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WATER JET BASED TOOLING STRATEGIES FOR MICROPRODUCTION

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Abstract:

This contribution presents an investigation about the possibilities of using Water Jet (WJ) technology in combination with Micro Electrical Discharge Machining (MEDM) for tooling production in micro manufacturing. In the first phase the tool used in MEDM is produced by WJ machining. Afterwards, the final tool in steel is produced by MEDM. Such kind of tools are intended to be used in processes like hot embossing, moulding, and other replication technologies in the field of micro manufacturing. The first results are very promising and the proposed tooling strategy, which involves besides MEDM also WJ technology, shows a lot of potential especially in the design and developing phase of micro-fluidic devices.

Keywords: tooling, non-conventional technologies, MEDM, WJ, micro-fluidics

1. Introduction

Machining of tools used to produce micro components is usually expensive and time consuming. Thus, the tool used for replication technologies such as hot embossing or moulding has to be well defined in advance, since once the tool is produced there is very little room for corrections or modifications.

The main objective of this contribution is to present a new tooling strategy based on the application of WJ machining, which would allow relatively quick and cost effective production of prototype micro components. In the first step the tool for MEDM is produced in copper by WJ technology. Then the copper tool is used by MEDM technology to produce the final tool in tool steel, which may be further used for replication processes such as hot embossing, pressure moulding and others. The complete process is shown in Figure 1.

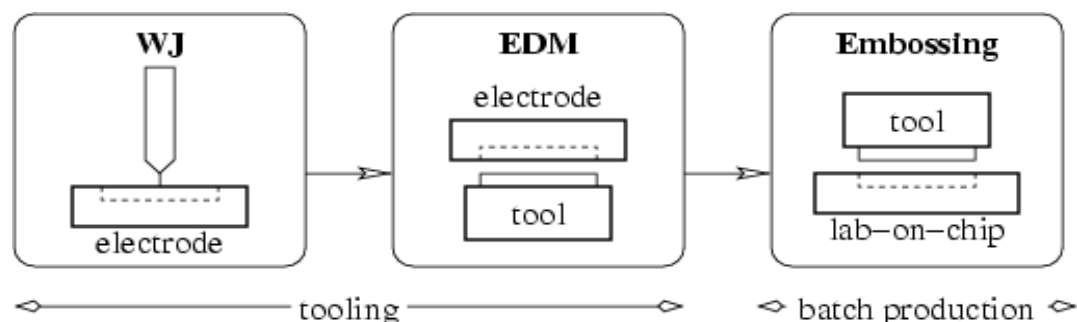


Figure 1. The process chain of micro-fluidic channel production.

The high flexibility and cost effectiveness of the proposed tooling strategies provide the designer of micro components with more freedom and testing opportunities during the development of new micro devices.

The main application field of the proposed tooling strategy is the design and development of micro-fluidic devices. Typically, these devices require a well controlled geometry and surface roughness [1]. With this technology these devices can be manufactured relatively fast and in a cost effective way. Therefore many new concepts and designs can be experimentally validated during the development phase in order to improve the performance of the final product. In the actual context of R&D, flexibility in the manufacturing process enables variety and innovation in the design. The proposed tooling strategy consumes most of its machining time in EDM machining while WJ machining accounts just for a small portion of the total machining time. However, facing this sequence of different processes, WJ machining of the EDM tool has an important influence on the final result.

The paper is organised as follows. The first section is an introduction to the proposed tooling strategy. The second section describes the WJ machining process applied to the machining of the tool that is used in EDM process. The characteristics of the EDM machining process of the final tool by the electrode previously described is given in third section. Fourth section is concerned with the achieved results. This constitutes the basis for the analysis and discussion that will be held in the fifth part. Finally, conclusions are given on the proposed tooling strategy.

2. WJ machining of EDM tools

WJ machining is a non-conventional process in which a high speed jet of water is used as the tool to remove the workpiece material by erosion. In order to generate such a tool, the water is first pressurized and then forced to pass through a small orifice. The water pressure is usually set up to 400 MPa and is generated with a hydraulic intensifiers specially designed for this technology. To generate an effective WJ, a specially designed nozzle with an orifice made in a sapphire insert is used. Typically, the diameters of orifices used for this technology are between 0.3 and 0.08 mm, depending on the application.

