Experimental Investigation on the Milling Performance of a 50 μm D-Shaped Micromilling Cutter with Different Materials

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Research Article

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Abstract

In micromilling, the performance and diameter of the milling cutter directly determine the service life of the milling cutter and the surface quality of the microgroove. Therefore, it is vital for high-precision milling to explore the milling performance of different materials and expand the application scope of micromilling cutter sizes. In this study, the milling performance of three kinds of material cutters—carbide, diamond coating and polycrystalline diamond (PCD)—was evaluated. A series of micromilling tests were carried out to determine the effects of cutter material type on cutter wear, surface quality and burr formation, particularly when a 50 μm micromilling cutter was used in the milling process. A D-shaped milling cutter with a diameter of 50 μm was manufactured on a self-developed high-precision modular machine tool by wire electrode electric discharge grinding (WEDG) technology. From theoretical and experimental perspectives, it is easy to master microgroove quality milled by different material cutters. The results show that the microgrooves processed with PCD cutters have fewer burrs, lower surface roughness values, and a smoother groove bottom morphology.

1. Introduction

As a kind of micromachining technology, micromilling has attracted increasing attention because of its high processing accuracy, high processing efficiency, strong three-dimensional processing ability, and wide range of workpiece materials [1-2]. In recent years, with the continuous progress of science and technology, there has been a higher precision demand for micro-small parts in aerospace, machinery, biomedicine and other industries. Therefore, Zhang et al. [3] producted that current micromilling technology has been required to become more efficient, economical, and precise.

As the size of the micromilling cutters decreases, the gap between the micromilling process and the traditional milling process has increased [4-5]. An et al. [6] stated the micromilling process usually encounters problems such as poor surface quality, severe surface burrs, rapid cutter wear, and easy fracture. SalmanMumtaz et al. [7] reported that coated cutters are widely used in the field of micromilling because of their high wear resistance, high-temperature oxidation resistance, good cutting performance and other advantages. Considering the influence coating type on cutter performance, Aslantas et al. [8] researched the effects of nanodiamond (NCD)-coated, TiN-coated, AlCrN-coated and uncoated carbide cutters on cutter wear and rough edge size in Ti6Al4 V alloy micromilling. The result indicated that maximum wear and burr size occurred on uncoated cutter. Their research expanded the application types of cutter materials. Liang et al. [9] investigated the cutting performance of Ti-6Al-V machined by a micromilling cutter with different coating materials. In contrast to an uncoated micromilling cutter, an AITIN-based coating can result in a reduction in cutting edge chipping and cutter wear length, which gives rise to a longer service life. Moreover, the surface roughness of machined Ti-6Al-4 V is the lowest. In order to verify the failure mechanism of coated carbide cutters in micro-milling experiments, Lu et al. [10] proposed a method, in which wear and breakage characteristics of cutter are considered. Their results showed that the main failure modes of the cutter were tip fracture, and the coating on the front angle and side fell off. Thepsonthi et al. [11] noted that polycrystalline diamond (PCD) materials can maintain high hardness at high temperature. Their research indicated that PCD cutters and PCBN cutters have less wear and better cutting performance than carbide cutters at higher milling speeds. Kaitao et al. [12] developed a Ti(C7N3) ceramic microend milling cutter and discussed its failure mechanism. micro-crack initiation and crack propagation cause cutter failure. Furthermore, they obsered that the tip fracture of Ti(C7N3)-based cermet micro end-mill cutter is lower compaired to WC micro end-mill cutter (176 μm). Ding et al. [13] asserted that a PCD cutter also showed better application performance than polycrystalline cubic boron nitride cutters due to higher abrasion wear and fracture resistance.

In addition to materials and coatings, micromilling performance also depends on cutter structure design and preparation method. Perveen et al. [14] carries out experiments for studying difference on the micro-grinding performance of four different geometry cutters (circular, D-shaped, triangular, and square), and their experimental result indicated that D-shaped cutter was considered to provide better performance in terms of the achieved surface finish, cutter wear and cutting force, which is conducsive to improve the precision in ultra precision manufacturing. Jan et al.[15] reported the design and manufacture of single-edge micro end-mills with diameters between 10 and 50 mm and a variable helix angle. Qing et al. [16] accounting for the effects of micro-texture conducted a comprehensive evaluation to assess cutting performance based on surface roughness, surface hardening, chip formation, and cutter wear. Their experimental result showed that the micro-texture of the cutter surface has an anti-wear effect, which is conducive to obtain superior workpiece surfaces and improve actual processing performance. Peiyuan et al. [17] proposed new the geometry of micro end mill and carried out experiments on brittle tool steel. The results show that the cutter maximum stress is significantly reduced, which is conducive to improve the geometric accuracy and resisted the formation of burrs. Fleischer et al. [18] developed a single edge micro milling cutter on the basis of statics. They found that the burr width and surface roughness could be effectively controlled at a milling cutter screw Angle of 30°. Uhlmann et al. [19] have found that, compared with traditional spiral milling cutters, D-cutters with simple shapes have higher flexural rigidity and strength in the micromilling process with decreasing machining size. Lu et al. [20] observed an increase in cutting temperature due to increase in cutter nose corner radius and main cutting edge radius resulting appearance of residual stress on workpiece and accelerated tool wear. Chern et al. [21] prepared 31μm diameter carbide micro-milling cutter by using wire electrode discharge grinding and applied it to the aluminum alloy AI6061-T6 milling experiment. Guo et al. [22] produced a non-coaxial spiral side edge microdrill with the best cross edge using a six-axis CNC grinder. Suzuki et al.[23] combined a focused ion beam with ultra-precision CNC milling to produce a 25μm diameter carbide micromilling cutter for PMMA process.

At present, Chen et al. [24] found that research on micromilling technology experiments has mainly focused on spiral milling cutters with diameters of 100 μm and above. To further expand the application range of milling cutter sizes, the present study is the first to apply a 50 micron micromilling cutter for experiments to compare the milling performance of carbides, diamond coatings and PCD cutters. A carbide cutter and PCD cutter were produced on a self-developed μEM-200CDS2 combined with a high-precision machining machine cutter. On this basis, diamond-coated cutters were prepared by vacuum coating. To master the milling performance of carbide cutters, diamond-coated cutters and PCD cutters, a series of milling experiments on pure copper workpieces were carried out. The cutter wear and bottom morphology of the microgroove for the carbide cutter, diamond-coated cutter and PCD cutter were captured and analysed. Subsequently, the width variation, depth variation, surface roughness and profile of the microgroove during milling were measured and analysed to obtain a cutter with better milling performance in the field of micromilling.

