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Rolf Wüthrich
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Second Edition

MICROMACHINING USING ELECTROCHEMICAL DISCHARGE PHENOMENON

Fundamentals and Application of Spark Assisted Chemical Engraving

Micro & Nano Technologies Series

Micromachining Using Electrochemical Discharge Phenomenon

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Preface

Since the publication of the first edition of this book an impressive amount of research on machining by electrochemical discharges has been conducted. Not only could a growing interest in academia be noted, but also from industry. In 2014, the Swiss company Posalux SA did bring to the market a first fully functional machine for microdrilling glass by electrochemical discharges. It is hard to imagine that only five years ago this technology was hardly known and far away from being used in industry. But there still remains a long way to go before Spark Assisted Chemical Engraving (SACE) becomes an established technology. In the academic world a real rebirth in the interest in SACE can be seen. Among many important establishments, interesting ones are improvement of machining precision of SACE, studying the importance of the tool shape, developing methods for controlling the surface texture of machined structures, and bringing up a better understanding of forces acting on the tool while machining.

Researchers are currently concerned with ways to develop feedback algorithms for the process, by using the machining force acting on the tool. A better understanding of the temperatures involved during machining and of the role of various electrolyte properties, such as electrical and thermal conductivity, viscosity or vaporization temperature, allows designing new machining strategies and optimized electrolyte properties. All these exiting developments in the field will hopefully soon establish SACE among one of the standard micromachining technologies for glass and other nonconductive materials.

The authors hope that engineers and researchers can build on this second edition, which tries to incorporate the knowledge developed around SACE and to present it in a comprehensive way, to further extend the capability of the process. With the first machine developed by Posalux SA, SACE enters now the industrial world. At this point, new questions and issues will be raised. If the present book can somehow contribute to address some of the new challenges, the objective set by the authors will be more than achieved.

This book would never have been possible without the help, support, and encouragement of ours colleagues and coworkers. It is not possible to mention all of them here. But we would like to express a particular appreciation to some of them. Rolf Wüthrich would like to particularly thank Prof. Dr Hannes Bleuler, valuing academic freedom at the highest possible level, for giving him the unique opportunity of working in his group over the course of many years, to Dr Hans Langen for introducing him to the field of micromachining with electrochemical discharges, to Prof. Dr Christos Comninellis who revealed many secrets of electrochemistry, to Prof. Dr Philippe Mandin for the stimulating discussions on multiphase flow, and to Prof. Dr Max Hóngler for guiding his research on nonlinear dynamics. The authors would like to also thank the Department of Mechanical and Industrial Engineering from Concordia University which offered an excellent working environment. A particular appreciation goes to Prof. Dr Martin Pugh, Chair of the department, who was always supportive of our, sometimes exotic, research. A great thank you goes as well to our current research group who in the recent years worked out many important results.

The authors would like to thank Elsevier for giving the opportunity to write this second edition of the book and for their help during all the phases of the manuscript preparation which made this publication possible.

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A particular recognition goes to Posalux SA, which, since many years, has believed in SACE and did not hesitate to invest time and resources in the development of this technology even at a time when having no clear market identified for this technology. This is true innovation. In particular, the authors want to thank Mr Philippe Grize, former Chief Operation Officer of Posalux and now director of the Engineering School of the University of Applied Sciences and Arts Western Switzerland, Dr Giuseppe Cusanelli who is Technology Manager at Posalux, and Damien Lüthi, Development Engineer of the SACE machine, all of which are true promoters of SACE.

