An investigation on the profile accuracy control in abrasive flow machining: CFD simulation and experiment case study

Kai Cheng, Yizhi Shao, Rodrigo Merlo and Mitul Jadva
Institute of Materials and Manufacturing
Brunel University London, Uxbridge UB8 3PH

Abstract

Abrasive Flow Machining (AFM) technology developed in 1960s is getting more and more interest by the industry and research community particularly in the context of increasing demands for post-processing of the additively manufactured and complex components. It is increasingly important to develop an industrial feasible approach to control and improving the profile accuracy (form and dimension) of the component as well as its surface roughness. In this paper, a Multiphysics multiscale simulation based approach is presented to model and simulate the AFM process against the form and dimensional accuracy control in particular. The modelling and simulation is developed in COMSOL which is a Multiphysics computational environment. Well-designed experiment trials are carried out on a purposely configured testing 'coupon' to further evaluate and validate the simulations. The AFM machine and specific machining media for the experiments are provided by the industrial collaboration company, with their further industrial inputs. Both the simulation and experimental trial results illustrate the approach is applicable to the profile accuracy prediction and control, which will be used as a foundation for further developing the simulation based AFM virtual machining system.

1 Introduction

In many industries, Modern high-value manufacturing (HVM) is characterised by use of high performance materials and geometrical complexity of components and products which owns < 5μm tolerances and so on. Currently primary manufacturing methods (turning, drilling and milling) are insufficient to complexity and manufacture geometry to customer specifications in the oil, gas and automotive sectors. As non-traditional material removal method, Abrasive Flow Machining (AFM) was brought out in 1960s by the Extrude Hone Corporation. In aviation industry, AFM is performed by extruding viscoelastic media, through a workpiece featuring complex free-form aero structures which is inaccessible by hand to surface finish. Furthermore, AFM is an essential means for surface processing for 3D additive conformed complex components, however, the process control needs to be more predictable, producible and highly productive manner. In this light, the prediction of abrasive flow machining (AFM) can improve the efficiency and performance of workpieces.

In previous work about the simulation, Jain (1999) utilized a 2D CFD model that assumed constant media viscosity of 543.48 Pa.s from an unidentified source, the simulation was used to determine the stresses on the workpiece to later use them as inputs for the abrasion model described in the previous section. Afterwards, a simulation model presented by (Jain & Jain, 1999) considered a purely geometrical assumption where material removal occurred whenever an assumed spherical simulated grain contacted the workpiece. The model was able to predict the trend of the material removal and change in surface roughness with variations of extrusion pressure, grit concentration and size and workpiece hardness. The doctoral dissertation by (Howard, 2014) simulated the flow using a CFD model which considers the shear rate and temperature dependence of viscosity, the simulation results where compared with machining results in a point of interest in order to determine a model that could relate the flow fields. In (Uhlmann, et al., 2013) the authors developed a Maxwell material model which should be capable of describing the viscoelastic characteristics of the media. In the journal article submitted by (Fu, et al., 2016) the flow around a simplified model of an IBR was tested and simulated using CFD.

The research presented in this article attempts to build a simulation for the profile accuracy prediction and control.

In this article, modelling and simulation is developed in COMSOL based on CFD module. With the simulation the material removal and profile accuracy of workpiece can be predicted. With a well-designed experiment the result of simulation is being tested. Then with analyse of material removal this simulation is adopted to predict the result from an industrial case.

2 CFD simulation-based analysis on machine effects

As a scientific and reliable production technique, readily available CFD software, COMSOL can be used to analyse the flow of media in an arbitrary geometry. The CFD module in COMSOL makes it possible to simulate the Pressure Distribution and shear rate on the surface of workpiece. With the appropriate setup of simulation, the result of Abrasive Flow Machining is predictable in controllable deviation.

2.1 Simulation setup

The CFD model presented in this section was built using the COMSOL Multiphysics, the model solves the Navier-Stokes equations by using a purely viscous model (power law). It seems to be the best available description of the medium viscosity media (MV) used as the (+1) level with the code named as 649-Z produced by Extruded Hone. The programed curve was adopted into the software using an interpolation function.