2. Test Equipment And Milling Scheme

2.1 Cutter preparation

A D-shaped carbide cutter with a diameter of 50 μm was prepared by wire electrode electrical discharge grinding (WEDG). As shown in Fig. 1a and 1b, a micromilling cutter was fabricated on a machine cutter, and on-machine micromilling processing was performed. During the test, the cutter blank was clamped on a high-speed spindle, and the milling cutter was prepared by WEDG technology. The milling test was then carried out, the z-axis minimum linear feed was 0.1 μm, and the spindle radial run out accuracy was 1 μm. A schematic diagram of the cutter is shown in Fig. 1d; the main features are as follows: the handle D1 is 3 mm in diameter, the bit D is 0.05 mm in diameter, the cutting edge length L1 is 0.15 mm, the cutter length L is 30 mm, the half cone angle of the cutter neck is 15°, the dorsal horn of the bottom cutting edge is 20°, the cutting edge inclination is 20°, and the thickness of the coating is 1μm. The diameters of the carbide cutter and the diamond-coated cutter are 50 μm and 56 μm, respectively. The diameter of the PCD cutter is 45 μm

2.2 Milling scheme

Ultrafine grain carbide (grain size of 0.4 μm) and polycrystalline diamond are used as the materials for the micromilling cutter in the test because of their high hardness, wear resistance and bending stiffness. Table 1 shows the main parameters of the carbide, diamond coating and PCD materials.

A schematic diagram of the micromilling process is shown in Fig. 1c. Three groups of different cutters were tested with the same milling parameters, and five straight grooves were milled in each group. The length of each microgroove was 3 mm, and a milling length of 15 mm was finally achieved in each group of experiments. Table 2 shows the milling parameters in the experiment. The milling depth of each feed was 0.002 mm, and the feed was 5 times. The total milling depth of each groove was 0.01 mm. The PCD material cutter was fed 10 times, and the total milling depth was 0.02 mm because the hardness of PCD was higher than that of the carbide cutter and diamond-coated cutter. The machined surface was cleaned by an ultrasonic machine. The surface roughness is measured along the feed direction by using a white light interferometer. In addition, the surface morphology of the microgroove bottom was observed by scanning electron microscopy.

3. Test Results And Discussion

3.1 Experimental results

3.1.1 Five grooves

The surface burr of the microgroove milled by a diamond-coated cutter is shown in Fig. 2. The experiments show that the groove bottom varies from smooth to gradually arise from the burr and arc with increasing milling distance. As shown in Fig. 2a, the first groove bottom is clean and tidy. This is because the milling cutter is sharp enough at the initial stage of milling. However, there are two discernible boundaries in the second groove shown in Fig. 2b. The reason behind this phenomenon is as follows. With the partial coating falling off, the milling cutter tip begins to wear as a result of a sharp point being produced. In contrast to the second groove, many small burrs exist in the middle of the third groove bottom, while the flank side of the groove is relatively flat, as shown in Fig. 2c. The reason is the wear loss of the cutter, as the material cannot be cut effectively, finally leading to chips attached to the sidewall. In addition, it can be seen clearly in Fig. 2(d-e) that the fourth and fifth groove bottoms exist in the shape of a circular arc without too much of a burr when the cutter head is basically ground flat and assumes a circular arc, as seen in Fig. 4b.

Fig. 3 illustrates the difference in morphology of the fifth groove bottom milled by a carbide cutter, diamond-coated cutter and PCD cutter. As shown in Fig. 3a, more burrs were generated at the sidewall of the microgroove milled by the carbide cutter when the uncut material broke at the milling terminal. Constant cutter wear is a significant contributory factor to the formation of burrs. Fig. 3b shows the microgrooves milled by a diamond-coated cutter. The burr is relatively small on the whole. There is no rotation path at the groove bottom. Fig. 3c shows the microgroove milled by the PCD cutter. The burr of the microgroove sidewall is low, and the morphology of the microgroove bottom is tidier.

3.1.2 Cutter wear

Fig. 4 shows the wear degree for the carbide cutter, diamond-coated cutter and PCD cutter. As shown in Fig. 4a, the tip of the carbide cutter was seriously worn after machining. The top of the contact surface between the cutter and the workpiece is worn out of a wedge shape and spreads around. Although the hardness value of the diamond-coated material is higher than that of the carbide material, the wear area of the diamond-coated cutter, as seen in Fig. 4b, is larger than that of the carbide cutters. The possible explanation for this phenomenon is as follows: first, the matrix material is exposed to the outside when the coating falls off. The increase in wear rate is mainly attributed to scratching between the matrix material and coating falling off at the groove bottom. Second, the chemical elements (Co, Fe, WC, etc.) of the diamond-coated cutter react with the chemical elements (Cr, Ni, etc.) in the workpiece. In addition, these elements (Co, Cr, Ni, etc.) diffuse into the matrix structure of the diamond-coated cutter under the condition of constant friction between the diamond-coated cutter tip and workpiece. Infiltration of new elements reduces the matrix material strength and aggravates diamond-coated cutter wear during the milling process (Huang et al.[25]). As shown in Fig. 4c, wear hardly occurs at the cutter tip, and fragments of pure copper still adhere to the surface of the cutting edges. The cutter tip shape can be well maintained within a milling distance of 15 mm. Experiments have indicated that PCD cutters have better wear resistance than carbide cutters and diamond-coated cutter.

3.2 Microgroove surface morphology

3.2.1 Three-dimensional morphology

Fig. 5 shows the 3-D morphology variances for the microgroove. The morphology of the groove bottom milled by a carbide cutter is illustrated in Fig. 5(a-c). There is an obvious cutter rotation trace pattern at the microgroove bottom, and the residual appears intermittently along the circular arc feed direction. Cutter path lines become increasingly obvious with increasing milling distance. This phenomenon is due to the increase in tip radius caused by cutter wear. The morphology of the groove bottom milled by a diamond-coated cutter is presented in Fig. 5(d-f). The first microgroove has a relatively clear bottom surface, as shown in Fig. 5(d). With the loss of coating and the gradual wear of the cutter, local uncut chips remain on the sidewall of the microgroove, resulting in two traces at the bottom of the groove, as shown in Fig. 5(e). More chips exist in the groove bottom along the cutter feed direction, as shown in Fig. 5(f). These residual chips reduce the surface quality of the microgroove. The trace lines, as shown in Fig. 5g-i, are concentrated in the cutting direction of cutter rotation. The trace lines are uniformly distributed and of the same size, without obvious changes with increasing milling distance. The PCD cutter exhibits superior performance in terms of better microgroove surface morphology and relatively straight sidewalls compared with carbide cutters and diamond-coated cutters.

