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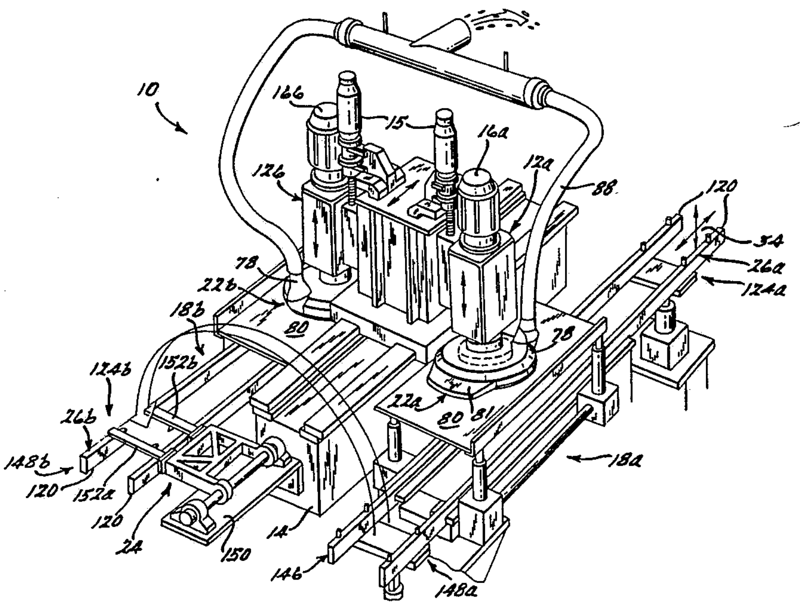

(57) Abstract

A very high speed adiabatic face milling machine (10) whose configuration and operation provide a highly efficient machining process suitable for production manufacturing conditions. The milling machine preferably operates at speeds of approximately 15,000 sfm and at efficiencies of approximately 7 cubic inches per minutes per horsepower. The preferred milling operation is conducted without the use of cooling liquids, instead employing a chip removal system which enables the milling machine to operate truly adiabatically such that no heat is transferred to the workpiece (20) or the cutter (22a, 22b). The efficiency of the chip removal system is such that chip recutting is nearly eliminated and tool life is improved. The milling machine also includes an improved cutter structure, fixturing, and transfer devices (24).

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ADIABATIC DRY DIAMOND MILLING SYSTEM

BACKGROUND OF THE INVENTION

1. FIELD OF THE INVENTION

The present invention generally relates to milling machines and their use in milling nonferrous metals, such as aluminum. More specifically, this invention relates to a face milling machine whose construction and operating parameters provide for an adiabatic very high speed machining process with improved tool life and operating efficiencies, wherein the chips are evacuated from the workpiece and the cutter without the use of cooling liquids or lubricants. In addition, the milling machine includes accessories that further promote the adiabatic operation, precision and efficiency of the milling operation.

2. DESCRIPTION OF THE PRIOR ART

Milling machines are widely used in manufacturing processes for producing close tolerance parts, from flat surfaces to slots, keyways and various complex contours. In particular, face milling machines are employed where planar surfaces are to be machined to flatness tolerances of 0.003 inches (0.076 millimeters) and less. Face milling machines typically include a spindle which is rotatably held perpendicular to the surface of a workpiece. The cutting element, or cutter, is generally a disc mounted to the end of the spindle. The cutter has a number of teeth formed on, or alternatively, a number of cutting inserts mounted at, its perimeter, such that the outside diameter of the cutter removes the stock from the workpiece being machined. The cutter is rotated by the spindle, which in turn is driven by a motor of suitable horsepower. Cooling liquids are commonly used to lubricate, cool and flush chips from the workpiece and cutter. Finally, the workpiece and spindle are moved relative to each other to feed the workpiece into the cutter, denoted as the feed rate and traditionally measured in inches per minute. Alternatively, feed rates are provided in inches per tooth, given by the formula:

$$FR/((RPM)(t));$$

where FR is the feed rate (the rate of relative movement between the workpiece and the spindle) in inches per minute, RPM is the rotational speed of the spindle in revolutions per minute, and t is the number of cutting teeth or inserts on the cutter.

Cutting speeds, and its relation to feed rates, are of primary importance if a milling machine is to efficiently produce close tolerance, high surface quality parts. In the past 25 years, particular attention has been concentrated on cutting speed and its effects on the quality and efficiency of the milling process. Cutting speeds are indicated in surface feet per minute (sfm) which can be calculated by the following formula:

$$2\pi(r)(RPM);$$

where r is the radial dimension of the cutting teeth from the spindle's axis of rotation in feet, and RPM is the rotational speed of the spindle in revolutions per minute. Appropriate cutting speeds are dependent upon several factors –primarily the material being cut and the material of the teeth or cutting inserts used, with nonferrous metals, such as aluminum, and carbide cutting inserts usually allowing for higher cutter speeds.

No one classification of cutting speeds has been generally accepted, but the 16th Volume of the Metals Handbook (9th Edition) entitled "Machining" and published by the American Society of Metals, suggests that cutting speeds can be classified as follows. Conventional cutting speeds are below 2000 sfm for nonferrous metals, and often less than 500 sfm for ferrous metals. Higher speeds of 2000 to 6000 sfm are deemed high speed machining, speeds of 6000 to 60,000 sfm are deemed very high speed machining, and speeds greater than 60,000 sfm are ultrahigh speed machining. Obviously, one advantage to higher machining speeds is faster machining time and thus higher production rates. A significant additional benefit to high speed machining is that, past a critical cutting speed which is characteristic of the particular material being machined, cutting forces actually decrease with increased spindle speed until a minimum is reached, which is again a characteristic of the given workpiece material. Accordingly, cutting forces at higher speeds can actually be comparable to or less than that at conventional speeds. Low cutting forces are not only desirable from the standpoint of the power requirement of the spindle's motor, but are particularly desirable when machining very thin, nonrigid workpieces.

Finally, an additional benefit to high speed machining is the ability to achieve a substantially adiabatic cutting operation in which nearly all of the heat generated during the machining process is transferred to the chips formed, thus keeping the cutter and the workpiece essentially at their original pre-machining temperatures. In addition to being able to handle the workpieces immediately after machining, other significant advantages to achieving an adiabatic operation are improved cutting efficiency, less spindle power, lower noise levels, higher precision cuts, less workpiece deflection, and improved tool life. Again, such advantages are particularly beneficial when machining thin, nonrigid workpieces.

Moreover, a coolant is not always needed under adiabatic machining conditions, and in fact may adversely serve to transfer heat from the chips back to the workpiece and cutter. Though cooling liquids generally improve tool life and the appearance of the machined surface, they require extensive delivery, filtering and often cooling systems. Also, the use and disposal of cooling liquids are a growing health and environmental concern. Accordingly, dry machining provides several significant advantages over the use of coolants.

However, to sustain a truly adiabatic cutting operation, particular attention must be given to the type of material being cut and the material of the teeth or cutting insert, the appropriate feed, speed and depth of cut, the precision by which the spindle is supported relative to the workpiece, the stiffness of the cutter, and the ability of the fixturing to rigidly and accurately support the workpiece.

To date, practically all scientific investigation in the area of high speed adiabatic machining of aluminum has been limited to small end mills (0.5 to 1 inch in diameter) at speeds from approximately 10,000 to approximately 60,000 rpm —or roughly 2600 to 15,700 sfm. In practice, such high rotational speeds are severely limited by bearing size, with smaller bearings allowing higher rotational speeds. However, smaller bearings simultaneously limit spindle power and stiffness, resulting in cutting speed being inversely proportional to power and stiffness. Consequently, cutting forces and horsepower limitations have effectively constrained testing to much lower speeds —typically, below 5000 sfm — for purposes of developing milling machines which are practical for use in production manufacturing. Simultaneously, stiffness of the spindle and the manner in which the cutter is mounted to the spindle has also limited cutter size, significantly limiting material removal rates.

In terms of cutting efficiency or unit power (cubic inches per minute per horsepower), the industry has generally concluded from testing thus far that, though cutting forces and specific power are reduced at higher speeds, these advantages tend to diminish above speeds of 5000 sfm. Maximum unit power for machining aluminum is generally believed to be approximately 3 and as much as 4 cubic inches per minute per horsepower at about 5000 sfm, with horsepower available from current motor technology being limited to approximately 30 horsepower at these high spindle speeds. Accordingly, to achieve higher material removal rates in excess of 40 cubic inches per minute generally requires higher-torque drive motors which result in lower cutting speeds, defeating the advantages of high speed cutting.

Moreover, cutting tool manufacturers do not recommend using cutting speeds in excess of 3000 sfm for aluminum cutting with diamond under realistic production manufacturing conditions, though a few recognize speeds as high as 12,000 sfm as being viable. However, such higher speeds have generally been limited to carbide and diamond cutting tools. Diamond cutting tools, such as polycrystalline diamond (PCD) -tipped carbides, have recently become popular for cutting aluminum because of improved tool life by a factor of 10 to 100 over tungsten carbide cutting tools. However, diamond cutting tools are relatively brittle and are therefore limited by the ability of the milling machine's stiffness and workpiece stability to avoid impact loads caused by workpiece and cutter vibration, particularly at higher cutting speeds Accordingly, diamond tool manufacturers currently recommend maximum cutting speeds of 1500 to 2500 sfm.

From the above discussion, it can be readily appreciated that the prior art testing does not suggest or support advantages to machining aluminum at speeds in excess of 5000 sfm. Generally, the limitations of high speed milling include spindle stiffness, excessive horsepower requirements, and cutting tool limitations, spindle/cutting tool interface limitations, and machine feed rate capability. Accordingly, high speed milling has not be widely employed under typical manufacturing conditions, even where there is a need to surface machine thin workpieces. As a result, the industry conventionally has turned to grinding for such applications. However, even where the above limitations have been achieved under strict laboratory test conditions, the prior art has failed to achieve high material removal rates, particularly in terms of specific power (i.e. cubic inches per minute per horsepower).

Accordingly, what is needed is a cost-efficient adiabatic milling machine capable of operating without cooling liquids at very high speeds, while affording improved tool life and material removal rates and surface finish, and which is particularly adapted for precision milling thin aluminum workpieces in production manufacturing.

<u>SUMMARY OF THE INVENTION</u>

According to the present invention there is provided an adiabatic very high speed face adiabatic milling machine whose configuration and operation provide a highly efficient machining process suitable for production volume manufacturing conditions. The milling machine preferably operates at speeds of approximately 15,000 sfm and at efficiencies of approximately 7 cubic inches per minute per horsepower — a factor of 2 greater than that known in the prior art. Moreover, the preferred milling operation is conducted without the use of cooling liquids, instead employing a chip removal system which enables the milling machine to operate truly adiabatically such that no heat is transferred to the workpiece or the cutter. The efficiency of the chip removal system is such that, unexpectedly, tool life is nearly double that which would be expected otherwise.

In particular, the milling machine of the preferred embodiment includes twin-spindles which move in unison on opposite sides of a base structure to allow for simultaneous machining and repositioning passes relative to two identical groups of workpieces being machined. In addition, the milling machine employs a cutter, spindle, fixturing and transfer devices which are all adapted to contribute to the adiabatic operation, precision and efficiency of the milling process. Having the above attributes, the milling machine of the present invention is able to adiabatically machine and repeatedly produce finished precision workpieces under high volume production manufacturing conditions where flatness and parallelism tolerances are 0.001 inch (0.025 millimeters) or less.

Each spindle is mounted to the base structure so as to be rotatably held nearly perpendicular to the surface of a workpiece. In addition, the base or a portion thereof is slidable in a longitudinal direction of the machine to reciprocate the spindles in unison relative to their respective workpieces at speeds of approximately 550 to 600 inches per minute. The cutters are each a large diameter disc mounted to the end of each spindle with a number of irregularly-spaced diamond cutting inserts mounted near the cutter's perimeter. To prevent cutting at the radially inward "heel" of the inserts, a cam adjustment feature is included between each spindle and the base such that the toe of the spindles can be readily adjusted to present only the radially outward cutting edge of each insert to the workpiece. In addition, each spindle can be finely adjusted to account for different toe requirements between roughing and finishing cuts. Due to added stiffness being induced by the manner in which each cutter is mounted to its spindle, the cutters are capable of being rotated by their respective spindles at high speeds without loss of precision in the cut or damage to the diamond cutting inserts at speeds which otherwise exceed levels recommended by the industry. Moreover, the large diameter of the cutters used permit cutting speeds to be readily attained in the range of 10,000 to 20,000 sfm to achieve an adiabatic machining operation. Finally, the large diameter of the cutters permits very high surface speeds without resorting to high rotational speeds, thereby avoiding the aforementioned limitations resulting from attempts at optimizing bearing size.

Due to the large diameter of the cutter and the high speeds at which it rotates, material removal rates in excess of 7 cubic inches per minute per horsepower are achievable. The large quantity of chips formed during the adiabatic machining operation are eliminated from the area of the cutter and workpiece through the chip removal system. The chip removal system includes a pressure source which generates a pressure differential between an enclosure that peripherally surrounds the cutter and fixturing that both supports and closely surrounds the workpiece. Clearances between the enclosure and fixturing, and between the fixturing and the workpiece, provide sufficiently high speed air flow from the ambient surroundings to completely envelope the workpiece. Preferably, the air speed corresponds to the speed of the chips as they leave the cutter to augment the manner by which they are evacuated. As a result, the air flow serves to efficiently and substantially evacuate all the chips from the immediate machining area, preventing heat transfer from the chips back to the workpiece and cutter. Moreover, efficient removal of the chips from the cutting area also prevents recutting of the chips, which would otherwise significantly reduce tool life as well as the overall efficiency of the process.

In addition to having significantly higher rigidity in relation to its mass, the cutter is also specially adapted to assist in excluding chips from between the cutter and workpiece. The cutter is disc-shaped having pockets in its peripheral surface to receive the cutting inserts and gullets which are specifically formed to assist in the elimination of the chips. The cutting inserts are preferably diamond-tipped carbides which perform well at high temperatures and are not prone to galling with nonferrous materials, thereby enhancing the adiabatic capabilities of the milling machine.

The milling machine includes fixturing which also utilizes techniques that induce added rigidity in the workpieces, while reliably clamping and damping each workpiece to enable machining to within small flatness tolerances. Finally, transfer devices are employed to accurately and securely locate the workpieces within the fixture and transfer the workpieces between subsequent stages of the milling machine to enable precision machining of both sides of the workpiece. Each of the above can be programmably controlled to optimize their operation while also minimizing the amount of manpower necessary to operate the milling machine.

According to a preferred aspect of this invention, the cutting speed is specially selected to enhance the adiabatic operation of the milling machine at a high workpiece feed rate through the cutter. The speed and feed of the milling machine are most suited to the machining of nonferrous materials, and more specifically cast aluminum and magnesium alloys. The combination of a very high cutting speed and high feed rate reduces unit power requirements on the order of two times that previously recognized by the prior art. In addition, the lower cutting forces associated with the lower unit power requirements allow for face milling of thin, non-rigid workpieces, such as automotive transmission valve bodies. Consequently, the milling machine of the present invention is also well suited for machining flat surfaces having numerous surface interruptions therein.

In addition, the manner in which the chips are handled after machining further complements the milling machine's adiabatic operation. The chip removal system precludes chips from fouling the workpiece or cutter so as to prevent heat transfer back to the cutter or workpiece. Efficient elimination of the chips from the cutting area also serves to improve tool life. The preferred operation of the milling machine is dry —i.e. without cooling liquids or lubricants. Accordingly, an added benefit is that the chips can be easily recycled without the need to separate the chips from a liquid in an expensive discrete chip removal system. Moreover, the absence of cooling liquid and lubricant vapors as well as waste allows the machining operation to be conducted in a more environmentally advantageous manner.

Another significant advantage of the present invention is that the use of a large diameter cutter enables the milling machine to operate at very high surface speeds while the added static and torsional rigidity of the cutter promotes accuracy and precision of the cut using diamond cutting inserts. The structure of the cutter enables the cutter to assist in eliminating the chips from the cutting area while also preventing chips from accumulating between the cutter and workpiece. In addition, the orientation of the spindle can be quickly adjusted to ensure that the toe of the cutter is appropriate for the type and condition of cut desired, i.e. roughing or finishing. The cutter can also be adjusted to minimize radial runout for achieving improved surface finish. Accordingly, the orientation and construction of the cutter and spindle is adapted to promote a fully adiabatic machining operation.

Finally, the manner in which the workpieces are fixtured relative to the cutter enables precision machining of thin nonrigid workpieces. Also, the manner in which the workpieces are transferred into and out of the fixturing device promotes precision positioning and machining of the workpieces under high volume production manufacturing conditions.

Accordingly, it is an object of the present invention to provide a face milling machine whose operation is adiabatic and whose cutting speed and feed rate provide material removal rates with lower cutting forces and unit power requirements superior to that of the prior art.

It is a further object of the invention that the milling machine include a dry chip removal system which substantially prevents heat transfer from the chips to the cutter or workpiece so as to enhance the adiabatic machining process.

It is still a further object of the invention that the dry chip removal system include a device for creating a pressure differential between an enclosure surrounding the cutter and the workpiece with the ambient surroundings, wherein the enclosure includes a shroud circumscribing the cutter and a mask having an opening therethrough sized to closely fit the contour of the workpiece so as to create accelerated air flow and create an air curtain effect.

It is another object of the invention that the milling machine include a disc-shaped cutter which is specifically structured to assist in the removal of chips from the cutting environment and to preclude chips from collecting between the cutter and the workpiece.

It is yet another object of the invention that the cutter have enhanced rigidity for precision operation at high cutting speeds.

It is still another object of the invention that the milling machine include a spindle whose orientation to the workpiece is finely adjustable to accommodate both roughing and finishing cuts as well as adjustment for runout tolerances.

It is an additional object of the invention that the milling machine include fixturing which can securely position and damp a workpiece during machining while also inducing added rigidity into thin workpieces and thin portions of workpieces to withstand cutting forces without vibration and obtain satisfactory machined workpieces within required tolerances.

