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Engineering

PRODUCTION OF MICROMIXER USING UNCONVENTIONAL TECHNOLOGIES

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ABSTRACT:
TECHNOLOGIES FOR MICROPRODUCTION ARE BECOMING MORE DIVERSE AND PRECISE. THE NEED FOR SMALL PRODUCTS IS INCREASING AND THERE ARE MANY OPTIONS TO PRODUCE DEVICES WITH ACCEPTABLE PROPERTIES. APPROPRIATE CHOICE OF MATERIALS AND PROCEDURES CAN BE BENEFICIAL BOTH FROM COST AND SPEED OF PRODUCTION POINT OF VIEW. IN THIS PAPER PROCESS CHAIN FOR PRODUCING MICROMIXER IS PRESENTED. TECHNOLOGIES USED ARE: WATER JET (WJ) AND ABRASIVE WATER JET (AWJ) CUTTING, DIE-SINKING ELECTRICAL DISCHARGE MACHINING (EDM) AND GRAVITY CASTING OF POLYDIMETHYLSILOXANE (PDMS). MAIN SOURCE OF ERROR AND DEVIATION WAS CUTTING WITH WJ, SINCE IT PRODUCED HIGH TAPER. AWJ WAS BETTER, BUT WIDTH OF CUT WAS NOT ACCEPTABLE FOR NARROW CUTS. OTHER TWO PROCESSES PERFORMED ADEQUATE TO MICROPRODUCTION STANDARDS, BUT CAN BE GREATLY IMPROVED AS WELL.

KEY WORDS: MICROMIXER, EDM, WATER JET, PDMS

INTRODUCTION

In recent years the demand for small and precise products has greatly increased. Not only the electronics and computer industry but most of other important branches of mass production are trying to make their products as small and as cost effective as possible[2]. New materials require different procedures for producing such small products with high accuracy and narrow tolerances.

Micro product is by definition of 4M association (Multi-Material Micro Manufacture) a product that contains geometries with 2 dimensions of less than 1 mm. Technologies for manufacturing such products vary greatly and depend on what the product will be used for. Rapid prototyping methods are used to quickly evaluate if the geometry and procedure are appropriate or not[3].

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[2] Whitesides, "The origins and the future of microfluidics", 368.
[3] Sabotin et al., "Repeatability and limitations", 151.

Microfluidics is one of the most important branches where products on micro scale are used. First applications of microfluidics were used in substance analysis. Small dimensions enable very good flow and temperature control, which results in high accuracy process control[4]. Possibility of analyzing substances with microfluidic devices and therefore needing just a fraction of quantity, which is usually needed when using conventional methods of analysis, is very cost and time effective[5]. If you needed 1 L of substance for analysis with conventional methods, this number drops down to 1 nL or even less for microfluidic devices. In the last two decades there has been great demand for so called LOC – lab-on-a-chip microfluidic devices, which enable very effective analysis and complex chemical reaction on very small scale.

The goal of the research was to investigate how accurately can micromixer be produced using technologies that are not yet established as parts of production chains and are mainly suited for machining macro parts. Two unconventional technologies for machining were used: water jet and EDM. Maximum amount of time that was supposed to elapse from start to finished product was less than 1 day.

MATERIALS AND METHODS

Proposed production process chain was: use of water jet (WJ) or abrasive water jet (AWJ) cutting to make electrodes from 1 mm thick copper plate suitable for EDM, EDM machining of stainless steel workpiece and finally casting liquid polymer PDMS over the tool to produce the final product.

