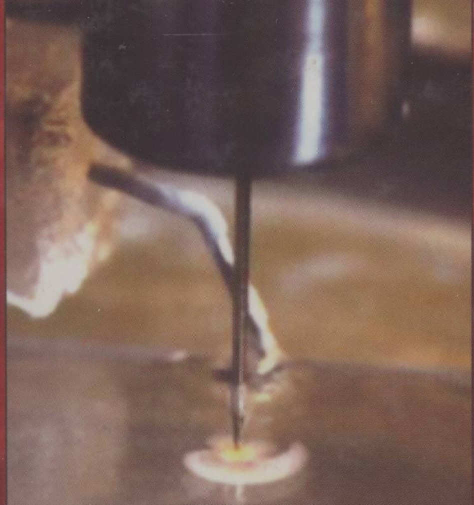
MICRO & NANO TECHNOLOGIES

# Micromachining Using Electrochemical Discharge Phenomenon

Fundamentals and Applications of Spark Assisted Chemical Engraving



Rolf Wüthrich

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# MICROMACHINING USING ELECTROCHEMICAL DISCHARGE PHENOMENON

## Fundamentals and Applications of Spark Assisted Chemical Engineering

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# MICROMACHINING USING ELECTROCHEMICAL DISCHARGE PHENOMENON

*To my wife Evgenia and my children Sandra and Alexandre*
*for their continuous support during my work.*

# Series Editor's Preface

The possibility of modifying materials using electrical discharges has fascinated mankind ever since he observed the results of lightning striking objects in nature. We do not, of course, know when the first observation took place, but we may be reasonably sure that it was a sufficiently long time ago that many millennia had to pass before electricity was "tamed," and subsequently put to work modifying materials in a systematic, "scientific" way—as exemplified by Humphry Davy's electrolysing common salt to produce metallic sodium at the Royal Institution in London.

But these are essentially faradaic processes (named after Davy's erstwhile assistant Michael Faraday), and such processes are also used extensively today for (micro)machining, as exemplified by electrochemical machining (ECM). They are relatively well known, and are applicable to conducting workpieces. Far less well known is the technology of what is now called spark-assisted chemical engraving (SACE), in which the workpiece is merely placed in the close vicinity of the pointed working electrode, and is eroded by sparks jumping across the gas bubbles that develop around the electrode to reach the electrolyte in which everything is immersed, the circuit being completed by the presence of a large counter-electrode.

This technology can therefore be equally well used for workpieces made from non-conducting materials such as glass, traditionally difficult to machine, especially at the precision microlevel needed for such applications as microfluidic mixers and reactors. The development of attractive machining technologies such as SACE is in itself likely to play a decisive part in the growth of microfluidics-based methods in chemical processing and medical diagnostics, to name just two important areas of application.

Since, as the author very correctly points out, knowledge about non-faradaic ECM methods is presently remarkably scanty within the microsystems community, this book is conceived as a comprehensive treatise, covering the entire field, starting with a lucid explanation of the physicochemical fundamentals, and ending with a thorough discussion of the practical questions likely to be asked, and an authoritative exposition of the means to their resolution.

I therefore anticipate that this book will significantly contribute to enabling the rapid growth of micromachining of non-conducting materials, for which there is tremendous hitherto unexploited potential.

Jeremy Ramsden
Cranfield University, United Kingdom
December 2008

# Preface

Micromachining using electrochemical discharges is a fairly new and still largely unknown micromachining technology for glass and other non-conductive materials, like composites for example. While first reports go back to the end of the 1950s in Japan, it is only recently that the fundamental phenomenon behind the process has been elucidated. Paradoxically, one of the main effects, the electrochemical discharges, has been known for more than 150 years, and was used previously for various technical applications ranging from X-ray imaging to wireless telegraphy. However, today only a very specialised research community is aware of it.

Even though micromachining using electrochemical discharges has been known for a half a century, so far, no industrial application is available, and it is only quite recently that a systematic investigation about the process's parameters has begun in earnest. The interest in micromachining with electrochemical discharges witnessed a renaissance a few years ago. Significant work on the fundamental and application side were made, some of which showed the highly promising potentials of this technique. In the growing field of microfluidics this micromachining technology could become a very useful tool for simple and rapid prototyping. Its capacity for machining high aspect ratio structures also makes the technique very interesting for microdevice connections.

This book is a first attempt to collect the state-of-the-art knowledge on micromachining using electrochemical discharges and to establish the fundamentals of this exciting technology. For glass material, the degree of knowledge reached a level high enough to allow several interesting applications. For other materials, work is still needed before applications may emerge. This monograph will hopefully contribute and stimulate new research activities and applications. The author is convinced that the great potential of electrochemical discharges is far from being exploited completely. For example, it is only recently that a completely new field was opened by showing that these phenomena could be used to synthesise metallic nanoparticles.

