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Research Paper

TO STUDY THE MACHINING CHARACTERISTICS OF THREE DIFFERENT MATERIALS USING HELICAL AFM PROCESS

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Abrasive Flow Machining (AFM) is method to deburr, polish, and radius difficult to reach surfaces like intricate geometries and edges by flowing a abrasive laden viscoelastic polymer over them. Based on the application, three different types of machines have been reported, i.e., one way AFM, two way AFM and orbital AFM. This research work focuses mainly on the issues related to the finishing like Metal Removal Rate (MRR), surface finish of different materials, i.e., brass, aluminum and mild steel with the use of Helical AFM set up. It has been observed that the finishing was done on hollow cylindrical work-pieces of brass only. So, for the present research work it is planned to develop the work-pieces of Brass, Aluminum and mild steel. To plan the experiments based on the L18 orthogonal array of Taguchi method and ANOVA to subsequently conduct the experiments. To analyze the observed results and estimate the optimal values of responses viz., MR and %Ra.

Keywords: Abrasive Flow Machining (AFM), Manufacturing technology

INTRODUCTION

In AFM, semisolid media, consisting of an abrasive and a polymer-based carrier in a typical proportion, is extruded under pressure through or across the surface to be machined. The abrasive grains are held tightly in place at this point and the media becomes a grinding stone, which conforms to the passage geometry. The AFM process offers both automation and flexibility in final machining operations as an integral part of the complete manufacturing cycle.

In the present work the effects of different process parameters, such as number of cycles, concentration of abrasive, abrasive mesh size and media flow speed, on material removal, surface finish of different materials using Helical Abrasive Flow machining (HLX-AFM) are studied. The dominant process parameter found is concentration of abrasive,

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followed by abrasive mesh size, number of cycles, and media flow speed. Experiments are performed with brass, aluminium and Mild Steel as test specimen. The machined surface texture is studied using scanning electron microscopy. It has been noticed that Abrasive Jet Machining (AJM), Water Jet Machining (WJM), and Ultrasonic Machining (USM) give almost comparable accuracy and possesses nearly similar capabilities but have no solution when the task requires better accuracy, high efficiency, economy and consistency. Taguchi method was adopted to explore the effects of the machining parameters associated with AFM on the experimentally observed values, such as the Material Removal Rate (MRR) and differences between the dimensions of the entrance and the exit of the micro hole.

AFM Principle

The principle of AFM process is to use a large number of random cutting edges with indefinite orientation and geometry for effective removal of material with chip sizes far smaller than those obtained during machining with tools having defined edges. The extremely thin chips produced in abrasive flow machining allow better surface finish, close tolerances, and generation of more intricate surface features.

Helical Abrasive Flows Machining

In helical abrasive flow machining process there are three parts of the nylon fixture, i.e., upper part, middle part and lower part. Drill bit is attached in the inner hole of work piece and this drill bit is held stationary. Lower and upper fixtures are tapered for proper media flow. The major difference between AFM and Helical-AFM machines is its tooling. In AFM machine, circular fixture plate allows the medium to flow as cylindrical slug. So, the abrasive intermixing (or reshuffling) purely depends on medium self-deformability. The abrasive particles follow the shortest contact length; hence, the material removal is less. In Helical-AFM, abrasive intermixing depends not only on medium self-deformability as in AFM but also on the pressure from the drill bit. In the present study there are three types of helix are used, i.e., two-start drill bit, three-start drill bit and a spline with the use of three different materials and comparison of the surface finishing between them. The abrasive particles follow the shortest contact length; hence, the material removal is less. In Helical-AFM, abrasive intermixing depends not only on medium self-deformability as in AFM but also on the pressure from the drill bit.

In Helical-AFM, three types of flows that occur in finishing zone (Figures 1-4) and remixing of medium at exit from the finishing zone(flow along the flute, axial flow, and scooping flow). Due to the combination of different flows, the work piece-abrasive contact length is no longer a straight line, rather it becomes curved; hence, the number of peaks that can be sheared increases, leading to higher material removal.