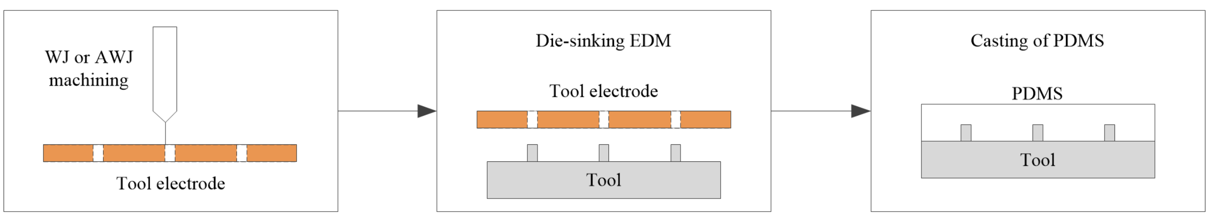

Figure 7: Production chain of micromixer

Electrodes, workpiece - tool and the final product – micromixer were measured using pictures taken with CCD camera which were analyzed in MATLAB. The main goal was to find out how do the geometries and dimensions change along the process chain. The proposed geometry of the micromixer can be seen in Figure 8. It is commonly known as Slanted Groove Micromixer (SGM). It consists of multiple grooves with desired width and spacing. Grooves are arranged in sequence with 45° angle in relation to main channel. Grooves cause lateral displacement of the fluid due to its entrainment. The effect of this is exponential increase of interface surface between two reactants, which through diffusion greatly enhances mixing[6]. Even though this is not optimized geometry of a micromixer, it was suitable for purposes of our research.

[4] Sia, "Microfluidic devices fabricated in poly(dimethylsiloxane)", 3563.
[5] McDonald, "Poly(dimethylsiloxane) as a material", 491.
[6] Sabotin et al., "Optimization of a bottom grooved", 196.

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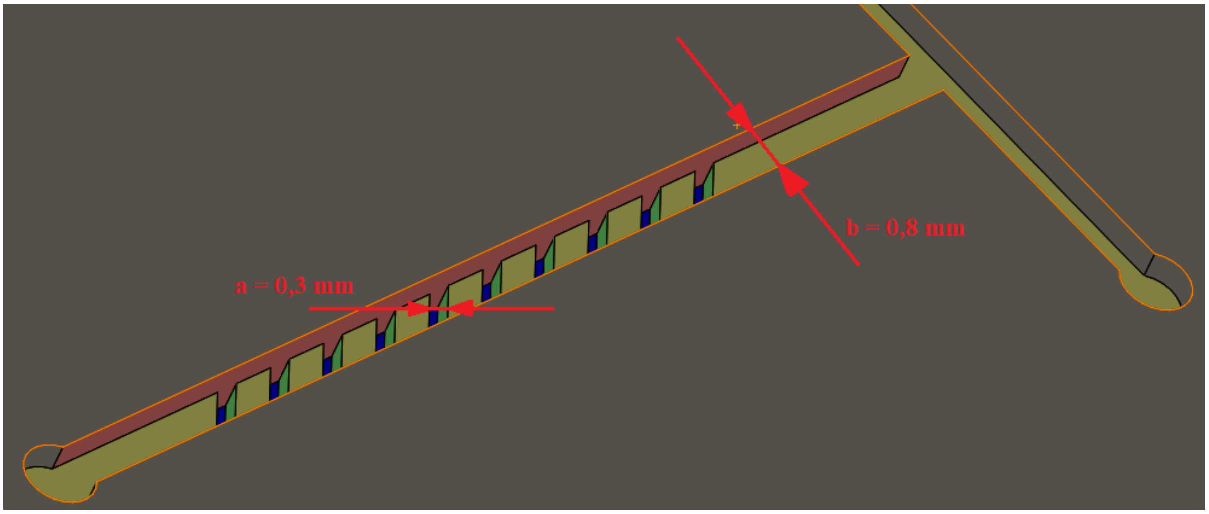

Figure 8: Proposed micromixer geometry

The arrows with numbers on Figure 9 present proposed measuring spots and are translated throughout the production chain. At numbers 1-4 only width of the channel was measured, but on numbers 5-14 width of ribs (on the tool) or grooves (on micromixer) was also measured.