It is yet an additional object of the invention that the milling machine include transfer devices which can secure the workpieces during transporting of the workpieces to the fixture, while also promoting accurate and secure placement of the workpieces for fixturing and machining.

Other objects and advantages of this invention will be more apparent after a reading of the following detailed description taken in conjunction with the drawings provided.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a perspective view of a face milling machine in accordance with the preferred embodiment of this invention;

Figure 2 is a front view of the face milling machine of Figure 1;

Figure 3 is a side view of the face milling machine of Figure 1;

Figure 4 is a cross-sectional view of the milling machine taken along line 4—4 of Figure 3;

Figure 5 is a front view of a transfer arm for use with the milling machine of Figure 1;

Figure 6 is a cross-sectional view of the transfer arm taken along line 6—6 of Figure 5;

Figure 7 is a cross-sectional view of the spindle and cutter of the face milling machine taken along line 7—7 of Figure 3 in accordance with the preferred embodiment of this invention;

Figure 8 is a top view of the cutter taken along line 8—8 of Figure 7;

Figure 9 is a detailed front view of the cutter in accordance with a preferred embodiment of this invention;

Figure 10 is a top view of a transfer bar of the milling machine of Figure 1;

Figure 11 is a front view of the transfer bar in accordance with a preferred embodiment of this invention;

Figure 12 is a cross-sectional view of the transfer bar taken along line 12—12 of Figure 10 in accordance with the preferred embodiment of this invention;

Figure 13 is a top view of a fixture of the milling machine of Figure 1 in accordance with a preferred embodiment of this invention;

Figure 14 is a cross-sectional view of the fixture taken along line 14—14 of Figure 13;

Figure 15 is a side view of the spindle taken along line 15—15 of Figure 2 and illustrating its mounting face; and

Figure 16 is a cross-sectional view of the spindle mounting face taken along line 16—16 of Figure 15 in accordance with a preferred embodiment of this invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

MACHINE CONFIGURATION

With reference to Figures 1 through 4, there is shown a dual-spindle face milling machine 10 in which a pair of spindles 12a and 12b are mounted on opposite sides of a base 14. The base 14 is equipped with a stroking device (not shown), such as a motor driven ball screw known in the art, which strokes the spindles 12a and 12b in unison in a fore and aft direction. The spindles 12 and 12b are also movable in a vertical direction by any suitable method, such as a motor driven ball screw 15 which strokes both the spindles 12a and 12b and a portion of the base 14 to which the spindles 12a and 12b are attached.

Each spindle 12a and 12b is independently powered by a variable speed motor 16a and 16b of a type known to the art. In the preferred embodiment, each motor 16a and 16b is capable of producing 30 horsepower and speeds of approximately 5000 rpm. However, it is preferable that the motors 16a and 16b draw current only to sustain the rotational speed of the spindles 12. Accordingly, only one motor 16a or 16b draws sufficient current to machine at any given time –i.e. each motor 16a and 16b draws sufficient current to maintain its rotational speed as a workpiece 20 is being machined by its corresponding spindle 12a or 12b, permitting the spindles 12a and 12b to be synchronized to alternate between machining and repositioning operations. As an example, while the first spindle 12a is driven by its motor 16a to perform a machining operation on a workpiece 20, the other spindle 12b also moves in the same direction, but practically coasts under its own inertia as it is being repositioned for its next machining pass.

Each spindle 12a and 12b is provided with a workpiece support structure 18a and 18b upon which the workpieces 20 are supported and transported in sequential fashion to and from a pair of cutting units 22a and 22b corresponding to the pair of spindles 12a and 12b. In the preferred embodiment, the workpieces 20 are transported on each side of the milling machine 10 in groups of three to increase efficiency of one spindle 12 during machining while minimizing the time needed to reposition the other spindle 12. In addition, there is a transfer arm 24 located between the workpiece support structures 18a and 18b for transferring the groups of three workpieces 20 therebetween. After the first cutting unit 22a machines a group of workpieces 20 on a first of two sides of each workpiece 20, the transfer arm 24 rotates the workpieces 20 180 degrees as they are transferred to the next workpiece support structure 18b so as to expose a second side of each workpiece 20 to the second cutting unit 22b.

Consequently, the path of a workpiece 20 is U-shaped around the milling machine 10. One set of workpieces 20 is first transported along the first workpiece support structure 18a to the first cutting unit 22a (i.e. down the upper half of the first leg of the U) and secured by a first set of fixtures 28a (to be described more fully below) to undergo a first machining pass of the first side of the workpieces 20. Simultaneously, a second group of workpieces 20 are being machined at the second cutting unit 22b (on the second leg of the U). During the machining pass of the first spindle 12a (either in a fore or aft direction), the second spindle 12b is moved in the same direction as the first spindle 12a for repositioning so as to be ready for its next machining pass. Subsequently, after the first group of workpieces 20 are machined by the first spindle 12a, they will be further transported down the first workpiece support structure 18a, rotated by the transfer arm 24 over to the second workpiece support structure 18b (i.e. along the base of the U), and transported upon the second workpiece support structure 18b (i.e. up the lower half of the second leg of the U) toward a second set of fixtures 28b where it is again secured to be machined by the second cutting unit 22b. While the second spindle 12b is machining the workpiece 20, the first spindle 12a is being repositioned to machine the next workpiece 20 (both being stroked in a direction opposite the first spindles's 12a machining pass and the second spindle's 12b repositioning pass). Throughout the above process, power is being directed to either spindle 12a or 12b, whichever is machining a workpiece 20, while the remaining spindle 12a or 12b is allowed to almost freewheel, thus conserving power consumption of the milling machine 10. Following the above process, machining of both sides of a workpiece 20 is accomplished. In the preferred embodiment, where separate rough and finish passes are required two milling machines 10 would be located adjacent each other, with a first milling machine 10 being used to perform a roughing cut, while the second performs a subsequent finishing cut on the same workpieces 20.

TRANSFER BAR

As illustrated in Figures 1, and 10 through 12, the workpiece support structures 18a and 18b each slidably support transfer bars 26a and 26b, respectively, by which the workpieces 20 are transferred to and from the cutting units 22a and 22b. Essentially, the transfer bars 26a and 26b are a pair of beams 120 which are spaced apart a distance less than the length of the workpieces 20 so as to be able to support the workpieces 20 lengthwise. Each beam 120 has a height substantially greater than its width. The lengths of the beams 120 are roughly half the length of the workpiece support structures 18a and 18b to allow reciprocation of the transfer bars 26 along the length thereof by a suitable stroking device 122 (see Figure 4) mounted to the workpiece support structure 18. The transfer bars 26a and 26b are each stroked between a loading station 124a and 124b and an unloading station 148a and 148b beneath their respective cutting units 22a and 22b.

As best seen in Figure 10, for each workpiece 20 there is a pair of locking arms 130 attached to the upper edge of each beam 120 at its end corresponding to its loading station 124. The locking arms 130 are each oriented to have its length substantially parallel to its corresponding beam 120. The locking arms 130 are positioned on the beams 120 to locate four corners 128 of the outer periphery of each workpiece 20. The locking arms 130 are each pivotably attached to its respective beam 120 with a pivot pin 140 between an abutment end 132 and a camming end 134 of the locking arm 130. The camming end 134 includes a slot 136 formed in the locking arm 130 which limits the pivoting movement of the locking arm 130 by camming against a pin 138 extending upwardly from the beam 120. Also mounted at the camming end 134 is a spring 142 or other suitable biasing device which biases the camming end 134 outward from the beam 120 so as to bias the abutment end 132 inward toward a corresponding corner 128 of the workpiece 20. As shown, each corner 128 on the workpiece 20 is preferably an arcuate slot sized to fit a corresponding radial contour of the abutment end 132.

Located at each loading station 124a and 124b on the outward side of each beam 120 are a pair of vertical columns 126 corresponding to each pair of locking arms 130. The columns 126 are located relative to their corresponding beam 120 so as to correspond to the location of their corresponding pair of locking arms 130 when the transfer bars 26 are positioned at the loading station 124 by the stroking device 122. The columns 126 each include a lateral arm 144 which extends sufficiently inward to cam against the camming end 134 of a corresponding one of the locking arms 130 when the beams 120 are at the loading station 124. The lateral arms 144 force the camming end 134 of each locking arm 130 inward, which forces the abutment end 132 outward to disengage the corner 128 of the workpiece 20 while the transfer bars 26 remain at the loading station 124.

In operation, a set of workpieces 20 are first loaded onto a platform 34 by any suitable lifting device (not shown). The transfer bars 26 are then raised by a lifting device 121 at the loading station 124 to lift the workpieces 20 from the platform 34. The transfer bars 26 then slidably move along the workpiece support structure 18 in the direction of the cutting unit 22. As the transfer bars 26 leave the loading station 124, the lateral arms 144 disengage their corresponding camming ends 134 of the locking arms 130, allowing the abutment ends 132 of each locking arm 130 to engage its corresponding corner 128 of a workpiece 20, thereby frictionally locking each workpiece 20 in place on the transfer bars 26. Once positioned below the cutting unit 22, the workpiece support structure 18 and the transfer bars 26 are both lowered over a fixture 28 (as hereinafter disclosed) by the suitable lifting device to forcibly disengage the workpiece 20 from the locking arms 130 and engage the workpiece 20 with the fixture 28. Thereafter, while the workpiece support structure 18 is still in the lowered position, the transfer bars 26 are moved back to the loading station 124 to pick up the next set of workpieces 20.

TRANSFER ARM

Once the machining operation is complete at the cutting unit 22, the workpieces 20 are again lifted off the fixture 28 by a rear portion 146 of the transfer bars 26 at the end of the transfer bars 26 opposite the locking arms 130. The workpieces 20 are then moved to the unloading station 148 of the workpiece support structure 18, where they are grasped by the transfer arm 24. The transfer arm 24, as illustrated in Figures 5 and 6, includes a suitable base structure 150 from which the transfer arm 24 rotates between the first workpiece support structure 18a and the second workpiece support structure 18b. The primary function of the transfer arm 24 includes rotating the workpieces 20 so that a machining operation can be performed on their opposite surfaces. However, it is necessary that the workpieces 20 be precisely picked and placed from one side of the milling machine 10 to the other so that the transfer bars 26b corresponding to the workpiece support structure 18b can grasp the workpieces 20 with their corresponding locking arms 130.

To achieve this feature, the transfer arm 24 includes a parallel pair of grasping arms 152 corresponding to each workpiece 20 to be transferred. The grasping arms 152 extend parallel to each other from the end of the transfer arm 24, as can be seen in Figure 6. Each adjacent pair of grasping arms 152 is spaced apart to form a slot 170 whose width is sufficient to receive the width of the workpiece 20. The grasping arms 152 each include at least one clamping arm 154. In the preferred embodiment, a first grasping arm 152a has one clamping arm 154a while the second grasping arm 152b has two spaced-apart clamping arms 154b and 154c as shown. As a result, the workpiece 20 is grasped at three points which stabilizes the workpiece 20 as it is transferred between the workpiece support structures 18a and 18b.

Each clamping arm 154 is pivotably secured within a cavity 168 in its grasping arm 152 by a pivot pin 156. Each clamping arm 154 has an engagement end 158 and a stroking end 160 on opposite sides of the pivot pin 156. Accordingly, the engagement end 158 is able to retract into its cavity 168 during repositioning of the transfer arm 24, and extend into the slot 170 between the grasping arms 152 to engage the workpiece 20. A torsion spring 164 biases the clamping arm 154 into the slot 170 to engage the workpiece 20, while a suitable stroking device 166, such as a hydraulic or pneumatic cylinder, is provided to force the clamping arm 154 to retract into the cavity 168 and thus disengage the workpiece 20. The travel of the clamping arm 154 into the slot 170 is limited by a stop 162 formed in the cavity 168 adjacent the stroking end 160 of the clamping arm 154.

In the operation of the transfer arm 24, the workpieces 20 are transported by the transfer bars 26 to the transfer arm 24 after machining. The transfer bars 26 align the workpieces 20 relative to their respective grasping arms 152 such that each workpiece 20 will nest within a corresponding slot 170 once the transfer arm 24 is moved into position. The transfer arm 24 is then rotated upon its base 150 to engage the workpieces 20. With the grasping arms 152 on either side of a workpiece 20, the clamping arm 154a of the first grasping arm 152a is allowed to rotate into the slot 170. The stop 162 sufficiently limits the rotation of the clamping arm 154a such that the clamping arm 154a is prevented from sharply impacting the workpiece 20, which would otherwise misalign the workpiece 20 relative to the transfer arm 24 and subsequently the transfer bars 26b of the second workpiece support structure 18b. As such, the clamping arm 154a serves as a datum point for locating the workpiece 20 relative to the transfer arm 24, the second grasping arm 152b and the transfer bars 26b. Thereafter, the second and third clamping arms 154b and 154c are allowed to rotate into the slot 170 and clamp the workpiece 20 against the first clamping arm 154a. The torsion springs 164 provide sufficient biasing to secure each workpiece 20 as it is rotated by the transfer arm 24 into position for the second pair of transfer bars 26b. Once in place on the second pair of transfer bars 26b, the process is repeated, beginning with the transport of the workpieces 20 to the second cutting unit 22b.

While the preceding description has specifically recited a dual-spindle arrangement for purposes of the preferred embodiment, it will be clear to those skilled in the art that the very high speed adiabatic operation of the milling machine 10, to be described below, is not dependent upon such limited structure. Accordingly, the teachings of the present invention outlined below are not limited to the above described structure or operation.

SPINDLE

As noted above, the face milling machine 10 of the present invention includes the spindles 12 which are mounted to the base 14. As best seen in Figure 7, the spindles 12 each include a housing 30 within which the spindles 12 are rotatably supported above their corresponding fixture 28. Mounted at the lower end of each spindle 12 is one of the aforementioned cutting units 22. The cutting units 22 are generally oriented perpendicular to the axis of rotation of the spindle 12 and substantially parallel to the fixtured workpieces 20.

With reference now to Figures 15 and 16, each housing 30 includes a mounting surface 60 which abuts the portion of the base 14 which is intended to move vertically with the spindle 12 during its operation. A number of holes 68 are formed along the perimeter of the mounting surface 60 through which slightly undersized bolts 70 can secure the spindle 12 to the base 14. Formed in the upper half of the mounting surface 60 on a vertical line of symmetry is an aperture 62 in which a hardened journal 64 is installed. The journal 64 is sized to receive a shaft 66 extending from the base 14, by which the housing 30 is supported by the base 14. The journal 64 and shaft 66 allow pivotal movement between the spindle 12 and the base 14 when the bolts 70 are sufficiently loosened.

Located on the perimeter of the mounting surface 60 is an opening 72 which serves as a camming surface for an eccentric shaft 74 rotatably extending from the base 14. Attached perpendicularly from the eccentric shaft 74 is a lever 76 by which the eccentric shaft 74 can be rotated. The lever 76 can be either operated by hand or by any suitable device, such as the hydraulic cylinder 75 shown. By rotating the eccentric shaft 74, its camming effect against the opening 72 causes the housing 30 to controllably pivot about the shaft 66. The radial spacing of the opening 72 from the journal 64 enables the spindle 12 to be angularly adjusted relative to a workpiece 20. Accordingly, sufficient toe of the cutting unit 22, i.e. the degree by which the cutting unit's plane of rotation differs from the plane of the workpiece 20, can be provided to avoid impacting the trailing edge of the cutting unit 22 against the workpieces 20 or otherwise creating cross-hatching in the machined surface, both of which result in drastically reduced tool life. The toe can also be selectively altered to adapt to a particular cutting operation, such as a roughing operation or a finishing operation. In the preferred embodiment, the toe for a roughing cut is approximately

0.0025 inches, while the toe for a finishing cut is approximately 0.0005 inches. These settings can be readily obtained by operation of the eccentric shaft 74 within the opening 72.

Moreover, by automating the adjustment of the spindle 12 with a device such as the cylinder 75, the spindle 12 can be pivoted to machine in two directions. As an example of an alternate embodiment employing this method, the spindle 12 can be oriented to provide a 0.0025 inch toe while the workpiece 20 is fed through the cutting unit 22 in one direction to perform a roughing cut; thereafter, the spindle 12 can be pivoted by the eccentric shaft 74 to provide a 0.0005 inch toe in the opposite direction to perform a finishing cut on the workpiece 20. Such an arrangement can, in certain applications, eliminate the need for two separate milling machines 10 which are each dedicated to either a roughing or finishing operation, by providing the capability for bi-directional cutting.

With further reference to Figure 7, each spindle 12 is supported by bearings 32 whose preloads ensure that the spindle 12 is sufficiently supported for operating at speeds up to approximately 4000 rpm. Each spindle 12 is driven through a coupling 36 by its respective motor 16. The lower end of each spindle 12 extends outside of its housing 30, terminating in the cutting unit 22. Each cutting unit 22 includes an annular-shaped adapter 38, a mounting device 40, and a cutter 42. The adapter 38 is mounted directly to the spindle 12 by a number of bolts 41, while the cutter 42 is mounted to the adapter 38 with the mounting device 40. The mounting device 40 preferably employs a ball-locking feature (not shown) which reduces the effort needed to operate the mounting device 40. Such a mounting device 40 is disclosed in U.S. Patent No's. 3,498,653 and 4,135,418.

There are two further advantages to the use of this type of mounting device 40 over the conventional method of using mounting bolts and keying the cutter 42 to the spindle 12. Firstly, such a mounting device 40 provides accurate axial mounting of the cutter 42 relative to the spindle 12. Secondly, the mounting device 40 provides infinite radial indexing of the cutter 42 relative to the adapter 38. Such indexing enables the total axial runout at the cutter 42 relative to the workpiece 20 to be reduced by matching the high axial runout region on the adapter 38 with the low axial runout region of the cutter 42. By doing so, the effect is for the axial runout regions to cancel each other to some degree, thereby reducing waviness in the workpiece's finished surface. Waviness of less than 0.0005 inch has been achieved using this method. Not only is this a significant advantage in terms of surface quality, but the effect is to improve tool life because waviness in the finished surface is usually the criterion applied to decide when to replace the cutter's inserts.

