ABRASIVE WATERJET AS A PART OF INDIRECT PROCESS CHAIN FOR MICROMIXER MANUFACTURING

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Microproduction-based lab-on-a-chip technologies have recently been substantially advanced and have become widely used in various multidisciplinary research fields, including biological, (bio-) chemical, and biomedical fields. A key factor in microproduction is micro tooling. For mass production it is of paramount importance to produce tools from materials with excellent mechanical properties, thus the machining processes need to be able to produce geometrical features smaller than 1 mm in such materials. In this paper, an indirect process chain for production of micromixer and comprising of waterjet (WJ) and abrasive waterjet (AWJ) machining, die-sinking electrical discharge machining (EDM) and casting of polydimethylsiloxane (PDMS) is presented. The main source of dimension deviations is WJ machining. AWJ machining performs much better – for the given application the precision is satisfactory, but the kerf width is too large.

KEYWORDS

AWJ, EDM, casting PDMS, micromixer, lab on a chip

1 INTRODUCTION

Microfluidic devices have a lack of high volume production, thus the development of a microreactor system is usually performed in the following steps. At first a microscale process is developed within a single microreactor. Then the dimensions of microreactor are extended as much as possible (scale-up). In the last step, microreactors are multiplied (scale-out/numbering-up) and connected together to obtain a required throughput and productivity. All the research of (bio)chemical reactions in microreactors is usually performed only in the first two steps. The last step has been done in only in a few cases. One of the obstacles for scaling-out is also manufacturing technologies [Wohlgemuth et al. 2015].

An important areas of applications for micro devices are medicine and biotechnology in general. In the late 20th century, microproduction has been a domain of silicon based microelectronic production and only in the recent years a demand for non-silicon based microproducts has arose [Menzet al. 2007]. Accordingly, new microproduction processes are in constant development in order to meet the market demands.

Since the application is intended to be applied in large scale worldwide, a reliable and cost effective production method is required. Natural candidates are replication process like hot embossing or injection moulding. However, design and manufacturing issues are switched to the tooling part of the overall process. Due to the specific characteristics of tool material and the difficulty to obtain the finished tool with a single process, a study of the product requirements and the achievable characteristics of the related manufacturing process is required. The intelligent combination of such processes, i.e. process chain, can be proposed as a strategy for tooling.

Various relatively complex strategies have been proposed in the literature to satisfy the needs of microfluidic systems. A good overview of micro systems technologies (MST), often referred as microfabrication technologies, applied in this field (e.g. photolithography, electron beam and focused ion beam direct writing) is given by [Ha et al. 2016]. But these technologies can not satisfy the demands of low cost mass production, which is necessary to bring microfluidic systems to industrial applications. [Bissacco et al. 2005] stated that manufacturing of polymer microfluidic components is a key technology for the implementation of microfluidic devices in consumer products. If microfluidic chips can be produced in an effective, accurate and economical way, a whole range of new applications will emerge and the applications already existing will attract much more attention. Low cost mass-production of polymer microfluidic components can be achieved using either injection moulding or hot embossing. Both techniques require a tool to transfer the microstructures to the polymer material. A key issue is therefore the manufacturing of the tool. [Uhlmann et al. 2016] made a good overview of micro engineering technologies (MET), often referred as micromanufacturing technologies, used for metal processing, e.g. micro milling, micro EDM milling, laser micromachining, etc.

There are basically two tooling strategies or two groups of process chains for microtool production, namely direct and indirect process chain. In direct process chain the features of the tool are produced directly whereas in indirect process chain the features are produced first in master and then transferred to the tool for mass production. Most often aluminium master is produced, nickel is deposited on top of it and then aluminium is dissolved leaving the nickel tool that is used for mass production. These process chains are thoroughly described by [Qin et al. 2015].

In this paper, an alternative indirect tooling strategy is presented and characterised. It includes waterjet (WJ) and abrasive waterjet (AWJ) machining to manufacture tool electrode, die-sinking EDM to manufacture tool insert and casting of polydimethylsiloxane (PDMS). The process chain presented in Figure 1 is used to produce a micromixer with slanted grooves (SGM). The obtained characteristic dimensions on tool electrodes, tool inserts and PDMS products were measured and the mapping of dimensions from one process to the next one was examined.

