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Investigations in to Parametric Analysis on Mrr in Elastic Emission Machining

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ABSTRACT

Elastic emission machining (EEM) is one of the ultra-precision machining methods used to fabricate shapes with 0.1 nm accuracy which is very useful in the manufacturing of high-precision optical mirrors used in X-ray microscopy and extreme ultraviolet lithography (EUVL). In this paper, a comparative analysis is carried out considering all the parameters affecting material removal rate, while using different type of tools - ball type and focusing nozzle type - for the flow control. In ball type EEM, the rotation speed of rotating sphere and particle concentration of machining slurry are the important factors affecting MRR (Material Removal Rate). In focusing nozzle type EEM nozzle aperture size, channel structure and stand-off distance affects MRR. Considering the physics of the EEM process and mechanisms governing the material removal phenomena, simulation has been carried out. It is observed that the experimental results match well with the results of simulation.

1. INTRODUCTION

Though Elastic Emission Machining (EEM) was developed as early as in 1976, it attracts the attention because of its ability to remove material at the atomic level by mechanical methods and to give completely mirrored, crystallographically and physically undisturbed finished surface. The material removal in conventional machining is influenced by enlargement of cracks originating from pre-existing micro cracks [1]. Using ultra-fine particles to collide with the workpiece surface, it may be possible to finish the surface by the atomic scale elastic fracture without plastic deformation. This new process is termed as Elastic Emission Machining (EEM) [2]. A surface profiler also plays a crucial role because figure correction is performed on the basis of measured data when the target accuracy is higher than 100 nm (p-v) [3]. EEM is one of the ultra-precision machining methods used to fabricate shapes with 0.1-nm accuracy without causing any crystallographic damage [4]. The EEM surfaces were observed by scanning tunneling microscopy and confirmed to have atomic flatness [5, 6]. Therefore, in this paper, the focus is to compare the two types of EEM (Elastic Emission Machining) - Nozzle type EEM and Ball type EEM. Stable fluid flow is obtained using the state of elasto-hydrodynamic lubrication between the surfaces of the rotating sphere and workpiece, which can maintain a non-contact state at the machining point during EEM. A continuous particle supply to the workpiece surface can be achieved by this stable fluid flow. The thickness and fluid flow velocity of a lubrication film depend on machining conditions of load, rotation speed and concentration of powder particles.

2. PRINCIPLE

In the Ball type EEM process a polyurethane ball, 56 mm in diameter, is mounted on a shaft driven by a variable speed motor. The axis of rotation is oriented at an angle of ~ 45° relative to the surface of the workpiece to be polished. The material removal rate for the workpiece was found to be linear with dwell time at a particular location, allowing the total thickness of material removed to be controlled to within 20 nm. The mechanisms of removal in rotating sphere and workpiece interface in ball-type elastic emission machining and its set-up are shown in Figs 1 & 2 respectively.

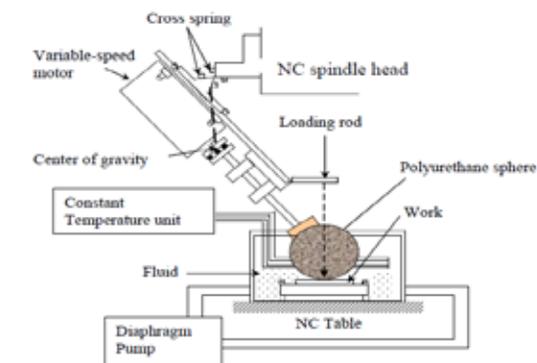


Fig. 2 A schematic diagram of set-up for rotating sphere and workpiece interface in Elastic Emission Machining

Fig. 3 shows a schematic drawing of the nozzle-type EEM system. In this system, the mixture fluid, which is composed of ultrapure water and fine powder particles, is supplied from the diaphragm pump to the nozzle head. The nozzle pressure is kept constant using the air compressor in the damper. The nozzle has a laminated structure consisting of two ceramic plates and a stainless steel sheet. The stainless steel sheet is cut according to the design of the channel structure (Fig. 4).