Figure 1: Flow Along Flute

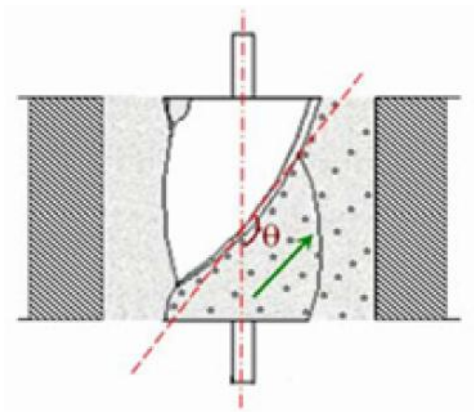


Figure 2: Reciprocating Axial Flow Motion

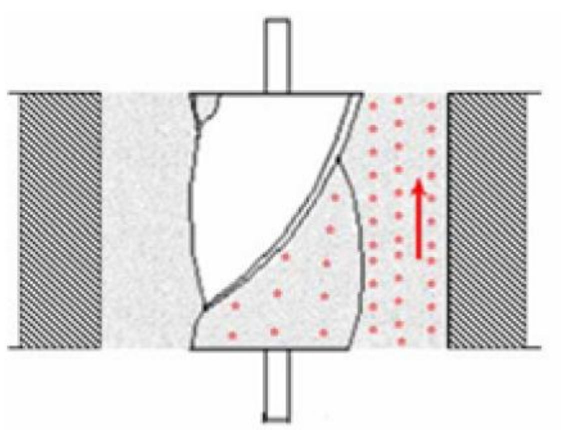


Figure 3: Scooping Flow

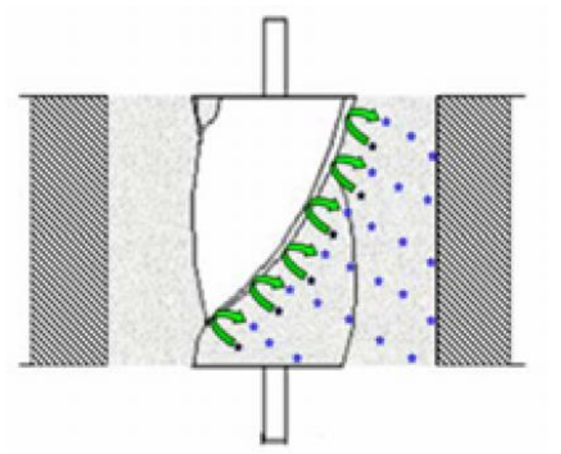
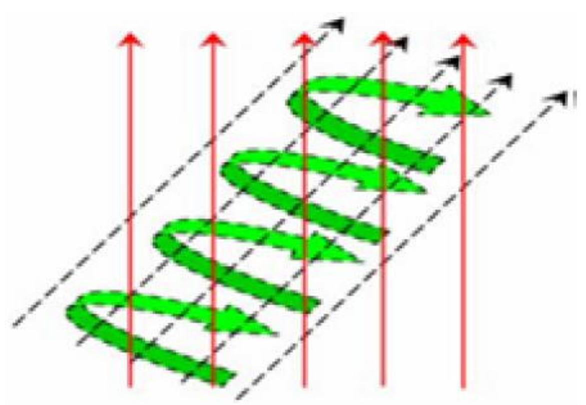


Figure 4: Three Motions (Flow Along the Flute, Axial Flow, and Scooping Flow) that Can Occur in Finishing Zone



Abrasive Media

In AFM, a semisolid media consisting of an abrasive and a polymer-based carrier in a typical proportion is extruded under pressure through or across the surface to be machined. This technique uses a non-Newtonian liquid polymer of containing abrasive particles of aluminium oxide, silicon carbide, boron carbide or diamond as the grinding medium and additives. The viscosity and the concentration of the abrasives can be varied Most widely used carrier is a high viscosity rheopectic fluid. The rheological properties of the abrasive media play an important role to find the good surface roughness in the complex holes. SiC are most suitable abrasives for many applications but Cubic Boron Nitride (CBN) and diamond are specifically used for special applications. These silicone gels have low flow property and do not stick on the work-piece surface after contact, so that they are the good abrasive media in AFM. And Silicon Carbon (SiC) is used as abrasive to mix in the silicone gel uniformly. Weight concentration of the abrasive in the polymer gels is 50%. have low flow property and do not stick on the work-piece surface after contact, so that they are the good abrasive media in AFM. And Silicon Carbon (SiC) is used as abrasive to mix in the silicon gel uniformly. Weight concentration of the abrasive in the polymer gels is 50%.

LITERATURE REVIEW

In the modern metal working industry the finishing processes are the most time and cost consuming ones. Moreover the complex finishing processes require the manual handling which is very slow and sometimes these repetitive works are detrimental for the health of the workers too. Modern difficult to machine materials, there manufacturing and complex designs of precision parts pose special machining and finishing challenges. AFM is one of the processes capable of addressing the above mentioned challenges. This process replaces a lot of manual finishing processes leading to more standardization of manufactured parts, hence there inter-changeability, mass production and reduced costs. Helical-AFM will improve the surface geometry and material removal.

Abrasive Particle Size

Range of the abrasion particle used in AFM is #8 grit (roughing and stock removal application) to #500 grit (small hole application). Larger size abrasive gives faster cut while smaller size abrasive gives better surface finish and can reach into complex and narrow passages. When the initial roughness of the work surface is less then we use finer abrasive According to one thumb rule 1984. The reason for a decrease in material removal is that with an increase in mesh size (or decrease in grain size in mm) the depth of penetration as well as width of penetration, decreases.