CUTTER

As can be seen in Figures 7 and 8, the cutter 42 is substantially disc-shaped. The cutter 42 includes a number of cutting inserts 54 mounted within a like number of pockets 56 formed on the cutter's perimeter 43. The preferred diameter defined by the placement of the inserts 54 on the cutter is approximately 20 inches. Accordingly, with a rotational speed of 2800 rpm, the surface speed of the inserts 54 is 14,660 sfm. The solid disc shape of the cutter 42 is contrary to prior art cutters, which are typically annular shaped to provide clearance between the cutter and a workpiece, to reduce weight, and to improve ease of handling. However, with the teachings of the present invention, the solid disc shape of the cutter 42 forms a planar lower surface 46 which clears the workpiece 20 by approximately 0.030 inches during machining. This minimal clearance prevents chips from accumulating in a recess of the cutter 42 which would otherwise create an imbalance and vibration in the cutter 42, while also serving to prevent the workpiece 20 from breaking free of its fixture 28 if a clamping anomaly occurs. The solid disc shape also provides added inertial mass which encourages the cutter 42 and spindle 12 to coast during repositioning.

In addition to the lower surface 46, the cutter 42 is defined by the cylindrical perimeter 43, an upper surface 48 and a central opening 44. The mounting device 40 is mounted in the central opening 44 so as to be flush with the lower surface 46 of the cutter 42. The mounting device 40 abuts a radially extending shoulder 55 in the opening 44, so as to draw the cutter 42 against the adapter 38 when the mounting device 40 is engaged with the adapter 38 and tightened. The upper surface 48 of the cutter 42 includes a central raised surface 50 circumscribing the opening 44, and a peripheral raised surface 52 at its perimeter 43. The peripheral raised surface 52 is preferably elevated approximately 0.002 inches above the central raised surface 50.

Accordingly, with the mounting device 40 tightened, the peripheral raised surface 52 contacts the outer perimeter of the adapter 38 first. Thereafter, further tightening of the mounting device 40 causes the cutter 42 to distort until the central raised surface 50 also abuts the adapter 38. Consequently, the lower surface 46 of the cutter 42 is concave by approximately 0.002 inches. By distorting the cutter 42 in this manner, significant added stiffness is induced into the cutter 42 relative to its mass, permitting high speed machining of flat surfaces with significant surface interruptions, such as channels formed in automotive transmission channel plates. In addition, the peripheral raised surface 52 serves as a frictional drive surface for the cutter 42, with no significant torsional loads being imposed on the mounting device 40 during operation of the cutter 42.

The manner in which the cutter 42 is mounted to the adapter 38 offers an added capability of adapting the cutter 42 to produce a roughing and finishing cut within the same pass of a workpiece 20. However, the diameter of the cutter 42 must be sufficient for the workpiece 20 to fit within the diameter defined by the inserts 54. In addition, the inserts 54 must be provided with both an outer and inner radial cutting edge. As an example, the outer radial cutting edge may be adapted for roughing while the inner radial cutting edge is adapted for finishing. In a stress-free state, the cutter 42 would orient the attitude of the inserts 54 to present the inner radial cutting edges to the workpiece 20. Finally, the mounting device 40 must be adapted to be adjustable while the cutter 42 is rotating.

Applying this method, the cutter 42 is deflected by the mounting device 40 a predetermined axial distance relative to the adapter 38 prior to encountering the workpiece 20. The axial distance is chosen to both deflect the cutter 42 sufficiently to induce rigidity and alter the attitude of the inserts 54 such that they present their outer radial cutting edges to the workpiece 20 for roughing. Once the leading edge of the cutter 42 has machined the workpiece 20 and the workpiece 20 is centrally positioned beneath the cutter 42 and not subject to machining by any of the inserts 54, the mounting device 40 is adjusted to decrease the deflection in the cutter 42 while maintaining sufficient rigidity in the cutter 42. However, the change in deflection in the cutter 42 is sufficient to reverse the attitude of the inserts 54 such that they present their inner radial cutting edges to the workpiece 20 for finishing. As a result, one single pass of the cutter 42 is capable of both roughing and finishing the workpiece 20.

This capability may also be desirable in combination with the rotatable spindle 12 to provide further capability of effectively altering the insert geometry or clearances to thereby effect the characteristics of the finished surface.

As best seen in Figure 8, the inserts 54 are irregularly spaced about the perimeter 43 of the cutter 42 in a nonrepeating fashion to substantially produce "white noise" during the operation of the cutter 42, thereby avoiding the inducement of vibration at a single frequency. In addition, the inserts 54 are recessed into their respective pockets 56 a predetermined depth toward the cutter's center. The depth to which each insert 54 is positioned is inversely proportional to the distance between the insert 54 and the insert 54 which precedes it during the machining operation. As a result, the additional material which would be removed from the workpiece 20 due to an insert's greater spacing from its preceding insert 54 is compensated for by recessing the insert 54 to reduce its depth of cut into the workpiece 20. Accordingly, chip load is substantially uniform, promoting more uniform tool wear and longer tool life. In addition, more uniform torsional loads result as each insert 54 successively engages the workpiece 20.

As shown in Figure 9, adjacent each insert 54 is a gullet 58 formed on the perimeter 43 of the cutter 42. Conventionally, gullets 58 provide a limited void adjacent an insert 54 into which chips can escape as they leave the insert 54. In contrast, according to the present invention the gullets 58 extend completely across the full width of the cutter 42 and guide the chips in an upward direction away from the workpiece 20. As viewed from the side of the cutter 42, the circumferential width of each gullet 58 increases toward the upper surface 48 of the cutter 42. As viewed from above, illustrated in Figure 8, the radial depth of each gullet 58 also increases toward the upper surface 48 of the cutter 42. Accordingly, as the cutter 42 is rotated at high rotational speeds, back pressure downstream of the gullet 58 is prevented. Moreover, a pressure differential is believed to be created between the upper surface 48 and the lower surface 46 of the cutter 42, further encouraging the chips to travel away from the workpiece 20 and toward the upper surface 48 of the cutter 42.

INSERTS

With further reference to Figure 9, the inserts 54 are preferably a square tungsten carbide body with a polycrystalline diamond (PCD) / tungsten carbide wafer brazed into a recess on one corner of the tungsten carbide body. Such construction is generally known in the art. The inserts 54 are also slightly wedge-shaped for purposes of increasing the clamping force upon the insert 54 when acted upon by centrifugal forces while rotating at high speeds.

As is also known in the art, diamond cutting tool materials are preferable for machining aluminum and its alloys due to their high temperature capability and their low tendency for bonding, or galling, with the aluminum during machining, as would be typical with tool steels and carbides. Traditionally, the tool industry has not recommended diamond cutting materials for cutting speeds greater than 2500 sfm due to their brittleness. However, the superior rigidity of the cutter 42 in conjunction with the ability to precisely set the toe of the cutter 42 with the spindle 12 enables the milling machine 10 of the present invention to utilize diamond inserts where the prior art has failed to achieve adequate insert life.

As illustrated for a finishing cut, the diamond inserts 54 have positive radial and axial rake angles of 5 degrees. In contrast, the diamond inserts 54 preferably have a negative radial and axial rake angle of approximately 5 degrees for roughing cuts. In addition, the corner radius of the inserts 54 is dependent upon the type of cut made. Preferably, an insert for a roughing cut has a radius of 0.060 inch while an insert for a finishing cut has a radius of 0.005 inch. The clearance angle of the inserts 54 for both types of cuts is preferably 14 degrees.

As noted above, the spacing of the inserts 54 is nonrepeating. To evaluate surface finish capability of a given insert geometry and also ascertain tool life relative to an insert's placement on the perimeter 43 of the cutter 42, testing is currently underway under manufacturing conditions in which each insert 54 is serialized with its corresponding pocket 56. The performance of each serialized insert 54 is then monitored by assessing the workpiece surface finish produced and tracking the number of workpieces machined with a given set of inserts 54. When the inserts 54 are removed, the condition of each insert 54 is then evaluated. Knowing the location of each insert 54 on the cutter 42 permits a statistical analysis of the surface finish of the part, including any tendency to produce waviness in the parts. To date 140,000 pieces per insert set have been achieved, with even greater tool life being anticipated with further modifications being suggested by present results.

ADIABATIC PROCESS

In combination, the above elements —including cutting speed, feed rate, cutting insert material and spindle and cutter construction —enable the milling machine 10 of the present invention to achieve a true adiabatic shearing operation of aluminum alloy workpieces 20 during chip formation. In the art of machining, adiabatic chip formation has been known to be attainable at sufficiently high surface speeds. However, surface speed rates which are practical for use in production manufacturing operations have been a significant limitation in the prior art, in part due to the inability to provide a spindle whose bearings will allow high rotational speeds while also providing sufficient rigidity. As a practical matter, surface speeds of greater than 5000 sfm have not been recognized as improving efficiency by the prior art when machining aluminum. In addition, the prior art has provided cutters which have limited rigidity for viable use of surface speeds of greater than 10,000 sfm. Insufficient rigidity of a cutter is incompatible with the brittle nature of a diamond cutting tool, whose use is preferable due to superior tool life and its ability to avoid galling with aluminum. Moreover, material removal rates greater than 4 cubic inches per minute per horsepower have generally been unattainable, thereby demanding excessive horsepower requirements at high surface speeds using large diameter cutters.

According to the present invention, an adiabatic process is achieved at speeds between 10,000 and 20,000 sfm, with optimal results being attained at speeds of approximately 14,660 sfm. With a diameter of 20 inches for the cutter 42 of the present invention, the required rotational speed of the cutter is approximately 2800 rpm. As noted above, the added rigidity of the cutter 42 due to its deflection as mounted to the adapter 38 is sufficient to overcome the shortcomings of the prior art attributable to insufficient rigidity for machining at these elevated speeds. In addition, lower cutting forces are also achieved at the preferred cutting speed, making the process particularly suited for machining very thin aluminum workpieces 20.

In conjunction with this preferred speed, the workpieces 20 are machined at feed rates of about 600 inches per minute, and more preferably at a feed rate of approximately 580 inches per minute (and specifically, 0.008 inches per tooth), as provided by the spindle 12 as it is propelled by its stroking device. Without the use of a liquid coolant and under standard manufacturing conditions the above parameters have provided a true adiabatic machining process in which both the workpieces 20, the cutter 42 and the inserts 54 exhibit no detectable temperature rise after being completely machined. Unexpectedly, the above parameters have also permitted efficiencies in excess of 7 cubic inches per minute per horsepower.

As a result, the milling machine of the present invention operates at efficiencies much greater than that known in the prior art. As an example, under actual manufacturing conditions aluminum has been machined at the rate of 720 cubic inches per minute. The machining operation of the present invention has also provided low cutting forces with the added advantage of preventing the formation of burrs and breakouts in the workpiece 20, a not uncommon occurrence when machining surfaces having irregular or intricate surface features. Moreover, surface flatness of less than 0.001 inch has been readily attainable without thermal distortion from high cutting temperatures. Tool life in excess of 130,000 workpieces has also been attained with the above described adiabatic machining operation of the milling machine 10 of the present invention.

VACUUM SHROUD AND DECK

Once a chip is severed from the workpiece 20 with all of the heat generated being absorbed in the chip, it is imperative to evacuate the chip from the area of the cutter 42 and the workpiece 20 to prevent heat transfer thereto. The importance of this aspect is compounded by the high material removal rate possible with the milling machine 10 of the present invention. Accordingly, to ensure that the chips are quickly evacuated, the milling machine 10 incorporates a chip removal system which includes a device for creating a pressure differential between the cutting environment, including a surrounding structure 90 enclosing the cutter 42, and the ambient surroundings. In the preferred embodiment, this device is a large capacity vacuum system (not shown) capable of creating a flow rate of approximately 3500 cubic feet per minute. However, the primary parameter has been determined to be the velocity of the air flow, which is preferably closely matched with the surface speed of the cutter 42, i.e. 14,660 feet per minute. The surrounding structure or enclosure 90 determines the air speed past the workpiece 20 and cutter 42 in conjunction with the air capacity of the vacuum system.

As best seen in Figure 14, the surrounding structure 90 includes a shroud 78 and a mask 80. The shroud 78 is mounted to the spindle 12 while the mask 80 is supported by a lifting mechanism 102 which transports the mask 80 between a lower machining position and an upper position. The upper position permits the transfer bars 26 to bring the workpieces 20 into position beneath the mask 80 while the mask 80 and its corresponding spindle 12 are both raised and the spindle is being repositioned for the next machining pass. The lifting mechanism 102 can be of any suitable design, such as a limited stroke hydraulic cylinder.

The shroud 78 circumscribes the cutter 42 to form a peripheral enclosure thereto, while the mask 80 has an opening 92 which closely follows the contour of the workpiece 20. Together, the mask 80 and the workpiece 20 form the lower surface of the surrounding structure 90. The air flow through the surrounding structure 90 enters between the shroud 78 and the mask 80, and between the mask 80 and the workpiece 20, as will be described in greater detail below. Along with the suspended chips, the air flow leaves the surrounding structure 90 through a duct 88, which in turn is routed to a suitable receiving container (not shown) or the like. To reduce the necessary capacity of the vacuum system, computer controlled dampers (not shown) are preferably installed in each duct 88 near the shroud 78 to provide air flow in the surrounding structure 90 only during a machining pass by that cutter 42.

As best seen in Figure 1, the shroud 78 has an elongated portion 81 extending in the direction of the spindle's travel relative to the workpiece 20 to better prevent chips from escaping if a large concave portion is encountered in a workpiece 20. Referring again to Figure 14, the shroud 78 has an upper and lower converging wall 82 and 84, respectively, and an intermediate wall 86. The lower converging wall 84 is disposed to be adjacent the mask 80, so as to form a predetermined clearance therebetween. The lower converging wall 84 also serves to deflect chips vertically upward into the air stream as they leave the cutter 42, thus improving the efficiency of the chip removal system. The upper converging wall 82 further serves to deflect the chips into the air flow as they enter the duct 88.

As noted above, the opening 92 in the mask 80 is sized to closely fit the contour of the workpiece 20, creating a second predetermined clearance. As will be described in greater detail below, specially adapted fixture 28 is provided to ensure that the workpieces 20 are able to withstand the significant peripheral air movement and the pressure differential between their upper and lower surfaces. Moreover, as a safety feature the minimal 0.030 inch clearance between the lower surface 46 of the cutter 42 and the workpieces 20 also serves to prevent the workpieces 20 from becoming completely disengaged from their fixture 28. The combination of the predetermined clearances between the shroud 78 and the mask 80, and the mask 80 and the workpiece 20 determine the air speed given a flow capacity provided by the vacuum system. By sufficiently limiting the clearances, speeds of at least 14,000 feet per minute are achieved, corresponding to the surface of speed of the cutter 42, and thus the speed of the chips as they leave the workpiece 20.

In addition, the air flow between the mask 80 and the workpiece 20 creates a peripheral air curtain that aids in deflecting errant chips back into the surrounding structure 90. As a result, no further enclosure of the milling machine 10 is necessary to contain the chips and protect bystanders. Accordingly, the surrounding structure 90 defined by the shroud 78 and the mask 80 is substantially smaller than enclosures typically employed in the prior art.

FIXTURES

As noted above, the fixture 28 which holds the workpieces 20 is specially adapted to withstand the loading of the workpieces 20 as they become subjected to the vacuum of the chip removal system. More importantly, the fixture 28 is specifically adapted to firmly secure extremely thin aluminum workpieces 20 in a manner that enables the cutter 42 to produce surfaces within a flatness tolerance of within 0.002 inch. As seen in Figures 13 and 14, each fixture 28 consists of at least three primary rests 94, one or more secondary rests 95, a three-jaw chuck 96, a two-jaw chuck 98, and a number of damping devices 100.

Generally, the primary rests 94 serve to support the workpieces 20 within the opening 92 of the mask 80 and at a predetermined vertical position relative to the cutter 42. The primary rests 94 are preferably spaced apart relative to one another or as the workpiece 20 design provides to ensure that a stable three-point platform is provided for each workpiece 20.

The three-jaw chuck 96 is a hydraulic or pneumatically-actuated device of the type well known in the art. The three-jaw chuck 96 has three jaws 97 whose composite outer perimeter is sized to engage a cavity or first aperture 108 in the workpiece 20 so as to securely clamp the workpiece 20 on the fixture 28 in the plane of the mask 80. As an added feature, the outer peripheral surface of each jaw 97 has a layer of chrome nodules 106 deposited thereon to a thickness of approximately

0.020 by which the workpiece 20 can be better gripped. The chrome nodules 106 can be deposited by any known method, such as electroplating. Attached to one of the jaws 97 so as to extend above each jaw 97 is a debris cover 101 to prevent chips from becoming trapped between the jaws 97.

The two-jaw chuck 98 is essentially a standard hydraulic or pneumatically-actuated chuck having two jaws 110 which are angularly spaced approximately 180 degrees apart from each other. With this arrangement, the two-jaw chuck 98 is adapted to engage a cavity or second aperture 112 in the workpiece 20 in a manner that, upon the jaws 110 engaging the aperture 112, the portion of the workpiece 20 between the apertures 108 and 112 is deflected slightly downward into the fixture 28. This externally induced deflection in the workpiece 20 causes rigidity in the workpiece 20, enabling the workpiece 20 to better withstand the cutting forces associated with the milling operation.

Similar to the three-jaw chuck 96, the two-jaw chuck 98 also includes a debris cover 101 and has a layer of chrome nodules 106 deposited to the outer periphery of each jaw 110 by which the workpiece 20 can be better gripped. In addition, the two-jaw chuck 98 includes an accelerometer 99 to detect vibration in the fixture 28. If the vibration exceeds a predetermined level, the output of the accelerometer 99 can be used to shut down the milling machine 10 to allow the fixture 28 to be corrected, and thereby avoid damage to the milling machine 10 and personnel.