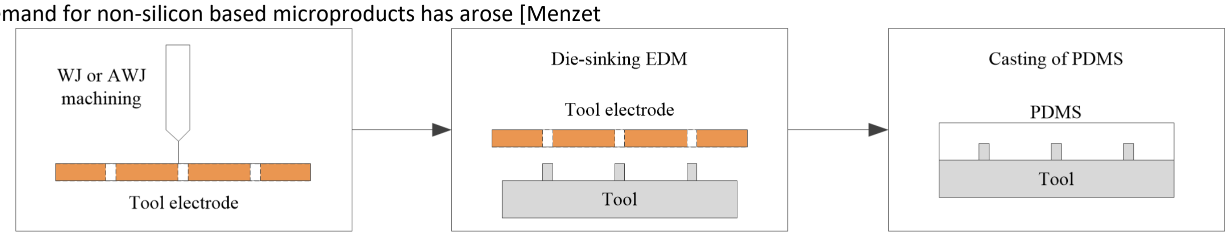

Figure 1. Microtooling process chain for casting of micromixer

A similar process chain was proposed by [Jurisevic et al. 2007] and [Sabotin et al. 2010], which was used for manufacturing of a microreactor. It is worth to note that die-sinking electrical discharge machining (EDM) process requires a tool electrode to be properly shaped to produce the required shape on the tool for mass production. Thus, all tool inserts machined by die-sinking EDM are literally machined via indirect process chain.

2 OVERVIEW OF THE MACHINING PROCESSES USED IN APPLIED MICRO-TOOLING PROCESS CHAIN

The required micromixer geometry is presented in Figure 2 as well as the tool insert for casting of micromixers. One can notice that a lot of material needs to be removed on the tool insert which requires a lot of machining time if micro milling or similar processes are utilised.

Thus, the use a die-sinking EDM with fine machining parameters and dedicated tool electrodes could be advantageous.

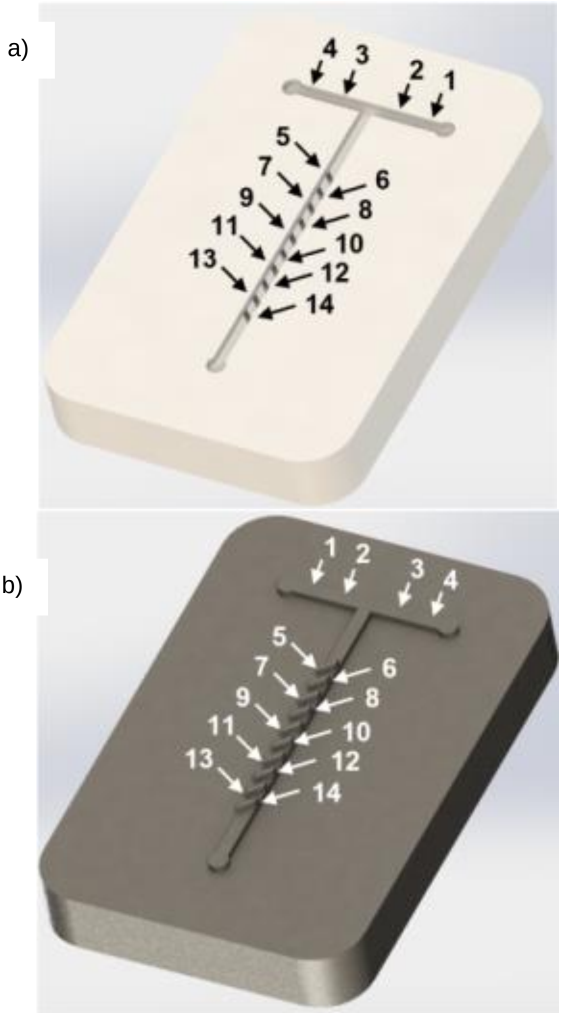

Figure 2. Tool insert with ribs used for casting of micromixer with grooves. Measurement points are marked and numbered. At points from 1 to 4, only the width of main channel was measured, at rest of the points both width of the main channel and width of the mixing features were measured.

a) Geometry of micromixer produced by casting of PDMS. b) Tool insert machined by EDM and used for casting.

