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Simulation of Force Generated and Material Removal in Abrasive Flow Finishing for Aluminium Material

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Abstract

Abrasive flow finishing is one of the non-traditional super finishing technique, for the production of excellent surface qualities of inner profiles that are difficult to access. Abrasive flow finishing process happens through mechanical abrasion of abrasive media, Radial force and axial force are responsible for the material removal. In the present work CFD approach using ANSYS-14 is applied to analyse the flow of visco-elastic abrasive polymer media in the aluminium tube component. An experimental study on the rheological properties of AFFM media using rheometer is considered in the CFD simulation to evaluate shear stress and velocity for variable pressure and abrasive mesh size. The number of abrasive grains per unit area is analysed using stereo microscopy. The normal and axial forces with material loss are calculated from the existing mathematical formulas, by taking the inputs from simulation and stereo microscopic analysis results. The theoretical model of material loss is compared with the experimental results for aluminium material Al-6061.

Keywords: Abrasive flow finishing machine AFFM, CFD, Rheometer, Material removal rate.

1. INTRODUCTION

Abrasive flow finishing process is identified for the excellent technique for super finishing, deburring, rediusing and recast layer removal, irrespective of regular/irregular geometry of the component. The viscoelasic polymer media with abrasive particle flows through the workpiece. The media act as the self forming multipoint cutting edges, with material removal in extremely thin chips allows fine surface finish. There are multiple factors affecting the final surface finish and material removal is one among them. In order to analyze the material removal theoretically, it is important to know the forces acting on the single abrasive grain. The CFD based flow simulation of viscoelastic fluid with mixture of solid abrasive particles is the simplified methods to achieve defect free and accurate results.

A number of research works was carried by researchers at different aspects as briefed below. Modeling of material removal and surface finish are analyzed through finite element method. The theoretical results through mathematical formulas and experimental data are compared [1, 2]. An advanced simulation technique through CFD evaluating stress generated during AFFM process is presented. The study reveals radial and axial forces effecting the material loss [3, 4]. Maxwell model for Non-Newtonian fluid is performed for rapid prototype component; shear rate and viscosity are estimated [5]. The rheological properties of abrasive media a complex shear modulus is studied using rheometer plate attachment in the AFFM setup, the measured forces theoretically determines the surface roughness [6]. Experimental setup for measurement of forces generated during AFFM process with the attachment of dynamometer in the AFFM setup. The study explains the material deformation under realistic condition [7]. Generation of surface profile and material removal in the AFFM process are simulated considering random distribution of abrasive grains in the media [8]. An experimental investigation demonstrating the mechanism of material loss and effect of extrusion pressure on material loss and surface finish through microscopic analysis were presented [9].

As observed in the above literature, no attempt is made to model the force generated and material loss during the AFFM process, considering the experimental inputs such as rheological properties of media and microscopic analysis of abrasive. However in the present work CFD simulation is carried for abrasive flow finishing of cylindrical hollow aluminum workpiece. The work theoretically demonstrates the quantification of forces generated during AFFM process, which is responsible for material loss. An attempt is made for comparative study on theoretical and experimental results of material loss during AFFM process.

Material removal in AFFM process:

Normal or Radial force and axial force are generated when extrusion pressure is applied on the abrasive medium from the hydraulic actuators. Normal force F_n is responsible for the indentation of the abrasive grain on the work piece surface while axial force F_A is responsible for material removal. Translating the abrasive grain of dia d_g with velocity V_f from indented depth of t from the work piece surface in the form of microchip. As demonstrated in the fig 1.

