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An experimental investigation on micro machining of fine grained graphite

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Abstract

Industrial applications of the micro milling process require sufficient experimental data from various micro tools. Research has been carried out on micro milling of various engineering materials in the past two decades. However, there is no report in the literature on micro milling of graphite. This paper presents an experimental investigation on micro-machinability of micro milling of moulded fine grained graphite. Full immersion slot milling was conducted using diamond coated, TiAlN coated and uncoated tungsten carbide micro end mills with a uniform tool diameter of 0.5mm. The experiments were carried out on a standard industrial precision machining centre with a high speed micro machining spindle. Design of experiments (DoE) techniques were applied to design and analysis of the machining process. Surface roughness, surface topography and burrs formation under varying machining conditions were characterized using white light interferometry, SEM and a precision surface profiler. Influence of variation of cutting parameters including cutting speeds, feedrate and axial depth of cut on surface roughness and surface damage were analyzed using ANOVA method. The experimental results show that feedrate has the most significant influence on surface roughness for all types of tools, and diamond tools are not sensitive to cutting speed and depth of cut. Surface damage and burrs analysis show that the primary material removal mode is still brittle fracture or partial ductile in the experimental cutting conditions. 3D intricate micro EDM electrodes were fabricated with good dimensional accuracy and surface finishes using optimized machining conditions to demonstrate micro milling is an ideal process for graphite machining.

Keywords: micro machining; micro milling; moulded fine grained graphite; Design of Experiments; ANOVA; micro EDM electrode.

1. INTRODUCTION

The need to fabricate high accuracy miniature components with dimensions ranging from a few hundred microns to a few millimetres or features ranging from a few to a few hundreds of microns has encouraged research on development of micro manufacturing processes. It is well recognized that micro manufacturing has been a key enabling technology in industrially producing useful micro products and processes [1, 2].

Micro electrical discharge machining (micro EDM) is a promising machining technology for the manufacture of micro parts and structures over a wide range of engineering materials. The strengths of micro EDM lie in its force-free material removal process, decent attainable accuracy and surface finish on the workpiece, hence it is especially suitable for micro machining hard-to-machine materials, e.g. hardened steel, titanium alloys, and electrically conductive technical ceramics, for fabrication of micro dies and moulds, and micro tools, in a small batch production.

Central to the micro EDM technology is the fabrication of micro electrodes especially 3D complex shape micro electrodes for micro die sink EDM. These micro EDM electrodes have characteristic dimensions normally in the order of tens to hundreds of microns, which will allow micro machining of features with a projection area of 1mm^2 or less [3]. Among several materials available for EDM electrodes, e.g. copper, tungsten-copper, graphite, etc. graphite is versatile and most widely used for conventional EDM electrodes. Due to its excellent thermal and electrical properties, graphite is believed to be still the first choice for electrode materials at meso/micro scale.

Currently a number of micro manufacturing processes, such as micro milling, micro laser machining, micro waterjet machining, can be used to produce micro graphite electrodes. Micro milling is believed to be the most flexible and versatile micro machining process. It is capable of generating a wide variety of complex micro components and microstructures due to its strengths in achievable precision and surface finish in addition to its simple set-up and versatility [2], and it will be a very promising process in fabrication of 3D micro graphite electrodes.

Graphite machining has been carried out extensively in the industry at conventional scale, but unlike metal cutting, reliable and widely accepted machining conditions cannot be found in the research literatures or machining handbooks. Only few publications are available in machining graphite electrodes [4-6]. Micro milling, as a newly emerged micro machining process, has attracted lots of attentions from academia and industries in the last two decades. The research on micro milling have focused on various applications and involved many engineering materials, including metals such as aluminum [7-9], copper [9- 12], Titanium alloys [13, 14] and steels [15, 16]; ceramics like tungsten carbides [17, 18], silicon [19-21], glass [22, 23], polymers [24-25], and composites [26]. However, to our knowledge, there are no publications available dedicated to micro-machinability of graphite material in the open literature.