True innovation brought as well the first research project on SACE to one of the authors. Near Bex, a small village in Switzerland, is located a salt mine. This mine has the particularity to be one of the poorest mines in the world. The content of salt of the rock is so low, one would never expect to be able to extract the white treasure in an economical way. But the people of Bex have done it since hundreds of years and created wealth for the whole region. Since the Middle Age, they flooded the galleries, today by injection of water under high pressure directly into the rock, to extract the small content of salt of the mountain. Not surprisingly, a major chemical industry chose to establish one of its production plants in the vicinity of the mine. They produce chlorine and sodium hydroxide by salt water electrolysis in order to be used in the production of colour pigments. An undesired side product of the process, hydrogen, gave birth to the development of another company fabricating industrial diamond. Since decades this company has drilled microholes, using laser, in the diamond pellets to manufacture high precision bearings for the Swiss watch industry. Here came SACE into play. The aim was to drill high quality microholes into the diamond. Of course we never succeeded. But it was the starting of a great adventure that eventually led to the development of the first commercial SACE microdrilling machine by Posalux SA.

To the innovative spirit of the people of Bex, who did create wealth to a whole region out of a mountain containing almost no salt, this book is dedicated.

Rolf Wüthrich, Jana D. Abou Ziki
Montreal, Canada
June 2014

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CHAPTER

1 MACHINING WITH ELECTROCHEMICAL DISCHARGES—AN OVERVIEW

CHAPTER OUTLINE

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 specialized materials (e.g., silicon, composites, 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 nonconductive 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 is 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 visualization 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).

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A representative example in which glass-to-silicon bonding is used is bulk micromachined accelerometers (Wolffenbuttel, 1995). 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.

The use of glass is also very common in sensors other 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 Figure 1.1 (Wüthrich and Fascio, 2005). 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 millimeters 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 polarized as a cathode, but the opposite polarization 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 1.2). Hydrogen gas bubbles are formed at the tool-electrode and oxygen bubbles at the counter-electrode, depending on their polarization and the electrolyte used. When the terminal voltage is increased, the current density also increases and more

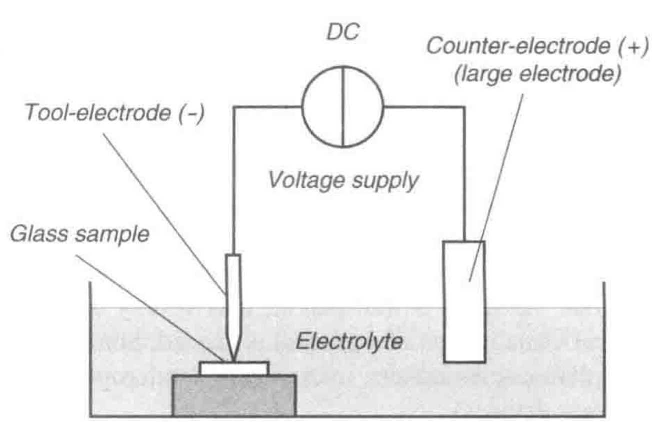

FIGURE 1.1

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 Wüthrich and Fascio (2005) with permission from Elsevier.

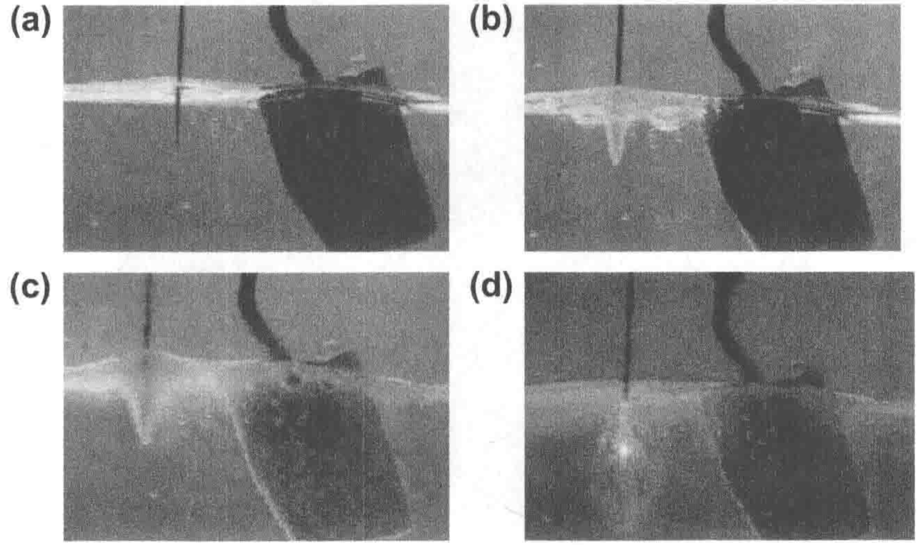

FIGURE 1.2

Successive steps toward 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.

