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ORIGINAL ARTICLE

Surface textures on cemented carbide cutting tools by micro EDM assisted with high-frequency vibration

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Abstract This paper demonstrates the process of micro electro-discharge machining (micro EDM) assisted with high-frequency vibration machining micro holes and linear grooves which are straight or inclined on WC/8 % Co (MA) and WC/15 % TiC/6 %Co (MB) cemented carbide cutting tool rake face or scrap reeling slot. Low-voltage sensing contact is introduced to determine the exact position of holes and grooves. Morphology of textured regions is examined and the elemental chemical composition of close proximity region to a straight hole is identified. Results show that micro holes and linear grooves with high dimension accuracy and exact position are machined as expected by micro EDM assisted with high-frequency vibration. There is no debris accumulating around the cavities. Materials of MA cutting tool adhere on the micro tool electrode slightly, while the dimension of adhesion position becomes constant after 3 μ holes are finished. However, the adhesion does not occur during machining MB cutting tools. The distance of edges of grain refinement regions and areas where elemental chemical composition varies to the contour of the hole is no more than 15 μm.

Keywords Micro EDM · High-frequency vibration · Cutting tool · Micro holes · Linear grooves

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1 Introduction

In metal cutting process, performance of cutting tool determines machining accuracy, efficiency, and surface quality. However, progressive friction occurs where cutting tool contacts with workpiece, i.e., on the rake face and the tool flank. Consequently, surface damage of cutting tool will be produced by wear, heat, and adhesion due to friction, thus extremely affecting machined surface quality and shortens tool lives [1–3].

Friction can be diminished by introducing lubricants into tool-chip interface and the effectiveness could be enhanced by appropriate surface textures on the cutting tool rake face [4–6]. This improvement is attributed to several physical mechanisms such as wear debris entrapment, local increase of lubricant supply by fluid reservoirs creation, and increase of load carrying capacity by a hydrodynamic effect [1, 7].

Wide spectrum processes have been used to machine surface textures on a functional surface. However, due to high strength and hardness, machining appropriate surface textures on cutting tools is technically challenging. Conventional surface finishing methods, such as mechanical honing, grinding, and polishing are not adequate to complete this work due to severe tool wear, low material removal rate, and challenge of further miniaturization [6]. The action of a high-velocity stream of abrasive particles and electro-chemical machining may be employed; however, the corresponding dimple size is larger, which increases the probability of the chip materials extruding into and clogging the textures [8–10]. Femtosecond laser, electron beam, and ion sputtering techniques are limited by throughput and strict working conditions. Besides, these technologies are secondary operation requiring expensive in-house equipment or the use of sub-contract companies [4, 7, 11–13].

Most surface textures are usually machined by conventional laser beam and micro EDM [14–19]. The equipment of both is cost saving and the production time is much shorter.

Table 1 Properties of the cemented carbide tool materials [1, 18, 24, 25]

Properties	Materials	
	MA	MB
Density (g/cm^3)	14.5	11.0~11.7
Hardness (GPa)	16.0	16.4
Flexural strength (MPa)	2000	1570
Thermal conductivity (W/(m.k))	75.4	33.5
Thermal expansion coefficient (10^{-6}/K)	4.51	6.5

Conventional laser beam has been widely used for surface texturing in the past decades. However, it still has some shortcomings. The entrance of micro holes machined by laser beam is elliptical rather than circular. The energy profile is a peak power in the center, leading to a large taper of each cavity, which decreases the amount of solid lubricants and causes stress concentration [7, 13, 20, 21]. Inclined micro holes or grooves on the rake face may enhance the performance of debris entrapment and lubricant supply. However, the absorption rate of laser decreases sharply, if an inclined incident angle is introduced. Therefore, it is a tough challenge to obtain inclined textures on the rake face or textures on scrap reeling slot. Without flushing fluid, ejection of melted materials will accumulate around areas with a close proximity to the cavities, providing an increased roughness and increasing initial asperity contacts [15].

The objective of this paper is to provide an alternative approach to overcome these shortcomings using micro EDM assisted with high-frequency vibration. Micro holes or linear grooves which are straight or inclined on cemented carbide cutting tool rake face or on scrap reeling slot can be obtained conveniently using proper micro tool electrodes and appropriate pulse parameters [22]. Lasting electro-discharge conditions between the micro tool electrode and cemented carbide materials can be improved by high-frequency vibration. Just set cutting tools some certain angles and inclined micro holes or grooves can be fabricated. The discharge energy profile of micro tool electrode is a circular area, making the contour of cavities like cylinder. Besides, the exact location of surface textures can be determined by low-voltage sensing contact which occurs between a micro tool electrode and a workpiece [20]. With flowing working fluid and high-frequency vibration, melted materials will be moved away from inner or around areas with a close proximity to micro cavities, which forms high accuracy and good surface quality. Besides, the generated surface comprises a large number of microscopic over lapping craters with a positive skewness, which are ideally predisposed to entraining lubricants [6, 20, 23].