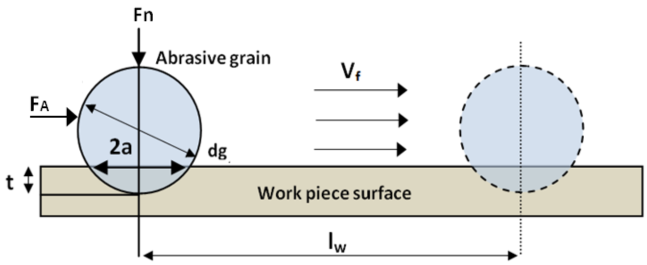

Fig 1. Forces acting on the abrasive particle in AFFM process

The normal (Radial) force exerted on a single abrasive grain is given by [1]:

$$Fn = \sigma r \, \frac{\pi \, dg^2}{4} \tag{1}$$

σr= Axial wall shear stress (N/mm^2)
dg =average diameter of the abrasive particle (mm)

The axial force exerted on a single abrasive grain is given by [1]:

$$Fa = (A - A') \, \tau y \tag{2}$$

A: Cross section area of abrasive particle (mm^2)
A': Cross section area of the groves (mm^2)

$$= \frac{d_g^2}{4} \sin^{-1}\left(\frac{2\sqrt{\left(t(d_g - t)\right)}}{d_g}\right) - \sqrt{\left(t(d_g - t)\right)} \left(\frac{d_g}{2} - t\right) \tag{3}$$

τy = Radial wall shear stress (N/mm^2)

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Weight of material loss in n number of cycle is given by [1]:

$$W = 2\pi N\rho l_s \frac{R_c^2}{R_w^2}\left[\frac{d_g^2}{4}\, sin^{-1}\left(\frac{2\sqrt{\left(t(d_g - t)\right)}}{d_g}\right) - \sqrt{\left(t(d_g - t)\right)}\left(\frac{d_g}{2} - t\right)\right]\sum_{i=1}^{2n}\left[1 - \frac{R_a^i}{R_a^0}\right] l_w \qquad (4)$$

$\boldsymbol{\rho}$: density of the work piece material (g/mm^3)

t :depth of indentation = $\frac{d_g}{2} - \sqrt{\frac{d_g^2}{4} - \frac{F_n}{H_w \pi}}$ (mm) (5)

H_w= Brinell hardness of the workpiece material (Kg/mm^2)

N: number of abrasive grains simultaneously acting per unit area of contact

l_s :Stroke length of AFFM media cylinder (mm)

R_w : Radius of cylindrical work piece (mm)

R_c: Radius of AFFM media cylinder (mm)

R_a^0 : Initial surface roughness of the work piece (µm)

R_a^i : Surface roughness after ith stroke (µm)

l_w: Total length of work piece (mm)

n: number of cycles

The mathematical model consists of certain assumption [2] such as the medium is homogenous, flow is quasistatic, incompressible, laminar, axisymmetric and there is no swirling motion of the fluid.

2. CFD SIMULATION

The simulation of AFFM process involves basic equations of continuity, momentum and constitutive [1]. The boundary conditions are the abrasive particle is assumed to be spherical. Each abrasive particle is having single point cutting edge. Load on the abrasive particle is constant with same depth of cut. At inlet uniform velocity and at outlet constant pressure is maintained. Workpiece is axis symmetric and Silicon carbide abrasive media volume fraction of 50%.

The CFD approach is considered to estimate the flow velocity, axial wall shear stress and radial wall shear stress. The simulation is done by using the software ANSYS-14, CFD (FLUENT). To simplify the model two dimensional (2D) simulation of the medium has been carried. As it is Non-Newtonian viscous fluid media, laminar mixture model is selected. Multiphase fluid model of mixture model is identified which allows selecting the granular size suspended in the media. The particle size of abrasives is considered as per Sieve number for the abrasive mesh of 60, 220, 400 and 800. The axial and radial stresses developed during the process are analyzed at different pressure ranging 20, 30, 40, 50, 60, 70 and 80 bar. A pressure based solver and steady formulation is taken for the purpose. The meshed 2D model is axi-symmetric with mesh size of 1 microns fig 2, AFFM media cylinder radius 75mm, stroke length of 250mm at two ends and work piece length of 18mm with inner dia of 5mm.