Abrasives Concentration

As the concentration of abrasive in the media increase, material removal increases while the surface roughness value decrease. However, its effect is visible only up to a certain percentage of abrasive concentration, beyond which it becomes insignificant. At higher concentration of abrasive particles viscosity of the media increases leading to more material removal. Further, a higher concentration of abrasive particles permits the media to sustain a larger cutting force. McCarty (1970) mentions the possibility of using a large range of concentration of abrasive in the media (2 to 12 times weight of carrier media). However, Siwert suggested that abrasive particle to base material ratio (by weight) should vary from 4:1 to 1:4 with 1:1 as the most appropriate ratio Singh (2010). Also observed that if the abrasive-to-media concentration is increased the material removal rate also increased.

Extrusion Pressure

When the extrusion pressure increases which results in faster cutting considering, with all other parameters remains constant. A part of total pressure is lost within the media due to its internal resistance to flow a part of total pressure is lost within and rest is imparted to abrasion particles contacting the work piece surface. Jain and Jain (1999) reported that at higher pressure the improvement in material removal just tends to stabilize probably due to localized rolling of abrasion particles. Singh and Sharma (2010) also observed that if the extrusion pressure is increased the material removal rate also increased.

Media Viscosity

Williams and Rajurkar (1992) have reported that viscosity of the media is one of the significant parameters of the AFM process. Keeping all other parameter constant, an increase in viscosity improves both material removal and surface roughness. Przyklenk 1986 has observed that the material removal capacity of the least viscous media differs from the most viscous one. This difference could be as much as 300 times. A thumb rules has been suggested by Kohut (1992) for the selection of viscosity in relation to work piece passage size. According to this if the passage length is substantially shorter than two times the passage width, a higher viscosity media should be used. On the other hand, if passage length is substantially longer than two times the passage width, a lower viscosity should be preferred. Concentration and abrasive particle size also affect the media viscosity, which may result in settling of particles thereby influencing the flow properties and overall abrasion process. Experiments show that the viscosity of the media increases with the percentage concentration of abrasives and decreases with temperature. It is further indicated that when media viscosity falls below 30 Pa the abrasive particle is less likely to remain in suspension within the media. There is a tendency of particles to sink under gravity to the bottom of the media.

Media Flow Rate

Media viscosity, extrusion pressure, and passage dimension determine the media flow rate (the speed of the abrasive slug passing through the restrictive passage) which affects the uniformity of the material removal and the formation of edge radius. Rhoades 1985 has reported that media flow rate is less influential parameter in respect to material removal. Slower slug flow rates are best for uniform material removal and high slug flow rates produce large edge radii [Rhoades]. It has been noted by Williams's *et al.* (1992) that if volume of flow is constant. The media flow rate is insignificant with regard to material removal. Jain and Jain (1999) the media flow rate influences both of the material removal and surface roughness.

Media Flow Volume

The media flow volume is one of the dominant process parameters in AFM for controlling the amount of abrasion and surface finish by a specific media composition. Keeping all other process parameters constant, a larger volume of media will cause more abrasion. The amount of abrasion or stock removal that occurs is directly related to the slug length of flow, which in turn is governed by media flow volume.

Media Temperature

Weller (1984) gives the experimental results that if increase the temperature during process than the cutting of material will be at faster rate. Under otherwise constant cutting condition. Jain and Jain (2001) analyzed the heat flow to the work piece and the medium in AFM process. In their study Hull et.al analyzed that some time there will be a permanent change in physical properties with increase in temp. (Temp. range within (30-70 °C). sometimes undergo a permanent change in physical properties with increase in temperature.

Number of Process Cycles

A number of cycles are required to achieve the desired surface finish and material removal. It has been reported in a number of studies that abrasion is more pronounced in some initial cycles after which improvement in the surface finish stabilize or reduce in some cases. Total number of process cycles range from one to several hundred. Within 1 to 8 cycles, a linear dependence between material removal and surface roughness versus number of cycles was indicated. In AFM the forward and backward extrusion back to the initial stage completes a cycle.

Material and Geometric Feature of Work-Piece

For a specified number of cycles, it has been observed that the more the reduction ratio the more will be the material removal from the work piece. Conical contraction towards centre was an interesting phenomenon termed as “Bell mouthing” noticed by steif and hann and przyklenk (1992). The nature of surface generated by AFM process is reported by Loveless *et al.* (1994) to differ significantly from the surfaces produced by other processes. The improvement in surface finish by AFM is also shown to be significantly affected by the type of prior machining process carried out on the work piece. Jain and Jain (1999) defined the “Reduction Ratio” as the difference between cross sectional area of media cylinder and that of extrusion passage divided by the cross sectional area of media cylinder.

Generally, work piece with single hole has been taken for processing but an investigation has also been carried on multiple holes specimen. It was observed that for a multiple hole specimen with one centre hole and four outer holes, the central hole experiences 30% more material removal. This has been explained by suggesting a non-uniform velocity distribution of media while flowing through a multiple-hole work piece. As the media takes the least resistance path, it tends to flow through the major bores even if they are not situated in centre but are staggered.

