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Study of magnetic assisted-AFM, mechanical properties of various abrasive laden polymer media and abrasive wear and force mechanism.

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ABSTRACT

Abrasive flow machining (AFM), also known as extrude honing, is a method of smoothing and polishing internal surfaces and producing controlled radii. A one-way or two-way flow of an abrasive media is extruded through a work piece, smoothing and finishing rough surfaces. In one-way systems, we flow the media through the work piece, then it exits from the part. In two-way flow, two vertically opposed cylinders flow the abrasive media back and forth. In the paper, the various types of abrasive laden polymer media, their work piece applications as well as the compatibility with the abrasives used is explained. The properties of the polymer used in AFM are compared and the best combination of polymer, abrasive and hydrocarbon oil is selected. Apart from polymer properties, the media flow equations, abrasive wear and forces is also studied.

Keywords: *Wear; Properties; AFM; Forces.*

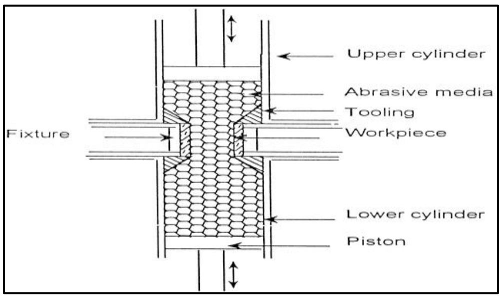
1.0 Introduction

With the time, technology is emerging and advancing day by day with the demand for highly accurate, precise and highly efficient machining process for advanced industries from critical aerospace and medical components to mass production automobile parts. This process has capability of finishing even the most areas which are not accessible, processing multiple, slots or edges, holes in one operation [1]. The development of materials having higher strength, hardness, toughness and other desired properties. This also needs to develop the advanced cutting tools material which can ease the process and are economical without compromising productivity

The applications of advanced abrasive finishing technique are increasing so as to get the highly accurate and highly efficient machining of complex shaped 3D components with nano level surface finish. Abrasive finishing can be employed to finish most mechanical parts with shape limitations. Initial surface roughness of 0.25μm Ra can be improved easily to 0.05 μm within a few minutes. In addition AFM process has many attractive advantages, such as self sharpening, self adoptability, controllability and finishing tool requires neither compensation nor dressing. There are various abrasive particles like Al2O3, SiC, CBN, diamond powder etc. are available which are being used for abrasive finishing process. To increase the MR and surface roughness, the abrasive are made magnetic in nature with ferromagnetic material by various techniques like sintering, mechanical mixing using ball mill etc. The theoretical and experimental research of thermal properties of media has been carried out by Fletcher et al.

Research reports on AFM are, however, not so enough. Researchers of Indian Institute of Technology have made a progress on AFM theory

Fig 1: Schematic Showing AFM Process



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Rhoades [2–4] studied the basic principle of AFM and reported that the depth of cut primarily depends upon abrasive grain size, relative hardness and sharpness and extrusion pressure. Przylenk[5] described that with small bore diameter of work piece, more grains come in contact with the wall and material removal increases.

The viscosity of this medium is expected to be different as compared to medium used for the industrial purposes. Finished surface characteristics have been studied by Williams and Rajurkar[6]. Three modes of metal deformation so far have been identified in any abrasive machining processes which are as follows [7]:

1. Elastic deformation associated with rubbing;
2. Plastic deformation or sloughing where majority of the material is displaced without being removed;
3. micro-cutting where removal of material takes in the form of miniature chips.

Gorana et al. [8] further reported that cutting force components and active grain density govern the surface roughness produced during AFM process.

Davies [9] experimentally found that viscosity of media is significantly affected by temperature. Jain et al. [10] also reported the effects of specific energy and temperature on AFM. In that report it has been got that work piece temperature increases with cycles and extrusion pressure.