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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 (Figure 1.3). Typically, the tool-electrode has to be closer than 25 μm from the workpiece for glass machining to take place.

However, the process is not as simple as it seems on first sight. 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 that heat-affected zones or even cracking can result.

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 Figure 1.4. The channel microstructure was machined with a cylindrical 90-μm-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^{-1}. The channels are about 100 μm

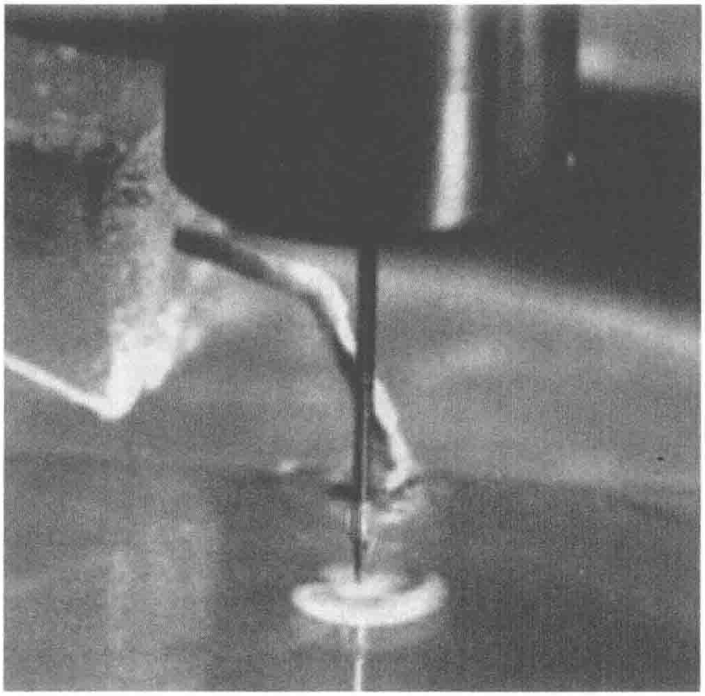

FIGURE 1.3

Close-up view of micromachining with electrochemical discharges.

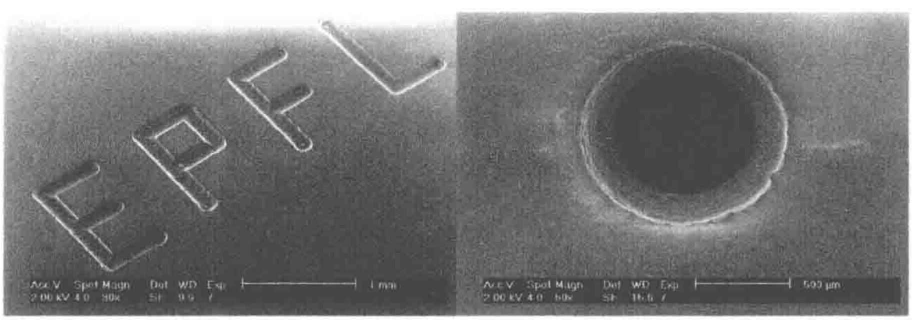

FIGURE 1.4

Micrographs of a SACE-machined channel-like structure (left) and a microhole (right) in Pyrex® glass.

