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PROCESS PARAMETERS AND THEIR IMPACT ON THE PRODUCT QUALITY IN ABRASIVE FLOW MACHINING/FINISHING

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ABSTRACT:- *Abrasive Flow Machining (AFM) uses elasto-plastic polymer as a fluid that carries the fine abrasive particles which together make a flexible tool. This tool can be used for fine finishing of difficult to reach areas like profiled holes, passages, complex hollow sections, etc. economically which is otherwise not possible using other micro finishing processes. Components produced using AFM have a consistently excellent uniformity and repeatability. The process parameters of AFM which have impact on the product quality are flow rate, flow volume, extrusion pressure, etc. This research paper is intended to study the effect of the process parameters of Abrasive Flow Machining on the intended outcomes as reported by various researchers.*

Keywords: *abrasive flow machining, process parameters, flow rate, flow volume, extrusion pressure, surface roughness.*

1. INTRODUCTION

The requirements of aerospace and other industries demand a very high level of accuracy and surface integrity in the critical components. The achievable accuracy and surface integrity of the components finished using polishing, burnishing, honing or super finishing are limited by the process capabilities. Abrasive Flow finishing is one machining method which uses a flexible tool made from a gel and fine abrasive particles which can overcome the aforementioned limitations. AFM is the only choice when the details to be finished require very high accuracy and surface integrity are relatively inaccessible.

AFM does fine finishing of components using a visco-plastic medium consisting of a polymer-based carrier and very fine abrasive particles. The medium acts like a flexible grinding tool when its flow is restricted in a passage. The three chief components of the process set up are machine, medium and fixture. The quality of the surface generated and the material removal rate (MRR) depend on these parameters. The extent of abrasion depends on the machine, the kind of abrasion is decided by the medium and the fixture determines the exact location at which machining is to be done. The most widely used carrier liquid is a high visco-plastic polymer (at any constant rate of shear its apparent viscosity increases with time to some maximum value). The carrier medium should be able to drag the abrasive grains along with it through various passages. Al_2O_3 and SiC are the two abrasives most suitable for many an application. B_4C and diamond are used for specialized applications only because of their exorbitant cost. The viscosity of the carrier fluid along with the size, type and quantity of the abrasive particles determine the properties of the medium. Although the abrasive does the actual cutting, it is the physical properties of the medium that play a vital role in the process effectiveness.

Al_2O_3 is applied for finishing air craft engine blades and vanes, semiconductor valves and tubing, and medical implants. SiC is very hard and durable over a wide range of applications. B_4C gives higher MRR than SiC. B_4C is employed for finishing materials having low machinability, like hardened tool steel, cobalt steels, nickel based super alloys, titanium and tungsten carbide applications. Diamond powder as an abrasive is very costly and is used for special applications like very hard workpieces requiring a very high-quality surface finish. Typical examples are extrusion, drawing and heading dies or where a high gloss finish is required. Figure 1 shows one way and Figure 2 shows two-way AFM process.

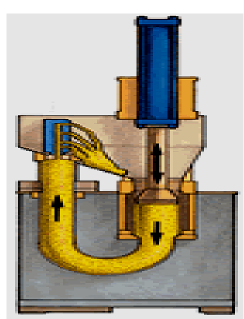


Figure 1 one-way flow

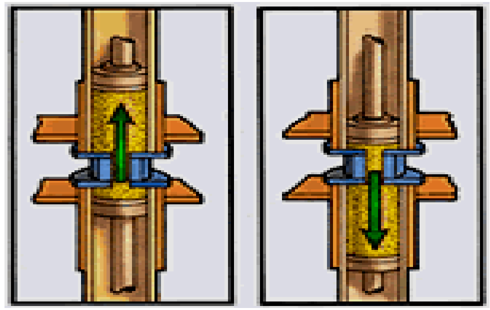


Figure 2 Two-way flow process

The typical AFM process (two-way flow) uses two vertically opposed cylinders which extrude an abrasive medium through passages formed by the workpiece and tooling. Abrasive action occurs wherever the medium enters and passes through the most restrictive passages. The parameters that require close control are the extrusion pressure, the displacement per stroke and the number of reciprocating cycles.