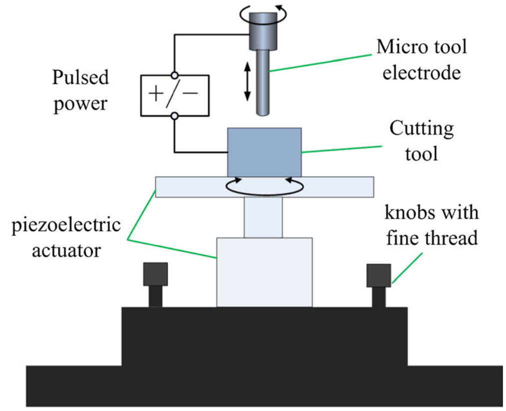

Fig. 2 Processing theory schematic diagram of high-frequency vibration-assisted machining

2 Experimental procedures

WC/8 % Co and WC/15 % TiC/6 % Co cemented carbide cutting tools are selected to be machined and are named MA and MB, respectively. Composition and physical and mechanical properties of these tool materials are listed in Table 1. The surfaces of rake face are modified by grinding and polishing to the roughness less than Ra 0.05 μm.

2.1 Preparation of micro tool electrodes

For machining micro textures with dimension of <100 μm, online reverse copying process is required to avoid re-clamping errors of micro tool electrodes. So, a hybrid online process combining the self-drilled holes method and wire

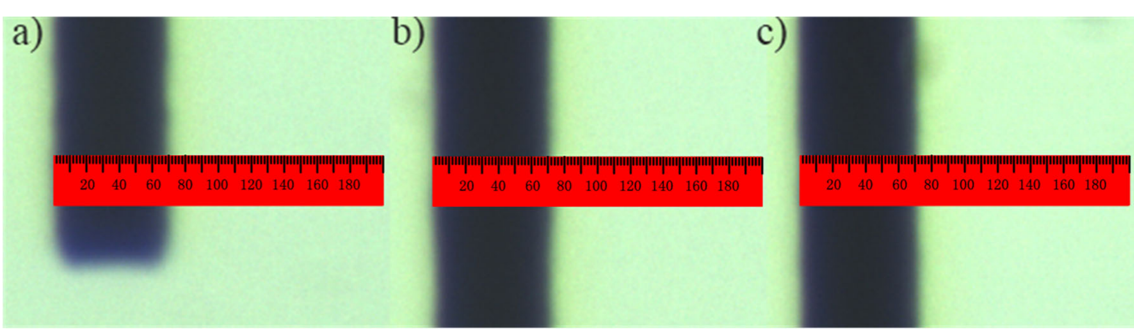

Fig. 1 Dimension consistency of one micro tool electrode. **a** Diameter of bottom position. **b** Diameter of middle position. **c** Diameter of top position

electro-discharge grinding (WEDG) method [20, 26] for complementary advantages of high efficiency and high accuracy is used. Dimensions of micro tool electrode can be observed online from a charge-coupled device (CCD) during the reverse copying process, according to a pixel ruler by calculating the relation between the pixel and the standard rule. As shown in Fig. 1, the diameters of bottom, middle, and top regions of a micro tool electrode after WEDG are almost 70 pixels. Each pixel represents 0.7 μm, so the dimensions (*d*) are 50 μm consistently. During the procedures of fabricating micro holes and linear grooves, the obtained micro tool electrode clamped on the rotating spindle will be surely consumed, but a new micro tool electrode will be machined again using the same methods.

2.2 High-frequency vibration-assisted machining

To improve lasting electro-discharge conditions between a micro tool electrode and cutting tool materials, a piezoelectric actuator module, assembled of a piezoelectric actuator and a plane adjusting platform, is attached to the worktable. Vibration energy, pumping, and eddy effect will be introduced, due to the intervention of high frequency. Melted material removal process will be promoted. Less debris will adhere to the abrasive grains or block the gap between the micro tool electrode and the workpiece [27–29]. Detailed processing theory schematic diagram of high-frequency vibration-assisted machining is shown in Fig. 2.

