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A Study of Surface Uniformity for Helical Passageways in Abrasive Flow Machining

***Abstract**. This work develops a mechanism with a helical passageway to perform multiple flowing paths of abrasive media, whose flowing behavior enhances polishing effectiveness by increasing the abrasive surface area and radial shear forces. Numerical results indicate that the design of a four helices passageway performs better in uniform surface roughness than other passageway by utilizing CFD-ACE$^+$ software. Moreover, experimental results show that a helical passageway presents an excellent solution to enhance surface roughness uniformity and roughness improvement rate.*

***Streszczenie.** W artykule rozwinięto mechanizm śrubowej ścieżki z wielokrotnym przepływem medium ściernego której właściwości można polepszać zwiększając ścieralność podłoża i siły radialne. (**Analiza jakości podłoża w śrubowej ścieżce z przepływem materiału ścierającego**)*

Keywords: Abrasive flow machining, a helical passageway, surface roughness uniformity, roughness improvement rate.
Słowa kluczowe: przepływ ścieralny, ścieżka śrubowa.

Introduction

Deburring and surface finishing methods represent a critical and important segment in precision machining. Defects or variations in surface could lead to weak and stressed components, which in turn could cause premature failure of function. Moreover, the parts become the order of nanometers up to a few microns in micro-electro-mechanical system (MEMS), the surface integrity of machined components was very critical to their function and performance.[1] Many approaches of non-traditional processes, such as ultrasonic lapping, electro-chemical polishing, magnetic abrasive finishing and ball burnish machining were being developed to meet industries demands.[2-5] However, above methods may exist disadvantages either increased cost due to prolonged machining or limited the shapes. Therefore, a simple, low-cost and high effective polishing called abrasive flow machining (AFM) is gaining acceptance in a wide range of applications.

The polishing efficiency of AFM had been analyzed using machining parameters and rheological properties of the abrasive medium. Many papers have been published to demonstrate the effectiveness of material removal and surface roughness by modifying some key input parameters of AFM, such as number of machining cycles, size of medium, extrusion pressure, abrasive concentration, viscosity of abrasive medium,……etc.[6-9] Furthermore, some studies had been developed to predict the motion behavior of the abrasive medium during AFM via theoretical models and numerical methods. For example, the material removal rate and surface roughness were estimated by using the finite element method.[10,11] Furthermore, the optimum design of passageway shape in a viscous flow field was also determined by utilizing a program of computational fluid dynamics (CFD).[12]

Although some studies demonstrated the AFM polishing efficiency relative to machining parameters and medium rheological properties, no effective methods were developed to achieve the surface roughness uniformity in the axial direction. However, conventional AFM methods have difficulty achieving uniform roughness of an axial distribution in polishing a circular hole due to unitary axial motion of abrasive media. Hence, a novel helical passageway for a circular hole polishing is proposed herein to create multiple flow paths of abrasive medium, whose flowing behavior enhances polishing effectiveness by increasing the abrasive surface area and radial shear forces. To achieve the stated objective, the first task is to evaluate the abrasive medium motion using CFD-ACE$^+$ numerical software. The key point of this method with respect to the other existing CFD methods is related to non-linear terms of material property have been used. Additionally, the second task is to develop mechanism designs for different passageways to verify the polishing effects of the surface roughness uniformity in the axial direction. Moreover, surface roughness measurements are taken to demonstrate the increase in the roughness uniformity and RIR for different passageways in AFM machine.

Method description

Material property

Generally, abrasive medium motion in AFM can be considered as a non-Newtonian flow from a macro perspective. Power law is adopted to determine the relationships among viscosity, the shear rate and the temperature. The following mathematical equation describes the material properties of an abrasive medium.

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

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

where : μ = viscosity of the abrasive media, μ_0 = zero shear rate viscosity, $\dot{r}$ = 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.

Furthermore, a rheological device is used to determine the curve of shear rates relative to viscosities. Figure 1 shows the relationship curve between the viscosities and the shear rates for this medium. The experimental result indicated viscosity of the abrasive medium had a high effect in different shear rates. Finally, the material properties of viscosity could be calculated after substituting the coefficients in Table 1 into equations (1) and (2).

