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Uniform surface polished method of complex holes in abrasive flow machining

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Abstract: Abrasive flow machining(AFM) is an effective method that can remove the recasting layer produced by wire electrical discharge machining(WEDM). However, the surface roughness will not be easily uniform when a complex hole is polished by this method. CFD numerical method is aided to design good passageways to find the smooth roughness on the complex hole in AFM. Through the present method, it reveals that the shear forces in the polishing process and the flow properties of the medium in AFM play the roles in controlling the roughness on the entire surface. A power law model was firstly set up by utilizing the effect of shear rates on the medium viscosities, and the coefficients of the power law would be found by solving the algebraic equation from the relations between the shear rates and viscosities. Then the velocities, strain rates and shear forces of the medium acting on the surface would be obtained in the constant pressure by CFD software. Finally, the optimal mold core put into the complex hole could be designed after these simulations. The results show that the shear forces and strain rates change sharply on the entire surface if no mold core is inserted into the complex hole, whereas they hardly make any difference when the core shape is similar to the complex hole. Three experimental types of mold core were used. The results demonstrate that the similar shape of the mold core inserted into the hole could find the uniform roughness on the surface.

Key words: abrasive flow machining; passageway; uniform roughness

1 Introduction

The complex holes, used in the punching or injection molds, are easily finished by WEDM process. However, the machined surfaces are full of micro cracks and craters due to heat erosion and these defects lead to bad quality of the products in the punching or the injection process. Although some methods have been proposed to remove the defects[1−4], they either take long time to work or limit the machined shape. Abrasive flow machining(AFM) is an effective method for the purpose of deburring, polishing and removing the recasted layers[5−8]. Machining parameters of AFM and the rheological properties of the abrasive medium are two key factors that will affect the efficiency in the polished process. The surface precision can be controlled by changing the AFM parameters (such as number of cycles, concentration of the abrasive, abrasive mesh size and medium flow speed) when the complex hole is polished[7−9]. Moreover, the medium viscosity and extrusion pressure will significantly affect the material removal and the surface roughness of AFM[8, 10]. The rheological properties of the abrasive media have also been studied by some reports[11−13], the experiments showed that not only the temperature could seriously influence the viscosity of the medium but also a small increase in the temperature would drastically reduce the medium viscosity in AFM. The results also present that the medium viscosity increases with the abrasive concentration but decreases with the abrasive size. Silicone rubber (a kind of polymer gel) with high viscosity and low flow rate is a good abrasive medium that can easily polish the WEDM surface to a smooth finish[14]. Furthermore, a new finishing method by applying a magnetic field around the workpiece was proposed to enhance the material removal rate and the surface roughness in AFM[15−16].

Theoretical models and numerical methods were developed to predict the polishing behavior of the abrasive medium during AFM[17−23]. The material removal rate and surface roughness were estimated using the finite element method[18, 21]. Stochastic simulation was used to determine the active grain density on the

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medium surface as well[22]. This method could easily extend to simulate the surface generation in AFM. Furthermore, the material deformation produced by the abrasive was developed to predict the force models of AFM[23]. The scratching experiments were used to study the material removal mechanism in the abrasive process. However, it is not easy to get uniform roughness in complex surface during AFM, because the shear forces acting on the complex surface will not be the same if the flow path is not regular[8]. In addition, there were no researches to develop a method to create the uniform surface roughness during AFM. So a non-Newtonian flow model was used to simulate the motion of the abrasive medium in AFM. In this simulation, excellent passageway could be designed when the uniform shear forces were found on the machined surface. These kinds of passageway could be applied to identify the uniform roughness of the complex hole in AFM.

