

ABRASIVE FLOW MACHINING APPARATUS, METHOD AND SYSTEM

FIELD OF THE INVENTION

This invention relates generally to an abrasive flow machining (AFM) apparatus and method, and more particularly to a bi/uni flow or orbital AFM method and apparatus that is scalable and configurable to surface finishing and polishing of external surfaces of a three-dimensional free form workpiece as well as internal passage surfaces of a workpiece.

BACKGROUND

Abrasive flow machining (AFM) is a machining technique in which an abrasive laden semi-solid viscoelastic media is extruded over the surfaces of a workpiece to be finished or polished. In the standard AFM technique, the abrasive media is reciprocally extruded by a pair of opposing cylinders.

AFM has been likened to a liquid file, and perhaps the greatest advantage of AFM lies in the ability to finish (deburr, polish and radius) complex internal passages or areas of a workpiece that are inaccessible to other finishing methods such as mechanical honing. The AFM technique has been applied over a wide range of applications. For example, AFM techniques have been applied in the finishing of critical aerospace and medical components to high-production volume of parts.

In conventional AFM devices, no additional tooling is necessary for processing internal surfaces, however, in the case of processing external surfaces of workpieces, additional tooling is required to ensure a sufficiently narrow gap between the tool and the workpiece.

A variant of the technique include one-way or uni-flow AFM in which the media is extruded in a one direction. Another variant is orbital AFM where the polishing action of the media between the workpiece and a conformal tool is effected by oscillating the workpiece. The most recent development in conventional AFM processes is micro AFM, which is an adaptation of one-way AFM for polishing microholes using relatively less viscous media.

The number of manufactures and suppliers of AFM systems is currently limited, and often due to the device specification, the only abrasive media that is suitable for the device is supplied by the manufacturers and suppliers of the AFM system. The media typically supplied is only available in three "standard" viscosities of low viscosity, medium viscosity and high viscosity, which may not be adequate for specific applications. The "standard" viscosities of the abrasive media may not be appropriate for very gentle polishing that does not impair the form of certain workpieces such as optical lens moulds.

For the relatively simple operations that these machines are required to perform, the cost of these machines is often prohibitive. These machines often come in standard sizes and customization of the overall system is therefore required which contributes to the system being even more costly. Furthermore, for certain applications such as polishing of miniature parts, such standard size machines would simply be impractically large and the use such standard machines may even be wasteful of the abrasive media.

Therefore, there is a need for an AFM apparatus, system and method that addresses or at least alleviates the problems associated with conventional AFM devices and systems.

SUMMARY

An aspect of the invention is an abrasive flow machining (AFM) apparatus for processing a surface of a workpiece, the apparatus comprising a first chamber for containing an abrasive media; a second chamber for containing the abrasive media, the first chamber arranged on one side of the workpiece and the second chamber arranged on another side of the workpiece and the first chamber and second chamber communicating the abrasive media; and a port in the first chamber for receiving a hydraulic fluid or pneumatic gas in the first chamber for applying a pneumatic or hydraulic pressure directly to the abrasive media itself to extrude the abrasive material across the surface of the workpiece from the first chamber to the second chamber.

In an embodiment the apparatus may further comprise a port (input/output) in the second chamber to exhaust a hydraulic fluid or pneumatic gas in the second chamber. The first chamber and the second chamber may be arranged around an internal surface of the workpiece, and an internal surface of the workpiece forms an aperture through the workpiece. The first chamber may comprise a first reservoir and the hydraulic fluid or pneumatic gas may be applied to the

abrasive media in the reservoir.

In another embodiment the apparatus may have a floating piston arranged between the abrasive media and the hydraulic fluid or pneumatic gas. The floating piston may be positioned in the first chamber, and another second floating piston may be arranged between the abrasive media and the hydraulic fluid or pneumatic gas in the second chamber. The floating piston may further comprise a sealing element. The floating piston may form a hermetic seal with the chamber. The sealing element may be an o-ring, a wiper ring, a square section seal or the like.

In an embodiment the apparatus may further comprise a pressure intensifier fixed to the floating piston. The pressure intensifier may have a larger or smaller or the same sized surface area than the floating piston for receiving the hydraulic fluid or pneumatic gas, wherein the pressure intensifier increases or decreases the pressure of the hydraulic fluid or pneumatic gas accordingly by between substantially twofold to fourfold.

In an embodiment the apparatus may further comprise a mixer for mixing the abrasives in the abrasive media. The mixer may be positioned between the floating piston and the workpiece.

In an embodiment the apparatus may further comprise at least one additional chamber for containing abrasive media and arranged on another side of the workpiece and in communication with the first and second chambers; and a polishing chamber formed by the intersection of the first, second and at least one additional chambers, the polishing chamber for receiving the workpiece and the abrasive media extruding across an external surface of the workpiece. The polishing chamber may be arranged to receive a plurality of workpieces. Magnetic coils may be arranged to control the viscosity of a magneto rheological fluid within the polishing chamber.

In an embodiment the apparatus may further comprise a limit switch connector. The floating piston may have a an element for detection by the limit switch where the element is a ferro-magnetic rod. The apparatus may further comprise a regulated pressure release port. The first chamber may have a manual valve for toggling manually. A solenoid may be interconnected to a micro-controller for controlling the solenoid in an automatic control of the hydraulic or pneumatic force. The pressure of the hydraulic fluid or pneumatic gas on the abrasive fluid is, for example, in the range of 6 to 10 bar. The viscosity of the abrasive fluid is, for example, in the range of 0.1 cP to 100,000 cP. A magnetic coil may be arranged to control the viscosity of a magneto

rheological fluid within any of the chambers where the magneto rheological fluid media is present.