2.0 Literature Review

An extensive literature review has been done on various types of abrasive laden polymer media, the processing oil and the workpiece used, which is listed below in the table 1and table 2. Magnetic assisted abrasive flow machining has been studied in detail and a number of research papers have been studied on the effect of magnetic field on AFM. Some of the key aspects related to magnetic AFM have been listed in the table 3.

3.0 Polymer Science

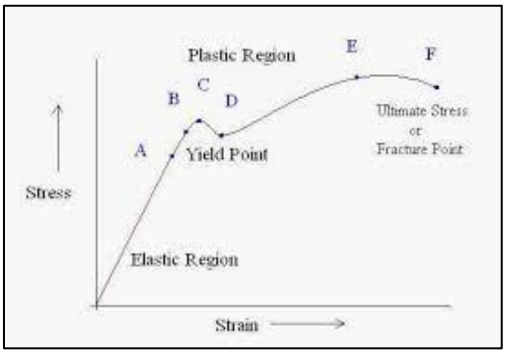
The mechanical properties of polymers used in AFM is explained below:

3.1 Elasticity

3.1.1 Continuous extension

The ratio of stress to strain is called modulus. In the low strain strain region, the stress and strain are directly proportional to each other, as shown in fig.2. When the strain reaches a yield value, the curve becomes non-linear. (a) Soft and weak material such as unfilled silicon rubber- “soft” refers to the fact that initial slope is small, which means low value of modulus. “Weak” refers to low ultimate strength. (b)Hard and brittle (Polystyrene)- “Hard” refers to initial slope or modulus is large. “Brittle” refers to the fact that maximum extensibility is small.

Fig 2: Stress vs Strain Diagram



3.1.1 Hooks elasticity

Young’s modulus $G=\frac{s}{\gamma}$ (1)

Rubber-like elasticity- A good operational definition of rubber-like elasticity is high deformability with essentially complete recoverability. The equation of state is

$$f^* = \frac{f}{A^*} = \vartheta kT(\alpha - \alpha^{-2}) \quad (2)$$

where f^* is nominal stress, f is equilibrium force, A^* is undeformed cross section, ϑ is number density of network chains, k is Boltzmann constant, T is absolute temperature, $\alpha = L/L_i$ is relative length of sample. This equation is similar to ideal gas law P = NkT/V, N is no. of gas molecules, V is volume, p is pressure.

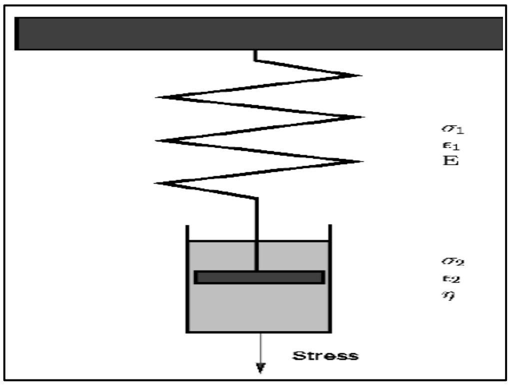
3.2 Viscosity

The viscosity n of a fluid may be defined by the equation

$$S = n\frac{d\gamma}{dt} = n\dot{\gamma}$$

Where s is force per unit area, □is rate of shear.

Fig 3: Maxwell Model for Visco-Elasticity



$$\dot{\gamma} = \frac{s}{n} + \left(\frac{1}{G}\right)\left(\frac{ds}{dt}\right) \quad (4)$$

The solution to this equation is

$$S = s_0 e^{-t/\tau} \quad (5)$$

Where s_0 is stress at initial t=0 and $\tau = {}^{n}/_{G}$ is relaxation time (the time required for the deformation to decrease to ${}^{1}/_{e}$ of its original value.

3.3 Visco-elasticity

It is the combination of viscous characteristics with elastic characteristics to describe the visco-elasticity of polymeric materials. The combination of spring and dashpot in series is called the Maxwell model (fig.3). It is used to describe the visco-elastic behavior of uncrossed-linked polymer.