The tool electrodes are produced by cutting thin copper sheets (cut in 2D) by WJ/AWJ technology, hence two electrodes are needed to machine 3D features on the tool insert. To compare the performance of WJ and AWJ technology, two pairs of tool electrodes are machined, both technologies are using the same tool path as shown in Figure 3. Since the kerf width depends on the width of the jet, much wider kerf is obtained when cutting with AWJ.

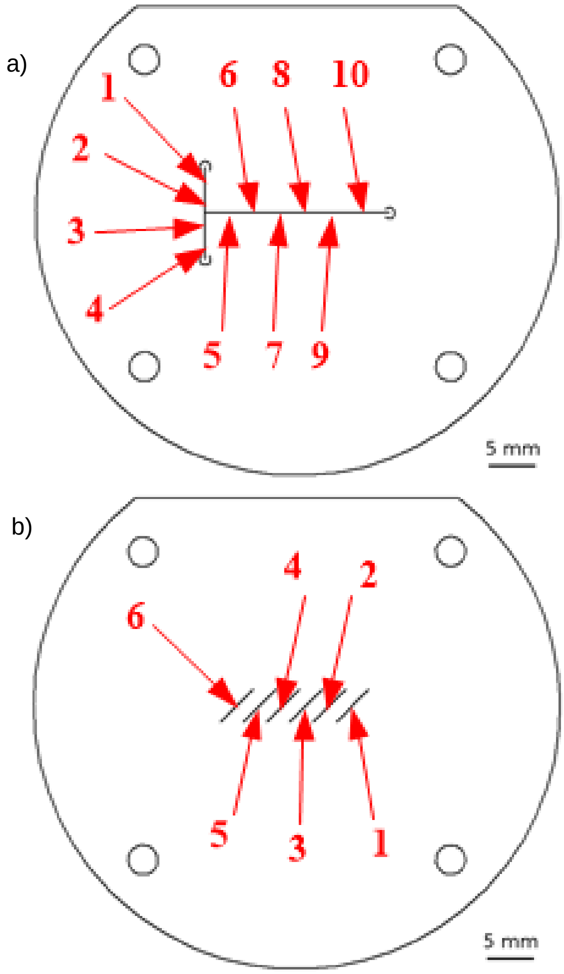

Figure 3. Contours of the tool electrodes used for tool insert machining by EDM. Measurement points are marked and numbered. a) Tool path for machining of the main channel – electrode A. b) Tool path for machining mixing elements in the main channel – electrode B.

Two tool inserts were manufactured. The first was machined by EDM utilising a pair of the tool electrodes machined by WJ and the second was machined by EDM utilising a pair of tool electrodes machined by AWJ. The dimensions on the tool electrodes were measured before and after EDM. The dimensions of the tool inserts were measured, as well. Based on the results, WJ and AWJ processes performances are compared and the appropriate processes for viable process chain are defined. Finally, the product (Figure 2a) is produced by casting of PDMS in a mould comprised of the tool insert (Figure 2b) and a housing, and the dimension were examined.

2.1 *WJ and AWJ machining of the tool electrodes*

In WJ machining, the material removal takes place due to erosion of high-speed water jet when impacting on the workpiece. Similar process is AWJ machining, where abrasive particles are added in the water jet in order to substantially increase the material removal process, but in general it causes greater kerf.

OMAX type 2652A/20HP abrasive jet cutting system powered by BöhlerEcotron 403 hydraulic intensifier capable of reaching water pressures up to 410 MPa was used. In the case of WJ, the 'cutting tool' is a high speed water jet which was generated in an orifice of 0.25 mm in diameter whereas in the case of AWJ, the ‘cutting tool’ was a high speed mixture of water and mineral abrasive which was generated in the injection cutting head with orifice of 0.25 mm in diameter and focusing nozzle of 0.8 mm in diameter. The tool electrodes were machined from 1 mm thick electrolytic copper sheet.