The downward direction in which the workpiece 20 is deflected is determined by the fact that the missing jaw would be the jaw furthest from the three-jaw chuck 96. As such, the two jaws 110 engage the side of the second aperture 112 nearest the first aperture 108 so as to compress the upper surface of the workpiece 20, forcing the lower surface of the workpiece 20 downward. The extent to which the workpiece 20 is deflected is determined by the secondary rests 95, which are positioned a predetermined distance below the plane of the primary rests 94. In the preferred embodiment, the secondary rests 95 are threaded posts which can be shimmed to accurately adjust the amount of deflection in the workpiece 20. Logic dictates that the predetermined distance must be less than the flatness tolerance of the workpiece 20, and more preferably the minimum amount necessary to achieve the desired effect.

The damping devices 100 are strategically positioned about the periphery of the workpiece 20 immediately below the mask 80 to damp vibrations in the workpiece 20 and selectively deflect specific portions of the workpiece 20 either toward or away from the cutter 42. The damping devices 100 each include a hydraulically or pneumatically actuated lever 114 which is pivotably mounted to a base 116. The lever 114 is oriented to be substantially vertical, having an upper engagement end upon which is deposited a layer of chrome nodules 106 for gripping the workpiece 20 in the same manner as the two-and three-jaw chucks 98 and 96.

The damping devices 100 can be positioned relative to the workpiece 20 such that the lever 114 engages the workpiece 20 either as the upper engagement end is rotating upward toward a vertical position or rotating downward from a vertical position. Under the former condition, the associated edge of the workpiece 20 will be deflected upward toward the cutter 42. Under the latter, the associated edge of the workpiece 20 will be deflected downward away from the cutter 42. Under either circumstance, added rigidity will be induced into the workpiece 20 to better withstand the cutting forces associated with the milling operation. In addition, the damping devices 100 can be positioned such that their cumulative effect is to urge the workpiece 20 against an abutment block (not shown), so as to provide another feature which serves to secure the workpiece 20.

In operation, the transfer bars 26 lower the workpieces 20 onto the fixture 28 while the mask 80 and spindle 12 are lifted out of the way. Because the workpieces 20 are frictionally held on the transfer bars 26 by the locking arms 130, the fixture 28 forcibly strips the workpieces 20 from the transfer bars 26, assuring that the workpieces 20 properly nest within the fixture 28 against the primary rests 94. Thereafter, the three-jaw chuck 96 engages its corresponding aperture 108, followed by the two-jaw chuck 98 which engages its corresponding aperture 112. The damping devices 100 then move in to abut the periphery of the workpiece 20. Together, the two-jaw chuck 98 and the damping devices 100 cooperate to selectively deflect the workpiece 20 in a manner that induces rigidity without distorting the surface of the workpiece 20 outside of the desired flatness tolerance.

A significant advantage of the milling machine 10 of the present invention is that the cutting speed is specially selected to enhance the adiabatic operation of the milling machine 10 at a high workpiece feed rate through the cutter 42. The speed and feed of the milling machine 10 are most suited to the machining of nonferrous materials, and more specifically aluminum alloys. The construction of the milling machine 10 also permits extremely high efficiencies of approximately 7 cubic inches per minute per horsepower – a factor of two greater than that known in the prior art. In addition, the lower cutting forces associated with the very high cutting speeds allow for face milling of thin, non-rigid workpieces 20, such as transmission channel plates. Consequently, the milling machine 10 of the present invention is also well suited for machining flat surfaces having complex surface patterns with significant surface interruptions, such as channels formed in automotive transmission channel plates.

In addition, the manner in which the chips are handled after machining further complements the milling machine's adiabatic operation. The chip removal system precludes chips from fouling the workpieces 20 and cutter 42 so as to prevent heat transfer thereto. The preferred operation of the milling machine 10 is dry – i.e. without cooling liquids or lubricants. Accordingly, an added benefit is that the chips can be easily recycled without the need to separate the chips from a liquid. Another advantage to dry machining is that the machining operation can be conducted in a more environmentally sound manner.

Another significant advantage of the present invention is that the cutters 42 are attached to their respective spindles 12 in a manner which supplements their rigidity, thus allowing the use of diamond cutting inserts 54 for machining aluminum at very high speeds. The cutters 42 are also formed to discourage chips from accumulating between the cutters 42 and workpieces 20. In addition, the orientation of the spindles 12 can be readily adjusted with the eccentric shaft 74 to ensure that the toe of each cutter 42 is appropriate for tolerance variations and for the type of cut desired, i.e. roughing or finishing. Accordingly, the orientation and construction of the cutter and spindle are adapted to promote a fully adiabatic machining operation.

Finally, the manner in which the workpieces 20 are fixtured relative to the cutter 42 and transferred into and out of the fixture 28 promotes precision and secure positioning and machining of the workpieces 20 under high volume manufacturing conditions. The fixtures 28 are able to deflect each workpiece 20 sufficiently to induce added rigidity into the workpiece 20 while remaining within the tolerance requirement for the surface of the workpiece 20. The fixtures 28, transfer bars 26 and transfer arms 24 are particularly adapted to be regulated by a suitable controller which would ensure synchronized cooperation between each device.

In contrast to prior art laboratory testing, the advantages of the milling machine 10 can be realized within a typical manufacturing environment at a combination of surface speeds, feed rates, rigidity and power which were previously unviable for such purposes. The milling machine 10 of the present invention has overcome previous bearing limitations by increasing the diameter of the cutter 42 to reduce the necessary spindle speed. The cutter 42 of the present invention is permitted to have a large diameter due to its solid construction and the added rigidity induced by the manner in which the mounting device 40 is able to adjustably clamp the cutter 42 to the adapter 38. The added rigidity of the cutter 42 also permits the use of diamond cutting inserts 54, which would otherwise have low tool life due to vibration. Tool life and uniform chip load are also promoted by locating the inserts 54 in a nonrepeating fashion on the perimeter 43 of the cutter 42 while simultaneously compensating for their irregular spacing by altering the radial position of each insert 54. Finally, the unique manner in which the chip removal system is able to completely evacuate the chips from the area of the cutter 42 and workpieces 20 enables the milling machine 10 to sustain the extremely high material removal rate which results from the very high machining surface speed. The cutter 42 is provided with gullets 58 which also assist in evacuating the chips from within the surrounding structure 90 surrounding the cutter 42 and workpiece 20. The chip removal system of the present invention also provides for superior tool life in excess of 130,000 workpieces per cutter set by preventing the recutting of chips. Each of the above features cooperate to provide an adiabatic face milling machine 10 which is practical for modern manufacturing conditions.

While the invention has been described in terms of a preferred embodiment, it is apparent that other forms could be adopted by one skilled in the art. Accordingly, the scope of the invention is to be limited only by the following claims.

What is claimed is:

1. An apparatus for performing a substantially adiabatic machining operation on a workpiece, said apparatus comprising:

means for cutting said workpiece;

means associated with said cutting means for transferring substantially all of the heat generated during said adiabatic machining operation to chips formed thereby;

enclosure means circumscribing said cutting means so as to define a peripheral enclosure for said cutting means;

means for fixturing said workpiece adjacent said cutting means; and

means in communication with said peripheral enclosure for creating a pressure differential between said peripheral enclosure and a reference pressure;

whereby said workpiece is located relative to said cutting means by said fixturing means such that said pressure differential means creates a fluid flow through said peripheral enclosure that substantially evacuates said chips from said peripheral enclosure, said cutting means and said workpiece, thereby substantially preventing heat transfer from said chips to said workpiece and said cutting means so as to achieve said adiabatic machining operation.

2. The apparatus of Claim 1 wherein said pressure differential is created between an ambient air pressure and said peripheral enclosure such that said fluid flow is air flow.

3. The apparatus of Claim 2 wherein said air flow forms an air curtain around said workpiece.

4. The apparatus of Claim 2 wherein said substantially adiabatic machining operation is a dry machining operation.

5. The apparatus of Claim 1 further comprising drive means mechanically connected to said cutting means for rotating said cutting means at surface speeds of at least 10,000 surface feet per minute.

6. The apparatus of Claim 1 wherein said cutting means comprises:

a base;

a disc-shaped cutter rotatably mounted to said base, said disc-shaped cutter having a perimeter;

a plurality of cutting inserts mounted on said perimeter of said disc-shaped cutter; and

drive means mechanically connected to said disc-shaped cutter for rotating said disc-shaped cutter.

7. The apparatus of Claim 1 wherein said transfer means associated with said cutting means comprises:

a disc-shaped cutter rotatable about an axis and supported by said base, said disc-shaped cutter having a pair of substantially parallel surfaces and a peripheral surface spaced radially from said axis and contiguous with said pair of substantially parallel surfaces;

a plurality of gullets extending across said peripheral surface so as to form a plurality of peripheral passages between said pair of substantially parallel surfaces;

a cutting insert mounted in each of said plurality of gullets; and

means mechanically connected to said disc-shaped cutter for rotating said cutting inserts at surface speeds of at least 10,000 surface feet per minute;

whereby substantially all of the heat generated during said adiabatic machining operation is transferred to said chips formed thereby, said chips being prevented from transferring heat to said workpiece and said disc-shaped cutter by being conveyed from said workpiece through said plurality of gullets to enter said fluid flow through said enclosure means.

8. The apparatus of Claim 7 wherein said transfer means associated with said disc-shaped cutter further comprises means for feeding said cutting means toward said workpiece at a rate of approximately 0.008 inches per cutting insert.

9. The apparatus of Claim 7 wherein said disc-shaped cutter comprises a substantially solid disc.

10. The apparatus of Claim 7 wherein said disc-shaped cutter has a drive surface with a central surface located at said axis and a peripheral surface spaced radially from said axis, said disc-shaped cutter being mounted to said rotating means such that said drive surface abuts said rotating means, said central surface is deflected toward said rotating means, and said peripheral surface is deflected away from said rotating means to form a concave surface opposite said drive surface, whereby the rigidity of said disc-shaped cutter is increased.

11. The apparatus of Claim 7 wherein said cutting inserts are spaced irregularly about said perimeter of said disc-shaped cutter.

12. The apparatus of Claim 7 wherein said cutting inserts are diamond inserts.

13. The apparatus of Claim 7 wherein said plurality of gullets are disposed obliquely relative to said axis and have a circumferential width that increases in a direction away from said workpiece.

14. The apparatus of Claim 1 wherein said enclosure means comprises a shroud circumscribing said cutting means, said shroud being located relative to said fixturing means and said cutting means so as to define a first predetermined gap between said shroud and said workpiece and a second predetermined gap between said shroud and said cutting means.

15. The apparatus of Claim 14 wherein said workpiece has a predetermined peripheral contour and said fixturing means comprises a planar surface having an opening closely corresponding to said predetermined peripheral contour so as to define a predetermined gap therebetween.

16. The apparatus of Claim 1 wherein said pressure differential means comprises:

a vacuum device in fluidic communication with said peripheral enclosure, said vacuum device creating a pressure differential between said peripheral enclosure and said reference pressure; and

passage means for transporting said chips from said peripheral enclosure.

17. A machining apparatus for performing a substantially adiabatic dry machining operation on a workpiece, said machining apparatus comprising:

a base member;

means for cutting rotatably mounted to said base member, said cutting means being substantially disc-shaped so as to define a perimeter;

a plurality of cutting members disposed near said perimeter of said cutting means;

means for rotating said cutting means at a predetermined surface speed at which substantially all of the heat generated during said adiabatic machining operation is transferred to chips formed thereby;

a shroud circumscribing said cutting means so as to define a peripheral enclosure for said cutting means;

means for fixturing said workpiece adjacent said cutting means;

means in communication with said peripheral enclosure for creating a pressure differential between said peripheral enclosure and an ambient air pressure; and

means for relative movement between said cutting means and said workpiece;

whereby said workpiece is located relative to said cutting means by said fixturing means such that said pressure differential means creates an air flow through said peripheral enclosure that substantially evacuates said chips from said peripheral enclosure, said cutting means and said workpiece, thereby substantially preventing heat transfer from said chips to said workpiece and said cutting means so as to achieve said adiabatic machining operation.

18. The machining apparatus of Claim 17 wherein said cutting means comprises:

a cutting disc rotatable about an axis and mounted to said base, said cutting disc having a peripheral surface spaced radially from said axis and a substantially planar axial end surface; and

a gullet associated with each of said plurality of cutting members, each said gullet extending obliquely across said peripheral surface relative to said axis;

whereby said planar axial end surface prevents said chips from collecting between said workpiece and said cutting disc, and whereby said gullets direct said chips along said peripheral surface of said cutting disc so as to enter said air flow through said peripheral enclosure such that substantially no heat generated during said adiabatic machining operation is transferred to said workpiece or said cutting disc.

19. The apparatus of Claim 18 wherein said gullets have a circumferential width that increases in a direction away from said workpiece.

20. The machining apparatus of Claim 17 wherein said cutting means is a cutting disc rotatable about an axis, said cutting disc having a drive surface with a central surface located at said axis and a peripheral surface spaced radially from said axis, said cutting disc being mounted to said rotating means such that said drive surface abuts said rotating means, said central surface is deflected toward said rotating means, and said peripheral surface is deflected away from said rotating means to form a concave surface opposite said drive surface, whereby the rigidity of said cutting disc is increased.

21. The machining apparatus of Claim 17 wherein said plurality of cutting members are spaced irregularly about said perimeter of said cutting means.

22. The machining apparatus of Claim 17 wherein said plurality of cutting members are diamond inserts.

23. The machining apparatus of Claim 17 wherein said shroud is located relative to said fixturing means and said cutting means so as to define a first predetermined gap between said shroud and said workpiece and a second predetermined gap between said shroud and said cutting means, said first and second predetermined gaps defining a passageway through said peripheral enclosure for said air flow, said air flow creating an air curtain surrounding said workpiece.

24. The machining apparatus of Claim 17 wherein said workpiece has a predetermined peripheral contour and said fixturing means comprises a table having an opening closely corresponding to said predetermined peripheral contour so as to define a predetermined gap therebetween, said predetermined gap defining a passageway around said workpiece and into said peripheral enclosure for said air flow.

25. The machining apparatus of Claim 17 wherein said pressure differential means comprises:

a vacuum device in fluidic communication with said peripheral enclosure, said vacuum device creating a pressure differential between said peripheral enclosure and said ambient air pressure; and

passage means for transporting said chips from said peripheral enclosure.

26. The machining apparatus of Claim 17 wherein said cutting means comprises a pair of cutting means oppositely disposed on said base for performing said adiabatic machining operation on a pair of workpieces, each of said pair of cutting means being sequentially driven by said rotating means, and wherein said machining apparatus further comprises:

means for translating said pair of cutting means along predetermined parallel paths, each of said pair of workpieces being supported in a corresponding one of said predetermined parallel paths;

whereby a first of said pair of cutting means is simultaneously driven by said rotating means and translated by said translating means to machine a corresponding one of said workpieces, while a second of said pair of cutting means is being repositioned by said translating means prior to machining a second of said workpieces.

27. The machining apparatus of Claim 17 further comprising means for transferring said workpiece to said fixturing means.

28. The machining apparatus of Claim 17 wherein said predetermined surface speed is a surface speed of at least 10,000 surface feet per minute.

29. The machining apparatus of Claim 17 wherein said relative movement means feeds said cutting means toward said workpiece at a speed of approximately 0.008 inches per cutting member.

30. A two-stage machining apparatus for machining a pair of workpieces, said two-stage machining apparatus comprising:

a base member;

a pair of cutting means rotatably mounted on said base member;

drive means associated with said pair of cutting means for sequentially driving each of said pair of cutting means;

means for fixturing each of said pair of workpieces adjacent a corresponding one of said pair of cutting means; and

means for simultaneously moving said pair of cutting means relative to said fixturing means and each of said pair of workpieces;

whereby a first of said pair of cutting means is simultaneously driven by said drive means and translated by said moving means to machine a first of said pair of workpieces, while a second of said pair of cutting means is repositioned by said moving means prior to machining a second of said pair of workpieces.

31. The apparatus of Claim 30 wherein said apparatus further comprises means for transferring said first of said pair of workpieces from said first of said pair of cutting means to said second of said pair of cutting means.

32. The apparatus of Claim 31 wherein said transferring means rotates said first of said pair of workpieces such that said first of said pair of cutting means machines a first surface of said first of said pair of workpieces, and said second of said pair of cutting means machines an opposite surface of said first of said pair of workpieces.

33. The apparatus of Claim 30 wherein said pair of cutting means are mounted on opposite sides of said base member.

34. The apparatus of Claim 30 wherein said moving means traverses said pair of cutting means along predetermined parallel paths, each of said pair of workpieces lying in a corresponding one of said predetermined parallel paths.

35. A method for substantially adiabatic machining of a workpiece, said method comprising the steps of:

fixturing said workpiece adjacent a cutting means;

enclosing said cutting means so as to define a peripheral enclosure for said cutting means;

creating a pressure differential between said peripheral enclosure and an ambient pressure; and

cutting said workpiece with said cutting means such that substantially all of the heat generated during said adiabatic machining is transferred to chips formed thereby;

whereby said workpiece is located relative to said cutting means such that said pressure differential creates a fluid flow that substantially evacuates said chips from said peripheral enclosure, said cutting means and said workpiece, thereby substantially preventing heat transfer from said chips to said workpiece and said cutting means so as to achieve an adiabatic machining operation.

36. The method of Claim 35 wherein said step of cutting includes the step of rotating said cutting means at surface speeds of at least 10,000 surface feet per minute such that each said chip is formed substantially adiabatically.

37. The method of Claim 35 wherein said step of cutting includes cutting said workpiece with a plurality of inserts at a feed rate of approximately 0.008 inches per insert such that each said chip is formed substantially adiabatically.

38. The method of Claim 35 wherein said step of creating a pressure differential comprises creating said pressure differential between said peripheral enclosure and an ambient air pressure such that said fluid flow is air flow.

39. The method of Claim 35 wherein said step of cutting is a dry machining operation conducted without a cooling liquid.

40. The method of Claim 35 wherein said step of cutting includes feeding said workpiece through said cutting means at a speed of at least 500 inches per minute.