3.2.2 groove depth and width

Fig. 6a shows the variation in microgroove width depending on milling distance. When the milling distance was 2 mm, the microgroove width of the carbide cutter was 51.2 μm, the microgroove width of the diamond-coated cutter was 56.8 μm and the microgroove width of the PCD cutter was 43.25 μm. Within a certain range, the microgroove width of the carbide cutter and diamond-coated cutter has a positive relationship with the milling distance, and the maximum value of the carbide cutter is 58.8 μm, while the other is 53.7 μm. However, the width of the microgroove milled by the PCD cutter is stably maintained at 44.08 μm. The variation in the width of the microgroove milled by the PCD cutter is more stable than that of the carbide cutter and diamond-coated cutter. Fig. 6b reveals the correlation between the microgroove depth and milling distance. There is a steady decline in the depth of microgrooves milled by carbide cutters, diamond cutters and PCD cutters. When the milling distance is 14 mm, the minimum depth values of the microgroove of the three cutters are 5.8 μm, 5.6 μm and 16.6 μm. The reason for the overall decrease in microgroove depth is that wear of the cutter and passivation of sharpness lead to ineffective cutting, which indicates that the PCD cutter has better wear resistance than the carbide cutter and diamond-coated cutter.

The variations in the profile during the milling process are described in Fig. 7. The grooved bottom milled carbide cutter has a circular arc shape, and the sidewall angle is small. The inclination angle of the sidewall has a positive correlation with the depth of the microgroove, as shown in Fig. 7a. Fig. 7b shows that the groove bottom milled by a diamond-coated cutter has a relatively flat surface and that the microgroove sidewall is relatively vertical. In addition, the microgroove bottom gradually becomes rounded, and the sidewalls gradually tilt. This phenomenon is mainly due to the removal of the coating and deterioration of the cutter tip shape. As shown in Fig. 7c, a flat groove bottom occurs on the microgroove bottom milled by the PCD cutter during milling. The sidewall inclination angle of the microgroove varies slightly, and the sidewalls are almost perpendicular to the groove bottom. It can be seen from the comparison results that microgrooves milled by the PCD cutter perform better in maintaining the groove profile.

3.2.3 Groove surface roughness

Fig. 8 shows the variation in surface roughness with milling distance. The roughness value of the grooved bottom milled by the carbide cutter is twice that of the diamond-coated cutter at the beginning, and the surface roughness increases with increasing milling distance. Although the roughness value obtained with the diamond-coated cutter is lowest within a milling distance of 12 mm, the roughness value dramatically increases when the milling distance exceeds 12 mm. Fig. 4b and Fig. 8 show that the wear degree of the diamond-coated cutter corresponds to the roughness of the groove bottom. This is due to peeling of the coating and deterioration of the cutter tip shape, which will generate residual chips and cause poor surface quality. However, the roughness of the groove bottom milled by PCD remains almost constant within a 15 mm milling distance. This indicates that a better surface roughness value is obtained with the PCD cutter and that the PCD cutter has a longer cutter life than the carbide cutter and diamond-coated cutter.

4. Conclusion

This paper presents an experimental study on the cutting performance of carbide cutters, diamond-coated cutters and PCD cutters in the micromilling of pure copper. An evaluation of the cutter wear, surface morphology and surface burr of microgrooves is conducted to determine the milling cutter material with the best milling performance. The following main conclusions are drawn:

1. Microgrooves milled by PCD cutters tend to have superior performance in terms of milling stability compared to carbide cutters and diamond-coated cutters. The roughness value obtained with the

PCD cutter remains almost constant. The milling distance and cutter wear greatly influence the roughness value of the carbide cutter and diamond-coated cutter.

2. The PCD cutter has a minimum wear rate and longer service life than the carbide cutter and diamond-coated cutter, which is attributed to the good wear resistance of the PCD cutter. In addition, microgroove milling by a PCD cutter has better groove retention ability.
3. A superior microgroove is obtained by the PCD cutter. The maximal burr exists in the microgroove sidewall of the carbide cutter, and the most obvious pattern of the cutter path is generated on the groove bottom milled by the carbide cutter.
4. The preparation of 50 micron milling cutter has important application value for expanding the range of machining dimensions and machining high precision parts with small geometric features in the field of ultra precision micro milling.

Declarations

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Authors Contributions: Chen Jiang: Methodology. Jin Xin Jiang: Writing. Yu Hao: date curation. Rui Gao: formal analysis. Yong Bin Zhang: supervision

Ethical Approval: Not Applicable

Consent of Publish: Not Applicable

Consent of Participate: Not Applicable

Data Material: Not Applicable

References

1. Sun ZW, To S, Zhang SJ et al (2018) Theoretical and experimental investigation into non-uniformity of surface generation in micro-milling. Int J Mech Sci 140:313–324. https://doi:10.1016/j.ijmecsci.2018.03.019
2. Wu Y, Chen N, Bian R et al (2020) Investigations on burr formation mechanisms in micro milling of high-aspect-ratio titanium alloy ti-6al-4 v structures. Int J Mech Sci 185: 105884. https://doi:10.1016/j.ijmecsci.2020.105884
3. Zhang Y, Li S, Zhu K et al (2020) Generic instantaneous force modeling and comprehensive real engagement identification in micro-milling. Int J Mech Sci 176: 105504. https://doi:10.1016/j.ijmecsci.2020.105504