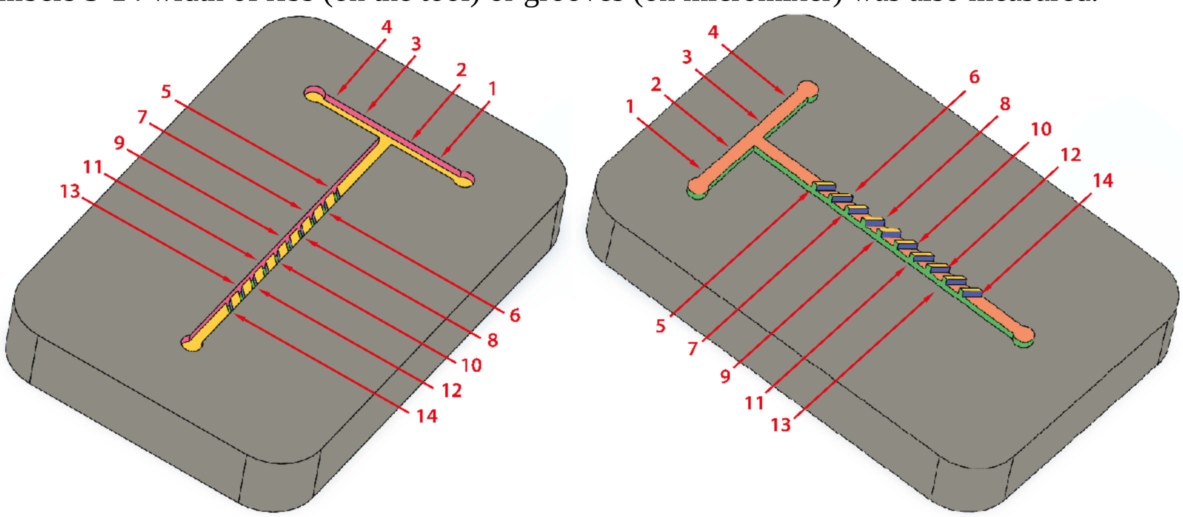

Figure 9: Model of micromixer (left) and tool (right)

WJ AND AWJ MACHINING

With known proposed geometry of micromixer, first step in process chain was possible. Machine tool used for WJ and AWJ machining was OMAX type 2652A/20HP with Böhler Ecotron 403 hydraulic intensifier capable of reaching 410 MPa water pressure. Water nozzle Type 91 from Allfi (Switzerland) with 0.3 mm inside diameter and focusing nozzle with 0.8 mm inside diameter from same manufacturer were used. Tool paths for cutting were programmed in 2D as seen on Figure 10. The difference between WJ and AWJ is in cutting speed and width of cut. Therefore, it was decided that 2 pairs of electrodes should be made, one with WJ and the other using AWJ. The electrode on Figure 10 (a) was named electrode A and was intended for EDM of the side and main channels. Electrodes on Figure 10 (b) and (c) were named electrode B, but the first electrode had only 6 cuts and the second one, which was later optimized and only cut with WJ, had 10 cuts. As seen on Figure 10 (c) lead-in and lead-out tool paths had to be made in order to move the point of piercing as far away from middle as possible, while still keeping it close enough for shorter time of cutting[7]. For cutting with WJ, water pressure was set to 300 MPa and the cutting speed was set to 5 mm/min. Cutting speed with AWJ was much faster at about 800 mm/min [6].

