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High-efficiency Approach for Fabricating MTE Rotor by Micro-EDM and Micro-extrusion

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Abstract: Micro-gas turbine engine (MTE) rotor is an important indicator of its property, therefore, the manufacturing technology of the microminiature rotor has become a hot area of research at home and abroad. At present, the main manufacturing technologies of the MTE rotor are directed forming fabrication technologies. However, these technologies have a series of problems, such as complex processing technology high manufacturing cost, and low processing efficiency, and so on. This paper takes advantage of micro electric discharge machining (micro-EDM) in the field of microminiature molds manufacturing, organizes many processing technologies of micro-EDM reasonably to improve processing accuracy, presents an integrated micro-EDM technology and its process flow to fabricate MTE rotor die, and conducts a series of experiments to verify efficiency of this integrated micro-EDM. The experiments results show that the MTE rotor die has sharp outline and ensure the good consistency of MTE rotor blades. Meanwhile, the MTE rotor die is applied to micro extrusion equipment, and technologies of micro-EDM and micro forming machining are combined based on the idea of the molds manufacturing, so the MTE rotor with higher aspect ratio and better consistency of blades can be manufactured efficiently. This research presents an integrated micro-EDM technology and its process flow, which promotes the practical process of MTE effectively.

Keywords: integrated micro-EDM, micro extrusion, MTE rotor, efficiency, consistency

1 Introduction

In the 21st century, micro-electromechanical systems (MEMS) technology has been applied more and more widely in mechatronics, communication engineering, aerospace, automobile industry, etc[1]. With the continuous development of space industry, miniature power device based on fuel burning with high power density and energy density will be applied more broadly. Except same working principles, the micro-gas turbine engine (MTE) has its own characters, such as the micro size, high speed, short burning time and difficult to process comparing the traditional gas turbine engine[2–3]. Therefore, MTE, as a micro-thruster, is applied to aerospace and weapon industry. However, the traditional technique wastes lots of resources and time for higher precision in fabrication[4]. Thus, how to carry out MTE with better efficiency and quality is considered as key point in current research. The MTE is first studied by Massachusetts Institute of Technology in 1994[5]. Stanford University has used silicon nitride as the main material to process the MTE based on casting and deposition technique, while this method is not suitable for shortening update cycle and remodeling products frequently[6]. In addition, Japanese researchers have studied fabrication of the MTE silicon carbide parts by Miniature machining in 2001. Micro cutting can be considered as a supplement of semiconductor silicon technology and (Lithographie, Galanoformung and Abformung) LIGA, which can achieve a better machining efficiency and surface quality[7]. However, this technology needs higher requirement on micro-tool and hardness. Accordingly, using silicon etching and micro-machining technology to process MTE still has some limitations. On one hand, the MTE components are two-dimensional structure, and blades with straight wall structure affect the fluid mechanical property; on the other hand, the processing is restricted by tool and material. Therefore, it is difficult to have mass production in micro-manufacture with lower budget.

Micro electric discharge machining (Micro-EDM), similar to conventional EDM, removes material from both workpiece and electrode by successive electrical discharges. Micro-EDM is a widely used mould manufacturing technique that uses thermal energy of the spark regardless of the hardness of the workpiece material, and it can machine intricate contours and cavities[8]. YU, et al[9], in Lincoln University did the further research on the wear of