2 Methods

2.1 Power law

Since the abrasive geometries are not uniform, the flow path (or motion) of each abrasive in the polymer gel cannot be predicted exactly in AFM. Therefore, it is difficult to describe the abrasive mechanism of AFM from the micro viewpoint. Polymer gel is always used as the base material of the abrasive medium in AFM. Since the gel is semi-solid, so can easily deform and mix uniformly with all kinds of abrasive, leading to the ability of having high viscosity and large deformation to produce good polished effect in AFM. Hence, the behavior of the abrasive medium in AFM can be looked upon as a non-Newtonian flow from the macro viewpoint. It then becomes simple and effective to describe the abrasive mechanism in AFM when such flow is used as the working model. Because the medium viscosities are drastically reduced when the temperature has a small increase in AFM, the relationship between the viscosities and the temperatures should be taken into consideration in this model. In this study, power law of the non-Newtonian flow was adopted to reveal the relations of the viscosities, the shear rates and the temperatures in CFD-ACE$^+$, which is appropriate to describe the motion of the abrasive medium in AFM and is presented as follows:

$$\mu = K\mu_0 \exp(a_1\theta - a_2\theta^2)\dot{\gamma}^c \tag{1}$$

$$c = n - 1 + a_3 \ln(\dot{\gamma}) + a_4\theta \tag{2}$$

where μ is the viscosity of the abrasive medium, Pa·s; μ_0 is the viscosity with zero shear rate, Pa·s; $\dot{\gamma}$ is the shear rate of the abrasive medium, s^{-1}; θ is the working temperature, ℃; n is the power law index; K, a_1, a_2, a_3, a_4 are coefficients of the abrasive medium in power law.

2.2 Abrasive medium

For the purpose of obtaining the coefficients of power law, some rheological properties of the abrasive medium should be found. Bouncing putty, supplied by Charlie-kao Toy Company[24], was used as the matrix of the abrasive medium in this research. This material is a kind of silicone gel with low flow characteristic and it would not stick on the workpiece after AFM. Silicon carbon (SiC) was chosen as the abrasive to mix in the silicone gel uniformly. In this study, rheological equipment was utilized to find the effects of the shear rates on the medium viscosities. Fig.1 shows the relationship between the viscosity and shear rate of this medium. The result displays that this abrasive medium has a high viscous effect in the shear rate test, and the coefficients revealed in Table 1 of the Eqs.(1) and (2) could be calculated simultaneously from the data in Fig.1.

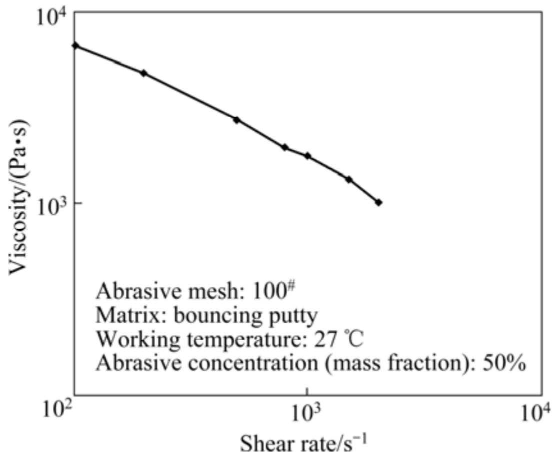

Fig.1 Effects of shear rate on viscosity of abrasive medium

2.3 Complex hole

In order to get uniform roughness on the complex surface, the chain hole of the punched mold (see Fig.2(a)) was chosen as the finishing geometry in AFM. The thickness of the chain hole was 22 mm. This shape was cut in the SKD-11 steel by WEDM. Fig.2 shows the dimension of the chain hole and mesh diagram of the abrasive medium. The mesh diagram could simulate the flow behavior during AFM when the medium was pushed

Table 1 Coefficients of power law for bouncing putty

K	μ_0/(kPa·s)	a_1	a_2/℃$^{-1}$	a_3/s	a_4/℃$^{-1}$	n	θ/℃
1	50	0.025 99	0.000 4	−0.123 07	0.071 55	1	27