41. A cutter adapted to be mounted to a drive member for machining a workpiece, said cutter comprising:

a disc-shaped body having an axis of rotation, an upper axial end, a lower axial end, and a peripheral surface spaced radially from said axis of rotation;

a planar surface disposed at said lower axial end, said planar surface comprising substantially all of said lower axial end and being contiguous with said peripheral surface; and

a drive surface disposed at said upper axial end, said drive surface defining a central raised surface located at said axis of rotation and an annular raised surface spaced radially from said axis of rotation adjacent said peripheral surface, said annular raised surface having a higher elevation than said central raised surface;

whereby said drive surface abuts said drive member such that said central raised surface is deflected toward said drive member to distort said planar surface so as to define a concave surface opposite said drive surface, wherein the rigidity of said cutter is increased.

42. The cutter of Claim 41 further comprising a plurality of gullets formed in and extending across said peripheral surface.

43. The cutter of Claim 42 wherein each of said plurality of gullets extend obliquely across said peripheral surface relative to said axis of rotation.

44. The cutter of Claim 42 wherein each of said plurality of gullets have a circumferential width that increases in a direction away from said lower axial end.

45. The cutter of Claim 42 wherein each of said plurality of gullets have a radial depth that increases in a direction away from said lower axial end.

46. The cutter of Claim 41 further comprising a plurality of receptacles for receiving a plurality of cutting inserts.

47. The cutter of Claim 46 wherein said plurality of receptacles are irregularly spaced on said peripheral surface.

48. The cutter of Claim 41 further comprising means for mounting said cutter to said drive member.

49. The cutter of Claim 48 wherein said means for mounting said cutter to said drive member is a variable adjustment means adapted to alter the concavity of said planar surface of said cutter.

50. A milling cutter adapted to be mounted to a drive member for machining a workpiece, said milling cutter comprising:

a disc-shaped body having an axis of rotation, an upper axial end, a lower axial end, and a peripheral surface concentric with said axis of rotation;

a cavity formed in said lower axial end at said axis of rotation;

a annular planar surface disposed at said lower axial end and circumscribing said cavity, said annular planar surface being contiguous with said peripheral surface;

means for adjustably mounting said milling cutter to said drive member disposed in said cavity;

a drive surface disposed at said upper axial end, said drive surface defining a central raised surface located at said axis of rotation and an annular raised surface spaced radially from said axis of rotation adjacent said peripheral surface, said annular raised surface having a higher elevation than said central raised surface; and

a plurality of gullets formed in and extending obliquely across said peripheral surface relative to said axis of rotation;

whereby said annular raised surface abuts said drive member and said adjustable mounting means secures said milling cutter to said drive member such that said central raised surface is deflected toward said drive member to distort said annular planar surface so as to define a concave surface opposite said drive surface, wherein the rigidity of said milling cutter is increased.

51. The milling cutter of Claim 50 wherein said adjustable mounting means defines a substantially coplanar surface with said annular planar surface.

52. The milling cutter of Claim 50 wherein each of said plurality of gullets have a circumferential width that increases in a direction away from said workpiece.

53. A cutter for machining a workpiece, said cutter comprising:

a disc-shaped body having an axis of rotation and a peripheral surface spaced radially from said axis of rotation; and

means disposed on said peripheral surface for receiving a plurality of cutting inserts, said receiving means being spaced irregularly along a circumferential direction of said disc-shaped body, each of said receiving means having a radial depth relative to said peripheral surface in a direction toward said axis of rotation, each said radial depth for a corresponding one of said receiving means being substantially inversely proportional to a distance between said one of said receiving means and a second of said receiving means, wherein said second of said receiving means proceeds said one of said receiving means when said cutter is rotated to machine said workpiece;

whereby said receiving means are irregularly spaced so as to substantially produce white noise as said cutter is machining said workpiece, and wherein said radial depths of said receiving means compensate for said irregular spacing so as to provide substantially equal material removal from said workpiece by each of said plurality of cutting inserts during a revolution of said cutter.

54. A cutter adapted to be adjustably mounted to a drive member for machining a workpiece with both a leading and trailing edge of said cutter, said cutter comprising:

a cutter body having an axis of rotation, an upper axial end, a lower axial end and a peripheral surface spaced from said axis of rotation;

a drive surface disposed at said upper axial end; and

means associated with said cutter body for adjustably mounting said cutter body to said drive member, said adjustable mounting means being adapted to adjustably create a concavity in said lower axial end of said cutter body while said cutter body is being rotated so as to axially deflect said peripheral surface of said cutter body.

55. A cutter adapted to be adjustably mounted to a drive member for infinite radial indexing of said cutter relative to a drive member, said cutter comprising:

a cutter body having an axis of rotation, an upper axial end, a lower axial end and a peripheral surface spaced from said axis of rotation;

a drive surface disposed at said upper axial end; and

means associated with said cutter body for adjustably mounting said cutter body to said drive member, said adjustable mounting means being adapted to provide radial indexing of said upper axial end relative to said drive member so as to compensate for axial runout of each said cutter body and said drive surface, thereby minimizing runout at said lower axial end of said cutter body adjacent said peripheral surface.

56. A transfer device for transporting a workpiece to and from a machining station, said transfer device comprising:

means for supporting said workpiece;

means mechanically connected to said support means for transporting said support means between a first position and said machining station so as to transport said workpiece from said first position to said machining station;

means mounted to said support means for frictionally abutting said workpiece, said abutting means being movable between an open position and a closed position;

means in communication with said abutting means for biasing said abutting means toward said closed position; and

camming means mounted to said support means for camming said abutting means between said open and closed positions;

whereby said workpiece is loaded on said support means at a loading station at which said camming means is engaged with said abutting means to open said abutting means so as to allow loading of said workpiece, and whereby said camming means disengages said abutting means so as to allow said abutting means to abut against said workpiece as said support means transports said workpiece toward said machining station.

57. The transfer device of Claim 56 wherein said support means is a pair of substantially parallel rails.

58. The transfer device of Claim 56 further comprising a base for slidably supporting said support means.

59. The transfer device of Claim 56 further comprising means adjacent said support means for dislodging said workpiece from said support means at said machining station.

60. A transfer device for transferring a workpiece from a loading station to a fixturing station, said transfer device comprising:

a base;

at least one rail movable on said base for transporting said workpiece between said loading station and said fixturing station;

at least one abutment member pivotably mounted to said at least one rail for frictionally abutting said workpiece, said at least one abutment member being movable between an open position and a closed position;

a spring engaged with said at least one abutment member for biasing said at least one abutment member toward said closed position;

a camming member mounted to said base adjacent said at least one rail, said camming member being engaged with said at least one abutment member when said workpiece is in said loading station to pivot said at least one abutment member into said open position;

fixturing means mounted below said at least one rail for supporting said workpiece at said fixturing station; and

means mechanically connected to said at least one rail for lowering said at least one rail toward said fixturing means to lift said workpiece from said at least one rail and to dislodge said workpiece from said at least one abutment member;

whereby said workpiece is loaded on said at least one rail at said loading station wherein said camming member is engaged with said at least one abutment member to open said at least one abutment member so as to allow loading of said workpiece, and whereby said camming member disengages with said at least one abutment member so as to pivot said at least one abutment member against said workpiece to positively retain said workpiece to said at least one rail as said at least one rail transports said workpiece away from said loading station and toward said fixturing station.

61. The transfer device of Claim 60 wherein said at least one rail is a pair of substantially parallel rails.

62. The transfer device of Claim 61 wherein said at least one abutment member comprises at least two pins, at least one of said at least two pins being pivotably mounted to each of said pair of substantially parallel rails.

63. The transfer device of Claim 61 wherein said at least one abutment member comprises at least two pins, said at least two pins being pivotably mounted to at least one of said pair of substantially parallel rails.

64. A fixturing device for supporting a workpiece during a machining operation, said fixturing device comprising:

means for supporting said workpiece; and

means adjacent said support means for engaging at least one edge of said workpiece, said engaging means deflecting at least a portion of said workpiece a predetermined distance toward said fixturing device;

whereby added rigidity is induced in said workpiece as a result of said deflecting.

65. The fixturing device of Claim 64 wherein said support means comprises at least three support members.

66. The fixturing device of Claim 64 wherein said predetermined distance is less than a predetermined tolerance of said workpiece.

67. The fixturing device of Claim 64 further comprising an abutment member adjacent said support means, wherein said engaging means creates a resultant force which urges said workpiece against said abutment member.

68. A fixturing device for supporting a workpiece during a machining operation, said fixturing device comprising:

means for supporting said workpiece on at least three points;

means adjacent said support means for engaging at least one edge of said workpiece, said engaging means deflecting at least a portion of said workpiece; and

secondary means for supporting said workpiece located adjacent said engaging means, said secondary support means having an elevation which is a predetermined distance below a plane defined by said at least three points, said secondary support means limiting the deflection of said workpiece to said predetermined distance;

whereby added rigidity is induced in said workpiece as a result of deflecting said workpiece said predetermined distance.

69. The fixturing device of Claim 68 further comprising an abutment member adjacent said support means, wherein said engaging means creates a resultant force which urges said workpiece against said abutment member.

70. The fixturing device of Claim 68 wherein said engaging means comprises a plurality of damping devices.

71. The fixturing device of Claim 68 wherein said plurality of damping devices each comprise an engagement surface having a coarse chrome layer deposited thereon.

72. A fixturing device for supporting a workpiece during a machining operation wherein said workpiece includes an aperture therethrough, said fixturing device comprising:

means for supporting said workpiece; and

means adjacent said support means for engaging said aperture asymmetrically, said asymmetric engagement means deflecting at least a portion of said workpiece a predetermined distance;

whereby added rigidity is induced in said workpiece as a result of deflecting said workpiece said predetermined distance.

73. The fixturing device of Claim 72 wherein said support means comprises at least three support members.

74. The fixturing device of Claim 72 wherein said asymmetric engagement means comprises an asymmetrical chuck having two jaws spaced less than 180 degrees apart, said two jaws being sized to be received in said aperture.

75. The fixturing device of Claim 72 wherein said predetermined distance is less than a predetermined tolerance of said workpiece.

76. The fixturing device of Claim 72 further comprising an abutment member mounted to said support means, whereby said asymmetric engagement means creates a resultant force which urges said workpiece against said abutment member.

77. The fixturing device of Claim 72 further comprising means for sensing vibration mounted to said asymmetric engagement means.

78. A fixturing device for supporting a workpiece during a machining operation wherein said workpiece includes an aperture therethrough, said fixturing device comprising:

means for supporting said workpiece on at least three points;

means adjacent said support means for engaging said aperture asymmetrically, said asymmetric engagement means deflecting at least a portion of said workpiece; and

secondary means for supporting said workpiece located adjacent said asymmetric engagement means, said secondary support means having an elevation which is a predetermined distance below a plane defined by said at least three points, said secondary support means limiting the deflection of said workpiece to said predetermined distance;

whereby added rigidity is induced in said workpiece as a result of deflecting said workpiece said predetermined distance.

79. The fixturing device of Claim 78 further comprising an abutment member adjacent said support means, wherein said asymmetric engagement means creates a resultant force which urges said workpiece against said abutment member.

80. The fixturing device of Claim 78 wherein said asymmetric engagement means comprises an asymmetrical chuck having two jaws spaced less than 180 degrees apart, said two jaws being sized to be received in said aperture.

81. The fixturing device of Claim 80 wherein said two jaws each comprise an engagement surface having a coarse chrome layer deposited thereon.

82. The fixturing device of Claim 78 further comprising means for sensing vibration mounted to said asymmetric engagement means.

83. A fixturing device for supporting a workpiece during a machining operation wherein said workpiece includes an aperture therethrough, said fixturing device comprising:

means supporting said workpiece;

clamping means adjacent said support means for engaging at least one edge of said workpiece; and

means adjacent said support means for engaging said aperture asymmetrically;

whereby said asymmetric engagement means and said clamping means deflect at least a portion of said workpiece a predetermined distance toward said support means so as to induce rigidity in said workpiece.

84. The fixturing device of Claim 83 wherein said support means comprises at least three support members.

85. The fixturing device of Claim 83 wherein said predetermined distance is less than a predetermined tolerance of said workpiece.

86. The fixturing device of Claim 83 further comprising an abutment member adjacent said support means, whereby said clamping means creates a resultant force which urges said workpiece against said abutment member.

87. A fixturing device for supporting a workpiece during a machining operation wherein said workpiece includes at least one aperture therethrough, said fixturing device comprising:

means for supporting said workpiece on at least three points;

secondary means for supporting said workpiece located intermediate at least two of said at least three points, said secondary support means having an elevation which is a predetermined distance below a plane defined by said at least three points;

means adjacent said support means for engaging at least one edge of said workpiece; and

an asymmetric chuck comprising two jaws spaced less than 180 degrees apart, said two jaws being sized to be received in said aperture;

whereby said two jaws of said asymmetrical chuck and said engagement means deflect at least a portion of said workpiece against said secondary support means so as to induce rigidity in said workpiece as a result of being deflected said predetermined distance.

88. The fixturing device of Claim 87 further comprising an abutment member mounted adjacent said support means, whereby said engagement means creates a resultant force which urges said workpiece against said abutment member.

89. The fixturing device of Claim 87 wherein said engagement means and said two jaws each comprise an engagement surface having a coarse chrome layer deposited thereon.

90. The fixturing device of Claim 87 wherein said workpiece has a second aperture therethrough, said fixturing device comprising a second chuck having a plurality of equally spaced jaws, said plurality of equally spaced jaws being sized to be received in said second aperture so as to stabilize said workpiece relative to said asymmetric chuck.

91. The fixturing device of Claim 87 further comprising means for sensing vibration mounted to said asymmetric chuck.

92. A method for supporting a workpiece during a machining operation, said method comprising the steps of:

supporting said workpiece on a fixture;

engaging at least one edge of said workpiece with at least one clamping member; and

deflecting at least a portion of said workpiece a predetermined distance with said at least one clamping member;

whereby added rigidity is induced in said workpiece as a result of said deflecting.

93. The method of Claim 92 wherein said step of supporting includes supporting said workpiece upon at least three support members.

94. The method of Claim 92 wherein said deflecting step causes said workpiece to deflect less than a predetermined tolerance of said workpiece.

95. The method of Claim 92 further comprising the step of providing an abutment member on said fixture wherein said step of engaging said at least one clamping member creates a resultant force which urges said workpiece against said abutment member.

96. The method of Claim 92 further comprising the step of limiting said deflecting to a predetermined distance.

97. A method for supporting a workpiece during a machining operation wherein said workpiece includes at least one aperture therethrough, said method comprising the steps of:

supporting said workpiece on a fixture; and

asymmetrically engaging said aperture so as to deflect at least a portion of said workpiece a predetermined distance;

whereby added rigidity is induced in said workpiece as a result of said deflection.

98. The method of Claim 97 wherein said step of supporting includes supporting said workpiece upon at least three support members.

99. The method of Claim 97 further comprising the step of limiting said deflection to a predetermined distance.

100. The method of Claim 99 wherein said step of limiting said deflection causes said workpiece to deflect less than a predetermined tolerance of said workpiece.

101. A method for supporting a workpiece during a machining operation wherein said workpiece includes at least one aperture therethrough, said method comprising the steps of:

supporting said workpiece on a fixture;

engaging at least one edge of said workpiece with at least one clamping member;

engaging said aperture with an asymmetrical chuck comprising at least two jaws spaced less than 180 degrees apart;

opening said asymmetrical chuck such that said at least two jaws engage said workpiece; and

deflecting at least a portion of said workpiece a predetermined distance with said at least two jaws and said at least one clamping member;

whereby added rigidity is induced in said workpiece as a result of said deflecting.

102. The method of Claim 101 wherein said step of supporting includes supporting said workpiece upon at least three support members.

103. The method of Claim 101 wherein said deflecting step causes said workpiece to deflect less than a predetermined tolerance of said workpiece.

104. A housing for rotatably supporting a milling spindle to a base relative to fixturing for supporting a workpiece, said housing comprising:

an axis corresponding to an axis of rotation of said spindle;

means disposed on said housing for pivotably mounting said housing to said base; and

means disposed on said housing for camming said housing relative to said base, said camming means being spaced from said mounting means;

whereby said axis of said housing can be adjusted relative to said workpiece by camming said housing relative to said base so as to adjust the toe of said milling spindle.

105. The housing of Claim 104 wherein said camming means comprises a camming surface and a camming member camming with said camming surface.

106. The housing of Claim 105 wherein said camming surface is an aperture in said housing.

107. The housing of Claim 105 wherein said camming member is an eccentric shaft rotatably mounted to said base.

108. The housing of Claim 104 wherein said base includes a pin and wherein said mounting means is a journal formed on said housing, said journal being pivotable upon said pin so as to provide relative rotation between said housing and said base.

109. A milling column for rotatably supporting a milling spindle to a milling machine base relative to fixturing for supporting a workpiece, said housing comprising:

an axis corresponding to an axis of rotation of said spindle;

means disposed on said housing for pivotably mounting said housing to said base;

a camming surface disposed on said housing in spaced relation to said mounting means; and

a camming member mounted to said base and slidably engaged with said camming surface;

whereby said axis of said housing can be adjusted relative to said workpiece by rotating said camming member within said camming surface to rotate said housing relative to said base so as to adjust the toe of said milling spindle.

110. The housing of Claim 109 wherein said camming surface is an aperture in said housing.

111. The housing of Claim 109 wherein said camming member is an eccentric shaft rotatably mounted to said base.

112. The housing of Claim 109 wherein said base includes a pin and wherein said mounting means is a journal formed on said housing, said journal being pivotably mounted on said pin so as to provide relative rotation between said housing and said base.