4. Zhang SJ, Zhou YP, Zhang HJ et al (2019) Advances in ultra-precision machining of micro-structured functional surfaces and their typical applications. Int J Mach Tool Manu 142: 16-41. https://doi:10.1016/j.ijmachtools.2019.04.009
5. Liang X, Liu Z, Wang B et al (2019) State-of-the-art of surface integrity induced by tool wear effects in machining process of titanium and nickel alloys: A review. Measurement 132: 150-181. https://doi:10.1016/j.measurement.2018.09.045
6. An Q, Cai C, Zou F et al (2020) Cutter wear and machined surface characteristics in side milling Ti6Al4V under dry and supercritical CO2 with MQL conditions. Tribol Int 151: 106511. https://doi:10.1016/j.triboint.2020.106511
7. Saleem MQ, Mumtaz S (2020) Face milling of Inconel 625 via wiper inserts: Evaluation of cutter life and workpiece surface integrity. J Manuf Process 56: 322–336. https://doi:10.1016/j.jmapro.2020.04.011
8. Aslantas K, Hopa HE, Percin M et al (2016) Cutting performance of nano-crystalline diamond (NCD) coating in micro-milling of Ti 6 Al 4 V alloy. J Precis Eng 45: 55–66. https://doi:10.1016/j.precisioneng.2016.01.009
9. Liang Z, Gao P, Wang X et al (2018) Cutting Performance of Different Coated Micro End Mills in Machining of Ti-6Al-4V. J Micromachines 9: 568. https://doi:10.3390/mi9110568
10. Lu XH, Jia ZY, Wang H et al (2016) Cutter wear appearance and failure mechanism of coated carbide cutters in micro-milling of Inconel 718 super alloy. J Ind Lubr Tribol 68: 267–277. https://doi:10.1108/ILT-07-2015-0114
11. Thepsonthi T, Özel T (2013) Experimental and finite element simulation based investigations on micro-milling Ti-6Al-4V titanium alloy: Effects of cBN coating on cutter wear. J Mater Process Technol 213: 532–542. https://doi:10.1016/j.jmatprotec.2012.11.003
12. Kaitao X, Zou B, Wang YS et al (2016) An experimental investigation of micro-machinability of aluminum alloy 2024 using Ti(C7N3)-based cermet micro end-mill tools. J Mech Work Technol 235: 13–27. https://doi:10.1016/j.jmatprotec.2016.04.011
13. Ding X, Liew WYH, Liu XD et al (2005) Evaluation of machining performance of MMC with PCBN and PCD cutters. J Wear 259: 1225–1234. https://doi:10.1016/j.wear.2005.02.094
14. Perveen A, San WY, Rahman M et al (2012) Fabrication of different geometry cutting tools and their effect on the vertical micro-grinding of BK7 glass. Int J Adv Manuf Technol 61: 101–115. https://doi:10.1007/s00170-011-3688-5
15. Jan CA, Ingo GR, Guido MS et al. (2012) Manufacture and application of ultra-small micro end mills. CIRP Ann Manuf Technol 61: 0–0. https://doi.org/10.1016/j.cirp.2012.03.012
16. Qiang L, Shucai Y, Zhang YH et al (2018) Evaluation of the machinability of titanium alloy using a micro-textured ball end milling cutter. J Adv Manuf Technol 98: 2083-2092. https://doi:10.1007/s00170-018-2319-9
17. Peiyuan L, Oosterling JAJ, Hoogstrate AM et al (2011) Design of micro square endmills for hard milling applications. Int J Adv Manuf Technol 57: 859–870. https://doi:10.1007/s00170-011-3330-6

18. Fleischer J, Deuchert M, Ruhs C et al (2008) Design and manufacturing of micro milling tools. J Microsyst Technol 14: 1771–1775. https://doi:10.1007/s00542-008-0652-x
19. Uhlmann E, Schauer K. (2005) Dynamic Load and Strain Analysis for the Optimization of Micro End Mills. CIRP Ann. Manuf Technol 54: 75–78. https://doi:10.1016/S0007-8506(07)60053-5
20. Lu X, Wang H, Jia ZY et al (2017) Effects of tool nose corner radius and main cutting-edge radius on cutting temperature in micro-milling inconel 718 process. California: International Manufacturing Science and Engineering Conference. https://doi:10.1115/MSEC2017-2997
21. Chern GL, Engin YJ, Cheng JC et al (2007) Study on burr formation in micro-machining using micro-tools fabricated by micro-EDM. J Precisc Eng 31: 122–129. https://doi:10.1016/j.precisioneng.2006.04.001
22. Guo HX, Wang XB, Liang ZQ et al (2018) Drilling performance of non-coaxial helical flank micro-drill with cross-shaped chisel edge. J Adv Manuf Technol 99: 1-11. https://doi:10.1007/s00170-018-2497-5
23. Suzuki H, Okada M, Fujii K et al (2013) Development of micro milling tool made of single crystalline diamond for ceramic cutting. CIRP Ann Manuf Technol 62: 59–62. https://doi:10.1016/j.cirp.2013.03.096.
24. Chen N, Li L, Wu J et al (2019) Research on the ploughing force in micro milling of soft-brittle crystals. Int J Mech Sc 155: 315–322. https://doi:10.1016/j.ijmecsci.2019.03.004
25. Huang X, Zhao J. (2013) Wear patterns and wear mechanisms of tool in high speed cutting of Inconel 718. Tool Engineering 6: 6-9. https://doi:10.16567/j.cnki.1000-7008.2013.06.008