It was observed that when processing two successive restrictions, equal cross sections receive equal abrasion while with unequal cross sections the smallest passage is abraded more. In case when processing parallel passage, the larger cross section passage receives more abrasion.

Jain and Adsul (2000) in their study mentioned that material removal is governed by initial surface roughness and work piece hardness. Softer material has higher material removal and more improvement in surface finish as compared to harder material. Material and geometrical dimensions of work piece are reported to greatly influence the abrasion process.

Generally, work piece with single hole has been taken for processing but an investigation has also been carried on multiple holes specimen. It was observed that when processing two successive restrictions, equal cross sections receive equal abrasion while with unequal cross sections the smallest passage is abraded more. In case when processing parallel passage, the larger cross section passage receives more abrasion as it allow more abrasive particle and hence more media flow to do the abrasion.

Rheology of Carrier Media

In AFM process abrasive laden media possesses special rheological characteristics. The study of the change in the form and flow of matter, embracing elasticity, viscosity and plasticity is called rheology. The abrasive laden media has time dependent rheopectic in nature. The piston stroke duration determine the maximum wall shear stress that obtained in a stroke: consequently, a large stroke length give higher material removal due to generation of higher shear stresses.

The psuedoplastic nature of media used in AFM process has been indicated by some studies. Jain *et al.* (2001) observed from the experiments that the viscosity of the media increase with the abrasive concentration and decreases with the abrasive mesh size and media temperature. A study has been conducted by Jha and Jain (2004) for precision finishing of complex internal geometries using smart magneto rheological polishing fluid. They reported that the process provides better control over rheological properties.

Advancements in AFM

There is a lot of research has been done on the AFM in the last five decades and a lot of improvements have done so far. Some of the processes are given below:

Magnetic Field Assisted Abrasive Based Micro Finishing

From the experimental results Jha and Jain (2004) analyzed that it is possible to externally control the forces acting on the work piece by varying DC electric current flowing in the electromagnet coil or by changing the working gap while using a permanent magnet. A change in the electric current changes magnetic flux density in the working zone due to which the normal force exerted by an abrasive particle on the work piece changes. This change in normal force changes finishing rate and critical surface finish that can be achieved by the process under the given finishing conditions. This class of processes is capable to produce surface roughness value of 8 nm or lower. Amit *et al.* (2007) studied about the simulation for the prediction of surface roughness in Magnetic Abrasive Flow Finishing (MAFF) and Magnetic field significantly affects both Surface Roughness and Material removal, the slope of the curve indicates that material removal increases more rapidly with magnetic field than the surface roughness.

Centrifugal Forced Abrasive Flow Machining

From experimental results by Walia and Shan (2006) it can be seen that addition of centrifugal forcewith help of external guided arrangements in media increase improvement in surface finish and material removal rate. A rotating Centrifugal Force Generating (CFG) rod was used inside the cylindrical work piece, which provides the centrifugal force to the abrasive particles normal to the axis of work piece. A further study have been done by Ramandeep (2012) on the the Effects of Centrifugal Force on Abrasive Flow Machining Process and concluded the results that The result shows that the process parameter number of cycles has the highest contribution towards the response characteristic and is 54% for the percentage improvement in ΔRa. As the number of cycles increases from 2 to 6, the percentage improvement in ΔRa is maximum at the second level of 4. So lesser number of cycles led to better surface finish.

Rotating Drill Bit and Stationary Work-Piece AFM

In order to enhance productivity of the process, Mondal and Jain (2009) has been introduced a concept of rotating the media along rotated drill bit axis to achieve higher rate of finishing and material removal. This process is termed as Drill Bit Guided-Abrasive Flow Finishing (DBG-AFF) process. In order to provide random motion to the abrasives in the medium and to cause frequent reshuffling of the medium, the medium is pushed through a helical rotated fluted drill, which is placed in the finishing zone.

Rotating Work Piece and Stationary Drill Bit AFM

Jain and Sankar (2009) have worked on drill bit type AFM, abrasive intermixing depends not only on medium self-deformability as in AFM but also on the pressure from the drill bit, three types of flows (flow along the flute, reciprocating axial flow motion, and scooping flow) that occur in finishing zone and remixing of medium at exit from the finishing zone. Due to the combination of different flows, the work piece-abrasive contact length is no longer a straight line, rather it becomes curved; hence, the number of peaks that can be sheared increases, leading to higher material (finishing rate also improves compared to AFM process. The gap between the work piece surface and the drill bit was varied by changing drill bit diameter and geometry. Increase in drill bit diameter provides more surface finish.

Helical-Abrasive Flow Machining (HLX-AFM)

Sharma developed a helical-AFM setup with the use of a stationary held drill-bit of two start. The drill bit is held axially inside the cylindrical surface to be machined. As the media extrudes through the recess it follows the helical path and a combination of axial, radial, centrifugal forces leads to improved surface finish and more material removal. Singh (2011) developed two more helix viz., drill bit of three starts and a spline. As the media passes through the three start drill bit helical path and straight in case of spline.