With the demand for micro parts and features increasing, many cutting tools manufacturers have made commercial micro tools available in the market. These commercial micro tools are fabricated using various materials, such as high speed steel, tungsten carbide, cubic Boron Nitride (cBN), single or poly-crystal diamond, and with various coating such as TiN, TiAlN, and diamond to improve wear characteristics. However since micro milling is still at its nascent stage, currently there are no reliable and widely accepted methods or guidelines available on how to choose cutting conditions in micro milling. Different tool manufacturers would recommend very different cutting conditions for same workpiece and tool materials. For example, for micro milling graphite using 1mm diameter diamond coated tungsten carbide tools, the recommended axial depth of cut, a_p , varies from 0.02mm to 0.25mm, i.e. the highest a_p is 12.5 times the lowest values as recommended by different manufacturers. Further, some recommended values are not obtainable in practice. For example, in order to achieve a recommended cutting speed for a small diameter end mill, a spindle speed of 100,000rpm or more could be required, which is not commonly used in industries.

Therefore it is much needed to conduct research on micro-machinability of graphite materials to improve the process efficiency and the workpiece quality. The aim of the research is to provide information not only on optimised machining data but also the research methods for the micro

manufacturing communities, especially for micro EDM industry to gain a better understanding of micro machining processes of graphite electrodes.

In this paper micro-machinability for micro milling of fine grained graphite was investigated experimentally. Three types of micro end mills, namely diamond coated, TiAlN coated and uncoated tungsten carbide end mills were used in the machining experiments. Surface finish, and burrs formation are analysed, and optimised machining parameters were obtained from the experiments with the aim of improving surface finish and productivity. Complex 3D micro die sink electrodes were fabricated using the optimal machining conditions to demonstrate the potential of micro milling in graphite electrode fabrication.

2. Moulded graphite and general issues on micro machining graphite

2.1 Moulded graphite

Moulded graphite is the most commonly used graphite material in the industrial world. It has found applications in many industrial sectors, such as aerospace, automotive, defense technology, electronics, to name a few. Typical products include EDM electrodes, carbon brushes, bearings and sliding elements, etc. Moulded graphite is a synthetic graphitic product manufactured by a compaction process from a mixture of carbon filler and organic binder which is subsequently carbonized and graphitized [27]. Moulded graphite is a polycrystalline material and the crystallites are randomly oriented. At macro scale, moulded graphite has isotropic mechanical and thermal performance, and is soft and brittle. Strength of moulded graphite is determined by the bond strength between crystallites. At ambient temperature these bonds resist plastic deformation and hence moulded graphite generally fails by brittle fracture and no yield occurs. On the other hand, the bond between atoms within the basal plane of a graphite crystal is considerably stronger than the bond between the planes with a large anisotropy ratio, which means that moulded graphite also has anisotropic behaviour at micro scale, and its mechanical and frictional properties vary in different crystalline orientations.

2.2 General issues on micro machining of graphite

Moulded graphite is generally considered as an easy-to-machine material in the light of its relatively low hardness and strength. Very little heat is generated in the cutting zone and hence less thermal distortion is presented on the workpiece, therefore high speed machining is possible in machining graphite materials. On the other hand, graphite is highly abrasive due to its bond strength between individual carbon molecules, severe tool wear occurs and leads short tool life and low productivity, especially at high speed machining [4, 5]. Tool wear is also one of the main causes of deterioration of surface finish and accuracy.

There are some issues specifically to micro machining of graphite electrodes. Graphite is a brittle material and material properties are very different from those of metals, such as hardness, microstructure, friction characteristics, which leads to different machinability and hence a different method to select tool and cutting parameters. Dimensional accuracy is important for EDM electrodes, as die sink EDM is a copy machining, and any errors on the electrode will be copied onto the workpiece. Unlike conventional machining, where some machining errors can be corrected by subsequent machining operations, for micro parts manufacture these subsequent machining operations are usually not possible or too costly to perform. Therefore, precision fabrication of electrodes directly by micro machining is the key for the success of micro EDM micro parts and features. Surface roughness is another important factor of graphite electrodes and other precision graphite components machining, because a better surface finish on the electrode can lower electrode wear during EDM. Moulded graphite is a porous material, so it is difficult to obtain good surface finish as metals. Therefore a study on how the process parameters affect the surface finish is much desirable to improve surface quality and productivity in micro milling of graphite.

