Strojniški vestnik - Journal of Mechanical Engineering 53(2007)12, 874-884
UDK - UDC 621.9.048
Strokovni članek - Speciality paper (1.04)

Alternativna strategija za izdelavo mikroorodij v masovni proizvodnji

An alternative strategy for microtooling for replication processes

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Mikroproizvodnja je ena od najhitreje rastočih vej industrije z vedno večjim trgom novih izdelkov. V tem prispevku je predstavljena alternativna strategija izdelave mikroorodij, ki je bila preizkušena na primeru izdelka s področja mikrofluidnih uporab. Orodje za masovno proizvodnjo izdelkov s postopkom tlačnega brizganja ali vtiskovanja je izdelano s postopkom potopne mikro-elektroerozijske obdelave (MEDM). Posebnost predstavljene strategije je v izdelavi elektrod MEDM z vodnim curkom (VC). Orodje je bilo uporabljeno za vtiskovanje v polimerni material. Globalno gledano, poteka strategija izdelave od izdelave elektrode za postopek MEDM, s katero bo izdelano orodje za masovno proizvodnjo, pa do izdelave mikroizdelka. Posebno pozornost smo posvetili lastnostim vsakega od postopkov in izbiri obdelovalnih parametrov ter tako izbiro najboljše kombinacije obdelovalnih postopkov za izdelavo končnega izdelka. Med raziskavo je prišlo do številnih odkritij. To znanje bo pripomoglo razvoju zanesljive in stroškovno najboljše strategije izdelave mikroorodij, kar je podrobneje opisano v prispevku. Poleg tega je podan pregled drugih podobnih raziskovalnih dejavnosti na Univerzi v Ljubljani.

(Ključne besede: mikroorodja, rezanje s curkom, vodni curek, potopna elektroerozija, procesne verige)

Microproduction is one of the fastest-growing fields in industry, with new demands from the market increasing every day. This work presents an alternative microtooling strategy, which was applied to a microfluidic device case study. This original strategy for a replication process, like hot embossing or injection molding, is based on the combination of the micro-electro-discharge machining (MEDM) process and an electrode machined with water-jet technology (WJ). The final tool was tested with a hot-embossing process by making some test parts in polymers. The process is considered in its global perspective, starting with the fabrication of the tool electrode that will be used to produce the mold involved in the final cast of the microproduct. The addressed issue consists of identifying the capability of each process and then choosing the machining process parameters that will allow the best process combination to obtain the final microproduct. During this investigation several ideas emerge. They should help to identify the most advantageous characteristics of the involved processes in order to develop a reliable and cost-effective tooling strategy, which are discussed in this contribution. Additionally, an insight is given into similar research activities at the University of Ljubljana.

(Keywords: microtooling, water jet cutting, micro die sinking EDM, process chains)

0 UVOD

Svetovni trg mikrotehnologij je ocenjen na 40 milijard evrov z 20-odstotno letno rastjo [1]. Po drugi strani je samo evropski trg izdelkov, ki vsebujejo mikrokomponente, ocenjen na 550 milijard evrov letno. V drugi polovici dvajsetega stoletja je na področju mikrotehnologije

0 INTRODUCTION

The global market for microsystems technology is €40 billion, with a growth rate of 20% per year [1]. On the other hand, the European market for products containing microsystems technology is estimated to be €550 billion annually. In the late 20th century microproduction was the domain of siliconprevladovala izdelava mikroelektronskih izdelkov iz silicija, toda v zadnjih letih se je pojavilo veliko povpraševanje po mikro izdelkih iz različnih materialov [2]. V ta namen se intenzivno razvijajo nove tehnologije mikroobdelave.

Pomembni področji uporabe mikroizdelkov sta medicina in biotehnologija. Razvoj diagnostičnih naprav, npr. laboratorij na ploščici, omogoča zgodnje odkrivanje ter učinkovito spremljanje in zdravljenje različnih bolezni [3]. Ker so take uporabe namenjene široki uporabi po vsem svetu, je treba razviti zanesljivo in cenovno ugodno metodo proizvodnje. Kandidati so seveda izdelovalni postopki, ki se uporabljajo v masovni proizvodnji, npr. vroče vtiskovanje, tlačno brizganje ter podobni postopki. Pri tem je potrebno oblikovalske oz. konstrukterske ter izdelovalne naloge rešiti že na stopnji izdelave orodja. Značilnosti materiala orodja in težave pri izdelavi orodja z enim obdelovalnim postopkom terjajo podrobno študijo zahtev za izdelek in značilnosti, ki jih lahko dosežejo izdelovalni postopki. Inteligentna kombinacija izdelovalnih postopkov, t.i. izdelovalna veriga, je primerna za izdelavo orodij.

Veliko razmeroma zapletenih strategij je predstavljenih v literaturi ([4] in [5]), da bi zadostili potrebam mikrofluidnih sistemov. V tej raziskavi je prikazana alternativna strategija izdelave mikroorodij na primeru izdelave laboratorija na ploščici, pri čemer glavne geometrijske značilnosti predstavljajo mikrokanali. Orodje je bilo preizkušeno z vtiskovanjem v polimerni material in rezultati so predstavljeni v nadaljevanju.

