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Electrorheological-Fluid-Assisted Ultrasonic Machining: Fundamentals, Mechanisms, and Applications in Micromachining

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Abstract

Ultrasonic machining is an effective non-conventional machining method for processing hard and brittle materials. In this process, an abrasive slurry is introduced into the machining gap to enhance material removal efficiency. The slurry is typically prepared by dispersing abrasive particles in a carrier liquid at a prescribed concentration. During machining, the ultrasonic vibration of the tool induces the movement of the abrasive particles within the tool–workpiece gap. However, the particles may be displaced away from the active machining zone, resulting in a reduction in the local abrasive-particle concentration and, consequently, a decrease in machining efficiency. To mitigate this limitation, particularly in micro-ultrasonic machining, electrophoretic assistance has been employed to control the movement of the abrasive particles. Under an applied electric field, the abrasive particles migrate in a controlled direction and become concentrated near the tool tip. This localized increase in abrasive-particle concentration can improve material removal efficiency, enhance the machined surface quality, and reduce edge chipping.

Keywords: Ultrasonic Machining, Electrophoretic Assistance, Abrasive Slurry, Micro-Ultrasonic Machining, Surface Quality, Edge Chipping

1. Introduction

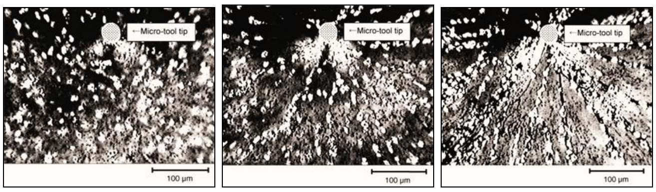
Electrophoresis refers to the migration of electrically charged particles under the action of an applied electric field. This motion is induced by the electric-force component of the Lorentz force [1]. In general, the Lorentz force is defined as the combined electric and magnetic forces acting on a point charge in an electromagnetic field [2]. Electrophoretic assistance is a technique in which abrasive particles are electrically charged and their migration within an electrorheological fluid is controlled by an externally applied electric field. This technique has been widely employed in chemistry, biochemistry, molecular biology, and medicine [1]. It has long been used for the purification and analysis of biomolecules and DNA, as well as in capillary electrophoresis [3-6]. Electrophoretic assistance was first introduced into machining processes in 2002 [7, 8] and was subsequently applied to ultrasonic machining in 2009 [9, 10]. This technique has demonstrated considerable potential in electrorheological-fluid-assisted machining (ERFM), particularly in electrorheological-fluid-assisted ultrasonic machining (ERFUSM).

2. Main Contents

2.1 Electrophoretic Assisted Machining

Electrorheological-fluid-assisted machining (ERFM) has been applied to the ultra-precision polishing of miniature components, such as microlenses, micromolds, and micromirrors fabricated from BK7 glass. Owing to the extremely small dimensions of the working region, effective interaction between the tool and the workpiece is difficult to maintain. To address this limitation, ultrafine silicon carbide (SiC) abrasive particles were dispersed in a silicone-oil-based electrorheological fluid to assist the ultra-precision polishing process.

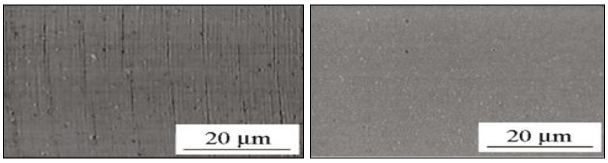
The results indicated that, under an applied electric field, the abrasive particles became highly concentrated along the electric field lines and in the vicinity of the tool tip, as illustrated in Fig 1. The highest abrasive-particle concentration was achieved using a circular electrode because this electrode configuration produced a more uniform distribution of electric field lines. Moreover, the number and thickness of the abrasive-particle bands, as well as the local abrasive-particle concentration, increased with increasing electric field strength. The material removal rate also increased as the electric field strength increased. Consequently, the machining performance was substantially improved, particularly in terms of surface roughness [7].



(a) Voltage DC 0 KV (b) Voltage DC 0.4 KV (c)Voltage DC 2.0 KV

Fig 1: Abrasive particle concentration in ERFM captured by CCD digital microscope

Electrorheological-fluid-assisted machining (ERFM) has also been applied to the polishing of tungsten-carbide micromolds. The results showed that the maximum polishing depth increased with the peripheral speeds of both the workpiece and the microtool. By contrast, the surface roughness was not significantly affected by the peripheral speed of either the workpiece or the microtool. The machined surface was effectively polished, resulting in a substantial improvement in surface finish, as illustrated in Fig 2. In addition, the surface roughness gradually converged toward a limiting value as the polishing process progressed [8].