Table 1: Abrasive Laden Polymer Media Used in AFM:

Author	Abrasive	Carrier medium and processing oil	Work piece
K.K. Kar, N.L. Ravikumar et al (2009) [11]	SiC abrasives (80, 220, 400, ….. mesh size) They constitute 28 to 78% by weight of the medium.	Visco-elastic carrier Natural rubber NR grade RMA-4 Butyl rubber IIR Commercial media is either silicon or poly borosiloxane (i.e. bouncing putty). Its cost is too high. Naphthenic oil is the processing oil.	En8, Al
S. Singh, H.S. Shan et al (2002) [12]	Brown super emery (trade name). It is magnetic in nature. It contains 40% ferromagnetic constituents, 45% Al_2O_3, 15% Si_2O_3.	Silicon-based polymer media. Hydrocarbon gel is the processing oil.	Cylinderical workpiece made of brass.
E. Uhlmann et al (2009) [13]	Polycrystalline diamond PDA311 of company element six ltd., Shannon, Ireland. D46 indicates grain size of abrasive.	MF10 indicates viscosity of polymeric carrier material (silicone basis). Grinding medium: MF10-D46-200 200 signify the weight ratio 1:2 between carrier media and abrasive grain.	Advanced ceramic materials
A.C. Wang, L. Tsai et al (2009)[14]	SiC	Bouncing putty (matrix of abrasive medium) : This is a kind of silicone gel with low flow characteristic and it would not stick on work piece after AFM.	
L. Tsai, A.C. Wang (2012) [15]	SiC or Al_2O_3	Silicone gel is a bonding gel to mix with ferromagnetic particles and abrasives. This gel is a semi-solid polymer and has deformation characteristics. Therefore ferromagnetic particles and abrasives mix with gel uniformly. With flexible property, gel abrasive can wrap around workpiece closely.	
H.J. Tzeng, B.H. Yan (2007) [16]	SiC	Silicone oil Polymer, wax medium	Stainless steel (SUS 304)
R.S. Walia, H.S. Shan, P. Kumar (2009) [17]	Brown super emery (trade name). It is one of the impure forms of conundrum.	The mixture of polymer and gel was used as carrier compound in media. Hydrocarbon oil is the processing oil.	
M. Ravisankar, V.K. Jain et al (2009) [18]	SiC mesh size 220, constituting 66.67% of media by weight.	Styrene Butadiene Rubber SBR is the polymer carrier. Hydrocarbon oil (manufactured by Indian oil). Its composition varies from 2.5 to 17.5% by weight.	Al alloy/SiC MMC (Metal Matrix Composites) with 0%, 10%, 15% SiC.
V.S. Sooraj et al (2014) [19]	Abrasive grits are embedded on polymer beads. The elastic abrasives have flexibility to deform itself in conformity to the shape of the work piece surface.	Elastomeric polymer bead of size (meso-micro range). It exhibits visco-elastic behaviour with low young's modulus and higher resilience, allowing base media to absorb energy when it is deformed elastically and recover it upon unloading.	Hardened steel (440C-58HRC)
S.Rajesha, G.Venkatesh, A.K.Sharma, P.Kumar (2010) [20]	Boron trioxide	Highly viscous and deformable new polymer abrasive carrier media consisting of di-methyl silicon oil and boric trioxide 90:10 by weight ratio respectively and naphthenic based processing oil. Natural rubber mainly contain ester group.	