Cutting tools are fixed on the upper part of the piezoelectric actuator, which can be rotated around its center. The angle between cutting tool rake face and axis of a micro tool electrode is adjusted by rotating the two knobs with fine thread on the plane adjusting platform.

2.3 Position of surface textures relative to the cutting edges

Compared with a non-textured cutting tool, extending the textures right to the cutting edges is counterproductive, which increases the cutting force and decreases mechanical strength. The textures stopping short of the cutting edges can be further beneficial in averting possible catastrophic tool failure, which could arise from the adverse surface integrity effects of micro EDM. When textures are around the position where serious friction occurs, the cutting force turns out to be minimal [1, 4]. Therefore, during surface texturing procedures, the exact position of the micro tool electrode relative to the cutting edges should be exact. Low-voltage sensing contact is suitable to overcome this issue. In this experiment, the distance of texture contour to the cutting edges and distribution density of micro holes and grooves are exhibited in Fig. 3.

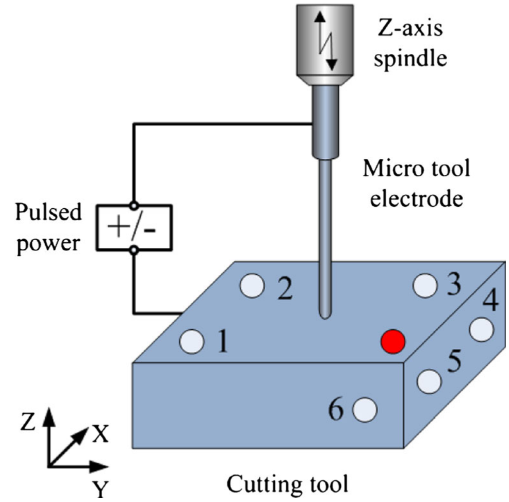

Fig. 4 Schematic diagram of determination of the exact texture position

Before machining micro holes and linear grooves with exact position, care should be taken to adjust the rake face perpendicular with *Z*-axis and make the cutting edges parallel with *XY*-axis. Fix a cutting tool on the piezoelectric actuator and change the pulsed power supply into low-voltage model. As shown in Fig. 4, positions 1, 2, and 3 are three different points selected arbitrarily on the rake face and are employed to determine a plane representing the tool rake face. *Z*-axis spindle moves down until the rake face is touched by the bottom of this micro tool electrode in position 1. Write down coordinate Z_1 which is obtained from computerized numerical control (CNC) system. Then, *Z*-axis moves and drives the bottom of this micro tool electrode to touch position 2. Write down coordinate Z_2. Usually, Z_1 is not equal with Z_2, so adjust the plane angle by rotating the two knobs until Z_1 is equal with Z_2. Use the same method to adjust Z_3 until Z_3 is equal with Z_2.

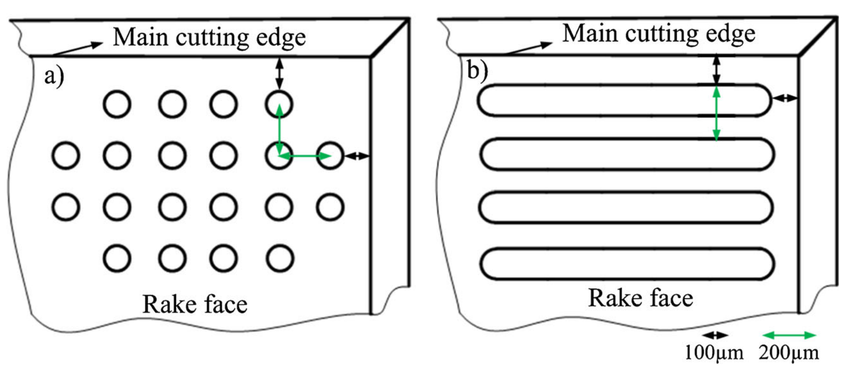

Fig. 3 Distribution of surface textures on cutting tool rake face. **a** Distribution of straight holes. **b** Distribution of linear grooves

Table 2 Arrangement of surface texturing

	Cutting tool rake face (flat surface)		Scrap reeling slot (curved surface)
MA	Straight holes	Inclined holes	Straight holes
MB	Straight linear grooves	Inclined linear grooves	Straight linear grooves

At this moment, positions 1, 2, and 3 have the same coordinate in the direction of Z axis. Therefore, the rake face is perpendicular with Z-axis. Due to spatial geometric relationship between the rake face and flank faces, all flank faces are parallel with the axis of this micro tool electrode.