According to findings of previous researches (Juriševič et al. 2007, Sabotin et al. 2010) and additional experimentation, water pressure *p* was set to 300 MPa for WJ and AWJ machining, feed rate (cutting speed) *v* was set to 5 mm·min^{-1} for WJ machining and 844 mm·min^{-1} for AWJ machining. In AWJ machining, abrasive Garnet mesh 80 was used with its mass flow rate of 0.45 kg·min^{-1}.

2.2 Die-sinking electrical discharge machining of the tool insert

Die-sinking electrical discharge machining (EDM) is a machining technique through which the material is removed by electrical discharges occurring in the gap between the tool electrode and the workpiece – in our case tool insert. The gap is flushed by the third interface element, the dielectric fluid.

Basically, several EDM processes are distinguished. In micro production, micro EDM milling and micro EDM drilling are most widely used (Pham et al. 2004). In EDM, which was used in the presented study, 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 since the orbital or planetary motion of the electrode was not used.

Die-sinking EDM was performed on an IT Elektronika 200M-E EDM machine. In order to stabilize the EDM process, special attention was put on the dielectric flow through the gap and the gap reference voltage. Too high or too low dielectric flow rates for flushing of the gap between the tool electrode and the workpiece cause process instability resulting in a fast electrode movements driven by a servo positioning system, which is controlled by the gap reference voltage. Hence, the electrodes were mounted on the EDM machine as shown in Figure 4. Such setup enables a good control of the gap flushing conditions. It is worth to mention that the bottom side of the electrode was always directed towards the surface to be EDM machined.

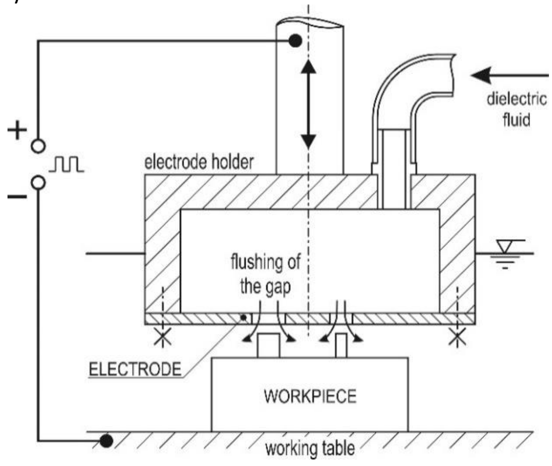

Figure 4. Electrode mounting while producing tool insert by die-sinking EDM.

When machining the main channel utilising electrode A, the surface area of machining is a little less than the surface area of the whole electrode, whereas when machining mixing features in the main channel utilising electrode B, surface area of machining is little less than the surface area of the main channel. Since a high surface current density in the gap results in unstable machining (Valentinčič et al. 2007), three sets of machining parameters were used (Table 1): two sets for machining main channel, i.e. rough and fine machining and one set for machining mixing features in the main channel. Ignition voltage was always 280 V.

	Electrode A rough mach.	Electrode A fine mach.	Electrode B
Peak current (A)	16.6	5.6	2.6
Pulse on time (μs)	350	60	45
Pulse off time (μs)	50	18	18
Discharge energy (μJ)	1700	10	3
Machining time (s)	35	20	29

Table 1. EDM parameters for machining of the tool insert.

2.3 Casting of PDMS

A special holder was manufactured and the tool insert was mounted on it in order to form a pool where the PDMS material was casted. Due to the mechanical properties and low price, QSil216 (ACC Silicones LTD, UK) was used. In order to eliminate micro bubbles that are present in the liquid PDMS due to mixing and casting, the tool insert, holder and liquid PDMS were exposed to under pressure of 70 mbar for half an hour. Total curing time at 25 °C was 20 hours.

3 ANALYSIS OF PROCESS PERFORMANCES

As expected, kerf width is much smaller in the case of WJ machining, but standard deviations of dimensions are smaller in the case of AWJ machining (Figure 5). One can notice, that WJ and AWJ machining are repeatable, since electrode A and B have mean value of dimensions within the standard deviations (represented by error bars) of all measurements. Thus, the measurement results of both electrodes can be merged together and evaluated together.