In preparing this book I benefited from discussions with my colleagues and coworkers. It is not possible to mention all of them here. I would like to express in particular my appreciation to Prof. Dr. Hannes Bleuler who gave me the great opportunity of working in his group over the course of many years; to Dr. Hans Langen who introduced me to the field of micromachining with electrochemical discharges; to Prof. Dr. Christos Comninellis who revealed to me many secrets of electrochemistry; to Dr. hab. Philippe Mandin who initiated me to mutli-phase flow simulations; and to Prof. Dr. Max Hongler who guided me in my researches in non-linear dynamics. I would like to also thank the whole Department of Mechanical and Industrial Engineering from Concordia University, who offered me an excellent and stimulating working environment. A great thank you as well to my current research group who in the recent two years worked out several important results adding definitively an important contribution to the present book.

I would like to thank William Andrew Inc. for giving me the opportunity to write this book, and for their help during all the phases of the manuscript, making publication possible.

Last but not least I would like to thank my spouse, Evgenia, and my children, Alexandre and Sandra, for their patience and understanding. Without their support this book would never have been possible.

The research of the author in the field of electrochemical discharges is sponsored by the Swiss Foundation of Science, the Natural Sciences and Engineering Research Council of Canada, and the Fonds Québéquois pour la Recherche sur la Nature et les Technologies.

Rolf Wüthrich
Montreal, Canada
December 2008

# Contents

# 1 Machining with Electrochemical Discharges—An Overview

Since the very beginning of history, and even prehistory, humanity has invested a lot of effort in developing the skill of processing materials. There is no need to present the fundamental importance of the capability of machining in any technology. Any new technology requires new machining skills. In the last century, the need for using more and more specialised materials (e.g., silicon, composites, or ceramics) greatly increased the already large arsenal of machining technologies.

The last century also saw the birth of micromachining, in particular micromachining of silicon. At present, a huge variety of micromachining techniques are available for silicon. A similar situation exists for electrically conductive materials, where, in particular, electrochemical machining (ECM) and electrical discharge machining (EDM) are two very powerful tools available. However, several electrically non-conductive materials are also of great interest for many applications. Glass and composite materials are two examples. The technical requirements for using glass in microsystems are growing. Medical devices requiring biocompatible materials are only one of many examples.

The importance of glass is also growing in the field of *microelectromechanical systems* (MEMS). The term MEMS refers to a collection of microsensors and actuators. MEMS emerged in the 1990s with the development of processes for the fabrication of integrated circuits. In particular, Pyrex® glass is widely used because it can be bonded by *anodic bonding* (also called *field-assisted thermal bonding* or *electrostatic bonding*) to silicon. Glass has some very interesting properties such as its chemical resistance or biocompatibility. It is amorphous and can therefore be chemically attacked in all directions. As glass is transparent, it is widely used in optical applications or in applications where optical visualisation of a process is needed. Some promising applications for glass in the MEMS field are microaccelerometers, microreactors, micropumps, and medical devices (e.g., flow sensors or drug delivery devices).

A representative example in which glass-to-silicon bonding is used are bulk micromachined accelerometers [121]. In this case, glass serves several functions:

- provides a seal and the desired damping;
- can be used as a capacitor when a metal plate is placed on it;
- can be an overload protection.

Rolf Wüthrich, *Micromachining Using Electrochemical Discharge Phenomenon*, 1–9,

The use of glass is also very common in other sensors than accelerometers using capacitive sensing technology.

## 1.1 Spark-Assisted Chemical Engraving

Various techniques are available to micromachine glass. However, one of the main limiting factors in incorporating glass into microdevices is its limited machinability. A similar situation exists for other hard-to-machine materials such as ceramics and composite materials. A possible answer to these issues could be spark-assisted chemical engraving (SACE), or electrochemical discharge machining (ECDM).

### 1.1.1 What is SACE?

SACE makes use of electrochemical and physical phenomena to machine glass. The principle is explained in Fig. 1.1 [128]. The workpiece is dipped in an appropriate electrolytic solution (typically sodium hydroxide or potassium hydroxide). A constant DC voltage is applied between the *machining tool* or *tool-electrode* and the *counter-electrode.* The tool-electrode is dipped a few millimetres in the electrolytic solution and the counter-electrode is, in general, a large flat plate. The tool-electrode surface is always significantly smaller than the counter-electrode surface (by about a factor of 100). The tool-electrode is generally polarised as a cathode, but the opposite polarisation is also possible.