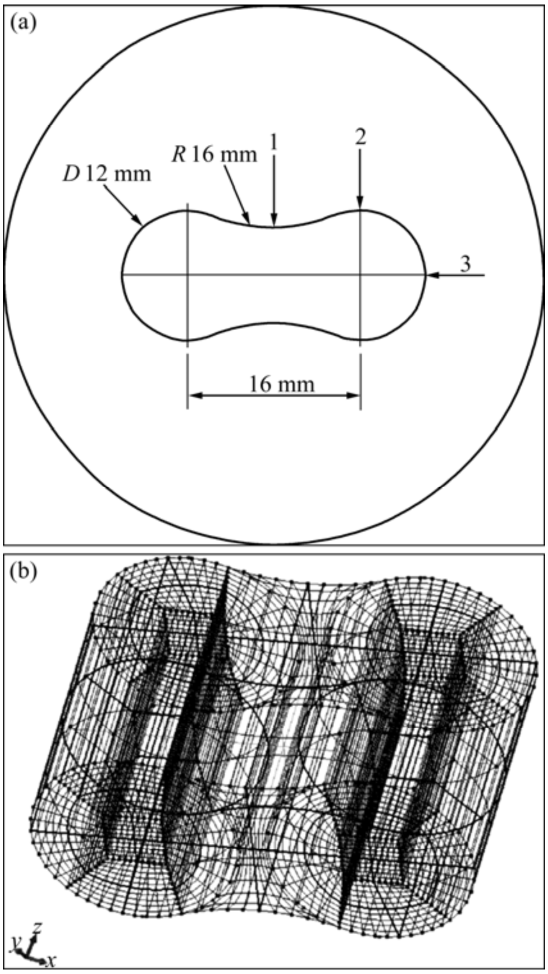

Fig.2 Geometry and mesh diagram of complex hole: (a) Geometry of complex hole (1, 2, 3 indicate simulate positions to measured roughness or shear force); (b) Mesh diagram of chain hole

through the chain hole and the shear force would become large when the abrasive medium passed through the narrow area[8]. Hence, the surface roughness of the chain hole would not be uniform because of the irregular flow path in AFM. With an eye to observing the surface roughness of the complex hole, three positions of this hole surface would be chosen to measure the roughness after AFM or to simulate the shear forces when the abrasive medium was pushed through these positions. These positions (1, 2 and 3) are indicated in Fig.2(a).

2.4 Mold core of chain hole

As to finding the uniform roughness of the chain hole in AFM, two types of mold core were designed to make the appropriate passageways. Because the shear force through the narrow area is greater than that through the wide area, the main purpose in this study was to design an equal or a regular flow path to find the same shear forces overall the machined surface. In Fig.3(a), two cylinders are used as mold cores putting into the center of the two circles. The distance between the cylinder and the circle is 3 mm. In Fig.3(b), mold core was designed as the chain shape inserted in the middle of the chain hole. The distance between the core and the chain hole is also 3 mm.

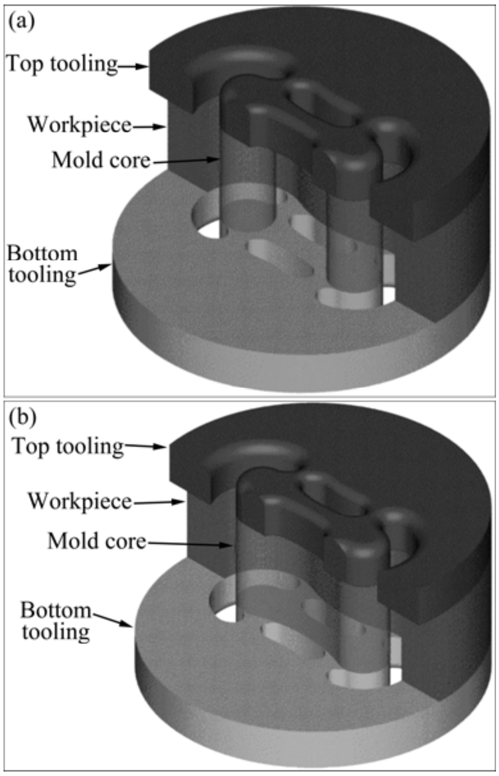

Fig.3 Two types of mold core in chain holes: (a) Mold core with two cylinders; (b) Mold core with chain shape