Table 2: Magnetic Assisted AFM study:

Author	Year	Tools and techniques used	Output results
V. Yadava, K.B.Judal [21]	2013	In electrochemical magnetic abrasive machining, the material is removed from the workpiece surface due to simultaneous effect of abrasion and electrochemical dissolution. Finite element method is used to calculate the distribution of magnetic field between the magnetic poles in which cylindrical shaped workpiece is placed. The cutting forces responsible for abrasion are calculated from the magnetic forces due to gradient of magnetic field in the working gap.	A surface roughness model is developed by considering total volume of material removed with the assumption of triangular surface profile.
S.Jha, VK Jain [22]	2009	The three constitutive models, viz. Bingham plastic, Herschel–Bulkleyand Casson's fluid, are used to characterise the rheological behaviour of MRP fluid by fitting the rheological data obtained from capillary magnetorheometer and evaluating respective constants in their constitutive equations.	The fluid flow behavior of MRP fluid exhibits a transition from weak Bingham liquid like structure to a strong gel-like structure on the application of magnetic field. Depending on the size and volume concentration of abrasives and carbonyl iron particles (CIPs) in the base medium, the rheological properties hence, bonding strength gained by abrasives through surrounding CIP chains varies.
H.Yamaguchi, SK Srivastava [23]	2014	The relationships between surface conditions of AlTiN-coated round tools, cutting forces, and wear characteristics were clarified by milling of Ti-6Al-4V alloys.	The roughness of coated tools was improved by 50–60% without deteriorating the cutting edge radius, and the tool life was extended by 150%.
G.Kumar, V.Yadav [24]	2009	From magnetic potential model, the magnetic pressure developed and corresponding heat flux generated on workpiece surface are evaluated. The effects of various operating input parameter on magnetic potential distribution in the gap and temperature rise in the workpiece has been studied.	A mathematical model is developed for the prediction of magnetic potential using Maxwell's equations and finite element method is used to find the magnetic potential distribution within the gap between tool bottom surface and workpiece top surface. Further a mathematical model is developed for heat transfer in the workpiece and again finite element method is used for the prediction of temperature rise in the workpiece.
A.C.Wang, S.J.Lee [25]	2009	A novel abrasive medium,using the silicone gel to mix the ferromagnetic particles and abrasive,wasdeveloped to enhance the disadvantages in MAF. Magnetic finishing with gel abrasive(MFGA)was utilized in to polish the cylindrical rod of mold steel	The results demonstrated that surface roughness of the cylinder part was reduced to 0.1 mm Ra from an initial value of 0.677mmRa within10min, and surface roughness could decrease to 0.038 mm Ra after30min in MFGA. Surface roughness reduction in MFGA was 3 times of surface roughness reduction in MAF using the unbounded magnetic abrasive as medium.
T.A. El Taweel [26]	2008	It emphasizes the features of the development of comprehensive mathematical models based on response surface methodology (RSM) for correlating the interactive and higher-order influences of major machining parameters, i.e. magnetic flux density, applied voltage, tool feed rate and workpiece rotational speed on MRR and SR of 6061 Al/Al2O3 (10% wt) composite.	The results demonstrate that assisting ECT with MAF leads to an increase machining efficiency and resultant surface quality significantly, as compared to that achieved with the traditional ECT of some 147.6% and 33%, respectively.
R.S.Mulik, P.M. Pandey [27]	2011	The experimental studies have been carried out with respect to five important process parameters namely supply voltage, abrasive mesh number, rotation of magnet, abrasive weight percentage, and pulse on time (Ton) of ultrasonic vibrations selected based on literature available in the area of MAF process and ultrasonic generator controls. Percentage change in surface roughness (ΔRa) for AISI 52100 steel workpiece has been considered as response and unbondedSiC abrasives are used in the work.	The surface roughness value obtained by UAMAF was as low as 22 nm within 80 s on hardened AISI 52100 steel workpiece using unbounded SiC abrasives.

Table 3: Abrasive Wear

Heat	Electricity	Molecular level	Mechanics	Gas evolution
Diffusion and chemical reactions	Sparc, arc	Cohesion, adhesion	Elastic and plastic strain	Oxygen, hydrogen

Now the variation of Mooney viscosity vs. temperature and the dynamic pressure variation with surface distance is analyzed and discussed as below. Fig 4 shows Mooney viscosity–temperature curves for three medias with different preliminary viscosity. It can be seen that temperature has a great influence on Mooney viscosity values for three medias.