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tool electrode, and conducted the processing micro three dimensions cavities with eighth ball clack cavities. Meanwhile, the Tokyo University has conducted the permalloy rotor and complicated micro three dimensional (micro-3D) structure with kinds of typical mechanical components (e.g., hemisphere, groove, gear, screw) in cylinder with 155 μm in diameter by micro-EDM[10–11]. Therefore, the micro-EDM has advantage in processing the micro-3D structure, and the technique has also been applied to machine of micro holes and micro-3D cavities[12]. Based on these advantages and characters of EDM, most of researchers have studied the process of MTE by using EDM. And the MTE is a six-wafer silicon combustion system with compact structure and precision processing fabricated by EDM[13]. However, its blade model is a straight wall structure, which effects aerodynamic performance affected seriously. Catholic University Lou vain BE has studied MTE by sinker EDM in 2002[14]. And the MTE is an axial-flow type engine with non-straight wall structure, whereas it has poor machining accuracy caused by electrode wear in processing and it is difficult to achieve fabrication of accurate three-dimensional structure. Although the machining accuracy can be affected by electro caloric effect, it can be reduced by controlling the processing energy rational. Meanwhile, micro-EDM has advantage in processing micro-mould; therefore, the fabrication of MTE rotor can be processed by designing suitable process path and using stamping or extrusion technology.

This paper analyzes some processes about micro-EDM and has a rational combination of these processes. Finally, it proposes a method of fabricating MTE rotor die by integrated micro-EDM. The advantages of this method can be demonstrated from two aspects. On one hand, the characteristic of micro-EDM are micro discharge energy and without mechanical stress, which can ensure machining accuracy of MTE rotor die; on the other hand, the fabrication of MTE rotor with lower budget and mass production can be completed by combination of mould manufacturing technology and micro-molding technology in processing.

2 Process Design of the MTE Rotor Die by Integrated Micro-EDM

2.1 Process flow of MTE rotor die

The consistency of blade shape and size is an important indicator to evaluate the performance of MTE, and the MTE rotor is important to the efficiency and stability of the MTE. Therefore, it is significant to research rotor processing which made the processing with higher quality and lower budget. However, it still has some limitation in processing micro-3D structure by micro-EDM. The process of complicated micro-3D structure can not be realized by conventional sinker EDM because the electrode with complicated shape is hard to machining. Concerning the shortage of sinker EDM in processing micro-3D structure, the micro-3D milling EDM is developed rapidly. However, it can not confirm machining accuracy due to the electrode wear, it has a lower processing efficiency, and the most important is that it is difficult to realize the fabrication of complicated structure with higher aspect ratio. Therefore, it can not be dependent on single processing method of micro-EDM to process MTE rotor die and needs to combine some different technological methods in reasonable manner. Meanwhile, the control technology of machining accuracy should be paid more attention when MTE rotor die is fabricated by micro-EDM.

As shown in Fig. 1, this paper presents a process flow of MTE rotor die by integrated micro-EDM. It can be seen that the reverse copying die, the punch of the MTE rotor and the MTE rotor die are fabricated by micro Wire Electric discharge machining (micro-WEDM), copying EDM and sinker EDM respectively. And the processing details are introduced in section 3.