2. Effect of process parameters on performance:

The process parameters can be classified as[1]

1. Medium properties: Viscosity (stiff to fluid), grit size (8 to 1000 mesh number), temperature (32 to 52 ^{0}C), polymer to diluents ratio (0.25:1 to 4:1).
2. Machine parameters: Extrusion pressure (10 to 200 bar), Flow volume (100 to 300 ml), flow rate (7 to 225 L/min), number of cycles (1 to 5).
3. Workpiece/fixture configuration: Production ratio, passage length, passage cross sectional area, passage profile complexity, initial surface condition.

The two dominant process parameters controlling the amount of abrasion by a specific medium composition are the medium flow volume and extrusion pressure. It is quite obvious that for all the other factors remaining constant, a greater volume of medium will cause more abrasion [2]. Extrusion pressure affects the final force acting on the abrasive grains [3]. A part of extrusion pressure is lost within the medium due to its internal resistance to flow and rest is imparted to abrasive grains contacting the workpiece surface. With increase in pressure, the improvement in material removal tends to stabilize due to localized rolling of grains [1].

The flow rate of media is less influential parameter as far as material removal is concerned [3]. Increased viscosity of the medium reduces speed and promotes the evenness of abrasion. Higher flow speed results in the edge abrasion of the passage as the medium flows faster at the centre than at the edges. The media flow rate also affects other parameters such as passage size, media viscosity, etc. and affects the abrasion process also.

Viscosity of medium is one of the very important parameters of the process. An increase in viscosity improves the material removal rate as well as final surface roughness, keeping all other parameters constant [4]. Viscosity of the medium itself is affected by composition, grain size and its temperature. Increase in temperature causes marked decrease in media viscosity, which influence the flow properties and overall abrasion process [5]. Bigger grains cut faster, while smaller grains give less MRR but provide better finish and can reach into complex and narrow passages. As a thumb rule, finer abrasives should be used when the initial roughness of the surface of workpiece is low [6].

Gorana et al. showed that the cutting force components and active grain density govern the surface roughness produced during the AFM process [7]. Experiments were conducted using three variables viz. extrusion pressure (MPa), abrasive concentration (%) and grain size (mesh number). The responses chosen for evaluation were material removal rate, surface roughness (Ra value), cutting forces and active grain density. The machined surface textures were studied using SEM. It was reported that extrusion pressure, abrasive concentration and grain size affected the cutting forces, active grain density and finally reduction in surface roughness (Ra value). The reduction in surface roughness (Ra value) was found to vary linearly with force ratio. Rubbing and ploughing were predicted to be the possible mechanisms for material deformation.

M. Ravi Sankar et al. [8] prepared different media using specially co-polymered soft styrene butadiene based polymer, plasticizer and abrasives. These media were evaluated for their Static and dynamic rheological properties. It was found that the media followed visco-elastic behavior with shear thinning nature. Temperature has a great effect on the properties of the medium. Finishing experiments were carried out on Al alloy and its metal matrix composites using rotational abrasive flow finishing (R-AFF). The static and dynamic rheological properties of the medium were measured. The material removal increased with the increase in yield stress. The linear visco-elastic range for creep recovery test was found to lie between 50 and 150 Pa. The radial force gradually decreased with the increase in viscous component decreasing MRR. As the storage modulus increased, the material removal increased gradually. Fig. 3 shows the variation of relaxation modulus with time.

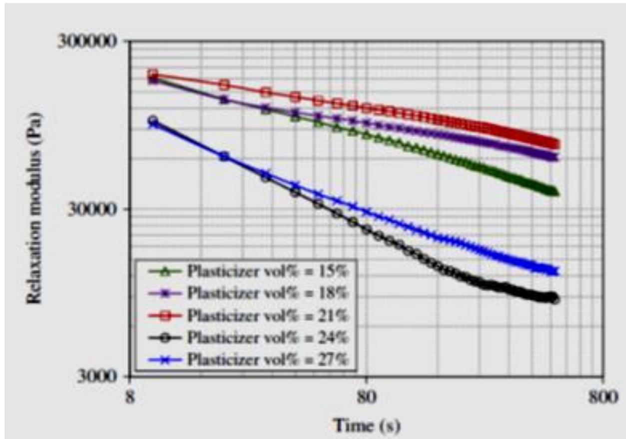


Figure 3 Variation of relaxation modulus with time (Logarithmic scale on both X and Y axes)

Kamal K. Kar et al. [9] attempted to develop a new medium based on visco-elastic carrier and its characterization for fine finishing using the AFM process. The newly developed medium was again characterized through rheological properties. It was found that temperature, shear rate, creeping time and frequency had an impact on rheological properties and the percentage ingredients of medium govern trends of their relations. Alternate medium for AFM process had been developed from different vicso-elastic carriers (natural rubber and butyl rubber), SiC abrasive and naphthenic oil. It was concluded that butyl rubber, silicon carbide and naphthenic oil mixed media showed better performance than natural rubber-based media. Also, surface roughness increased with the increase in abrasive loading.