V prvem poglavju je podana izbrana strategija izdelave orodja za vtiskovanje mikroizdelkov. Lastnosti obravnavanih obdelovalnih postopkov, t.j. VC in PPME so podani v prvem poglavju. Študija predlagane izdelovalne verige je podana v drugem poglavju in vodi do razprave glede celotne optimizacije postopkov, ki je podana v tretjem poglavju. Sklepi in obeti za nadaljnje izboljšanje zmožnosti obdelovalne verige so podani v zadnjem, četrtem poglavju.

1 PREDLAGANA STRATEGIJA IZDELAVE MIKROORODIJ

Ni tehnologije, ki bi zadostila rasti zahtev glede izdelave zahtevnih 3D mikrooblik in integraciji raznih oblikovnih elementov različnih

based microelectronic techniques; only in recent years has the demand for non-silicon-based microproducts arisen [2]. As a result, new microproduction processes are constantly being developed in order to meet the demands of the market.

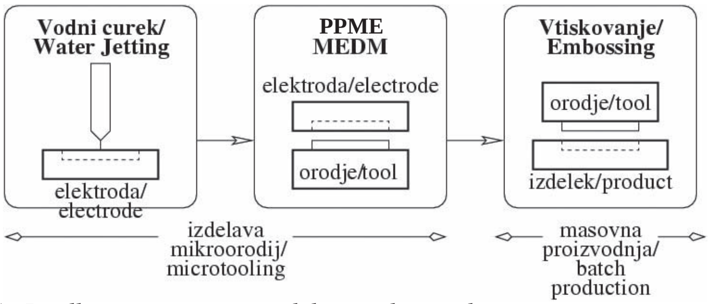
An important area of applications for micro-devices is medicine and biotechnology in general. The development of diagnostic devices such as the lab-on-a-chip analyzer makes possible the early discovery of various diseases and effective monitoring of the therapy [3]. Since the application is intended to be applied on a large scale, worldwide, a reliable and cost-effective production method is required. Natural candidates are replication processes like hot embossing or injection molding. However, design and manufacturing issues are switched to the tooling part of the overall process. Due to the specific characteristics of the tool material and the difficulty in obtaining 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., a process chain, can be proposed as a strategy for tooling.

Various relatively complex strategies have been proposed in the literature ([4] and [5]) to satisfy the needs of microfluidic systems. In this investigation an alternative tooling strategy is presented along with an application example, i.e., a simple lab-on-a-chip part, mainly featuring micro-channels. The final tool was tested on a polymer material using the hot-embossing process, and the results are presented.

In the first section the selected strategy to manufacture the tool for the embossing of the microproducts is presented. The characteristics of the machining processes, i.e., the WJ and MEDM processes, are considered in the first section. A case study of the proposed process chain is presented in the second section, which leads to a discussion about the optimization of the whole process, given in section three. Finally, the conclusions, including possible prospects to enhance the overall process-chain capability, are given in the last, fourth section.

1 PROPOSED MICROTOOLING STRATEGY

There is still a lack of a single technology that can satisfy the constantly increasing requirements associated with the manufacture of complex 3D micro structures,



Sl. 1. *Predlagana strategija izdelave mikroorodij za masovno proizvodnjo*
Fig. 1. *Proposed microtooling strategy*

velikostnih razredov v zahetvno 3D obliko ([6] in [7]). Zato se je porodila zamisel po kombinaciji raznih mikroizdelovalnih tehnologij in tako uporabi delne prednosti vsake od njih. Ob pričakovanju masovne proizvodnje, izdelovalno verigo sestavljata izdelava orodja, ki izpolnjuje specifične zahteve za določeno orodje, in izdelovalnega postopka, ki se uporablja v masovni proizvodnji. Predstavljena strategija izdelave mikroorodij temelji na izdelavi bakrene elektrode z vodnim curkom (VC) ter izdelave končnega orodja za vtiskovanje s postopkom potopne mikroelektroerozije (PPME - MEDM), kar prikazuje slika 1.

Med predstavljeno raziskavo je bila podrobno opazovana vsaka faza predlagane strategije izdelave mikroorodij z namenom določitve prednosti in omejitev vpletenih postopkov. Oba postopka (VC in PPME), vpletena v izdelavo mikroorodja za vtiskovanje, sta podrobneje opisana v nadaljevanju.

and the integration of them for features on different length scales ([6] and [7]). Thus, the idea of combining some compatible micromanufacturing process to take advantage of their specificities has emerged. Aiming at batch production with a replication process, the process chain consists of producing the replication tool, fulfilling the specific requirements for such a part, and the technology for batch production. The proposed microtooling strategy consists of machining the MEDM electrode in copper (which is obviously not an appropriate material for theembossing) with water-jet technology and then the production of the final tool in tool steel with MEDM, as shown in Figure 1.