The values of additional parameters the simulation requires have been entered in a way that replicates the settings available in the machine (Table 1), using equations to calculate different values when required by the software.

Table 1 Additional parameters and variables for simulation

Type	Name	Expression	Description
Equations	*st*	V/Q	Processing time
	stmin	st/60 * 1 [1/s]	Processing time minutes
	U0	Q/(pi/4*D^2)	Inlet speed
Abrasion model	*Kva1*	20.75e-6 [(m/m^3)/(1/s)]	Abrasion coefficient 1
	Kva2	8.36e-6 [(m/m^3)/(1/s)]	Abrasion coefficient 2
Machine Parameters	*D*	80e-3 [m]	Piston Diameter (D)
	Q	16.4e-6 [m^3/s]	Flow rate (Q)
	V	60e-3 [m^3]	Total Processing Volume (V)
	V1	2e-3 [m^3]	First Cycle Volume (V1)
	Bp	3.23 [MPa]	Back Pressure
Flow rate estimation	*EpTarget*	6.1 [MPa]	Target Extrusion Pressure
	Qmax	120e-6 [m^3/s]	Max Q for EpSim
Variables	*pVol*	t*Q	Processed volume
	Kva	if(pVol<V1,Kva1,Kva2)	Abrasion Coefficient

The time the simulation runs for (st) is linked to the machine parameters Volume (V) and Flow Rate (Q), the speed at the inlet (U0) depends on flow rate (Q) and machine piston diameter (D).

There are also parameters needed if the flow rate (Q) needs to be estimated from known extrusion pressure (Ep) and backpressure (Bp).

Additionally, the simulation is partly based on the further AFM trails in the next part of this paper. The AFM trials were conducted on a specially designed fixture which attempts to replicate the flow condition present in a single blade of an IBR, the fixture is shown modelled in 3D CAD in Figure 1, the fully dimensioned 3d file is also available in the digital annex, the geometry was then converted through addition of the cylinder geometry and Boolean operations into the fluid domain in Figure 2

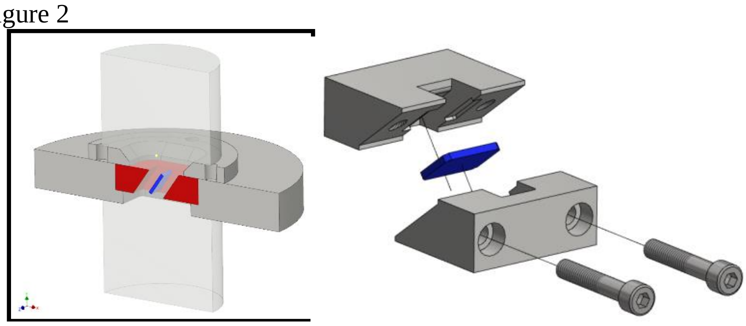

Figure 1 The test geometry for AFM trial and Fluid Domain used in simulation of AFM trial

2.2 Boundary conditions

After the geometry has been imported it is necessary to define the boundary conditions that apply to the model, for this purpose, it was assumed that the process was at the middle of the stroke, where the piston motion produced a constant velocity at the inlet (always set up on top), the outlet corresponds to the face of the bottom piston, in which a constant pressure matching the machine backpressure setting was selected, through the use of parameters.
These settings match the software's recommendation for a well posed CFD problem, the code in COMSOL does allow to input different conditions that at first seem useful to AFM users, who might typically only know the inlet and outlet pressures, but that condition is not as numerically stable as the one described before, for this reason, an optimization algorithm has also been set-up in the model so that the velocity at the inlet (or flow rate) may be found from known extrusion and back pressures, in order to avoid running into numerical instabilities, the software iterates the solution of the stable boundary conditions on a coarse mesh until the corresponding pressures are found, it then reports the flow rate needed to achieve that pressure, the problem can then be run using the calculated flow rate.