Sunil Jha and V K Jain developed a new precision fine finishing process namely, magnetorheological abrasive flow finishing (MRAFF) for complex internal geometries [10]. Magnetorheological (MR) polishing fluid comprised of carbonyl iron powder and silicon carbide abrasives dispersed in the visco-plastic base of grease and mineral oil. It exhibits change in rheological behaviour in presence of external magnetic field. Experiments were conducted on stainless steel workpieces at different magnetic field strength to observe its effect on final surface finish. No measurable change in surface roughness was observed after finishing at zero magnetic field. However, for the same number of cycles the roughness reduced gradually with the increase of magnetic field.

Sehjpal Singh and H S Shan attempted to improve surface roughness and MRR by applying a magnetic field around the workpiece in AFM. A set-up had been developed for a composite process named magneto abrasive flow machining (MAFM). The impact of key parameters on the performance of the process was studied. Relationships were developed between the material removal rate and the percentage improvement in surface roughness of brass components when finish-machined using this process. ANOVA was applied to identify significant parameters and to test the adequacy of the models. Experimental results indicated significant improvement in the performance of MAFM over AFM [11].

Jain and Adsul investigated the effects of process parameters, like number of cycles, concentration of abrasive, abrasive mesh size and media flow speed, on material removal and surface finish. The dominance of process parameters on MRR and surface finish were found to be concentration of abrasive, followed by abrasive mesh size, number of cycles, and media flow speed respectively. Experiments were performed on brass and aluminium. Material removal (MR) was reported to be governed by initial surface finish and workpiece hardness. Softer the material higher was the MRR. Increase in the percentage concentration of abrasive in the medium increased material removal and improved surface finish upto a certain extent only. Reduced mesh size of the abrasive reduced MRR and improved surface finish [12].

Sankar et al. provided rotary motion to the workpiece in order to improve the performance of AFF [13]. Comparison is done between AFF and R-AFF processes to evaluate their performance in terms change in *R*a (Δ*R*a) and material removal. The workpiece materials used were Al alloy, Al alloy/SiC (10%) and Al alloy/SiC (15%) metal matrix composites (MMCs). Indigenously developed semi solid abrasive laden medium was used in the study. As the number of cycles increased, Δ*R*a increased. Δ*R*a also increased as extrusion pressure and processing oil content increased till 6.5MPa and 10%, respectively, and then decreased gradually. Among the chosen three workpiece materials, better Δ*R*a was achieved on Al alloy/SiC (10%) MMC.

Williams designed an AFM monitoring system using acoustic emission (AE) technology, built and tested it. It was tried to establish relationship between the acoustic emission level and AFM process parameters. It was shown that metal removal in AFM could be fairly accurately predicted knowing the RMS of the AE signal and the levels of the machining parameters. A high correlation was found between AFM flow rate and AE RMS over certain ranges. Data Dependent Systems (DDS) analysis of the acoustic emission signals revealed distinct frequency bands during AFM that were linked to the process mechanisms. Good agreement was found between DDS frequency decomposition and the results of a spectral analysis option on the new data acquisition system[14].

J. Kenda et al. investigated the effect of the process parameters on surface integrity, i.e. surface roughness and induced residual stresses. The hardened tool steel AISI D2 samples machined using EDM were chosen as work material to be finished with AFM. It was shown that AFM was capable of removing skin damaged by EDM and improve the surface finish to a great extent. It is also induced high compressive residual stresses in the machined surface, in a very thin sublayer of ~10 μm. AFM can be an alternative finishing process, beneficial from the surface integrity and product quality point of view[15].

