An experimental-based investigation on micro milling of micro-featured dies/moulds in hardened steel

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Abstract：

In this paper, an experimental based industrial feasible approach is presented on micro milling of micro-featured precision dies and moulds in hardened steel. The approach covers the micro features characterization on the die and mould, CAD/CAM programming, micro milling trials and metrology analysis, and the process optimization. The approach is further explored and evaluated by industrial application case study from an industrial company client, which is the micro punch die made from the quenched 45 steel and with micro features. By comparing the cutting efficiency, the surface roughness and tool wear performance, the optimum CNC micro milling protocol is developed including the appropriate milling tool path and optimized cutting parameters setup. The CAD/CAM is based on UG NC programming and the KERN EVO five-axis NC machine is utilized for undertaking the micro milling trials. The die components machined are assessed against the industrial requirements from the company client, further supported by the results, analysis and discussion. The paper concludes with a further discussion on the potential and applications of the approach for broad micro milling production.

1 Instrument

Hardened steel is a typical material which is wear resistant and difficult to machine with 50-65 HRC hardness after quench hardening and low temperature stress relieving. The most commonly used way in finishing hardened steel is precision grinding [1,2], which is less and less able to meet the demand as micro-complex structural parts with high hardness are used in industrial production and scientific research more and more, along with the society development and industrial progress.

Hard milling is a branch of high-speed machining technology with high production efficiency, high precision, good surface quality, low cost, little environmental pollution and other significant advantages [3-5]. Compared with the traditional process flow as processing - heat treatment - reprocessing, hard milling to the heat-treated workpiece can get higher dimensional accuracy and more accurate spatial characteristics, because it can not only avoid the reprocessing, but also eliminate the warp, bending deformation and other defects caused by heat treatment [6]. As a new method of finish machining hardened steel, hard milling is gradually replacing the traditional process and changing the rules of mold manufacturing[5-7].

Micro-hard milling is the application of hard milling technology in micro-machining. It can greatly improve the flexibility in hardened steel micromachining and better deal with the complex microcomponents and microstructures on hardened workpiece. Some examples of high accuracy, micromilled components and microstructures are illustrated in Figure 1

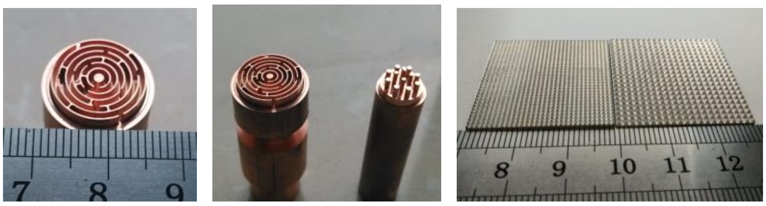


Figure 1: Some workpiece micromilled by the author

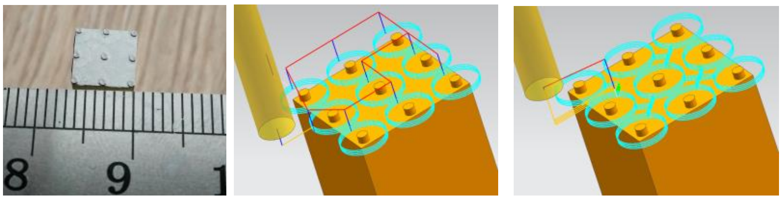
However, there are some problems, such as tool vibration and tool wear, in micro-hard milling, which will directly affect the final processing quality and seriously hinder the further development and adhibition [8].

In the milling process, a reasonable tool path and proper cutting amount can not only improve the quality of the product, but also reduce the manufacturing cost and increase the efficiency [9]. In this paper, an experimental based industrial feasible approach is presented on micro milling of micro-featured precision dies and moulds made from the quenched 45 steel. And the reasonable machining path based on CAD/CAM of UG and optimized cutting parameters were obtained with the study on machining efficiency, surface quality and tool wear.