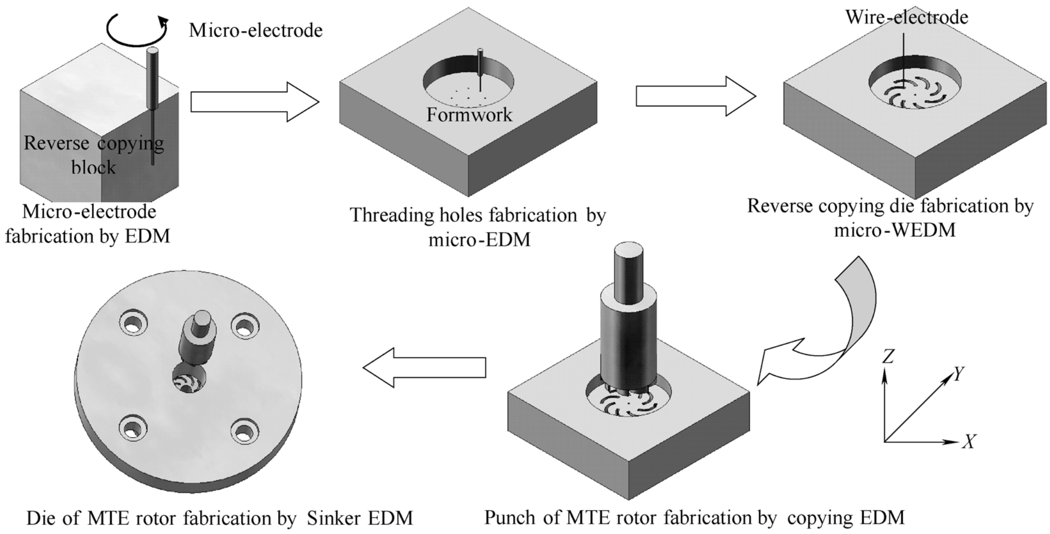


Fig. 1. Process flow diagram of MTE rotor die by integrated micro-EDM

To realize the efficient fabrication of the MTE rotor, the MTE rotor die is applied to micro extrusion equipment to complete mass production of MTE rotor; because this die has the mold cavity with non-through structure, single micro-WEDM which has high accuracy can not be adopted to process MTE die directly. To complete the fabrication of this MTE rotor die with non-through structure, this paper designed the process flow in Fig. 1.

The designed process flow includes many micro-WEDM methods and the process is completed by using two equipments; therefore, the processing accuracy control becomes inevitable problem, and some methods are adopted to improve the processing accuracy. First, the charge-coupled device (CCD) on line vision systems are configured in two equipments, so the locating hole is processed in reverse copying die to reduce second location error by means of CCD. Second from analyzing the process flow, it can be known that the forming accuracy of the reverse copying die decides the accuracy of the MTE rotor punch, and the micro-WEDM equipment in this study can control the processing energy to make the processing error less than 1 μm. Therefore, the MTE rotor die which is suitable for the extrusion process can be fabricated by using integrated micro-EDM through suitable experimental parameters.

2.2　Experimental setup

To fabricate the designed MTE rotor die, the micro-WEDM and the micro-EDM equipments are developed by Harbin Institute of Technology shown in Figs. 2(a) and 2(b). The micro-WEDM equipment used the granite machine itself, the *X*/*Y* motion platform is settled under the worktable to combine the wire-moving system to achieve the micro wire-electric discharge machining. The *X*/*Y* motion platform with 0.1 μm in resolution is composed of precise servo rotor and driver which driven by piezoelectric ceramic rotors, utilizing high precision grating ruler as position feed-backs component. Therefore, it can make the processing precision achieve lower 1 μm to supply the processing demand.

(a) Micro-WEDM equipment　　(b) Micro-EDM equipment　　(c) Processing partial views

Fig. 2.　Integrated micro-EDM equipments for micro-gas turbine engine rotor

The Micro-EDM machining equipment mainly consists of three-axis linear platform of *X*, *Y* and *Z*, *A*-axis rotary table, rotary spindle, pulse power control system, and CCD displaying device. The precision rotating *Z* spindle is driven by the direct current (DC) rotor, its radial run-out is lower than 1 μm and the rotate speed can be adjusted in 0–4000 r/min. The CCD displaying device is used to observe figuration and dimension of the tool electrode and micro hole.

The RC-transistor combined pulse generator is applied to two machine tools. It is developed for providing micro discharge energy in process. It is advanced because of its narrow pulse duration and without maintaining voltage. That means the lower pulse power can be obtained. The control systems of this two machined tools mainly consist of the discharge machining system, the servo motion control system and the I/O state detection model. Its control function is realized through a variety of testing/interface circuit.

3　MTE Rotor Die Fabrication by Integrated Micro-EDM

A series of experiments of MTE rotor die were conducted by an in-house developed micro-WEDM and micro-EDM equipment. To ensure the processing accuracy, there are personal errors to be avoided as much as possible. To reduce the processing error, the guide block of micro-WEDM equipment is adjusted before processing to make the workpiece processing vertically; and to avoid the parallelism error of the reverse copying die, the dial indicator and the contact perception function of the machine tool can be used to accord with the processing requirement.