Tina Bremerstein et al. examined the wear of the abrasive media before and after abrasive flow machining [16]. Two media were examined with workpieces under identical working conditions to evaluate the effect of wear of abrasive media on the results of the machining process. It was reported that the change in rheological behavior and composition of the abrasive medium as well as particle shape and size were responsible for the degradation of the abrasive efficiency. The increase in viscosity of the abrasive medium and blunting of the large abrasive particles were the main factors that caused a decreased MRR and deteriorated surface quality.

Harlal Singh Mali & Alakesh Manna [17] employed AFM to finish conventionally machined cylindrical surface of Al/15 wt% SiCp-MMC workpiece. The influences of AFM process parameters on surface finish and material removal were analyzed. The mathematical models for Ra, Rt, ΔRa, and ΔRt and material removal were also established to investigate the influence of AFM parameters. Conformation test results verified the effectiveness of these models and optimal parametric combination within the considered range.

Sachin Singh et al. [18] suggested a model to predict the axial and radial forces developed during AFF process using the rheological properties of the visco-elastic medium used in the process. The calculated forces using the model were used to predict the surface roughness profile of the workpiece. Theoretically, the change in surface roughness is correlated with the change in extrusion pressure, number of piston strokes, and amount of the plasticizer. Simulated results and the experimental results were found to be in good agreement with each other.

Hsinn-Jyh Tzeng [19] developed a self-modulating abrasive medium with adjustable viscosity and fluidity. The workpiece material was (SUS304) stainless steel. A channel was cut on it using EDM and then finished with AFM. The process variables to be evaluated were, abrasive particle size, concentration, extrusion pressure and machining time. It was shown that as the particle size increased, surface roughness also increased. Machining quality improved with the increase in extrusion pressure and machining time due to increased fluidity of the medium.
Rajendra K. Jain et al. have investigated [20] into the mechanism of abrasive flow machining (AFM) process. A finite element model is developed for the flow of media during AFM and the same is used to evaluate the stresses and forces developed during the process. The results of theoretical analysis match well with the published experimental results.

V.K. Jain et al. [21] attempted to analyze the AFM process using finite element method (FEM) for finishing external surfaces. A finite element model of forces acting on a single grain has been developed to study the material removal mechanism of AFM. RSM is used to carry out an experimental research to analyze the effect of extrusion pressure and number of cycles on material removal and surface finish. Results obtained from FE analysis for material removal have been compared with the experimental data obtained during AFM on brass to study the effect of pressure and number of cycles on material removal and surface finish. It is found that as the extrusion pressure increased the material removal also increased. Material removal ceases to increase after 20 cycles. Theoretical and experimental results are quite close proving the validity of the model.

Mohammad Ali Marzban & Seyed Jalal Hemmati [22] proposed abrasive flow rotary machining (AFRM). Due to the elimination of reciprocal motion of abrasive material and only stirring and rotating the workpiece, it is proposed that the use of material will be optimized. With the new configuration, the process is applicable by simpler tools on lathe. During the research process, effective parameters and the role of each one on MR and surface roughness were studied and artificial neural networks were trained by experimental data. Predicted results show meaningful agreements with reported results of Jain et al. [21] for aluminum material.

K Malla Reddy et al. [23] worked on centrifugal force assisted abrasive flow machining (CFAAFM). The effects of key parameters on the performance of the process were studied. Relationships were developed for material removal and improvement in surface quality of cast Al alloy (2014) cylindrical components. Results indicated that CFAAFM significantly improved performance over AFM in terms of enhanced surface finish and material removal. It was observed that the combination of a high extrusion pressure and a higher speed of the centrifugal force generating (CFG) rod gave a higher degree of surface finish, while the combination of a larger grain size and a higher speed of the CFG rod resulted in enhanced material removal.

Mamilla Ravi Sankar et al. [24] introduced a concept of rotating the medium along its axis to achieve higher rate of finishing and material removal. This process was termed as drill bit-guided abrasive flow finishing (DBG-AFF) process. The medium was pushed through a helical fluted drill placed in the finishing zone in order to provide random motion to the abrasives in the medium and cause frequent reshuffling of the medium. The experiments compared AFF and DBG-AFF processes with AISI 1040 and AISI 4340 as workpiece materials. The performance of DBG-AFF as compared to AFF was found to be encouraging, specifically with reference to percentage change in average surface roughness (% ΔRa) and amount of material removed.

