Journal of
Mechanical
Science and
Technology

Journal of Mechanical Science and Technology 21 (2007) 1593~1598

Study of the rheological properties and the finishing behavior of abrasive gels in abrasive flow machining

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(Manuscript Received May 31, 2007; Revised August 30, 2007; Accepted September 30, 2007)

Abstract

Abrasive flow machining (AFM) is an effective method to finish the smooth surface in the complex holes. Abrasive media are key elements which dominate the polished results in AFM. But it is hard to develop the machining model of these abrasive gels because of its complicated mechanism. In this research, a non-Newtonian flow is used to set up the abrasive mechanism of the abrasive media in AFM. Power law is a main equation of the non-Newtonian flow to describe the motion of the abrasive media. Viscosities vs. shear rates of different abrasive gels are used to establish the power law in CFD-ACE$^+$ software first. And the working parameters of AFM were applied as input to study the properties of the abrasive gels in AFM. Finally, the relationships between the simulations and the experiments were found. And the abrasive mechanism of the abrasive gels was set up in AFM. The simulated results show that the abrasive gel with high viscosity can entirely deform in the complex hole than the abrasive gel with low viscosity. And the abrasive gel with high viscosity generates a larger shear force than the abrasive gel with low viscosity in the same area. Moreover, the strain rate is seriously changed when the abrasive gel cross over the narrow cross-section of the complex hole. It also means that abrasive gel will produce large finish force in that area. And these results indeed consist with the experiments in AFM.

Keywords: Rheological property; Abrasive gel; Abrasive flow machining

1. Introduction

Polishing is an effect method to improve the accuracy and the roughness of the workpiece in the high precision machining. Many methods have been proposed to enhance the surface roughness during the polished machining [1-2]. But they either cost long time to work or limit the machined shape. AFM is an effective method to deburr, polish and remove the recast layers by wire electrical discharge machining (WEDM) [3-5]. The surface precision can be controlled by changing the AFM parameters (such as number of cycles, concentration of the abrasive, abrasive meshes size and medium flow speed) when the complex hole is polished [5-6]. The material removal and surface roughness of AFM are significantly affected by the medium viscosity and extrusion pressure [5, 7]. The rheological properties of abrasive media have also been studied by some researchers [8-9]. The experiments show that the viscosity of the medium is seriously influenced by the temperature. The medium viscosity is drastically reduced by even a small increase in temperature. The results also show that the medium viscosity increases with the abrasive concentration and decreases with the abrasive size. Silicone rubber (a kind of polymer gel) with high viscosity and low flow rate is a good abrasive medium which can easily polish the WEDM surface to a smooth finish [10]. Furthermore, a new finishing method by applying a magnetic field around the workpiece has been proposed to enhance the

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material removal rate and the surface roughness in AFM [11-12].

Theoretical models and numerical methods are developed to predict the polishing result of the abrasive medium during AFM [13-16]. The material removal rate and surface roughness are estimated using the finite element method [13, 14]. The active grain density on the medium surface is also determined by stochastic simulation [15]. This method can be easily extended to simulate the surface generation in AFM. Furthermore, the material deformation produced by the abrasive is developed to predict the force models of AFM [16]. And the scratching experiments are used to study the material removal mechanism in the abrasive process. However, the abrasive mechanism in AFM will have clear description if the flow situation of abrasive media can be found. But there are no researches to study the flow of the abrasive media in the polishing process. Therefore, a non-Newtonian flow is used to simulate the motion of the abrasive media, and to analyze the polished effect of the different abrasive gels in AFM.

2. Method

Since the abrasive geometries are not uniform, the flow path (or motion) of each abrasive in the media can not predict exactly in AFM. So it is hard to describe the polishing mechanism of AFM by the micro viewpoint. Polymer gels are always used as the base material of the abrasive media in AFM. Since these gels are semi-solid, they can easily deform and mix uniformly with all kinds of abrasive. And they must have high viscosity and large deformation ability to produce good polished effect in the machining. Therefore, the behavior of abrasive media in AFM can look like as non-Newtonian flows in the macro viewpoint. The mathematical and finite volume model will be developed by CFD-ACE$^+$ in the following.

2.1 Power law

Abrasive media are the key elements that will control the polishing results in AFM. So the abrasive behavior can be predicted if the motion of the abrasive media in AFM can be found exactly. The media are the polymer gels mixed with the abrasives and have low flow property in usual. The viscosities of these media dominate the flow property that will control the abrasive effects in AFM. But the viscosity will change when the working temperature is different in AFM [6, 8]. So the relationship between the viscosity and the temperature must be set up in the mathematical model. Power law of the non-Newtonian flow shows the relation of the viscosity, the shear rate and the temperature in CFD-ACE$^+$ software. Power law can clearly describe the effect of the temperature on the viscosity in AFM. Equation of the power law is presented as following:

$$\mu = K\mu_0 e^{(a_1 T - a_2 T^2)} \dot{\gamma}^c \quad (1)$$

where $$c = n - 1 + a_3 \ln(\dot{\gamma}) + a_4 T \quad (2)$$

and

μ = viscosity of abrasive media

μ_0 = Zero shear rate viscosity

$\dot{\gamma}$ = Local calculated shear rate

n = Power law index

T = Local calculated temperature

K, a_1, a_2, a_3, a_4 = fluid properties of abrasive media.