2.5 Procedure

There were two procedures in this study. Firstly, the non-Newtonian flow to simulate the abrasive medium going through the chain hole by CFD-ACE$^+$ was employed in this case, where different types of mold core putting in the chain hole were utilized to display the flow behavior of the abrasive medium in this chain holes. The extrusion pressure as the initial condition and working temperature of abrasive medium were set at 2.76 MPa (400 psi) and 27 ℃, respectively. A step function of velocity set to simulate the flow of abrasive medium in up and down motion is as follows:

$$v = 0.003\times\mathrm{STEP}(10-t)+0.003\times\mathrm{STEP}(t-11) \qquad (3)$$

where v is the working velocity of the abrasive medium, m/s; t is the time step of the simulation; coefficient 0.003 m/s is the average velocity of abrasive medium. The abrasive medium moved 30 mm in 10 time steps of half cycle. In this study, the velocities, strain rates and shear forces are three main characteristics to show whether the motion of the abrasive medium was uniform or not in the chain hole. The other process was to find the surface roughness during AFM when different mold core was inserted into the chain hole. In this case, the mold would be set up to fit different mold cores to find the uniform roughness in the experiments.

3 Results and discussion

The main purpose of this research is to find the appropriate passageway, which could make uniform roughness in the complex surface. Hence, a numerical method was aided to simulate the motion of the abrasive medium in the chain hole and to find the relationships between the flow properties of the abrasive medium and the polished roughness in AFM. In this case, the velocities, strain rates and shear forces of the abrasive medium would be obtained after the simulated results, then finding the roughness in the different positions on the chain hole when mold core or no mold core was put into the hole in the experiments. Working area of the abrasive medium in AFM and its mesh diagram to simulate the motion of the abrasive medium are shown in Figs.4(a) and 4 (b), respectively. In Fig.4(b), up and down cylinders are the medium barrels, and the passageways and workpiece are set in the middle section.

3.1 Chain hole without mold core

The motion of the abrasive medium was firstly discussed in this section in the absence of the mold core from the chain hole. The cross section of the half thickness of the chain hole was to demonstrate the simulated results of the three positions. From the distributions of the velocities and the strain rates of the abrasive medium as shown in Fig.5, the velocities change sharply from the center to the wall of the chain hole as displayed in Fig.5(a). The main reason is that high viscosity of the abrasive medium would hinder it to flow in the up and down motion, resulting in the velocities loss of this medium near the wall transferred to pressures in the polishing process. Therefore, these pressures would polish the surface with the up and down motion. However, the abrasive effect is different on the whole surface during this process. Fig.5(b) indicates the strain rates of the abrasive medium in the flow motion, which shows the deformable value per unit time of the abrasive medium in the polished area. The strain rates are large in the narrow cross section, larger abrasive forces in these areas would happen. Because the step function of the velocity was adopted in the simulation, the shear forces, at each time step, are almost the same but with positive and negative sign in the same position. Therefore, the shear forces in the Z direction show only positive values in the half cycle. These shear forces in the different positions of the chain hole are shown in Fig.6. It is revealed that the indicated position (position 1) in

