Abrasive Flow Machining: A Review on New Developed Hybrid AFM Process

Ali Kiani*
Department of Mechanical Engineering,
Isfahan University of Technology, Iran
E-mail: a.kiani@me.iut.ac.ir
*Corresponding author

Mojtaba Esmailian
Department of Mechanical and Aerospace Engineering,
Malek-e-Ashtar University of Technology, Isfahan, Iran
E-mail: M.Esmailian@mut.ac.ir

Hosein Amirabadi
Department of Mechanical Engineering,
University of Birjand, South Khorasan, Iran
E-mail:hamirabadi@birjand.ac.ir

Received: 14 August 2015, Revised: 23 October 2015, Accepted: 25 November 2015

Abstract: The abrasive flow machining technique uses a self-deforming tool, an abrasive laden media that is passed back and forth in the passage geometry of the hollow workpiece with the assistance of two hydraulically operated cylinders placed opposite to each other. The material is removed by abrasion generating finer surfaces in the area where flow is restricted. But this method has a low material removal rate. As the time passed, various variants of AFM have been developed by different researchers to increase the productivity and improve the surface finish. Thus a combination of AFM and its process variants were developed to increase material removal rate and surface finish. This article provides a comprehensive review of recent developments in the process variants of AFM and the respective media.

Keywords: Abrasive flow machining, Hybrid process, Material removal rate, Surface roughness

Reference: Kiani, A., Esmailian M., and Amirabadi H., 'Abrasive Flow Machining: A Review on New Developed Hybrid AFM Process', Int J of Advanced Design and Manufacturing Technology, Vol. 9/No. 1, 2016, pp. 45–55.

Biographical notes: A. Kiani received his MSc in Mechanical Engineering from Isfahan University of Technology 2008. He is currently PhD candidate at the Department of Mechanical Engineering, Isfahan University of Technology, Isfahan, Iran. His current research interest includes Abrasive finishing and Additive manufacturing. **M. Esmailian** is a researcher of Mechanical engineering at the Malek-e-Ashtar University of Technology, Iran. He received his MSc in Mechanical engineering from K.N. Toosi University of Technology, Iran and BSc in Manufacturing from the Isfahan University of Technology, Iran. His current research focuses on non-traditional machining and metal forming. **H. Amirabadi** is Associate professor of Mechanical engineering at the University of Birjand, Iran. He received his MSc in Mechanical engineering from Ferdowsi University, Iran and BSc in Manufacturing from the Isfahan University of Technology, Iran. He finished the PhD from University of Mazandaran in mechanical engineering. His current research focuses on non-traditional machining.

1 INTRODUCTION

Abrasive flow machining (AFM) was developed by Extrude Hone Corporation, USA in 1960 [1]. There are three types of AFM machines: one way AFM, two way AFM [2] and orbital AFM [3]. Commonly used AFM is Two-way AFM in which two vertically opposed cylinders extrude medium back and forth through passages formed by the workpiece and tooling as shown in Fig. 1.

AFM is used to deburr, radius and polish difficult to reach surfaces by extruding an abrasive laden polymer medium with very special rheological properties. It widely has used finishing process to finish complicated shapes and profiles. The polymer abrasive medium which is used in this process possesses easy flowability, better self-deformability and fine abrading capability. Layer thickness of the removed material is about 1 to 10 µm. Best surface finish that has been achieved is 50 nm and tolerances are +/- 0.5 µm. In this process tooling plays very important role in finishing of material.

In AFM, deburring, radiusing and polishing are performed simultaneously in a single operation in various areas including normally inaccessible areas. It can produce true round radii even on complex edges. AFM reduces surface roughness by 75 to 90 percent on cast and machined surfaces. It can process dozens of holes or multiple passage parts simultaneously with uniform results. Also air cooling holes on a turbine disk and hundreds of holes in a combustion liner can be deburred and radiused in a single operation.

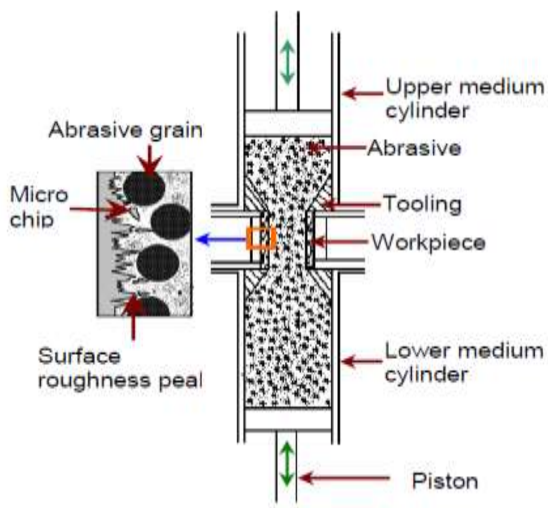

Fig. 1 Two way AFM process [4]

AFM produces uniform, repeatable and predictable results on an impressive range of finishing operations. Important feature which differentiates AFM from other finishing processes is that it is possible to control and select the intensity and location of abrasion through fixture design, medium selection and process parameters. It has applications in many areas such as aerospace, dies and moulds, and automotive industries. The present article attempts to report developments in the variants of the AFM process, its tooling and media. A review based on the reported experimental works has been presented.

2 CLASSIFICATION OF AFM MACHINE

As mentioned earlier, AFM machines are classified into three categories: one way AFM, two way AFM and orbital AFM. A brief discussion of the same is given below.

One way AFM process

One way AFM process apparatus is provided with a hydraulically actuated reciprocating piston and an extrusion medium chamber adapted to receive and extrude medium unidirectionally across the internal surfaces of a workpiece having internal passages formed therein, as shown in Fig. 2.