In order to examine the effect of cycle varying on Mooney viscosity during the test, the media temperature after each test is measured, then, Mooney viscosity–temperature curve is used to get Mooney viscosity–cycle curve.

The fig.5 explains that the gradient of the dynamic pressure is also increased with decreasing the media viscosity.

The properties of various polymeric materials are as: *Polyethylene PE-* The crystalline , melting point, tensilestrength, stiffness, hardness, abrasion resistance, dissolution temp. in benzene, chemical resistance increasewith increase in density of PE.

Fig 4: Variation of Mooney Viscosity with Temperature forthree Types of Suspensions. L. Fang et al

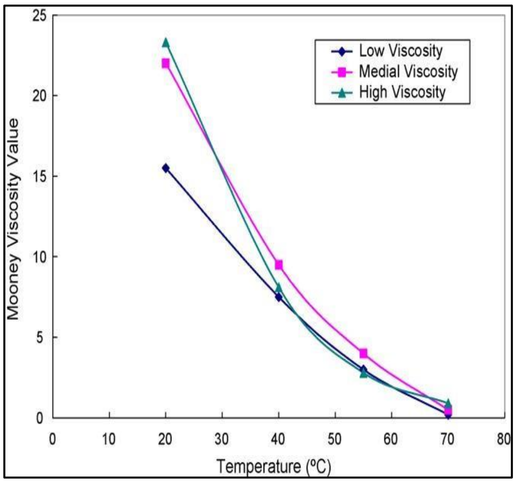
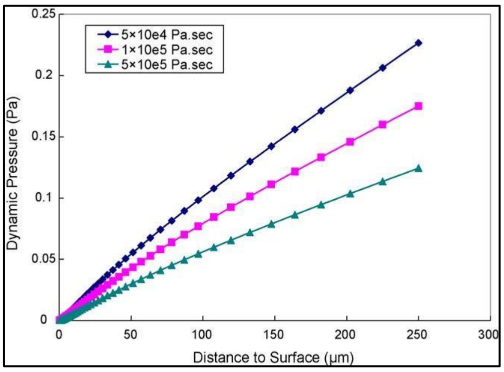


Fig 5: Dynamic Pressure Distribution Normal To Specimen Surface With Different Media Viscosity For 5mpa ExtrusionPressure.



Polystyrene PS- It is an amorphous polymer with high degree of branching. It has good chemical stability towards acids, alkalis, water. The most important weaknesses are its brittleness, low thermo stability, low resilience and flammability. The last property can be improved by introduction of halogen atoms in benzene ring [28].

Polymethyl methacrylate PMMA- It is amorphous, has better thermal stability. The solubility and viscosity of this group of polymers depend on the alcoholic group. Polymethacrylates are superior to polyacrylates in chemical stability, thermal stability and stability to water. When heated, polyacrylates soften before the correspondingpolymethacrylates.

Styrene butadiene rubber SBR- It is general purpose rubber. Its permeability, heat resistance, resistance to wear, and aging is superior to natural rubber. SBR requires more severe milling than natural rubber, however over milling causes a considerable decrease in tensile strength. Larger amounts of plasticizer and softener are required. At an increased vulcanization temp., a decrease of young’s modulus, relative elongation and even abrasion resistance has been observed. [29]

Silicon oils- Silicon oils consist of linear polydimethylsiloxane macromolecules with a MW in the range of 4000-25000. The reason of low viscosity at high MW is low intermolecular force in polydimethylsiloxanes. This also explains the small temperature dependence of silicon oils and elastomers.[30]