Figures

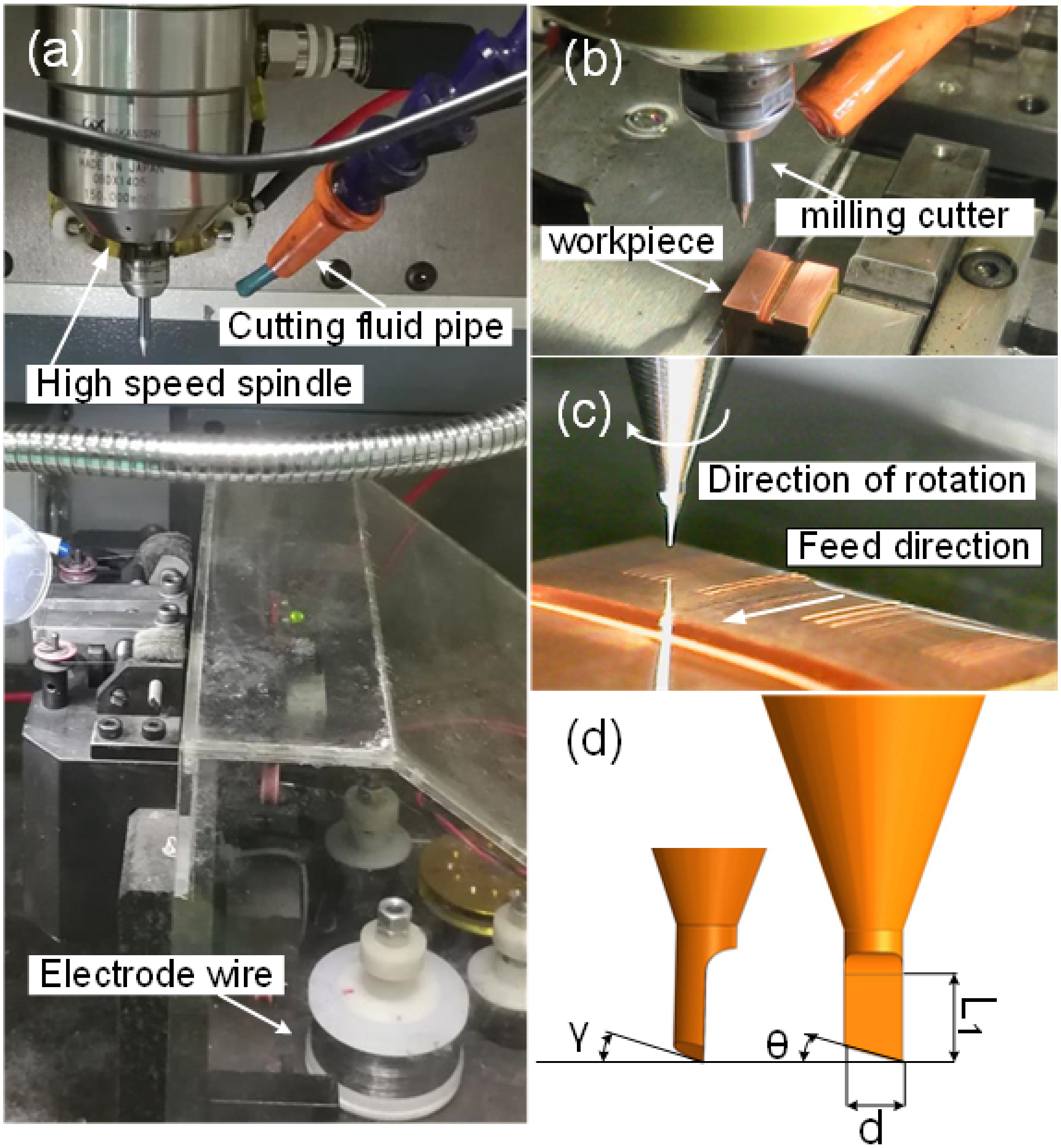

Figure 1

Micromilling cutter fabrication and on-machine micromilling processing of the μEM-200CDS2 machine cutter. (a) On-machine micromilling cutter fabrication by WEDG, (b) micromilling cutter process for copper workpiece, (c) micromilling process, (d) schematic diagram of cutter mode

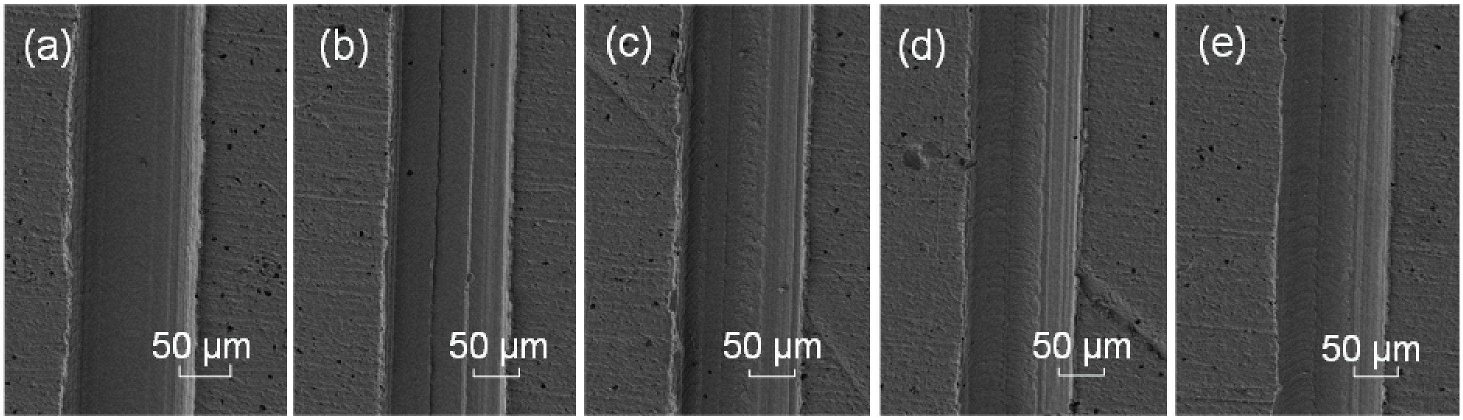

Figure 2

Surface morphology of microgroove. (a-e) Five straight grooves milled by a diamond-coated cutter in turn.