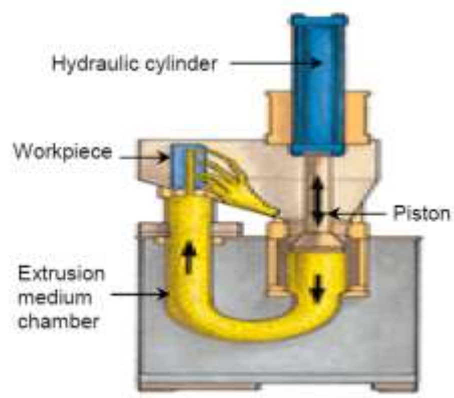

Fig. 2 Unidirectional AFM process [2]

Fixture directs the flow of the medium from the extrusion medium chamber into the internal passages of the workpiece, while a medium collector collects the medium as it extrudes out from the internal passages. The extrusion medium chamber is provided with an access port to periodically receive medium from the collector into extrusion medium chamber. The hydraulically actuated piston intermittently withdraws from its extruding position to open the extrusion medium chamber access port to collect the medium in the extrusion medium chamber. When the extrusion medium chamber is charged with the working medium, the operation is resumed.

Two-way AFM process

Two way AFM machine [5] has two hydraulic cylinders and two medium cylinders. The medium is extruded, hydraulically or mechanically, from the filled chamber to the empty chamber via the restricted passageway through or past the workpiece surface to be abraded (Fig. 1). Typically, the medium is extruded back and forth between the chambers for the desired fixed number of cycles. Counter bores, recessed areas and even blind cavities can be finished by using restrictors or mandrels to direct the medium flow along the surfaces to be finished.

Orbital AFM process

In orbital AFM, the workpiece is precisely oscillated in two or three dimensions within a slow flowing 'pad' of compliant elastic/plastic AFM medium. In Orbital AFM, surface and edge finishing are achieved by rapid, low-amplitude, oscillations of the workpiece relative to a self-forming elastic plastic abrasive polishing tool. The tool is a pad or layer of abrasive-laden elastic plastic medium (similar to that used in two way abrasive flow finishing), but typically higher in viscosity and more in elastic. Orbital AFM concept is to provide translational motion to the workpiece.

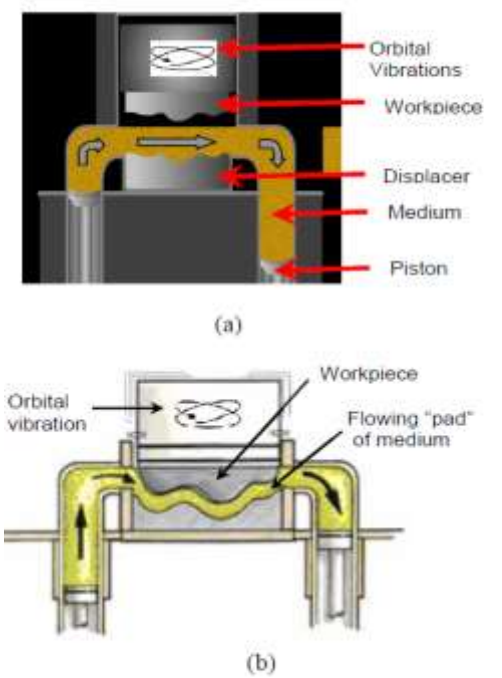

Fig. 3 Orbital AFM (a) Before start of finishing, (b) While finishing [3]

When workpiece with complex geometry translates, it compressively displaces and tangentially slides across the compressed elastic plastic self-formed pad (layer of viscoelastic abrasive medium) which is positioned on the surface of a displacer which is roughly a mirror image of the workpiece, plus or minus a gap accommodating the layer of medium and a clearance. A small orbital oscillation (0.5 to 5 mm) circular eccentric planar oscillation is applied to the workpiece so that, at any point in its oscillation, a portion of its surface bumps into the medium pad and elastically compresses (5 to 20%) and slides across the medium as the workpiece moves along its orbital oscillation path. As the circular eccentric oscillation continues, different portions of the work piece slide across the medium. Ultimately, the full circular oscillation engages each portion of the surface.

To assure uniformity, the highly elastic abrasive medium must be somewhat plastic in order to be self-forming and to be continually presenting fresh medium to the polishing gap. For finishing applications, AFM medium allows the use of a simple arrangement for feeding and evacuating the abrasive medium pad to achieve uniform results. Regions of the medium pad that overly fill the gap generally get pushed aside and are shaped by the oscillation of the workpiece itself. Regions of medium in the gap that are worked excessively become warmer, due to deformation heating, and consequently become less elastic and more plastic and are squeezed out of the work gap.

Since all areas except internal features that are even smaller than the oscillation amplitude are equally worked in the process, orbital AFM's small (0.5 to 5 mm) oscillation amplitude allows finishing highly complex geometries. The controlled and cushioned, but still repeated, bumping of the workpiece against the self-shaped tool imparts beneficial residual compressive stresses to the workpiece surfaces. The tangential translation of the workpiece across the elastically compressed and cushioned abrasive particles provides remarkable improvements in surface roughness.

Orbital AFM can be applied to many different workpieces from many different industries from precision ground aerospace components to cast aluminum wheels. Coining dies used to make proof coins can be polished from a 0.5 μm before surface to an amazing 0.01 μm after finish after only seven minutes of Orbital AFM processing. Orbital AFM is used to produce extremely fine finishes on the complex geometry of prosthetic devices while maintaining critical dimensional tolerances. Beverage container blow molds are finished using the Orbital AFM process dramatically reducing polishing costs while, at the same time, improving consistency, increasing production rates, and reducing the need for skilled labor.

3 APPLICATIONS OF AFM

Precision finishing of mechanical parts is a critical requirement in many applications. There are a number of traditional as well as non-traditional processes available, however, most of the processes were unable to finish the complex geometries. AFM is one of the non-traditional finishing processes that has the potential to overcome this problem. The applications of AFM include deburring,50 radiusing edges, removal of recast layer [6, 7] finishing of difficult-to-machine materials (Inconel [8], MMCs [9, 10] ceramics [11]), finishing of microholes [12, 13], polishing dies and moulds, titanium discs for turbine blades, automobile components, textile machinery components and medical implants. In the aerospace industry AFM plays a significant role as it is used to remove the carbon deposits from the engine. So AFM is used in rebuliding aircraft engines.