S. Kathiresan & B. Mohan [25] attempted to improve the surface quality of AISI stainless steel 316L to a nano-level by magneto rheological abrasive flow finishing process. RSM and desirability analysis were used to determine the effect of input process parameters toward the responses such as final surface roughness (SR) and material removal rate (MRR). Minimum SR and maximum MRR obtained were 53.46 nm and 1.757 mg/s, respectively, and their optimized values were 53.10 nm and 1.817 mg/s. the voltage to the electromagnet was found to be the most significant parameter to produce minimum SR and maximum MRR. Moderate and least significant parameters were found to be hydraulic pressure and number of cycles, respectively.

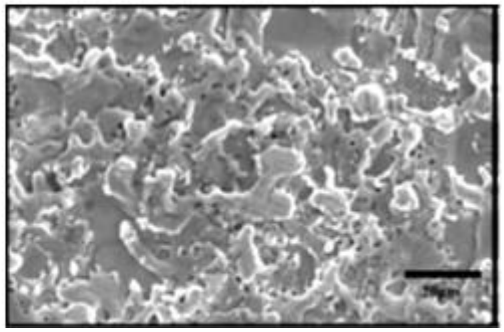
Mittal Sushil et al. [26] machined composite materials with high percentage of SiC (like 20-60 % SiC in Al/SiC composites) using AFF. The effect of input parameters like extrusion pressure, percentage of oil in media, mesh number of grit, concentration of abrasives, workpiece material and number of cycles on material removal rate (MRR), change in surface roughness (ΔRa) and surface topography was studied. Extrusion pressure was found to be the most significant factor for MRR and ΔRa. MRR and ΔRa increased with increase in extrusion pressure. MRR and ΔRa increased with increase in the number of cycles. ΔRa was initially high and then reduced with increase in the number of cycles. The reason could be, initially, the bigger peaks and valleys get abraded faster.

Liang Fang et al. [27]used commercial AFM equipment and test rig are used to carry out AFM experiments. Both AISI1080, 1045 and A36 steels are used as specimens in the tests. It has been found from AFM tests that media viscosity decreases continuously with increasing temperature. Media temperature increased with increasing cycles, meaning media viscosity decreased with increasing cycles. Media with more viscosity give better MRR and improved surface finish.

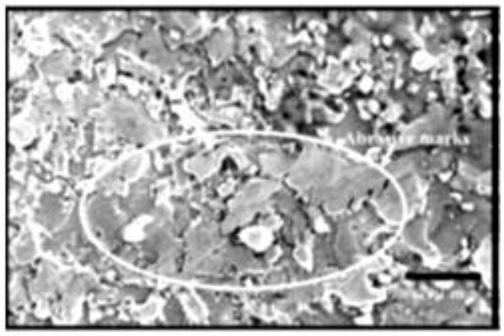
J. Kenda et al. [28] have shown that AFM generates constant surface quality along with reduced cost and processing time. The achieved roughness was homogeneous on the entire machined surface and it reduced from Ra=0.68 μm to Ra=0.08 μm in 120 s without damaging the tooth profile of the plastic gears. Processing parameters depend on the type of the abrasive machine, the polishing paste and part geometry.

Hsinn-Jyh Tzeng et al. [29]used AFM to evaluate the characteristics of various levels of roughness and finishing of the complex shaped micro slits fabricated by wire EDM. The process parameters selected were abrasive particle size, concentration, extrusion pressure and machining time. Fig. 4 shows the SEM micrographs of surface under abrasive particle size. It has been shown that AFM is suitable for machining the complex micro slit surface. It also can clean the deckle edge of the micro slit and remove the recast layer from the wire-EDM. Viscosity improves with the concentration, which improves the surface roughness. A higher concentrated medium reduces surface roughness (SR) values. A high extrusion pressure reduces the precision of the surface.

A-Cheng WANG et al. [30] have shown that the shear forces in the polishing process and the flow properties



(a) Wire EDM Ra= 2.4 μm



(b) AFMed (150 μm) Ra=0.8 μm

Fig. 4 SEM micrographs of surface under abrasive particle size

of the medium in AFM play the roles in controlling the roughness on the entire surface. The results showed that the shear forces and strain rates changed sharply on the entire surface if no mold core was inserted into the complex hole, whereas they hardly made any difference when the core shape was similar to the complex hole. Three experimental types of mold core were used. It was demonstrated that the similar shape of the mold core inserted into the hole could give uniform roughness on the surface.