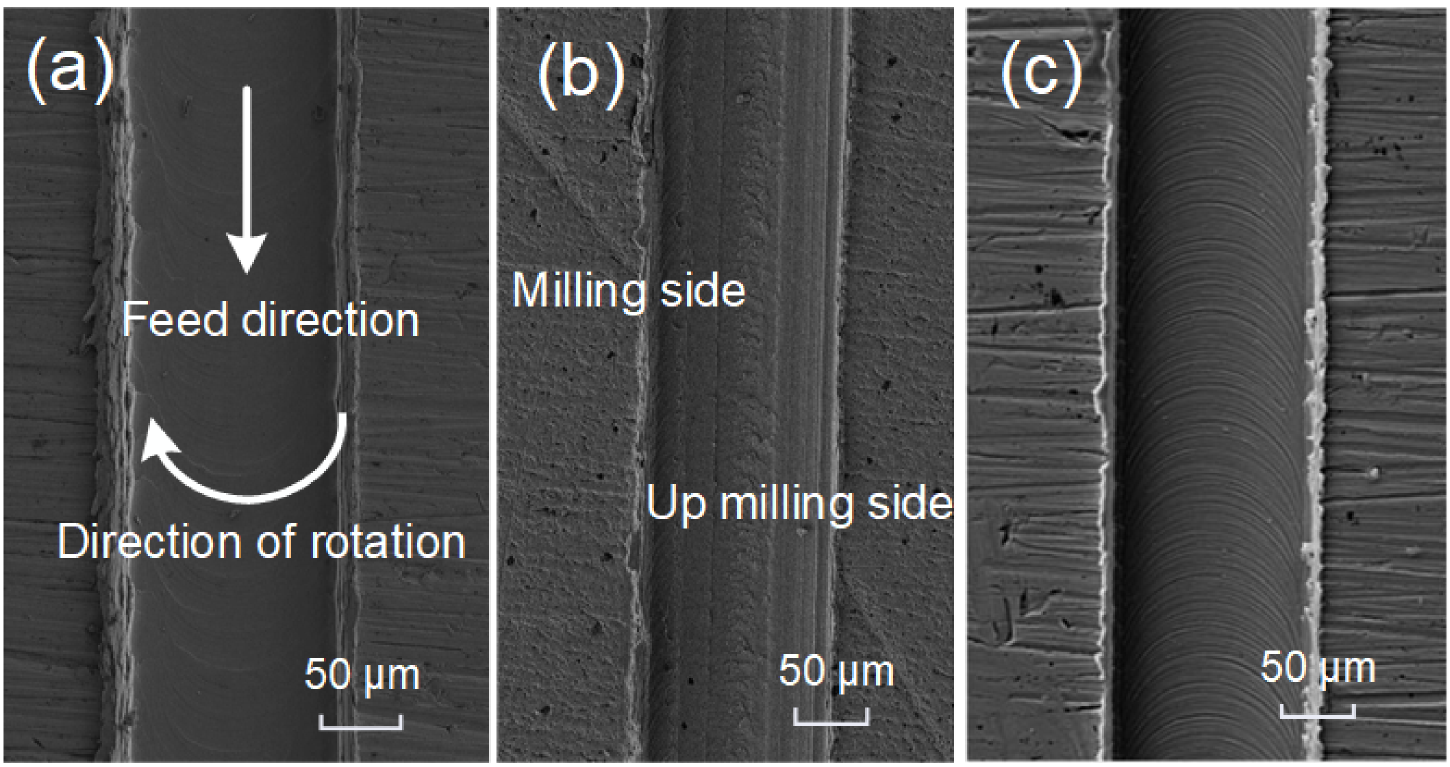

Figure 3

Microgroove morphology. (a) Milling the fifth groove with a carbide cutter, (b) milling the fifth groove with a diamond-coated cutter, and (c) milling the fifth groove with a PCD cutter.

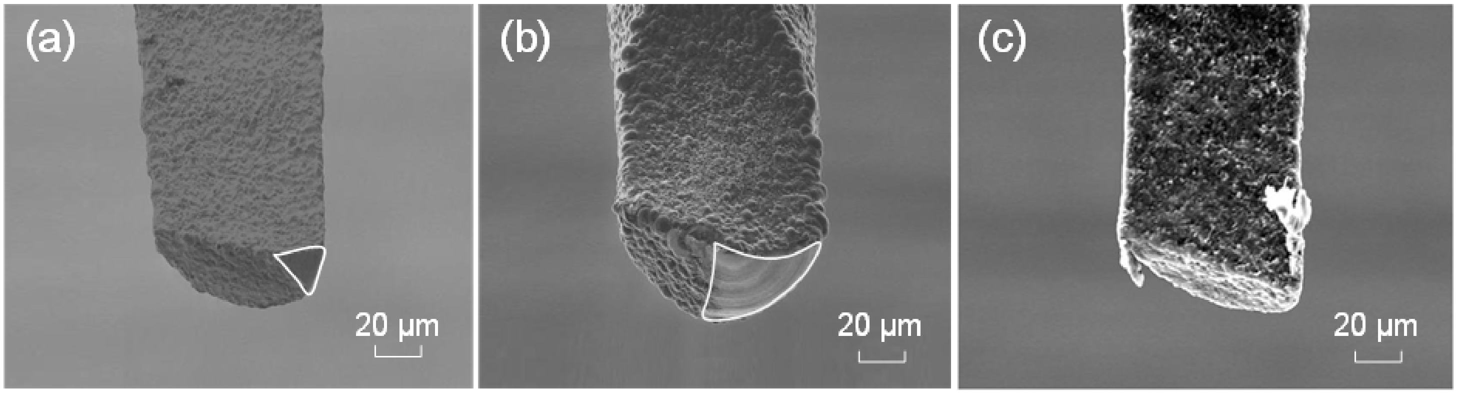

Figure 4

Cutter wear under scanning electron microscopy. (a) Carbide cutter, (b) diamond-coated cutter, (c) PCD cutter.

