows the curve for normal tool steels, i.e., AISI 4150 and the approximate limit of conventional grinders. Since the maximum attainable force intensity P_m is related to the wheelhead horsepower by

$$(B) \quad P_m = \frac{33000\mu}{s.f.p.m.} \frac{HP}{W}$$

it is easy to show that P_m lies between 10 and 20 lb./in. for most commercial grinding machines. Consequently, it is practically impossible to grind T-15 at a hardness of Rockwell "C" =65 on any conventional equipment, as people have found.

Much remains to be learned about thermal damage and residual stress in high temperature alloys. However, it is apparent that thermal damage to the workpiece can be minimized by operating at high workspeed. The elimination of heat checks and considerably improved tool life have been observed in carbide tools sharpened at 600 f.p.m. workspeed. (See Trans. ASME, May, 1956 "The Relation Between Grinding Conditions And Thermal Damage In The Workpiece" by R. S. Hahn). It is clear that residual stresses can be kept within reasonable limits by using high workspeeds and force intensities which keep the wheel in a sharp condition.

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. Method of grinding a workpiece formed of a high-temperature alloy, comprising the steps of:
 - a. supporting the workpiece,
 - b. advancing a peripheral face of a rotating abrasive wheel into contact with the workpiece to perform a stock-removal operation, and
 - c. maintaining the force intensity between the wheel and the workpiece in the range from 200 to 400 pounds per inch of wheel width.
2. A method of grinding as recited in claim 1, wherein a hard abrasive wheel is used.

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