An aspect of the invention is an abrasive flow machining (AFM) system for processing a surface of a workpiece, the system comprising an AFM apparatus comprising a first chamber for containing an abrasive media; a second chamber for containing the abrasive media, the first chamber arranged on one side of the workpiece and the second chamber arranged on another side of the workpiece and the first chamber and second chamber communicating the abrasive media; and a port in the first chamber for receiving a hydraulic fluid or pneumatic gas in the first chamber for applying a pneumatic or hydraulic pressure directly to the abrasive media itself to extrude the abrasive material across the surface of the workpiece from the first chamber to the second chamber; and the system further comprising a hydraulic fluid or pneumatic gas supply port for receiving a hydraulic fluid or pneumatic gas supply.

An aspect of the invention is an abrasive flow machining (AFM) method for processing a surface of a workpiece, the method comprises introducing an abrasive material into a first chamber and a second chamber, the first chamber arranged on one side of the workpiece and the second chamber arranged on another side of the workpiece and the first chamber and second chamber for communicating the abrasive media; and applying a hydraulic fluid or pneumatic gas in the first chamber for applying a pneumatic or hydraulic pressure directly to the abrasive media itself to extrude the abrasive material across the surface of the workpiece from the first chamber to the second chamber.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that embodiments of the invention may be fully and more clearly understood by way of non-limitative examples, the following description is taken in conjunction with the accompanying drawings in which like reference numerals designate similar or corresponding elements, regions and portions, and in which:

FIG. 1A-B is a cross-sectional view of an AFM apparatus showing the reciprocally extruded viscoelastic media laden with abrasives from the majority of media extruded through the workpiece from one chamber (FIG. 1A) to another chamber (FIG. 1B) in accordance with an embodiment of the invention;

FIG. 2A-B is a cross-sectional of an AFM apparatus showing the reciprocally extruded viscoelastic media laden with abrasives from the majority of media extruded through the workpiece from one chamber (FIG. 2A) to another chamber (FIG. 2B) in accordance with an embodiment of the invention;

FIG. 3A-B is a graphical model representation of the Kelvin-Voigt model (FIG. 3A) and Maxwell model (3B) of the behavior of features of an AFM system in accordance with an embodiment of the invention;

FIG. 4 is cross-sectional view of an AFM apparatus in accordance with an embodiment of the invention;

FIG. 5 is cross-sectional view of an AFM apparatus in accordance with an embodiment of the invention;

FIG. 6 is a block diagram of an AFM apparatus in accordance with an embodiment of the invention;

FIG. 7 is a block diagram of an AFM system in accordance with an embodiment of the invention;

FIG. 8 is a perspective view of an AFM system in accordance with an embodiment of the invention;

FIG. 9A-B are graphs showing the strain and relax response of a viscoelastic material to a constant pressure (FIG. 9A), and the strain and relax response of a viscoelastic material to a pulsating pressure action (FIG. 9B);

FIG. 10 is a cross-sectional view of an AFM apparatus having a pressure intensifier in accordance with an embodiment of the invention;

FIG. 11A-D show the pressure intensifier and floating piston arrangement shown in FIG. 10 in more detail (FIG. 11A), sealing elements for the floating piston and the pressure intensifier (FIG. 11B), grooves of the floating piston (FIG. 11C), and the floating piston with sealing elements configuration (FIG. 11D) in accordance with an embodiment of the invention;

FIG. 12A-B are a cross-sectional views of an AFM apparatus having a plurality of media chambers with a polishing chamber (FIG. 12A), and with a three-dimensional free form workpiece in the polishing chamber and electromagnetic coils (FIG. 12B) in accordance with an embodiment of the invention;

FIG. 13 is a cross-sectional view of an AFM apparatus having a mixer in accordance with an embodiment of the invention; and

FIG. 14 is a flow chart of a method in accordance with an embodiment of the invention.

DETAILED DESCRIPTION

An abrasive flow machining (AFM) apparatus, method and system is disclosed for processing a surface of a workpiece by hydraulically or pneumatically extruding an abrasive media across a surface of a workpiece from one chamber on one side of the workpiece to another chamber on another side of the workpiece. The nature of embodiments of the invention of the AFM design and the viscosity of the abrasive media is such that the extrusion of the abrasive media is accomplished by applying the pneumatic or hydraulic pressure directly to the abrasive media itself or at the surface of the abrasive media itself. The chambers on either side of the workpiece may be partially defined by a floating piston, and a pressure intensifier may be employed together with a floating piston to increase the pressure of the hydraulically or pneumatically driving force. A mixer may be employed to ensure mixing of the abrasives in the media, and multiple abrasive media chambers may be arranged to form a polishing chamber for processing external or internal surfaces of three-dimensional free form workpieces.

In particular, embodiments of the invention may be arranged in different AFM configurations such as bi-flow, uni-flow, orbital, and the like. Embodiments of the AFM system are scalable and configurable to surface finishing and polishing of external surfaces of a three-dimensional free form workpiece as well as internal passage surfaces of a workpiece. Embodiments of the invention are both accessible and cost effective, and may be machined using equipment that is typically available in a job shop.

Furthermore, embodiments of the invention can be readily scaled and configured to a particular application. Also, because of the simplicity and design of these devices, novel methods of

abrasive flow machining may be readily and naturally realized. Abrasive media can be "home-made" and the viscosities of the media can be conveniently varied using readily available materials. For example, the range of viscosity of the media may range from for example 0.1 cP to 100,000 cP. Embodiments of the invention enable practically any job shop with a relatively modest investment can add AFM to their shop inventory and capabilities.

