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Modelling of Material Removal in Abrasive Flow Machining Process Using CFD Simulation

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Abstract: **In the AFM process, a semi solid media containing a special type of polymer having specific properties and abrasive particles are extruded through the surface to be finished. The factors affecting the surface finish and material removal are the media viscosity, density, the extrusion pressure, piston velocity, abrasive hardness, particle hardness and work piece hardness. Computational fluid dynamics approach is applied to see the flow within the work piece, the movement of the media within the work piece and interaction with the wall. In the current work a 2D model was designed and the flow analysis, force calculation and material removal model was done. CFD simulation was done by using ANSYS FLUENT. The fluid was assumed to be non-Newtonian fluid and as there are two phases in it, a mixture laminar flow model was chosen with no wall slip. The work piece was assumed to be a small tube within which the abrasive media was flown at a particular pressure and volume fraction at a time. The abrasive material assumed for the analysis was silicon carbide and the media consisted of polyborosiloxane and grease. The flow analysis at different pressure was done. The shear stress and strain rate were also calculated. The material removal was estimated by using the shear stress from the existing formulae.**

Keywords: Abrasive flow machining, radial force, axial force, active grain density

1. INTRODUCTION

The dimensional accuracy and quality of surface finish are taken care of some precision finishing operations such as deburring, honing, lapping and grinding. These abrasive finishing processes are limited to only flat or cylindrical work pieces. So, to meet the requirement of a finishing process which has wider bounds of application areas, better quality performance, higher productivity, and automatic operation, abrasive flow machining process (AFM) was developed. It is mainly used in aerospace, defense and diesel industries [1].

In AFM a semi-solid medium consisting of a polymer of special properties and an abrasive mixed in a definite proportion is extruded under pressure through or across the surface to be finished. The work pieces are held between upper and lower media cylinder with the help of fixtures. The abrasive fluid is enclosed within the space formed by abrasive cylinder, work piece and fixture [2]. The advantages of AFM is highlighted in difficult to reach areas, complex geometries with an improved surface finish, lower cost, extended working time and reduced reworking time and rejection.

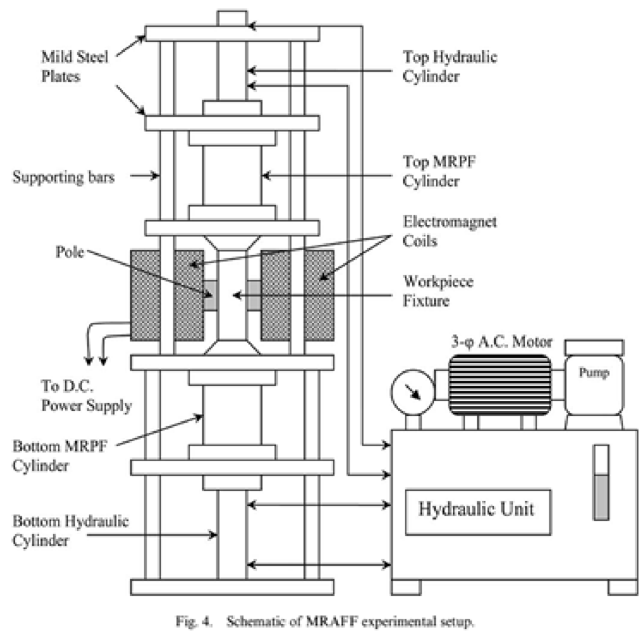

Fig. 1. Flow during abrasive AFM process

The surface precision can be controlled by changing the parameters such as abrasive concentration, abrasive mesh size, number of cycles, media flow speed and extrusion pressure [3-5]. Gorana et al. reported that the cutting force component and active grain density affect the roughness of the work piece [6]. They further gave a model on force prediction model during deformation process in AFM. Theoretical models and numerical methods were developed for the prediction of the finishing behavior of AFM [7-9]. The material removal and surface roughness were estimated by finite element analysis. It is not easy to get a uniform roughness in complex surface in AFM because the shear forces acting on the complex surface will not be the same if the flow path is not regular [10].