Material Survey

There are several researches have been done on the Abrasive Flow Machining (AFM). The researchers are always trying to improve the surface finishing with the use and change the different parameters. These parameters give the information about the improvement in surface finishing of the intrinsic parts of the material where conventional machining process cannot work. Abrasive Flow Machining (AFM) process which is used for the production of excellent surface qualities of inner profiles that are difficult to access and outside edges, as well as for deburring and edge rounding. The grinding medium used in AFM consists of a polymer fluid, the so-called base, in which the abrasive grains are bound. The grinding medium is pressed along the contours at a defined pressure and temperature. Depending on the respective machining task, different specifications of media are used. The description of process-related material removal mechanisms requires the knowledge of material removal mechanisms in AFM. Based on findings in flow mechanism, analyses have been made on material removal mechanisms. In the present investigation there is different materials are taken, i.e., brass, aluminium and mild steel. The experiments were conducted with the use of these materials on helical AFM set up.

Brass

In order to enhance the productivity Walia *et al.* (2006) takes brass (yellow brass: 65% Cu, 35% Zinc, having 156 BHN hardness) as work-piece material was used in the Centrifugal Force Assisted Abrasive Flow Machining (CFAAFM). The media formulation used for this study consisted of a silicon based polymer, hydrocarbon gel and abrasive grains. The abrasive called Brown Super Emery (trade name) consisting mainly of Al_2O_3, supplied by an Indian company, was used in this study Mirg investigate the results on Centrifugal Force Assisted Abrasive Flow Machining (CFAAFM) with the percentage contribution of Shape of CFG rod is 25.49% and 29.94% respectively for the MR and %age improvement in ΔRa. The MR and the percentage improvement in surface roughness increases in the sequence of Triangular rod, Rectangular rod and Spline rod. Spline shape CFG rod gives better MR and surface finish compared to other two different shape rods which are used. Increase in Abrasives-to-media ratio from 1:1.25 to 1.25:1 leads to improvement in both the response characteristics, which is the unique advantage of AFM, as it leads to faster finishing.

Sharma studied on Helical AFM by taking a two start helical drill bit with the use of brass material. By the experimental investigation it was found that brass material gives the better surface finish. A further improvement in this process has been done by Singh with the use of three helix viz. Two start drill bit, three start drill bit and spline and found the comparative results with use of same work-piece material. Ramandeep (2012) works on the effects of the centrifugal force on afm process on a brass work-piece and the result shows that the process parameter number of cycles has the highest contribution towards the response characteristic and is 54% for the percentage improvement in ΔRa. As the number of cycles increases from 2 to 6, the %age improvement in ΔRa is maximum at the second level of 4.

Aluminium

Jain and Adsul (2000) carried out experiments to study the effect of process parameters (e.g., abrasive concentration, abrasive mesh size, numbers of cycles and flow rate of media) on material removal and surface roughness of aluminium work-pieces with the use of The silicon carbide of 80, 220, 400, 800 and 1200 mesh size experimental work. They have concluded that the concentration of abrasives in media followed by mesh size, numbers of cycles and flow rate of media are the influencing parameters. Further investigations have done on the using of different materials by researchers. Ravisankar (2010) worked on aluminium with use of the process Rotational Abrasive Flow Finishing (R-AFF). Mali *et al.* (2010) test the abrasive flow machining conditions during fine finishing of Al/15 wt% Sic-MMC material and found the results AFM process can be utilized for finishing of Al/15 wt% SiC p-MMC components. However, plowing and rubbing are observed on Al/15 wt% SiC p-MMC work-piece during AFF operation, indicating a spoil of surface finish if process parameters are not controlled effectively. Any attempt to increase the abrasive-work-piece interaction reduces the finishing time and increases the finishing rate of the process. For this, a set-up has been developed to rotate the work-piece (Al alloy, Al alloy/SiC MMCs) so that the probability of active abrasive particle to follow the helical path in the work-piece finishing region is higher which, in turn, improves both finishing rate and material removal rate. Jung et.al. performs experiment using a hard disk slider composed of a hard material (Al_2O_3-TiC), which has a complex 3D surface configuration. Its actual surface profile, obtained using an optical microscope.

