Title of PhD (Engineering) Thesis: EXPERIMENTAL INVESTIGATION INTO ELECTROCHEMICAL DISCHARGE MICRO-ROOVING ON GLASS

Index No. 15/18/E

Abstract:

The progressive development of micro-manufacturing processes has led to the introduction of hybrid machining technologies that combine the benefits of electrochemical and spark discharge mechanisms. One such innovative hybrid machining technique is the Electrochemical Discharge Micro-Grooving (μ-ECDG), which has emerged as a promising method for machining electrically non-conductive materials such as glass, ceramics and composites materials. These materials are extremely difficult to machine using conventional processes due to their high brittleness and low thermal conductivity. The present research focuses on the experimental investigation of μ-ECDG for micro-grooving operations on both flat and cylindrical glass surfaces. The primary aim is to design and develop an indigenous, cost-effective, and high-precision μ-ECDG setup, while systematically studying the effects of major process parameters like applied voltage, electrolyte concentrations, pulse frequency, tool polarity etc. on essential μ-grooving performance indicators such as Material Removal Rate (MRR), Overcut (OC), Heat Affected Zone (HAZ), Width of Groove (WG), and Depth of Groove (DG).

To achieve these objectives, a comprehensive experimental setup was designed and fabricated. The μ-ECDG system primarily consists of three major sub-units-Mechanical Hardware Unit, Electrolyte Supply Unit, and DC Power Source. The mechanical unit serves as the structural backbone of the setup, incorporating a machining chamber, tool and workpiece holders, and a feed mechanism. The chamber is made from Perspex, chosen for its excellent transparency that allows real-time observation of spark generation and for its shock-resistant nature. The tool holder, fabricated from mild steel, includes a screw-nut arrangement to hold the micro-tool securely. To maintain consistent tool-workpiece contact and minimize tool deflection during the operation, a spring-feed mechanism is incorporated, ensuring controlled feed and consistent groove depth. Additionally, a curved guiding template helps maintain uniform tool motion, leading to better control over groove geometry.

The electrolyte supply unit plays a critical role in stabilizing the electrochemical discharge phenomenon. A stagnant electrolyte layer is maintained at the tool tip to ensure steady bubble formation and efficient spark initiation at the tool bottom edge. The electrolyte flow rate is

Md. Niamat Al.

Professor
Production Engineering Department
Jadavpur University
Kolkata - 700 032

finely regulated using a flow control valve, and the electrolyte level is carefully adjusted to maintain optimal gas film formation. Stable gas film formation is essential for maintaining consistent sparking and preventing uncontrolled arcing, thereby ensuring uniform micro-grooves. The power system of the μ-ECDG setup uses a rectified DC source equipped with a silicon diode-controlled rectifier, capable of providing an output voltage in the range of 20 to 55 V and a current below 2 A. The power source includes digital voltage and current displays for accurate monitoring, while a digital oscilloscope is connected to observe pulse characteristics such as pulse frequency (PF) and duty ratio (DR) in real-time. This control allows precise tuning of the discharge energy, which is important for μ-grooving operations where thermal stability and uniformity are highly sensitive to parameter variations.

For micro-grooving on cylindrical surface, the μ-ECDG setup was modified to incorporate a rotational mechanism. The modified system includes a machining chamber, job holding and rotating unit, tool holding unit, auxiliary electrode, and feeding arrangement. A graphite plate is used as auxiliary electrode and submerged in the electrolyte bath. The cylindrical glass workpiece is mounted on a rotating spindle driven by a stepper motor, allowing precise control over rotational speed. This rotational movement enhances electrolyte circulation and improves flushing action in the discharge zone, ensuring stable and uniform spark distribution around the workpiece surface.