A-Cheng WANG et al. [30] have shown that the shear forces in the polishing process and the flow properties of the medium in AFM play the roles in controlling the roughness on the entire surface. The results showed that the shear forces and strain rates changed sharply on the entire surface if no mold core was inserted into the complex hole, whereas they hardly made any difference when the core shape was similar to the complex hole. Three experimental types of mold core were used. It was demonstrated that the similar shape of the mold core inserted into the hole could give uniform roughness on the surface.
Franci Pusavec and Jani Kenda [31] have proposed abrasive flow machining with a movable mandrel (AFMmm) due to the drawbacks of AFM like reducing the finishing time, process control, ensuring a clean process, and energy efficiency. It is shown that the application of the novel AFMmm method removed WEDM-damaged surface and produced a polished surface under dry conditions, leaving the machined surface clean.

Mamilla Ravi Sankar et al. [32] ground an MMC-aluminum alloy and its reinforcement with SiC and then finished them to the *R*a value of 0.25±0.05μm using AFM. The effects of different process parameters, namely, extrusion pressure, number of cycles and viscosity of the medium were evaluated on a change in average surface roughness (Δ*R*a) and material removal. The relationship between extrusion pressure and Δ*R*a shows an optimum at about 6MPa. In the same way, the relationship between weight percentage of processing oil (plasticizer) and Δ*R*a also shows an optimum at 10 wt%. Further, an increase in workpiece hardness requires more number of cycles to achieve the same level of improvement in Δ*R*a. Material removal also increases with an increase in extrusion pressure and number of cycles while it decreases with an increase in processing oil content in the medium.

Manas Das et al. [33] reported the improvement in out-of-roundness of stainless steel tubes finished by Rotational–Magnetorheological Abrasive Flow Finishing process. It was reported that R-MRAFF process potentially reduced roundness error of axi-symmetric parts (maximum improvement in OOR = 2.04μm) improving their reliability and wear resistance. The study showed that, OOR improves with an increase in the rotational speed of the magnet up to an optimum value beyond which the improvement in OOR reduces. From the SEM micrographs and atomic force micrographs it was found that the abrasive cutting marks in R-MRAFF process generated cross-hatch pattern which help in oil retention in cylindrical workpieces to reduce friction.

P J Davies, and A J Fletcher [34] conducted experiments using low viscosity, medium viscosity and high viscosity polyborosiloxane based media, with silicon carbide abrasive grit of 60 and 100 mesh size, the ratios of the grit to base polymer of 0, 1 and 2. The test pieces used were mild steel dies. Experiments were conducted on an Extrude Hone mark 7A machine. It was found that increase in viscosity of the base medium produced a reduction in the temperature rise (for example from 32 to 10 **"C** over 30 cycles) as well as an increase in both the average pressure drop across the die and the processing time. In addition, the temperature of the medium was found to be an important variable in the AFM process due to its effects on viscosity.

V. K. Jain et al. [35] studied the effects of concentration and mesh size of abrasive particles, and temperature of medium on the medium viscosity. Study was conducted at different abrasive concentrations and mesh sizes, and medium temperatures. It was observed that the viscosity of the medium increased with the abrasive concentration and decreased with the abrasive mesh size and medium temperature. Theoretical values obtained from mathematical model, and experimental results were compared. The results of viscosity were correlated with the process performance parameters, i.e. material removal and surface roughness. It was found that as viscosity of the medium increased an material removal increased and surface roughness value decreased.

M. Ravi Sankar et al. [36] have discussed rotational abrasive flow finishing (R-AFF) process in which complete tooling is externally rotated and the medium reciprocates with the help of hydraulic actuators. Experiments were conducted on Al alloy and Al alloy/SiC metal matrix composites (MMCs) at different extrusion pressures. The same optimum conditions were used to study the effect of workpiece rotational speed on (ΔRa), material removal (MR), and change in workpiece hardness and surface topology. It was found that as the workpiece rotational speed increased, the experimental helix angle decreased and the helical path length increased. It was established that R-AFF produced 44% better ΔRa and 81.8% more MR as compared to the AFF process. R-AFF generates micro cross hatch pattern on the finished surface that can improve lubricant holding capabilities.