Fig. 4 Polishing internal surface of cylinder (Right), Finishing a fuel manifold (Left) [1]

4 MAJOR AREAS OF EXPERIMENTAL RESEARCH IN ABRASIVE FLOW FINISHING

Process parameters and their influence on output responses (Ra and MR)

Experimental investigations have been carried out by various researchers to investigate the effects of process parameters like extrusion pressure, number of cycles, viscosity, abrasive concentration and grain size on the output responses namely, surface finish and material removal during AFM. Rhoades [14, 15] experimentally investigated the basic principle of AFM process and identified its control parameters. He observed that when the medium is suddenly forced through restrictive passage then its viscosity temporarily rises. Significant material removal is observed only when medium is thickened. The amount of abrasion during AFM depends on design of tooling, extrusion pressure, medium viscosity and medium flow volume. All these parameters ultimately change the number of particles interacting with the workpiece and the force acting on individual abrasive grain. A higher volume of medium flow increases number of interacting abrasive grains with the workpiece, hence more abrasion takes place. Number of cycles depend on the velocity of medium, during a given time period. Flow pattern of medium depends on its slug (medium exiting the workpiece) flow speed, medium rheology and passage size (cross-sectional area). AFM can be used in industrial applications such as precision deburring, edge contouring, surface finish, removal of thermal recast layers, etc. [16].

Williams and Rajurkar [17] used the full factorial experimental design to study the effect of medium viscosity and extrusion pressure on metal removal and surface roughness. Medium’s viscosity effect is more significant on material removal as compared to extrusion pressure. It is also reported that major change in the surface finish is observed after finishing for only a few cycle.

Jain and Adsul [18] reported that initial surface roughness and hardness of the workpiece affects material removal during AFM process. Material removal and reduction in surface roughness value are reported higher for the case of softer workpiece material as compared to harder material. Material removal and reduction in surface roughness increases when percentage concentration of abrasive in the medium increases. They also concluded that among all the process parameters studied, the dominating one is the abrasive concentration followed by abrasive mesh size, and number of cycles.

Loveless [19] reported that the type of machining operation used to prepare the specimen prior to AFM is important and affects the improvement achieved during finishing. As compared to the turned and milled surfaces, WEDM’d surfaces are found to be more suitable for AFM. The amounts of material removal from the WEDM’d and milled surfaces are significantly different from that of turning and grinding, because these machining processes produce different micro surface contours.

Davies and Fletcher [20] reported a relationship between the numbers of cycles, temperature and pressure drop across the die for the given type of polymer and abrasive concentration. Increase in temperature results in decrease in medium viscosity and increase in volumetric flow rate. With increase in processing time, medium temperature increases that causes a change in medium viscosity. They concluded that rise in temperature is due to a combination of internal shearing of the medium and finishing action of the abrasive grit.

Process modelling and optimization

Williams and Rajurkar [21] developed a stochastic model of AFM generated surfaces by using Data Dependent Systems (DDS) methodology. They have estimated the ratio of surface roughness peak to valley height (Rz) to centerline average surface roughness value (Ra) by DDS methodology and found to be between 1.4 and 2.2 for the AFM process. It was established in their research that AFM finished surface profiles possess two distinct wavelengths, a large wavelength that corresponds to the main path of abrasive while the small wavelength is associated with the cutting edges. Good agreement is found between the primary frequency ranges obtained in DDS modeling and those derived from spectral analysis function. It is stated that these frequency bands are related to different material removal modes in AFM; consequently, the mechanism of material removal in AFM is considered to consist of ploughing responsible for creation of characteristic flow lines and micro-cutting. They also proposed an expression for estimating the abrasive grain wear and the number of active grains (Cd). The estimated value of Cd is used as a cutting life criterion for abrasives. For small number of cycles its value should remain fairly stable but with more and more processing the abrasive particles may fracture thereby increasing the Cd value.

The downturn of Cd value indicates that the medium has absorbed too much work piece material and need replacement. Jain et al. [22] also carried out simulation of finished surface profile and material removed considering the interaction of abrasive grains with workpiece.

Rajeshwar et al. [23] proposed a mathematical simulation model to determine the characteristics of the medium flow during finishing and its experimental verification was carried out. This model was developed using constitutive equations of Maxwell model considering the medium characteristics as non-Newtonian flow. They reported that a linear relationship exists between shear stress acting on the surface and the layer thickness of the removed material. A finite element approach was developed by Jain et al. [22] for prediction of the stresses developed during finishing of a cylindrical passage by AFM process (axi-symmetric flow). In their study it is assumed that medium exhibits linear viscous flow property and medium properties are independent of temperature and are constant with regards to time and space. They also presented a theoretical model which is based upon the considering abrasion process in AFM i.e., combination of micro-ploughing and micro-cutting by assuming that all the abrasive particles are spherical in shape having a single cutting edge with same size. It is also assumed in this model that the load acting on each particle is constant and every grain achieves the same penetration depth depending upon applied load.

Gorana et al. [24] developed a theoretical model of forces acting on a single abrasive grain for studying the finishing mechanism of AFM process. Comparison of theoretical model results with that of experimental data of force and active abrasive grains density obtained during AFM process was done.

Fletcher et al. [25] studied the relationship between medium rheological properties and the AFM process. Shear rate of the polymer increases when it passes through the restriction (or reduced cross-sectional area). Capillary rheometer is used to find the relationship between wall shear stress and shear rate for medium viscosity of polyborosiloxane medium. They concluded that coefficient of viscosity decreases but shear stress increases as shear rate increases. Variation of wall shear stress with time is also studied. They also concluded that greater finishing action could be achieved as a result of longer piston stroke durations, due to higher wall shear stress generated.

Petri et.al, [26] adopted neural network modeling technique for developing a comprehensive model for AFM. They presented three neural network models (Polishing applications, surface removal applications with a circular flow path and surface removal application with a non-circular flow path).