3. EXPERIMENTAL SET-UP

3.1 Machine tool

Experiments for this work were carried out on a precision CNC machining centre (Hurco VM10). The use of standard CNC machine tools is to ensure the results from the experiments are more industrial feasible. The main spindle of the CNC machining centre was locked during the experiments, and a

high speed spindle (NSK-HES810) with electric drive and ceramic bearings was mounted onto the main spindle. The high speed spindle offers a continuous power output of 350W and an output torque of 3cNm over the speed range of 20,000 to 80,000rpm. The high speed spindle allows a reasonable higher cutting velocity even small diameter cutters are used. Ultra-precision collets were used to clamp the micro end mills and the spindle run-out was controlled within 1 μ m. Although the precision machining centre offers single axis positioning accuracy of 5 μ m, as it will be detailed in Section 3.4 that only single axis feeding was used in the optimisation experiments, i.e. along Y axis. Therefore the slideway positioning errors will only influence dimensional accuracy in Y direction which is not of interests in the optimisation experiments, and will not influence the surface roughness and topography which are actually the focus of the research. Spindle errors are believed to have significant influence on the surface finishes. Since the main spindle of the machine tool with higher run-out was mechanical lock throughout the experiment, only the run-out and vibration of the precision high speed spindle would influence the surface finish. This experimental set-up ensures that both the main spindle errors, e.g. vibration and run-out, and slideway inaccuracy have been eliminated or minimized. Therefore main spindle and slideway errors on surface finishes will not be explicitly taken into account in the analysis.

3.2 Workpiece material

Moulded graphite can be considered as homogenous and isotropic materials at macro scale. However this assumption may not hold true because of the well-known grain size effect. Commercial moulded graphite has grain sizes ranging from a few microns to tens of microns, and the grain sizes determine its material properties. Fine grained graphite is used in the experiment, since it has high strength and hardness, lower porosity, and better achievable surface roughness. Table 1 lists the workpiece material properties of the fine grained graphite used in the experiment.

Table 1. Material properties of the fine grained graphite

Properties	Values
Density (Kg/m ³)	1830
Porosity (%)	10
Modulus of elasticity (GPa)	13.5

Compressive Strength (MPa)	90
Hardness (Shore, °S)	60
Thermal expansion coefficient ($10^{-6}/K$)	4.8
Thermal conductivity (W/m·K)	105
Average Grain Size (μm)	5

3.3 Micro end mills

Three types of micro flat end mills, namely diamond coated tungsten carbide (DC), TiAlN coated tungsten carbide (TiAlN) and uncoated tungsten carbide tools (WC), were used in the experiments. Three tools have a same nominal diameter of 0.5mm. A uniform tool shank diameter of 3mm is used for all micro tools to fit 3mm ultra-precision spindle collet. A relative large tool diameter was selected in the experiments to avoid premature tool breakage in those aggressive cuts, and hence ensure that all tools can last without excess tool chipping and wear. Table 2 lists the geometries of micro end mills used in the experiments.

Table 2. Geometries of micro tools used in the experiments

	Diamond coated	TiAlN coated	Uncoated
Nominal diameter (mm)	0.5	0.5	0.5
No. of flute	2	2	2
Helix angle (°)	25	20	20
Flute length (mm)	1	1.5	1.5
Rake angle (°)	-5	-2	0
Clearance angle (°)	10	20	17
Nominal Corner radius (mm)	0.05	0	0
Tool edge radius (μm)	9	4	3

(a)

Figure 1. Cutting edge radius measurement by SEM, (a) diamond coated tool; (b) TiAlN coated tool; (c) uncoated tool.

The cutting edge radius was measured on the cross sectional SEM images by fitting a circle, as illustrated in Figure 1. The estimated values are $9\mu\text{m}$, $4\mu\text{m}$ and $3\mu\text{m}$ for diamond coated, TiAlN coated and uncoated tools, respectively. Section 4 will discuss if tool sharpness would affect surface finish. In previous research on micro milling of metals, a critical minimum chip thickness was observed. The critical minimum chip thickness determines the transition between cutting and plowing, i.e. if the uncut chip thickness is less than a critical value, there will be no chip formation, and corresponding cutting forces and surface roughness values changes to reflect this size effects. Feedrate range in the experiments were selected to be same order as cutting edge radius in order to investigate if there exists a critical minimum chip thickness in micro machining of graphite.