M. Ravi Sankar et al. [37] conducted experiments on hard steel (AISI 4340) cylindrical tubes at different extrusion pressures, workpiece rotational speed, number of cycles and medium compositions for finding optimum conditions of the same for higher change in out of roundness (ΔOOR) and material removal (MR). Soft styrene-butadiene- and silicone polymer-blended medium was used for finishing. The results of R-AFF have been found to be encouraging and the experiments have shown that R-AFF has a very promising future for the industries in terms of better finishing.

Sachin Singh et al. [18] have attempted to model the forces generated during AFF process using the rheological properties of the visco-elastic medium. By using the calculated forces, simulation of the final surface roughness profile of the workpiece has been presented. The simulated results are in good agreement with the experimental results.

R. S. Walia et al. [38] studied the effects of changing the parameters such as shape and rotational speed of CFG rod, extrusion pressure, number of process cycles and abrasive grit size. The results indicated that all the input variables had significant effect on the response parameters, viz. material removal and surface roughness.

A-Cheng WANG et al. [39] used a non-Newtonian flow to set up the abrasive mechanism of the abrasive media in AFM. Power law is the main equation of the non-Newtonian flow to describe the motion of the abrasive media. Simulation was carried out applying the working parameters of AFM to study the properties of the abrasive gel. The simulated results showed that the abrasive gel with high viscosity can entirely deform in a complex hole than the abrasive gel with low viscosity. The abrasive gel with high viscosity generated a larger shear force than the abrasive gel with low viscosity in the same area. The strain rate changed when the abrasive gel passed the narrow cross-section of the complex hole.

A-Cheng WANG et al. [40] used Magnetic finishing with gel abrasives (MFGA) in the AFM. Silicone gel as a carrier medium played a crucial role to locate the abrasion behavior and establish the mechanism of MFGA. Concentration of steel grit, machining time, and kinds of abrasive dominated the behaviors of the MFGA process. The analytical S/N ratio was found to be very similar to the S/N ratio (less than 8%) from experiment.

The effects of AFM was investigated by T.R. Loveless et al. [41] on surfaces produced by turning, milling, grinding, and wire electrical-discharge machining. Material removal and surface finish improvement were the two characteristics studied. The initial machining process affected both metal removal and surface finish results. The initial surface condition also significantly affected the amount of metal removal. All of the Wire EDM surfaces were improved greatly by AFM. Media viscosity significantly affected only surface improvement, while extrusion pressure did not have a significant effect.

R. E. Williams [6] reported on the development of an acoustic emission (AE) based monitoring strategy and the AE characteristics of abrasive flow machining. Initial results showed that AE was a viable sensing method for determining the performance characteristics of AFM for simple extrusion passage geometries. Frequency decomposition of the AE signals revealed distinct frequency bands which have been related to the different material removal modes in AFM and to the workpiece material. Extremely high correlations were found between the AE signal and both the orifice diameter and the volumetric flow rate.

K.C. Cheng [42] et al. have developed mechanism designs for different passageways to obtain multiple flowing paths of abrasive medium. The flowing behavior of the media enhanced the polishing effectiveness by increasing the abrasive surface area and radial shear forces. The motion of the abrasive medium was studied by utilizing different shapes of mold cores like, circular, hollow and helical passageways. The numerical results obtained from CFD-ACE^{+} software indicated that passageways with six helices performed better in the uniform surface roughness than circular and hollow. Experimental results showed that roughness deviation of six helices passageway of approximately 0.100 μm Ra was significantly better than those on a circular passageway of around 0.1760 μm Ra. Additionally, the six helices passageway was also superior to circular passageway in reducing roughness improvement rate (RIR) by roughly 87% compared with RIR 67.7% for the circular passageway.

A.C. Wang and S.H. Weng [43] reported that Vinyl-silicone polymer (or silicone rubber) had good deformation and low flow effect and it could flow through the complicated holes easily. The silicone rubber did not stick to the workpiece surface after machining. Abrasive particles and silicone rubber were mixed uniformly to form the flexible media in this study. A chain hole, cut by WEDM, was polished by these media in AFM. It was reported that the surface roughness decreases from 1.8 to 0.28 μmRa after five machining cycles (with abrasive concentration 60% (wt.%). In this case, the roughness improvement rate (RIR) reached 84%. Coarse abrasives gave faster MRR but increased surface roughness and vice versa. Fig. 5 shows the machining diagram of the AFM. As the experimental process includes the equipment, material selection and machining method, this section is divided into three parts.