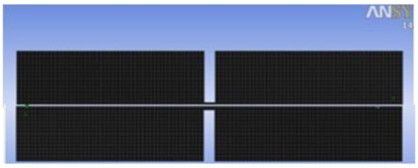

Fig 2.Meshed model for simulation

3. EXPERIMENTAL WORK

The key elements involved to perform the experiment are machine, fixture and abrasive media. An indigenously developed Abrasive flow finishing machine, AFFM-150D (fig 3) by CMTI in collaboration with IIT Kanpur has been used for present experimental studies. The machine consists of a rigid mechanical structure, hydraulic unit and control system. The setup is designed for extrusion pressure ranging 10-120 bar. AFFM-150D is inbuilt with thermal jacket for media cylinder to maintain the abrasive media temperature. The machine can also perform 2 way cycles with suitable fixture design for the workpiece. For the present study of aluminum sample, fixture plate made out of mild steel material is used.

Figure 3: Abrasive flow finishing machine setup (AFFM-150D)

Figure 4: Aluminium Workpiece and fixture

The visco-elastic polymer media used in the AFFM process is polyborosiloxane (Silly putty). Density of the polymer media is 1220kg/m^3. The media and abrasives are mixed in 1:1 weight ratio. The abrasive polymer media type Silicon carbide (SiC) mesh size of 60, 220, 400 and 800.

4. EXPERIMENT PROCEDURES:

Experiments were performed for hollow aluminum component fig 4, at constant abrasive mesh of SiC 60 with varying pressure 20, 30, 40, 50, 60, 70 and 80 bar and with constant pressure of 50 bar with varying abrasive mesh of SiC 220, 400 and 800. The parameters are varied in order to know the influence of material loss at different combinations. Analytical weighing balance (Sartorius CPA225D) with least count of 0.01mg is used to monitor the material loss of the aluminium sample, before and after the completion of each cycle in AFFM. Mitutoyo (SJ410) surface roughness analyzer is used to measure the initial and final surface roughness of the component, required in the theoretical equation of weight of material loss.

5. RESULTS AND DISCUSSION

5.1. Rehological Study on Media

The rheological properties of visco-elastic AFFM poymer media is estimated using Rheometer (DHR2-Waters). Initially frequency sweep test is conducted to know the shear rate of the polymer media. Viscosity of 10227 Pa-s is reported from the experimental plot (fig 4) of viscosity with respect to shear rate and temperature.

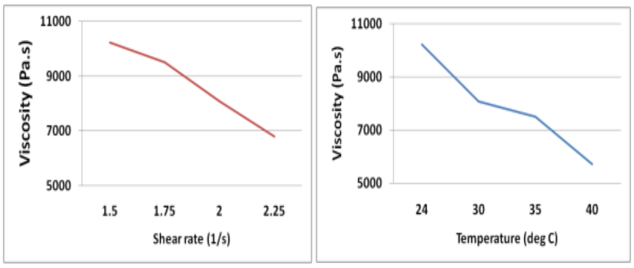

Fig 4. Variation of Viscosity with Shear rate & Temperature

The viscosity of the polymer media is temperature dependent and varies with increasing temperature. A thermal control unit maintains the temperature during AFFM process.

5.2. CFD Analysis

CFD Analysis results are recorded for the flow of abrasive media inside the workpeice considering the values obtained from experiments conducted using rheometer, by varying the pressure and diameter of suspended abrasive particle. The velocity magnitude is maximum at the centre axis. As shown in the fig 5, the velocity decreases near the wall and maximum while flowing through the constricted workpeice. Shear stress graph in the workpeice region is plotted projecting radial shear wall stress and axial shear wall stress. The radial shear wall stress increases with proceeding axial length and the radial shear wall stress decreases with proceeding axial length because of sudden change in the area of section (fig 6).