When the cell terminal voltage is low (lower than a critical value called *critical voltage*, typically between 20 and 30 V), traditional electrolysis occurs

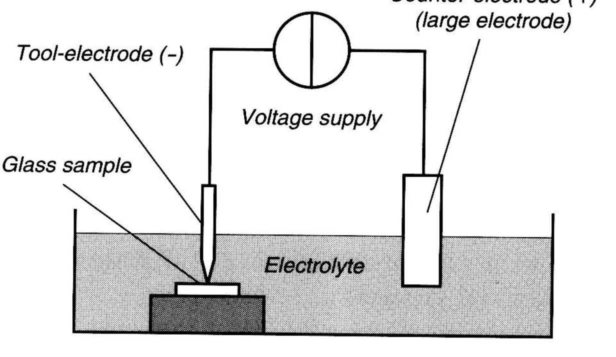


**Figure 1.1** Principle of SACE technology: the glass sample to be machined is dipped in an electrolytic solution. A constant DC voltage is applied between the tool-electrode and the counter-electrode. Reprinted from [128] with permission from Elsevier.

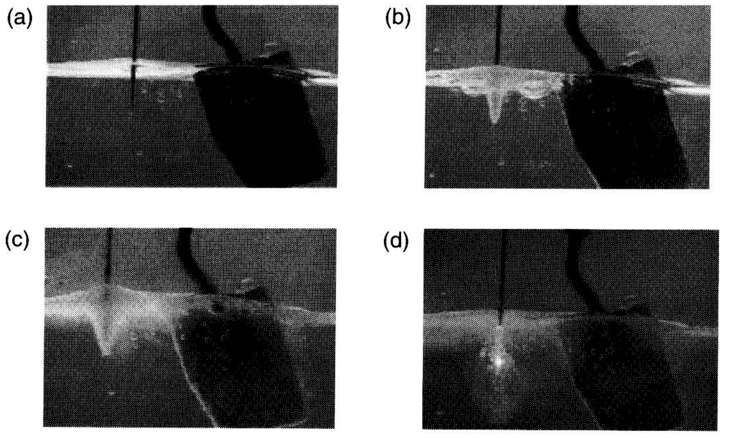


**Figure 1.2** Successive steps towards the electrochemical discharge phenomena: (a) 0 V; (b) 7.5 V; (c) 15 V; (d) 40 V. Two electrodes are dipped into an electrolyte. The terminal voltage is progressively increased from 0 to 40 V. At around 25 V a gas film is formed around the cathode, and at around 30 V the electrochemical discharges are clearly visible. Reprinted from [128] with permission from Elsevier.

(Fig. 1.2). Hydrogen gas bubbles are formed at the tool-electrode and oxygen bubbles at the counter-electrode depending on their polarisation and the electrolyte used. When the terminal voltage is increased, the current density also increases and more and more bubbles are formed. A *bubble layer* develops around the electrodes. As presented in Chapter 3, the density of the bubbles and their mean radius increase with increasing current density. When the terminal voltage is increased above the critical voltage, the bubbles coalesce into a *gas film* around the tool-electrode. Light emission can be observed in the film when electrical discharges, the so-called electrochemical discharges, occur between the tool and the surrounding electrolyte. The mean temperature of the electrolytic solution increases in the vicinity of the tool-electrode to about 80–90°C. Machining is possible if the tool-electrode is in the near vicinity of the glass sample (Fig. 1.3). Typically, the tool-electrode has to be closer than 25 μm from the workpiece for glass machining to take place.

However, things are not as simple as they seem. The gas film around the tool-electrode is not always stable. Microexplosions may occur destroying the machined structure locally. During drilling of holes, the local temperature can increase to such an extent, resulting in heat affected zones or even cracking.

### 1.1.2 Machining Examples

SACE technology can be used for flexible glass microstructuring. Channel-like microstructures and microholes can be obtained. Two examples are illustrated in Fig. 1.4. The channel microstructure was machined with a cylindrical 90 μm