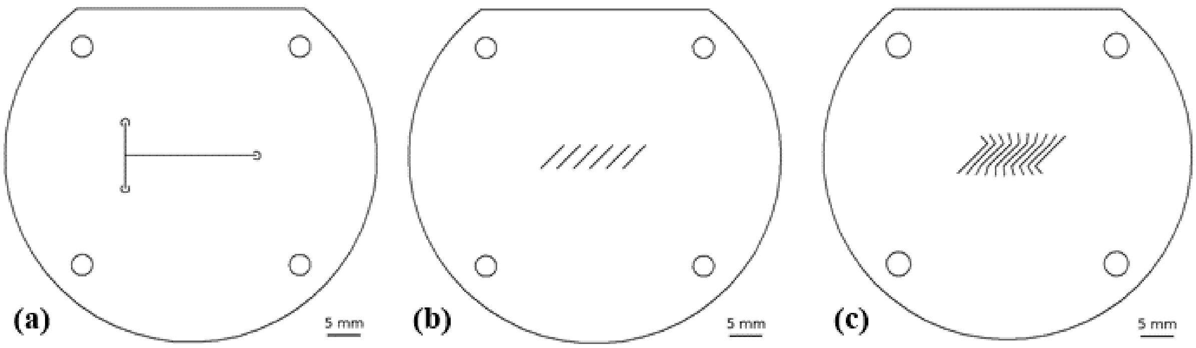

Figure 10(a) toolpath for cutting electrode A, (b) toolpath for cutting electrode B, (c) toolpath for cutting optimized electrode B

ELECTRICAL DISCHARGE MACHINING

Die-sinking EDM was used to machine stainless steel workpiece with electrodes shown in Figure 9. IT Elektronika 200M-E EDM machine was used. Special holder was used to fix the electrode and provide flow of dielectric fluid from inside. This meant that the gap flushing was very good. First, electrode A was used to machine the side and main channels. Depth of machining was set to 1 mm. Since a lot of material had to be removed it was decided that rough machining should be used first and later switch to fine machining. Parameters used for both settings are presented in Table 1.

Table 1: Machining parameters for electrode A

EDM setting	Peak current [A]	Voltage [V]	Pulse on time [μs]	Pulse off time [μs]
Rough	16	280	350	50
Fine	5	280	60	18

With the use of fine machining parameters, gap reduces and so does the heat affected zone. Low material removal rate (MRR) was also consequence of fine machining parameters, which meant longer time of machining. Fine parameters were used as late as possible.

[7] Valentinčič et al., “Alternativne tehnologije: učbenik za tretji letnik”, 102.

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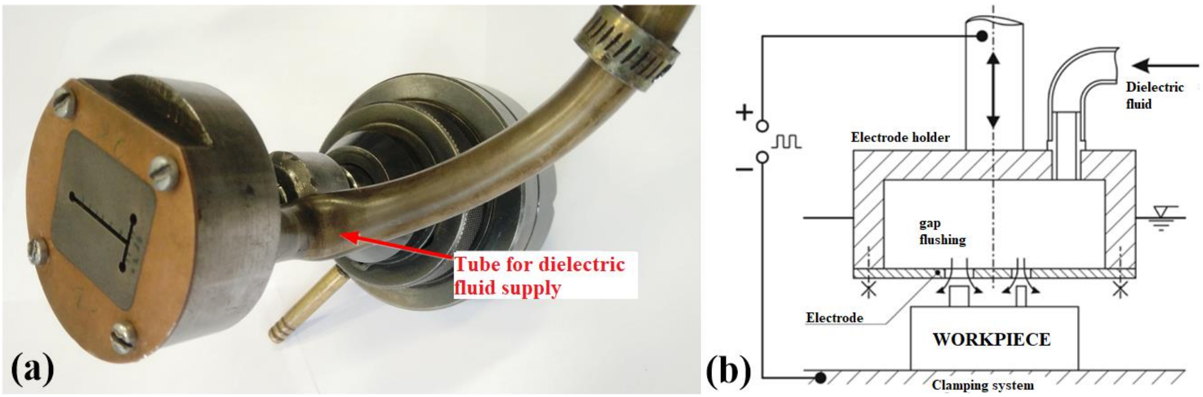

Figure 11: (a) holder with mounted electrode, (b) cross section of the holder

Seen on Figure 11 is the special holder and cross section of the same holder. Gap was flushed from the inside. Since very small geometries were machined, it was of great importance to avoid disturbances during discharges. Machining with electrode B was always done with fine machining parameters, because the eroding surface was very small. Parameters for machining with electrode B are presented in Table 2.

Table 2: Machining parameters for electrode B

EDM setting	Peak current [A]	Voltage [V]	Pulse on time [µs]	Pulse off time [µs]
Fine	2	280	45	18

With some testing it was concluded that electrode A cut with AWJ and electrode B (with 10 cuts) cut with WJ shall be used for machining the tool needed for further manufacturing. Final result of the machining was tool insert seen on Figure 12.