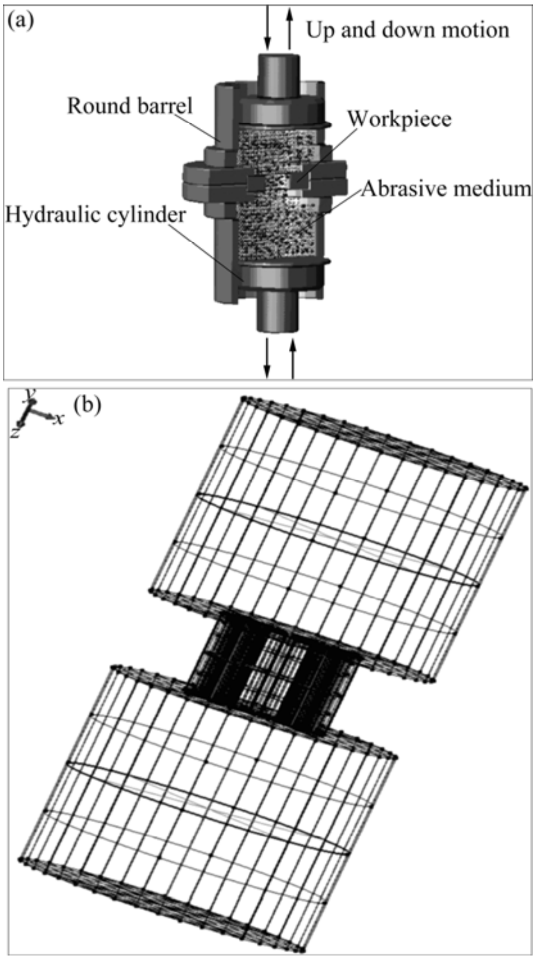

Fig.4 Working area and working mesh diagram of abrasive medium: (a) Working area of abrasive medium in AFM; (b) Mesh diagram (from Fig.4(a)) used to simulate motion of abrasive medium

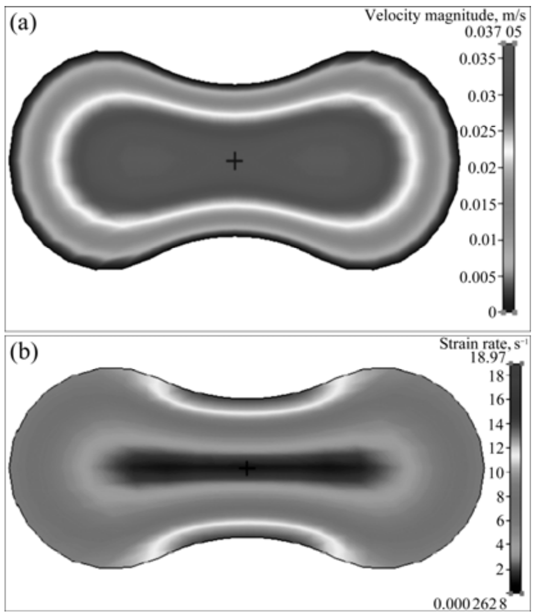

Fig.5 Velocities and strain rates of abrasive medium with no mold core in chain hole: (a) Velocities of abrasive medium in chain hole; (b) Strain rates of abrasive medium in chain hole

the narrow cross section would be polished by large shear force while small shear forces exerted at the other positions (positions 2 and 3) are almost the same. Large and small shear forces are obviously different in this situation, causing different polished effects when the complex hole is used as finished geometry. Fig.7 shows the effects of up and down cycles on the surface roughness in the different positions. This experiment displays that the surface roughness decreases when the up and down cycle increases. Moreover, position 1 has better roughness than the other positions after AFM. Positions 2 and 3 have almost the same roughness by virtue of the fact that the shear forces in positions 2 and 3 are so small (see in Fig.6), the surface roughness of these positions would not be close to the surface roughness in position 1. However, this roughness is very similar to the *Z*-axis shear forces. This means that the surface roughness could be predicted by *Z*-axis shear force in the simulated results.

3.2 Chain hole with two cylinders

Contrary to the case in the above subsection, two cylinders are used here as mold core put in the center of the two circles, in which case Fig.8 presents the velocities and the strain rates of the abrasive medium when chain hole was inserted two cylinders as the mold core. Medium velocities shown in Fig.8(a) between the cylinders and wall are uniform whereas the velocities in the middle of the chain hole are still large. The result reveals that the abrasive medium passing through the middle of the chain hole was more than through the other areas. Fig.8(b) displays the strain rate of the abrasive medium in the flow motion. Similarly, it also shows that the strain rates are large between the middle sections because of the large amount of the abrasive medium passing through these sections. Therefore, these areas have bigger abrasive forces than the other sections.