3.1　Reverse copying die fabrication by micro-WEDM

In this paper, the fabrication of reverse copying die is achieved. To complete the procedure, a series of threading holes for micro-WEDM can be conducted by using tungsten electrode with diameter of 100 μm in copper plate with thickness of 2.5 mm. Meanwhile, the positional precision can be ensured by the accurate position system of the machine tool. The precision of rotor shape is affected directly by reverse coping die precision, so the key point in this research is to realize the high machining accuracy for micro-WEDM. As it mentioned above, the discharge section of wire-electrode is ellipse due to the position error of guide block and the affection by discharge force, which can influence the machining accuracy. To improve the precision, the discharge force is reduced by lessen process energy. And the advanced contour can be obtained by improving tension force and reducing the incline of wire-electrode.

The experimental conditions of reverse copying die by micro-WEDM are shown in Table 1. The tungsten wire-electrode with 30 μm in diameter can be used to reduce the process fillet to improve accuracy. The CCD images of reverse copying die by micro-WEDM are shown in Fig. 3.

Table 1. Experimental conditions of the reverse copying die by micro-WEDM

Parameter	Condition	Parameter	Value
Wire-electrode	Tungsten (Φ30 μm)	Open voltage Vo/V	85
Initial holes	Φ100 μm	Servo feed voltage Vf/V	82
Workpiece	Copper plate	Servo back voltage Vb/V	80
Working fluid	Kerosene	Resistance R/kΩ	1
Polarity	Negative (wire-electrode)	Pulse duration Ton/μs	1
Capacitance C/pF	Stray capacitance	Pulse interval $Toff$/μs	10
Current Ip/A	0.05	Feed rate v/(mm • min^{-1})	0.048

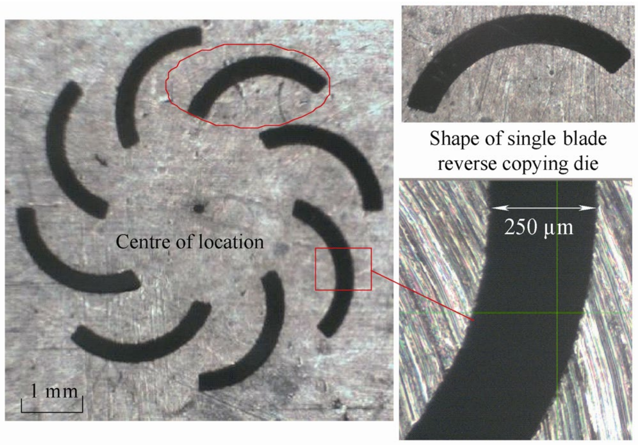


Fig. 3. CCD images of reverse copying die by micro-WEDM

3.2 MTE rotor punch fabrication by copying micro-EDM

The larger machining errors are existed in workpiece bottom for the serious wear of reverse copying die in copying micro-EDM. Lots of experiments present that carbon deposition with high strength and heat resistance can be formed in the surface of reverse copying die when the negative polarity adopted. And this carbon deposition can reduce the electrode wear. However, to generate this carbon deposition, larger processing rules are needed, which has poor surface roughness and machining accuracy. So this paper confirmed the experimental conditions of MTE rotor punch by copying micro-EDM as shown in Table 2 through a lot of experiments. Fig. 4 shows the punch of MTE rotor by copying micro-EDM.