Cylindrical surface of the micro tool electrode and flank face of the cutting tool are used to make the cutting edges parallel with XY-axis. Positions 4 and 5 are two different points on the flank face. Z-axis moves right along the positive direction of Y-axis and moves down at a certain distance. Then, Z-axis moves left until the flank face is touched by cylindrical surface of the micro tool electrode at position 4. Write down coordinate Y_4. Then, Z-axis moves and drives cylindrical surface of the micro tool electrode to touch position 5. Write down coordinate Y_5. Rotate the upper part of the piezoelectric actuator around its center and make Y_4 equal with Y_5. At this moment, the flank face containing positions 4 and 5 is parallel with X-axis. Due to spatial geometric relationship of cutting tools, the cutting edges are parallel with XY-axis, simultaneously.

Coordinate X_6 of position 6 on another flank face can be obtained easily using the same method. The typical position ($X_6+d/2$, $Y_5-d/2$) is the tool nose, which is a meeting point of cutting edges on the rake face, and can be used as a reference point of texture distribution. Move the axis of micro tool electrode to the red point which represents the planned starting position of texturing, and micro holes or grooves can be machined by micro EDM assisted with high-frequency vibration experimental system.

2.4 Surface texturing procedures

To verify the feasibility of micro EDM assisted with high-frequency vibration machining micro holes and linear grooves which are straight or inclined on cutting tool rake face or on scrap reeling slot, arrangement of surface texturing is listed in Table 2. For machining inclined holes or inclined linear grooves, cutting tools just need to set some required angles.

Depth of the holes should be limited to prevent sharp decreasing of mechanical strength of cutting tools. Appreciable depth of holes (h) can be estimated from the difference between the feeding distance of spindle (h_1) and consumption of the micro tool electrode (h_2). From CNC system and CCD, h_1 and h_2 could be obtained easily. A constant gap of 5 μm between the bottom of micro tool electrode and the rake face is set before and after each hole is machined. Consequently, appreciable depth of h can be estimated.

$$h \approx h_1 - h_2 \tag{1}$$

Depth of linear grooves is controlled by means of setting appropriate scanning speed and reciprocating times of the micro tool electrode. After several preliminary experiments, scanning speed is set to 0.4 mm/s and reciprocating time is twice the scanning speed.

3 Results and discussion

To examine the accuracy of machined micro holes, linear grooves, and collateral damage caused by micro EDM, the morphology of textured regions is examined by optical microscopy and scanning electron microscopy (SEM). The chemical composition of close proximity region around a straight hole on MA cutting tool rake face is also identified by energy-dispersive x-ray spectroscopy (EDX).

3.1 Morphology of micro textures

3.1.1 Morphology of micro holes

Straight and inclined holes on MA cutting tool rake face as well as micro holes on scrap reeling slot are successfully obtained. The general view is depicted in Fig. 5. Owing to flowing working fluid and high-frequency vibration, there is

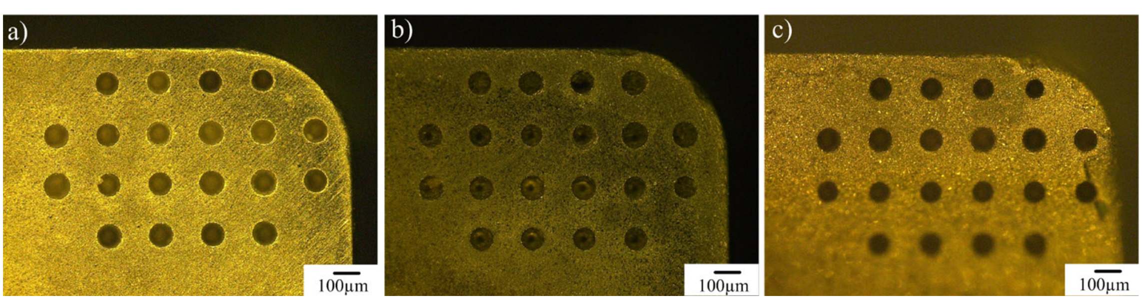

Fig. 5 Photos of micro holes machined on MA cutting tool rake face and on scrap reeling slot. **a** Straight holes on rake face. **b** Inclined holes on rake face. **c** Micro holes on scrap reeling slot