During this investigation, we first considered each phase of the proposed microtooling strategy in order to specify the advantages and limitations of the involved technologies. Observations helped to define more precisely what can be done originally, and also to define any possible process enhancement by tuning the parameters. Both technologies (water jetting and MEDM) involved in the tooling phase are presented and described in the following.

1.1 Izdelava mikroorodij z vodnim curkom

Obdelava z VC je razmeroma nov postopek, razvit v zadnjih treh desetletjih. Pri tem postopku pride do odnašanja materiala obdelovanca zaradi erozivnega delovanja VC. Poleg obdelave z VC obstaja tudi postopek obdelave z abrazivnim vodnim curkom (AVC). Razlika med postopkoma je v dodajanju abrazivnih delcev pri slednjem, kar bistveno izboljša učinkovitost postopka s vidika odnašanja materiala obdelovanca. Kljub temu je bil v predstavljeni raziskavi uporabljen postopek obdelave z VC, ker omogoča izdelavo tanjših rezov. Učinkovitost odnašanja materiala ni pomenila pretirane ovire, ker so bile količine odnesenega materiala razmeroma majhne.

1.1 Water-jetting technology in microtooling

Water-jetting technology is a relatively new machining process developed in the past three decades. The basic principle involved is material removal due to erosion by a high-speed water jet (WJ) when impacting on the workpiece. In addition to WJ machining, we used abrasive water jet (AWJ) machining, which is a similar process. The only difference is that abrasive particles are added to the WJ in order to substantially improve the performance of the process. However, a WJ is much more suited to micromanufacturing because the jet diameter is smaller than with AWJ machining, while the machining performance is still acceptable due to the small volume of removed material. This consequently reduces the field of potential materials that can be machined with this technique.

V zgodnjih osemdesetih letih prejšnjega stoletja je bilo napovedano, da bodo obdelovalni postopki prihodnosti zmožni obdelovati vse vrste materialov na energijsko učinkovit način [8]. Obdelava z VC in AVC je zelo prilagodljiva ter omogoča obdelavo praktično vseh znanih materialov. Poleg tega skoraj ne povzroča toplotno prizadete cone v obdelovancu.

Po drugi strani je največja pomanjkljivost postopka v doseganju velikih natančnosti obdelave. Običajna natančnost izmer znaša približno 100 μm, medtem ko je za zdaj največja mogoča približno 50 μm. V primerjavi z drugimi postopki mikroobdelave, na primer mikrofrezanje, se zdi obdelava z VC neprimerna za področje mikroobdelave. Dodatna pomanjkljivost postopka je v nadzorovanju globine prodiranje curka v material obdelovanca pri 3D obdelavi, saj je ta tehnologija namenjena predvsem obrisnemu rezanju. Kljub temu je izdelava mikroorodij z VC mogoča v primeru, ko končni izdelek vsebuje le 2D oblike, kakor je prikazano na sliki 2.

As already anticipated in the early 1980s, manufacturing technologies of the future will have the ability to machine a variety of different materials in an energy-efficient way [8]. Water-jetting technology, especially AWJ machining, is a very flexible process, which can be used for virtually any known material. Additionally, there is almost no heat-affected zone on the machined part, which represents a clear advantage compared to other processes, like laser material removal.

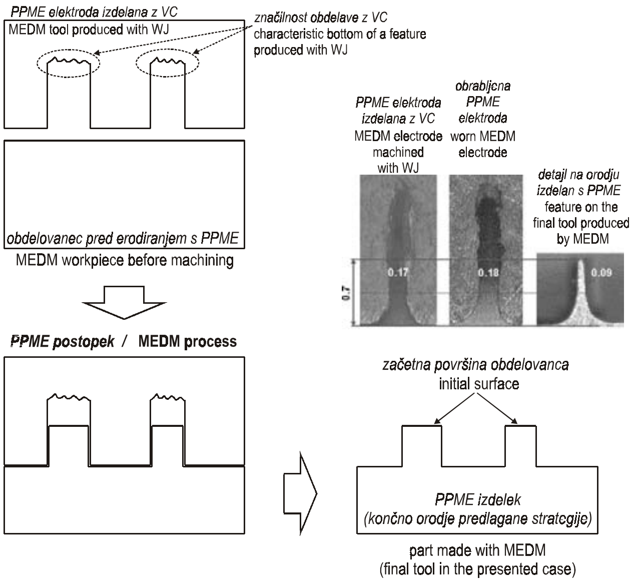
The main disadvantage of this technology is the achievable machining accuracy. Normally, the dimensional accuracy is about 100 μm, while state-of-the-art accuracy is down to 50 μm. Such poor accuracy compared to other micromachining processes, like micro-milling, could indicate that this process does not fit the requirements of microproduction. In fact, this assertion is partially wrong. We must consider the 3D aspect of the machined feature and distinguish the water-jet axis from the other axes. The drawback when machining 3D features is controlling the depth of penetration of the jet, since this technology is mostly used for cutting through the workpiece material. As a result, a WJ can be still applied when the significant features are contained in the plane perpendicular to the water jet direction. Thus, the final product has only 2D-relevant features, as illustrated in Figure 2.