This technology is mostly used to cut softer materials like wood, plastics, rubber, etc. For metals and other hard to machine materials, Abrasive Water Jet (AWJ) is more appropriate due to a higher Material Removal Rate (MRR) comparing to WJ machining [2]. Basically, in order to produce an AWJ a WJ is lead through a mixing chamber where abrasive particles are added from the abrasive inlet, which are further accelerated in the focusing tube by the WJ. Figure 2 illustrates how a WJ and AWJ are generated inside the cutting head, respectively.

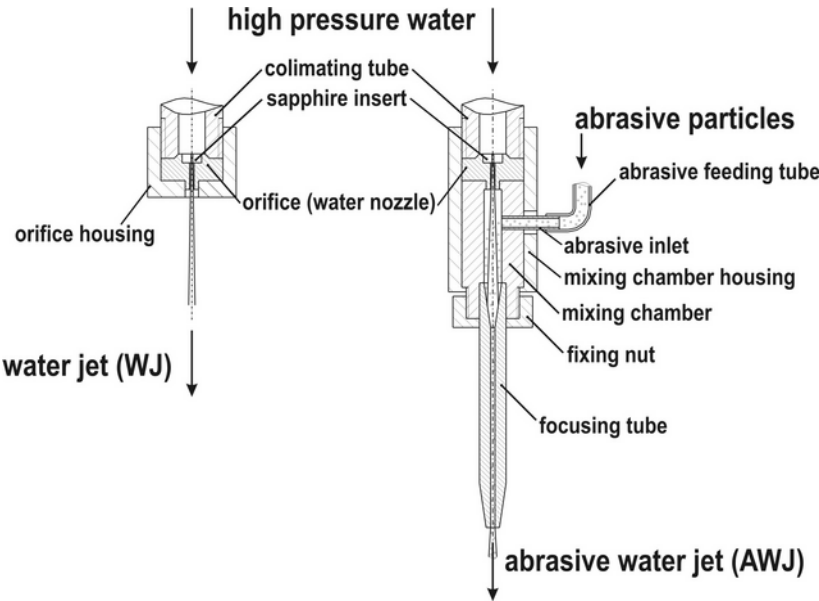


Figure 2. WJ and AWJ cutting head.

Nevertheless, WJ was selected instead of AWJ for the presented applications for two reasons: the size of the jet and the integrity of the machined features. In the first place, the size of the WJ is smaller than the size of the AWJ, which allows to machine smaller features. After several attempts it was observed, that AWJ produces more damage on the machined surface due to abrasive particles impacts.

In spite of all the advantages that WJ technology brings when producing electrodes for EDM, the main problem is how to control the penetration depth of the WJ into the workpiece material. It has been shown that the jet has still up to 90 % of the initial kinetic energy after exiting from the workpiece [3]. Because of this, the AWJ technology is mostly used for two dimensional cutting of parts out of a plate. Investigations in the field of AWJ milling [4-6] showed how difficult is to predict and control the depth of penetration of the AWJ into the workpiece material. In general, the depth of penetration depends on several process parameters. One of the most important is the traverse velocity of the cutting head, which defines the exposure time of the workpiece to the AWJ. This means that only 2.5 D tools for EDM can be produced with this technology. Because the depth of penetration can not be accurately controlled during WJ machining all features are deeper than required for the EDM process as shown in Figure 3. Thus the bottom of the slots of the EDM tool, machined with WJ, will not be functional surfaces.