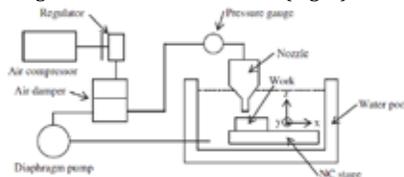


Fig. 3 Nozzle type Elastic Emission Machining system

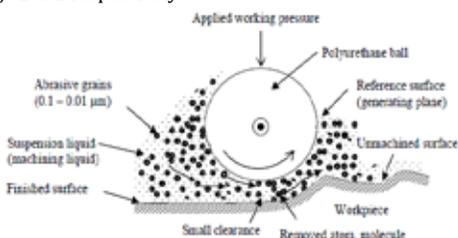


Fig. 1 Mechanism of material removal in elastic emission machining



Fig. 4 The mechanism of cutting of sheets in Elastic Emission Machining [1]

3. METHODOLOGY

In this work, a parametric analysis is conducted on the material removal rate in both types of EEM-Ball type and Focusing nozzle type. It is generally observed that certain factors are affecting the MRR while using different types of tools for flow controlling.

3.1 Analysis of Ball type elastic emission machining

In ball type EEM two different relationships were examined. One is between the removal rate and the rotation speed of the rotating-sphere head, and the other is between the removal rate and the concentration of particles in machining slurry. Experimental results are shown in Fig. 5 a-b. In the examination of the relationship between removal rate and head rotation speed, removal rate is observed to be negatively correlated with rotation speed. Moreover, in the examination of the relationship between removal rate and particle concentration, removal rate is observed to rapidly decrease after peaking at 15 %.

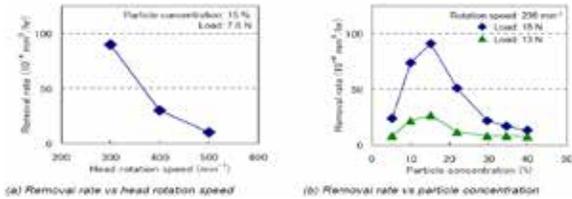


Fig. 5 a-b Experimental results a. Relationship between removal rate and head rotation speed, b. Relationship between removal rate and particle concentration [1]

Increases in rotation speed and particle concentration cause an increase in the number of particles passing through the lubrication film per unit time. However, the number of particles supplied to the workpiece surface per unit time, or removal rate, does not simply increase. This may be due to the presence of forces preventing particles from being supplied to the workpiece surface. These forces can be considered to increase when the fluid flow velocity and the concentration of particles in the lubrication film increase.

3.2 Analysis of particle behavior

To investigate the fact that removal rate is not positively correlated with the increase in the number of particles passing through the lubrication film per unit time, particle behavior is analyzed by taking forces acting on particles into consideration.

Figure 6 shows the forces acting on a particle passing through a lubrication film. F_{Dx} and F_{Dz} are the Stokes drag forces in the x and z directions, and F_G and F_B are the gravity and buoyant forces, respectively. F_L is the lift force generated in fluid flow with a velocity gradient, which is known as the Saffman force.

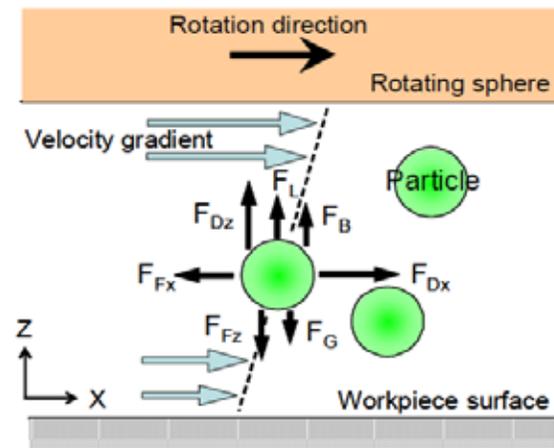


Fig. 6 Forces acting on a particle passing through lubrication film [5]

3.3 Focusing nozzle type elastic emission machining

In nozzle-type EEM, to transport particles to the workpiece

surface and remove them from the surface, a high shear flow is required on the surface. The removal area and removal rate depend on the velocity distribution of the fluid in contact with the surface. The simulation parameters are listed in Table 1.