1.2 Tehnologija PPME

Pri vseh elektroerozijskih postopkih (EPO) se površina električno prevodnega obdelovanca

1.2 MEDM technology

Electrical discharge machining (EDM) is a machining process in which the surface of a metal



Sl. 2. *Posebnosti tehnologije VC pri izdelavi mikroorodij za PPME [9]*
Fig. 2. *MEDM tool production with WJ [9]*

Preglednica 1. *Primerjava postopkovnih parametrov EPO in PPME*
Table 1. *EDM and MEDM machining parameters*

Postopkovni parameter Machining parameter	EPO/EDM	PPME/MEDM
razelektritveni tok discharge current	do/to 200 A	do/to 3 A
trajanje razelektritve discharge duration	do/to 1000 μs	do/to 50 μs
premor med razelektritvami pulse interval	do/to 1000 μs	do/to 200 μs

oblikuje kot posledica razelektritev v reži med elektrodo in obdelovancem. Reža med elektrodo in obdelovancem se izpira z dielektrično tekočino. Postopek sestoji iz številnih naključno porazdeljenih posameznih razelektritev. Med samo razelektritvijo nastane tok plazme, ki rabi kot prevodnik med elektrodo in obdelovancem in kot vir toplote. Na mestu razelektritve nastane krater, katerega velikost je odvisna od energije razelektritve. Energijo razelektritve se nastavi s tokom in trajanjem razelektritve. Napetost razelektritve, ki tudi določa energijo razelektritve, se ne da izrecno nastaviti, ker je odvisna od reže med elektrodo in obdelovancem [10]. Stopnja odvzema materiala (MRR) je definirana s prostornino posameznega kraterja in frekvenco nastajanja kraterjev oz. energijo in frekvenco razelektritev. Slednje je določeno s trajanjem razelektritev in premorom med dvema razelektritvama. Velikost reže med elektrodo in obdelovancem je običajno med 0,01 in 0,1 mm. Stopnja odvzema na obdelovancu je približno 100-krat večja kakor na elektrodi, kar pomeni obrabo elektrode.

Razlika med EPO in PPME je v natančnosti podajalnega sistema elektrode oz. servosistema ter preostalih postopkovnih parametrov. Primerjava postopkovnih parametrov postopkov EPO in PPME je podana v preglednici 1.

Med obdelavo z PPME običajno uporabljamo paličaste elektrode. Pot elektrode je podobno kakor pri frezanju nadzorovana z računalniškim krmilnikom. Najmanjše elektrode, dostopne na trgu, imajo premer 170 μm. Manjše premere lahko izdelamo z žičnim EPO brušenjem ali jedkanjem [11].

1.3 Primer mikrofluidne uporabe

Kombinacija zgoraj predstavljenih tehnologij ni očitna. Predlagana strategija temelji na analizi komplementarnosti VC — prednost VC postopka pred AVC je v tanjšem curku, ki omogoča

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 mono-discharges. During a discharge, a plasma channel is formed as the current conductor and the heat generator. At the spot of the discharge a crater appears. The size of the crater depends on the discharge energy, which can be set on the machine by adjusting the discharge current and the discharge duration. The discharge voltage, which also determines the discharge energy, cannot be adjusted on the machine explicitly, since it depends on the gap width between the workpiece and the electrode [10]. The material removal rate (MRR) is determined by the crater size and the frequency of the crater generation, i.e., the discharge energy and the frequency of the discharges. The latter is influenced by the discharge duration and the pulse interval between two discharges. The gap width between the workpiece and the electrode is in the range 0.01–0.1 mm. The MRR is around 100 times higher on the workpiece than on the electrode.

The main difference between the EDM process and the MEDM is in the accuracy of the electrode feeding system, also called the servo system, and the machining parameters. The comparison is given in Table 1.

The MEDM machining is usually performed with a rod electrode, whose path is controlled by a CNC controller. The commercially available rod electrodes have diameters down to 170 μm. Smaller electrode diameters are obtained by wire EDM grinding or etching [11].

1.3 The proposed strategy

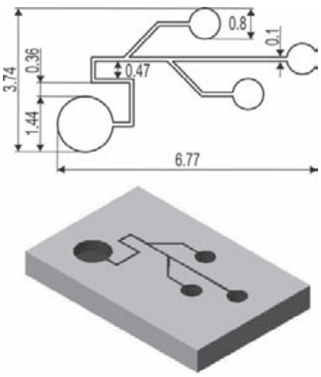
A combination of the two previously presented technologies is not an obvious method. The proposed strategy is based on an analysis of the complementarities of WJ (preferred to AWJ because of the smaller jet izdelavo manjših oblik (kanalov, reber itn.) — in postopka PPME. Glavna prednost kombinacije dveh postopkov je delitev zahtevanih izmer v dva sklopa. Izmere v oseh *x* in *y* so določene pri obdelavi z VC in morajo biti zagotovljene s pravilno izbiro obdelovalnih parametrov postopka PPME. Tretja izmera (višina) je odvisna le od globine obdelave PPME.