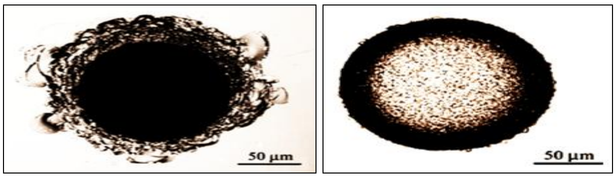


(a) Polishing grinding (b) Polishing grinding supported by ERFM

Fig 2: Polished tungsten carbide surface

2.2 Ultrasonic machining assisted by electrophoretic fluid

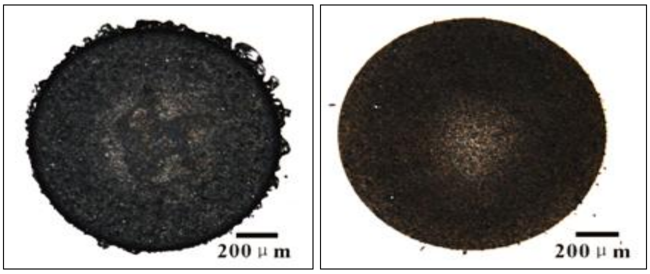
T. Tateishi *et al.* (2009) [9-11] investigated the fabrication of microholes with a diameter of 150 μm in quartz using electrorheological-fluid-assisted ultrasonic machining (ERFUSM). The working fluid consisted of silicone oil and SiC abrasive particles. The machining conditions included an applied voltage of 1400 V, an ultrasonic vibration amplitude of 20 μm, a feed rate of 1 μm/s, and a tool rotational speed of 300 rpm. A tungsten-carbide tool with a diameter of 143 μm was employed. The results demonstrated that ERFUSM reduced edge chipping around the hole entrance by approximately 70%, as illustrated in Fig 3.



(a) not assisted by electrophoresis (b) assisted by electrophoresis

Fig 3: Ultrasonic vibration machining of micro holes without and with electrophoresis assistance

H. S. Lian (2014) [12-14] conducted experimental research on electrorheological fluid-assisted ultrasonic machining (ERFUSM). The workpiece material was monocrystalline silicon (SiC), with a hardness of 9.5–11.5 GPa. The machining tool was made of tungsten carbide with a diameter of ⌀1.0 mm. The results showed the following: ERFUSM offers several clear advantages over conventional ultrasonic micromachining. ERFUSM significantly reduces hole entrance chipping (Fig 4). An increase in voltage does not lead to a corresponding increase in the material removal rate. Abrasive grain size has the greatest influence on machining performance, followed by machining force, tool feed rate, spindle speed, DC voltage, and ultrasonic power.

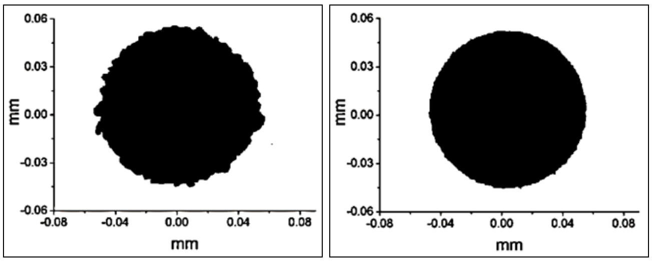


(a) not assisted by electrophoresis (b) assisted by electrophoresis

Fig 4: Ultrasonic machined hole surface

Junfeng He (2018) [15] investigated the mitigation of edge chipping in microholes with a diameter of 100 μm fabricated in single-crystal silicon (Si) using electrorheological-fluid-assisted ultrasonic machining (ERFUSM). The experiments were conducted under a machining force of 0.1 N, an abrasive-particle diameter of 0.1 μm, an applied voltage of 5 V, and an ultrasonic power of 21 W.

The results showed that the abrasive particles in the working slurry became concentrated around the microtool tip. This localized concentration enhanced the effective utilization of the abrasive particles and mitigated direct tool–workpiece impacts. Consequently, edge chipping caused by direct interactions between the tool and the workpiece was reduced. Moreover, the improved utilization of the abrasive particles contributed to a substantial increase in the material removal rate, as illustrated in Fig 5.