Lam and Smith [27, 28] applied Cascade-Correlation neural network modeling to finishing of automotive engine air intake manifold. They used it to predict the instant at which the finishing process should terminate to meet the airflow specifications.

Jain and Jain [29] proposed a generalized back propagation neural network model and a second network which parallelizes the augmented Lagrange multiplier (ALM) algorithm. The model determines optimal finishing parameters by minimizing a performance index subject to appropriate operating constraints.

Sarah et al. [30] presented a neural network model as an off-line controller for AFM of automotive engine manifold to predict when the AFM process should be stopped to achieve the required airflow rate through manifold body.

Monitoring of AFM process

For online monitoring of material removal and surface roughness in AFM process, Williams and Rajurkar [31] applied acoustic emission technique (elastic stress waves generated by the rapid release of strain energy within a material due to a rearrangement of its internal structure is called "acoustic emission"). In a full factorial experiment, the effect of extrusion pressure, medium viscosity, abrasive grit size, number of cycles, and work piece material was investigated on material removal, root mean square of acoustic emission signal (AERMS), and surface roughness improvement. From the above parameters only grit size showed insignificant effect on material removal. They studied acoustic emission signals for grinding to analyze the mechanism involved in AFM and found that the acoustic emission signal is highly dependent on the characteristics of the initial surface roughness of the workpiece. The AERMS of the signal is sensitive to extrusion pressure and other AFM process parameters, which affect material removal.

5 RECENT DEVELOPMENTS IN AFM PROCESSES

Though there are many advantages of AFM process, it has a few disadvantages, such as low finishing rate, and incapability to correct the form geometry. Many researchers have been working to improve the finishing rate, surface integrity and compressive residual stresses produced on the workpiece surface. In this section some of new developed hybrid AFM processes have been introduced and their advantages have been described in comparison with pure AFM.

Magnetic-based AFM

A number of researchers have applied a magnetic field around the tooling to improve the surface finish [32-35]. A magnetic field has been applied around the workpiece in the basic AFM process to develop a new hybrid method known as magnetically assisted AFM (MAAFM) [35]. It was observed that under the application of a magnetic field, a sideways pull (Figure 5) was experienced by the abrasive media, which mainly consisted of ferromagnetic particles. These particles impinged on the workpiece, causing the phenomena of micro chipping and micro ploughing. The combination of high magnetic flux density and low flow rates increased the MRR and reduced the surface roughness. The wear behavior of different workpiece materials was studied and it was found that the magnetic field enhances the MRR for non-ferromagnetic materials, however, for ferromagnetic materials, the 'shielding effect' was observed [36] Consequently, in brass and aluminum, more MRR and more percentage improvement in R_a was observed, as compared with mild steel.

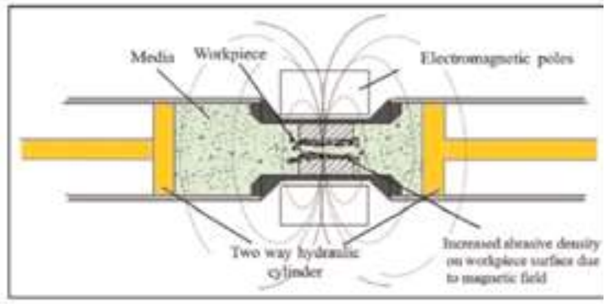

Fig. 5 Schematic of MAAFM set-up [35]

There was no significant percentage improvement in Roughness average (R_a) and MRR for mild steel after MAAFM when compared with AFM. The use of magnetorheological polishing fluids (MRPF) has been done by many researchers in precision finishing [37-39]. MRPF containing carbonyl iron particles (CIPs) and SiC abrasives have been used as a media in AFM to develop magneto rheological abrasive flow finishing (MRAFF) [40]. The specialty of this media was that, on application of an external magnetic field, chain formation of CIP particles occurred, which assisted the motion of the SiC abrasives. It was observed that the rotation of the abrasive grains stopped and they were able to shear the asperities without rolling over them. Constant magnetic flux and different pressures were applied to study the effect of the number of cycles on the workpiece surface [41]. Initially, the surface finish improved, but as the number of cycles increased, the surface finish deteriorated and later again improved. The loosely held material filled the asperities initially, later with an increase in cycles, these loose materials were removed and it exposed the actual surface irregularities, which increased the surface roughness.

After this, as the number of cycles increased, the surface finish improved. Increasing the pressure, the surface finish was found best at 3.75MPa, after which it began to deteriorate. The mathematical modelling and simulation to predict the surface roughness has also been done in MAAFM and MRAFF [42, 43].

The similar principle of MRAFF was used to finish an external curved surface, by not only applying a magnetic field around, but also providing rotation to the workpiece (Figure 6(a)) [44]. The chain formation of CIPs for external surfaces is shown in Figure 3(b). It was found that at higher rotation speed of the workpiece, the maximum surface finish improved by

25% at a certain threshold limit (0.633 Tesla (T)), after which the results remained constant.

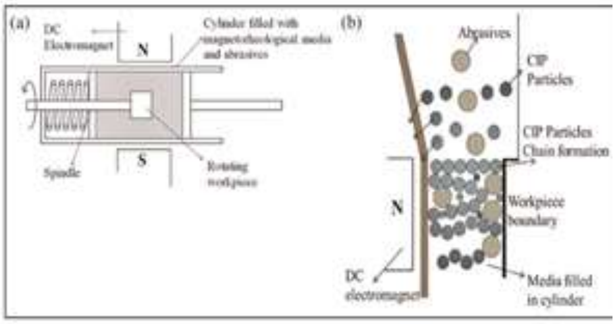

Fig. 6 (a) Schematic of magnetorheological abrasive honing (b) Rearrangement of CIPs and abrasives during the process [44]

Centre tooling-based AFM

Fine finishing of workpieces has been done by placing special toolings inside the workpiece in many finishing processes [45-51]. In a center tooling-based AFM, the set-up consisted of special tooling [35] as shown in Figure 7, which had the provision of rotating different rods in the fixture through the gear train and motor arrangement. The rod kept at the center of the workpiece can be stationary or rotating. The travelling path of the abrasives in media increased, owing to centrifugal force generating (CFG) rods or stationary drills that guided media in a helical path.