CFD (Computational Fluid Dynamics) method overcomes defects and deficiencies of traditional theoretical analysis and test measurement method. To simplify CFD modelling a 2D model was constructed and to get accurate result in fluid field data, the meshes are divided correctly. In the simulation the commercial ANSYS FLUENT package was used.

2. MULTIPHASE MODEL IN FLUENT

In multiphase flow, a phase can be defined as an identifiable class of materials that has a particular inertial response to and interaction with the flow and the potential field in which it is immersed. Different-sized solid particles of the same material can be also treated as different phases because each collection of particles with the same size will have similar dynamical response to the flow field. A general multi-phase model has generally 4 types of model. Mixture model is one of them and it is selected for non-Newtonian fluids flowing with same or at different velocities.

The mixture model can model n phases (fluid or particle) by solving the momentum, continuity and energy equations for the mixture, the volume fraction equations for the secondary phases and the algebraic expressions for the relative velocities. It is a good substitute for the full Eulerian multiphase model. The model allows to select granular phases and calculates all the properties of the granular phase. It is applicable for the solid-liquid flow.

The concentration of the particle is an important factor in the calculation of the effective viscosity of the mixture. The volume weighted average for the viscosity would now contain shear viscosity arising from particle momentum exchange due to translation and collision.

The CFD simulation in the present work was modelled for a laminar and incompressible flow. Laminar flow is taken into consideration when fluid flows in parallel layer and no disruption between layers. When a fluid is flowing through a closed channel such as pipe or between two flat plates, the flow may be taken as laminar or turbulent depending upon the velocity. For lower velocities the velocity is taken as laminar. Incompressible flow refers to a flow in which the material density is constant with the fluid flow. An equivalent statement is that the divergence of the fluid velocity is zero.

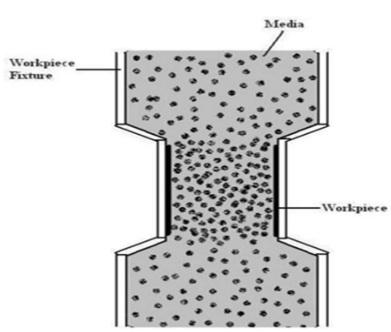

Fig. 2. The work piece and the fixture

The above diagram shows a longitudinal section of the work piece with fixture and the media flow within it. In FLUENT this was modeled to see the flow analysis as well as to determine the force and material removal.

3. CFD MODELING AND SIMULATION

In AFM process, a normal load is 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. 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. The driving force can be estimated by analyzing the horizontal flow velocity and pressure. Pressure while flowing through the tunnel can be resolved into 2 parts that is static pressure and dynamic pressure. The static pressure drives the whole media from inlet to outlet in the AFM tunnel and dynamic pressure is important for the particle movement. The static pressure and dynamic pressure is good monitor for estimation of horizontal force. So, CFD approach is taken into account to estimate the flow velocity, pressure as well as the strain rate and shear force.

To simplify the model a 2D approach of the problem is made by using ANSYS FLUENT. As it is a non-Newtonian viscous fluid media, so a laminar mixture flow model was selected. As the maximum pressure at which the AFM works was taken as 100bar, here at different extrusion pressures the velocity and pressure were analysed and later on the forces were calculated from the wall shear. The extrusion pressures are 20bar, 40bar, 60bar and 80bar. The analysis was done for both work piece with fixture and work piece without fixture.

The particle size was taken as 250µm during simulation. A pressure-based solver and steady formulation were taken for the purpose.