FIG. 1A-B is a cross-sectional view of an AFM apparatus 10 showing the reciprocally extruded viscoelastic media laden with abrasives 22 from the majority of media 20 extruded through the workpiece 12 from an abrasive material reservoir 24 and one media chamber 14 (FIG. 1A) to another media chamber 16 and abrasive material reservoir 26 (FIG. 1B) in accordance with an embodiment of the invention. The workpiece 12 has a surface 18 to be processed. In this embodiment the surface of the workpiece to be processed is the internal area or passage of the workpiece. Of course, it will be appreciated that other surfaces of the workpiece can be processed such as the external surface of the workpiece.

In operation, shop air 42 is supplied to an intake 44 of the reservoir 24 with the majority 20 of abrasive media to force by pneumatic means directly to the abrasive media itself at the surface of the abrasive media, and extrude the media from the first reservoir 24 through the first conduit 34 between the reservoir 24 and the chamber 14, through the workpiece 12, through the second chamber 16 and second conduit 36 to the second abrasive media reservoir 26 with the minority 30 of abrasive media. The air pressure is maintained at the intake 44 until the majority amount of media is in the second abrasive media reservoir 26 as shown in FIG. 1B. In a uni-flow embodiment, the process is complete after the majority of media is extruded across a surface of the workpiece and is in the second abrasive media reservoir 26. However, in another embodiment such as a bi-flow embodiment, the process is reciprocated at least once or more times as desired. The direction of the air is reversed. The shop air is forced into intake 46 into the second abrasive media reservoir 26, and shop air is exhausted out of the outtake 44 of the first abrasive material reservoir. Intake 44 becomes an outtake as the flow direction of media is reversed, and the outtake 46 becomes an intake as the flow direction of the media is reversed.

The system in accordance with an embodiment of the invention may be configured as a positive pressure blow system. In another embodiment, the system may be arranged with a primarily positive pressure blow system with a suck assist for achieving a greater differential pressure across the workpiece. In another embodiment, the system may be configured with a pressure

restrictor valve for a lower pressure differential across the workpiece and hence a higher overall media pressure.

It will be appreciated that other pressure means may be implemented other than shop air. For example, apart from air, any chemically neutral gas, such as nitrogen, helium, and the like may be employed in the system. Similarly, any chemically neutral liquid such as hydraulic fluid or the like may be employed. The chemically neutral gas or liquid may be chemically neutral with respect to the media.

FIG. 2A-B is a cross-sectional of an AFM apparatus 50 showing the reciprocally extruded viscoelastic media laden with abrasives from the majority of media extruded through the workpiece from one chamber (FIG. 2A) to another chamber (FIG. 2B) in accordance with an embodiment of the invention having floating pistons 54,56. The floating pistons also prevent contamination of the abrasive media from the pneumatic gas or hydraulic liquid in particular. In an embodiment the floating pistons 54, 56 form a hermetic seal between the shop air and the abrasive material. In another embodiment, the floating pistons do not form a hermetic seal between the media and the shop air of the reservoir chambers 24, 26. Although, in the configuration shown in FIG. 2A and 2B it is preferable to have a hermetic seal between the media and the shop air for the reasons stated above, it is not necessary to have such a seal. In such a case, the floating piston simply acts as a position marker to activate a proximity switch at each chamber in an automated operation, and/or simply as a barrier to avoid churning of the abrasive media by the shop air. The air pressure pushes the floating piston and therefore exerts a force on the abrasive material similarly as compared with the embodiment shown in FIG. 1A-B. The embodiment shown in FIG. 1A-B however provides less number of moving parts and lends itself especially when manual operation of the machine suffices for a particular application.

As the abrasive media is typically of a semi-solid, viscoelastic consistency, from a phenomenological point of view, its rheology may be understood as partway between a solid and a liquid. For the purpose of the description of embodiments of the invention, it would suffice to employ the simplest models, namely the Maxwell or Kelvin-Voigt models, representing this behavior.

FIG. 3A-B is a graphical model representation of the Kelvin-Voigt model 60 (FIG. 3A) and Maxwell model 70 (FIG. 3B) of the behavior of features of an AFM system in accordance with an embodiment of the invention. Graphically, the Kelvin-Voigt model 60 is represented as a spring

62, which in turns represents solid-like behavior, and a dashpot 64, which represents liquid-like behavior- connected in parallel as shown in FIG. 3A. The graphical representation of the Maxwell model 70 is a spring 62 and dashpot 64 in series as shown in FIG. 3B.

The corresponding constitutive equation for the Kelvin-Voigt model is:

$$\sigma = G\gamma + \eta \dot{\gamma} \quad (1)$$

where σ is the stress, γ is the strain – and hence $\dot{\gamma}$ is the strain-rate - G is the bulk modulus and η is the viscosity; and the corresponding constitutive equation for the Maxwell model is:

$$\dot{\gamma} = \frac{\dot{\sigma}}{G} + \frac{\sigma}{\eta} \quad (2)$$

Thus the relative values of G and η , of course, depend on the particular formulation of the media.