2 Experimental set-up and procedures

2.1 Cutting path

According to the structural characteristics and geometrical dimensions of the workpiece(see Figure 1), the 1mm diameter end mill was selected as the most appropriate tools. And by comparing the length of the tool path in different feed patterns, the tool path shown in Figure 2 (b) was proved much more efficient in removing the material. However, the frequent up-and-down movement of the tool will not only affect the processing efficiency, and also can lead to unwanted axial force between the tool and workpiece, which will form the tool marks on workpiece surface , affect the quality of processing, or even damage the tool. Therefore, it is necessary to avoid the axial movement of the tool on the milling region without lowering the working efficiency, as shown in Figurer b after the optimization of the tool path. Based on the above considerations, the tool path is further optimized to a new pattern shown in Figure 2 (c).



（a）　（b）　(c)

Figure 2: Design of the cutting path

2.2 Experimental condition

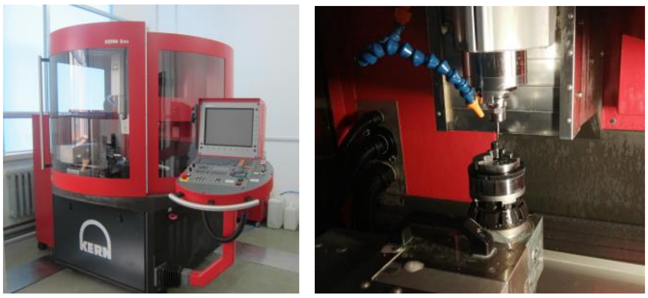


Figure 3: The 5-axis precision milling machine, KERN Evo

Micro-hard milling has a high requirement for the good machine performance. Experiments for this work were carried out on a 5-axis precision milling machine, KERN Evo, as shown in Figure 1, and the main performance parameters of the machine can be got from Table 1.

Table 1 Performance parameters of the machine

Model	Spindle speed（r/min）	Feed（mm/min）	Positional accuracy（μm）	Resolution（μm）
KERN Evo	500 ~ 50000	0.01 ~ 16000	±0.5	0.1

The tool used in this experiment is made of carbide with coating, whose key performance parameters was shown in Table 2. The workpiece material was

quenched 45 steel with the hardness HRC55. Liquid coolant was used throughout the cutting process
.

Table 2 Tool parameters

Brand	Diameter	Edge length	Edge number	Helix angle	Coating	Granularity	Microhardness
KiK	1mm	3mm	4	35°	TiAlSiN	0.4μm	37.7Gpa

As shown in Figure 4, the surface roughness of the bottom surface of the micromilled workpiece was measured using a small roughness tester (Surtronic S-series), while the tool wear was observed with a coaxial imager (TESA Optive).

Figure 4: Workpiece detection and tool wear observation

2.3 Experimental method

It is not necessary to process a large number of the moulds to study the effect of the machining parameters on the workpiece surface quality. In order to save the workpiece material and test time, there was a substitute with similar configuration to the mould in the experiment as shown in Figure 5, whose one end face includes six small test surfaces for different cutting parameters. New micro tools were used for each set of experiments so that there is little influence of tool wear on the surface.

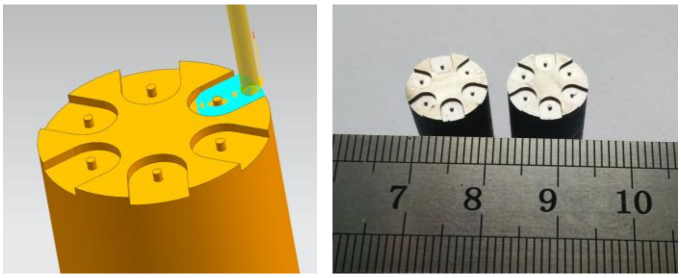
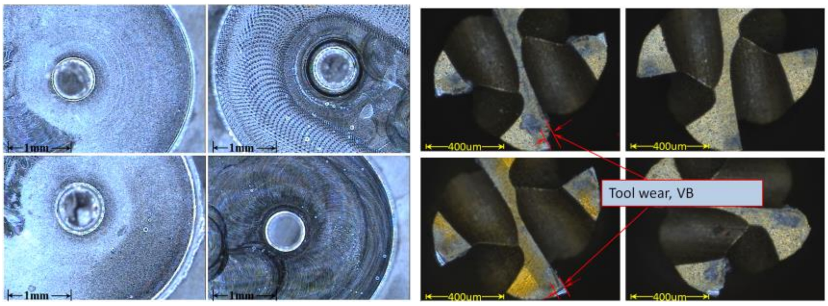