Experimental procedure

In this study, A-silicone gel is chosen as the medium based on its good polishing results during AFM.[13] Generally, A-silicone gel has a low flow property and easily separates on a work-piece surface after testing, thus, it is an excellent abrasive medium for AFM. Silicon carbon (SiC) is used as the abrasive material and mixed with the silicone gel uniformly. The weight concentration of the abrasive in the polymer gels is approximately 50 % and abrasive mesh of SiC is #100. In AFM process, a semi-solid polymer gel mixed in a typical proportion of abrasives is extruded by two hydraulic cylinders with a constant pressure to polish a work-piece surface. The extrusion pressure of hydraulic cylinder is 4.2 MPa and back pressure is around 2.1 MPa in this process. Figure 2 shows the simple diagram of machining process in AFM.

This investigation focuses on the uniform roughness of an axial distribution when polishing circular holes. The diameter of a circular hole is 16.0 mm and the length is approximately 30.0 mm. Next, the polishing effectiveness of different passageways in a circular hole was evaluated by designing different mold cores to study the motion of the abrasive medium. Figure 3 shows the diagram for a helical core with approximately 15.0 mm diameter.

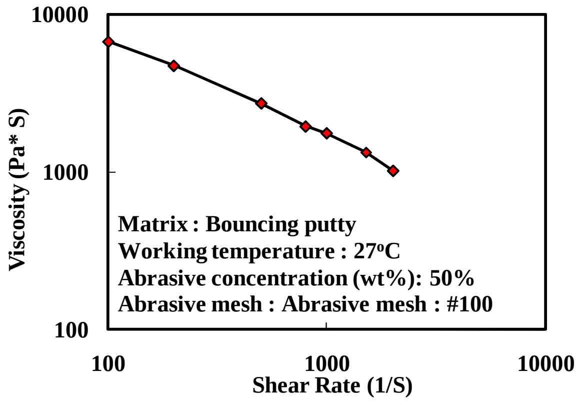


Fig. 1. The curve diagram of viscosity relative with shear rates

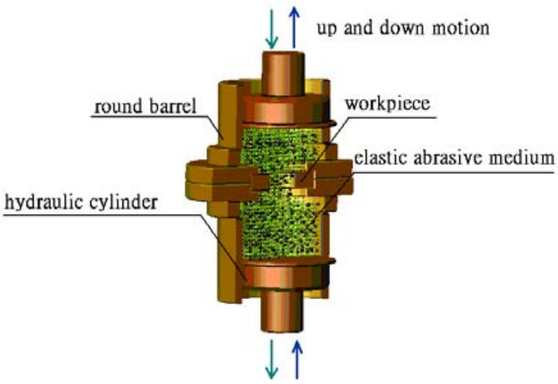


Fig.2. Diagram of machining process in AFM

Fig. 3. Diagram of a four helices core

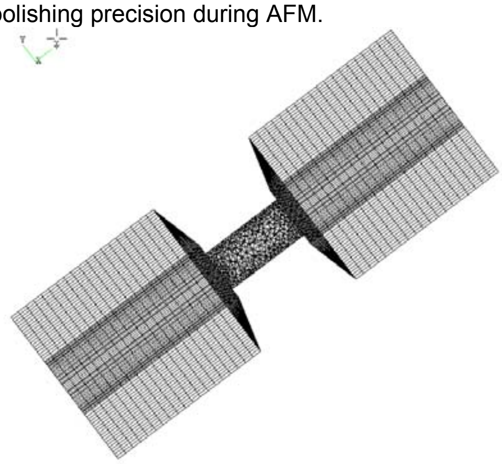
Table 1. The coefficients of A-silicon material property

Parameter	Coefficient
K	1
μ_0	50000
a_1	0.02599
a_2	0.0004
a_3	-0.12307
a_4	0.07155
n	1