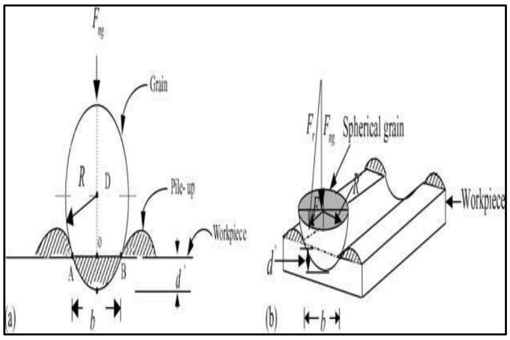
Epoxy polymers[31]- have excellent chemical resistance to alkaline environment, outstanding adhesion to variety of substrates, very high tensile, compressive, flexural strengths, low shrinkage on cure, dimensional stability, remarkable resistance to corrosion, a high degree of resistance to physical abuse, ability to cure over a wide range of temperatures, superior fatigue strength.

4.0 Abrasive Wear and Force Analysis

The mechanical wearing processes consist of separation of particle from the interactive surfaces in the way of micro- machining by loss of micro-roughness or by the loss of abrasive particles. Fatigue of material upper layer caused by the cyclic load is a mechanical cause of wear as well. Physical wear processes are generally connected with adhesion of bodies which rub together.

The volumetric relative wear can be described as volumetric cathode removal divided by machined material.

Fig 6: Forces Acting on Abrasive Grain



4.1 Radial force on a single grain

When the radial force is applied during AFM on a grain, it will indent to a depth *d_* into the work piece (Fig. 6)

With side flow of the material.

$$F_{ng} = \sigma \times A = \sigma \times \pi \times \left(\frac{b}{2}\right)^2 \qquad (6)$$

Where b = diameter of projected area

σ =flow stress of workpiece

4.2 Axial force on a single grain

It has two components-

4.2.1 Force P -required to plough the metal from the front of grain [24]

$$P = 0.062\frac{b^3}{R}\sigma \qquad (7)$$

4.2.2 Friction force FR - between the work piece material and abrasive

$$F_R = F_{ng} \times \mu \qquad (8)$$

$$F = P + F_R$$

$$= .062\frac{b^3}{R}\sigma + \sigma \times \pi \times \left(\frac{b}{2}\right)^2 \mu \qquad (9)$$

Fig.7 shows a schematic drawing of an active particle acted by several forces. A normal load acted by total pressure in AFM tunnel and a horizontal driving force acted on the profile face of particle. The horizontal driving force is transferred by the media. From fluid dynamics principle, the transferred driving force in the horizontal direction has an uneven distribution.

If a simplified analysis is made, resultant forces acted on a particle can be divided into four concentrated forces as shown in Fig.7, that is, normal force mainly produced by cylinder total pressure, driving force transferred by the pressure of the media and two resistant forces from material surface plastic deformation.

5.0 Analysis of Surface Roughness and Weight Loss Variation with Number of Cycles

Liang Fang experiments and found that the variation of surface roughness and MRR by number of cycles.

Fig. 8 represents the effects of the number of cycles on the surface roughness for AISI 1080, 1045 and A36 steel as test materials It is observed that an increase in the cycles result in an associated decrease in the overall surface roughness. In general, the surface roughness is basically depended on the polishing cycles.

It is on the whole insensitive to material hardness. However, the surface roughness is obviously changed only at first 20 cycles no matter what types of steels are used.

Fig. 9 displays the effects of the number of cycles on the wear weight losses for three kinds of steels.

It can be seen from Fig. 9 that wear weight losses increase with increasing the number of cycles.

The steel removal efficiency, however, dramatically deteriorates after 20 cycles. It is also shown that the material removal efficiency decreases dominantly with increase of steel hardness for the initial stage of test, which is differ from the effects to surface roughness.

Fig 7: Schematic of Force Analysis Acted on A Particle in Afm Suspension Media.