2.2 Abrasive media

The rheological properties of the abrasive media play an important role to find the good surface roughness in the complex holes. In this study, a pure silicone rubber (P-Silicone) and silicone rubber with additives (A-Silicone) are chosen as the media. In general, P-Silicone is used to make the plastic mold in metal casting with low melting temperature. And A-Silicone is much like the material of the silly putty which is used for the toy clay. These silicone gels have low flow property and do not stick on the workpiece 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 %.

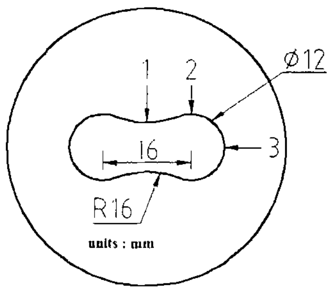
2.3 Finishing geometry

Since abrasive media can change their shapes easily by the external force. These media are very suitable for polishing the complex shape in AFM. So a chain hole of the punched mold (Fig. 1) is chosen as the finishing geometry in AFM. The thickness of the chain hole is 22 mm. This shape is cut in the SKD-11 steel by WEDM. Fig. 1 shows the hole dimension and mesh diagram of the abrasive media. The mesh diagram [Fig. 1(b)] can simulate the flow behavior in

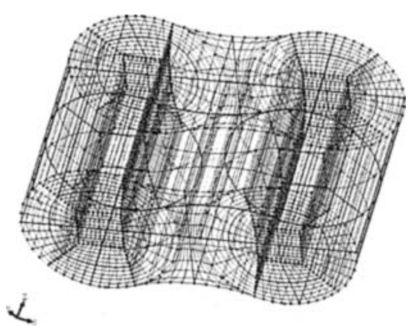
AFM when the media are pushed through the chain hole. Due to the shear force will become large when abrasive medium is gone through the narrow area [6]. So the surface roughness of the chain hole will not be uniformed because of the irregular flow path in AFM. For observing the effect of the abrasive media acting on the surface, three positions of this hole will be chosen to measure the roughness after AFM, or to simulate the shear forces when the abrasive medium is pushed through these positions. These positions (1, 2 and 3) are indicated in Fig. 1(a).

2.4 Procedure

There are two procedures in this study. First process uses the non-Newtonian flow to simulate the abrasive medium going through the chain hole by CFD-ACE^{+}. In this case, different abrasive media are utilized to see the flow results in the chain holes. The extrusion pressure is 3.45 Mpa and back pressure of hydraulic cylinder is 2.07 Mpa in AFM. Working temperature of abrasive medium is set at 27°C. Two step functions of velocity are set to simulate the flow



(a) The geometry of the complex hole (1,2,3 indicate the measured roughness or the shear force simulated positions)



(b) Mesh diagram of the chain hole

Fig. 1. Geometry and mesh diagram of the complex hole.

of A-Silicone and P-Silicone in the up and down motion. Equations of the velocity are presented as following:

$$V = -0.003 \times STEP(10-T) + 0.003 \times STEP(T-11) \quad (3)$$

$$V = -0.058 \times STEP(0.5-T) + 0.058 \times STEP(0.6-T) \quad (4)$$

where Eq. (3) is A-Silicone velocity and Eq. (4) is P-Silicone velocity in the simulation and T is the time step. The coefficients 0.003 (m/sec) and 0.058 (m/sec) in front of equations are the average velocities of the abrasive media in AFM. The abrasive medium moves 30 mm in 10 time steps of half cycle. Since P-Silicone has the high velocity in AFM, so each time step is set at 0.05 second. And A-Silicone moves slowly in polishing process, therefore each time step is set at 1 second.

3. Results and discussion

The main purpose of this research is to develop the numerical method which can predict the flow of abrasive media in the complex hole. In order to find the relationship between the motion of the abrasive medium and the roughness on the hole surface in AFM. Velocities, pressures, strain rates and shear forces of the abrasive medium will be found in this case. And these results will be used to explain the roughness in different position on the chain hole.

3.1 Coefficients of power law

For obtaining the coefficients of power law, some rheological property of the abrasive media must be found. In this study, rheological equipment is utilized to find the effects of the shear rates on the media viscosities. Fig. 2 shows the relationship between the viscosities and the shear rates of these media.

