Micro and nano electrical discharge machining in microfluidics and micro nanotechnology

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ABSTRACT: Potential applications of micro and nano EDM in the research in micro nanotechnology and microfluidics are first discussed. Milling EDM, one variation of EDM, is proposed as a flexible tool for such applications. In practice EDM milling is a process rarely used because it is difficult to prepare thin electrode tools. Therefore the use of electrochemically etched Pt-Ir electrode tool for EDM machining is demonstrated. In addition a compact micro EDM machine is described. Preliminary results concerning the micromachining of silicon are also shown.

Key words: Micro electrical discharge machining, EDM, Microfluidics, Microtechnology, Nanotechnology.

1 INTRODUCTION

1.1 Micro and nanotechnology

One bottleneck in the research in micro and nanotechnology (MEMS, microphotonics, etc.) is still the lack of easy and low cost machining technique to get parts when the resolution is in the the 100 nm – 1 µm range (we are considering here prototyping not production). At this level of resolution, it is not easy to combine conventional UV photolithography and wet or dry etching techniques like Reactive Ion Etching (RIE) or deep RIE (DRIE). Of course it is possible to make use of e-beam lithography, LIGA and Focused Ion Beam (FIB). However these technologies require often long machining time, are extremely expensive and must be operated by highly skill personal. New lithography techniques based on nano-imprinting and microcontact printing are also under development with a resolution reaching 50 nm, but these techniques require the machining of a master part with the same resolution. So the bottleneck is unchanged. In other respects, femtosecond laser machining is an interesting solution but with limited resolution in the field of nanotechnology. Additional problems arise when high aspect machining ratio is required. In this case, LIGA is the only possibility with the aforementioned drawbacks.

1.2 Machining of non semiconducting materials

The discussion above was about the machining of semiconductors (Si, InP, AsGa, etc.) but there are also new needs for the micromachining of materials which can be considered as unconventional in microtechnology.
For example in the field of microfluidics, besides silicon, materials like glass and polydimethylsiloxane (PDMS) are more and more widely used. On the contrary stainless steel remains largely unused although it has a high potential in microchemistry (chemical microplants). Stainless steel is a standard material in “conventional” chemistry because it is (to some extent) chemically inert, mechanically strong and can withstand elevated temperature. But micromachining of silicon is challenging [1].
Another important emerging application is microinjection molding of thermoplastic polymers [2], specially to produce microfluidics parts with better mechanical and chemical properties than PDMS. In this case, the bottleneck is the machining of micromolds in hard materials like WC.

1.3 Potential of micro and nano EDM

It is well known that even extremely hard materials can be machined by EDM [3] as long as they are electrically conductive or semiconductive: silicon, SiC, Molybdenum, stainless steel, titanium, WC, etc. High aspect ratio can be obtained. We are targeting applications related to prototyping or manufacturing of a master piece. So even a long machining time can be accepted as long as the process is flexible, cost efficient and fully automatic. Micro EDM, which is the miniaturization of EDM, has the potential to fulfil these requirements [4].

2 STATE OF THE ART

Different types of EDM machining are known with 20-100 µm resolution. The principal ones are:

- die-sinking with a complex 3D electrode (machined itself by milling or also by EDM)
- wire-cutting with a circulating wire electrode EDM
- hole-drilling with an electrode tip like a tube.

There is also a last configuration, named "EDM milling", which consists in using a tip electrode to perform the machining by computer numerical control. In theory this gives to the process the flexibility to machine parts with complex geometry and high aspect ratio from CAD CAM data. In practice EDM milling is a process rarely used probably because it is difficult to prepare thin electrode tools and it is necessary to compensate the wear of the electrode. As a matter of fact, at 20-100 µm resolution, EDM milling is less competitive than CNC milling but the situation has to be completely re-evaluated for the targeted resolution.

So far, electrode tools are prepared by milling, by EDM [5] or by reverse EDM (the electrode is machined against the workpiece while the applied voltage pulses polarity is reversed) [6-8]. We propose to use a straightforward low cost electrochemical process, developed for the manufacturing of Scanning Tunnelling Microscope (STM) tips and applied to the best of our knowledge for the first time to EDM.

3 EXPERIMENTAL SET UP AND RESULTS

3.1 Preparation of thin electrode tools

We report here on the electrochemical etching of thin Pt-Ir electrodes. This method is fast and easy to implement. Moreover it does not involve hazardous chemicals. Pt-Ir material was chosen due to its good electrical conductivity, stability (the electrode does not oxidize during the machining process), and high melting temperature but tungsten works also. Thin electrodes can be obtained with sharp apex of a few atoms, which is necessary for STM.