Table 1 Simulation parameters for nozzle type elastic emission machining

Parameters	Model or values
Turbulence model	k-ε model
Pressure	0.5 MPa
Atmosphere	Pure water at 20°C
Density	998.23 kg/m ³
Viscosity	1.006 × 10 ⁻³ Pa s

Figure 7 shows the simulation results for the focusing-flow channel. The velocity distributions on the XZ plane including the center line are shown in Figure 7-a. The velocity distribution on the plane, 1 μm from the workpiece surface, is shown in Figure 7-b. The experimental parameters are listed in Table 2.

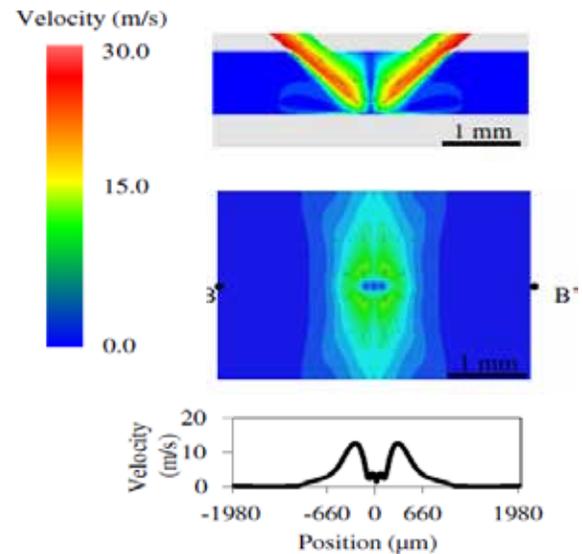


Fig. 7 a-b Simulation results, a. Velocity distribution on the XZ plane, b. Velocity distribution on plane 1 μm from workpiece surface [3]

Parameters	Values
Work material	Quartz glass
Powder particle	SiO ₂ 2 μm φ
Pressure	0.5 Mpa
Machining time	1 min
Solution concentration	3 vol.%
Stand-off distance	0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8 mm

Table 2 parameters for experimental validation

Figure 8-a shows the removal distributions of stationary spot profiles obtained using focusing-flow nozzles, respectively, when the stand-off distance is 1 mm. Figure 8-b shows the cross-sectional profile of the spot for stand-off distances from 0.4 to 1.8 mm. The stand-off distance affects the shape, depth and size of the spot. Figure 8-c shows the relationship between the stand-off distance, removal volume, and spot size, where the diameter of the region including 80% of the total volume is defined as the spot size.

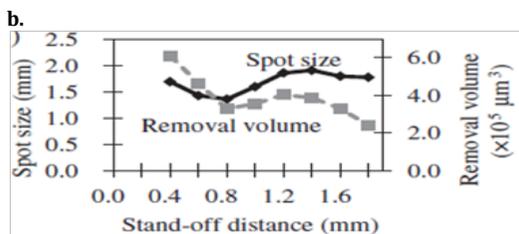
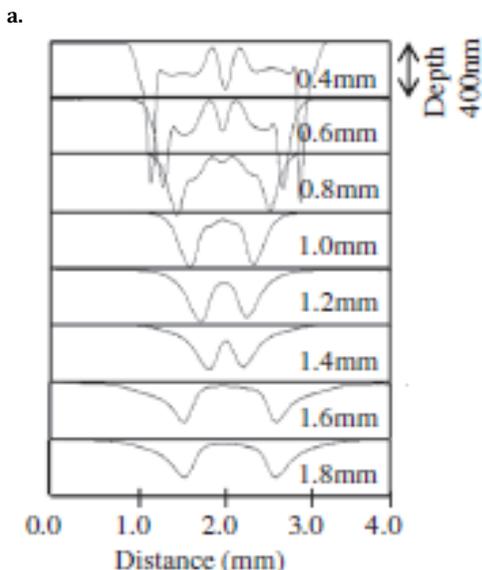
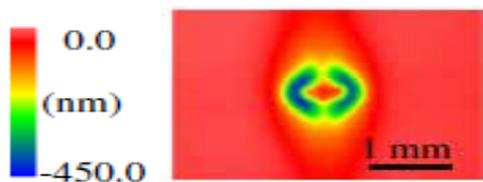