Mild Steel

Jain and Jain (2001) carried out a series of experiments on the internal surfaces of the mild steel pieces with the use of polyborosiloxane carrier mixed with SiC abrasive particles on AFM set-up. These experiments were done to determine the Specific energy and temperature in abrasive flow machining process. Temperature at the work-piece surface during AFM has been measured using copper-constantan thermocouples. A multi-channel digital temperature indicator having resolution of 0.1 °C was used for recording temperature. The properties of the carrier, abrasive particles and work-piece. A model has been developed for the evaluation of specific energy in abrasive flow machining process. The specific energy for AFM (10-110 J/mm^3) process is overlapping with the range of specific energy for grinding (5-60 J/mm^3). This justifies the inference of researchers that machining action in AFM compares to grinding. A simple model has been developed for one dimensional heat transfer analysis of AFM process. By the use of this model, a fraction of heat entering into the work-piece and abrasive medium can be determined. The model is capable to predict the change in work-piece temperature. A further investigation has been done by Sahijpal *et al.* using by AFM as well as by MAAFM by employing varying number of cycles. It was basically comparison of wear behaviour of different materials viz., brass, aluminium and mild steel. After the whole process of study the employed abrasive and number of process cycles in MAAFM could not cause appreciable MR and surface roughness improvement for mild steel specimens. Gorana predict the surface roughness during abrasive flow machining. Based on the findings reported in the work, it is concluded that active grain density during the AFM process increases with an increase in extrusion pressure and percent abrasive concentration in the medium. This results in an increase in percent reduction in Ra value. Initial Ra of the work-piece is found to be an important parameter in AFM. A.Sadiq studied on the improvement in the finishing of non-magnetic surfaces in magneto-rheological abrasive honing process and as a result of that Effect of magnetic flux density in finishing ferromagnetic material has been investigated. As the work-piece becomes magnetized, the finishing medium is attracted towards it. Hence the relative movement of the abrasives in the medium with respect to the work-piece surface is considerably reduced. Therefore, the change in roughness is not appreciable, even when the magnetic flux density is increased. The presence of magnetic material in the holder improves the strength of magnetic field near the holder surface. Using a novel method proposed, MRAH is carried out with non-magnetic specimens inserted in the opposite slots and magnetic specimens in the other slots of the holder. This has led to improved yield strength of the finishing fluid, thereby enhancing the capability of the MRAH process to finish non-magnetic materials. For a magnetic field of 0.65 T, 6.7% and 24.2% improvements in finish are obtained for process duration of 10 and 20 min respectively with non-magnetic specimens alone, while the proposed method yielded 41.7% and 43.5%.

PROBLEM FORMULATION:

Abrasive Flow Machining (AFM) was developed in 1960s as a method to deburr, polish, and radius difficult to reach surfaces like intricate geometries and edges by flowing a abrasive laden viscoelastic polymer over them. Based on the application, three different types of machines have been reported, i.e., one way AFM, two way AFM and orbital AFM. Because of simplicity in analyzing the physics, analysis of AFM process always refers to two way AFM. It uses two vertically opposed hydraulic cylinders, which extrude medium back and forth through passage formed by the work-piece and tooling. Abrasion occurs wherever the medium passes through the highly restrictive passage. The key components of AFM process are the machine, tooling and abrasive medium. Process input parameters such as extrusion pressure, number of cycles, grit composition and type, tooling and fixture designs have impact on AFM output responses (such as surface finish and material removal). AFM is capable to produce surface finish (Ra) as good as 0.05 µm, deburr holes as small as 0.2 mm and radius edges from 0.025 mm to 1.5 mm. AFM has wide range of applications in industries such as aerospace, medical, electronics, automotive, precision dies and moulds as a part of their manufacturing activities. For better surface integrity, texture and its performance, continuous developments are taking place for modifying the existing AFM process technology and AFM machine configuration. But there are some of the draw backs such as low finishing rate. To overcome this drawback Mohit developed and improved AFM process, named as Helical-AFM (HLX-AFM). Parwinder developed two more helix such as drill bit of three start and a spline. The present research work focuses on the finishing of different materials (Brass, Aluminium and Mild Steel) using all the three types of helix viz., drill bit of two start, drill bit of three start and spline.

PROPOSED RESEARCH

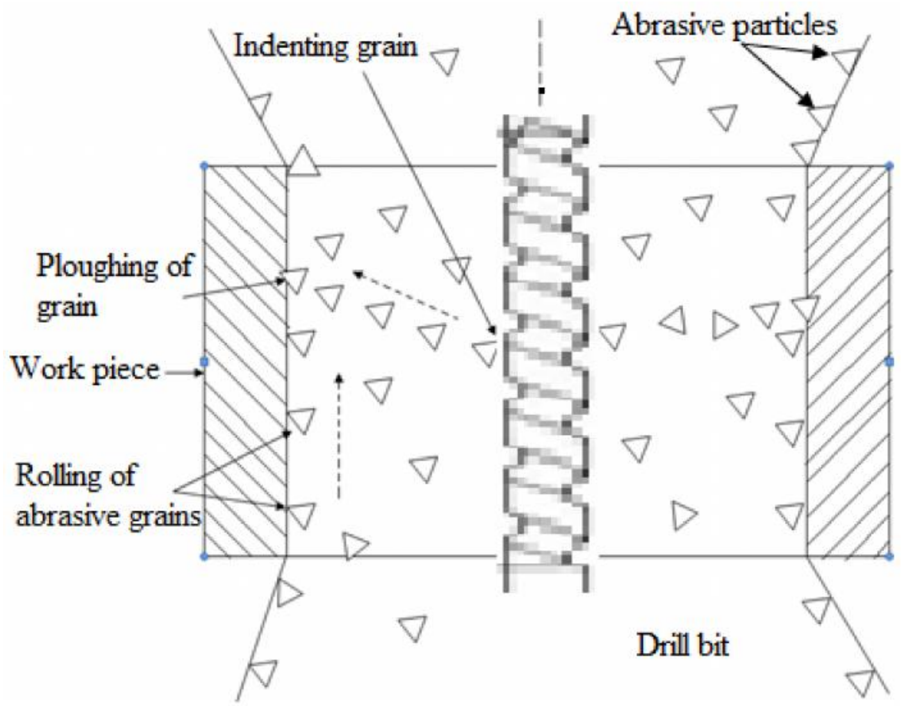
This research work focuses mainly on the following issues related to the finishing of different materials, i.e., brass, aluminium and mild steel with the use of Helical AFM set up.