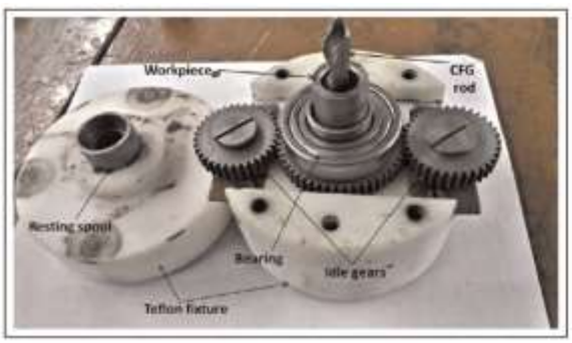

Fig. 7 Elements of the rotating attachment used in the CFAAFM set-up [35]

Rods of different shapes have been used to increase the number of active grains striking the workpiece surface. The rotation of the rods generated centrifugal force to act on the abrasive media, which threw the abrasives at an angle of 'attack' towards the surface, enhancing the surface finish and MRR [50]. It was reported that with the increase in rotational speed, the MRR increased and the surface finish improved. The rectangular rod produced the best surface finish, whereas the splined rod increased the MRR [52]. Further, it was found that with a combination of high extrusion pressure and higher CFG rod speed, the process exhibited 56.37% increase in surface finish, whereas a combination of a larger grain size and higher CFG rod speed led to a maximum increase in MRR [49].

It was proposed that if a stationary drill bit is placed in the media flow path in drill bit - guided abrasive flow finishing (DBG–AFF), the media will pass through a helical flute drill that will cause mixing and reshuffling of abrasives [51]. The intermixing flow mechanism of abrasive media was observed to be a combination of three different motions – flow along the flute path, reciprocating axial flow and scooping flow. All these processes led to an increase in the travelling path of abrasives. The scratches on the candidate surface (Figure 8) show that the abrasives strike at an angle of abrasion, inclined to the initial grinding lay, which is given by $\gamma = \alpha - \beta$ where α=helical flute angle of the drill bit and β=angle of abrasion on the work surface. The increase in the drill bit diameter decreased the cross section area through which the medium flows and resistance to flow increased, which resulted in an increased indentation depth of abrasives assisting in shearing of peaks.

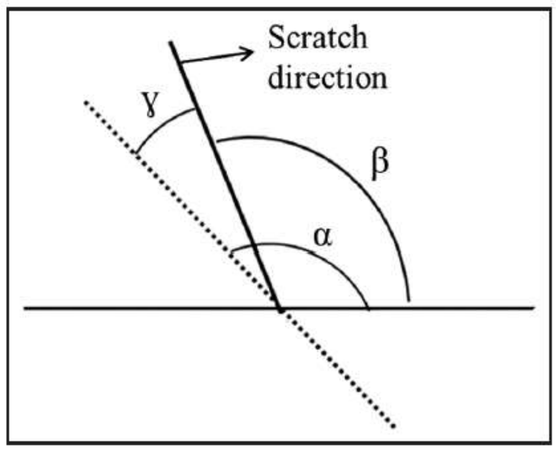

Fig. 8 Active abrasive grain scratch at an angle β [51]

The probability of rotating the media at the abrasive-workpiece region was found to be low in DBG-AFF. The helical motion of media imparted only at the central region of the media and there were considerable flow losses. So another variant, known as rotational abrasive flow finishing (R-AFF), was developed in which external tooling was used to rotate the workpiece [9]. As compared with AFM, an improvement of 81.8% more MRR and 44% better DRa (improvement in surface finish) has been reported. It was also observed that mechanism of material removal in RAFF while machining metal matrix composite (MMC) alloys was different from metal alloys owing to the presence of reinforced particles. When rotation was given to the MMC workpiece, the abrasives in contact followed a helical path trying to shear the peaks at an angle. At a lower rotational speed (r/min) the abrasives possessed a low tangential force and low tangential velocity owing to which they were unable to shear the large surface areas and reinforcement particles. In order to enhance the performance of the process, the travelling velocity of abrasive particles was increased by a combination of centrifugal force-assisted abrasive flow machining (CFAAFM) and DBG-AFF to form a new hybrid AFM process known as spiral flow-assisted AFM (SFAAFM) [45]. In this process a spiral rod was rotated inside the workpiece through a specially designed gear train mechanism (Figure 9). It was reported that increasing the speed of the spiral rod improved the surface finish owing to less pitch of spiral action of the abrasive edges on the cylindrical surface of the workpiece. With a further increase in speed, the spiral action became ineffective and it acted like a circular rod resulting in lower surface finish improvement (DR_a).

Recently, a newly design and developed solution is formed as electrochemical and centrifugal force assisted abrasive flow machining process (EC2A2FM) for various range of parameters. In this process, the electrochemical process is added to centrifugal force acting on abrasive grains to increase active force on them and improve material removal rate. The analysis of results showed that there was enhanced material removal in EC2A2FM as compared to the other hybrid AFM process, as well as the operating pressure was allows 6 N/mm^2 [53].

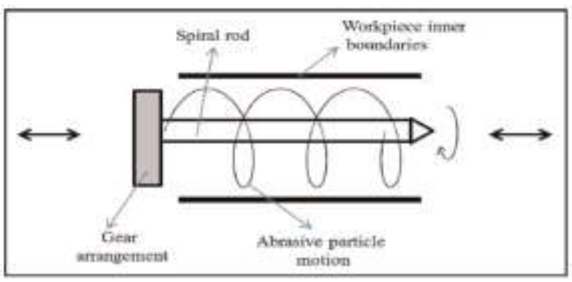

Fig. 9 Schematic of SFAAFM process [45]

Ultrasonic-based AFM

The first hybrid AFM process was the ultrasonic flow polishing (UFP) method reported in the year 1998 [54]. In UFP, the media flowing through the workpiece was energised by the magnetostrictive or piezoelectric transducer. The vibrations induced by the tool were passed to the media slurry, which resulted in an increase in the active abrasives on the workpiece surface.