Table 2. Experimental conditions of MTE rotor punch by copying micro-EDM

Parameter	Condition	Parameter	Value
Electrode	Copper rod (Φ6 mm)	Open voltage Vo/V	220
Workpiece	Reverse copying die	Capacitance C/pF	104
Polarity	Negative	Current Ip/A	4
Working medium	Kerosene	Pulse interval Ton/μs	10
Servo voltage Vg/V	150	Pulse duration $Toff$/μs	20

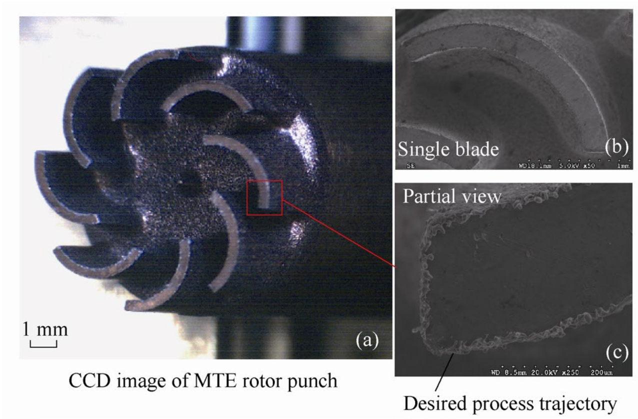


Fig. 4. MTE rotor punch by copying micro-EDM

It can be seen from Fig. 4(a) that the rotor blade height of the MTE rotor punch is about 2.5 mm and the aspect ratio is 10:1. Fig. 4(b) shows that the single blade has a better consistency in vertical direction. So the results indicate that the 3D structure generated by integrated micro-EDM has advancement compared with micro-milling EDM. Carbon deposition and large discharge gap generated by larger pulse power is benefit for reducing electrode wear and removing debris particles. It can be found form Fig. 4(c) that there is almost no wear in top of the rotor, and the recast layer and carbon deposition can be removed by ion beam polishing technology.

3.3 MTE rotor die fabrication by sinker micro-EDM

To carry out mass production of MTE rotor with high precision, the rotor die must be designed for a better precision. This paper finished the fabrication of MTE rotor die using punch of MTE rotor as shaped electrode by sinker micro-EDM. And the experimental conditions of MTE rotor die by sinker micro-EDM are shown in Table 3.

In order to reduce the wear of MTE rotor punch, the high frequency jumping is used in sinker micro-EDM. As illustrated in Fig. 5, the MTE rotor die with 5:1 in aspect ratio has a clear outline, a better consistency of width of the single rotor blade die, which can be used as the die of micro-stamping or micro-extrusion processing to achieve the mass production of MTE rotor.

Table 3.　Experimental conditions of MTE rotor die by sinker micro-EDM

Parameter	Condition	Parameter	Condition
Electrode	MTE rotor punch	Working medium	Kerosene
Workpiece	Stainless steel	Polarity	Positive
Current I_p/A	1.1	Pulse duration T_{on}/μs	2
Servo voltage V_g/V	80	Pulse interval T_{off}/μs	10
Capacitance C/pF	223	Jumping cycle T/s	4
Open voltage V_o/V	100	Jumping height H/mm	1

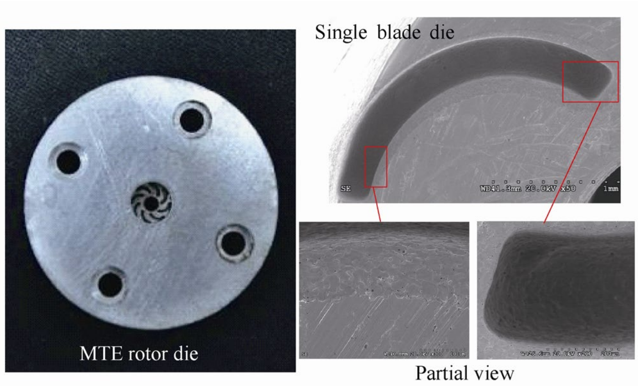


Fig. 5.　MTE rotor die by copying micro-EDM

4　MTE Rotor Fabrication by Micro Extrusion

The processing quality of MTE rotor die decides the property of MTE rotor finished pieces, and suitable forming conditions mainly judge the work life of MTE rotor die.