In an embodiment, the abrasive media may include, for example, a combination of three of the following readily available, and mutually miscible constituents in various amounts resulted in a medias of varying viscosities: BRASSO polishing liquid (BRASSO is a trademark of Reckitt Benckiser plc of the United Kingdom), AUTOSOL polishing paste (AUTOSOL is a trademark of Dursol Fabrik Otto Durst GmbH & Co. KG of Germany) and Dow Corning 3179 Dilatant Compound, also known as Silly Putty (of Dow Chemical Company of Midland, Michigan, United States of America). For example, diluting AUTOSOL with BRASSO resulted in a media that is less viscous than the original AUTOSOL; and likewise for Silly Putty diluted with the less viscous AUTOSOL paste. It will be appreciated that other abrasive compounds can be used and different combinations of the above media may be arranged.

The abrasives in the media may be abrasives such as silicon carbide and aluminum oxide powders and grits, cheaper abrasives such as those used in abrasive water jets, for example, olivin and garnet were also effective.

For example, a composition of about 37.5 ml of #60 garnet in 90 ml of AUTOSOL was found effective in improving the surface roughness tenfold from about 3 - 4 microns Ra to about 0.2 to 0.3 microns Ra while removing recast layers in EDM cut holes.

Also a composition of about 37.5 ml of #120 olivin 90 ml of AUTOSOL was effective in improving the surface roughness of a drilled or reamed hole from 0.5 – 1 microns Ra to 0.06 – 0.1 microns Ra in a polishing time of 15 mins.

SiC microgrit #280 was found useful only if the initial surface is fairly good, say in the 0.1 to 0.2 microns Ra range.

A basic element of an embodiment of the invention comprises a pair of opposing floating pistons 54,56 reciprocally extruding abrasive-laden media over the surfaces of a workpiece to be processed, as shown in FIG. 4. FIG. 4 is cross-sectional view of an AFM apparatus 80 in accordance with an embodiment of the invention. The floating pistons may either be powered either hydraulically or pneumatically. Pneumatic power is preferred as shop air is commonly available in most machine job shops. As shop air is readily available in most job shops, embodiments of the invention are a much simpler system design than previously achievable with conventional AFM systems. In this embodiment the floating pistons 54,56 have sealing elements 98 such as o-rings, wiper rings, square section seals, or the like. The o-rings may be configured with two o-rings as shown, however any number of o-rings may be implemented, for example, one, two, three or more. FIG. 4 shows an endblock 90,92 at the first and second chambers. Air ports 84,86 and limit switch connectors 94,96 may be formed in the end block.

The floating pistons 54,56 may be made of a strong and chemically resistant material such as stainless steel, ceramics or the like, such that the floating piston substantially remains shape in operation. The floating piston may have grooves 99 at each end of the floating piston for accommodating typical sealing elements 98 such as o-rings, wiper seals, square section seals, and the like. The configuration of the floating piston 54, grooves 99 and sealing elements 98 are shown in more detail in FIG. 12A-B. Additionally, in FIG. 4 the floating piston 54,56 is shown with a ferro-magnetic rod 53,55 that extends into the air chamber. The ferro-magnetic rod serves as a position marker for detection by a proximity sensor 94,96,134,136.

As shown in FIG. 5 and in more detail in FIG. 7, provision is also made for automatic operation of the device by means of proximity or limit switches 94,96,134,136 and solenoid valves 124,126

connected to electronic control circuitry 122. Regulated pressure release ports 104,106 are shown at the end connecting blocks 90,92. FIG. 5 is cross-sectional view of an AFM apparatus 100 in accordance with an embodiment of the invention, and FIG. 7 is a block diagram of an AFM system 120 in accordance with an embodiment of the invention.

FIG. 5 shows a configuration for pulsed processing operation with regulated pressure release ports 104,105. By controlling the closure and opening of a pressure regulating valve or even simple shut-off valve, the movement of the floating may be pulsed in the forward direction, as shown in FIG. 5. If the pulse time is within the relaxation time of the media, this would enhance the abrading action of the media as further explained in greater detail below with reference to FIG. 9A-B.

The basic element of device may be manually or automatically operated. For example for to be manually operated by toggling a manual valve 112, for example a manual 5/2 valve or the like, which would reciprocate the pair of floating pistons as illustrated in FIG. 6. FIG. 6 is a block diagram of an AFM apparatus 110 in accordance with an embodiment of the invention with floating pistons 54,56 and manual toggle valve 112.

Referring to FIG. 7, in automatic operation for example, when proximity switch A 134 detects the end of travel of piston A, the micro-controller will send a signal to de-energize solenoid B 136 and to energize solenoid A 134. This would move the pair of pistons 54,56 in the opposite direction. When proximity switch 136 detects the end of travel of piston B 56, the micro-controller 122 will send a signal to de-energize solenoid A 124 and to energize solenoid B 126. This would move the pair of pistons 54,56 in the other direction. Hence the pair of pistons will therefore reciprocate automatically until a command is sent to the micro-controller to end the control sequence.

FIG. 8 is a perspective view of an AFM system 150 in accordance with an embodiment of the invention. The AFM system 150 has electronic interface 152 between the processor of the computer 128 and the controller and power electronic circuitry 122. The interface/controller by way of the computer 128 controls the solenoid control valves 124,126 and proximity switches 134,136 which controls the desired air supply and force on the floating pistons 54,56. The tubing pneumatically or hydraulically connecting the devices and components within the system may be standard pneumatic or hydraulic tubing that is commercially available for realizing manual or automatic systems in accordance with embodiments of the invention..