2.3 Simple abrasion model

The abrasion model presented here is an example of how the flow simulation may be leveraged to produce data that can help an engineer predict the process response before first trials, reducing the amount of testing needed to develop a new part.
This model makes two main assumptions about the material removal in any given condition:
The first one is the material removal is higher where the polymer slips faster against the wall and this occurs where the simulated velocity gradient (shear rate) is higher. What is more, the material removal rate is constant with respect to the processed volume, and may be estimated from two straight lines, one for the initial cycle where material removal is more aggressive, and another for subsequent cycles
Given these two assumptions one may write an expression for the material removal as a function of both the processed volume and the shear rate:

$$MRR_v(V, \dot{\gamma}_{simulated}) \ \left[\frac{m}{m^3}\right] = K_{va}(V)\left[\frac{m}{m^3 \cdot s^{-1}}\right] \cdot \dot{\gamma}_{simulated}\,[s^{-1}]$$

$$K_{va}(V) = \begin{cases} K_{va1} & if \ \ V \leq \ \ V_1 \\ K_{va2} & if \ \ V > \ \ V_1 \end{cases}$$

Where MRR_v is the material removal rate by volume (i.e. for each cubic meter of processed media), γ˙_simulated is the shear rate at the wall obtained in simulation, K_{va1} and K_{va2} are proportionality constants which may be found by testing, which will depend on the media, abrasives and workpiece material used, V_1 is the volume of the initial cycle where material removal is more aggressive.

The procedure to determine the values for K_{va} consists of finding the removal rate on each cycle from the data and dividing it by the shear rate found by the steady state simulation of the initial geometry (Figure 2).

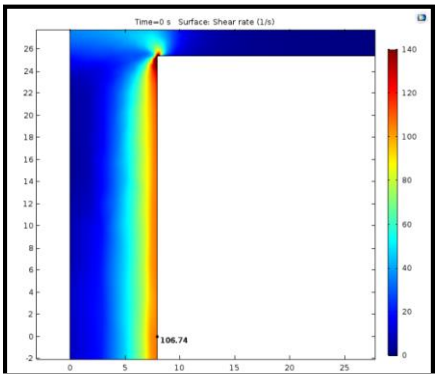

Figure 2 Shear rate at the wall simulated for Experiment 1 in (Williams, 1993)

The simulation was run with machine parameters:

$$Q = 36 \left[\frac{ml}{s}\right], \qquad D = 101.6\ [mm],$$

$$V = 22.94\ [l], V1 = 2.294\ [l]$$

These parameters produce the pressure drop of 4.1 MPa measured during the experiment.

The shear rate at the point where the material removal was measured is $106.74\ [s^{-1}]$ extrusion pressure and 错误!未找到引用源。 contains the MRR_v calculated for the first and subsequent cycles, the calculated abrasion coefficients are then:

$$K_{va1} = \frac{MRR_{v1}}{\dot{\gamma}_{simulated}} = \frac{2.214 \times 10^{-3} \left[\frac{m}{m^3}\right]}{106.74\ \ [s^{-1}]} = 20.75 \times 10^{-6} \left[\frac{m}{m^3 \cdot s^{-1}}\right]$$

$$K_{va2} = \frac{MRR_{v2-10}}{\dot{\gamma}_{simulated}} = \frac{891.94 \times 10^{-6} \left[\frac{m}{m^3}\right]}{106.74\ \ [s^{-1}]} = 8.36 \times 10^{-6} \left[\frac{m}{m^3 \cdot s^{-1}}\right]$$

These coefficients apply to media described by the author as “Medium Viscosity” with 70 grit SiC abrasive in a 66% concentration by weight and a Mild Steel part.

To input this model into the moving mesh simulation, the displacement of the boundary needs to be programmed as a function of time not volume, the flow rate (Q) being pushed through the part is assumed constant so:

$$MRR_t\left[\frac{m}{s}\right] = Q\left[\frac{m^3}{s}\right] \cdot MRR_v\left[\frac{m}{m^3}\right]$$

The main strength of this model is that it may be used to predict the localized material removal within a part, in the case of the test geometry the edge radius on each corner will be compared with the experimental findings, it the case of IBRs, it could be developed to predict the removal in the leading and trailing edges.