The experimental system for MTE rotor manufacturing includes micro forming pressure equipment, heating coil and temperature control system and so on, which are shown in Fig. 6. The micro stamping equipment with precision controlled based on the servo motor is applied, and the temperature of isothermal forging is 450℃, the forming load is 6000 N, the forming speed is 0.1 mm/s. And the MTE rotor finished pieces are shown in Fig. 7(a).

To verify the validity and advantage of this MTE rotor manufacturing method, the laser scanning confocal microscope (LSCM) is used to measure tree-dimensional morphology of the MTE rotor blade. And the results show that the width of the MTE rotor blade is 0.3 mm, its height is 0.832 mm and the middle part of blade is high and both ends of blade are low. This blade structure because that the middle part has lower flow resistance and on the contrary the both ends have larger flow resistance in processing of MTE rotor extrusion forming. However, this blade structure can reduce flow resistance of the combustible gas in micro runner and separated flow loss[15], so the MTE efficiency can be improved.

As shown in Fig. 7(b), the surface of extrusion forming MTE rotor is absorbed by the impurities firmly. These impurities include metal filing, dust, and so on. And the ion beam polishing technology is adopted to remove them. Finally, the cleaning MTE rotor is obtained and shown in Fig. 7(c).

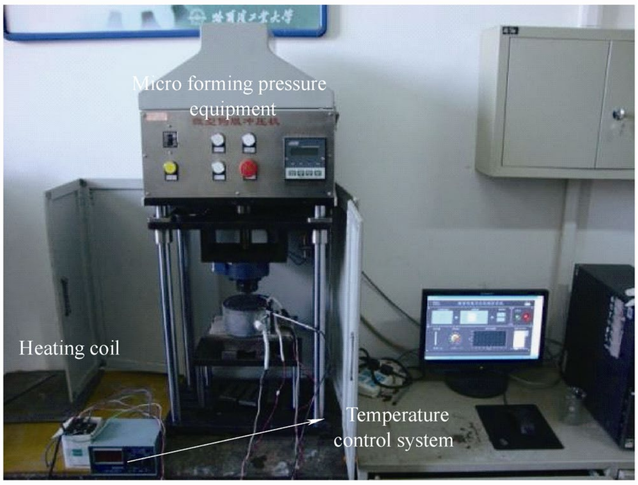
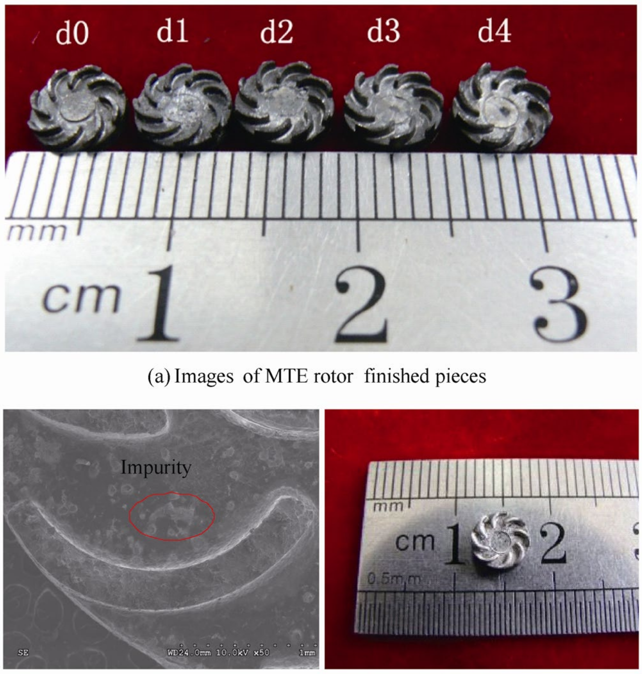


Fig. 6.　Forming experiment system of MTE rotor



(a) Images of MTE rotor finished pieces

(b) Single blade of MTE rotor　　(c) Cleaning MTE rotor

Fig. 7.　MTE rotor by extrusion processing

5　Conclusions

(1) Aiming at improving the high processing cost and low processing efficiency in microminiature rotor processing, this paper proposes an integrated processing technology to manufacture MTE rotor by micro-EDM and micro-extrusion.