3.4 Experimental procedure

The experiments in this work include full immersion slot milling. The experimental set-up is illustrated in Figure 2. For each test, a 5mm long and 0.5mm wide micro slot was milled along Y direction. Before experiments, the top surface of the workpiece was prepared using a 12mm end-mill. A small axial depth of cut of $5\mu\text{m}$ at each pass was used for the surface preparation to eliminate

surface damage. A machine vision system (InfiniStix™ microscope) is integrated into the machine tool providing $3\mu\text{m}$ resolution in Z direction to assist positioning the cutter to the workpiece surface.

Figure 2. Experimental set-up for micro milling of graphite (a) schematic diagram; (b) machining set-up photo.

Dry machining was performed to avoid contamination, and ventilation system was used to control and collect powdery dust. Three controlled quantitative factors used in the experiments are cutting speed (m/min), feedrate ($\mu\text{m}/\text{tooth}$) and axial depth of cut (μm). Because there are only three controlled factors considered for each type of micro tools in the experiments, full factorial designs were implemented to capture all of the main effects and their interactions. Two levels of cutting speed and depth of cut were selected, albeit four levels of feedrate were selected. The $4 \times 2 \times 2$ mixed level full factorial design matrix is presented in Table 3. Each set of cutting parameter was repeated once to reduce machining errors and separate effect due to interactions from measurement noise, so total 32 slots were machined for each cutter. In order to reduce the influence of tool wear on the surface and burr formation, brand new micro tools were used for the experiments. Extra slots (Exp #17, see Table 3) were milled at the end of experiments using the same cutting conditions as Exp #1 (see Table 3). This validation slot was then compared with the first slot (Exp #1).

Table 3. Experimental matrix of micro milling of graphite and mean measured surface roughness, R_a

Exp No	Experimental matrix - controlled factors ¹			Responses		
	Feedrate	Cutting speed/Spindle Speed		Depth of Cut	Measured Surface roughness, R_a^2 (μm)	
	f_z , ($\mu\text{m}/\text{tooth}$)	V_c , (m/min)	n , (rpm)	a_p , (μm)	Diamond coated	TiAlN coated Uncoated
1	0.5	31.4	20,000	20	0.29	0.35 0.47

2	2	31.4	20,000	20	0.4	0.48	0.75
3	5	31.4	20,000	20	0.54	0.65	0.78
4	10	31.4	20,000	20	1	1.2	1.13
5	0.5	78.5	50,000	20	0.29	0.49	0.79
6	2	78.5	50,000	20	0.52	0.61	0.9
7	5	78.5	50,000	20	0.76	0.95	0.84
8	10	78.5	50,000	20	0.87	1.45	1.31
9	0.5	31.4	20,000	60	0.3	0.4	0.47
10	2	31.4	20,000	60	0.45	0.54	0.61
11	5	31.4	20,000	60	0.66	0.62	0.69
12	10	31.4	20,000	60	0.78	1.04	1.21
13	0.5	78.5	50,000	60	0.39	0.42	0.6
14	2	78.5	50,000	60	0.48	0.45	0.7
15	5	78.5	50,000	60	0.75	0.97	1.08
16	10	78.5	50,000	60	0.82	1.05	1.09
17 ³	0.5	31.4	20,000	20	0.30	0.33	0.55

¹ Uncontrolled factors: Width of Cut, $a_e = 0.5\text{mm}$; Cutter Diameter, $D = 0.5\text{mm}$; No of Flutes, $Z = 2$; Slot length = 5mm;

² Surface roughness values presented in the table are the arithmetic mean of measured Ra values;

³ Validation slot, same machining condition as Exp #1.

a. Metrology issues

The average surface roughness of the bottom surface of the micro milled slots was measured using a white light interferometer (Zygo NewView 5000) along the centreline of the slots. To reduce the measurement uncertainty and assess repeatability, four measurements on different area were conducted for each slot and an average value of surface roughness (Ra) is used for analysis. An optical microscope and surface profiler (Talysurf Serial-2) were used to assess burr formation. Besides, the surface morphology was analyzed on the basis of SEM micrographs. Analysis on the response – surface roughness will be presented in section 4. Mean values of measured surface roughness, Ra, are listed in Table 3.