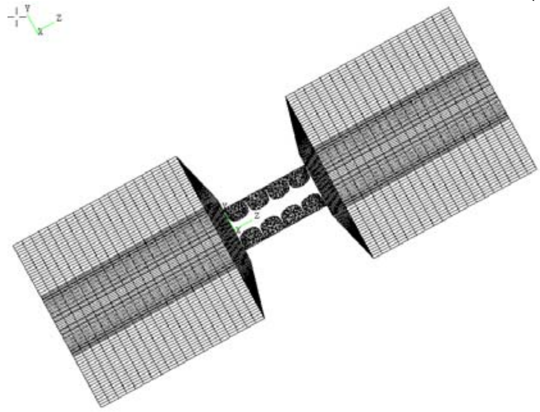
Results and discussion

Simulation results

This study has developed a numerical method to predict the flow behaviors of the abrasive medium in a circular hole before a series of AFM-related experiments. Figure 4 shows the mesh diagram of the abrasive media. Simulation results for velocities and strain rates of the abrasive medium are used to determine how these different passageways affect the polishing precision during AFM.



(a)



(b)

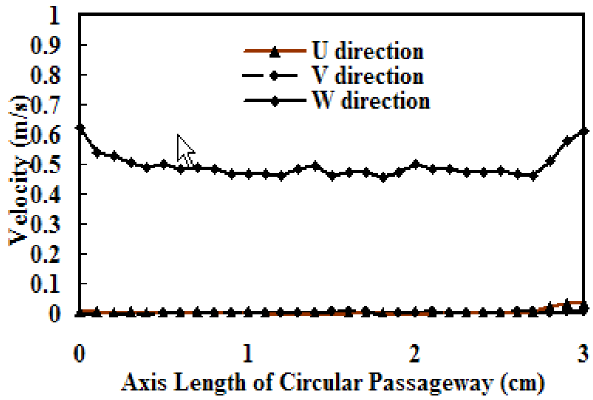
Fig. 4. CFD modeling diagram of the abrasive medium
(a) without a helical passageway. (b) with a helical passageway.

1. Circular hole without a mold core.

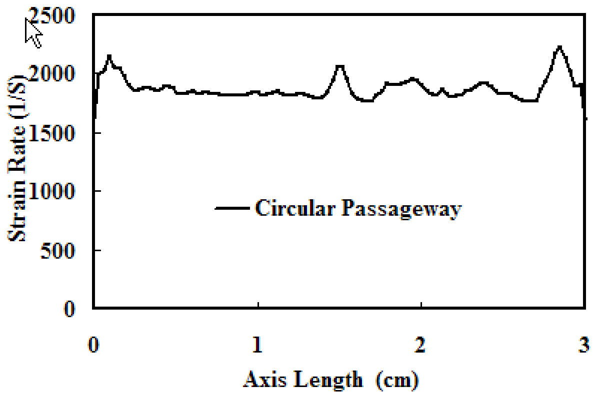
This subsection considers the motion of the abrasive medium without the mold core in a circular hole polishing. The results indicate the velocity curves are near zero value for U and V directions, only W direction has a regular curve of velocity. The velocity distribution in Figure 5(a) demonstrated the abrasive medium retained a unitary axial motion. Furthermore, Figure 5(b) shows the axial curve diagram of strain rates distribution. The curve of strain rate performed a big deviation of surface roughness from peak to peak. The strain rate range of upper and lower limit is widely distributed from 2300 to 1700, and the change percentage of strain rate is 26%. Therefore, this simulation result indicates that the deviation of strain rate distributes different abrasive shear forces on entire circular surface during axial motion, and predicts to reduce the uniformity precision of polishing circular holes.

2. Circular hole with a four helices core.

This study developed a novel helical passageway to improve the motion of the abrasive medium in AFM. Several mold cores with different shapes were developed to determine whether the flowing motion of an abrasive medium was altered. An optimal design of a four helical core was obtained based on simulated results. The axial curves of three velocities were given in Figure 6(a). This result indicated the velocities of the abrasive medium changed obviously during the flowing process; this result also induced abrasive medium from unitary axial motion to multiple axial motions. The helical passageway created motion in multiple directions to increase the shear force and abrasive area in the radial direction. Next, Figure 6(b) showed the axial curve diagram of strain rates, it performed a low deviation of surface roughness from peak to peak. The strain rate range of upper and lower limit was distributed from 575 to 460, and change percentage of strain rate was 19%. This result showed that strain rate percentage of four helices passageway of approximately 19% was significantly better than those on a circular passageway of around 26%. Therefore, a uniform abrasive effect occurred when abrasive medium motion was in multiple directions and this effect was very helpful to increase uniformity of an axial distribution in polishing a circular hole.