Fig. 8 a-c Experimental results a. Removal distribution, b. Cross-sectional profile and c. Relation between spot size, MRR and stand-off distance [4]

4. RESULTS AND DISCUSSION

In this section, the main results of this comprehensive work are discussed. Figure 9 a-b shows comparisons of changes in removal rate between the analysis and experimental results obtained in two experiments with Ball type EEM.

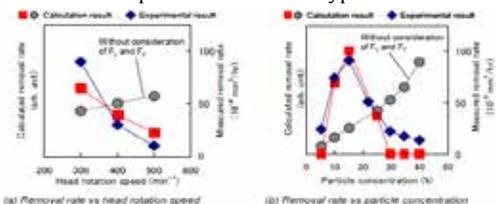


Fig. 9 a-b Comparative analysis of simulation and experimental results a. Relationship between MRR and head rotation speed, b. MRR and particle concentration [5]

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Three different curves are represented in each graph: one is an experimental result and the other two are calculation results. One of the calculation results is obtained by solving the equations of motion without considering FL, FFx and FFz. However, when all forces are taken into consideration in the calculations, the calculation curve reasonably agrees with the experimental curve indicating that forces FL and FF strongly affect changes in removal rate.

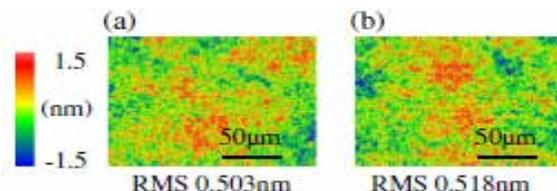


Fig. 10 a-b Results of surface roughness a. before and b. after processing using focus flow nozzle [6]

Raster scanning was carried out on a quartz surface over a square area of side length of 5 mm before and after processing using the focusing-flow nozzle, as shown in Figure 10 a-b, for getting roughness results. The RMS values before and after processing are almost the same; thus, whereas the nozzle type EEM is mainly employed for figure correction, the focusing-flow nozzle can also be used for the figure correction of advanced optical devices. Thus, the shape of the stationary spot profiles can be predicted, which indicates that fluid simulators can be used for the further development of EEM nozzles suitable for figuring of various types of mirror.

5. CONCLUSIONS

In this paper on elastic emission machining, two types of tools were used -i.e. Ball type and Nozzle type -an in-depth parametric analysis is conducted on material removal mechanism of the process. Based on the results of this comparative analysis, the following conclusions can be drawn:

- In Ball type EEM the rate of material removal is affected by rotation speed of the rotating sphere head and concentration of particles in machining slurry. Removal rate does not simply increase with an increase in the rotation speed of the rotating-sphere head or the concentration of particles in machining slurry.
- Particle behavior is strongly affected by forces acting on a particle generated by a velocity gradient of fluid flow and by a mutual interaction of particles, which results in changes in removal rate.
- In focusing-nozzle type EEM, the material removal rate is influenced by the aperture size and channel structure of the nozzle and more importantly on the stand of distance.
- In the study on nozzle type EEM experimentally tested the control of the shape of a stationary spot profile by realizing focusing-flow state between the nozzle outlet and the work piece surface in EEM.
- The simulation results indicate that the focusing-flow nozzle sharpens the distribution of the velocity on the work-piece surface. The results of the machining experiments verified those of the simulation.