3 Experimental trials set-up and validation

3.1 Machine set-up

The extrude hone machine used in this experiment is equipped with what the manufacturer calls "AUTOFLOW" control which allows the user to set up the machine in one of 3 different modes. The machine counts volume only on upwards strokes so the total processed volume is twice the set value, the values for volume in this section will always be the total processed volume.
In this project we choose the flow control mode with back pressure on. In this mode the machine will actively control the pressure in the cylinder opposing the motion, but the target in this case is keeping the flow rate constant (obtained by measuring the displacement rate of the cylinders), in this case if media viscosity reduces due to temperature build up, the backpressure rises (reducing the pressure drop across the restriction effectively compensating the viscosity drop to keep the flow rate constant), the machine stops the processing when it senses the cylinders have displaced the required volume.

3.2 Trial Factors

The High-Low levels for the factors are:

Table 1 AFM trial levels

FACTOR	Unit	Low	High
		-1	+1
Flow Rate (Q)	ml/s	16.4	32.8
Volume (V)	l	20 (10)	60 (30)
Media (M)	-	D100	649Z
Age (A)	-	Old	New

To determine the media with the lowest and highest viscosities in the absence of manufacturer provided information, a simple flow test was devised, the media was extruded through a simple circular die, the machine was set up in flow control mode with backpressure enabled: Q=20 ml/s, V=5000 ml (2500 ml), Ep=10 MPa. The result about test of viscosities is shown in Figure 1

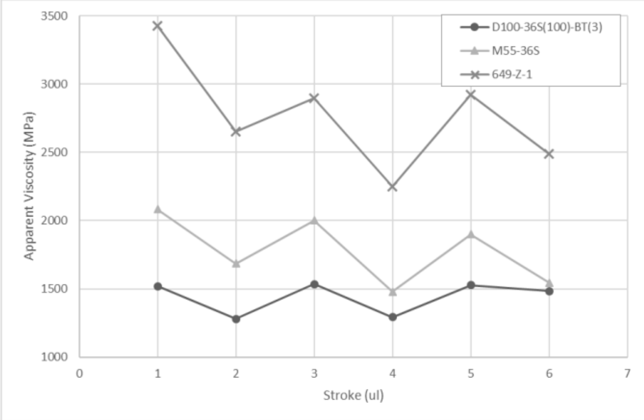

Figure 1 Relative apparent viscosities of tested media

4 Comparation between simulation and trails on material removal

The experimental trials provide more data to test the simulation model against, the conditions for the coupon with the highest material removal were simulated first, in order to test if the abrasion coefficients obtained independently from these tests could be used to predict the process response, they were left unmodified for this simulation, the simulated shear rate field and the material removal results in thickness are shown in Figure 2.

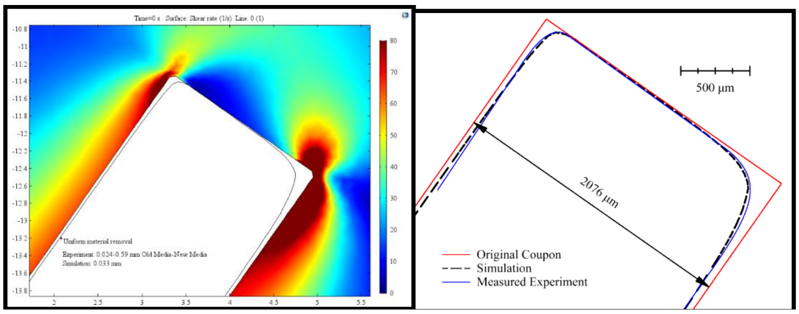

Figure 2 Simulation of material removal in AFM trials

The simulated material removal estimated in this case lies in between the amount obtained by experimentation with old and new media, considering the abrasion coefficients where obtained from William's experiments and not from testing the actual media/material combination in our experiment, this is a reasonably close approximation.

The simulation was able to predict the resulting profile with reasonable accuracy, it is good enough that if such a prediction can be made before processing a single part, engineers could reduce the number of tests required when developing new parts with the process.

5 An industrial case study on the polishing of Integrally Bladed Rotors (IBR)

The rotors processed by AFM are normally made of Inconel 718 or Ti-6Al-4V alloys no information is currently available to calculate the abrasion constants for that material/media combination. This means that all of the results on this section serve as a qualitative indication of the abrasion but no quantitative results can be obtained. Furthermore, the post AFM geometry is measured on a point-by-point basis with no actual digital profiles available to enable a comparison similar to what is shown in Figure 3, even if the profiles where routinely captured by the manufacturer, obtaining the information for academic research could prove very difficult due to confidentiality policy.