GRAVITY CASTING OF POLYDIMETHYLSILOXANE (PDMS)

PDMS is a two-component polymer which consists of base material and curing agent. We used QSil216 from ACC Silicones (United Kingdom). Special casting device was manufactured from aluminum which enabled to firmly secure and cast the machined side of the tool. Two components of the polymer were first mixed in a cup and then exposed to 70 mbar vacuum for 15-30 minutes to remove air bubbles from the mix. Once most of the air was removed, liquid polymer was poured into the device and then exposed to vacuum again. When the polymer had appropriate properties in terms of air content, it was exposed to 100 °C for about 1 hour, which allowed the polymer to cure. Final product was easy to remove from the device. In total, 5 micromixers were produced.

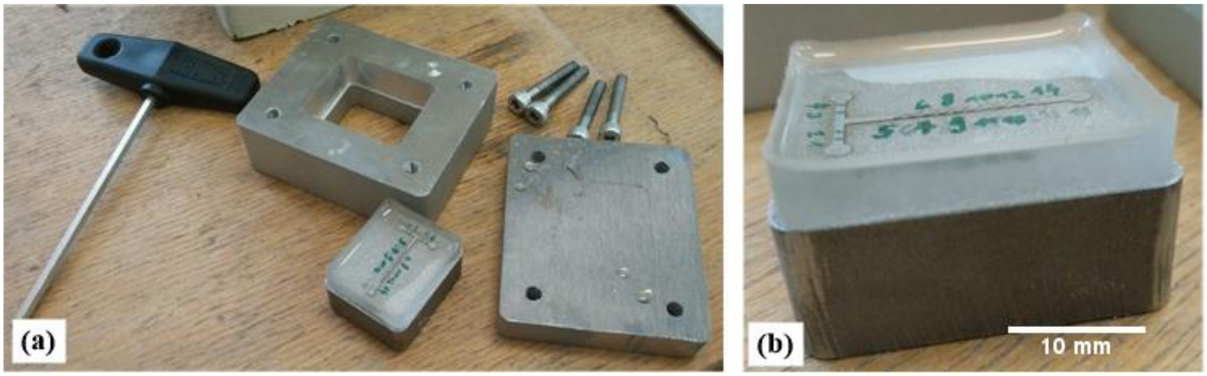

Figure 12: (a) disassembled casting device and tool, (b) cured final product on the tool

RESULTS AND DISCUSSION

As expected, cuts made with AWJ were wider than those made with WJ only. AWJ provided better repeatability in terms of cutting kerf, because the standard deviation was much smaller. Both procedures performed well when cutting electrode A and electrode B with 6 cuts. In case of electrode B with 10 cuts (only WJ), the cutting process was far more difficult. With slower cutting speed this meant that there was a lot of taper present. It was discovered that brand new water nozzle had to be used, otherwise WJ would become too wide and would erode or rip off material between cuts. With brad new orifice, the cuts could be as close as 1.2 mm apart and had less taper.

While machining with EDM, minor electrode wear was observed. Wear resulted in decrease of taper and its deviation on both A and B electrodes cut with WJ as well as AWJ. Comparison of width is shown on Figure 13. In case of AWJ, taper is much smaller by default, because of mechanism by which material is removed. Width of cuts on electrodes A and B was increased after use on the EDM machine. Width increased by less than 10%, but again, deviation of the cut decreased as well. This was present on electrodes cut with WJ and AWJ almost proportionally to width of the cut. Width of cut on the electrodes increased mostly after 1st use of the electrode on EDM machine. After further use of electrodes, wear was barely perceptible. Deviation kept decreasing with more electrode use, which was expected.