(a) not assisted by electrophoresis (b) assisted by electrophoresis

Fig 5: Ultrasonic machined hole surface chipping abrasive grains and significantly improving the material removal rate

J. F. He *et al.* (2019) [16] investigated the fabrication of microholes in single-crystal silicon using electrorheological-fluid-assisted ultrasonic machining (ERFUSM). The workpiece dimensions were 20 × 10 × 0.6 mm. A WC–Co microtool with a diameter of 100 μm and diamond abrasive particles with a mean diameter of 0.1 μm were employed. The experimental setup included a 30-mm brass electrode, an applied voltage of 7.5 V, an ultrasonic power of 22.5 W, and a spindle speed of 300 rpm, as illustrated in Fig 6.

The results showed that the abrasive-particle concentration on the tool surface was substantially higher than that obtained in conventional ultrasonic machining without electrophoretic assistance. The local abrasive-particle concentration increased rapidly from 1 mol/m³ to 4.68 mol/m³ within 10 s. The edge-chipping ratio achieved using ERFUSM was 0.03, which was markedly lower than the value of 0.22 obtained without electrophoretic assistance. In addition, the material removal rate reached 1.916×10^{-4} mm³/min, exceeding the value of 1.718×10^{-4} mm³/min obtained in conventional ultrasonic machining without electrophoretic assistance. The optimal ERFUSM parameters were identified as an applied voltage of 7.5 V, an ultrasonic power of 22.5 W, a spindle speed of 300 rpm, and an abrasive-particle mass fraction of 10%.

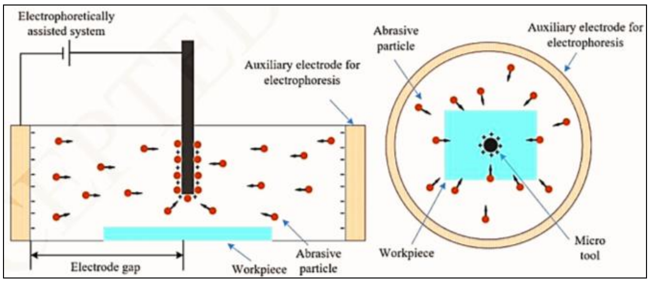


Fig 6: ERFUSM model

Junfeng He *et al*. (2019) [17] investigated the improvement in machining quality achieved by electrophoresis-assisted micro-ultrasonic milling compared with conventional micromilling. The experiments were conducted on Al 6061 workpieces with dimensions of 10 × 10 × 0.5 mm. A cemented-carbide microtool with a diameter of 450 µm and a cutting-edge length of 1.5 mm was employed. The tool material comprised tungsten carbide, titanium carbide, and tantalum carbide. Diamond abrasive particles with a mean diameter of 1 µm were dispersed in the working fluid. The experimental conditions included a 30-mm brass electrode, a DC voltage of 10 V, a tool feed rate of 20 µm/s, a depth of cut of 0.5 mm, an ultrasonic vibration frequency of 38 kHz, and a vibration amplitude of 3 µm, as illustrated in Fig 7.

The results demonstrated that electrophoretic assistance markedly suppressed burr formation and reduced the surface roughness of both the bottom and sidewall surfaces of the machined microstructures compared with conventional micromilling, as shown in Fig 8. When abrasive particles with a mean diameter of 0.34 µm were employed, vertical groove sidewalls without evident taper were obtained. Moreover, as the spindle speed increased, the machined groove width varied from 486 to 498 µm.

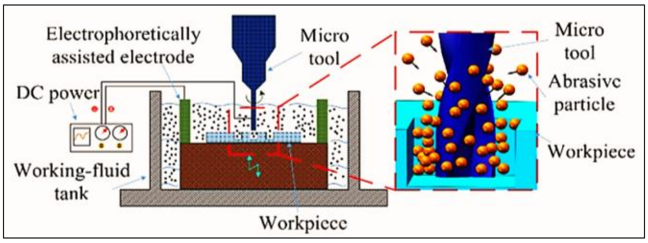
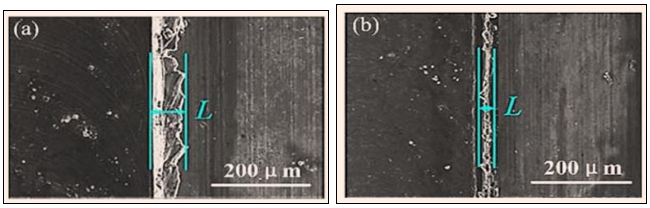