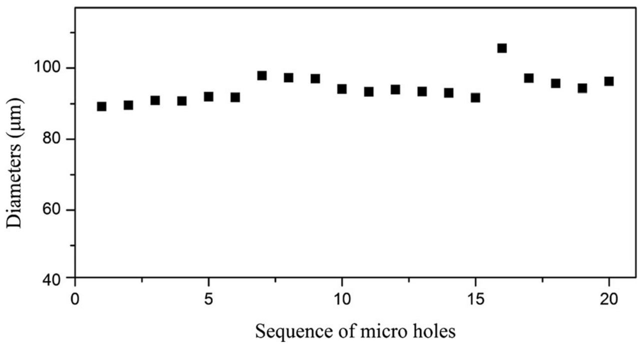

Fig. 6 The diameters of straight holes on MA cutting tool rake face

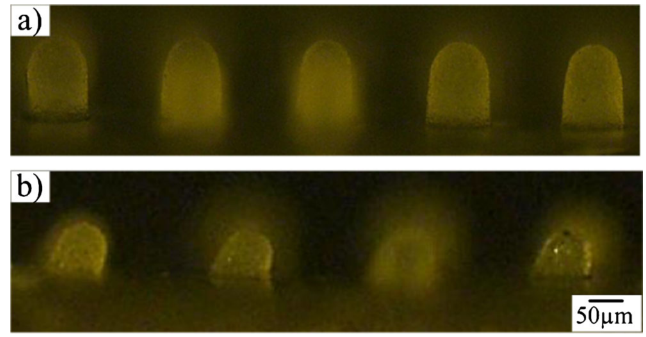

Fig. 8 Image of micro holes from a replica technique. **a** Replica of straight holes. **b** Replica of inclined holes

no debris accumulating around micro holes and no surface burns on the textured surfaces. The entrances of straight holes on rake face are standard cylinder, indicating that the rake face is perpendicular with *Z*-axis, while the entrances of inclined holes on rake face and micro holes on scrap reeling slot are a little elliptic because of the angles between textured surfaces and *Z*-axis. Lines of texture contour in each row and each column are parallel with cutting edges, indicating that the cutting edges are parallel with *XY*-axis. As excepted, distance of texture contour to the main cutting edge is 100 μm and distances of each row and each column are 200 μm, approximately. These results demonstrate that low-voltage sensing contact is reliable on determining the exact position of the textures on the rake face.

According to the sequence of processing, diameters of each straight hole are shown in Fig. 6. With highly consistent accuracy, the average diameter of micro holes is 94.22 μm and the standard deviation are 3.73 μm, respectively, which indicates high stability of micro EDM assisted with high-frequency vibration process.

The diameter is larger than that of micro tool electrodes with Ø50 μm after WEDG, because of discharge gap and adhesion during the micro EDM process. Investigated from CCD, during micro EDM process, materials of MA cutting tool will adhere on the micro tool electrode, causing the diameter of discharge location larger than the rest part of the micro tool electrode (see Fig. 7). Interestingly, the discharge diameter becomes 70 μm constantly, after 3 holes are finished. So, 3 holes should be prepared in advance before surface texturing beginning.

Average diameter of holes (d_h) is about 24 μm larger than diameters of discharge position (d_e). So, the discharge gap (g) could be calculated based on the following formula:

$$g \approx (d_h - d_e)/2 \quad g \approx 12\,\mu\text{m} \tag{2}$$

To investigate the inner morphology of straight and inclined holes, a replica technique is employed to achieve accurate volume representation. The bottom dimension, corresponding to the entrance size of holes, is approximate 90 μm. As shown in Fig. 8a, morphology of straight hole contour is approximately cylindrical and no large taper exists in each cavity. It can be inferred that discharge energy profile of micro tool electrode is a circular area rather than a peak power in the center. As a result, holes could contain more lubricants and stress concentration of the bottom is diminished. As shown in Fig. 8b, contour of cylinders is inclined,