- From the research work of Mohit and Parwinder in which the Helical AFM setup has been developed and further modified respectively.
- It has been observed that the finishing was done on hollow cylindrical work-pieces of brass only. So, for the present research work it is planned to develop develop the work-pieces of Brass, Aluminium and mild steel which have identical geometry as taken by Mohit and Parwinder.
- To plan the experiments based on the L18 orthogonal array of Taguchi method and to subsequently conduct the experiments.
- To analyze the observed results and estimate the optimal values of responses viz., MR and %Ra.

SCHEMATIC OF HELICAL-AFM PROCESS

The abrasive laden media with high pressure passes through drill bit causes an abrasion of the work piece. Due to stationary drill bit, there are three types of flows (axial flow, reciprocating flow and scooping flow) and forces (axial, radial and centrifugal forces) that occur in finishing zone and remixing of medium at exit from the finishing zone in Helical-AFM process. Due to the combination of different flows and forces, the work piece-abrasive contact length is no longer a straight line, rather it becomes curved; hence, the number of peaks that can be sheared increases, leading

Figure 5: Schematic of Helical-AFM Process



to higher material removal. In Helical- AFM process rolling, ploughing and indentation of the abrasive grains is due to motions and forces as shown in Figure 5.

TAGUCHI EXPERIMENTAL DESIGN AND ANALYSIS

In the Taguchi method, the results of the experiments are analyzed to achieve one or more of the following objectives:

1. To establish the best or the optimum condition for a product and/or process.
2. To estimate the contribution of the individual variables and their interactions.
3. To estimate the response under the optimum conditions.

Taguchi suggests two different routes to carry out the analysis of the experiments. In first approach, the results of a single run or the average of repetitive runs are processed through main effect and ANOVA analysis (Raw data analysis). The second approach is for multiple runs where signal to noise ratio (S/N ratio) is used. The S/N ratio is a concurrent quality metric linked to the loss function. By maximizing S/N ratio, the loss associated with a product or process can be minimized. The S/N ratio determines the most robust set of operating conditions from variations within the results. It is treated as a response parameter (transform of raw data).

Taguchi recommends the use of outer array to force the noise variation into the experiment. Generally, the processes are subjected to many noise factors that in combination strongly influence the variation of the response. Most often, it is sufficient to generate repetitions at each experimental condition of the controllable parameters and analyze them using an appropriate S/N ratio.

LOSS FUNCTION AND S/N RATIO

The heart of Taguchi method is his definition of nebulous and elusive term 'quality' as the characteristic that avoids loss to the society from the time the product is shipped. Loss is measured in terms of monetary units and is related to quantifiable product characteristics. Taguchi defines quality loss via his 'loss-function'. He unites the financial loss with the functional specification through a quadratic relationship that comes from Taylor series expansion.

$$L(y) = k(y - m)^2$$

where,

L = Loss in monetary unit

m = Value at which the characteristic should be set

y = Actual value of the characteristic

k = Constant depending on the magnitude of the characteristic and the monetary unit involved.

DATA ANALYSIS

A number of methods have been suggested by Taguchi for analyzing the data: observation method, ranking method, column effect method, ANOVA, S/N ANOVA, plot of average responses, interaction graphs, etc (Agrawal *et al.*, 2005). In the present investigation, following methods are used.

- Plot of average response curves
- ANOVA for raw data
- ANOVA for S/N data

The plot of average responses at each level of a parameter indicates the trend. It is a pictorial representation of the effect of a parameter on the response. Typically, ANOVA for OA's are conducted in the same manner as other structured experiments (Agrawal *et al.*, 2005). The S/N ratio is treated as a response of the experiment, which is a measure of the variation within a trial when noise factors are present. A standard ANOVA is conducted on S/N ratio, which identified the significant parameters.

PARAMETER DESIGN STRATEGY

Parameter Classification and Selection of Optimal Levels

ANOVA of raw data and S/N ratio identifies the control factors, which affect the average response and the variation in the response respectively. The control factors are classified into four groups:

Group I: Parameters, which affect both average and variation

Group II: Parameters, which affect variation only

Group III: Parameters, which affect average only

Group IV: Parameters, which affect nothing

The parameter design strategy is to select the suitable levels of groups I and II parameters to reduce variation and group III parameters to adjust the average values to the target value. The group IV parameters may be set at the most economical levels.