2 ŠTUDIJA NA PRIMERU: MIKROFLUIDNI PRIPOMOČEK

Predlagana strategija izdelave mikroorodij in kasnejšega vtiskovanja je bila preizkušena na izdelku, prikazanem na sliki 3. Primer izdelka je bil izbran zaradi značilnih oblik, izmer in kakovosti površin, ki se pojavljajo pri mikrofluidnih izdelkih.

V prvem koraku je bila bakrena elektroda izdelana z uporabo obdelave z VC. Obdelava je potekala na sistemu za rezanje z AVC izdelovalca OMAX (tip: 2652A/20HP) priključenega na visokotlačno črpalko oz. hidravlični ojačevalnik proizvajalca Böhler (tip: Ecotron 403), ki zmore tlake vode do 410 MPa. Glede na predhodne izkušnje je bil tlak vode nastavljen na 300 MPa, podajalna hitrost na 10 mm/min, razdalja med šobo in obdelovanci na 2 mm. VC je bil oblikovan v šobi s premerom 100 mm. Čas obdelave je znesel 4,9 min. Tako izdelana elektroda za PPME je prikazana na sliki 4.

V naslednjem koraku je bilo izdelano mikroorodje za vtiskovanje s postopkom PPME na elektroerozijskem stroju tipa 200M-E izdelovalca IT Elektronika. Za izdelavo mikroorodja so bili



Sl. 3. *Skica in 3D model opazovanega primera s področja mikrofluidnih uporab*
Fig. 3. *Sketch and 3D model of the presented case study: a microfluidic device (lab-on-a-chip)*

diameter that allows a smaller minimum dimension of features like ribs, channels, etc.) and MEDM. The main advantage is being able to divide the dimension required into two stages. The dimensions in *x* and *y* axes are defined by the WJ process, and must be further guaranteed by MEDM through process-parameter control. The third dimension (height) only depends on the depth of the machining with the MEDM process.

2 CASE STUDY: A MICROFLUIDIC DEVICE

The proposed microtooling strategy was tested and the embossing operations were performed on the part shown in Figure 3. This case study was selected because of the typical dimensions, shapes and surface-quality requirements for microfluidic products.

In the first step the MEDM tool was machined in copper using WJ technology. This operation was executed on the OMAX-type 2652A/20HP abrasive-water-jet cutting system powered by a Böhler Ecotron 403 hydraulic intensifier capable of reaching water pressures up to 410 MPa. Based on previous experience the water pressure was set at 300 MPa, the cutting velocity was 10 mm/min and the stand-off distance between the cutting head and the workpiece was 2 mm. The high-speed water jet was generated in an orifice with a diameter of 100 µm. The machining time was 4.9 min and the resulting MEDM tool is shown on Figure 4.

In the next step of the proposed microtooling strategy the final tool for embossing was produced with MEDM on an EDM machine IT Elektronika 200M-E. The following process

Sl. 4. *Elektroda za PPME, izdelana z VC*
Fig. 4. *MEDM electrode machined with WJ technology*

uporabljeni naslednji postopkovni parametri: tok razelektritve i_e=1 A, vžigna napetost u_i=180 V, trajanje razelektritve t_e=8 μs ter premor med razelektritvami t_o=36 μs. Globina erodiranja je bila nastavljena na 700 μm. Čas erodiranja je bil približno 12 ur.

Mikroorodje za masovno proizvodnjo z vtiskovanjem, izdelano s postopkom PPME, je prikazano na sliki 5.

Med obdelavo s PPME se elektroda obrablja, kar je treba upoštevati pri načrtovanju tehnologije. Slika 6 prikazuje obrabljeno elektrodo po izdelavi mikroorodja za vtiskovanje, kjer je opaziti zaokrožene robove na elektrodi kot posledico obrabe elektrode. Najpreprostejša rešitev za zmanjšanje vpliva obrabe elektrode pri postopku PPME bi bila uporaba dveh povsem enakih elektrod, eno za grobo in drugo za fino obdelavo. Ker je praktično nemogoče izdelati dve enaki elektrodi z VC ta možnost odpade. Razlog je v za zdaj nedodelanem vpenjalnem in nastavitvenem sistemu sedanjih naprav za obdelavo z VC.

Uporaba dveh elektrod, ene za fino in druge za grobo obdelavo, torej v našem primeru ni priporočljiva zaradi problemov nastavitve in vpenjanja, ki bi povzročali večje napake, kakor jih povzroča obraba elektrode. To je očitno ena od ovir, ki omejuje določitev zaporedja obdelovalnih opravil. Tako predlagana strategija sloni na enostopenjski obdelavi PPME s skrbno izbranimi obdelovalnimi parametri, ki povzročajo najmanjšo obrabo.