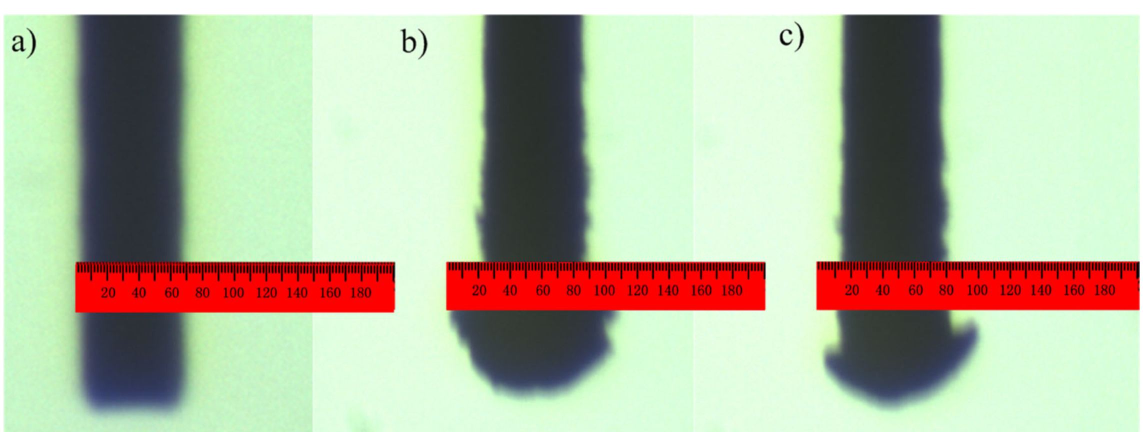

Fig. 7 Photos of micro tool electrode machining straight holes on MA cutting tools. **a** Initial micro electrode tool, with Ø50 μm. **b** Micro electrode tool after three holes, with Ø70 μm. **c** Micro electrode tool at last, with Ø70 μm

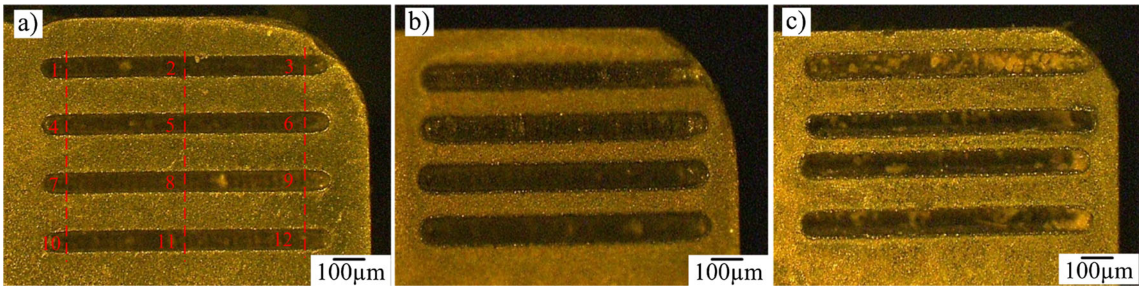

Fig. 9 Photos of linear grooves textured on MB cutting tool rake face and scrap reeling slot. **a** Straight linear grooves on rake face. **b** Inclined linear grooves on rake face. **c** Linear grooves on scrap reeling hot

demonstrating that topographies which are inclined or on curved surface can be machined successfully. Based on micro EDM, the relationship between tilt direction of surface textures and debris entrapment as well as lubricant supply can be researched. In addition, topographies can be introduced on scrap reeling slot using micro EDM, which may further enhance the effectiveness of surface textures.

3.1.2 Morphology of linear grooves

Straight and inclined linear grooves on MB cutting tool rake face as well as linear grooves on scrap reeling slot are well distributed (see Fig. 9). Having corner radius similar to the radius of micro tool electrodes, linear grooves are parallel with the main cutting edge. Owing to the angle between the textured surface and *Z*-axis, discharge area is larger during machining inclined linear grooves and linear grooves on scrap reeling slot, so dimension of width is obviously larger than that of straight linear grooves on rake face.

To investigate the dimension accuracy, widths of each straight linear groove on rake face are optically measured at 3 points. As shown in Fig. 10, widths fall in the range of 77~79 μm and the standard deviation is 0.99 μm, which demonstrates that material MB has better electro-discharge machining performance. As expected, the distance of lines to the main cutting edge is 100 μm and distances of each groove are 200 μm, approximately. Besides, as shown in Fig. 11, there is almost no adhesion between material MB and the micro tool electrode.

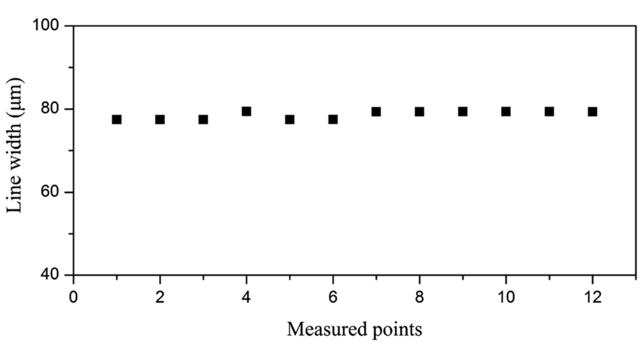

Fig. 10 Widths of straight linear grooves on MB cutting tool rake face

3.2 Thermal-affected zones of micro texture

Micro EDM is undeniably a thermal process which may cause collateral damage and reduce performance of cutting tools [30]. Thermal-affected zones are difficult to be investigated from photos of optical microscopy mentioned above. However, observation of the textured regions close to micro holes and linear grooves with SEM is an convenient approach. Subsequently, chemical composition of close proximity region to a straight hole on MA cutting tool rake face is identified by EDX to detect material migration.