The Pt-Ir electrode is etched electrochemically using the setup in figure 1. Saturated NaCl solution is used. The tip etching process is commonly referred as a drop-off process [9]. The capillary forces of the electrolyte form a meniscus around the wire when it is immersed into the electrolyte. In the meniscus, the etching rate is enhanced, thus, a necking phenomenon is observed. Finally, this part of the wire becomes so thin that can not hold the lower end of the wire, so the latter breaks off and a sharp tip is left behind as shown in figure 2.

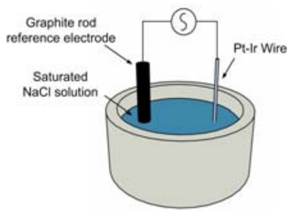

Fig. 1. Experimental setup for Pt-Ir wire etching to form a micro EDM electrode tool.

In practice, the etching is performed in several steps:

- apply AC 30 V for initial fast etching to make the neck of the wire more thin;
- adjust voltage to 20 V just before drop-off stage;
- lower voltage to 5-10 V to perform an accurate final drop-off step.

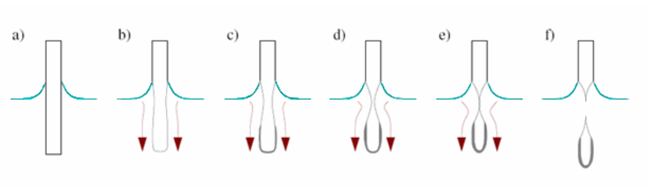

Fig. 2. Drop-off method for sharp tip electrode tool fabrication: a) meniscus formation; b) to e) necking phenomenon (arrows show Cl^- ions flow); f) drop-off of the lower part of the wire.

With this protocol, conic tools with a diameter of 1-10 µm, are obtained in a few minutes as shown in figure 3. It is known that 300 nm tips can be obtained [10]. Tools with cylindrical form can be prepared by drawing the metal wire during etching (for a detailed discussion see [11]). Surprisingly to the best of our knowledge, this method was never applied to the manufacturing of micro EDM tools.

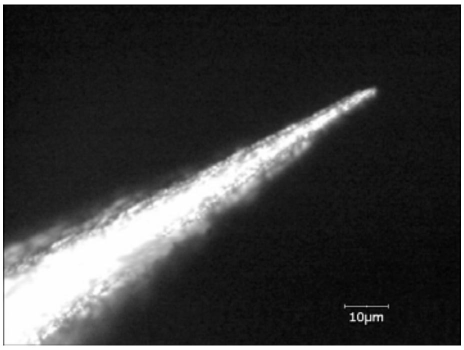

Fig. 3. Pt-Ir wire tip fabricated by electrochemical etching in NaCl solution (optical microscope ×50).

3.2 *Micro EDM machine*

Therefore we have developed a low cost and compact micro EDM machine with high resolution technology commonly used by the AFM-STM community (figure 4). We use a combination of micrometric and nanometric positioning actuators in order to achieve large working volume and high accuracy. It consists first in a motorized XY table with an independent motorized Z stage holding the working electrode (all stages are driven by stepper motors with 2.5 μm/step and speed up to 1000 steps/s). A second table driven with XYZ piezoactuators is mounted on the first XY one. We use Melles-Griot piezoactuators, with feedback correction, which provide 10 nm displacements along 30 μm range. The piezo-driven table carries a PTFE tank vat for keeping EDM dielectric liquid (50:50% vol glycerol:deionised water in our case).

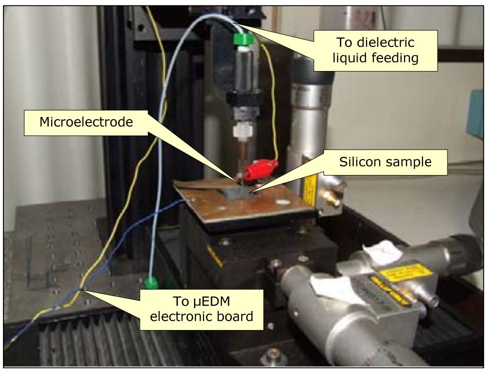

Fig. 4. Micro EDM machine with the Pt-Ir microelectrode, XYZ piezoelectric actuators and XY-Z micrometric translation stage (PTFE vat removed).