V zadnji fazi predstavljene raziskave je bilo izdelano mikroorodje preizkušeno z vtiskovanjem v polimerni material. Rezultat preizkusa je prikazan na sliki 6.

parameters were applied: discharge current i_e=1 A, ignition voltage u_i=180 V, discharge duration t_e=8 μs and pulse interval t_o=36 μs. The eroding depth was set at 700 μm, consuming about 12 hours of machining time.

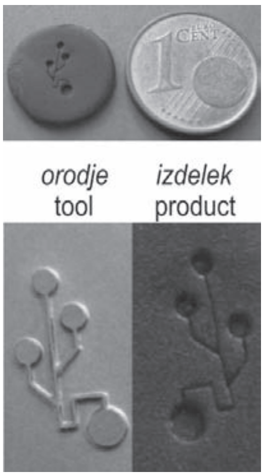
The resulting tool made in tool steel for the embossing process is shown in Figure 5.

During MEDM machining the electrode is subject to wear, which has to be taken into account when designing the technology. The wear results in rounding of the edges of the electrode (Figure 6). The simplest solution would be to use two equal electrodes, one for rough MEDM machining and the other for the finishing. Unfortunately, this is not an option within this strategy because it is very difficult to machine two identical electrodes with WJ technology. The main reason lies in the rather poor positioning and clamping system that is available in water-jetting technology.

The use of rough electrodes in addition to a finishing electrode is therefore not advisable because the repositioning of one relative to other would generate geometric errors that are probably worse than the errors due to the electrode wear. This is clearly the kind of obstacle that limits the choice of process sequence. Hence, the proposed strategy is based on single-step MEDM manufacturing with parameters chosen to narrow the electrode-wear effect.

In the final step the performance and the functionality of the machined tool were tested by embossing the polymer materials, as shown in Figure 6.

Sl. 5. *Orodje za masovno proizvodnjo izdelano s PPME*
Fig. 5. *Final tool produced by the MEDM process*



Sl. 6. *Testni primer, izdelan z vtiskovanjem v polimerni material*
Fig. 6. *Test part made of polymers by embossing*

3 RAZPRAVA

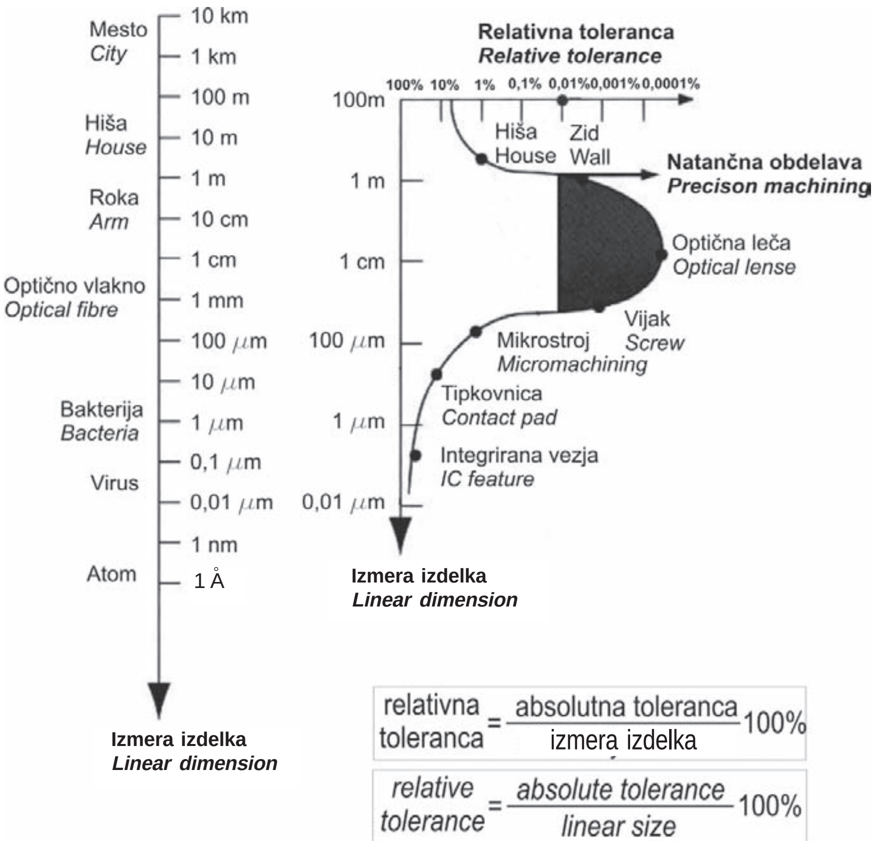
Predlagana strategija izdelave mikroorodij je bila eksperimentalno opazovana po posameznih fazah od izdelave bakrene elektrode z VC, erodiranja orodja s PPME pa vse do izdelave končnega izdelka in polimernega materiala s postopkom vtiskovanja.