Fig.9 indicates the shear forces in different positions of the chain hole. All the shear forces become large when two cylinders are used as mold core. Shear forces in position 1 are still larger than those in the positions 2 and 3. Nevertheless, when compared with the values in Fig.6, the shear forces (almost 0.20 N) in position 2 are even larger than the those (about 0.12 N) in position 1 without the mold core, and the shear forces in position 3 (almost 0.10 N) are much closer to the large shear forces in Fig.6.

Fig.10 presents the effects of up and down cycles on the surface roughness in different positions. It is also observed that an increase in the cycles resulted in an associated decrease in the overall surface roughness. Position 1 still has better surface roughness than the other positions in the beginning, but the surface roughness would be very close in these positions when the number of working cycle is over 50 in AFM. The reason is that the shear forces in Fig.9 are larger than the

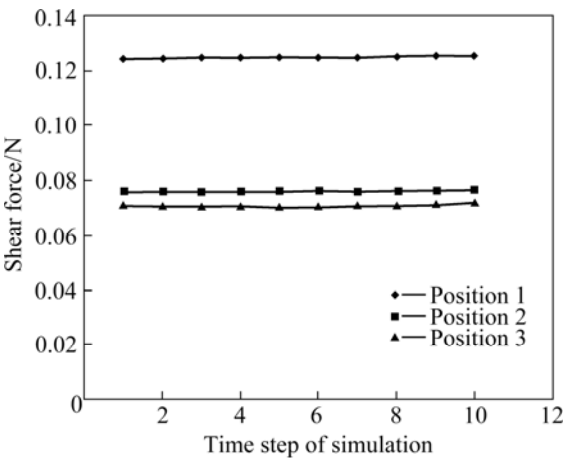

Fig.6 Shear forces in different positions with no mold core in chain hole

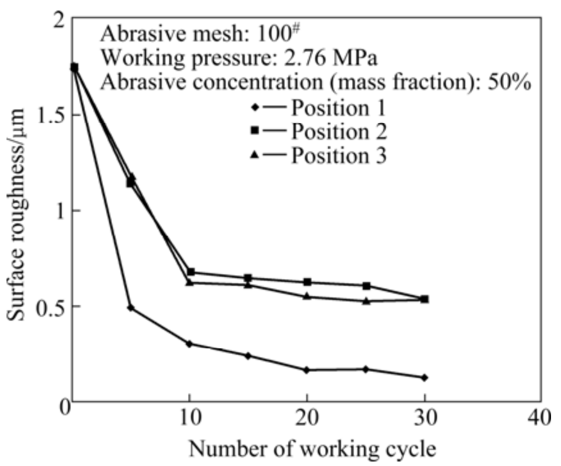

Fig.7 Effects of number of working cycles on surface roughness at three positions

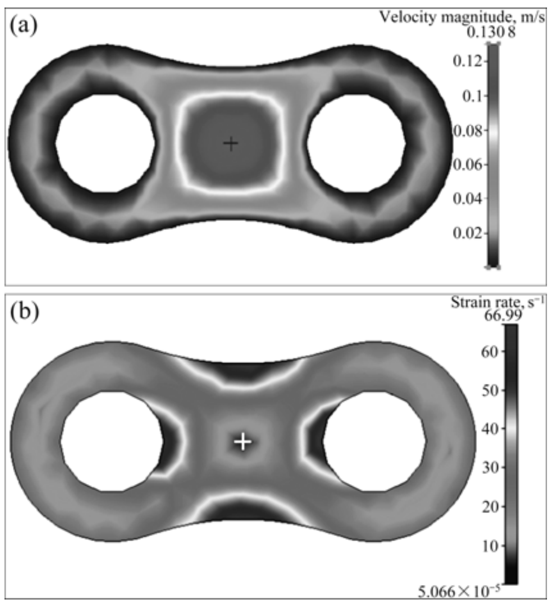

Fig.8 Velocities and strain rates of abrasive medium with two cylinders as mold core: (a) Velocities of abrasive medium in chain hole; (b) Strain rates of abrasive medium in chain hole