Prediction of Mean

After determination of the optimum condition, the mean of the response (μ) at the optimum condition is predicted. This mean is estimated only from the significant parameters. The ANOVA identifies the significant parameters. Suppose, parameters *A* and *B* are significant and A_2B_2 (second level of both *A* and *B*) is the optimal treatment condition. Then, the mean at the optimal condition (optimal value of the response characteristic) is estimated (Agrawal *et al.*, 2005) as:

$$\mu = \overline{T} + (\overline{A}_2 - \overline{T}) + (\overline{B}_2 - \overline{T})$$

$$= \overline{A}_2 + \overline{B}_2 - \overline{T}$$

$\overline{T}$ = Overall mean of the response

$\overline{A}_2$, $\overline{B}_2$ = Average values of response at the second levels of parameters *A* and *B* respectively.

It may sometimes be possible that the predicated combination of parameter levels (optimal treatment condition) is identical to one of those in the experiment. If this situation exits, then the most direct way to estimate the mean for that treatment condition is to average out all the results for the trials which are set at those particular levels (Agrawal *et al.*, 2005).

Determination of Confidence Intervals

The estimate of the mean («) is only a point estimate based on the average of results obtained from the experiment. It is a statistical requirement that the value of a parameter should be predicted along with a range within which it is likely to fall for a given level of confidence. This range is called Confidence Interval (CI). Taguchi suggests two types of confidence intervals for estimated mean of optimal treatment conditions.

- CI_{CE} – Confidence Interval (when Confirmation Experiments (CE)) around the estimated average of a treatment condition used in confirmation experiment to verify predictions. CICE is for only a small group made under specified conditions.
- CI_{POP} – Confidence Interval of population; around the estimated average of a treatment condition predicted from the experiment. This is for the entire population, i.e., all parts made under the specified conditions.

The Confidence Interval of Confirmation Experiments (CICE) and of Population (CIPOP) is calculated by using the following equations:

$$CI_{CE} = \sqrt{F_\alpha (1, f_e) V_e \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad ...(4.5)$$

$$CI_{POP} = \sqrt{\frac{F_\alpha (1, f_e) V_e}{n_{eff}}} \quad ...(4.6)$$

where,

$F_{\sim}(1, f_e)$ = The F-ratio at the confidence level of (1 –:~) against DOF 1 and error degree of freedom f_e, f_e = Eerror DOF, *N* = Total number of result, *R* = Sample size for confirmation experiments, V_e = Error variance,

$$n_{eff} = \frac{N}{1 + [DOF\ associated\ in\ the\ estimate of\ mean\ responce]}$$

CONCLUSION

The important conclusions of this research work are enlisted below:

- In the experimental investigation on the Helical-AFM setup, different materials used for workpiece and observed their respective material removal and %age improvement in the surface roughness.
- Helical AFM with the different helical profiles on the different materials.

- For the Design of Experiments, the Taguchi Method approach has been employed. L18 OA has been used for the plan of experiments.
- The four process parameters viz extrusion pressure, workpiece material, helical profile and the no. cycles (within the selected ranges) have significant effect on the response parameter of %age improvement in the surface finish based on raw data, whereas the effect of Helical profile type on the response parameter of MR is insignificant as on the basis of raw data.
- The results show that the process parameter of helical profile type has 3.75% contribution for the response parameter of %age improvement in Ra based on raw data (insignificant for S/N ratio data), but is insignificant for the response parameter of MR (based on both raw data and S/N ratio analysis). Presence of three-start helical profile type led to 61.40% improvement in the surface finish with no effect on MR (means no extra machining effort).
- The parameter workpiece material is the most significant parameter (based on both of Raw Data and S/N Ratio Data) and is observed that its effect dominates over that of the other three parameters. It has 53.24% contribution towards %age improvement in surface finish and 87.14% effect on the Material Removal (MR). Within the experimental range of abrasives-to-media concentration ratio, as the abrasives concentration increases, both the response parameter of MR and %age improvement in Ra increase.
- Number of Cycles has a contribution of 5.29% and 8.09% towards the MR and %age improvement in Ra respectively. Within the selected range of number of cycles from 4-12 cycles, as the number of cycles increase, the response parameters of MR increases but the %age improvement in Ra decrease.
- The Extrusion pressure is also significant but least effective within the selected range. Extrusion pressure has no contribution towards MR and 14.70% contribution towards %age improvement in the surface finish. At the third level of extrusion pressure 8 MPa, MR is less but it gives a good surface finish.

A maximum improvement of 61.40% has been observed in the Surface finish. With the initial roughness of 1.3 microns, an improvement to 0.50 microns has been observed on the inner cylindrical surface of a brass work-piece.

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