3.3 *Generation of microdischarges*

A simplified circuit schematic of the electronics developed in this work for microdischarge generation is shown in figure 5. The circuit is composed of three fast ignition gate bipolar IBGT transistors (25 ns switch time). The first switch, controlled by the ‘charge’ signal, allows charging the working capacitor C through the current limiting resistor R by using an external power source. The second switch, controlled by the ‘discharge’ signal, closes the capacitor on the electrode-workpiece gap producing a discharge of the capacitor. The third switch, controlled by the ‘reset’ signal, is used to implicitly reset the residual charge of capacitor (or even the whole charge if the spark did not occur). A voltage drop on the diode connected to the workpiece is used as a reference to produce the feedback signal, called ‘sense’. The RC-charge/discharge process is fully controlled by the microcontroller (MCU) which communicates with a host computer. So high speed pulses (25 ns of ramp) are generated with a voltage of 10-100 V at programmable repetition rate (up to 50 kHz) so as to deliver energetic pulses from μJ to mJ level. The MCU controls also the positioning of the substrate against the working electrode by sending appropriate voltage to the different positioning stages.

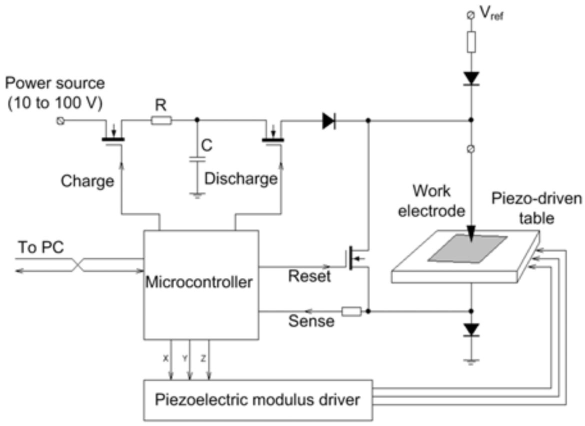

Fig. 5. Simplified circuit schematic.

3.4 *Gap monitoring*

As shown in figure 6, when approaching the tool toward the substrate, different events can occur:

- no discharge (A)
- current leaks between electrode and workpiece with no machining (B)
- normal discharge occurrence with machining (C)
- short circuit occurrence (D).

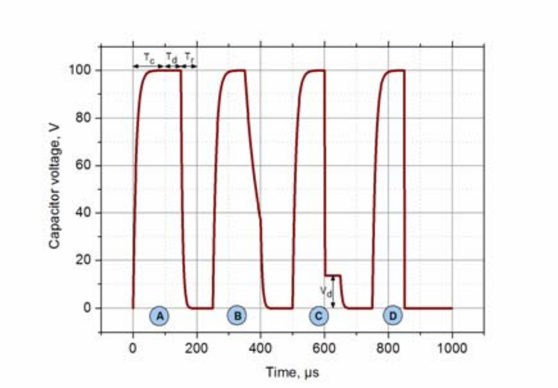

Fig. 6. Capacitor voltage waveform (C=100 nF, R=100 Ω, T_c=100 µs, T_d=50 µs, T_r=50 µs - repetition frequency = 4 kHz)

During machining, the tool has to be translated down since the gap between the tool and the part increases. The EDM system constantly balances between open and short circuit modes (A and D) to maintain a stable spark discharge (C). It is also necessary to avoid non machining discharge (B). Several methods are known for the monitoring of EDM discharge to obtain a stable machining process. In a first approach, we simply decided to count the number of "good" discharges (C) using the 'sense' signal of figure 5.

3.5 Preliminary results with silicon

The machining of silicon has been reported in a pioneering work by [12] with a commercial EDM machine. The feasibility of the micromachining of p+ doped Si wafer with (100) crystallographic orientation was demonstrated with our set up. See for example the cavity with pillar shown in figure 7. Process parameters are under development for Si, WC and stainless steel.

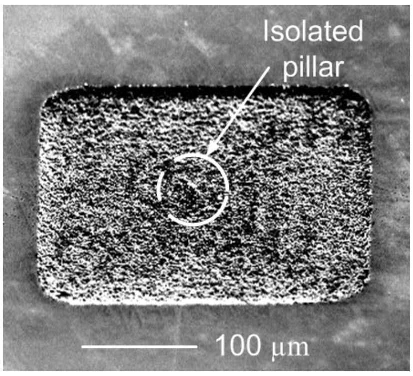

Fig. 7. SEM view of a 250×250 µm cavity machined in silicon with an isolated pillar (~ ∅ 1 µm) raised in the centre.

4 CONCLUSIONS

The use of electrochemically etched Pt-Ir electrode tool for EDM machining has been demonstrated. This solves one of the main issue which has delayed the development of micro EDM. In addition a compact micro EDM machine has been developed. This machine is close in terms of size and technology to STM instruments which are familiar in research laboratories. Taking account the potential applications, we believe that such technology may be of high interest in micro nanotechnology and microfluidics.

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