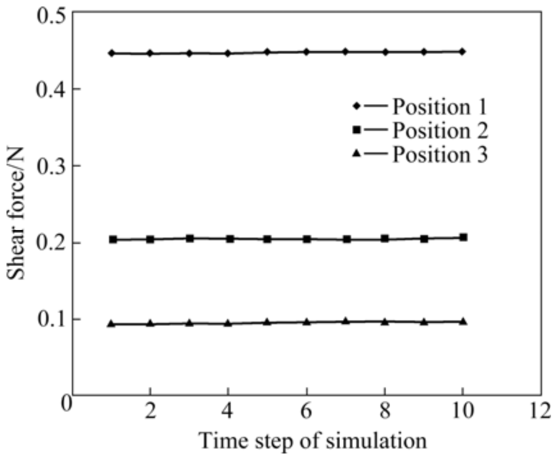

Fig.9 Shear forces in three positions with two cylinders as mold core

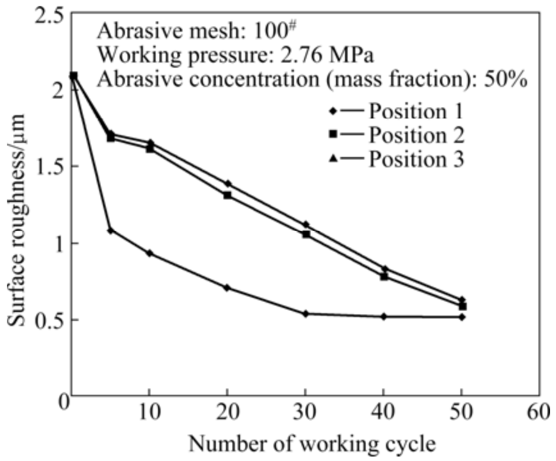

Fig.10 Effects of number of working cycles on surface roughness with two cylinders as mold core

shear forces in Fig.6, especially when the shear forces in position 2 and 3 had obviously increased in this kind of mold core. Therefore, the surface roughness in the positions 2 and 3 would be close to the surface roughness in position 1 after 50 working cycles. This result presents that the chain hole with two cylinders as mold core could produce more uniform roughness than the chain hole without mold core. However, it still needs lots of time to find the uniform roughness in the complex hole.

3.3 Chain hole with chain shape core

The above results indicate that inserting two cylinders into the chain hole would obtain larger shear forces, and the surface roughness would become smoother after AFM. Therefore, a core with chain shape put into the center of the chain hole would be adopted in this study. The velocity and strain rate of the abrasive medium is presented in Fig.11 and the medium velocities and the shear rates change uniformly in the whole chain loop. The result revealed that equal distance between the hole and core would cause uniform flow in the simulation. This kind of abrasive flow would make uniform shear forces in the overall surface. Fig.12 indicates the shear forces in the three positions of the chain hole. These shear forces are very close to each other when the core with chain shape is used. Moreover, these shear forces (position 1 are almost 0.76 N, position 2 are almost 0.72 N and position 3 are almost 0.69 N) are larger than those (about 0.45 N) in position 1 with two cylinder as mold core. Hence, the uniform and large abrasive forces would be found if the mold core has similar shape to the complex hole. As to the experiment, the effect of working cycles on the surface roughness in the three positions is presented in Fig.13. The results show that an increase of working cycles would reduce the surface roughness of the chain hole and the surface roughness of the three positions are almost the same in all working cycles. It reveals that the equal distance between the hole and core would be capable of producing the uniform roughness in the complex hole.

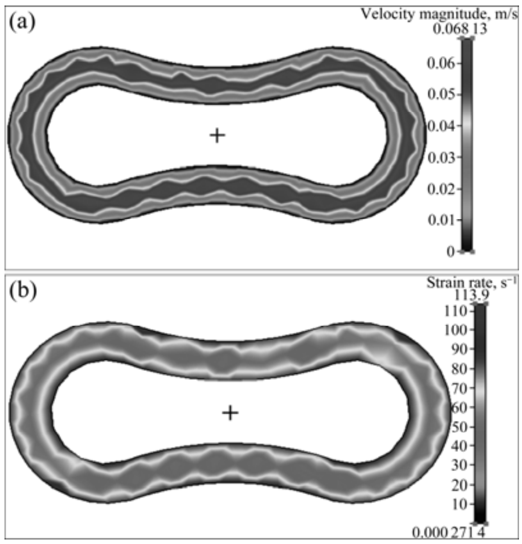

Fig.11 Velocities and strain rates of abrasive medium with chain shape as mold core: (a) Velocities of abrasive medium in chain hole; (b) Strain rates of abrasive medium in chain hole