FIG. 9A-B are graphs 160, 170 showing the strain and relax response 162 of a viscoelastic material to a constant pressure (FIG. 9A), and the strain and relax response 170 of a viscoelastic material to a pulsating pressure action (FIG. 9B). For pulsed pressure operation, interestingly, how the media behaves depends on the experimental or observation time, of the action of the deforming strain, according to the Deborah number, D_e :

$$D_e = \frac{\tau}{t} \quad (4)$$

which is the ratio of the stress relaxation time τ , and the observation or experimental time, t . The media behaves solid like for $D_e \gg 1$, visco-elastic like for $D_e \approx O(1)$ and liquid-like for $D_e \ll 1$.

The stress in a viscoelastic material rises to maximum value on application of a strain and the relaxes as shown in FIG. 9A. The characteristic relaxation or decay time, τ_m is given by:

$$\tau_m = \frac{\eta}{G} \quad (5)$$

which is the time taken for the stress to fall to $1/e$ of its initial value.

By applying a pulsating strain or pressure, we may decrease the experimental time and hence make the viscoelastic media behave more like a solid by increasing the Deborah number. In other words, we can control the hardness or softness of a media of a given formulation by manipulating the Deborah number, and so control the polishing rate.

Pulsed pressure operation may be realized by simply adding an on/off valve at each end of a basic element of the invention as shown in FIG. 9B. For example, closing and opening on /off valve A and keeping the on/off valve B closed, would cause floating piston A to start and stop; in other words, to pulse whilst moving along.

Maximum shop air pressure is typically about 6-10 bar. If this air pressure is inadequate, then the operating pressure can be easily increased by means of a pressure intensifier as shown in FIG.

10. FIG. 10 is a cross-sectional view of an AFM apparatus 180 having a pressure intensifier in accordance with an embodiment of the invention. The pressure intensifier 182 intensifies the operating pressure of the shop air. The pressure intensifier 182 is positioned within a chamber 184 that is hermetically sealed with the chamber of the floating piston. The pressure intensifier is connected to the floating piston via a connector 188. The pressure intensifier has an sealing elements 186 such as o-rings, wiper rings, square seals and the like. The sealing elements such as the o-rings shown may be configured with two o-rings as shown, however any number of o-rings may be implemented, for example, one, two, three or more. The o-rings 98,186 are shown in more detail in FIG. 11B. Configuration of the floating piston 54 design is shown in more detail in FIG. 11C and FIG. 11D.

In an embodiment of the invention, in the spirit of simplicity and accessibility, the source pressure or intensifier piston 182 is preferably of the similar shape, design and material as the floating piston 54, as shown in FIG. 11A-D. Hence, similar sealing elements 98,186 and grooves 99 may be employed in the intensifier piston. The intensifier 182 and floating piston 54 are to be rigidly connected by a rigid connector rod 188, secured at both ends by any robust means such as welding or threaded connections as shown below, such that, in effect, a pair of connected floating pistons is realized.

If shop air pressure or any such source pressure is inadequate, it may be increased or intensified. For this purpose, the diameter of the intensifier must be greater than the diameter of the floating piston. On the other hand, if the operating pressure needs be reduced, the diameter of the intensifier piston must be smaller than diameter of floating piston. For example, if the shop air pressure is limited to for example, 8 bars and an operating pressure of about 32 bars is required, for example for aggressive processing. If the diameter of the floating piston is for example 2 inches (50.8 mm), then from equation (3) below, the calculated diameter of the intensifier piston is 4 inches (101.6 mm). On the other hand, if the minimum source pressure is for example 2 bars and an operating pressure of half a bar is required for delicate processing. Then if the diameter of the floating piston is 3 inches (76.2 mm) then from equation (3) below, the calculated diameter of the intensifier piston is be 1.5 inches (38.1mm).

The operating pressure may be readily increased by means of the configuration shown in FIG. 10 for pressure intensification. Now, if the diameter of the larger piston is D_L and the diameter of

the smaller floating piston is d_{fp} , it can be shown, from a simple force balance, that, if the shop air pressure is p_{sa} , then operating pressure, p_{op} is given by:

$$p_{op} = \left(\frac{D_L}{d_{fp}} \right)^2 p_{sa} \quad (3)$$

Thus, if the diameter of the pressure intensifier 182, i.e. the larger piston D_L is twice, the smaller floating piston is d_{fp} , then the operating pressure, p_{op} would be intensified fourfold over the shop air pressure is p_{sa} .

FIG. 12A-B are a cross-sectional views of an AFM apparatus 190 having a plurality of media chambers with a polishing chamber (FIG. 12A), and with a three-dimensional free form workpiece in the polishing chamber 200 and electromagnetic coils 204 (FIG. 12B) in accordance with an embodiment of the invention. A combination of plurality of basic elements of the AFM shown in FIG. 4 may be combined as shown in FIG. 12A-B. The third basic element comprises the floating piston 192 defining a media chamber 194 and an air chamber 196. For illustrative purposes, only three basic elements are shown, however, any number of elements as is practicable may be envisaged. Additionally, the basic elements are shown on the same plane, however, the basic elements may be positioned at any angle with respect to each other and positioned at respective mouths of the polishing chambers. Such a configuration would be useful for processing 3-dimensional external free form surfaces. More importantly, this particular configuration bridges the technological gap between abrasive flow machining and a mass finishing process known as drag finishing.

The movement of the floating pistons could be sequence in a random manner whilst rotating the workpiece to promote even or isotropic polishing. The workpiece may also be dragged through the media, for example, in a planetary motion whilst being rotated for enhanced polishing.