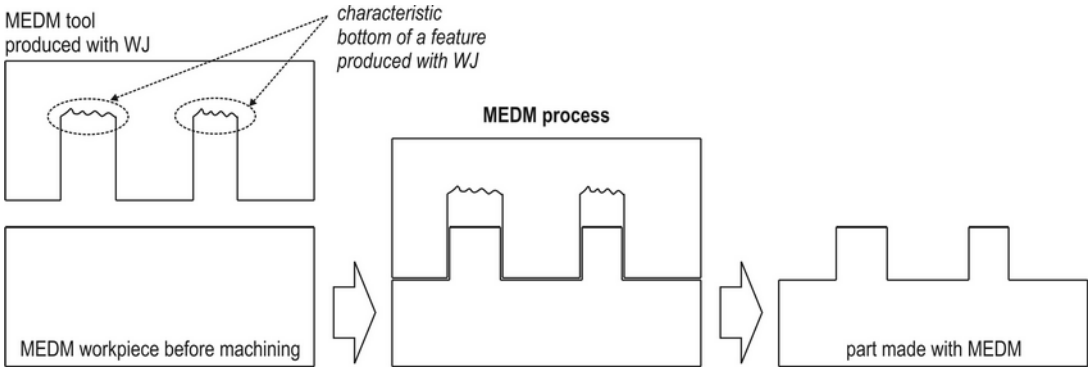


Figure 3. Specifics of MEDM tool production with WJ.

As a case study the production of the tool for a lab-on-chip application was chosen, which is presented in Figure 4. Dimensions specified on this figure are the ones expected on the final tool. They're derived from the expected dimensions of the features on the lab-on-chip part.

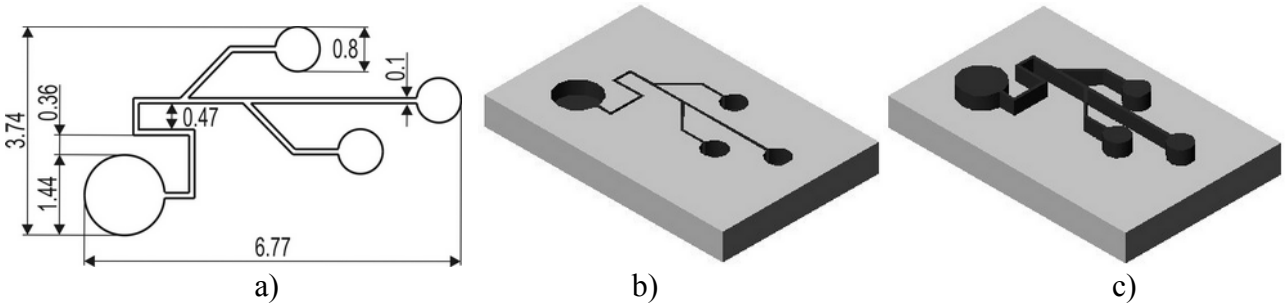


Figure 4. Lab-on-chip feature - a case study. (a) Dimensions of a finished part. (b) The shape of the MEDM copper electrode. (c) The shape of steel embossing tool.

Machining of the MEDM tool took place on the OMAX type 2652A/20HP abrasive water jet cutting system powered by a Böhler Ecotron 403 capable of reaching water pressures up to 410 MPa. In this case only a WJ cutting head was used with the orifice diameter of 100 μm. The water

pressure was set at 300 MPa, the traverse velocity of the cutting head was 10 mm/min and the stand off distance between the cutting head and the workpiece was kept constant at 2 mm.

The results of this machining phase are collected and analyzed in the conclusions together with the results of the MEDM machining phase.

3. MEDM production of the final tool

Electrical Discharge Machining (EDM) is a machining technique through which the surface of a metal workpiece is formed by discharges occurring in the gap between the tool, which serves as an electrode, and the workpiece. The gap is flushed by the third interface element, the dielectric fluid. The process consists of numerous randomly ignited monodischarges. During a discharge, a plasma channel is formed as the current conductor and the heat generator. On the spot of discharge a crater appears. The size of the crater depends on the discharge energy (Eq. 1), which can be set on the machine by adjusting the discharge current (i_e) and the discharge duration (t_e); the discharge voltage (u_e) is kept constant at about 25 V, but the ignition voltage (u_i) is set on the machine. The higher the ignition voltage, the easier is the formation of the plasma channel, but also the gap between the electrode and workpiece is greater.

$$E = u_e i_e t_e \quad (1)$$

The MRR is determined by the crater size and the frequency of crater generation, i.e. discharge energy and the frequency of discharges. The latter is influenced by the discharge duration (t_e) and the pulse interval (t_o) between two discharges.