Figure 5: The experimental method and workpiece

Orthogonal test method was used in this paper. The spindle speed n was varied at 15 000, 23 000, 31 000, and 39 000 r/min, while the feed per tooth Fz was varied at 1μm, 2μm, 3μm, and 4μm with the axial depth dz varied at 0.01mm, 0.04mm, 0.07mm， and 0.1mm. All the different cutting parameters were used to process the target configuration with same shape and size, respectively. Then the influence of each cutting factor on surface roughness and tool wear was obtained with the same total cutting amount.

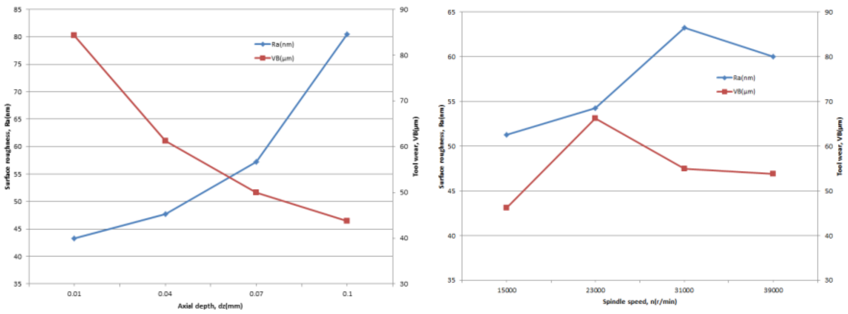
3.Result and discussions



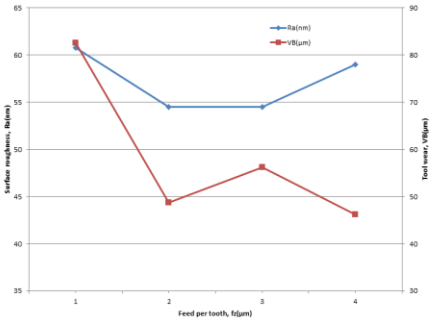
(a) (b）

Figure 6: Workpiece surface and tool wear

As shown in Figure 6, there are obvious differences among the quality of workpiece surface and tool wear.



(a) (b)



(c)

Figure 7: Average surface roughness Ra and tool wear VB as a function of spindle speed, feed rate fz , and axial depth dz

The Figure 7 shows the average surface roughness Ra and tool wear VB as a function of spindle speed, feed rate fz , and axial depth dz. It can be observed that axial depth dz is the most important factor affecting surface roughness and tool wear.

It can be observed from Figure 7 (a) that the tendency is towards higher roughness values and lower tool wear with increases in axial depth when the axial depth is between 0.01mm and 0.1mm. A surface roughness, Ra, about 40nm was achieved at an axial depth of 0.01mm, however, the tool wear was very serious. From the picture observed by TESA Optive, it can be seen that a large piece of adhesive wear appeared in the tool end with the axial depth 0.01mm, which needs more milling times and longer processing time than using bigger axial depth with the same total cutting amount.

Figure 7 (b) shows that the spindle speed has a negative effect on the surface quality, the higher the cutting speed, the higher the surface roughness value when the speed is between 15000r/min and 31000r/min. The tool wear came to the maximum as the spindle speed at 23000r/min. A nicer surface and lower tool wear can be achieved with the spindle speed about 15000r/min.