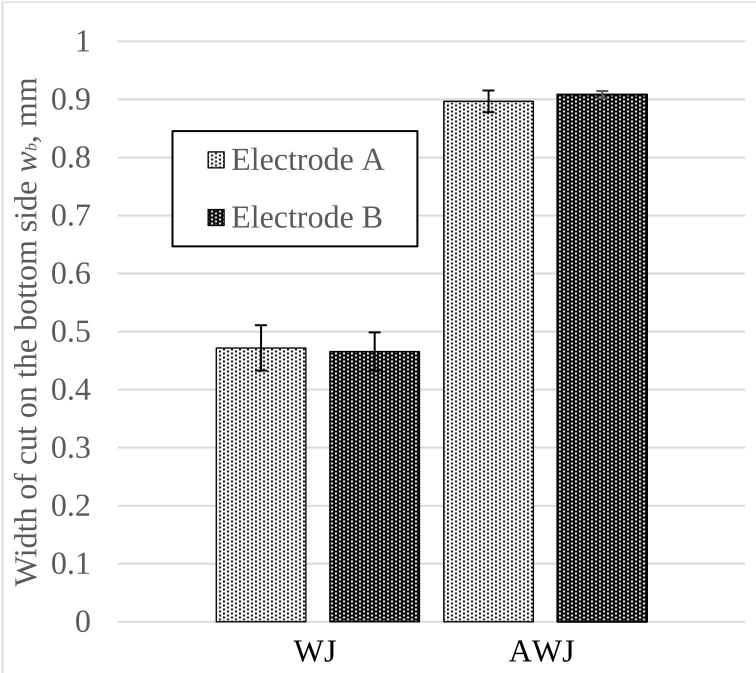

Figure 13: Width of cuts on the bottom side of electrodes

Final tool was machined with electrode A, cut with AWJ and electrode B (with 10 cuts) which was cut with WJ. Where electrodes had cuts, material was left on the tool and presented negative of the final product. Some differences in dimensions were expected, since a gap between the electrode and the workpiece is always present. The difference was in range of few hundreads of a milimeter. Features on tool are therefore of smaller dimension due to gap. Width of the gap depended on operating parameters. Fine parameters resulted in smaller gap and therefore smaller difference in dimensions.

With 5 micromixers produced, it was possible to compare measurements. It is known that polymer shrinks about 1% during transition from liquid to solid. Measurements were conducted on each micromixer and averages for main channels and features were calculated respectively. Main channel widths were always narrower than 0.8 mm. Widths of grooves were expected to be greater than theoretical value of 0.3 mm. It turned out that width was around 0.4 mm. Eventhough dimensions were acceptable, the deviation between separate micromixers was too high for mass production. There are many factors for differences between micromixers‘ dimensions including deformation during curing, not using clean room for casting, not curing at constant temperature, when removing products from the tool it is possible to use too much force and deform micromixer.

Changes in dimension throughout the production chain were greater in case of main channel as seen on Figure 14. More significant changes were present because of diferent EDM parameters used in machining. Electrode wear was clearly visible on electrode A. So much wear was caused by discharges which were far more powerful than those with electrode B. Difference in surface area was extensive as well. Wear was not noticed in case of electode B. Dimensions on the tool were smaller in both cases, but decreased less with electrode B, that is again due to fine machining parameters, which caused much narrower gap during machining and therefore less difference in dimensions between the electrode and the tool. Difference in dimensions on tool and micromixer were about the same in both cases which means that PDMS material shrinked evenly.