The gap width between the workpiece and the electrode varies from 10 to 100 μm . The MRR is around 100 times higher on the workpiece than on the electrode [7]. Basically, several EDM processes are distinguished. In sinking EDM, the electrode has a negative shape of the required shape on the workpiece. The accuracy of the electrode shape is directly transferred into the workpiece if the orbital or planetary machining by employing CNC controller is not used. By wire EDM the contour cutting is performed by a thin wire which serves as an electrode and it is pulled through the workpiece from a supply spool onto a take up mechanism [8]. Due to the new trends (smaller, cheaper, better), machines should consume less power, should be smaller and more accurate. Following the trends, the MEDM process emerged, which can produce cavities even smaller than 20 μm in diameter [9].

The MEDM machining is usually performed with rod electrode, whose path is controlled by CNC controller. The commercially available rod electrodes have diameters down to 170 μm . Smaller diameters of electrodes are obtained by wire EDM grinding or etching [10]. In the present research, the tool for embossing of the micro-fluidic channels is made with a sinking EDM, since large volume must be removed in order to obtain the pin-like shape of the tool that is used to produce cavity-like micro-fluidic channels (Figure 3). To successfully produce such small features on the tool, relatively low electrical discharge energy (Equation 1) is used.

The following machining parameters were used: discharge current $i_e=1$ A, ignition voltage $u_i=180$ V, discharge time $t_e=8$ μs and pause time $t_o=36$ μs .

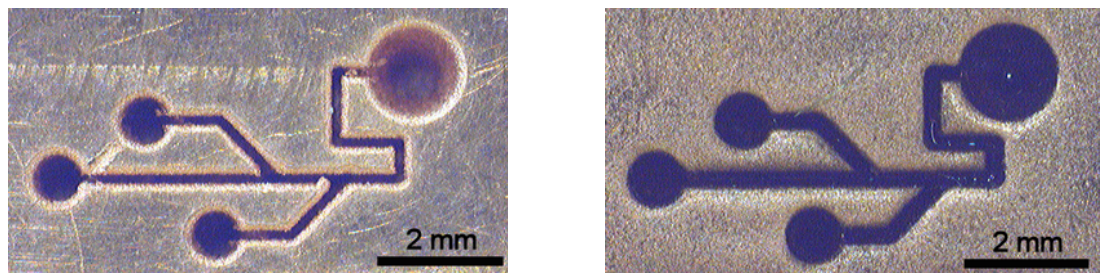


Figure 5. Electrode before and after the machining of the tool.

The wear phenomenon can be observed in the Figure 5, while the tool produced by the given electrode is presented in Figure 6.

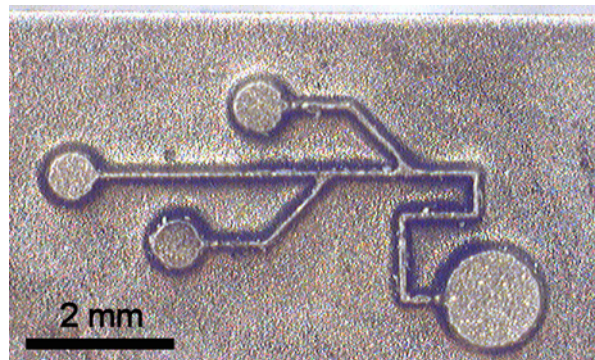


Figure 6. Steel tool for hot embossing Lab-on-chip application.

4. Results

When the embossing tool was finished, it was observed that the distribution of the machining time between different processes was in accordance with the assumptions made at the beginning. In order to produce the feature showed in Figure 4 with WJ process parameters, the machining time was less than 5 minutes. Compared to the MEDM machining time, which took about 12 hours for finishing this micro tool, this figure is really negligible. It is worth noticing that the MEDM machining time is related to the relatively low MRR ($0.051 \text{ mm}^3/\text{min}$) and the removed volume achieved (more than two times the volume of material left on the tool).

From the product point of view, various measurement points on the Lab-on-chip feature were measured as shown in Figure 7. The results of measurements are given in Table 1. In the first column desired dimensions of the micro-channels are given. We choose to control specific dimensions to evaluate the discrepancy between expected values (called Drawing) and obtained values (Steel tool).