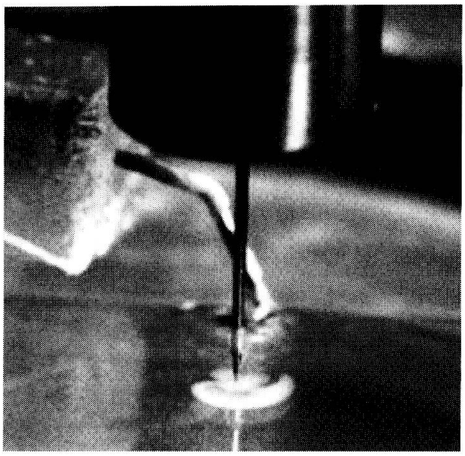

**Figure 1.3** Close-up view of micromachining with electrochemical discharges.

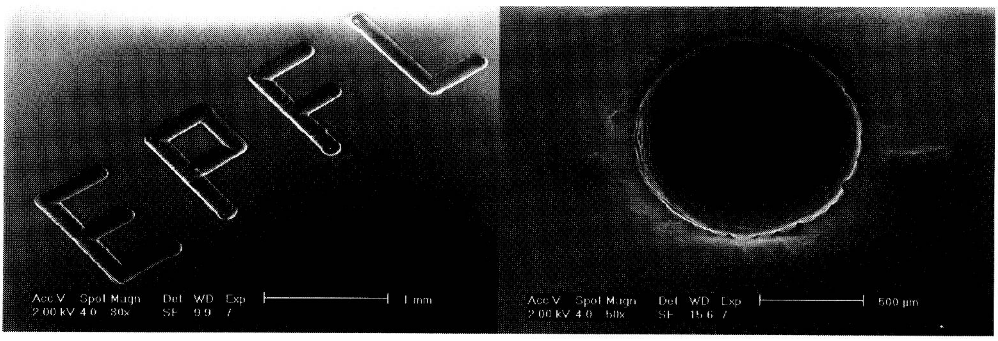


**Figure 1.4** Micrographs of a SACE-machined channel-like structure (left) and a microhole (right) in Pyrex® glass. Reprinted from [128] with permission from Elsevier.

diameter tool-electrode at an applied voltage of 30 V. Machining was done in one step with a tool speed of 0.05 mm/s. The channels are about 100 µm wide and 200 µm deep. The microhole illustrates the possibility of machining relatively deep structures. In this case the microhole is 1 mm deep.

The most interesting characteristic of SACE is its flexibility. No mask is needed, and just as in traditional machining, the desired structure can be machined directly. A typical four axes SACE machining facility is shown in Fig. 1.5. This facility includes two processing units. The first unit, called the *WEDG unit*, allows the manufacturing of tools with different shapes using the wire electrical discharge grinding (WEDG) technology [85]. The second processing unit is the *SACE-unit*, in which glass machining is done. The unit is designed for a maximum of 10 inch glass wafers. An interesting aspect of this machining prototype is the possibility to machine glass and the tool-electrodes

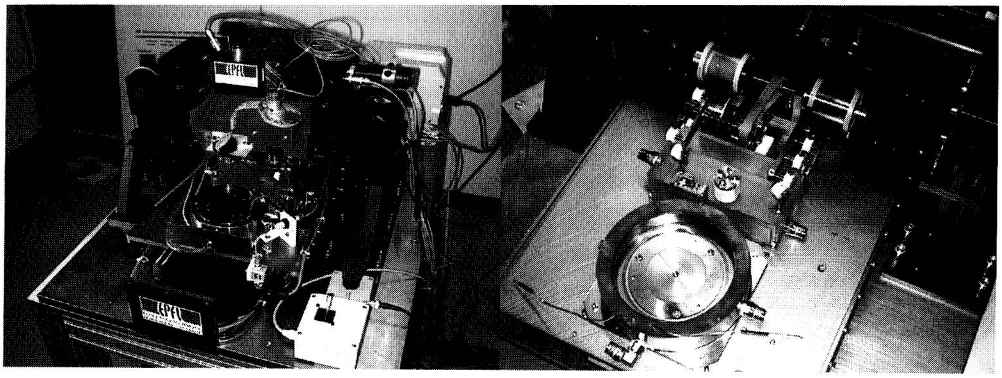

**Figure 1.5** Overview of a SACE prototype (left) and close-up view of the processing units (right) [32,123].

needed in the same facility, which avoids alignment problems and offers more flexibility.

### 1.1.3 A Short Historical Overview

SACE was first developed in Japan in the late 1950s with some applications in diamond die workshops (Table 1.1). The paper by Kurafuji and Suda, in 1968, was one of the pioneering reports about this new technology, which they termed *electrical discharge drilling* [76]. The authors demonstrated that it was possible to drill microholes in glass, and they studied the effect of electrolyte chemical composition and tool-electrode material. The machining mechanism was open to debate and questions were raised about the similarities with EDM and ECM. This debate went on five years, until the paper by Cook et al. [21]. The authors stressed that the process described by Kurafuji and Suda is different from EDM and ECM and suggested a new name for it, *discharge machining of non-conductors*. They showed that the process can be applied to a broad range of non-conductive materials and investigated further the effect of the electrolyte. The authors also quantified drilling rates as a function of the

**Table 1.1 Some Important Dates in the History of SACE**

| | |
|---|---|
| 1968 | First report by Kurafuji and Suda |
| 1973 | First characterisations by Cook et al. |
| 1985 | Extension to travelling wire-ECDM by Tsuchiya et al. |
| 1990 | First functional devices |
| 1997 | First models by Ghosh et al. and Jain et al. |
| 2000 | Study of SACE in the light of electrochemistry |
| 2004 | SACE and nanotechnology |