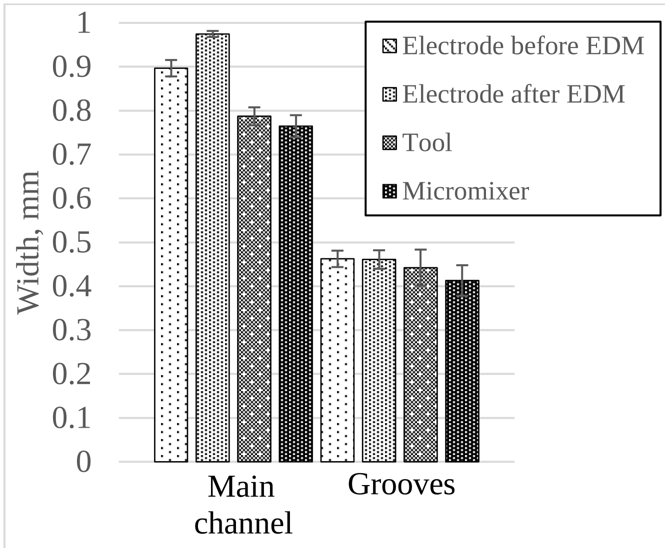

Figure 14: Comparison of dimensions throughout production chain

Final dimension of grooves in the main channel changed less and decreased in every step of production chain to final dimension of around 0.41 mm. Average dimension difference between electrode and micromixer was 0.06 mm. On main channel dimensions changes were greater and mostly due to rough machining parameters on EDM machine. Overall difference in width of main channel was 0.14 mm, starting with 0.9 mm on electrode and ending with 0.76 mm on micromixer. Width on micromixer was smaller even if electrode was significantly widened due to wear. Deviations did not show any trend of becoming smaller through production chain.

CONCLUSION

Presented production process chain is relatively simple and reliable, but for more precision better machines and more fine parameters should be used. At present state the production process chain would not be appropriate for mass production. It is obvious that precision mostly depends on how good AWJ and WJ processes are. Especially in WJ, where deviation of width and taper are significant. A lot of error is due to sapphire orifice which could be replaced with a diamond one. Diamond orifice starts showing signs of wear after longer time than the sapphire one and retains its shape much longer, therefore it would be more suitable. Precision of machining with EDM depends on machining parameters. For this research we tried to optimize time of machining, but sacrificed some precision because of it. For more precise tool insert, we would have to use fine machining throughout the EDM process and try to decrease them even further when machining with electrode B, since its surface area is very small. Replication with PDMS proved to be suitable, but differences between each micromixer were present and obvious after measurements. Even so, the PDMS replication of the tool insert was so good that separate craters created by EDM machining were visible on micromixers surface. For more precision, casting should be performed in more controlled environment and parameters should be closely monitored (humidity, temperature, time). Deviations between micromixers were too great to consider using this process for mass production.

It was proved that this production process chain can be used to manufacture micromixers, but accuracy must be improved. Machines with greater accuracy should be used for further research as well as appropriate room for handling with PDMS. It would be possible to produce acceptable products with existing production chain, but repeatability must be improved greatly.

REFERENCES

1. **McDonald, J. Cooper; Whitesides, M. George**; *Poly(dimethylsiloxane) as a material for fabricating microfluidic devices*, Accounts of Chemical Research, 2002, 35, 7, p. 491- 499;
2. **Sabotin, Izidor; Bissacco, G.; Tristo, G.; Valentinčič, Joško**, *Optimization of a Bottom Grooved Micromixer Design, 4M 2011, Proceedings of the 8th International Conference on Multi-Material Micro Manufacture.* Stuttgart, Germany, 2011, p. 196-200;
3. **Sabotin, Izidor; Valentinčič, Joško; Cvjetčanin, Mladen; Junkar, Miha**, *Repeatability and limitations of water jet based micro-tooling process chain,* 4M 2010, Proceeding of the *7th International Conference on Multi-Material Micro Manufacture*. Bourg en Bresse and Oyonnax, France, p. 151-154;
4. **Sia, K. Samuel; Whitesides, M. George**, *Microfluidic devices fabricated in Poly(dimethylsiloxane) for biological studies,* Electrophoresis 21, 2003, p. 3563– 3576;
5. **Valentinčič, Joško; Orbanić, Henri; Kramar, Davorin; Junkar, Miha; Tušek, Janez; Kopač, Janez**, *Alternativne tehnologije: učbenik za tretji letnik visokošolskega strokovnega študijskega programa I. stopnje*, Fakulteta za strojništvo, Ljubljana, 2012;
6. **Whitesides, M. George**; *The origins and the future of microfluidics,* Nature 7101 (2006) p. 368-373;