4. RESULTS AND DISCUSSIONS

ANOVA was performed on surface roughness data to isolate main effects of each source of variations and determine effects of interactions. Table 4-6 summarise the results of AVOVA on surface roughness (Ra values) for three types of micro end mills. All tabulated F values ($\alpha = 0.05$) except the interaction of cutting speed and depth of cut in table 5 and 6 are smaller than the calculated values as shown in Table 4-6, which corresponds to a confidence level of 95% in evaluation of process parameters.

Table 4. ANOVA for micro milling of graphite experiment using diamond coated tools

Source of Variation	Sum of Squares	Degrees of freedom	Mean Square	F (Calculated)	F (Tabulated, $\alpha = 0.05$)	P-Value	Contribution ratio %
Feedrate (A)	2.753	3	0.918	235.765	2.80	1.02E-28	85.232
Cutting speed (B)	0.0225	1	0.0225	5.78	4.04	0.020118	0.697
Depth of Cut (C)	5.63E-05	1	5.63E-05	0.0145	4.04	0.90482	0.002
AB	0.101	3	0.0337	8.656	2.80	0.000107	3.127
AC	0.078	3	0.026	6.673	2.80	0.000741	2.415
BC	0.004	1	0.004	0.13	4.04	0.71996	0.016
ABC	0.0873	3	0.029	7.474	2.80	0.000334	2.703
Error	0.187	48	3.89E-03	235.765			5.789
Total	3.23	63					

Table 5. ANOVA for micro milling of graphite experiment using TiAlN coated tools

Source of Variation	Sum of Squares	Degrees of freedom	Mean Square	F (Calculated)	F (Tabulated, $\alpha = 0.05$)	P-Value	Contribution ratio %
Feedrate (A)	5.712	3	1.904	211.731	2.80	1.13E-27	80.6
Cutting speed (B)	0.304	1	0.304	33.793	4.04	4.83E-07	4.3
Depth of Cut (C)	0.113	1	0.113	12.574	4.04	0.000885	1.6
AB	0.203	3	0.068	7.528	2.80	0.000316	2.9
AC	0.202	3	0.067	7.471	2.80	0.000334	2.8
BC	0.068	1	0.068	7.590	4.04	0.008268	1
ABC	0.057	3	0.038	2.946	2.80	0.13471	0.7
Error	0.432	48	0.009				
Total	7.086	63					

Table 6. ANOVA for micro milling of graphite experiment using uncoated coated tools

Source of Variation	Sum of Squares	Degrees of freedom	Mean Square	F (Calculated)	F (Tabulated, $\alpha = 0.05$)	P-Value	Contribution ratio %
Feedrate (A)	3.133	3	1.044	120.887	2.80	2.24E-22	70.7
Cutting speed (B)	0.353	1	0.353	40.845	4.04	6.32E-08	8.0
Depth of Cut (C)	0.064	1	0.064	7.351	4.04	0.009271	1.4
AB	0.105	3	0.035	4.050	2.80	0.012052	2.4
AC	0.131	3	0.044	5.056	2.80	0.004006	3.0
BC	0.011	1	0.011	1.276	4.04	0.26421	0.2
ABC	0.218	3	0.073	8.396	2.80	0.000137	4.9
Error	0.415	48	0.009				9.4
Total	4.428	63					

The ANOVA tables show that feedrate has the most significant influence on surface roughness for all three types of micro end mills, and it contributes to 85.2%, 80.6% and 70.7% overall responses for diamond coated, TiAlN coated and uncoated micro end mills respectively. Cutting speed also has influence on surface roughness for TiAlN coated and uncoated tools, whereas cutting speed has almost no influence on surface roughness when diamond coated tools were used. Depth of cut has positive influence on surface roughness when TiAlN coated and uncoated tools were used, i.e. an increase in axial depth of cut will improve surface roughness.