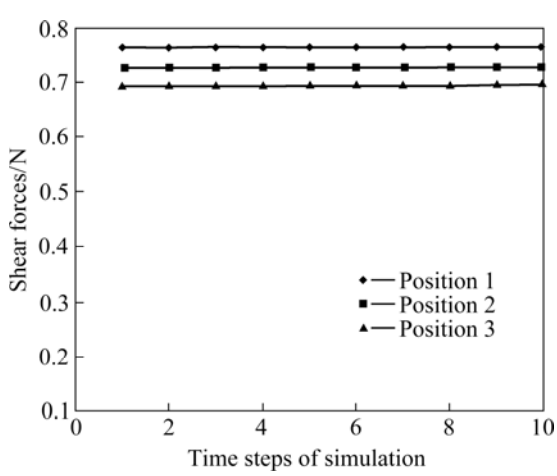

Fig.12 Shear forces in three positions with chain shape as mold core

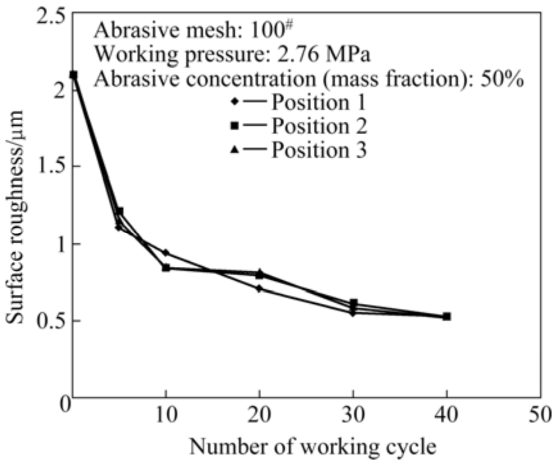

Fig.13 Effects of number of working cycles on surface roughness with chain shape as mold core

From both the numerical simulations and the experiments, the above results show that the simulated results could describe the polished effect in AFM. Hence, CFD method could be aided to design the excellent passageway to find the uniform roughness in this polished process.

4 Conclusions

1) The effect of the shear rates on the medium viscosities could be utilized to set up a power law model. This model in the CFD software package would find the velocities, the strain rates and the shear forces of the medium. Therefore, excellent passageway could be obtained when the shear force acting on the surface is uniform.

2) In the case of no mold core in the chain hole, the strain rates and the shear forces (nearly 0.12 N) are larger in position 1 when compared with those in the other two positions. Hence, the corresponding polished effect in position 1 is more obvious than in other positions. However, the shear forces in positions 2 (nearly 0.08 N) and 3 (nearly 0.07 N) are so small that the surface roughness of these positions would not be close to the roughness in position 1. Similarly, the strain rates and the shear forces (closed to 0.45 N) are large as well in position 1 when using two cylinders as mold core. Nevertheless, the shear forces in the position 2 (nearly 0.2 N) and 3 (nearly 0.1 N) are large enough, so the surface roughness in positions 2 and 3 would be close to the surface roughness in position 1 after 50 working cycles. In the third case, the strain rates and shear forces are uniform between the whole chain loop when the mold core with the chain shape is put into the hole. The surface roughness in these positions are much closer to each other with the nearest shear forces (position 1 is almost 0.76 N, position 2 is almost 0.72 N and position 3 is almost 0.69 N) acting on the surface. Therefore, it is more convenient to use the non-Newtonian flow to simulate the motion of the abrasive medium in AFM. The appropriate passageway would be easily designed when the uniform shear force acting on the surface could be found.

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