113. A transfer device for precision picking and placing of a workpiece, said transfer device comprising:

a pair of juxtaposed members spaced apart to form a slot therebetween for receiving said workpiece;

means attached to said pair of juxtaposed members for moving said pair of juxtaposed members between a first position and a second position;

a clamping member pivotably attached to each of said pair of juxtaposed members, said clamping member having a pivot end for pivotably mounting said clamping member to each of said pair of juxtaposed members and an engagement end which is pivotable into said slot for engaging said workpiece;

means engaged with each said clamping member for biasing each said clamping member into said slot;

stop means associated with each said clamping member for limiting the extent to which each said clamping member extends into said slot such that said clamping members are spaced apart a predetermined distance when in an extended position, said predetermined distance being less than a corresponding width of said workpiece; and

means associated with said clamping members for holding each said clamping member in a retracted position, said holding means sequentially allowing a first clamping member and a second clamping member, respectively, to extend into said slot;

whereby upon being released by said holding means, said first clamping member moves toward said workpiece until said first clamping member engages said stop means, said stop means defining a predetermined position for said first clamping member, and upon being released by said holding means, said second clamping member moves toward said workpiece until said second clamping member engages said workpiece, said second clamping member clamping said workpiece against said first clamping member so as to locate said workpiece in a predetermined position for transport.

114. The transfer device of Claim 113 wherein said moving means comprises:

a base associated with said pair of juxtaposed members;

an arm pivotably mounted to said base, said pair of juxtaposed members being mounted to said arm; and

control means associated with said arm for rotating said arm between said first and second positions.

115. The transfer device of Claim 113 wherein said first position is a workpiece loading station and said second position is a workpiece unloading station.

116. The transfer device of Claim 113 wherein there is one said first clamping member mounted to a first of said pair of juxtaposed members and two said second clamping members mounted to a second of said pair of juxtaposed members.

117. The transfer device of Claim 116 wherein said two second clamping members are in spaced apart relationship, said one first clamping member being positioned intermediate said two second clamping members.

118. The transfer device of Claim 113 wherein said holding means comprises a cylinder corresponding to each said clamping member, said cylinder being energized to hold each said clamping member in said retracted position and de-energized to allow each said clamping member to rotate into said slot.

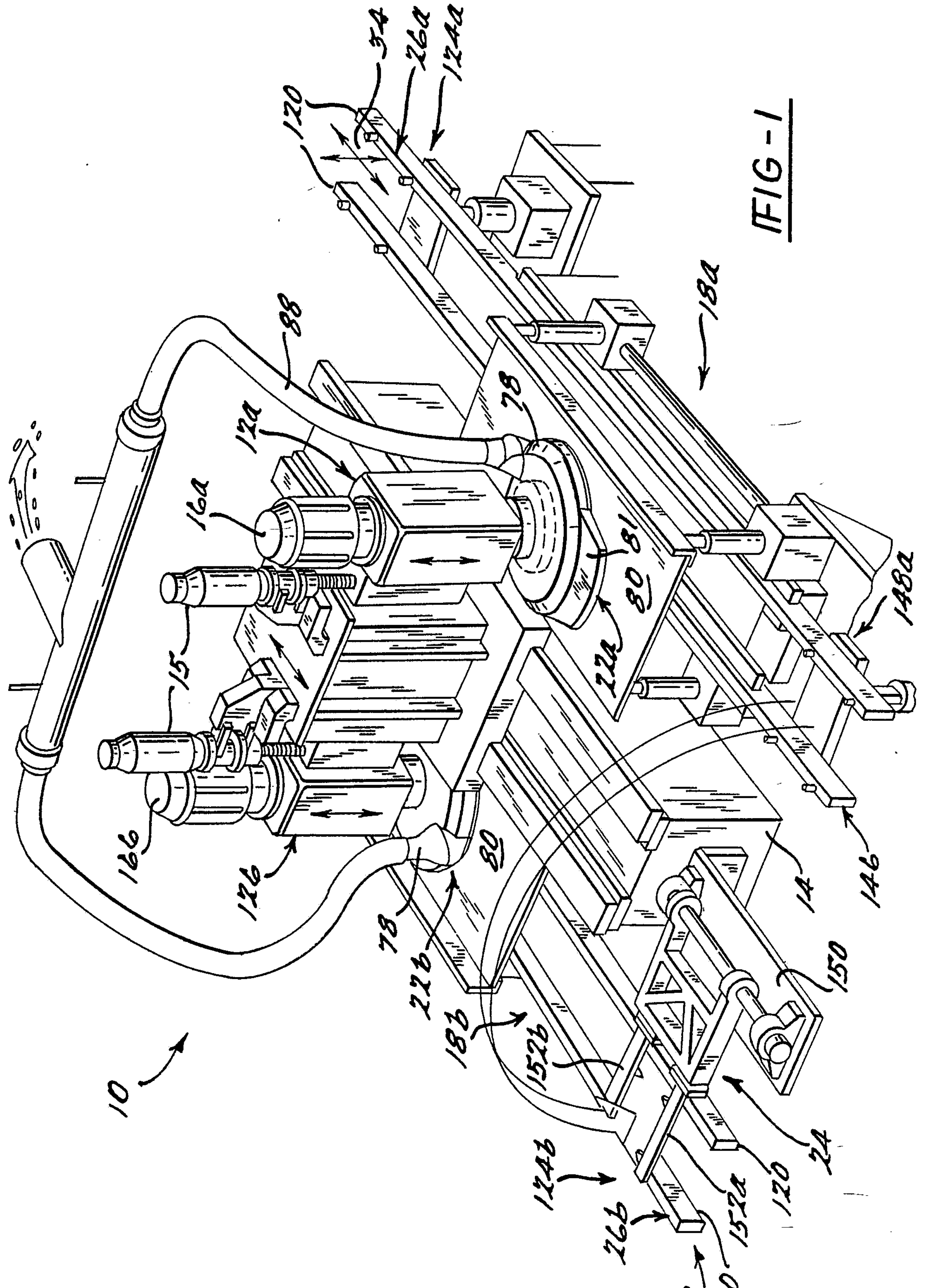
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FIG-1

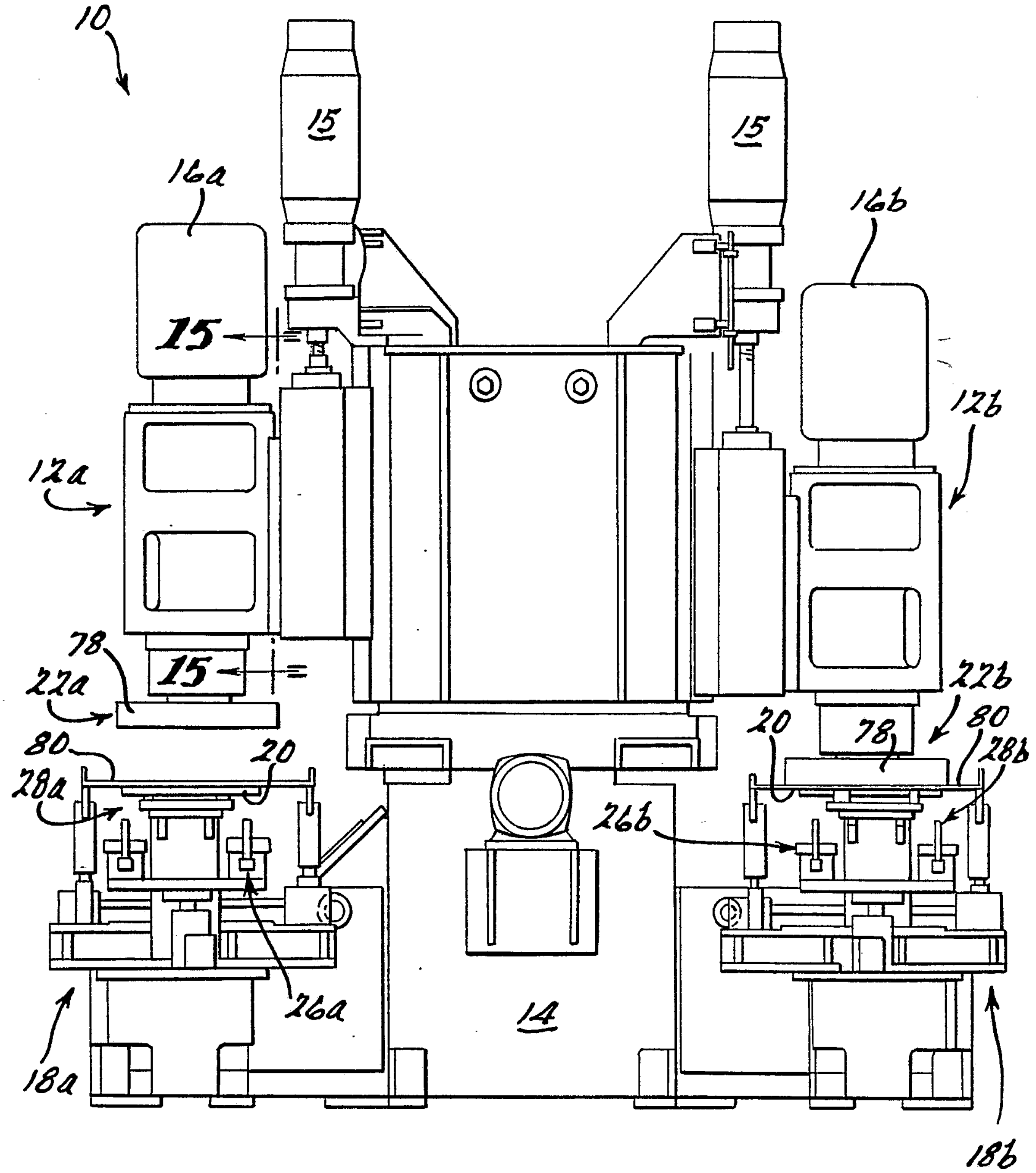
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FIG-2

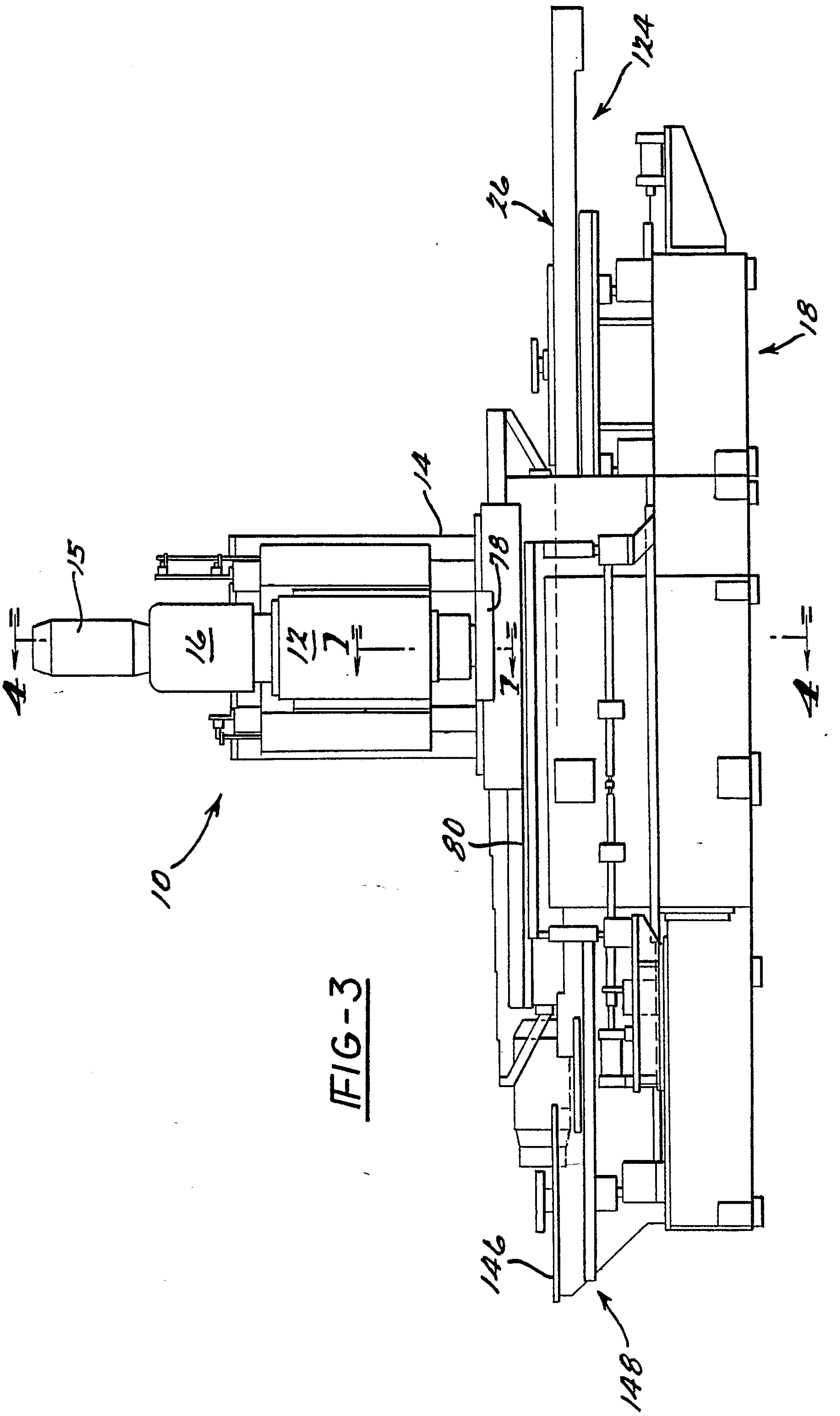

FIG-3

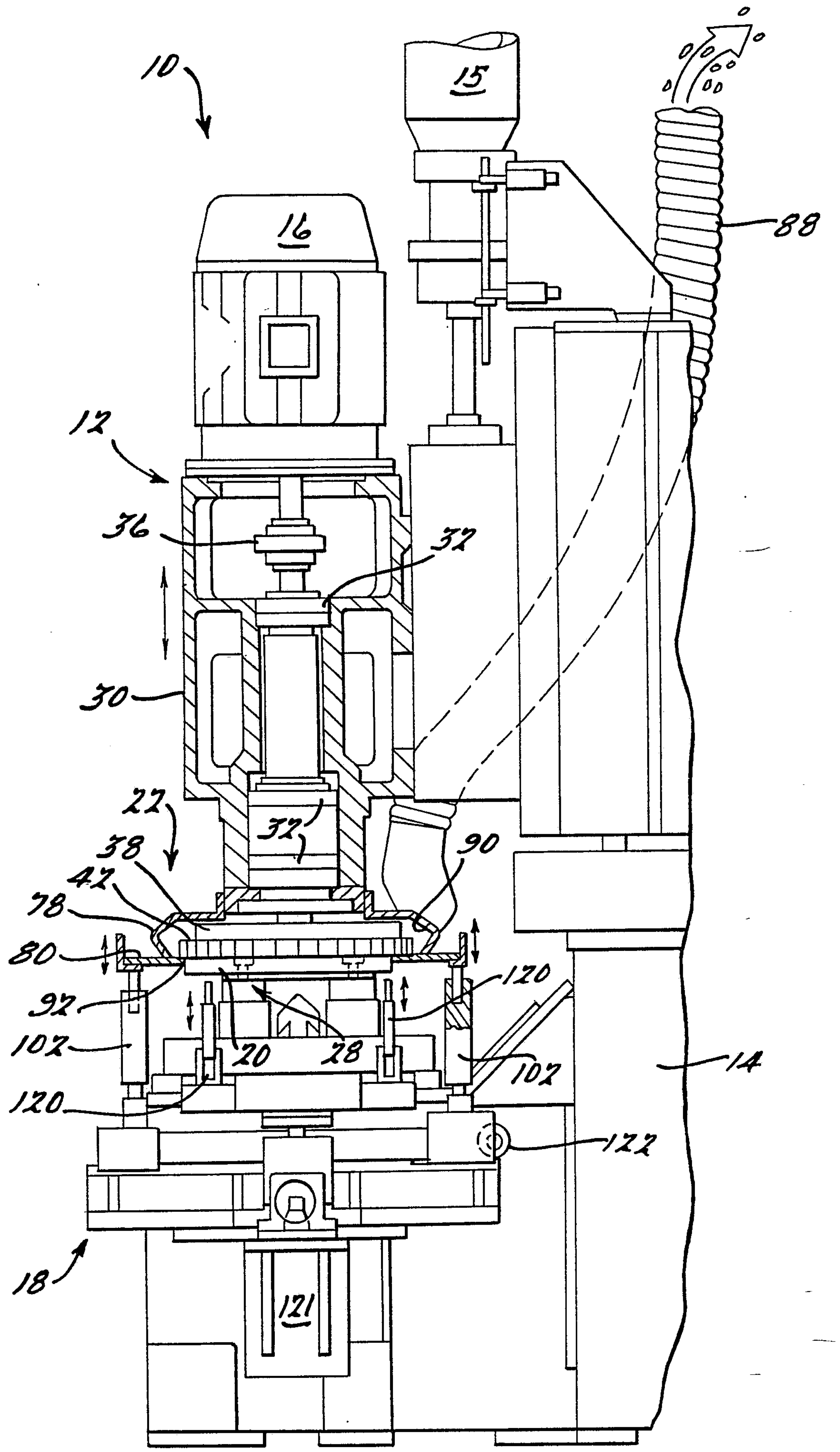
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FIG-4

