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ML-driven Real-time Monitoring of Glass Microchannel Fabrication with Spark-Assisted Chemical Engraving (SACE) Technology

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ABSTRACT

Spark-Assisted Chemical Engraving (SACE) is a nonconventional micromachining process designed for fabricating non-conductive materials, primarily glass. The process operates within an electrochemical cell, where the tool and counter electrodes acting as the cathode and anode, respectively, are submerged in an electrolyte. When a voltage higher than the critical amount is applied, a hydrogen gas film forms around the tool, electrically insulating the tooltip and enabling high-energy discharges through the gas film layer. These discharges induce localized heating, accelerating the chemical etching process.

The correlation between the process parameters and machining outcomes in SACE remains unpredictable due to uncertainties arising from inherent stochasticity and gas film instability. Consequently, the process exhibits low repeatability, with output variations under identical conditions. A process signature-based approach could be a more reliable method for predictive modeling leading to improved repeatability. Process signatures are interdependent parameters influenced by operating conditions that, in turn, affect machining performance. Key SACE process signatures include the gas film shape and size, machining zone temperature, gas film formation time and lifetime, as well as discharge mean current and energy.

This study introduces a novel method of anomaly detection through extracting the process signatures by analyzing the machining current signal to establish correlations between these signatures and microchannel machining quality. The process signatures are derived using an intelligent characterization algorithm that utilizes time series classification to segment the machining current into distinct phases—gas film formation and discharging—to extract relevant signatures. These signatures serve as input features for a supervised machine learning (ML) model, which then classifies the SACE machining quality into three classes: Smooth, Rough, and Fractured. The anomaly detection algorithm has about 89% sensitivity, where the Rough and Fractured classes indicate machining anomalies and process uncertainties.

Furthermore, the anomaly detection model is implemented in real-time for SACE condition monitoring during microchannel fabrication. The model operates at a high detection frequency of 62.5 *kHz* to capture spark events and is developed in a preemptive multitasking environment using dSPACE technology. Real-time validation confirms its accuracy and reliability. This study lays the groundwork for future advancements in real-time process control for high-quality, high-speed glass microstructure fabrication using SACE.