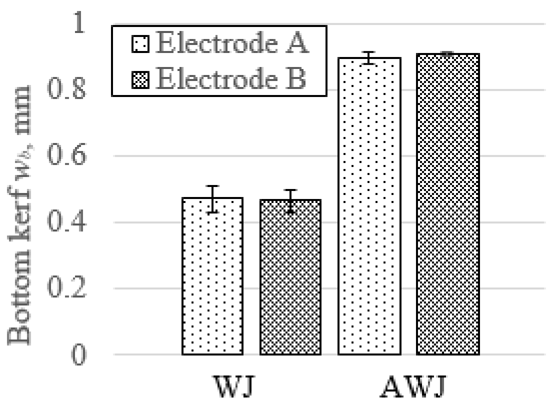

Figure 5. Kerf width measured on the bottom of the tool electrodes machined by WJ and AWJ technology. Electrode A is used to machine main channel channel whereas electrode B is used to machine mixing features in the channel.

Taper is calculated according to the equation 1

$$T_R = \frac{w_t}{w_b}, \tag{1}$$

wherew_t is kerf width measured on the top of the workpiece and w_b is kerf width measured on the bottom of the workpiece. According to the results given in Figure 6 (before EDM), cut made by AWJ has much less taper and smaller deviation of the kerf width, i.e. the cut is smoother. During EDM process, the wear of the tool electrode occurs. A significant reduction of the taper due to the electrode wear is observed; in the case of WJ machining, also a significant reduction of deviation is observed. Both results are expected. Cut made by WJ is not smooth since only the water kinetic energy causes material removal. During EDM, the wear mechanisms on the tool electrode smoothen the cut and reduce the taper. The latter is reduced since the kerf is smaller on the bottom side of the electrode and during EDM the wear increases the kerf.

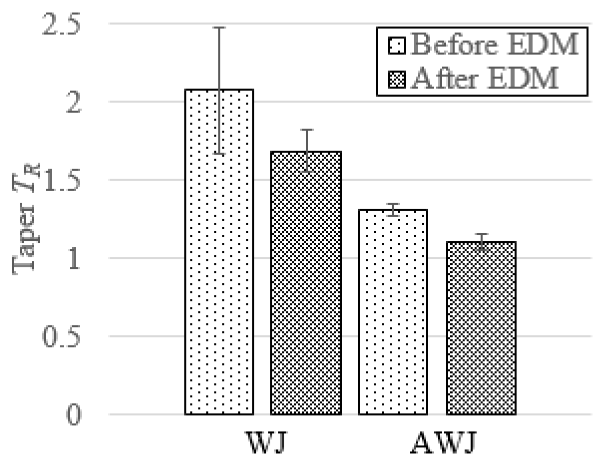

Figure 6. Taper on the electrodes measured before and after they were applied in EDM process

From the electrodes the shapes are transferred to the tool insert by die-sinking EDM process. The difference in dimensions are only due to the side gap between the electrode and the workpiece, which is defined by EDM machining parameters. Discharges with greater energy cause greater gap. Since the machining parameters with lower energy were used when machining the mixing features on the bottom of the main channel, these features are wider than the main channel. Again, the deviation of width is smaller when applying AWJ machining (Figure 7).

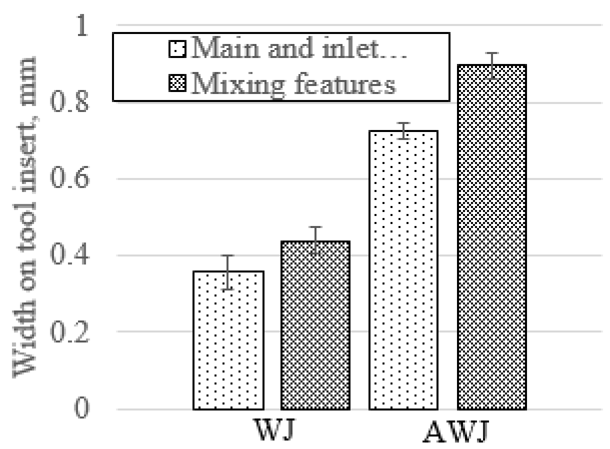

Figure 7. Measured widths of the features on the tool insert machined by EDM.