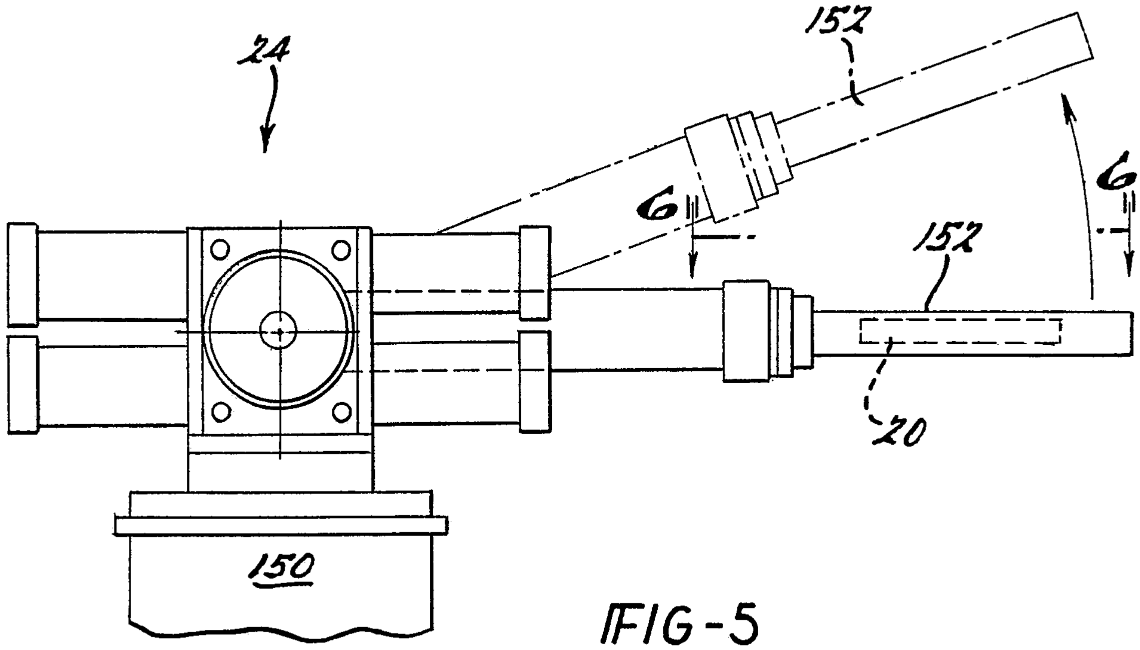
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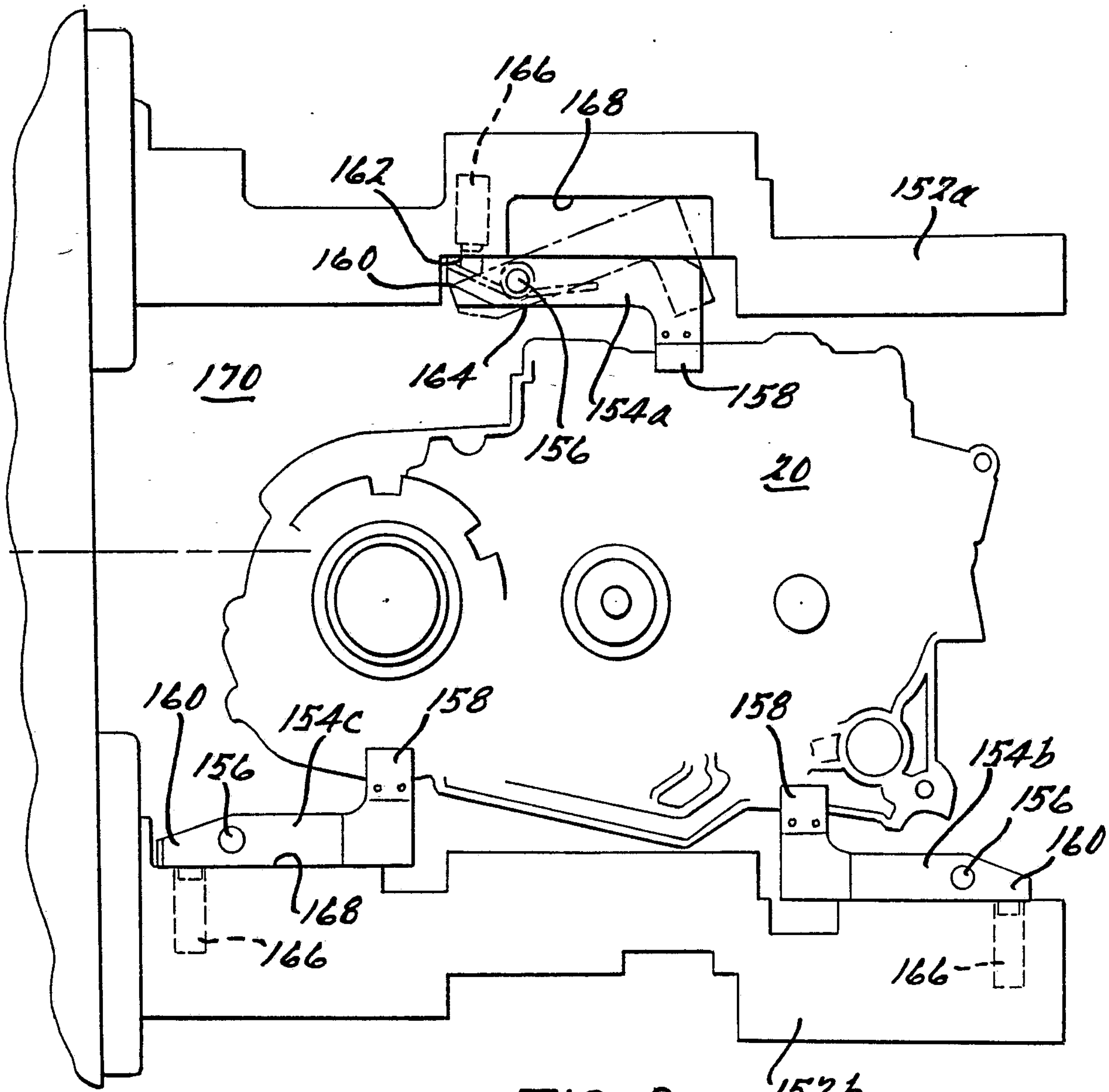
FIG-5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154c
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154b
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152b