Instead of using abrasive media, a fluid having properties response to a magnetic field such as a mageto-rheological fluid (MRF) may be used. As shown in figure FIG. 12B, if this is the case, provision would be made to have electromagnetic coils 204 around the polishing chamber 200 to control the viscosity of the MRF. The electromagnetic coils may be connected to an electrical

power source, which may be controlled, either manually or by automatic means such as computer 128 according to any particular strategy to vary the strength of the magnetic field and hence the viscosity of the MRF media. It will be appreciated that the use of MRF may be used in any of the embodiments of the invention as discussed herewith or shown in the drawings. Accordingly, the electromagnetic coils 204 can be arranged in any of the embodiments of the AFM apparatus, systems or methods discussed herewith or shown in the drawings.

The polishing chamber is arranged to be large enough to encompass the workpiece or workpieces to be finished. In fact, this embodiment is particularly advantageous for finishing the external surfaces of an array or plurality of small or miniature workpieces. In effect, the external surfaces altogether constitute an internal surface or surfaces. In the case of FIG. 12A-B, in which a plurality of pistons is employed, any number of floating pistons, except one, may be pressurized at the same time. In such a configuration at least one must not be pressurized. However, it is preferable to have one piston pressurized at one time. Additionally, the pistons may be reciprocated in some orderly sequence but preferably in a random manner to effect evenly and randomly finished surfaces.

In the case of the embodiment shown in FIG. 12B in which a magneto rheological fluid (MRF) is used as a media, activation of the electromagnetic coils create a magnetic field which serves to control the viscosity of the MRF media and hence control the strength of the finishing process. The magnetic coils shall encompass the polishing chamber such that the said magnetic field permeates the whole of the polishing chamber.

FIG. 13 is a cross-sectional view of an AFM apparatus 210 having a mixer 212 in accordance with an embodiment of the invention. As the abrasive media is typically of semi-solid consistency, the media flow is likely to be orderly, laminar or the like. If the same abrasive particles are continually used, the abrasive particles have a tendency to become worn and the effectiveness of the abrasive particles deteriorates. To ensure fresh abrasives and even use of the abrasive particles within the media are revealed to the surfaces of the workpiece to be processed, a static mixer 212 may be superposed between a floating piston and the workpiece as shown in FIG. 13. The mixer of FIG. 13 is configured to ensure that the abrasives are mixed within the media. The mixer 212 is within a mixer chamber and may be positioned proximate the workpiece. Of course, the mixer 212 may be positioned on either side of the workpiece, or there may be another mixer located on either side of the workpiece. In the configuration of the apparatus having a polishing chamber, the mixer may be located at or proximate to any or each

of the mouths of the polishing chamber. Standard static mixers are commercially available. Any standard commercially available static mixer of robust design may be used. It will be appreciated that other configurations and placements of the mixer may be implemented to achieve the desired result of ensuring adequate mixing of the abrasives.

FIG. 14 is a flow chart of a method 220 in accordance with an embodiment of the invention. The method 220 is an AFM method for processing a surface of a workpiece. The method comprises introducing 222 an abrasive material into a first chamber and a second chamber. The first chamber and is arranged 224 on one side of the workpiece and the second chamber arranged on another side of the workpiece and the first chamber and second chamber for communicating the abrasive media. Contacting 226 the abrasive media to the surface of the workpiece to be processed. Applying 228 a hydraulic fluid or pneumatic gas in the first chamber for applying a pneumatic or hydraulic pressure directly to the abrasive media itself to extrude 230 the abrasive material across the surface of the workpiece from the first chamber to the second chamber. In an embodiment the process is reciprocated 232 by applying the pressure of the hydraulic fluid or pneumatic gas in the second chamber.

Examples of surfaces of workpieces that may be processed in embodiments of the invention include holes through the workpiece such as straight holes, hourglass holes, multi-step holes, and the like. Other surfaces of workpieces that may be processed include surfaces s-curved surfaces, trenches, internal and external features having different configurations and the like.

It will be appreciated that practically all components of embodiments of the invention can be fabricated by a typical machine job shop without the need of special equipment. Furthermore, embodiments of the invention can be powered by compressed shop air which is also a commonly standard facility in a typical machine job shop. Embodiments of the invention can be operated manually or automatically. Due to the basic simplicity of design of the embodiments of the invention, automation is very affordable by using a micro-controller or a control software, such as LabView, which are both accessible. As discussed, abrasive media can also be easily formulated using easily available off-the-shelf products. Hence, with all the above merits, embodiments of the invention realizes an affordable and accessible abrasive flow machining (AFM) technology, which can therefore be adopted as any another 'standard' tool in a typical machine job shop.

A feature of embodiments of the invention is the fundamentally fluidic nature which allows the permutations of the configurations described above to be easily and naturally realized. This

feature also allows embodiments of the invention to be easily automated. Being easily automated, embodiments of the invention permit abrasive flow machining (AFM) methods that have not been achievable in previous conventional designs. Such an application discussed above is the application of pulsed pressure and the use of a plurality of basic elemental devices for polishing of external 3D free-form surfaces. Using the methods of embodiments of the invention, additional tooling would not be required, in contrast to the state of the art.

While embodiments of the invention have been described and illustrated, it will be understood by those skilled in the technology concerned that many variations or modifications in details of design or construction may be made without departing from the present invention.