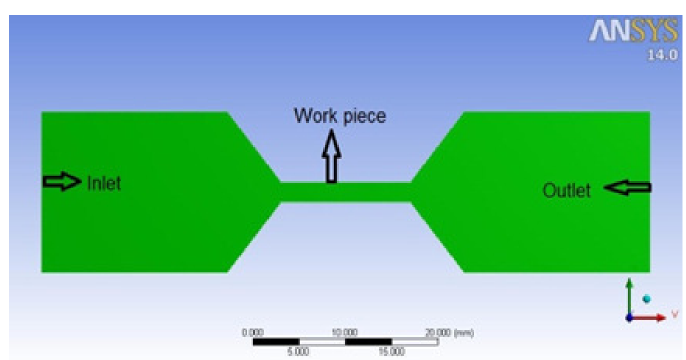

Fig. 3. Finite elements domain for CFD analysis

The colour contour shows the velocity distribution during the flow. It shows that the velocity decreases near the wall and maximum while flowing through the constricted work piece. The flow vector approaches zero as a limit at the nearest position of the specimen surface.

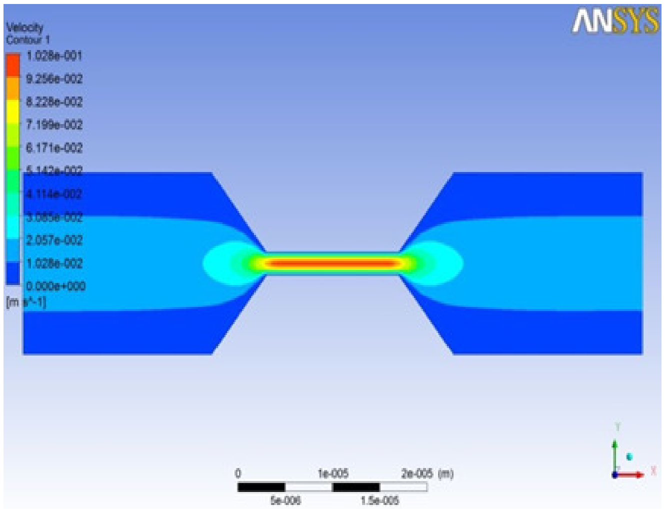

Fig. 4. Velocity contour from the simulated result

The velocity distribution of the work piece without fixture if observed shows that the velocity is almost uniform throughout the work piece but it is uneven from the center towards the wall. So, to give a uniform distribution of velocity from the wall towards the center, the constriction in the fixture arrangement is provided.

The Static pressure distribution in the tube is quite different with that of dynamic pressure.

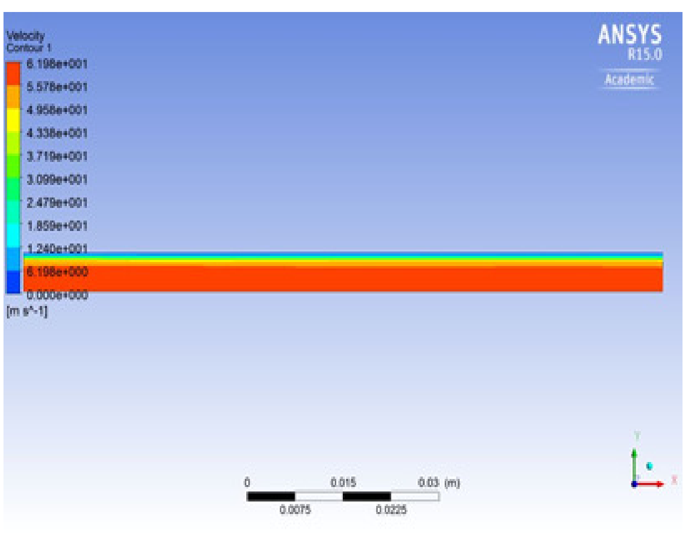

Fig. 5. Velocity contour from the simulated result for work piece without fixture