Fig 7: Electrophoresis assisted micro-ultrasonic milling



(a)not assisted by electrophoresis (b) assisted by electrophoresis

Fig 8: Burr formation during ultrasonic micro milling

Lian *et al*. (2023) [18, 19] experimentally investigated template-based electrophoretically assisted micro-ultrasonic machining (TBEPAMUSM) for the fabrication of microchannels. The experiments were performed on N-type single-crystal silicon workpieces with dimensions of 38 × 12 × 0.7 mm. A duralumin template tool, fabricated using a DY400-E CNC engraving and milling machine, was employed. The template tool had a diameter of 30 mm and a thickness of 0.8 mm, while its protruding template structure measured 4.0 × 0.4 × 1.0 mm. Diamond and silicon carbide (SiC) abrasive particles were used, with mean particle sizes of 13, 18, 23, 28, and 33 µm. The diamond and SiC abrasive particles were mixed at a ratio of 1:19. The experimental conditions included an ultrasonic power setting of 80%, an abrasive-particle concentration of 18%, a DC voltage of 40 V, an average machining force of 1.5 N, and a tool feed rate of 0.01 mm/s. The positive terminal of the DC power supply was connected to the template tool, whereas the negative terminal was connected to an annular copper-coil electrode immersed in the working-fluid tank.

The results showed that the mean abrasive-particle size, ultrasonic power, abrasive-particle concentration, and DC voltage substantially influenced both the material removal rate and the surface roughness. Increasing the mean abrasive-particle size and ultrasonic power enhanced the material removal rate; however, these increases were accompanied by a deterioration in surface roughness. Increasing the abrasive-particle concentration also increased the surface roughness, while the material removal rate initially increased and subsequently decreased when the concentration exceeded an appropriate level. The application of a suitable DC voltage effectively improved the balance between material removal efficiency and surface quality. Among the investigated process parameters, the mean abrasive-particle size exerted the greatest influence on both the material removal rate and the surface roughness. Considering the trade-off between machining quality and machining efficiency, the optimal parameters were identified as an ultrasonic power setting of 70%, a mean abrasive-particle size of 18 µm, an abrasive-particle concentration of 18%, and a DC voltage of 40 V, as illustrated in Figs. 9–11.

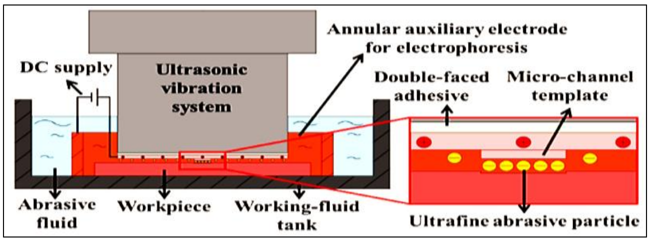


Fig 9: Schematic diagram of ultrasonic assisted electrophoresis micromachining based on sample microtool

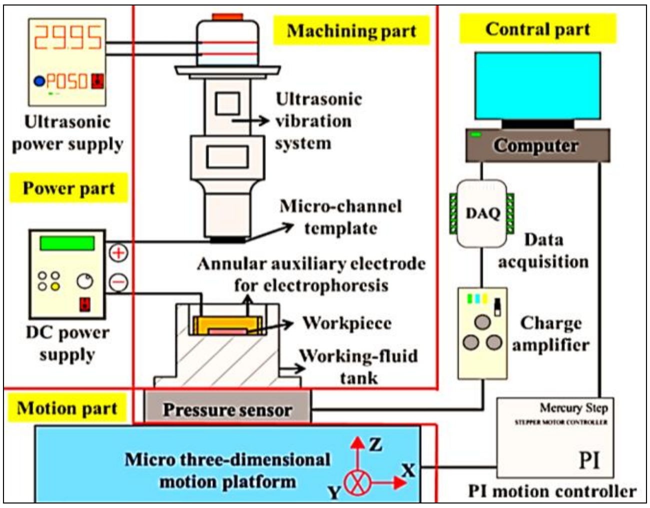
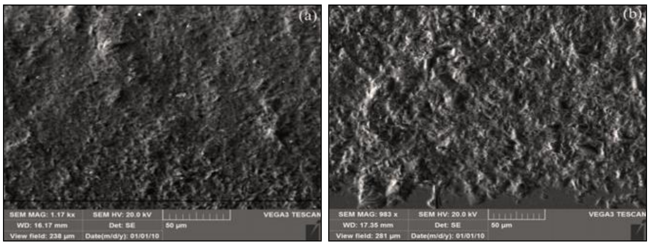