4 PROCESS CHAIN

WJ machining can produce smaller kerf width, but the variation of dimensions is greater that in the case of AWJ machining. Since the width of mixing features should be in the range of 150 µm [Sabotin et al. 2013], it is feasible to use WJ technology to manufacture electrode B for machining of mixing features and AWJ technology to manufacture electrode A for machining main channel. To further improve mixing capabilities of micromixer, the mixing features were machined as close as possible by using the electrode given in Figure 8. Therefore, the final process chain is as follows: AWJ machining of electrode A, WJ machining of electrode B, EDM machining of main channel by electrode A and EDM machining of mixing features on main channel by electrode B. The final product is produced by casting of PDMS.

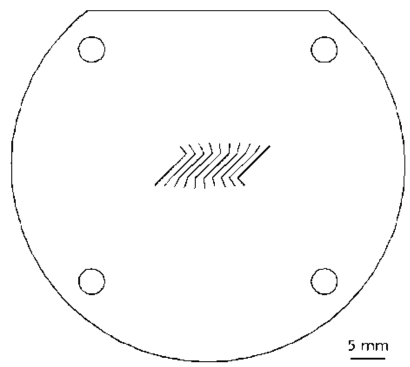

Figure 8. Tool path to machine tool electrode B with WJ machining.

At each process step, the dimensions were evaluated and the results are gathered in Figure 9. Due to the taper and rough cut surface on the electrode, a relatively high wear occurs on the electrode during EDM process.

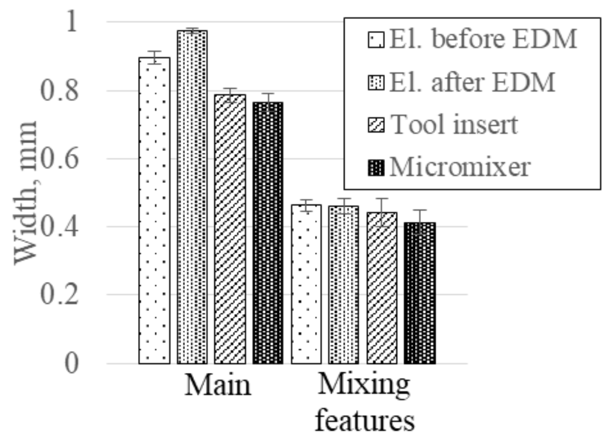

Figure 9. Characterisation of dimensions obtained at each process included in the process chain

The width of main channel increases for 80 µm. Although the taper is greater on electrode B, which is machined by WJ, the increase of the mixing features width due to EDM is insignificant. The reason is the EDM machining time required to produce mixing features, which is only a half of the machining time required to machine main channel (Table 1). Comparing the width on the electrode and on the tool insert, the difference is greater in the case of the main channel manufacturing. Rough and fine machining was applied without orbital motion of the electrode when machining main channel, whereas only fine machining was applied when machining mixing features. Additionally, fine machining parameters for mixing features machining determined lower discharge energy then fine machining parameters for main channel machining, and hence smaller gap in the former case. The difference in mixing features dimensions is 18 µm whereas in the case of the main channel, the difference is 190 µm. The shapes and dimension are transferred to the casted micromixer and width reduction of 25 µm is observed on the main channel and mixing features due to the shrinkage of material during curing.

Finally, five micromixers were casted and their dimensions are given in Figure 10. One can notice that the mean values of main channels are varying significantly. The same is valid for the widths of mixing features. An analysis of variance (ANOVA) shows that the five micromixers are not belonging to the same population since F is greater than F_{cr} (Table 2). For all five micromixers, the same tool insert was used, thus the process chain has no influence on the obtained result, but only the process of casting. Before casting, the resin was prepared from two components and the percentage of hardener influence on the shrinkage of the resin during curing. The variation in percentage of hardener might be the source of width variation.