3.2.1 Analysis of SEM microphotographs

As shown in Fig. 12, there is no surface burns, micro cracks, and other defects on the rake face around the hole, owing to flowing working fluid and high-frequency vibration. After high magnification of close proximity region to the hole, the behaviour of grain refinement can be found on the right of the red line. The dimension of grain refinement area is just 15 μm, which proves that there is no serious thermal-affected phenomenon on the textured surface.

To examine the thermal-affected phenomenon on MB material, cutting tool with straight grooves on the rake face is cut by wire cutting machine in the direction

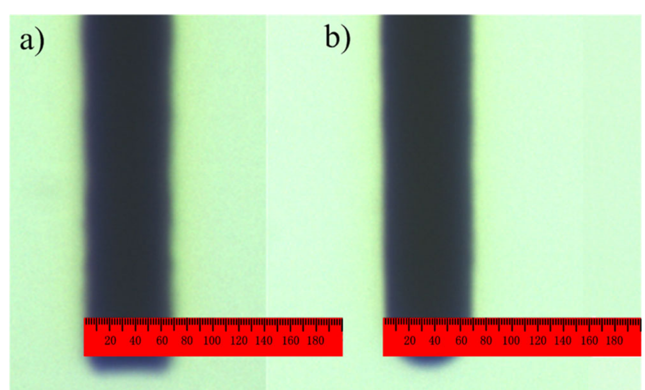

Fig. 11 Photos of micro tool electrode machining linear grooves on MB cutting tool rake face. **a** Initial micro electrode tool, with Ø50 μm. **b** Micro electrode tool at last, with Ø50 μm

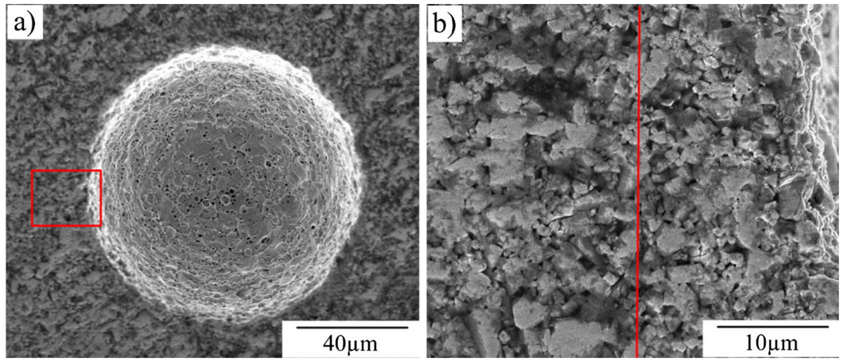

Fig. 12 SEM micrograph of a hole machined by micro EDM. **a** Whole morphology of a single hole. **b** High magnification of the marked region

perpendicular with grooves. To remove the influence of wire cutting, the discharge surface is modified by grinding and polishing. SEM micrograph of cross section of a line groove and high magnification of the inner wall are shown in Fig. 13.

The cavity contour of the linear groove is also close to cylindrical. Dimension of the contour is almost the same as that of micro tool electrode. Remelted layer is found on the inner wall of the groove. However, the thickness is negligible. Besides, there is no obvious grain refinement phenomenon found in close proximity region to the cavity.

3.2.2 Analysis of elemental chemical composition using EDX

The variation of elemental chemical composition of close proximity region to a straight hole can indicate the dimension of thermal-affected zones. Five points along the EDX line are selected. The position of 5 points and corresponding weight percentage of C, O, C_O, and W in each point are shown in Fig. 14.

Point 5 is located in the interior of this micro hole. The distances of points 4 and 3 to the edge of micro hole are approximately 10 and 20 μm, respectively. Points 2 and 1 are far from the hole. Along the EDX line scanning from