Magnetic field-assisted processes were observed to be not so effective on a ferromagnetic workpiece [45]. The DBG-AFF, SFAAFM and CFAAFM have their own limitations, as these can only be used to work upon simple workpiece geometries. These processes might not be effective on very complex geometries or for geometries having multiple passages, blind holes or slits. With a view to eliminating these problems, a new technique called ultrasonic-assisted AFM (UAAFM) was developed [55].

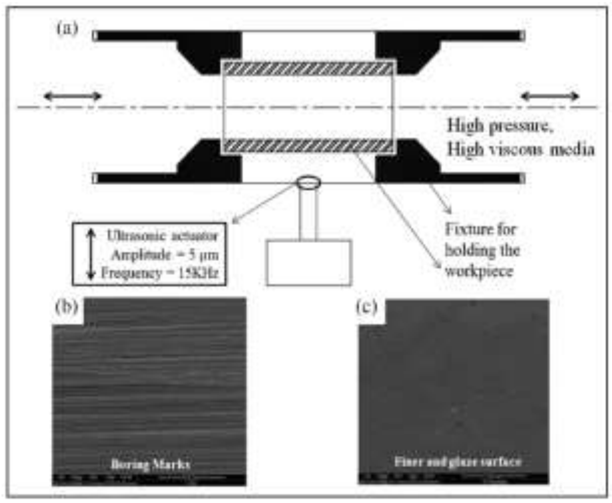

Fig. 10 (a) Schematic of UAAFM, comparative study of the surfaces; (b) before UAAFM and after UAAFM [45]

In this process, an actuator was mounted on the base of the AFM set-up (Figure 10(a)). The actuator shaft was connected by a coupling and collar to the workpiece. As abrasive media was pushed through the workpiece axially, controlled vibrations were induced to the workpiece in a perpendicular direction to the media flow. The workpiece was subjected to vibrations at high frequency with small amplitude. The moving abrasives interacted with the peaks of vibrating workpiece, which improved the surface finish [56]. The time of abrasive and workpiece interaction decreased with an increase in frequency resulting in finer chips. The scanning electron microscope (SEM) images (Figure 10(b) and (c)) show the Inconel 718 surface before UAAFM and after UAAFM. A finer and glazed surface was observed with the UAAFM.

The possible behaviour of the tool (media) during UAAFM and its effect on the machining process through a computation based approach have been investigated [57]. Commercially available simulation tool was used to study the effect of the media in response to different set of machining conditions. The responses were evaluated in terms of changes in the fluid pressure, velocity profile of the fluid, temperature distribution in the working fluid and the possible wall shear on the work surface. Results show that while changes in the amplitude of applied vibration (10 µm and 50 µm) significantly affect the wall shear, the media velocity and pressure profiles are only marginally sensitive to this parameter.

7 CONCLUSION

The work presented here is an overview of recent developments of AFM and future research directions. The major conclusions of the study are as follows.

- AFM is a prominent non-traditional finishing process for finishing intricate profiles of both internal and external surfaces.
- Media acting as a deformable tool is the key element for the AFM process; many attempts have been made to develop efficient, environmental friendly, cost effective media and hybridisation.
- The important advancement of hybrid AFM is finishing of difficult-to-machine materials (Inconel 718, MMC's) with high surface finish, surface integrity and low machining time.
- The MAAFM process has recorded better surface finish on non-ferrous materials like brass and also less number of cycles is required for the same MRR when compared with simple AFM. But it is recorded that only a marginal surface finish improvement took place when worked on mild steel. This process is inappropriate for ferrous materials.
- The MRAFF, CFAAFM, DBG-AFF and R-AFF processes were tried to increase the number of active abrasive grains towards the workpiece surface, which results in high MRR and surface finish. In CFAAFM and SFAAFM, special tooling to rotate the medium was used. An R-AFF mechanism for rotation of the workpiece has been used, which can cause higher interaction when compared with other media rotated processes. The CFAAFM has provided apparently higher MRR, although MRR has not much significance in this finish machining process.
- The rotation of centrifugal rods as well as the workpiece may be difficult for complex geometries; this is where UAAFM has a clear advantage over other processes. The process uses ultrasonic energy for additional interaction.