(2) This paper also designs the process flow of this integrated micro-EDM method, and machines the MTE rotor die with 5:1 in aspect ratio successfully. By this

method, the die which is eligible to perform as the forming die in micro-extrusion processing, has sharp outline and good width consistency.

(3) Equipped in micro-extrusion machine tools, the MTE rotor dies have a promising prospective in the mass production of MTE rotors which have 4:1 in aspect ratio. The rotors manufactured in this method have improved dimensional consistency and 3D morphology, satisfy the real requirement of MTE; and are ready to be installed in MTEs as the power units to conduct further experimental tests.

References

[1] EDWARD L S. *MEMS and NEMS: system, devices and structures*[M]. Florida: CRC Press, 2002.

[2] SPEARING S M, CHEN K S. Micro-gas turbine engine materials and structures[J]. *Ceramic Engineering and Science Proceedings*, 1997, 18(4): 11–18.

[3] PILAVACHI P A. Mini-and micro-gas turbines for combined heat and power[J]. *Appl. Therm. Eng.*, 2002, 22: 2003–2014.

[4] ALAN H Epstein. Millimeter-scale, MEMS gas turbine engines [C]//*Proceedings of ASME Turbo Expo 2003 Power for Land, Sea and Air*, Atlanta, Georgia, USA, June 16–19, 2003, 1: 1–28.

[5] AMIT Mehra, ZHANG Xin, ARTURO A Ayón. A six-wafer combustion system for a silicon micro gas turbine engine[J]. *Journal of Microelectromechanical System*, 2000, 9(4): 517–527.

[6] HANSOJRG Schlip. *Fabrication of turbine-compressor-shaft assembly for micro gas turbine engine*[D]. Stanford University, 2000.

[7] CHEE Weiwong, ZHANG Xin, STUART A Jacobson. A self-acting gas thrust bearing for high-speed micro rotors[J]. *Journal of Micro Electro Mechanical Systems*, 2004, 13(2): 158–164.

[8] DINESH Rakwal, EBERHARD Bamberg. Slicing, cleaning and kerf analysis of germanium wafers machined by wire electrical discharge machining[J]. *Journal of Materials Processing Technology*, 2009, 209: 3740–3751.

[9] YU Zuyuan, TAKAHISA Masuzawa, MASATOSHI Fujino. 3D Micro-EDM with simply shaped electrode[J]. *Annals of the CIRP*, 1997, 46(1): 1–8.

[10] THORNELL G, JOHANSSON S. Microprocessing at the fingertips[J]. *Journal of Micromechanics and Microengineering*, 1998(8): 251–262.

[11] TAKAHATA K, AOKI S. Fine surface finishing method for 3-dimensional micro structures[C]//*Proceeding IEEE MEMS*, San Diego, CA, USA, July, 1996: 73–78.

[12] KUNIEDA M, LAUWERS B, RAJURKAR K P, et al. Advancing EDM through fundamental insight into the process[J]. *CIRP Ann*, 2005, 54(2): 599–622.

[13] SPADACCINT C M, ZHANG X. Preliminary department of a hydrocarbon-fueled catalytic micro-combustor[J]. *Sensors and Actuator A: Physical*, 2003, 203(1–2): 219–224.

[14] SPADACCINI C M, MEHRA A, LEE J, et al. High power density silicon combustion systems for micro gas turbine engines[J]. *Journal of Engineering for Gas Turbines and Power*, 2003, (125): 709–719.

[15] ZHANG Q D, SHAN X C, GUO G X, et al. Performance analysis of air bearing in a micro system[J]. *Materials Science and Engineering*, 2006, 423: 225–229.

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