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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-axis SACE machining facility is shown in Figure 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

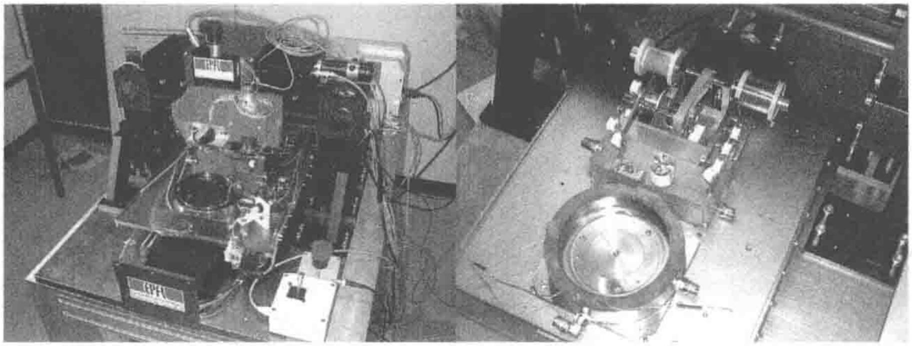

FIGURE 1.5

Overview of a SACE prototype (left) and close-up view of the processing units (right) (Fascio, 2002; Wüthrich, 2003).

discharge grinding (WEDG) technology (Masuzawa et al., 1985). The second processing unit is the *SACE-unit*, in which glass machining is done. The unit is designed for 10-inch-maximum glass wafers. An interesting aspect of this machining prototype is the possibility to machine glass and the tool-electrodes 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* (Kurafuji and Suda, 1968). The

Table 1.1 Some Important Dates in the History of SACE

1968	First report by Kurafuji and Suda
1973	First characterizations by Cook et al.
1985	Extension to traveling 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 light of electrochemistry
2004	SACE and nanotechnology
2006	Systematic studies on gravity-feed drilling Introduction of pulsed voltage machining
2008	Systematic studies on SACE 2D machining
2009	Machining structures less than 100 μm
2011	Study of various tool geometries Etch stop layer
2013	Surface texturing by SACE Study of forces in constant velocity feed drilling
2014	First commercial machine by Posalux SA

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 for five years, until the paper by Cook et al. (1973). 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 nonconductors*. They showed that the process can be applied to a broad range of nonconductive materials and investigated further the effect of the electrolyte. The authors also quantified drilling rates as a function of the microhole depth and compared the machining between negatively and positively polarized tool-electrodes. However, the material removal mechanism remained an open question.

In 1985, Tsuchiya et al. presented a new variant of the process developed by Kurafuji and Suda by using a wire as a tool-electrode (Tsuchiya et al., 1985). They termed this process *wire electrochemical discharge machining* and showed that glass and various ceramics can be cut using this technique. This variant was further developed by Jain et al. (1991) under the name *electrochemical spark machining*. The authors highlighted the similarity with electrochemical arc machining, a variant of ECM.

In the 1990s, the first applications in the field of MEMS were published (Esashi et al., 1990). Simultaneously, several studies on the fundamentals of the process were undertaken (Allesu et al., 1992; Basak and Ghosh, 1996; Jain et al., 1999). In particular, Ghosh et al. established, for the first time, a clear link between the machining process and the electrochemical discharge phenomenon. At that time, the main material removal mechanism was believed to be the melting of the workpiece. The chemical aspect of the material removal mechanism was investigated more systematically at the beginning of this century. A pioneering work in this area is the one by Yang et al. (2001), who defined the material removal mechanism as a high-temperature etching process. Further investigations on the electrochemical contributions were done by Fascio et al. (Fascio, 2002; Fascio et al., 2003, 2004). Based on their results, and to avoid further confusion with ECM and EDM, the group proposed to use the terminology *SACE*. This acronym, which is used throughout this book, emphasizes the contribution of chemical etching to the machining process. The same group also conducted further studies on the mechanisms behind the formation of the gas film with practical application to the improvement of the machining process (Wüthrich, 2003; Wüthrich et al., 2005a; Wüthrich and Hof, 2006). The application of the SACE technology to microfactories was also suggested (Wüthrich et al., 2005c). In 2005, a first review paper on the process was published (Wüthrich and Fascio, 2005). Since 2006 a real renewal in interest in the technology has emerged. An impressive number of studies on the process fundamentals emerged. Systematic characterizations of various machining strategies were conducted and process improvements were proposed. (The number of publications on SACE from 1968 to 2005 and between 2005 and 2008 are about the same.) Besides many other developments, the utilization of pulsed voltage machining is a very promising technique (Kim et al., 2006; Zheng et al., 2007a,b). It was demonstrated how structures smaller than 100 μm can be manufactured by SACE (Cao et al., 2009) (Figure 1.6). One of the latest developments is the application of electrochemical discharges to nanotechnology (Lal et al., 2008; Wüthrich et al., 2005b; Wüthrich et al.).