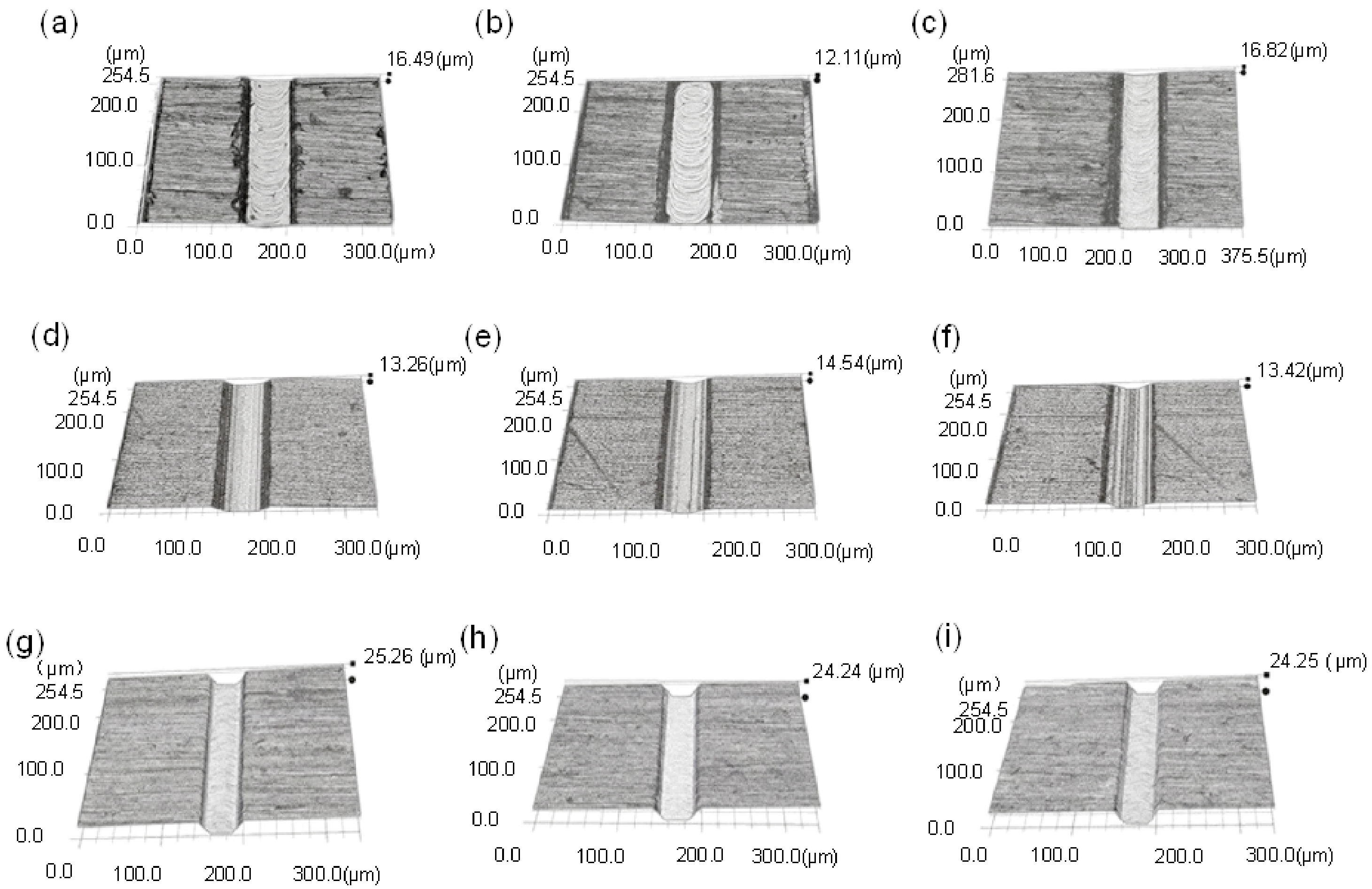

Figure 5

3-D morphology of the microgroove captured by ultra-depth-of-field microscopy. (a-c) Bottom morphology of microgrooves milled by carbide cutters, (d-f) bottom morphology of microgrooves milled by diamond-coated cutters, and (g-i) bottom morphology of microgrooves milled by PCD cutters.

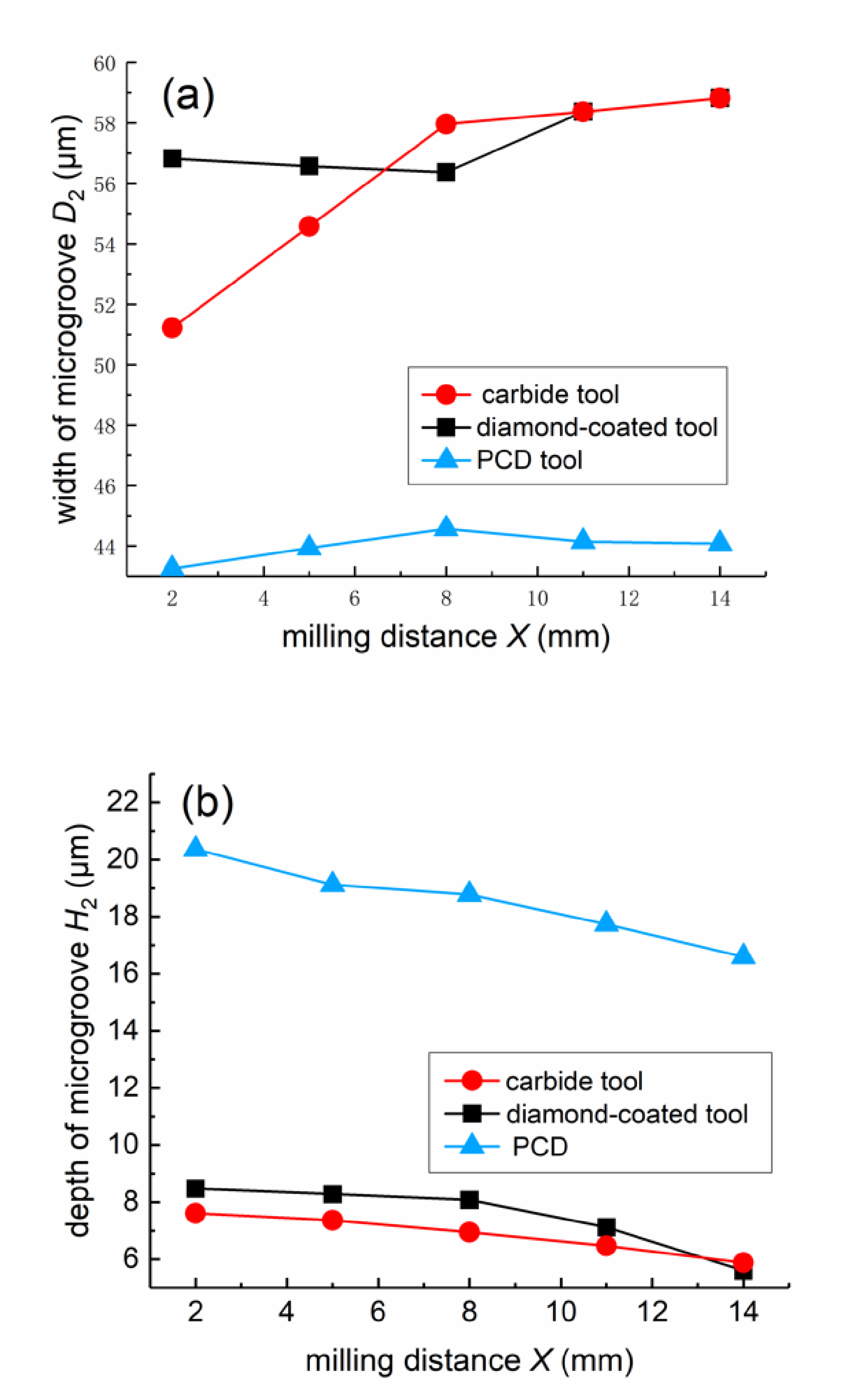

Figure 6

Variation in microgroove width and depth with milling distance. (a) Variation in microgroove width with milling, (b) variation in microgroove width with milling.