The feed per tooth has no significant effect on the surface roughness (see Figure 7(c)), however, an obvious size effect can still be seen when the feed per tooth is smaller than 2µm. As a dominant factor for the material removal mechanism and chip generation physics in micromachining, size affect may cause cutting, ploughing, or slipping phenomena in the machine process, leading a poor surface quality on the workpiece and serious tool wear[10–12].

4 Conclusion and future work

An optimized tool path for a micro-featured precision dies and moulds that from an industrial company client was obtained. The carbide tool with coating has been used to micro-mill quenched 45 steel, and the influence of spindle speed, feed rate, axial depth on the machining quality and tool wear has been studied. The following major conclusions can be drawn from this work.

1. The axial depth has a significant effect on surface roughness and tool wear. Using a larger axial depth of cut is an effective way to increase machining efficiency and protect the milling tool. However, larger axial depth may cause a negative effect on the surface.
2. Size effect is a factor that can not be ignored in micro-hard milling. It is important to choose the appropriate feedrate according to the characteristics of the tool.
3. A better surface quality and smaller tool wear can be obtained in the micro-hard milling using the proper cutting parameters, for example, 15000r/min, 2μm/flooth, and 0.05mm depth in milling quenched 45 steel with carbide tool.

The application of micro-hard milling is becoming more and more extensive[13]. Future work should be focused on improving the experimental data and more deeply understanding of the relationship between the milling quality and cutting parameters.

Reference

1. Alexandre M Abrao, David K Aspinwall. The Surface Integrity of Turned and Ground Hardened Bearing Steel.J. Wear,1996,196：279-284.
2. W Konig, A.Verktold, K.F.Koch. Turing Versus Grinding a Comparison of Surface Integrity Aspects and Attainable Accuracy.J. Annaid of the CIRP, 1993, 42(1):39-44.
3. Ai X. High - speed milling technology .M. Beijing: National Defense Industry Press, 2003
4. Zhang BL, Yang DQ and Chen CN. High Speed Cutting Technology and Its Application. Electrical and Mechanical Engineering Technology, 2003,32 (5): 106-107
5. Zhuang Z. High-speed Milling of Hardened Steel .J. Electromechanical Engineering Technology, 2004,33 (8): 153 -154
6. Shashidhara, Shreyas, Liu XY, Zhu WH, Curry, James, Zaloom, Victor. Experimental investigation of the tool wear and tool life in micro hard milling .J. ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE),2013
7. Liu ZQ, Wan L and Ai X. Study on Cutting Force in High-speed Milling .J. China Mechanical Engineering, 2003,14 (9): 734-737
8. Huo DH and Cheng K. Experimental investigation on micromilling of oxygen-free, high-conductivity copper using tungsten carbide, chemistry vapour deposition, and single-crystal diamond micro tools .J. International Journal of Advanced Manufacturing Technology 47(9):867-877 · April 2009.
9. Wei XP, Wang J and Zhang JM. Optimization of Roughing Milling Process for Multi - pass end face .J. China Mechanical Engineering, 2003,14 (10): 854
10. Ikawa N, Shimada S, and Tanaka H. Minimum thickness of cut in micromachining. Nanotechnology, 1992, 3, 6–9.

11. Ikawa, N , Donaldson, R R , Komanduri, R , W, Aachen, T H, McKeown, P A , Moriwaki, T, and Stowers, I. F. Ultra-precision metal cutting – the past, the present and the future. Ann. CIRP, 1991, 40(2), 587–594.
12. Yuan, ZJ , Zhou M, and Dong S. Effect of diamond tool sharpness on minimum cutting thickness and cutting surface integrity in ultra-precision machining. J. Mater. Proc. Technol., 1996, 62, 327–330.
13. Li P, Oosterling, J.A.J, Hoogstrate, A.M, Langen, H.H. Improvement of micro endmill geometry for micro hard milling application .J. Proceedings of the 10th Anniversary International Conference of the European Society for Precision Engineering and Nanotechnology, EUSPEN 2008,2,157-160.