REFERENCES

[1] Extrudehoneafm.Com, Accessed 2015/7/10; http://extrudehoneafm.com/.
[2] Rhoades, L. and Kohut, T., Reversible Unidirectional Afm, US patent, No. 5,070,652, 1991.
[3] Rhoades, L., Orbital and or Reciprocal Machining with a Viscous Plastic Medium, International patent no: WO, Vol. 90, No. 05044, pp. 17.
[4] Sankar, M. R., Jain, V. and Ramkumar, J., "Abrasive Flow Machining (Afm): An Overview", 2011.
[5] Rhoades, L. J., Abrasive Flow Machining[Afm], Manufacturing Engineering, Vol. 101, No. 5, pp. 75-78, 1988.
[6] Tzeng, H.-J., Yan, B.-H., Hsu, R.-T. and Lin, Y.-C., Self-Modulating Abrasive Medium and Its Application to Abrasive Flow Machining for Finishing Micro Channel Surfaces, Journal of Advanced Manufacturing Technology, Vol. 32, No. 11-12, pp. 1163-1169, 2007.
[7] Tzeng, H.-J., Yan, B.-H., Hsu, R.-T. and Chow, H.-M., Finishing Effect of Abrasive Flow Machining on Micro Slit Fabricated by Wire-Edm, Journal of Advanced Manufacturing Technology, Vol. 34, No. 7-8, pp. 649-656, 2007.
[8] Kozak, J. and Oczoś, K. E., Selected Problems of Abrasive Hybrid Machining, Journal of Materials Processing Technology, Vol. 109, No. 3, pp. 360-366, 2001.
[9] Sankar, M. R., Jain, V. and Ramkumar, J., Experimental Investigations into Rotating Workpiece Abrasive Flow Finishing, Wear, Vol. 267, No. 1, pp. 43-51, 2009.
[10]Mali, H. S. and Manna, A., Optimum Selection of Abrasive Flow Machining Conditions During Fine Finishing of Al/15 Wt% Sic-Mmc Using Taguchi Method, The International Journal of Advanced Manufacturing Technology, Vol. 50, No. 9-12, pp. 1013-1024, 2010.
[11]Uhlmann, E., Mihotovic, V. and Coenen, A., Modelling the Abrasive Flow Machining Process on Advanced Ceramic Materials, Journal of Materials Processing Technology, Vol. 209, No. 20, pp. 6062-6066, 2009.
[12]Jung, D., Wang, W., Knafl, A., Jacobs, T., Hu, S. J. and Assanis, D., Experimental Investigation of Abrasive Flow Machining Effects on Injector Nozzle Geometries, Engine Performance, and Emissions in a Di Diesel Engine, International Journal of Automotive Technology, Vol. 9, No. 1, pp. 9-15, 2008.
[13]Lin, Y.-C., Chow, H.-M., Yan, B.-H. and Tzeng, H.-J., Effects of Finishing in Abrasive Fluid Machining on Microholes Fabricated by Edm, The Journal of Advanced Manufacturing Technology, Vol. 33, No. 5-6, pp. 489-497, 2007.
[14]Rhoades, L., Abrasive Flow Machining with Not-So-Silly Putty, Met. Finish., Vol. 85, No. 7, pp. 27-29, 1987.
[15]Rhoades, L., Abrasive Flow Machining: A Case Study, Journal of Materials Processing Technology, Vol. 28, No. 1, pp. 107-116, 1991.
[16]Perry, W., Abrasive Flow Machining: Principles and Practices, Nontraditional Machining, pp. 121-127, 1985.
[17]Williams, R. and Rajurkar, K., Stochastic Modeling and Analysis of Abrasive Flow Machining, Journal of

manufacturing science and engineering, Vol. 114, No. 1, pp. 74-81, 1992.
[18] Jain, V. and Adsul, S., Experimental Investigations into Abrasive Flow Machining (Afm), Journal of Machine Tools and Manufacture, Vol. 40, No. 7, pp. 1003-1021, 2000.
[19] Loveless, T., Williams, R. and Rajurkar, K., A Study of the Effects of Abrasive-Flow Finishing on Various Machined Surfaces, Journal of Materials Processing Technology, Vol. 47, No. 1, pp. 133-151, 1994.
[20] Davies, P. and Fletcher, A., The Assessment of the Rheological Characteristics of Various Polyborosiloxane/Grit Mixtures as Utilized in the Abrasive Flow Machining Process, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Vol. 209, No. 6, pp. 409-418, 1995.
[21] Williams, R., Rajurkar, K. and Kozak, J., Metal Removal Distribution and Flow Characteristics in Abrasive Flow Machining, Transactions of the North American Manufacturing Research Institution of SME., Vol. 20, pp. 145-150, 1992.
[22] Jain, R. K., Jain, V. K. and Dixit, P., Modeling of Material Removal and Surface Roughness in Abrasive Flow Machining Process, Journal of Machine Tools and Manufacture, Vol. 39, No. 12, pp. 1903-1923, 1999.
[23] Rajeshwar, G., Kozak, J. and Rajurkar, K. P., Modeling and Computer Simulation of Media Flow in Abrasive Flow Machining Process, in Proceeding of, 965-971.
[24] Gorana, V., Jain, V. and Lal, G., Forces Prediction During Material Deformation in Abrasive Flow Machining, Wear, Vol. 260, No. 1, pp. 128-139, 2006.
[25] Fletcher, A., Hull, J., Mackie, J. and Trengove, S., Computer Modelling of the Abrasive Flow Machining Process, in: Surface Engineering, Eds., pp. 592-601: Springer, 1990.
[26] Petri, K. L., Billo, R. E. and Bidanda, B., A Neural Network Process Model for Abrasive Flow Machining Operations, Journal of Manufacturing Systems, Vol. 17, No. 1, pp. 52-64, 1998.
[27] Lam, S. S. and Smith, A. E., Process Monitoring of Abrasive Flow Machining Using a Neural Network Predictive Model, in Proceeding of, 477-482.
[28] Lam, S. S. and Smith, A. E., Process Control of Abrasive Flow Machining Using a Static Neural Network Model, in Proceeding of.
[29] Jain, R. K. and Jain, V. K., Optimum Selection of Machining Conditions in Abrasive Flow Machining Using Neural Network, Journal of Materials Processing Technology, Vol. 108, No. 1, pp. 62-67, 2000.
[30] Lam, S. S. and Smith, A. E., Cascade-Correlation Neural Network Modeling of the Abrasive Flow Machining Process, University of Pittsburgh, 1998.
[31] Williams, R., Acoustic Emission Characteristics of Abrasive Flow Machining, Journal of manufacturing science and engineering, Vol. 120, No. 2, pp. 264-271, 1998.
[32] Chang, G.-W., Yan, B.-H. and Hsu, R.-T., Study on Cylindrical Magnetic Abrasive Finishing Using Unbonded Magnetic Abrasives, Journal of Machine Tools and Manufacture, Vol. 42, No. 5, pp. 575-583, 2002.
[33] Jiang, M. and Komanduri, R., Application of Taguchi Method for Optimization of Finishing Conditions in Magnetic Float Polishing (Mfp), Wear, Vol. 213, No. 1, pp. 59-71, 1997.
[34] Hanada, K., Yamaguchi, H. and Zhou, H., New Spherical Magnetic Abrasives with Carried Diamond Particles for Internal Finishing of Capillary Tubes, Diamond and Related Materials, Vol. 17, No. 7, pp. 1434-1437, 2008.
[35] Singh, S. and Shan, H., Development of Magneto Abrasive Flow Machining Process, Journal of Machine Tools and Manufacture, Vol. 42, No. 8, pp. 953-959, 2002.
[36] Singh, S., Shan, H. and Kumar, P., Wear Behavior of Materials in Magnetically Assisted Abrasive Flow Machining, Journal of Materials Processing Technology, Vol. 128, No. 1, pp. 155-161, 2002.
[37] Kim, J.-D. and Kim, K.-D., Deburring of Burrs in Spring Collets by Abrasive Flow Machining, The Journal of Advanced Manufacturing Technology, Vol. 24, No. 7-8, pp. 469-473, 2004.
[38] Jang, K.-I., Seok, J., Min, B.-K. and Lee, S. J., An Electrochemomechanical Polishing Process Using Magnetorheological Fluid, Journal of Machine Tools and Manufacture, Vol. 50, No. 10, pp. 869-881, 2010.
[39] Sidpara, A. and Jain, V., Experimental Investigations into Forces During Magnetorheological Fluid Based Finishing Process, Journal of Machine Tools and Manufacture, Vol. 51, No. 4, pp. 358-362, 2011.
[40] Jha, S. and Jain, V., Design and Development of the Magnetorheological Abrasive Flow Finishing (Mraff) Process, Journal of Machine Tools and Manufacture, Vol. 44, No. 10, pp. 1019-1029, 2004.
[41] Jha, S., Jain, V. and Komanduri, R., Effect of Extrusion Pressure and Number of Finishing Cycles on Surface Roughness in Magnetorheological Abrasive Flow Finishing (Mraff) Process, Journal of Advanced Manufacturing Technology, Vol. 33, No. 7-8, pp. 725-729, 2007.
[42] Wani, A. M., Yadava, V. and Khatri, A., Simulation for the Prediction of Surface Roughness in Magnetic Abrasive Flow Finishing (Maff), Journal of Materials Processing Technology, Vol. 190, No. 1, pp. 282-290, 2007.
[43] Das, M., Jain, V. and Ghoshdastidar, P., Analysis of Magnetorheological Abrasive Flow Finishing (Mraff) Process, Journal of Advanced Manufacturing Technology, Vol. 38, No. 5-6, pp. 613-621, 2008.
[44] Sadiq, A. and Shunmugam, M., Investigation into Magnetorheological Abrasive Honing (Mrah), Journal of Machine Tools and Manufacture, Vol. 49, No. 7, pp. 554-560, 2009.
[45] S, R., Some Studies to Enhance the Capabilities of Abrasive Flow Machining Process, PhD Thesis, IIT Roorkee, 2011.
[46] Yan, B.-H., Tzeng, H.-J., Yuan Huang, F., Lin, Y.-C. and Chow, H.-M., Finishing Effects of Spiral Polishing Method on Micro Lapping Surface, Journal of Machine Tools and Manufacture, Vol. 47, No. 6, pp. 920-926, 2007.
[47] Wang, A., Tsai, L., Liang, K.-Z., Liu, C.-H. and Weng, S.-H., Uniform Surface Polished Method of Complex