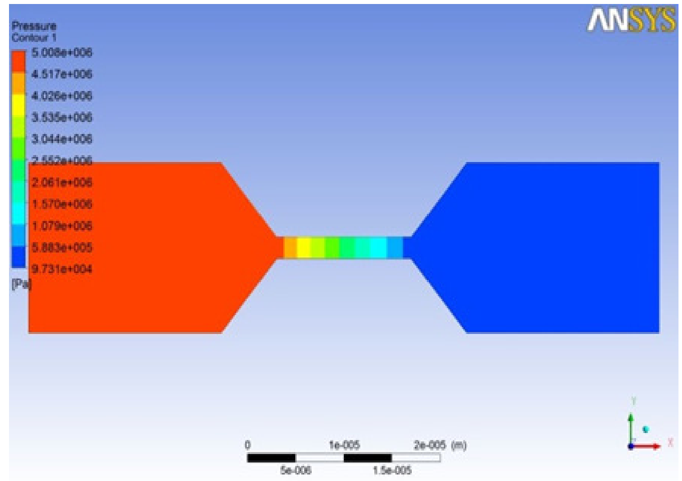

Fig. 6. Static pressure contour from the simulation for work piece with fixture

If the pressure distribution is observed in the work piece with fixture and without fixture, the static pressure in work piece with fixture is more than the static pressure without fixture. So, this arrangement of fixture is preferable.

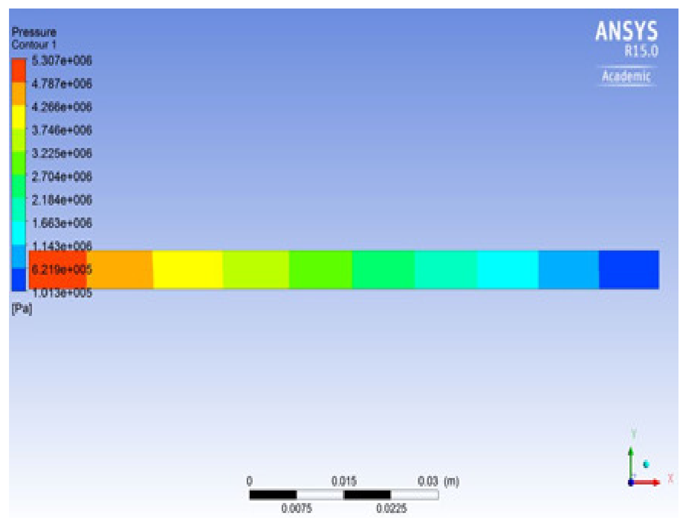

Fig. 7. Static pressure contour from the simulation for work piece without fixture

It can be seen that the static pressure distribution variation is along the tunnel in the direction of normal specimen surface. The static pressure can be considered as the normal load and driving factor of particle sliding and the dynamic pressure can be mainly regarded as the driving factor of particle rolling because of a large normal pressure gradient.

Wall shear was plotted in the work piece region and it was a measure of radial wall shear stress.

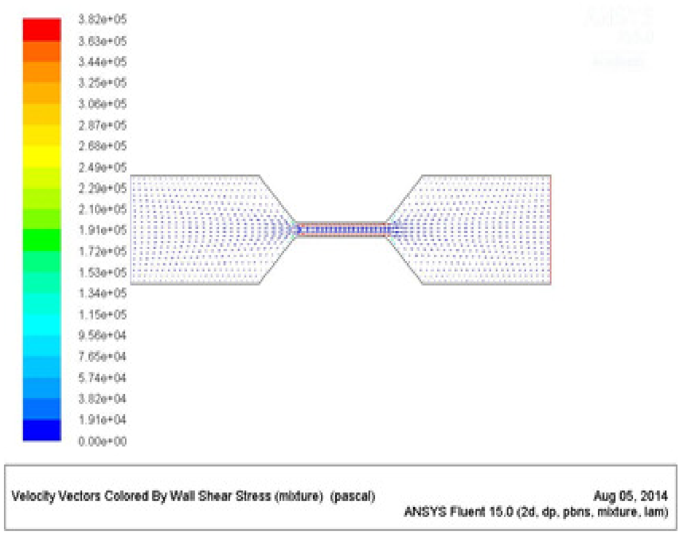

Fig. 8. Contour of the wall shear stress

As previous mentioned the average particle size is 250μm, all computing data within 250μm distance from specimen surface are picked up after the simulation.