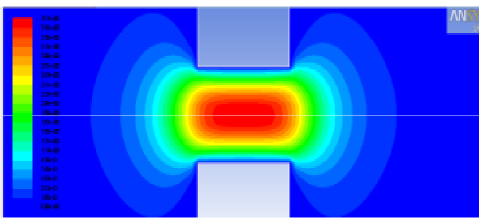

Fig 5. Velocity distribution from simulated result at 50bar with SiC 60

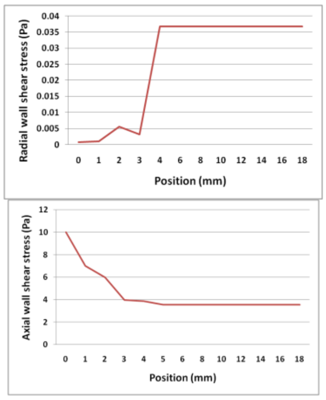

Fig 6. Variation of Axial and Radial wall shear stress along the axial length of workpiece at 50bar with SiC 60

5.3. Stereo Microscopic Analysis for Abrasive Particle

The number of abrasive grains simultaneously acting per unit area for theoretical evaluation of weight of material loss is analyzed using Stereo microscope (Discovery V20).

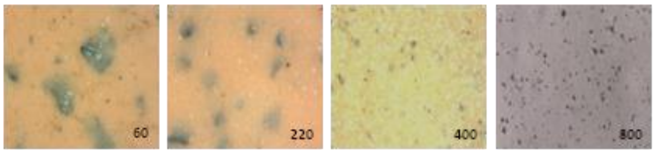

Fig 7. The number of abrasive particle count per unit area

The SiC abrasive mesh size of 60 is having 3 numbers of grains per 1mm^2, 220 mesh size of 11 numbers, 400 mesh size of 28 numbers and 800 mesh size of 49 numbers (fig 7). The count of the abrasive grains in polymer media increases with increasing mesh size, whereas size of the abrasive particle decreases with increasing mesh size.

5.4 Normal and Axial Forces

The normal and axial forces are generated on single grain abrasive at variable hydraulic pressure and abrasive mesh size is estimated. The shear wall stress determined from CFD simulation is utilized for solving forces through mathematical equations.

Table1: Variation of parameter at different pressure

Hydraulic Pressure (bar)	Radial wall shear stress (N/mm^2)	Axial wall shear stress (N/mm^2)	Depth of indentation (mm)	Radial force (N)	Axial force (N)
20	9.725 X 10^{-9}	9.85 X 10^{-7}	1.3702X 10^{-11}	4.9006X 10^{-10}	4.9634 X 10^{-7}
30	1.012 X 10^{-8}	1.525 X 10^{-6}	1.4257X 10^{-11}	5.099X 10^{-10}	7.6844 X 10^{-7}
40	2.111 X 10^{-8}	2.452 X 10^{-6}	2.9741X 10^{-11}	1.0637 X 10^{-9}	1.2355 X 10^{-6}
50	3.671 X 10^{-8}	3.652 X 10^{-6}	5.1657X 10^{-11}	1.8498 X 10^{-9}	1.8404 X 10^{-6}
60	3.751 X 10^{-8}	3.851 X 10^{-6}	5.2845X 10^{-11}	1.8901 X 10^{-9}	1.9405X 10^{-6}
70	3.994 X 10^{-8}	4.112 X 10^{-6}	5.6271X 10^{-11}	2.0126 X 10^{-9}	2.0721X 10^{-6}
80	4.125 X 10^{-8}	4.552 X 10^{-6}	5.8115X 10^{-11}	2.0786 X 10^{-9}	2.2786X 10^{-6}

The effect of increase in the hydraulic pressure with abrasive mesh of SiC 60 is shown in the Table 1. The low increments in the shear stress of abrasive media at higher pressure results in minor increase in the generation of forces above 50 bar. The increase in the normal force at higher pressure leads to deeper indentation of abrasive on the workpeice surface.