CLAIMS:

1. An abrasive flow machining (AFM) apparatus for processing a surface of a workpiece, the apparatus comprising:
a first chamber for containing an abrasive media;
a second chamber for containing the abrasive media, the first chamber arranged on one side of the workpiece and the second chamber arranged on another side of the workpiece and the first chamber and second chamber communicating the abrasive media; and
a port in the first chamber for receiving a hydraulic fluid or pneumatic gas in the first chamber for applying a pneumatic or hydraulic pressure directly to the abrasive media itself to extrude the abrasive material across the surface of the workpiece from the first chamber to the second chamber.
2. The apparatus according to claim 1 further comprising a port in the second chamber to exhaust a hydraulic fluid or pneumatic gas in the second chamber.
3. The apparatus according to claim 1 or 2 wherein the first chamber and the second chamber are arranged around an internal surface of the workpiece.
4. The apparatus according to claim 3 wherein the internal surface of the workpiece forms an aperture through the workpiece.
5. The apparatus according to any one of the preceding claims wherein first chamber comprises a first reservoir and the hydraulic fluid or pneumatic gas is applied to the abrasive media in the reservoir.
6. The apparatus according to any one of the preceding claims further comprising a floating piston arranged between the abrasive media and the hydraulic fluid or pneumatic gas.
7. The apparatus according to claim 6 wherein the floating piston is in the first chamber.
8. The apparatus according to claim 6 or 7 wherein a second floating piston is arranged between the abrasive media and the hydraulic fluid or pneumatic gas in the second chamber.

9. The apparatus according to any one of claims 6 to 8 wherein the floating piston further comprises a sealing element.
10. The apparatus according to any one of claims 6 to 9 wherein the floating piston forms a hermetic seal with the chamber.
11. The apparatus according to claim 9 wherein the sealing element is an o-ring, a wiper ring, or a square section seal.
12. The apparatus according to any one of claims 6 to 11 further comprising a pressure intensifier fixed to the floating piston having a larger surface area than the floating piston for receiving the hydraulic fluid or pneumatic gas.
13. The apparatus according to claim 12 wherein the pressure intensifier increases the pressure of the hydraulic fluid or pneumatic gas by between substantially twofold to fourfold.
14. The apparatus according to any one of claims 6 to 11 further comprising a pressure intensifier fixed to the floating piston having a smaller surface area than the floating piston for receiving the hydraulic fluid or pneumatic gas.
15. The apparatus according to any one of the preceding claims further comprising a mixer for mixing the abrasives in the abrasive media.
16. The apparatus according to claim 12 as depending from any one of claim 6 to 11 wherein the mixer is between the floating piston and the workpiece.
17. The apparatus according to any one of the preceding claims further comprising at least one additional chamber for containing abrasive media and arranged on another side of the workpiece and in communication with the first and second chambers; and a polishing chamber formed by the intersection of the first, second and at least one additional chambers, the polishing chamber for receiving the workpiece and the abrasive media extruding across an external surface of the workpiece.
18. The apparatus according to claim 17 wherein the polishing chamber is arranged to receive a plurality of workpieces.

19. The apparatus according to claim 17 or 18 further comprising magnetic coils arranged to control the viscosity of a magneto rheological fluid within the polishing chamber.
20. The apparatus according to any one of the preceding claims wherein the first chamber further comprises a limit switch connector.
21. The apparatus according to claim 6 to 20 wherein the floating piston has an element for detection by the limit switch.
22. The apparatus according to claim 21 wherein the element for detection by the limit switch is a ferro-magnetic rod.
23. The apparatus according to any one of the preceding claims wherein the first chamber further comprises a regulated pressure release port.
24. The apparatus according to any one of the preceding claims wherein the first chamber further comprises a manual valve for toggling manually.
25. The apparatus according to any one of the preceding claims further comprising a solenoid interconnected to a micro-controller for controlling the solenoid in an automatic control of the hydraulic or pneumatic force.
26. The apparatus according to any one of the preceding claims wherein the pressure of the hydraulic fluid or pneumatic gas on the abrasive fluid is in the range of 6 to 10 bar.
27. The apparatus according to any one of the preceding claims wherein the viscosity of the abrasive fluid is the range of 0.1 cP to 100,000 cP.
28. The apparatus according to any one of the preceding claims further comprising a magnetic coil arranged to control the viscosity of a magneto rheological fluid within the first chamber.
29. An abrasive flow machining (AFM) system for processing a surface of a workpiece, the system comprising:
an AFM apparatus comprising a first chamber for containing an abrasive media;

a second chamber for containing the abrasive media, the first chamber arranged on one side of the workpiece and the second chamber arranged on another side of the workpiece and the first chamber and second chamber communicating the abrasive media; and
a port in the first chamber for receiving a hydraulic fluid or pneumatic gas in the first chamber for applying a pneumatic or hydraulic pressure directly to the abrasive media itself to extrude the abrasive material across the surface of the workpiece from the first chamber to the second chamber; and
the system further comprising a hydraulic fluid or pneumatic gas supply port for receiving a hydraulic fluid or pneumatic gas supply.

30. The system according to claim 29 further comprising a port in the second chamber to exhaust a hydraulic fluid or pneumatic gas in the second chamber.

31. The system according to claim 29 or 30 wherein the first chamber and the second chamber are arranged around an internal surface of the workpiece.

32. The system according to claim 31 wherein the internal surface of the workpiece forms an aperture through the workpiece.

33. The system according to any one of claims 29 to 32 wherein first chamber comprises a first reservoir and the hydraulic fluid or pneumatic gas is applied to the abrasive media in the reservoir.

34. The system according to any one of claims 29 to 33 further comprising a floating piston arranged between the abrasive media and the hydraulic fluid or pneumatic gas.

35. The system according to claim 34 wherein the floating piston is in the first chamber.

36. The system according to claim 34 or 35 wherein a second floating piston is arranged between the abrasive media and the hydraulic fluid or pneumatic gas in the second chamber.