4. MATHEMATICAL MODELING OF MATERIAL REMOVAL

Abrasive flow machining is considered to be a scratching action performed by abrasive grains in the AFM media. The normal force applied to a spherical grain will cause it to penetrate in the surface. The grain produces a groove on the work piece surface whose section corresponds to the profile of the grain. As the grain is translated horizontally, it removes material from the work piece surface. The amount of stock removal is then equal to the total volume of the grooves produced on the work piece surface by each grain in the media. The idealized classical model of abrasive wear provides a theoretical basis for the determination of material removal by AFM process. If the number of active grains, their shape and depth of the groove produced are known, the volume of stock removal can be calculated.

4.1 Assumptions

The following assumptions are adopted for the analysis of material removal by AFM process.

1. Most of the abrasive grains were assumed to be spherical in shape. Observation of abrasive grains shows that for the most part, they are generally rounded in shape and not composed of acute cutting edges.

2. It is assumed that each grain has single cutting edge. If there will be more than one cutting edges in one grain, there is no space to store the chip between cutting edges.

3. For mathematical convenience, it is assumed that the load on each particle is constant and equal to average load.

4. Every abrasive grain is assumed to achieve same penetration depth depending upon the applied force.

5. All active grains are of same size and metal is available to be cut by abrasive grain.

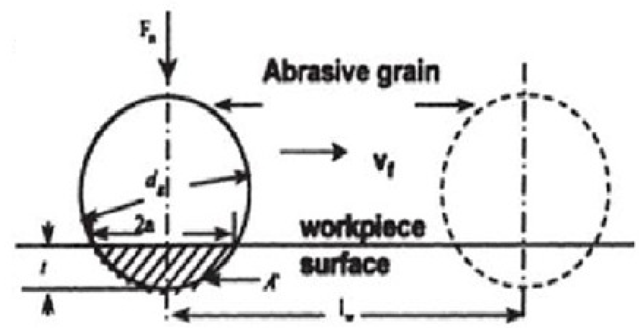

Fig. 9. Spherical abrasive grain

The normal force acting on a spherical grain will cause it to penetrate the surface. When this grain is translated horizontally, the plastically deformed zone beneath the surface will be inclined and give rise to upward flow thus forming a chip which is sheared from the surface.

The indenting force F_n on spherical grain of diameter d_g is given as

$$F_n = \sigma_r \frac{\pi d_g^2}{4} \tag{1}$$

Where, σ_r is normal stress acting on the grain.

If a is the radius of the projected area of indentation ΔA, t is depth of indentation and H_w is hardness of the work piece material, then

$$F_n = H_w \nabla A \tag{2}$$

From the geometry of Fig. 3(a), radius of the projected area a of the indent made and depth of indentation (t) can be obtained as given below.

$$a = \sqrt{t(d_g - t)} \tag{3}$$

$$t = \frac{d_g}{2} - \sqrt{\left(\frac{d_g^2}{4} - \frac{F_n}{H_w \pi}\right)} \tag{4}$$

The cross sectional area of groove generated *A'* (shaded portion of the grain) can be derived from the geometry

$$A' = \frac{d_g^2}{4}\sin^{-1}\frac{2\sqrt{t(d_g-t)}}{d_g} - \sqrt{t(d_g-t)} \quad (5)$$

The volume of material removal (V_a) can be given by the product of *A'* and the contact length *Li.*

$$V_a = \left[\frac{d_g^2}{4}sin^{-1}\frac{2\sqrt{t(d_g-t)}}{d_g} - \sqrt{t(d_g-t)} - \left(\frac{d_g}{2}-t\right)\right]L_i \quad (6)$$

4.3. Strain Rate

Strain rate is directly proportional to deformation of material and surface finish. When the abrasive grains are flown past the work piece surface, there is deformation created on the surface of work piece. In Fluent it is shown by the strain rate. This deformation shows variation according to the concentration of abrasive media. With the increase in abrasive concentration, the strain rate tends to increase.