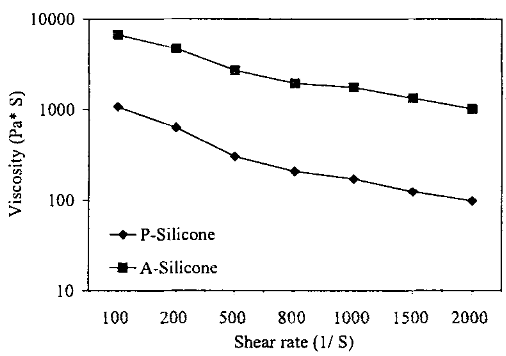
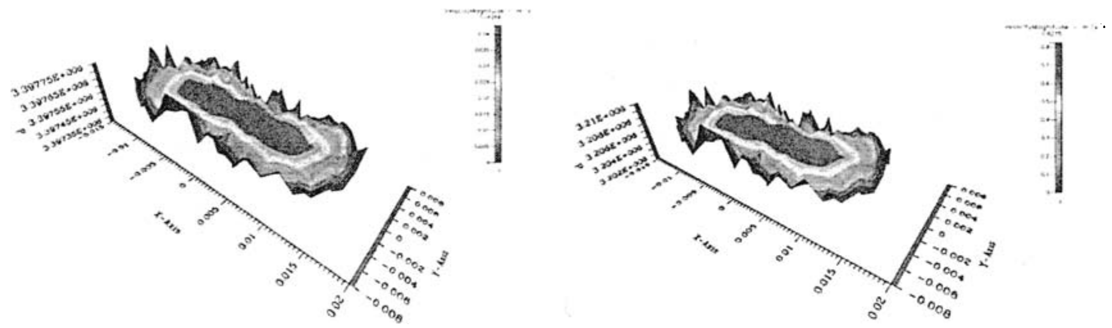


Fig. 2. The effects of shear rates on the viscosity.

Table 1. The coefficients of the power law.

Matrix	K	μ_0	a_1	a_2	a_3	a_4	n
A-Silicone	1	50000	0.02599	0.0004	-0.12307	0.07155	1
P-Silicone	1	9000	0.02748	0.0005	-0.10683	0.05490	1



(a) Velocities and pressures of A-Silicone (b) Velocities and pressures of P-silicone

Fig. 3. Simulation results of velocities and pressures.

Working temperature 27 °C is closed to the polishing temperature in AFM. The result shows that the A-Silicone has higher viscosity than the P-Silicone in shear rate test. And the viscosities are decreased with increasing the shear rates. The coefficients of the Eqs. (1) and (2) can be calculated from the data of Fig. 2. These coefficients are showed in the table 1.

3.2 Simulation results

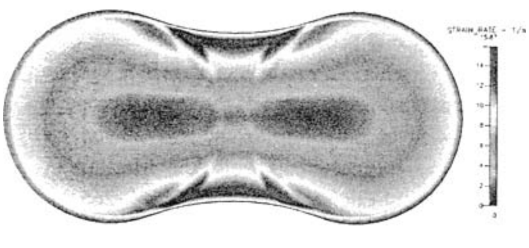
The motions of the abrasive media are discussed here to see how these media affect the polished effects in AFM. Simulated results of three positions (Fig. 2) are the half thickness of the chain hole.

3.2.1 Velocities and pressures

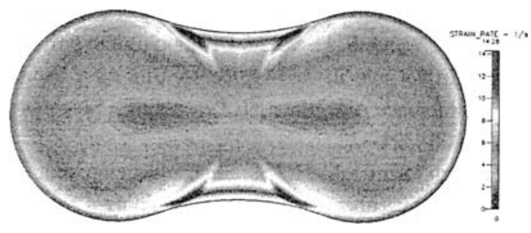
Velocities and pressures of different abrasive media are shown in Fig. 3. The velocities of A-Silicone and P-Silicone are changed a lot from the center to the wall of the chain hole. P-Silicone has higher velocity (0.82 m/s) than A-Silicone (0.043 m/s) in the simulations. The reason is that A-Silicone has higher viscosity than P-Silicone (Fig. 2). High viscosity media will hinder it to flow in the up and down motion. However, energy loss of these media near the wall is transferred to abrasive forces or heat in the polishing process. Pressures near the wall are larger than the other place of the chain hole because of the back pressure in the hydraulic cylinder. A-Silicone can produce bigger pressures than P-Silicone after the motion of the abrasive media.