37. The system according to any one of claims 34 to 36 further comprising a pressure intensifier fixed to the floating piston having a larger surface area than the floating piston for receiving the hydraulic fluid or pneumatic gas.

38. The system according to claim 37 wherein the pressure intensifier increases the pressure of the hydraulic fluid or pneumatic gas by between substantially twofold to fourfold.
39. The system according to any one of claims further 29 to 38 comprising a mixer for mixing the abrasives in the abrasive media.
40. The system according to claim 39 as depending from any one of claim 34 to 38 wherein the mixer is between the floating piston and the workpiece.
41. The system according to any one of claims 29 to 40 further comprising at least one additional chamber for containing abrasive media and arranged on another side of the workpiece and in communication with the first and second chambers; and a polishing chamber formed by the intersection of the first, second and at least one additional chambers, the polishing chamber for receiving the workpiece and the abrasive media extruding across an external surface of the workpiece.
42. The system according to any one of claims 29 to 41 wherein the first chamber further comprises a limit switch connector.
43. The system according to any one of claims 29 to 42 wherein the first chamber further comprises a regulated pressure release port.
44. The system according to any one of claims 29 to 43 wherein the first chamber further comprises a manual valve for toggling manually.
45. The system according to any one of claims 29 to 44 further comprising a solenoid interconnected to a micro-controller for controlling the solenoid in an automatic control of the hydraulic or pneumatic force.
46. The system according to any one of claims 29 to 45 wherein the pressure of the hydraulic fluid or pneumatic gas on the abrasive fluid is in the range of 6 to 10 bar.
47. The system according to any one of claims 29 to 46 wherein the viscosity of the abrasive fluid is the range of 0.1 cP to 100,000 cP.

48. The system according to any one of claims 29 to 47 further comprising a magnetic coil arranged to control the viscosity of a magneto rheological fluid within the first chamber.

49. An abrasive flow machining (AFM) method for processing a surface of a workpiece, the method comprises:

introducing an abrasive material into a first chamber and a second chamber, the first chamber arranged on one side of the workpiece and the second chamber arranged on another side of the workpiece and the first chamber and second chamber for communicating the abrasive media; and applying a hydraulic fluid or pneumatic gas in the first chamber for applying a pneumatic or hydraulic pressure directly to the abrasive media itself to extrude the abrasive material across the surface of the workpiece from the first chamber to the second chamber.

50. The method according to claim 49 further comprises exhausting a hydraulic fluid or pneumatic gas from the second chamber.

51. The method according to claim 49 or 50 wherein arranging the first chamber and the second chamber around an internal surface of the workpiece.

52. The method according to any one of claims 49 to 51 wherein arranging the first chamber with a first reservoir and applying the hydraulic fluid or pneumatic gas to the abrasive media in the reservoir.

53. The method according to any one of claims 49 to 52 further comprises providing a floating piston between the abrasive media and the hydraulic fluid or pneumatic gas.

54. The method according to claim 53 wherein the floating piston is in the first chamber.

55. The method according to claim 53 or 54 further comprises providing a second floating piston between the abrasive media and the hydraulic fluid or pneumatic gas in the second chamber.

56. The method according to any one of claims 53 to 55 further comprises providing a pressure intensifier to the floating piston, the pressure intensifier having a larger surface area than the floating piston; and applying a hydraulic fluid or pneumatic gas to the pressure

intensifier.

57. The method according to claim 56 wherein applying the hydraulic fluid or pneumatic gas to the pressure intensifier increases the pressure of the hydraulic fluid or pneumatic gas by between substantially twofold to fourfold.

58. The method according to any one of claims 49 to 57 further comprises providing a mixer for mixing the abrasives in the abrasive media.

59. The method according to claim 58 as depending from any one of claim 53 to 57 wherein providing the mixer between the floating piston and the workpiece.

60. The method according to any one of the claims 49 to 59 further comprises providing at least one additional chamber for containing abrasive media and arranging the at least one additional chamber on another side of the workpiece and in communication with the first and second chambers; and forming a polishing chamber formed by the intersection of the first, second and at least one additional chambers, the polishing chamber for receiving the workpiece and the abrasive media extruding across an external surface of the workpiece.

61. The method according to any one of the claims 49 to 60 further comprises controlling the pressure of the pneumatic gas or hydraulic fluid on the abrasive material with a limit switch connector.

62. The method according to any one of the claims 49 to 61 further comprises controlling the pressure of the pneumatic gas or hydraulic fluid on the abrasive material with a regulated pressure release port.

63. The method according to any one of the claims 49 to 62 further comprises manually controlling the pressure of the pneumatic gas or hydraulic fluid on the abrasive material with a manual valve for toggling.

64. The method according to any one of the claims 49 to 63 further comprises controlling the hydraulic or pneumatic force by controlling a solenoid interconnected to a micro-controller.

65. The method according to any one of claims 49 to 64 further comprises maintaining the pressure of the hydraulic fluid or pneumatic gas on the abrasive fluid is in the range of 6 to 10 bar.
66. The method according to any one of claims 49 to 65 further comprises providing an abrasive media having the viscosity within the range of 0.1 cP to 100,000 cP.
67. The method according to any one of claims 49 to 66 further comprises controlling the supply of the hydraulic fluid or pneumatic gas on the abrasive fluid to have a pulsed pressure action.
68. The method according to any one of claims 49-67 further comprises controlling a the viscosity of a magneto rheological fluid within the first chamber with a magnetic coil arrangement.