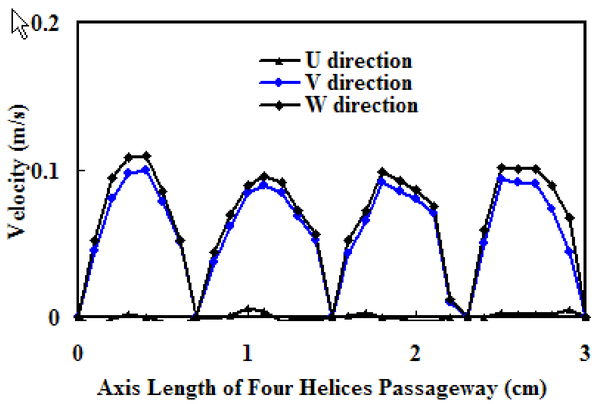


(a) Velocity in axial direction

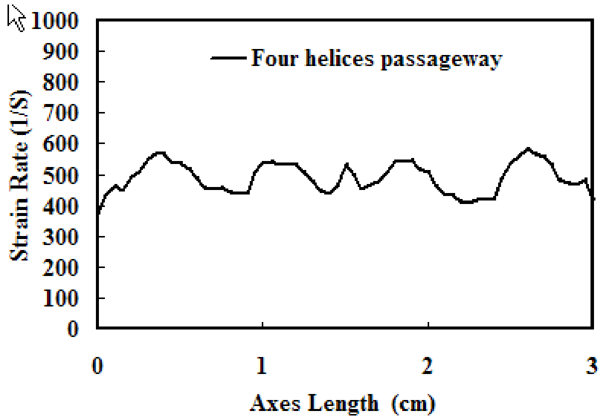


(b) Strain rate in axial direction

Fig. 5. The simulation results of axial curve diagram for a circular passageway on (a) velocity and (b) strain rate.



(a) Velocity in axial direction



(b) Strain rate in axial direction

Fig. 6. The simulation results of axial curve diagram for a helical passageway on (a) velocity and (b) strain rate.

Experimental results.

A batch samples of circular holes of SKD-11 steel are cut out using WEDM process, in which the average surface roughness of circular holes are approximately 0.6 μm Ra after machining. Next, circular holes with different passageways can then be finished after the WEDM by using AFM. Generally, a series of experiments picked up fifteen positions in an axial surface to test the surface roughness after AFM. To verify simulation accuracy, surface roughness measurements of different passageways were implemented to demonstrate the improvement in roughness uniformity and RIR. It is defined as following equation (3):

$$RIR = \frac{SR_{origin} - SR_{polishing}}{SR_{origin}} \tag{3}$$

where SR_{origin} indicates the original roughness before AFM and $SR_{polishing}$ expresses the surface roughness after polishing. The roughness uniformity is defined for the deviation of surface roughness along the axial direction (15 points of surface roughness), as shown in equation (4):

$$\text{Uniformity} = \text{roughness})_{max.} - \text{roughness})_{min.} \tag{4}$$

Experiments were designed different types and different sizes of mold cores to verify the effectiveness of a helical passageway in AFM, such as the number of helical grooves, the gap of workpiece and helical core, the slot thickness and the number of turns. According to the simulation results, we adopted a four helices passageway with different designs to conduct a series of experiments, and a optimal design conditions including for four helices groove, 0.5 mm gap, 0.5 mm slot thickness and one helical turn was obtained. Finally, the polishing effects with a four helices passageway describes as follows:

1. The effects on surface roughness.

Figure 7 presents the polishing effects of the number of alternating cycles on surface roughness during AFM for 25 cycles in different passageways. This figure displays that surface roughness decreased with increasing in number of working cycles. However, a passageway with four helices performed better than a circular passageway during polishing in terms of efficiency, RIR was only 61% in the circular passageway, but RIR reached 76% in the four helices passageway. This is largely owing to abrasive medium in the circular passageway only created unitary axial motion, therefore, surface roughness reduced slowly in AFM. Moreover, abrasive medium in the four helices passageway created dramatic changes in RIR when this medium was pushed through the passageway. Additionally, the material removal of a four helices passageway is also significantly better than a circular passageway during AFM. Therefore, this study demonstrates the effectiveness of helical passageway for changing motion from unitary motion to multiple motions, which obviously affects the average RIR.