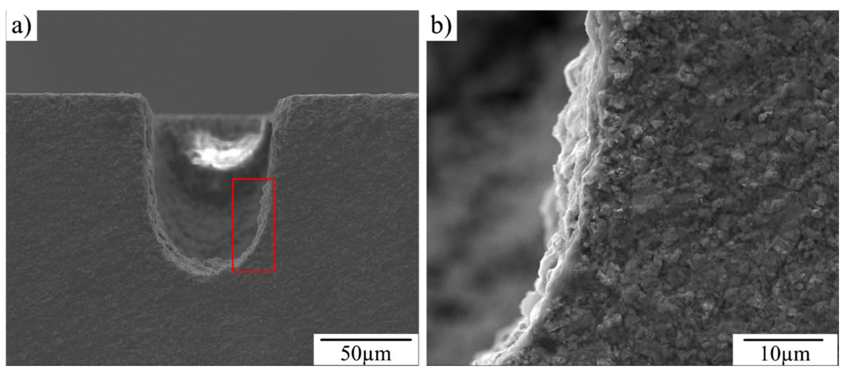

Fig. 13 SEM micrograph of a linear groove machined by micro EDM. **a** Cross section of a single groove. **b** High magnification of the marked inner wall

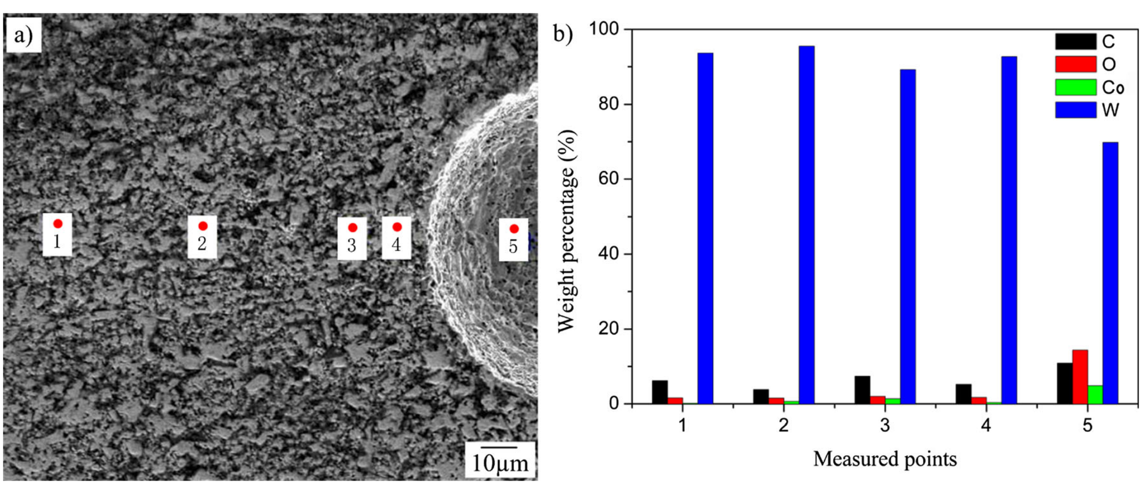

Fig. 14 Analysis of element chemical composition. **a** The position of five points. **b** The variation of elemental chemical composition

points 1 to 4, the corresponding weight percentage of *C*, *O*, C_O, and *W* keeps invariant, which indicates that these areas are not affected by micro EDM. However, for point 5, the weight percentage of *C*, *O*, and C_O increases, while *W* decreases obviously. So the edge of thermal-affected zone is surely on the right of point 4, which indicates the dimension is no more than 10 μm.

4 Conclusions

Micro holes and linear grooves on cemented carbide cutting tool rake face and scrap reeling slot are well machined as expected by micro EDM assisted with high-frequency vibration. Morphology of textured regions is examined by replica technique, optical microscopy, and SEM. The elemental chemical composition of close proximity region to a straight hole is identified. The following conclusions are obtained:

1. The exact position of the textures on the rake face is determined by low-voltage sensing contact. The bottom and cylindrical surface of the micro tool electrode are used to make the rake face perpendicular with *Z*-axis and the cutting edges parallel with *XY*-axis. Distance of texture contour to cutting edges is 100 μm approximately.
2. The Ø50-μm micro tool electrodes are used to machine micro holes and linear grooves which are straight and inclined on flat cutting tool rake face or on curved scrap reeling slot. Distances of each row or each column are 200 μm, approximately. The average diameters of straight holes on MA cutting tools and straight linear grooves on MB cutting tools are 94.22 and 78 μm, respectively. Materials of MA cutting tool adhere on the micro tool electrode slightly, while the dimension of adhesion position becomes constant after 3 holes are prepared in advance. However, the adhesion does not occur during machining MB cutting tools.
3. Owing to flowing working fluid and high-frequency vibration, textured regions are clean. There are no surface burns, micro cracks, and melted materials accumulating around the cavities. Cavity contours of micro holes and cross section of linear grooves are close to cylindrical. The distance of edges of grain refinement regions and areas where elemental chemical composition varies to the contour of the hole is no more than 15 μm.

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