Analiza obdelovalnih časov je pokazala, da je bila večina časa porabljena za erodiranje orodja do globine 700 μm, kar je trajalo približno 12 ur. Izdelava elektrode za PPME je bila bistveno hitrejša. Razmeroma veliko območje okoli sistema kanalov v kombinaciji z višino reber na orodju zahteva odvzem večje prostornine materiala, kar se kaže v daljšem obdelovalnem času. Nasprotno je čas, potreben za izdelavo bakrene elektrode z VC neprimerno krajši; za izdelavo elektrode je bilo potrebnih le 4,9 minut. Poudariti je treba, da elektroda, izdelana s postopkom VC, ki predstavlja časovno najkrajšo fazo izdelave orodja, že definira večino od pomembnih značilnosti končnega izdelka. Nadalje to pomeni, da so nekateri

3 DISCUSSION

The proposed microtooling strategy has been experimentally observed from the machining of the MEDM electrode with a WJ, through to the production of the final tool and up to the phase where test samples were made by embossing.

The machining-time analysis showed that most of the time is spent on the MEDM operation, which took approximately 12 hours to machine the final tool, on which the features are 700-μm high. Naturally, the wide area around the channel system combined with the height of the ribs on the tool is responsible for the large volume of material needing to be removed, hence the long machining time. In contrast, the machining time of the WJ electrode was much shorter. It took only 4.9 minutes to produce the electrode. Here, it is important to note that the electrode made by WJ, which is the shortest phase of the tool manufacturing, already provides some of the definitive characteristics of the final product. This means that some controls can already



Sl. 7. *Področje natančne izdelave [12]*
Fig. 7. *Domain of precision engineering [12]*

ukrepi za zagotavljanje kakovosti lahko izvedeni že v tej fazi strategije izdelave orodja.

Kljub dejstvu, da je postopek obdelave z VC manj natančen od odrezovalnih postopkov, ki so običajno uporabljeni za izdelavo elektrod za PPME, je ta raziskava pokazala, da je z nadaljnjim razvojem lahko predlagana strategija časovno in stroškovno učinkovita alternativa znanim postopkom.

Po navadi je izraz mikroobdelava povezan z natančno obdelavo, kar ne drži popolnoma. Slednje je ponazorjeno na sliki 8, kjer se izkaže, da so relativne tolerance mikroizdelkov, ki imajo značilno izmero okoli 100 μm, primerljive s tolerancami v gradbeništvu, kjer so značilne izmere reda velikosti 10 m.

Ob upoštevanju zmogljivosti obdelave z VC z vidika natančnosti izdelave je jasno, da trenutno stanje tehnike ne omogoča izdelave orodij za masovno proizvodnjo. Kljub temu se tej tehnologiji odpira zanimivo področje mikrofluidnih sistemov, pri katerih bi hitra in poceni izdelava prototipov in s tem povezanih orodij omogočala razvijalcem teh naprav bistveno prednost. Na tem področju je bila pred kratkim začeta raziskava v sodelovanju s Kemijskim inštitutom v Ljubljani. Glavni cilj te raziskave je v opazovanju vpliva prečnega prereza mikrokanalov na kemijskem mikroreaktorju. V ta namen je bilo izdelano orodje za izdelavo mikroreaktorja. Trenutno so prvi prototipi v fazi preizkušanja. Prvi mikroreaktorji bodo izdelani z ulivanjem prozorne snovi na temelju silikona v orodje, izdelano s predlagano strategijo. V kasnejši fazi se lahko orodje uporabi za postopke kakršna sta vtiskovanje ali tlačno brizganje prozornih materialov.

4 SKLEPI

Kljub obetavnim rezultatom predstavljene raziskave je še veliko prostora za izboljšavo predlagane strategije izdelave mikroorodij. V prihodnosti bo treba odpraviti določene pomanjkljivosti, med katerimi so nekatere opisane v spodaj.

Pri izdelavi elektrod z VC lahko izdelamo še manjše detajle z uporabo manjšega premera vodnega curka. V tej raziskavi je bila uporabljena vodna šoba s premerom 100 μm, medtem ko je na trgu najmanjši razpoložljiv premer 80 μm. V laboratorijskem okolju so najmanjše razpoložljive šobe premera 10 μm in celo manj. Sama natančnost izdelave se lahko izboljša z uporabo bolj

be performed at this stage of the tooling strategy.

Despite the fact that WJ machining is less accurate than cutting processes, which are normally used to produce electrodes for MEDM, this contribution shows that with the further development of this technology, especially on the tooling side, it should represent a time- and cost-effective alternative.

Micromachining is a term that is usually amalgamated with precision machining, which is not the case. It can be clearly seen in Figure 7 that the relative tolerance of microproducts with a size of about 100 μm is similar to those in construction engineering, where the characteristic dimension is about 10 m.