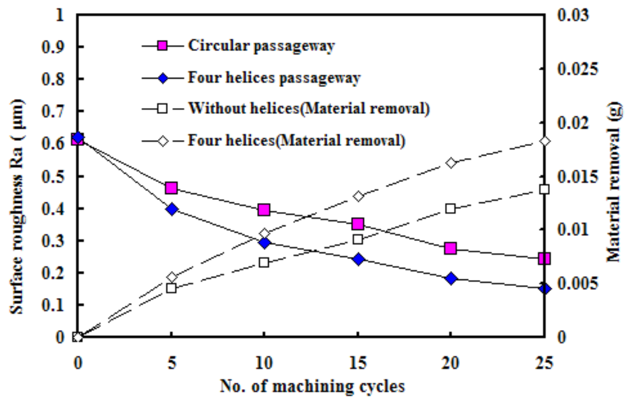


Fig. 7. The comparison curves diagram for helical passageway effects on surface roughness and material removal rate.

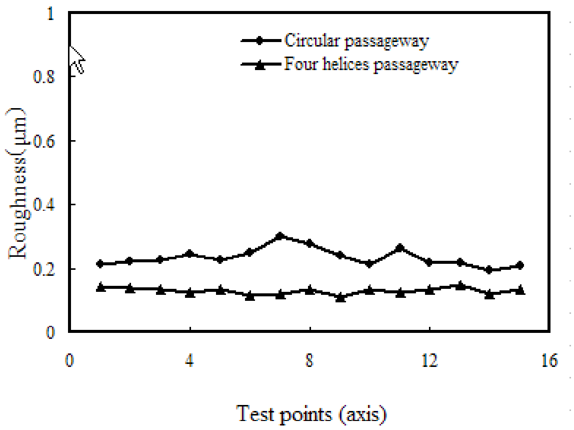


Fig. 8. The comparison curves diagram for helical passageway effects on uniformity of surface roughness.

2. The effects on uniformity of surface roughness.

Figure 8 shows the effects of different passageways on surface roughness in the axial direction. According to the test results, surface roughness deviation was 0.104 μm Ra with circular passageway in AFM; but surface roughness deviation reduced to 0.035 μm Ra when a passageway with four helices was utilized. This investigation demonstrates the effectiveness of the four helices passageway in surface roughness uniformity based on calculating the percentage of improvement rate around 66%. Thus, these results indicated that surface of the circular holes were not very even in the axial direction regardless of circular passageway. On the other hand, surface is smooth when a four helices core was utilized as passageway. The reason was the same as above result, abrasive medium in the passageway with four helices could create multi-axial motion, inducing uniform polishing effect; therefore, even surface could be easily located in this special passageway.

Conclusions

Based on the foregoing discussions in investigating the AFM polishing optimization of different passageways in circular holes, the main conclusions are summarized as follows.

First, CFD-ACE$^+$ numerical software was an effective and precise simulation tool for demonstrating the optimum design of a four helices passageway. Simulated results demonstrated that velocities and strain rates of abrasive medium improved obviously in the four helices passageway, inducing multiple flowing motion in AFM.

Next, experimental results indicated polishing efficiency in a passageway without mold core was not very remarkable, RIR was only 61%, but RIR in a four helices passageway reached 76% after 25 working cycles. Moreover, surface roughness uniformity of the circular hole was 0.104 μm Ra with using circular as passageway in AFM; nevertheless, roughness uniformity reduced to 0.035 μm Ra when a four helices passageway was utilized as finishing passageway. The percentage of improvement rate reached 66% in the roughness uniformity. Therefore, a four helices passageway was indeed produced multiple flowing motion of abrasive medium in AFM and created notable efficiency and good roughness uniformity in a circular hole.

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