All these combined developments and interests in the technology eventually made their way to industry and, since 2014, the Swiss company Posalux SA is commercializing a SACE drilling facility.

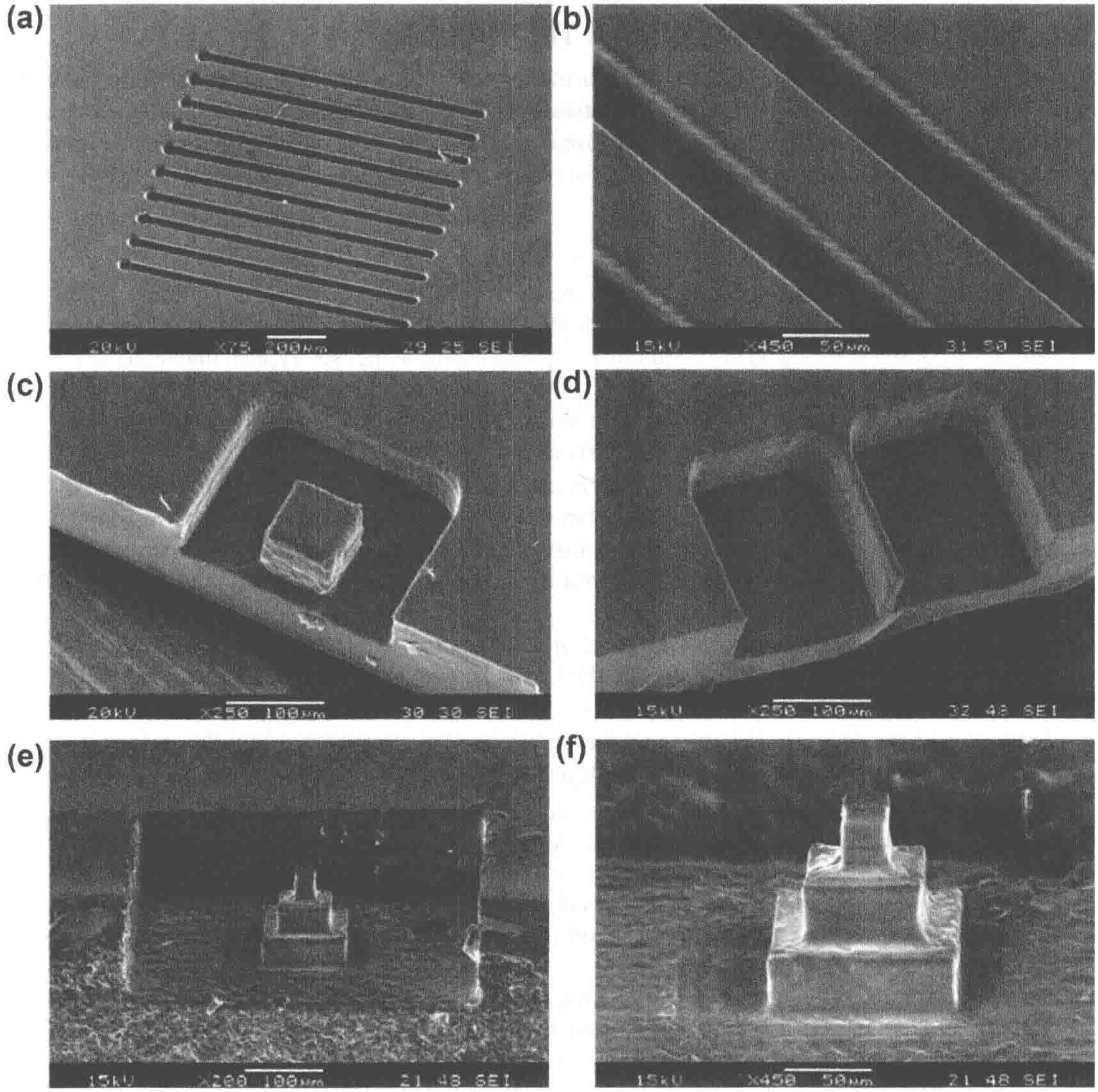

FIGURE 1.6

Examples of structures less than 100 μm machined by SACE in glass (KOH 30 wt%, 23 V pulse voltage, 1 ms/1 ms pulse on/off-time ratio, cylindrical tungsten carbide tools of 30–33 μm diameter, 3 μm s^{-1} feed rate, and 300 rpm rotational speed): (a and b) micro-grooves, (c) micro-pillar, (d) micro-wall, and (e and f) micro-pyramid.

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1.2 SACE AS A MICROMACHINING TECHNOLOGY

Several machining technologies can be used to microstructure workpieces. These different technologies are often complementary and are sometimes used together. Machining technologies can be classified into mechanical, chemical, and thermal technologies. The following sections present a succinct overview of some of the most commonly used micromachining techniques.

1.2.1 MECHANICAL MACHINING

- *Mechanical drilling* (with diamond tool) or diamond cutting can be used for glass machining. This is not a typical micromachining technology. The main limitation is the tool size. So far, only drilling or cutting is used and no 3D microstructuring can be achieved. Typical diameters that can be obtained are around 400 μm.
- *Water jet machining* uses water mixed with abrasive materials projected with high pressure (typically 0.7 MPa) and focused on the workpiece.
- *Powder blasting*, or *abrasive jet machining*, is a technique in which a particle jet (typically Al_2O_3 particles of 3–30 μm) is directed toward a target for mechanical material removal. It is a fast (typically, 500 μm depth in 20 min), inexpensive, and accurate directional etch technique for brittle materials like glass, silicon, and ceramics. For complex and small structures a mask can be used.