FIG-6

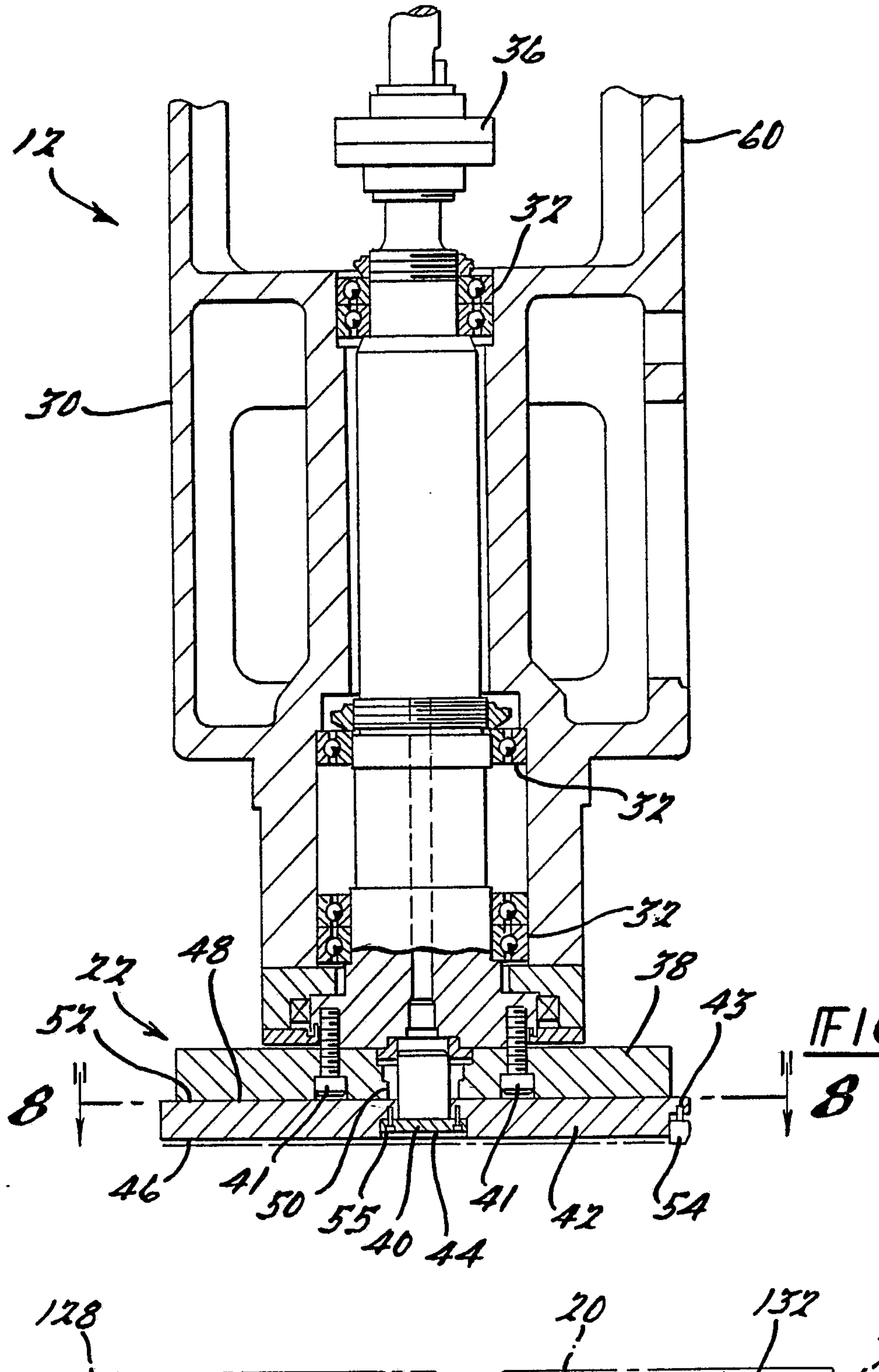

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FIG-7

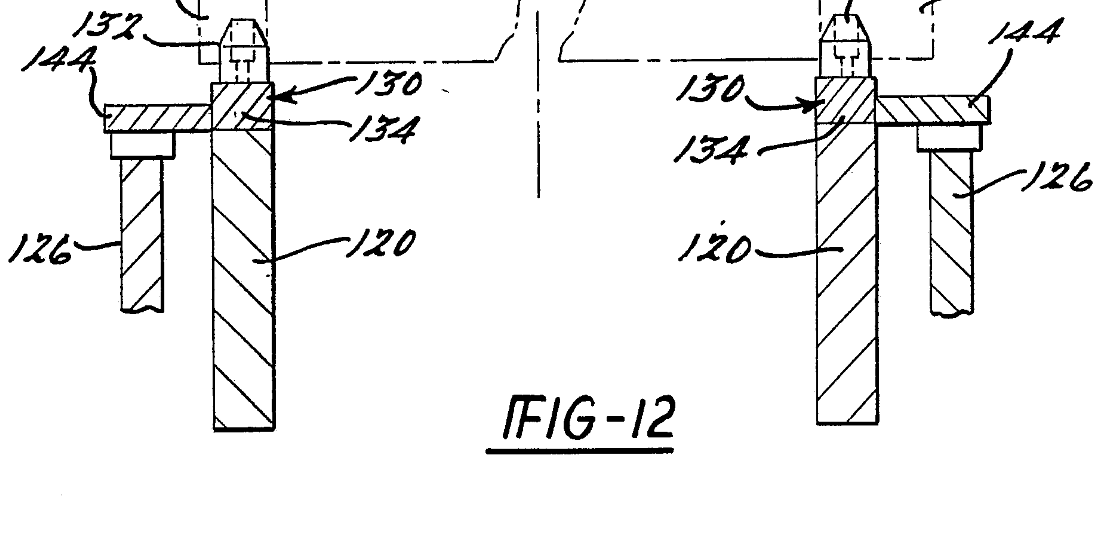

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FIG-12

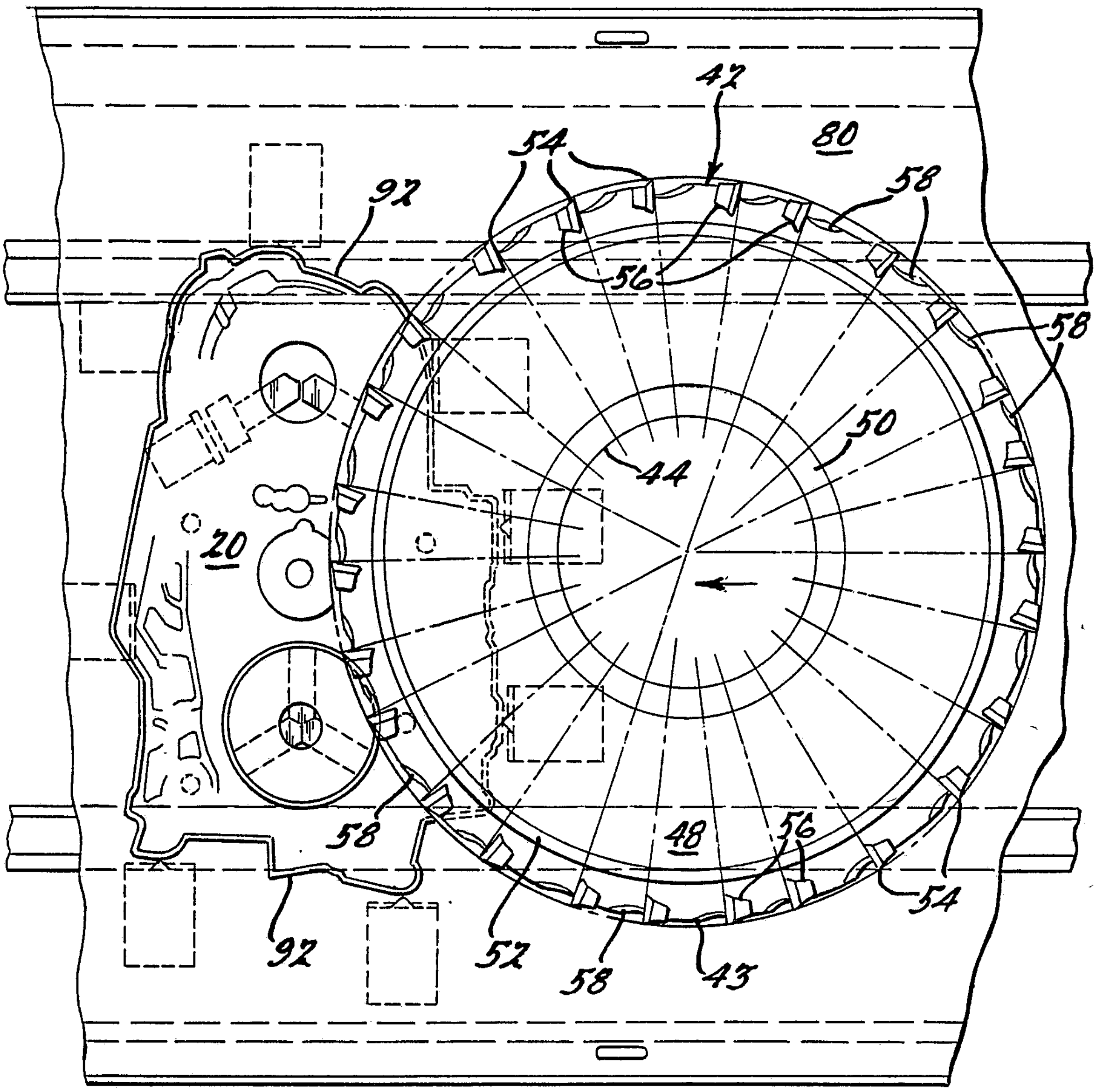


FIG-8

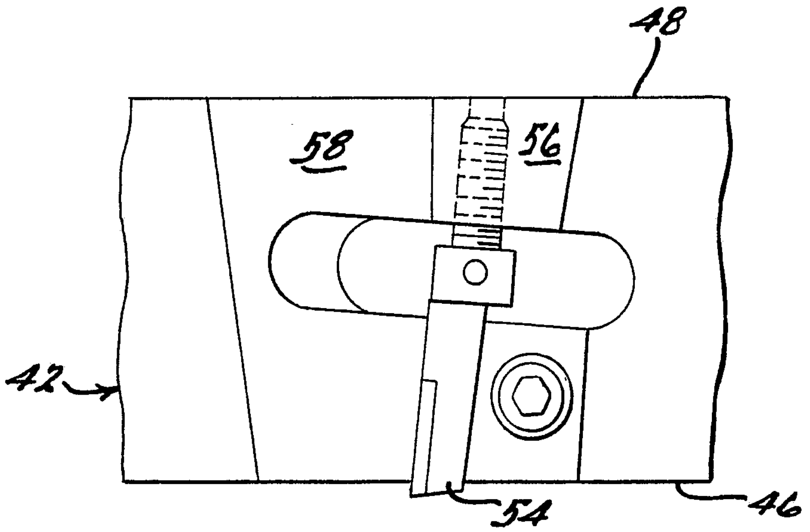


FIG-9

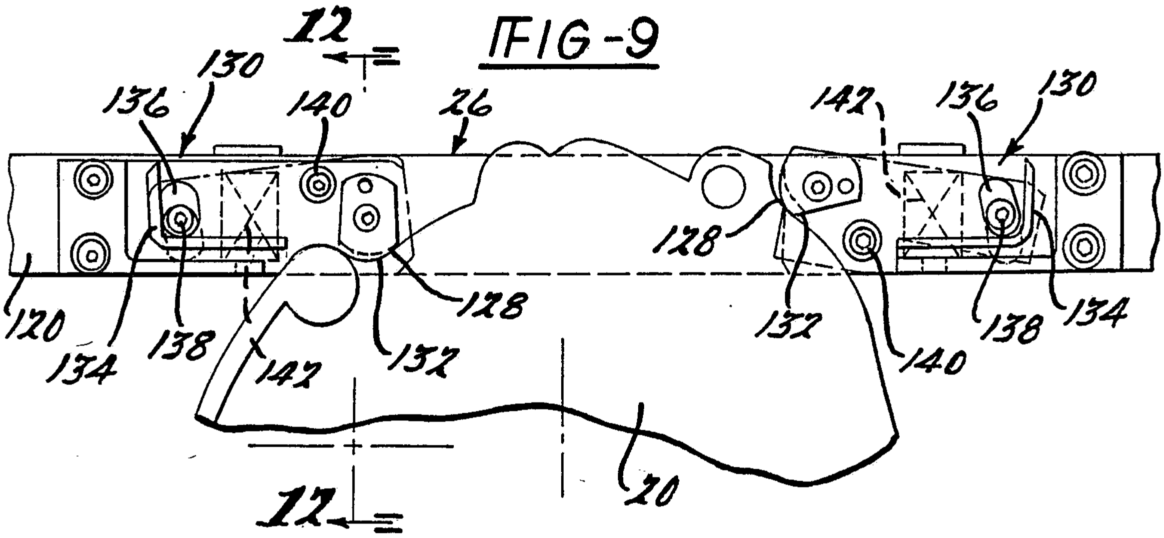


FIG-10

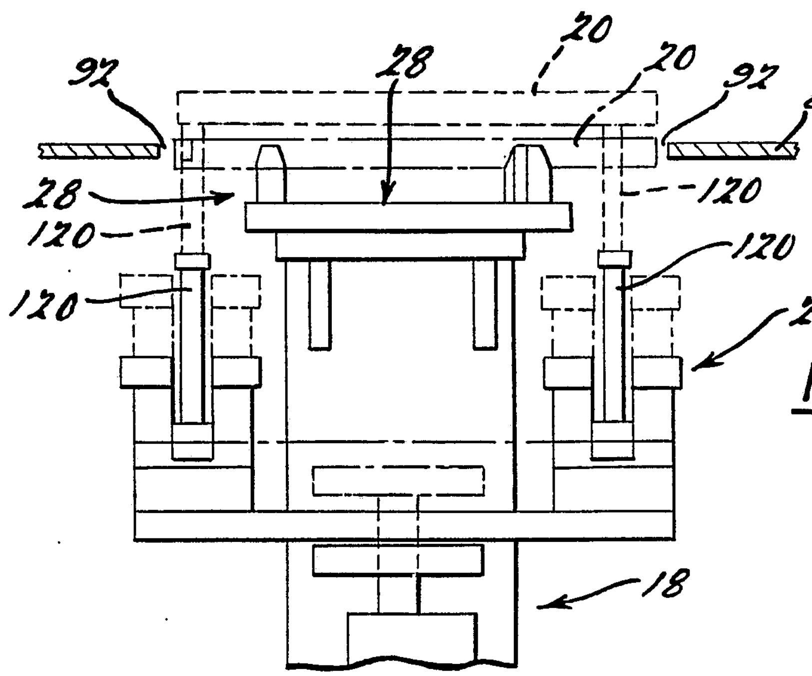
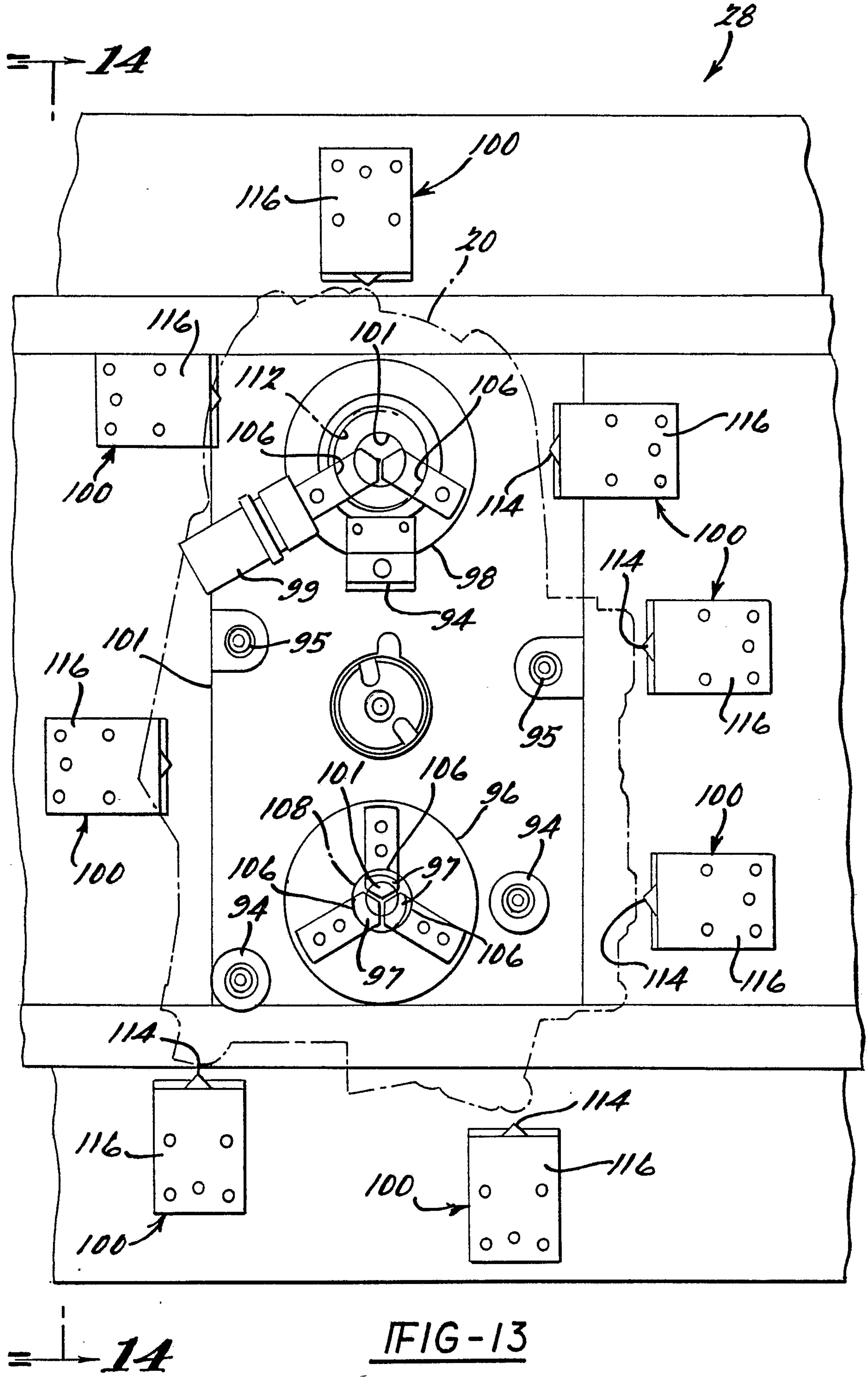


FIG-11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IFIG-13

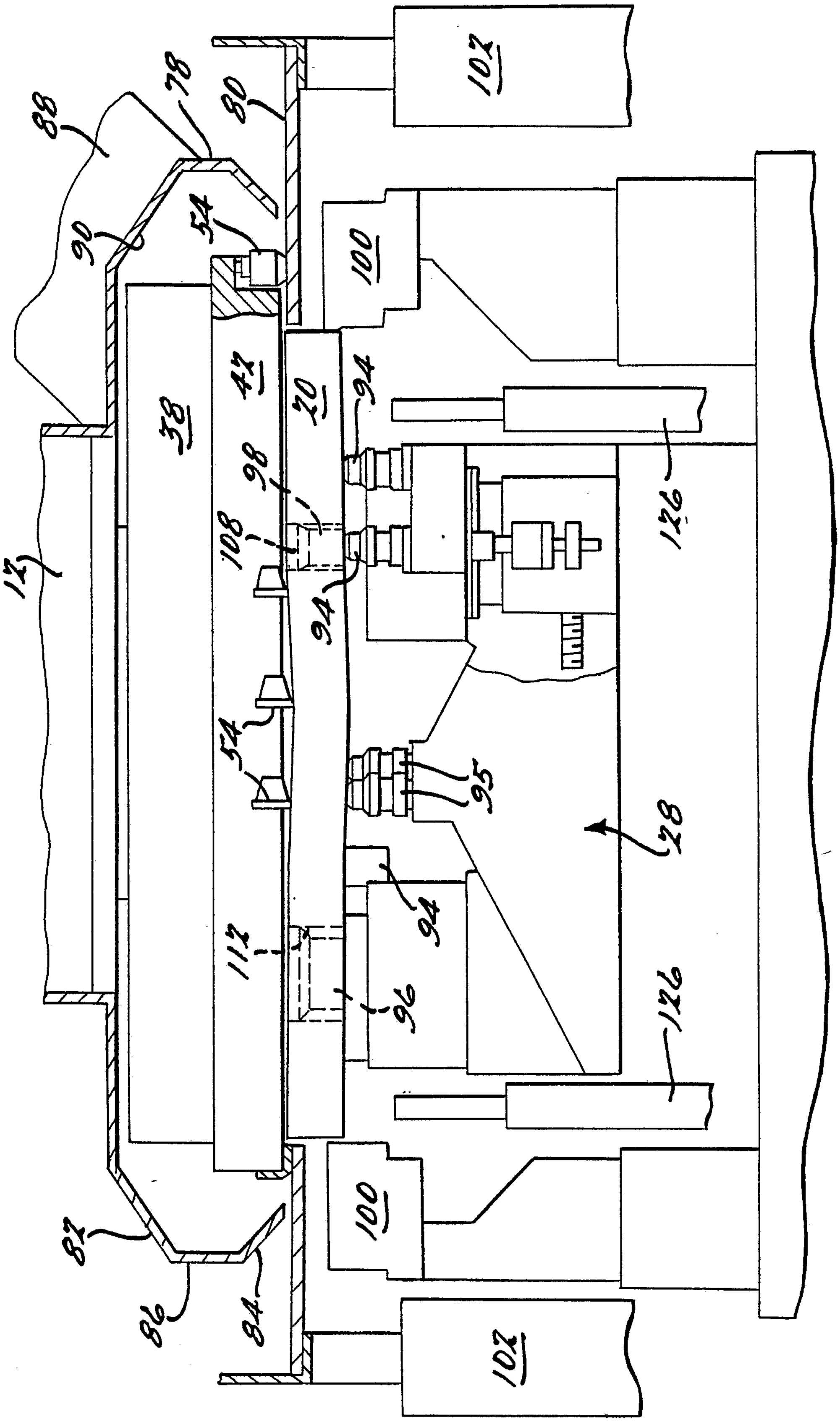
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FIG-14

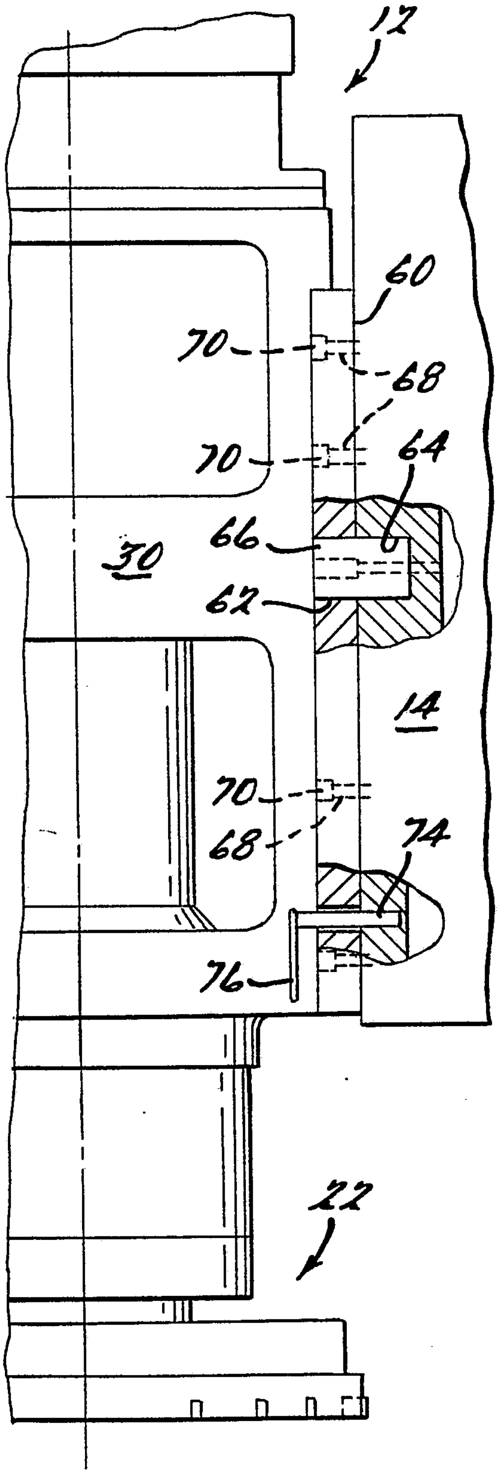
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FIG-16

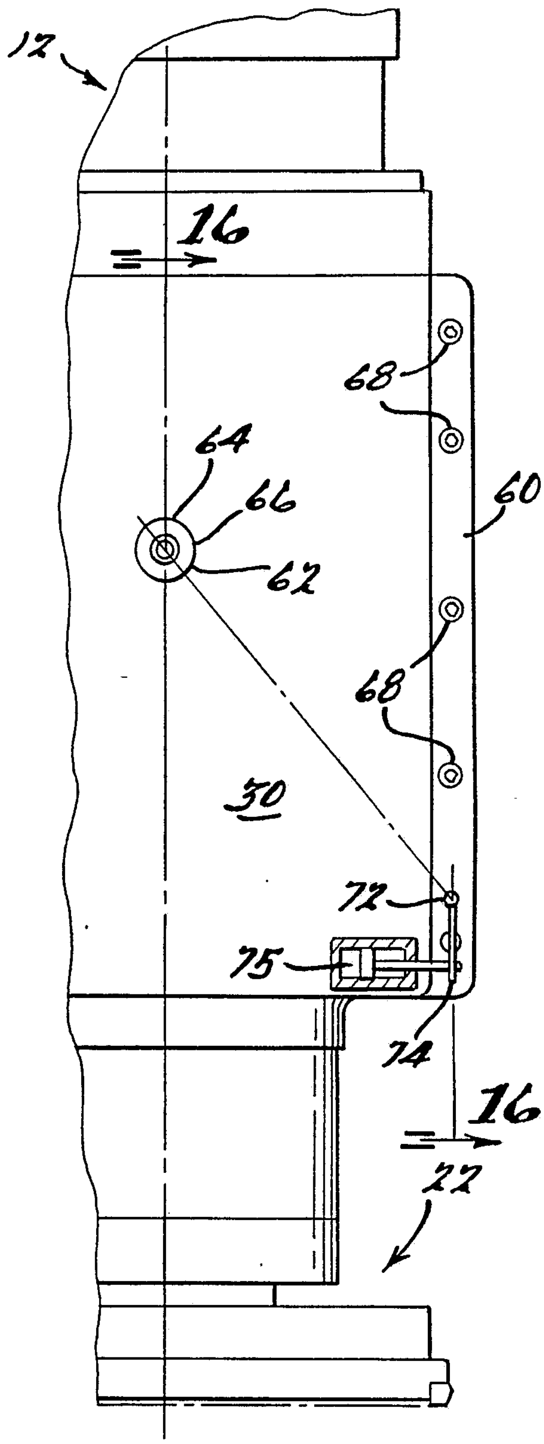
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FIG-15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/03841

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :B23D 39/00; B23P 15/28
US CL :409/132,249; 407/56,58
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : Please See Extra Sheet.

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 3,167,260(Gibbons et al) 26 January 1965, see entire document	1-29,35-40
Y	US, A, 3,855,680(Wirefelt) 24 December 1974, see entire document	6-13,18-22
Y	US, A, 4,011,792(Davis) 15 March 1977, see entire document	6-13,18-22
Y	US, A, 4,563,115(Abe et al) 07 January 1986, see entire document	1-29,35-40
Y	US, A, 4,794,740 (Keith et al) 03 January 1989, see entire document	1-29,35-40
Y	US, A, 5,061,129 (Baudermann) 29 October 1991, see entire document	6-13,18-22

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be part of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 September 1993	27 SEP 1993
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. NOT APPLICABLE	Authorized officer TIMOTHY V. ELEY Telephone No. (703) 308-1824

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/03841

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US, A, 5,082,400 (Shiratori et al) 21 January 1992, see entire document	6-13,18-22
Y,P	US, A, 5,125,190 (Buser et al) 30 June 1992, see entire document	1-29,35-40

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/03841

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Please See Extra Sheet.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-29,and 35-40

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/03841

B. FIELDS SEARCHED
Minimum documentation searched
Classification System: U.S.

409/132,249,231,232,233; 407/56,5834,40-42,44,45,51,52,56-58,61,73,85-87,113; 51/273;
83/169; 408/239R,239A,240

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING
This ISA found multiple inventions as follows:

Group I-Claims 1-29, and 35-41 are directed to an apparatus and method for performing a substantially adiabatic machining operation on a workpiece classified in class 409, subclass 132 and have the special technical features of means for transferring substantially all of the heat generated during the adiabatic machining operation to chips formed thereby, and means in communication with a peripheral enclosure for creating a pressure differential between the peripheral enclosure and a reference pressure.

Group II-Claims 30-34 are directed to a two-stage machining apparatus for machining a pair of workpieces classified in class 409, subclass 203 and have the special technical feature of means for simultaneously moving a pair of cutting means relative to a fixturing means and each of a pair of workpieces.

Group III-Claims 41-55 are directed to a cutter classified in class 409, subclass 232 having the special technical features of a planar surface comprising substantially all of a lower axial end and being contiguous with a peripheral surface, receiving means irregularly spaced so as to substantially produce white noise as the cutter is machining the workpiece, means for adjustably mounting the cutter body and minimizing runout at the lower axial end of the cutter body.

Group IV-Claims 56-63 are directed to a transfer device for transporting a workpiece to and form a machining station classified in class 198, subclass 774.1 having the special technical feature of means mechanically connected to a support means for transporting the support means between a first position and a machining station so as to transport the workpiece from the first position to the machining station.

Group V-Claims 64-91 are directed to a fixturing device for supporting a workpiece during a machining operation classified in class 409, subclass 219 having the special technical features of means adjacent a support means for engaging at least one edge of a workpiece, and means adjacent the support means for engaging an aperture in the workpiece.

Group VI-Claims 92-103 are directed to a method for supporting a workpiece during a machining operation classified in class 29, subclass 559 having the special technical features of engaging at least one edge of a workpiece, and engaging an aperture in the workpiece.

Group VIII-Claims 113-118 are directed to a transfer device for precision picking and placing of a workpiece classified in class 198, subclass 774.1 having the special technical feature of a pair of juxtaposed members spaced apart to form a slot therebetween for receiving a workpiece.