3.2.2 Strain rates and shear forces

Fig. 4 indicates the strain rates of the abrasive media in the flow motion. The results present that no matter what kind of abrasive media are used, the strain rates are large between the narrow cross section. But the strain rates of A-Silicone have the larger variance than P-Silicone. It means the abrasive media can produce huge deformations in AFM. These deformations will generate large abrasive forces in the narrow cross section of the chain hole. Because the step function of velocity is used in AFM, the shear forces are almost the same with positive and negative sign. Therefore, Z axis shear forces are shown to be only positive values in the half cycle. These shear forces in different positions of the chain hole are shown in Fig. 5 and Fig. 6. These figures reveal that A-Silicone can make the larger shear forces (magnitude order: 10^{-2} N) in the simulation, but P-Silicone only creates the smaller shear force (magnitude order: 10^{-4} N). These results indicate that A-Silicone has a good polished effect in AFM. Moreover, point 1 in the narrow cross section will be polished by large shear force in both abrasive media. But there is obvious difference between position 1 and other positions when A-Silicone is used as abrasive medium. So the polished effect will be quite different between position 1 and other positions in A-Silicone.



(a) Strain rates of A-silicone



(b) Strain rates of P-silicone

Fig. 4. Simulation results of strain rate.

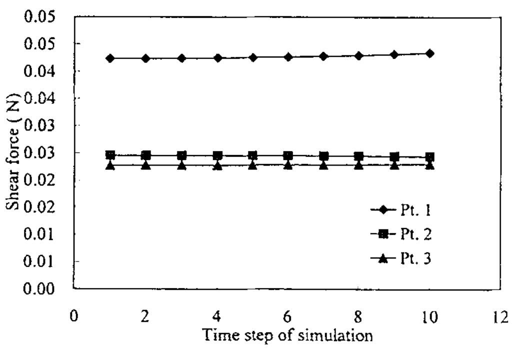


Fig. 5. The effect of time step of simulation on shear force (A-Silicone).

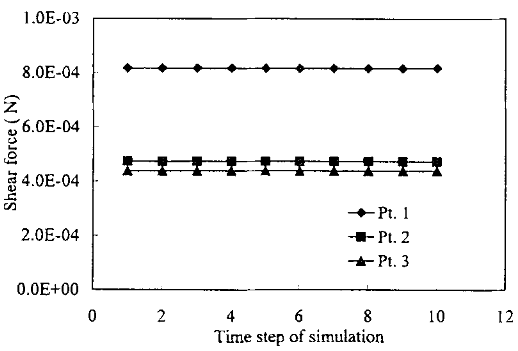


Fig. 6. The effect of time step of simulation on shear force (P-Silicone).

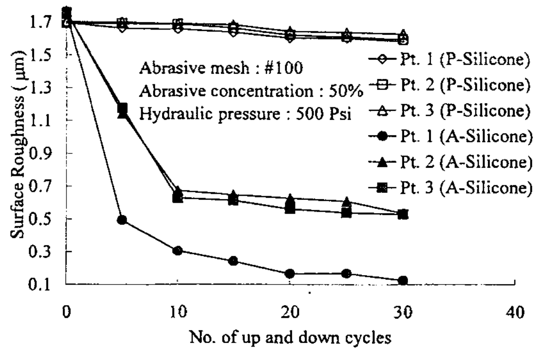


Fig. 7. The effect of No. of up and down cycles on the surface roughness.

3.3 Experiments

For verifying the accuracy of simulations, surface roughness of the complex holes in AFM is taken as an index to assess the simulated results. Fig. 7 presents the effects of the number of up and down cycles on the surface roughness. It is observed that no matter what kinds of abrasive media are used, an increase in the cycles results in an associated decrease in the overall surface roughness. But the polished effect of P-Silicone is not obviously in AFM. The reason is the shear forces made by P-Silicone are very small (Fig. 6), so the surface roughness cannot have clear change after machining. Fig. 7 also shows that the abrasive media with high viscosities (A-Silicone) can find good polished results in AFM. However, the roughness is not uniform in the whole surface because the width of the cross section is not uniform. Narrow cross section (position 1) has better roughness than the other points after AFM. Positions 2 and 3 have almost the same roughness. The surface roughness is very similar to the Z-axis shear force as shown in Fig. 5. It means surface roughness can be predicted by Z-axis shear force in the simulated result.

4. Conclusions

In this study, non-Newtonian flow is used to simulate the motion of the abrasive media in AFM. The flow model of abrasive media can be set up by the power law, if the rheological properties of the media are found. Step functions of velocity are set to simulate the flow of A-Silicone and P-Silicone in the up and down motions. The velocity of A-Silicone is about 1/20 of P-Silicone in the motion. The strain rates of A-Silicone have the larger variance than P-Silicone. Therefore, A-Silicone can produce larger shear forces than P-Silicone in the polishing area.

The experiments show that the polished effect is not obvious when the abrasive media with low viscosity is used to finish the complex hole. Surface roughness is quickly reduced to a low level when A-Silicone is taken as the abrasive media. But the roughness is not uniform in the whole surface because the width of the cross section is not the same. These effects are very consistent with the simulated results in this study.

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