Taking into consideration the achievable machining precision of WJ machining, it is clear that the current state of the art of this technology does not allow the production of tools for mass production if accuracy is the main attribute. However, the development of microfluidic systems is still an interesting field of application. The fast and cost-effective fabrication of prototypes gives the designer a powerful tool to gain significant advantages. In this respect a research study has been undertaken together with the Institute of Chemistry, in Ljubljana. The main goal of this investigation is to test the different microchannel cross-section geometries of a chemical microreactor. A microtool for the microreactor has already been produced and is currently in the testing phase. The first microreactor will be produced by filling the tool with a transparent silicon-based material, but the possibility of using other replication processes, like embossing and injection molding, are being investigated as well. Particular attention will be paid to the geometry and the impact of electrode wear.

4 CONCLUSIONS

Despite the encouraging results obtained in this investigation, there is still room for improvement with the proposed microtooling strategy. Accordingly, several issues have to be addressed, which will be further discussed.

The first stage of improvements can be made in the steps of the process chain. During the machining of the MEDM electrodes smaller features may be obtained by using smaller jet diameters. In this investigation a 100-μm orifice (nozzle) was applied, while the smallest commercially available orifices have a diameter of 80 μm and the state-of-the-art orifices reach diameters of 10 μm, or even less. Machining izpopolnjenih poti orodja, vendar je pri obdelavi z VC največja pomanjkljivost v neustreznem vpenjalnem in nastavitvenem sistemu. Izboljšan vpenjalni in nastavitveni sistem bi omogočal izdelavo večjega števila enakih elektrod, ki bi bile uporabljene za izdelavo istega orodja (grobo in fino erodiranje).

Prva stopnja izboljšav se tiče samih obdelovalnih postopkov, vključenih v izdelovalno verigo. Za izdelavo orodja s PPME je treba bistveno več časa v primerjavi z izdelavo elektrode z VC. V veliki meri je to posledica slabih razmer pri izpiranju reže med postopkom PPME. Ponuja se možnost izdelave elektrode iz tanke pločevine, kjer se izdela želene oblike z rezanjem z VC. To bi omogočalo izpiranje reže med elektrodo in obdelovancem skozi elektrodo. Takšen postopek bi vplival tudi na nadaljnji razvoj strategije izdelave orodja, kar je druga stopnja izboljšav. Na primer, postopek PPME z elektrodo iz tanke pločevine ima lahko velik vpliv na obrabo elektrode, kar seveda vpliva tudi na določitev izdelovalne strategije.

Prihodnje raziskave na tem področju bodo vsebovale izsledke predstavljene študije. Z nadaljnjimi učnimi primeri bo mogoče odkriti področja, kjer bi predlagana strategija lahko nadomestila dosedanje obdelovalne postopke za izdelavo elektrod za mikroorodja, predvsem mikrofrezanje. To vključuje tudi izdelavo elektrod iz grafita, kar je bilo že uspešno preizkušeno.

precision may be improved by alternative tool paths as well, but the major drawback is the positioning and clamping systems, which both need further development. An advanced positioning system would make it possible to produce several identical electrodes for rough and smooth machining of the same final tool.

The machining of the final tool with MEDM takes an extremely long time compared to the WJ phase. This is partially so because of the poor flushing conditions in the gap between the electrode and the machined part. One possibility would be to make electrodes out of thin plates in which the desired features would be cut through the electrode. This would enable an additional flushing of the gap through the electrode itself. Of course, integrating such modifications into the manufacturing process will also surely bring some modifications to the tooling strategy. That is the second point of improvement. For example, MEDM with a thin-plates electrode would considerably change the electrode wear problem, and surely lead to a new strategy.

Further research in this field will incorporate the findings obtained during this investigation. Various new case studies will be tested in order to find the gaps between the proposed microtooling strategy and today's commonly used microtooling techniques, especially micromilling. This includes the fabrication of graphite electrodes, which was already tested and the first results are very promising.

Zahvala

Predstavljeno delo je bilo opravljeno v okviru evropskih mrež odličnosti: "Multi-Material Micro Manufacture: Technology and Applications (4M)" Network of Excellence, pogodba NMP2-CT-2004-500274 ter "Virtual Research Lab for a Knowledge Community in Production (VRL-KCiP)" Network of Excellence, pogodba: NMP2-CT-2004-507487, oba v okviru 6. Evropskega Okvirnega Programa. Predstavljeno delo je del bilateralnega projekta PROTEUS med Republiko Slovenijo in Republiko Francijo, pogodba: BI-FR/05-06-017.

Acknowledgement

This work is supported by the "Multi-Material Micro Manufacture: Technology and Applications (4M)" Network of Excellence, Contract Number NMP2-CT-2004-500274 and by the "Virtual Research Lab for a Knowledge Community in Production (VRL-KCiP)" Network of Excellence, Contract Number NMP2-CT-2004-507487, both within the EU's 6th Framework Program. This work was initiated within the context of a bilateral project PROTEUS between the Republic of Slovenia and the Republic of France, Contract Number BI-FR/05-06-017.

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Prejeto:
Received: 14.2.2007

Sprejeto:
Accepted: 25.4.2007

Odprto za diskusijo: 1 leto
Open for discussion: 1 year