Experimental investigations were carried out in two major stages-micro-grooving on flat glass surfaces and on cylindrical surfaces. For micro-grooving on flat surface of glass, experiments were performed using silica glass as the workpiece and micro-tool of stainless steel of 300 μm diameter. The effects of process parameters such as applied voltage, pulse frequency, duty ratio, electrolyte type, concentration, and tool polarity were studied. Electrolytes used included NaOH, KOH, and a mixed combination of NaOH and KOH, while both direct and reverse polarities were investigated. The parameter ranges included voltage from 35-55 V, pulse frequency from 200-1000 Hz, duty ratio between 45-65%, and electrolyte concentration from 10-30 wt%. The responses measured were MRR, Overcut, and HAZ. For cylindrical surfaces, soda-lime glass was used as the workpiece, and copper was employed as micro-tool electrode. Two experimental approaches were followed-One Factor at a Time (OFAT) to determine individual parameter effects, and Response Surface Methodology (RSM) to develop empirical models and perform multi-parameter optimization. The key input parameters included applied voltage, electrolyte concentration, and rotational speed of the workpiece, with corresponding output responses such as MRR, Width of Groove (WG) and Depth of Groove (DG).

The results demonstrated that the indigenously developed μ-ECDG system effectively produced stable discharges and precise micro-grooves on both flat and cylindrical glass workpieces. The process proved to be highly adaptable for different glass compositions and mechanical properties. For flat surfaces, MRR was found to increase with rising voltage, electrolyte concentration, and duty ratio, while it decreased with increasing pulse frequency. Higher voltages caused greater thermal input, resulting in an increase in both overcut and HAZ area. Among the tested electrolytes, KOH provided superior performance with higher MRR, lower overcut, and a smaller HAZ area, while NaOH produced comparatively larger overcut (approximately 198.8 μm) and HAZ (around 908.92×10^3 μm^2). In cylindrical surface experiments, the use of KOH electrolyte also yielded the highest machining efficiency. Both MRR and WG increased with electrolyte concentration, with maximum MRR of 5.06 μg/s and WG of 538.46 μm achieved at 20–25 wt% electrolyte concentration under direct polarity. Increasing voltage further enhanced both MRR and WG, reaching maximum values of 9.72 μg/s and 486.49 μm at 55 V. However, an increase in workpiece rotational speed led to a decrease in both MRR and WG, as higher speeds reduced electrolyte retention at the spark zone and limited localized heating. The highest MRR of 1.67 μg/s was obtained at 10 RPM, while WG reached a maximum of 364.47 μm at 20 RPM.

Statistical analysis using ANOVA revealed that voltage was the most influential factor affecting MRR, followed by electrolyte concentration and rotational speed of workpiece. For WG, electrolyte concentration was found to be the dominant factor, whereas for DG, EC exhibited the strongest linear effect, with voltage and speed contributing both linear and nonlinear effects. Optimization of process parameters was conducted using Desirability Function Analysis (DFA) for both single and multi-objective cases. In single-objective optimization, the highest MRR of 95.31 μg/s was obtained at 30 wt% electrolyte concentration, 12.83 RPM, and 55 V. For achieving a target width of groove and depth of groove of approximately 500 μm, optimal parameter values were found near 29.8 wt% EC, 50 RPM, 53.8 V and 27.4 wt% EC, 10 RPM, 50.7 V, respectively. In multi-objective optimization, a maximum MRR of 58.04 μg/s was achieved with a desirability score of 1.0000, while the groove dimensions (WG of 493.99 μm, DG of 498.74 μm) were nearly ideal. The optimized parameter combination was EC of 28.70 wt%, RPM of 30.20, and Voltage of 50.56 V.

In conclusion, the research successfully demonstrated the feasibility and efficiency of an indigenously developed μ-ECDG setup for micro-grooving operations on both flat and cylindrical glass surfaces. The process proved suitable for μ-grooving any non-conducting material irrespective of its composition. Among electrolytes, KOH under direct polarity provided the best overall results, offering high MRR, reduced overcut, and minimized HAZ area. The rotational speed of the workpiece was found to significantly affect μ-grooving by altering electrolyte flow dynamics and thermal stability within the spark zone. Voltage and electrolyte concentration emerged as the most dominant parameters influencing MRR and groove geometry. The empirical models developed through statistical analysis effectively predicted process behaviour, and optimization studies confirmed the reliability and precision of the μ-ECDG system. Overall, this research establishes μ-ECDG as a promising hybrid μ-grooving technique for producing high-quality micro-grooves on glass components used in microfluidic devices, biomedical implants, and MEMS-based applications.

Md. Niamat Ali

Professor
Production Engineering Department
Jadavpur University
Kolkata - 700 032