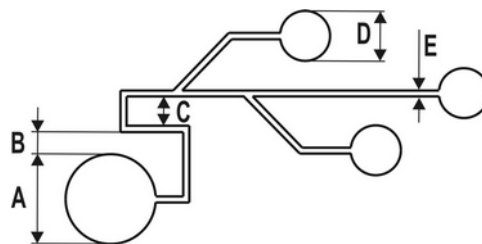


Figure 7. Drawing of a Lab-on-chip feature measurement points.

The side gap obtained by the MEDM machining parameters used is as big as $100 \mu\text{m}$. Surprisingly small is the tip of the rib. It has a width of only $40 \mu\text{m}$ due to the poor flushing causing the debris not to be removed from the gap. The ribs are a little conical.

Table 1. Results of MEDM of the tool.

Measure	Drawing [mm]	Steel tool [mm]	Electrode [mm]	Worn electrode [mm]
A	1.44	1.26	1.45	1.61
B	0.44	0.44	0.34	0.28
C	0.57	0.52	0.43	0.28
D	0.8	0.61	0.77	0.95
E	0.1	0.04	0.18	0.34

5. Discussion

Regarding the results obtained, some analysis can be done.

It can be observed that WJ performed very well as the deviation from the desired dimension is not so large, less than 30 μm . There was slight problem with the width of the main channel, which should be only 100 μm wide (the diameter of the WJ) but came out wider for 80 %. The reason is the back flow of the water jet that is widening the main channel. However, this is not balanced by the EDM. In spite of very good accuracy, due to the gap between the electrode and the workpiece (tool), which is in the given case around 100 μm , the size of the channel is smaller on the tool than on the electrode (Table 2). The size of the gap depends on the machining parameters and knowing the machining parameters in advance, the gap can be estimated with the precision of some micrometers.

Further improvements can be done if wear of electrode is kept under control. Figure 4 illustrate the electrode produced by WJ before and after machining of the tool by MEDM process. Electrode wear is quite big due to the poor flushing of debris from the gap. In the given case, the flushing was performed by additional nozzles supplying fresh dielectric in the gap. Better performance could be achieved by flushing through the electrode, which requires additional holes in the electrode. However, the gap is the bottleneck of the debris flushing and there are little chances that these extra holes could enhance the circulation of the debris.

The conical shapes of the ribs are mainly due to the conical shape of the side walls made by machining the electrode by WJ. Additionally, poor flushing of the gap during MEDM machining also contributed to the conical shape of the rib. Nevertheless, this must not be considered as a drawback because a draft angle is necessary to achieve the further manufacturing process, which is embossing or moulding. This parameter has to be efficiently controlled to better integrate the constraints related to the further usage of the tool.

Two prospects have to be developed. The first one is the opportunity of involving CNC controlled MEDM machining, also called orbital or planetary machining. This solution is quite complex to implement and needs to be studied with regards to the topology of the part (proximity of features could lead to interferences in the tool geometry).

The other way is by dividing the EDM machining stage in two or more phases. The big job of removing the major part of the material can be done with rough conditions while the finishing is leaved to a finishing electrode with more appropriate conditions. Of course, the influence of debris flushing would decrease drastically as the machining of the functional surfaces would not be treated by the rough machining phase.

6. Conclusions

The future work will be focused on enhancing the process. Starting with the flushing of the gap, improvement will be performed by flushing through the electrode. Other electrode materials, such as graphite, will be used in experiments.

Research will also concentrate on the relationship between the expected EDM tool dimensions and the final tool dimensions by taking into account the wear of the electrode which strongly depends on the machining parameters. Using multiple MEDM tools in various conditions will surely help to master the key parameters. In general, efforts will be made to characterise the whole process and to model it. Strong interactions exist that should be highlighted to better master the process.

Finally, a detailed study of the surface roughness should be held in order to refine the process parameter. Microfluid flowing behaviour is very sensible to the surface quality and the ability of the process to obtained the desired roughness will make, with no doubt, a decisive advantage

Acknowledgement

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