- In the *ultrasonic machining* process, the tool, made of softer material than that of the workpiece, oscillates at high frequency (typically 20 kHz) with an amplitude about 25 μm. Ultrasonic machining, used on very hard ceramics, works by grinding or eroding material away. A liquid slurry around the drill bit contains loose hard particles that are smashed into the surface by the vibrations, eroding material away and creating more loose hard particles.

1.2.2 CHEMICAL MACHINING

- *Photofabrication* or photoforming is an optical method that is similar to the stereolithography or the photomask layering process, which involves the solidification of a photochemical resin by light exposure.
- *Chemical etching*: For glass, chemical etching can be classified into two types: dry and wet etching. Typical wet etching is done by using hydrofluoric acid (HF) or potassium hydroxide (KOH). Selective etching is obtained by using masks. The typical etching rate in 50 wt% HF at 40 °C is 6 μm min^{-1} and 80 nm h^{-1} for a 35 wt% KOH solution.
- *ECM* achieves controlled material removal by electrochemical dissolution of the workpiece, which consequently should be electrically conductive. The technique is characterized by the excellent surface qualities that can be achieved.

1.2.3 THERMAL MACHINING

- *Laser machining* is based on the local supply of energy to materials. At the surface of the material, the laser light is transformed into heat, which is available for processing. Glass can be micromachined with relatively high accuracy using this technology (better than 5 μm for