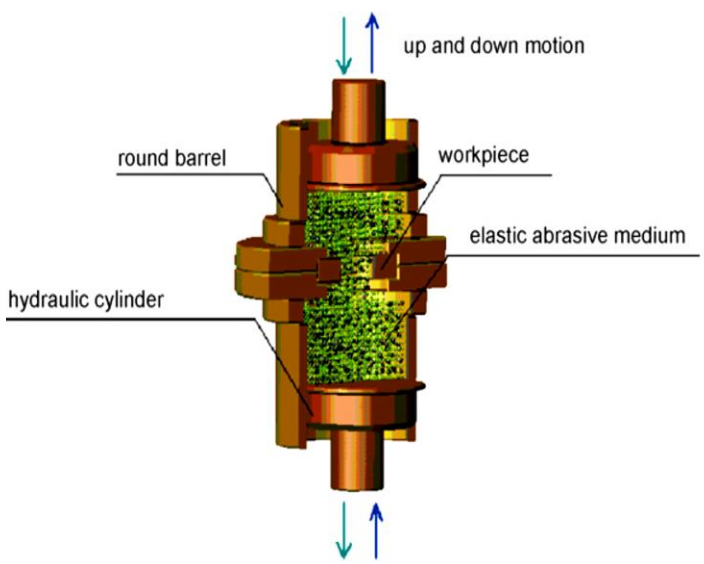


Fig. 5 The machining diagram of AFM

Rahul Kumar et al. [44]used a three start helical drill bit coaxially within the hollow cylindrical workpiece using three piece nylon fixture to improve MRR. The drill bit forced the abrasives laden media to follow a helical path within the finishing zone. Curvature in the path of the media developed of centrifugal forces and flow along the flute, axial flow, and scooping flow and remixing of medium at exit from the finishing zone. The parameters affecting the process are described and the effect of the key parameters on the performance of process has been studied.
Ravi Butola et al [45] used a drill bit assisted AFM setup and studied a developed spline, two start helical profile and three start helical profile. Use of new developed profile led to an improvement in the response parameter of percentage

improvement in surface finish and material removal. Three types of drill bits are used spline, two star helical and three star helical in the present investigation. The result showed that the percentage contribution of type of rod was 33.4%, extrusion pressure 23.46% and number of cycle 19.53 % contribution in MRR. A maximum reduction of 69.06% has been observed in the surface roughness with the selected parameters. The roughness reduced from 6.2 μm to 1.91 μm on the inner cylindrical surface of the cast iron work piece.

Jeong-Du Kim and Kyung-Duk Kim [46] used AFM to remove burrs from internal and external spring collets. The microburrs inside the small and large diameter adversely affect the properties of the collets. AFM was employed as it almost impossible to remove burrs by any other method economically. Abrasive grain media for abrasive flow processing were developed by blending a silicon polymer with abrasive grains. It effectively removed edges and burrs by flowing through the interior and micro grooves of the spring collet. Fig. 6 shows the deburring process of the spring collet.

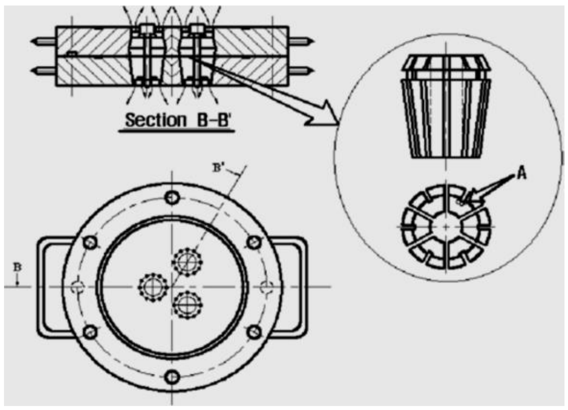


Fig. 6 Deburring process of spring collet

Dirk Bähre et al. [47] studied the parameters like medium pressure and lead time on the surface quality and form tolerance. A commonly used automotive steel AISI 4140 was used for the investigation. Additionally, an in-process measurement setup was developed in order to measure the influence of the applied medium pressure on the machined part of the work piece with the help of an axial force sensor.

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