Fig 10: Schematic diagram of the setup for ultrasonic micromachining assisted with electrophoresis based on sample microtools



(a) not assisted by electrophoresis (b) assisted by electrophoresis

Fig 11: Micromorphology of ultrasonically machined surface

3. Conclusions

Electrorheological-fluid-assisted ultrasonic machining (ERFUSM) integrates ultrasonic machining with a direct-current power supply to generate an electric field within the machining zone. The power supply is equipped with short-circuit protection and allows the applied voltage to be adjusted. It provides two electrodes: an anode (+) and a cathode (−). In a typical configuration, the anode is connected to the workpiece, whereas the cathode is connected to the machining tool. The two electrodes are electrically coupled through an electrorheological abrasive slurry, in which abrasive particles are dispersed within a liquid medium.

The electric field established between the electrodes causes electrically charged abrasive particles to migrate within the machining zone. More precisely, the direction of particle migration depends on the polarity of the particle charge: positively charged particles migrate toward the cathode, whereas negatively charged particles migrate toward the anode. Under appropriate operating conditions, the abrasive particles become concentrated along the electric field lines and accumulate in the vicinity of the tool tip. This localized increase in abrasive-particle concentration enhances the availability of active abrasive particles within the tool–workpiece interaction zone and, consequently, improves the machining efficiency.

In ERFUSM, both the workpiece and the machining tool may be fabricated from either electrically conductive or non-conductive materials. When the workpiece and the tool are electrically conductive, they can directly function as the two electrodes. Alternatively, an external anode may be positioned beneath the workpiece.

The proposed schematic configuration of the ERFUSM process is presented in Fig 12.

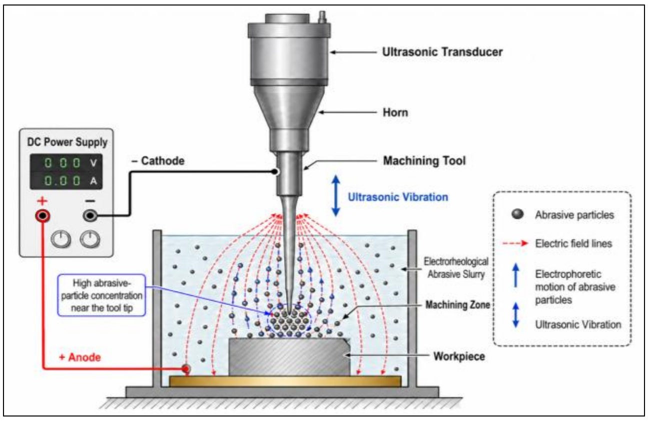


Fig 12: Schematic configuration of the ERFUSM process

In micro-ultrasonic machining, the extremely small dimensions of the active machining zone make it difficult to maintain an adequate concentration of abrasive particles at the tool–workpiece interface. To address this limitation, ultrafine abrasive particles are dispersed in a liquid medium, and electrophoretic assistance is employed to stabilize their distribution and promote their localized accumulation in the vicinity of the tool tip. In addition to inducing the controlled migration of electrically charged abrasive particles, the applied electric field produces an electrorheological effect, thereby increasing the apparent viscosity and yield stress of the electrorheological abrasive slurry. The electrorheological fluid is typically formulated as a liquid suspension containing abrasive particles dispersed in silicone oil or a polymer-based medium.

The electric field within the machining zone is generated using a direct-current power supply. Depending on the specific machining configuration, the applied voltage may range from several tens of volts to several thousand volts.

Electrorheological-fluid-assisted ultrasonic machining (ERFUSM) has primarily been investigated for micro-ultrasonic machining and the precision finishing of hard and brittle materials, including glass, ceramics, quartz, sapphire, ruby, diamond, and certain carbide-based materials. Electrophoretic assistance has also been incorporated into other machining processes, such as milling, micromilling, grinding, and microgrinding.

4. Acknowledgement

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