Table2: Variation of parameter at different abrasive mesh size

Mesh Size (SiC)	Radial wall shear stress (N/mm^2)	Axial wall shear stress (N/mm^2)	Depth of indentation (mm)	Radial force (N)	Axial force (N)
60	3.671×10^{-8}	3.671×10^{-5}	5.1657×10^{-11}	1.8498×10^{-9}	1.8404×10^{-6}
220	2.365×10^{-8}	2.456×10^{-5}	9.1528×10^{-12}	8.9281×10^{-11}	9.1829×10^{-8}
400	1.785×10^{-8}	1.678×10^{-5}	3.7682×10^{-12}	2.0243×10^{-11}	1.90303×10^{-8}
800	9.895×10^{-9}	9.02×10^{-6}	1.0444×10^{-12}	2.8055×10^{-12}	2.5574×10^{-9}

At constant pressure of 50 bar with different abrasive mesh size (Table 2), the radial and axial force drops gradually at increasing mesh size. The area of abrasive particles decreases for higher mesh size, leading to reduction in the generation of forces on abrasive and depth of penetration.

5.5 Material Loss

Substituting the experimental result in the equation (4), weight of material loss in the aluminum sample is estimated theoretically. An experiment is performed for similar variable parameters for aluminum workpiece with suitable fixture. A comparative study is possible after extracting theoretical and experimental results.

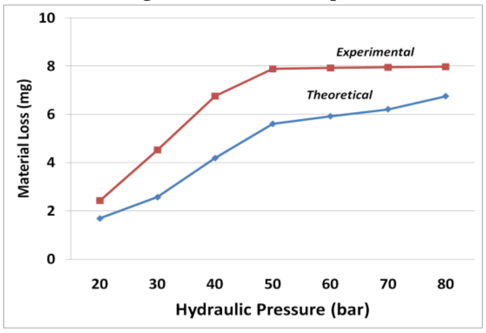

Fig 11. Variation of Material loss with hydraulic pressure at SiC 60

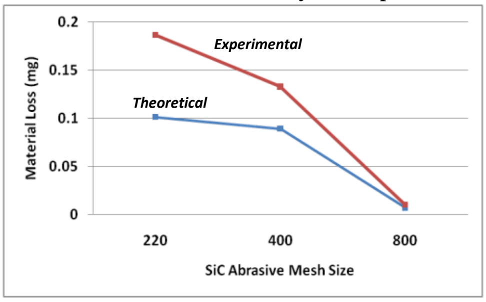

Fig 12. Variation of Material loss with Abrasive mesh size at 50 bar

Increase in the material loss is observed at higher pressure range and lesser material loss at higher mesh sizes. As the value of axial and radial forces gets saturated at higher pressure range, less amount of material is removed above hydraulic pressure of 50 bar (fig 11). As the depth of indentation drops with higher mesh size with lesser force on the area of abrasive particle, material loss decreases with higher abrasive mesh size (fig 12).

6. CONCLUSION

In the present work attempt is made to find the forces generated through CFD techniques considering viscosity determined from rheological study. An experimented input of stereo-microscopic analysis and surface roughness is taken into account for theoretical study of axial, radial forces and material loss at variable pressure and mesh size. CFD results are substituted in the mathematical equations and theoretical material loss is calculated. Material loss in aluminium sample at different pressure and mesh size during AFFM process is recorded. Comparative results of theoretical and experimental data are of good agreement. Following conclusions are made based on the study.

- From the theoretical model values of axial force is higher than the radial force which leads to the removal of material from the work surface.
- With increase in the pressure axial and radial forces increase which results in the higher material loss.
- With increase in the abrasive mesh size axial and radial forces decrease which results in the lesser material loss.
- AFFM hydraulic pressure above 50 bar is found to provide higher axial and radial forces on the work surface which leads to the remove higher material.
- The selected abrasive mesh size of 60 is found to provide higher axial and radial forces on the work surface which leads to the remove higher material.

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