Both the interaction between feedrate and cutting speed and the interaction between feedrate and depth of cut have effects on the measured surface roughness, although these interaction effects are not significant as single factor main effects. Higher order interactions was not significant, therefore it does not seem worthwhile to examine the statistical significance of these effects.

Main effects were plotted in Figure 3-5 to quantitatively assess the effect of each process parameters on micro machining process. Tool sharpness in terms of cutting edge radius is believed to have a positive influence on surface roughness at the order of a few microns, i.e. smaller tool edge radius is expected to result in better surface finish. However it can be seen from Table 3 and Figure 3-5 that under same cutting conditions, diamond coated tools give better surface roughness although the diamond coated tools are the bluntest among three types of micro tools. There is no clear difference between TiAlN coated tools and uncoated tools in terms of achievable surface quality, indicating TiAlN coated tools are not a good choice for micro milling of graphite if optimization of surface quality is the main concern. Within the cutting parameter range used in the experiments, minimum average surface roughness value of around $0.3\mu\text{m}$ was measured at low feedrate of $0.5\mu\text{m/tooth}$ and under both low and high depth of cut when using diamond coated tools. Maximum surface roughness mean value of around $1.4\mu\text{m}$ was measured at high feedrate of $10\mu\text{m/tooth}$ under high depth of cut of $60\mu\text{m}$ when using either TiAlN coated or uncoated tools.

It is observed from Figure. 3(a),4(a) and 5(a) that an increase in feedrate from 0.5 to $10\mu\text{m/tooth}$ for all three micro tools results in increase of surface roughness values and this tendency is very linear in

the machining conditions used in the experiments. This tendency is also similar to that for micro milling of metallic materials.

When cutting speed increases from 31.4m/min to 78.5m/min, there is around 20% increase in surface roughness value for TiAlN coated and uncoated tools, whilst only 5% increase in surface roughness value was observed for diamond tools, as shown in Figure. 3(b), 4(b) and 5(b). This suggests that higher cutting speed hence higher machining efficiency can be achieved by using diamond coated tools without significantly compromising surface quality.

The surface roughness decreases by 10% when depth of cut was increased from 20 μ m to 60 μ m when TiAlN coated and uncoated tools were used as shown in Figure 4(c) and 5(c). This trend is different from conventional machining of graphite materials and can be explained by grain size effect. The average graphite grain size in the workpiece was measured by the manufacturer as 5 μ m. When the grain size is close to or smaller than depth of cut, brittle fracture may occur within the grain, so that the material cannot be considered as homogenous and isotropic. The grain size effect will affect the micro cutting processes, including mechanism of chip formation and surface generation [28-29]. Local material strength within the grain is higher than the bulk value, more specific cutting energy is required to remove material, and therefore the surface finish is deteriorated. When the depth of cut increases, the material becomes more statistically homogenous and the material property tends to be similar to that of bulk materials, and therefore higher feedrate can promote good surface finish within a certain range. However this effect has not been clearly observed when diamond coated tools were used (Figure 3(c)).

In micro milling of metals, the cutting edge radius and minimum chip thickness size effect is the dominant factor for material removal mechanism and chip generation physics. In previous micro milling of metallic materials, numerous researchers have investigated this size effect and the critical minimum chip thickness was reported to be around 0.1 – 0.4 of cutting edge radius for various materials [10, 15, 30-32]. Micro tools used in this work have a cutting edge radius in the range of 3 – 9 μ m from SEM measurement results and the ratio of uncut chip thickness to cutting edge radius are

in the range of 0.05 to 1, however no explicit cutting edge radius size effects were observed in the experiments for all three types of cutters. Further examinations on surface defects show that micro cracking occurred in the bottom and side surface of the slots. Figure 6 shows typical surface damages in the form of fractured craters and residual flake chips. Different to micro milling of metals, no tool marks were observed on machined surfaces from TiAlN coated and uncoated tools, whilst indistinct tool marks were found by close examination on surfaces machined by diamond coated tools. Surface damages and absence of tool marks on the machined surfaces indicate that the primary cutting mode was still brittle fracture or partial ductile under the cutting conditions in the experiments. Another evidence of graphite materials being cut primarily at brittle fracture mode is that no obvious burrs were observed for all the slots machined, which is similar to conventional machining of most brittle materials.