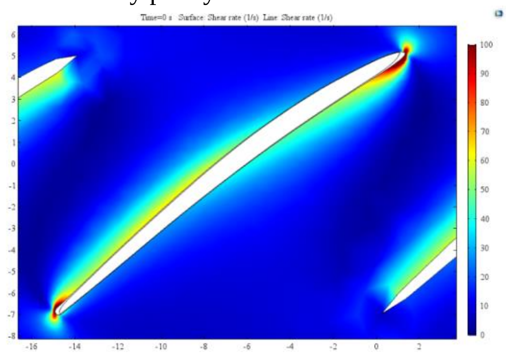

Figure 3 Simulated shear rate around the IBR profile (Section View)

It may be seen in Figure 4 that the predicted shear rate around the IBR profile suggests that material removal will not be uniform across along the profile, and the location of the points with higher abrasion corresponds to the most repeated AFM principle: abrasion occurs at the point where media enters the point of higher restriction, with almost no abrasion present in the leading side of the low pressure face (top) and the trailing side of the high pressure face (bottom).

The simulation suggests that the leading edge will change shape due to the non-uniform flow around it, the profile at 2 different simulation times is shown in **错误!未找到引用源。** the lower part is subjected to higher abrasion due to the restriction created with the adjacent blade, the flow bending around the front of the profile causes a rather high chord length reduction when compared to the uniform material removal observed in the rest of the profile.

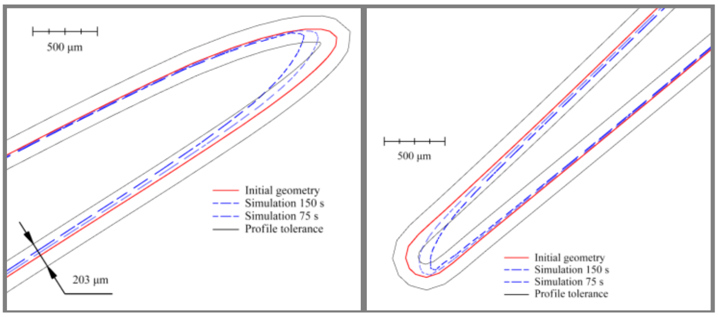

Figure 4 Simulated leading edge and trailing edge profile

The trailing edge simulation shows similar behaviour, in this case the high abrasion area is swapped to the low pressure (top) side of the blade, again this coincides with the restriction created with the other adjacent blade, again the total chord length will be affected, the total reduction on the chord length is 0.34 mm at 150 s and 0.18 mm at 75 s, for reference the maximum IBR reduction aimed for the manufacturer is around 0.152 mm, so the simulation for 75 s should be fairly similar to what the end product looks like, the time taken to achieve this state will likely be much higher, due to the harder workpiece material.

6 Conclusion

Experimental trials were conducted in Extrude Hone Ltd according to a 2^4 full factorial experiment, the results shine some light into the relative importance of the different input parameters involved in AFM.

From the analysis of experimental trails, Volume (V) and Media (M) consistently created the largest difference in system response, with volume being exceptionally easy to modify, it should be the go-to parameter for tuning a process. Media is much harder to modify as companies that use AFM for IBR processes will likely require prohibitively large batches for testing before switching media.

On the other hand, changes in Flow Rate (Q) produced the smallest responses, but is nevertheless important due to its relationship with processing time (i.e. productivity) and heat generation.

The Age (A) factor used was also important when determining the response of the system but additional experiments are needed to be able to conclude on the shape of the response. The fact that media age is such an industrially important factor but failed to achieve statistical significant responses in some of the experiments suggests that the ageing process used was not long or aggressive enough.

Better control of the initial workpiece roughness is required when performing experiments that look at the surface roughness response of AFM, it is very difficult to discern actual effects from noise incoming from a non-constant initial roughness on top of the stylus' measurement noise. Material removal is not as heavily affected because the initial coupon thickness can be consistently measured and subtracted from the final value, there is no evidence to indicate that the initial coupon thickness would have changed the material removed significantly.

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