Holes in Abrasive Flow Machining, Transactions of Nonferrous Metals Society of China, Vol. 19, pp. s250-s257, 2009.

[48] Wang, A. C., Yan, B. H., Li, X. T. and Huang, F. Y., Use of Micro Ultrasonic Vibration Lapping to Enhance the Precision of Microholes Drilled by Micro Electro-Discharge Machining, Journal of Machine Tools and Manufacture, Vol. 42, No. 8, pp. 915-923, 2002.

[49] Reddy, M. K., Sharma, A. and Kumar, P., Some Aspects of Centrifugal Force Assisted Abrasive Flow Machining of 2014 Al Alloy, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 222, No. 7, pp. 773-783, 2008.

[50] Walia, R., Shan, H. and Kumar, P., Determining Dynamically Active Abrasive Particles in the Media Used in Centrifugal Force Assisted Abrasive Flow Machining Process, Journal of Advanced Manufacturing Technology, Vol. 38, No. 11-12, pp. 1157-1164, 2008.

[51] Sankar, M. R., Mondal, S., Ramkumar, J. and Jain, V., Experimental Investigations and Modeling of Drill Bit-Guided Abrasive Flow Finishing (Dbg-Aff) Process, The International Journal of Advanced Manufacturing Technology, Vol. 42, No. 7-8, pp. 678-688, 2009.

[52] Walia, R., Shan, H. and Kumar, P., Abrasive Flow Machining with Additional Centrifugal Force Applied to the Media, Machining Science and Technology, Vol. 10, No. 3, pp. 341-354, 2006.

[53] Vaishya, R., Walia, R. and Kalra, P., Design and Development of Hybrid Electrochemical and Centrifugal Force Assisted Abrasive Flow Machining, Materials Today: Proceedings, Vol. 2, No. 4, pp. 3327-3341, 2015.

[54] Jones, A. and Hull, J., Ultrasonic Flow Polishing, Ultrasonics, Vol. 36, No. 1, pp. 97-101, 1998.

[55] Sharma, A., Kumar, P. and Rajesha, S., An Improved Ultrasonic Abrasive Flow Machining and a Device Therefor, Patent number, Vol. 3578, 2011.

[56] Venkatesh, G., Sharma, A. K. and Kumar, P., On Ultrasonic Assisted Abrasive Flow Finishing of Bevel Gears, International Journal of Machine Tools and Manufacture, Vol. 89, pp. 29-38, 2015.

[57] Gudipadu, V., Sharma, A. K. and Singh, N., Simulation of Media Behaviour in Vibration Assisted Abrasive Flow Machining, Simulation Modelling Practice and Theory, Vol. 51, pp. 1-13, 2015.