For three types of micro tools, it is observed that there is no significant difference between first set of slots (exp #1) and validation slots (exp #17) in terms of surface roughness and micro surface morphology. Therefore the tool wear effect is regarded negligible under this certain cutting distance in this work.

Figure 3. Main effect plots for influences of single factors on surface roughness with diamond coated micro end mills: (a)feedrate, f_z ; (b)cutting speed, V_c (c) axial depth of cut, a_p .

Figure 4. Main effect plots for influences of single factors on surface roughness with TiAlN coated micro end mills: (a)feedrate, fz; (b)cutting speed, Vc (c) axial depth of cut, ap.

Figure 5. Main effect plots for influences of single factors on surface roughness with uncoated micro end mills: (a)feedrate, fz; (b)cutting speed, Vc (c) axial depth of cut, ap.

(a)

(b)

(c)

Figure 6. SEM micrographs of the micro machined surface morphology (cutting conditions: $V_c=31.4$ m/min; $f_z = 2\mu\text{m/tooth}$, axial depth of cut = $20\mu\text{m}$) by (a) diamond coated tool; (b) TiAlN coated tool; (c) uncoated tool.

5. EXAMPLES OF MICRO DIE SINK EDM ELECTRODES

Micro EDM electrodes with high aspect ratio and complex shapes were fabricated using the optimal cutting conditions obtained through this research. Figure. 7 shows the SEM image of three 3D intricate micro machined electrodes. Fine grained tungsten carbide end mills with diameter of 0.2mm were used to machine these samples. An average surface roughness of $0.8\mu\text{m}$ was measured on the bottom surfaces, and slot width deviations were controlled well within $10\mu\text{m}$ based on surface profiler measurements. Good dimensional accuracy and surface roughness obtained from the experiments demonstrated that micro milling is a promising process for fabrication of 3D micro EDM electrodes.

Figure 7. Examples of micro machined EDM electrodes (a) micro thin-walled structure, (b) micro pillar array, (c) micro mixing device

6. CONCLUSIONS

This paper presents an experimental investigation on micro milling of moulded fine grained graphite. Diamond coated, TiAlN coated and uncoated tungsten carbide micro end mills with 0.5 mm diameter were used to create full width slots. Various cutting conditions including feedrate, cutting speed and axial depth of cut were experimentally investigated based on Design of Experiments techniques, and

their influences on surface finish were assessed using ANOVA method. The following conclusions can be drawn from this work:

- Feedrate has the most significant influence on surface roughness for all three types of micro tools. Higher feedrate results in higher surface roughness values and this linear tendency is similar to that of micro milling of metallic materials.
- The diamond coated tools give better surface roughness although the diamond coated tools have much larger tool edge radius than other two types of micro tools used in the experiments. High speed machining with diamond coated is more effective in improving machining productivity and achieving good surface finish.
- The surface roughness decreases when depth of cut is increased when TiAlN coated and uncoated tools were used, and this phenomenon can be explained by grain size effect. Higher depth of cut is therefore recommended under certain machining conditions from optimizing machining productivity and surface finish point of view. Different to micro milling of ductile metallic materials, no cutting edge size effect and minimal chip thickness were observed for all three types of micro tools.
- No obvious burrs and clear tool marks were observed for all machined slots, whilst surface damages were found in the forms of fractured craters, residual flake chips and micro-cracks, which indicate that the primary cutting mode is still brittle fracture or partial ductile under the cutting conditions in the experiments.

Micro EDM electrodes with high aspect ratio and complex shapes were fabricated using the optimal cutting conditions obtained through this research. The results are also useful for micro milling of other brittle materials, such as glass and silicon. Although tool wear was found negligible in the experimental conditions in this research, future efforts will be made on characterization of tool wear in micro milling of graphite.

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