5. RESULTS AND DISCUSSIONS

The simulation procedure involves the determination of stresses. The normal stress was obtained by the solution of the flow model and it was used for the estimation of material removal.

The simulation for material removal was carried for two extrusion pressures i.e. for 20bar, 40bar, 60bar and 80bar and calculation for the force and material removal was done.

Table 1. Data taken for theoretical analysis

Work piece material	Copper
Brinell Hardness	34HB=874MPa
Abrasive particle	silicon carbide
Particle diameter	250µm
Media for abrasive flow	Polyborosiloxane
Density of media	1219 kgm^{-3}
Viscosity of the media	0.789 $kgm^{-1}s^{-1}$
Volume fraction of silicon carbide	40%

The material removal calculated from the above model were found to be 4.47558×10^{-4}g for 20bar, 6.7352×10^{-4} g for 40 bar, 8.3512×10^{-4}g for 60 bar and 10.6541×10^{-4}g for 80 bar. The material removal found here is only for single extrusion of the upper media piston. The same can be found out for extrusion of the lower piston. The material removal can be determined for certain number of cycles keeping the extrusion pressure and volume fraction constant.

Table 2. Variation of parameters at different extrusion pressure for a work piece with a fixture (data from FLUENT analysis)

Extrusion pressure (bar)	20	40	60	80
Max Velocity of flow(ms^{-1})	0.0073	0.01595	0.02413	0.05182
Max static pressure (Pa)	2×10^6	4×10^6	6×10^6	8×10^6
Max dynamic pressure (Pa)	3.7×10^{-2}	15.5×10^{-2}	35.48×10^{-2}	15.45×10^{-1}
Strain Rate(s^{-1})	1.46×10^5	2.9×10^5	4.47×10^5	9.2×10^5
Wall shear(Pa)	1.2×10^5	2.5×10^5	3.8×10^5	5.3×10^5

5.1 Effects on velocity

The velocity of flow for the different extrusion pressures were observed from the simulation. It was seen that with increase in extrusion pressure, maximum velocity of flow through the passage increases. It increases up to a certain extrusion pressure but after that it decreases.

5.2 Effects on dynamic pressure

Dynamic pressure also increases with increase in extrusion pressure from 20bar to 80bar. Dynamic pressure is an important factor as it determines the horizontal force.

5.3 Effects on strain Rate

Strain rate increases significantly with increasing the extrusion pressure. Strain rate indirectly determines the material removal. So, it is assumed that with increase in strain rate, the material removal also increases and more surface finish can be obtained.

5.4 Effects on wall shear

Wall shear was determined from the simulation and was observed to be increased with increase in extrusion pressure. Putting the wall shear value in the equation, the normal force was calculated followed by material removal. But wall shear starts decreasing after a certain extrusion pressure.

6. CONCLUSION

The simulation results for the laminar mixture model for a copper work piece and silicon carbide abrasive particles were obtained. The CFD analysis was done for a constant volume fraction and constant density of the media. The flow analysis during the flow of the media through work piece- fixture passage was analyzed. The material removal here calculated for a half cycle i.e. only due to the extrusion of the upper piston. As it is a precision finishing operation, very less amount of material is removed. The material removal can be increased by increasing the number of cycles, mesh size of the abrasive particles, increasing the number of abrasive particles in the media and also increasing the extrusion pressure. The FLUENT analysis of the process gives a level for the experimental analysis because the experimental analysis including so many parameters is labour intensive as well as time-taking. The optimum parameters for the process can be obtained by experiments.

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