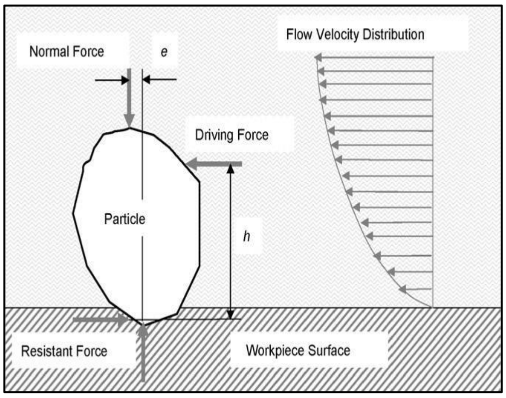


Fig 8: Relation of the Number of Cycles to Surface Roughness Ra for AISI 1045, 1080

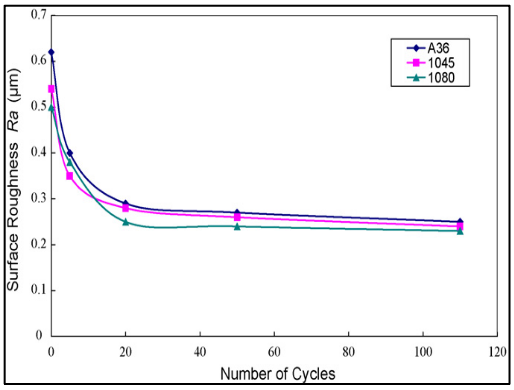
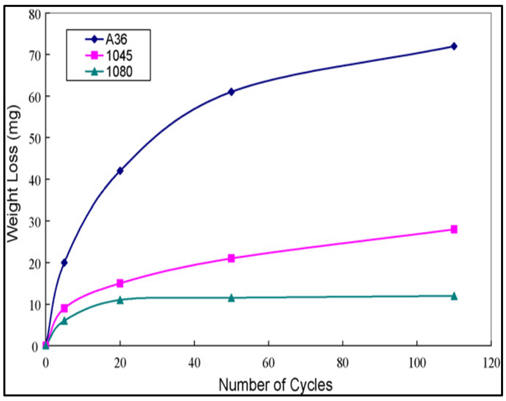


Fig 9: Relation of the Number of Cycles to wear Weight Losses for AISI 1045, 1080 and A36 Steel.



6.0 Principle of Abrasive Flow and Governing Equations of the Flow Pattern

The media used in AFM is composed of semisolid carrier mixed with abrasives which exhibits inear viscous flow property [32]. The media is isotropic and homogeneous. Since cylindrical work piece is considered, media flow is taken as axi-symmetric. The media flow is steady.

5.1 Continuity equation

The condition of volume conservation can be expressed as,

$$\dot{\epsilon}_{\theta\theta} + \dot{\epsilon}_{rr} + \dot{\epsilon}_{zz} = 0$$

where, $\dot{\epsilon}_{\theta\theta}$, $\dot{\epsilon}_{rr}$ and $\dot{\epsilon}_{zz}$ are components of strain rate tensor in azimuthal, radial and axial directions respectively.

5.2 Momentum equation

$$\rho\left[v_r\frac{\partial v_r}{\partial r} + v_z\frac{\partial v_r}{\partial z}\right] + \frac{\partial p}{\partial r} - \left[\frac{1}{r}\frac{\partial(r\tau_{rr})}{\partial r} - \frac{\tau_{\theta\theta}}{r} + \frac{\partial \tau_{rz}}{\partial z}\right] = 0$$

where, p is density of media, p is pressure (hydrostatic stress).

5.3 Constitutive equation

The media behaves as a Newtonian fluid with shear stress being the linear function of shear rate.The total stress tensor:-

$$\sigma_{ij} = -p\delta_{ij} + \tau_{ij}$$
$$= -p\delta_{ij} + \mu_a\, \dot{\epsilon}_{ij}$$

Where, μa is apparent viscosity and δij is identity tensor.

7.0 Conclusions

Analysis and comparison of various abrasive laden polymer media has been done successfully and their properties have been studied. The compatibility and suitability of the various polymers with different work piece materials has been analyzed. Different abrasive grains, hydrocarbon oil used were studied in detail and the wear and forces acting on abrasive are properly explained in the paper.

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