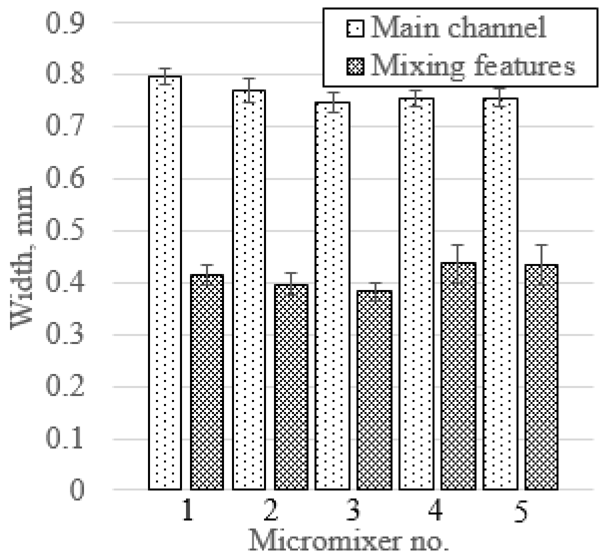

Figure 10. Dimensions obtained on five micromixers produced by casting.

	Main channel			Mixing features		
SoV	**BG**	**WG**	**Tot.**	**BG**	**WG**	**Tot.**
SS	0.0224	0.0213	0.0437	0.0223	0.0366	0.0590
df	4	65	69	4	45	49
MS	$5.6 \cdot 10^{-3}$	$3.3 \cdot 10^{-4}$		$5.6 \cdot 10^{-3}$	$8 \cdot 10^{-4}$	
F	17.086			6.864		
P-value	$1.27 \cdot 10^{-9}$			$2 \cdot 10^{-4}$		
F_{cr}	2.513			2.579		

Table 2. ANOVA report for Main channel width and Mixing features width for the five micromixers produced by casting. *SoV* – Source of Variation, BG – Between Groups, WG – Within Groups, Tot. - Total

5 DISCUSSION

On casted micromixer, the average main channel width is 764 µm and average mixing features width is 413 µm, the average dimensions on electrodes are 901 µm and 470 µm respectively. The difference is 137 µm and 57 µm respectively. Thus, the features on the electrode have to be machined 137 µm greater than the required dimensions of the features on the casted micromixer when AWJ machining is utilised and 57 µm greater when WJ machining is applied. The precision is of paramount importance in micromachining. Although the overcut is defined, the problem of proposed process chain is precision of machining processes. Deviations given by error bars in the given figures indicate the AWJ and WJ processes are not precise enough. Taking 95% confidence interval, expected dimensions are ±31 µm and ±70 µm, respectively. These variations are mapped also to the tool insert (±40 µm and ±80 µm, respectively) and further on to the casted micromixer. ANOVA shows the dimensions of five micromixers are significantly different, thus process of casting should be better mastered.

6 CONCLUSIONS

The precision obtained by the presented process chain mainly depends on the precision of the first process, namely WJ and AWJ machining. It was shown that using the cutting parameters for time efficient cutting, better cuts are produced by AWJ technology and the machining time is more than 150 times shorter. Therefore, WJ technology is not suitable for precise cutting of metals. On the other hand, AWJ technology produces much larger kerf width and hence micro features are difficult to machine by this technology. A more precise technology should replace WJ and AWJ technology in the presented process chain, e.g. wire EDM, laser cutting or maybe micro suspension AWJ cutting.

Die-sinking EDM performed well in the proposed process chain. In order to reduce machining time, rough and fine machining was applied. The required machining time to produce the tool insert is significantly shorter compared to the machining time the other micro technologies require, e.g. laser ablation or micro milling. To further improve process performances, especially the obtained precision of the machined features, the machining with orbital motion of the tool electrode should be used.

Casting can be used for a serial production, but it is not really a technology for mass production. The results show that the process parameters were not completely under control and hence the dimensions of five micromixers are significantly different. Further research will be focused on technologies for mass replication such as micro injection moulding and hot embossing.

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