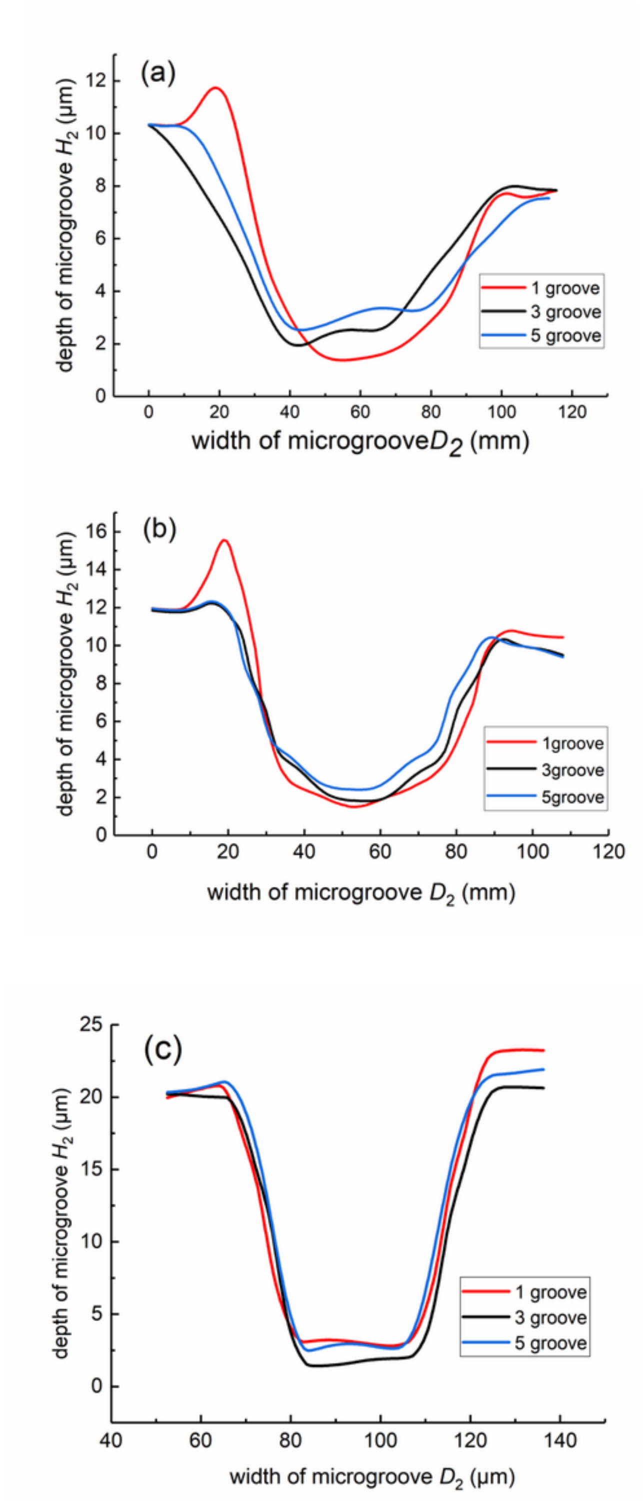

Figure 7

Profile of the microgroove milled by carbide cutters, diamond-coated cutter and PCD cutter. (a) Carbide cutter, (b) diamond-coated cutter, (c) PCD cutter.

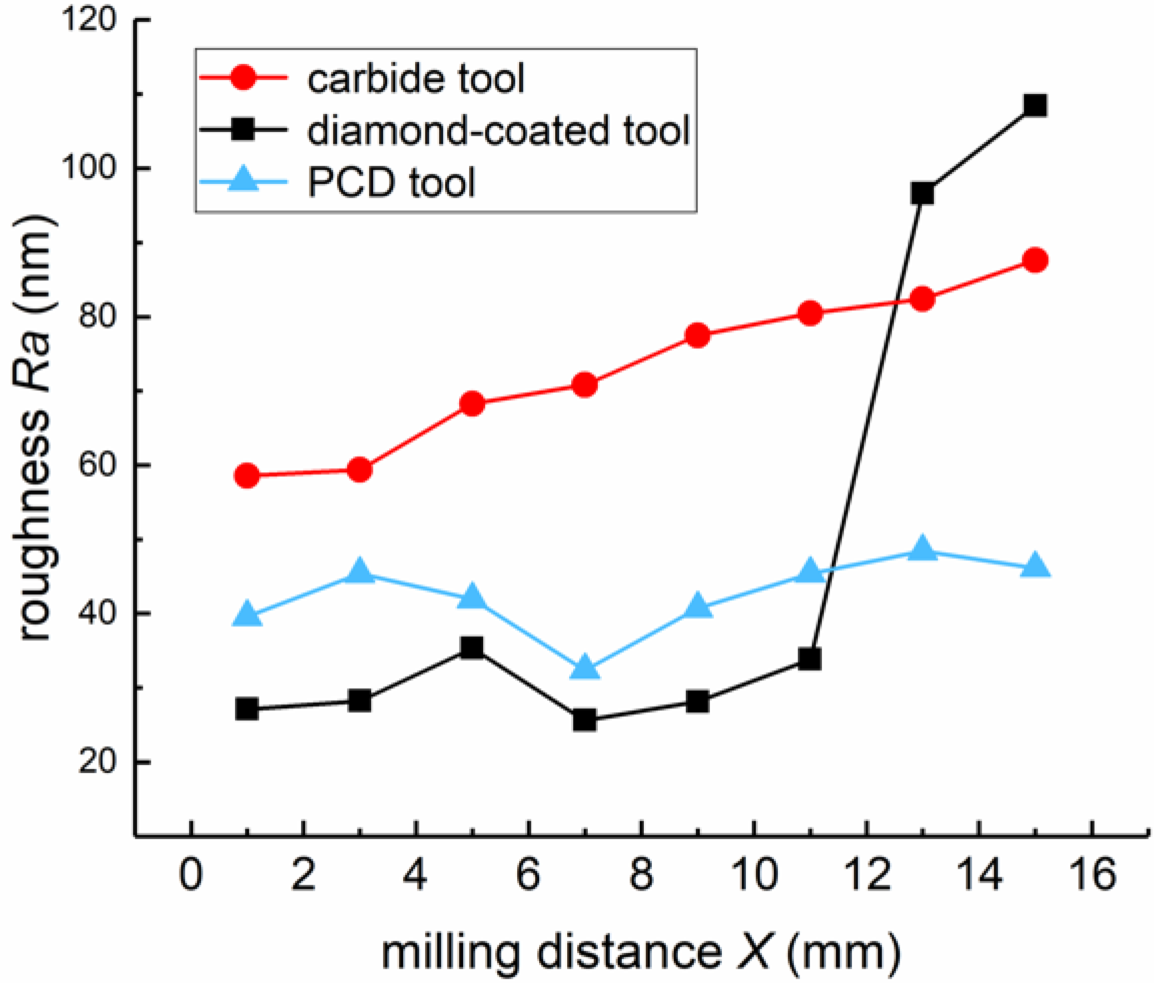

Figure 8

Surface roughness of machined-grooved bottom captured by white light interferometer.