An Investigation on the Cutting Physics and Mechanisms in Two-dimensional Vibration-assisted Micro-end-milling

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Abstract

In this investigation, two-dimensional vibration-assisted machining was applied to micro-end-milling so as to render two-dimensional vibration-assisted micro-end-milling (2D VAMEM) and thus lead to improvement of the fabrication process in terms of surface finish, minimizing burr formation, and tool life. The cutting physics and mechanisms of 2D VAMEM were explored and analysed and the corresponding experiments have been undertaken to further validate the scientific understanding.

1 Cutting physics and mechanisms

In 2D VAMEM, periodical vibrations with small amplitude (0.5μm-3μm) and low frequency (500 Hz-3,000 Hz) are imposed on the workpiece in feed and normal directions. As a result, the trajectory of the tool tip relative to the workpiece becomes more complex and the formation of undeformed chip thickness differs greatly from traditional micro end milling.

1.1 Tool tip path

The tool tip path in feed direction is composed of three components : feed movement, spindle rotation and the vibration. The latter two components contribute to the tool tip path in normal direction. The tool tip in 2D VAMEM differs greatly from that in micro milling, which illustrates distinct characters particularly when different vibration modes are applied. The tool tip path is a jaggier line and the amplitude varies distinctly when the modes are both sinusoid while it is a spiral line and profiles are all the same when the modes are sinusoid and cosine wave. Furthermore, with the help of vibrations, the tool tip path interference is normal in 2D VAMEM and the next several cuts will clean up the previous tool marks helpful to the surface finish.

1.2 Undeformed chip thickness

In 2D VAMEM, the undeformed chip thickness of the i^{th} cutting is not only influenced by the last previous cutting, but also by several previous cuttings, which is greatly different from that in micro milling in which the chip thickness is formed only by two adjacent cuttings.

Fig.1 shows the undeformed chip thickness in 2D VAMEM. It is obvious that it is a interrupted cutting process and the chip thickness varies evidently due to two dimensional vibrations. With the help of two-dimensional vibrations, the tool is rapidly separated from the workpiece periodically, providing more intervals enabling the cutting fluid to go into the gap between the tool and workpiece. Then, the cutting fluid will take away the cutting heat, provides excellent chip-removal condition and lubrication, and reduce the friction, i.e. thus leading to the decrease of cutting force and temperature. As a result, the cutting process becomes more stable and uniform as chip removal being carried out in a tribological-friendly manner, which consequentially results in machining accuracy improvement, burr reduction and tool life extension. In addition, the undeformed chip thickness can rapidly exceed the minimum chip thickness to remove materials at the moment when the tool engages in or out of the workpiece, which can minimize the size effect so as to improve the micro-milled surface quality, suppress burr generation and prolong the tool life.

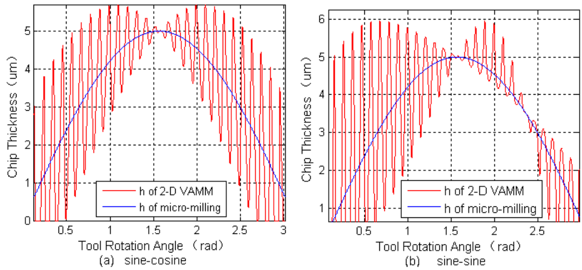


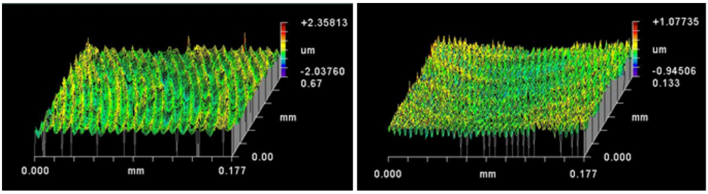
Figure 1: The undeformed chip thickness in 2D VAMEM

2 Experimental study and discussions

In order to assess the cutting performance of 2D VAMEM, the experiments have been conducted on a precision milling machine with a two dimensional vibrating platform driven by two piezoelectric actuators. The vibrating platform can provide 0.5μm to 5μm vibration amplitude and up to 3,000 Hz vibration frequency.

2.1 Surface roughness

Fig. 2 shows two topography images of the machined surface, taken at a Zygo 3D surface profiler. It is found that, without vibration large feed marks as well as some scratches and irregularities appear on the machined surface as shown in Fig. 2(a); with VAMEM applied, the tool feed marks are leveled off and the machined surface becomes more smooth as shown in Fig. 2(b). The surface roughness Ra generated with vibrations is 0.15µm, which is much better than that without vibrations applied (Ra=0.53 µm). 2D VAMEM can improve the surface roughness with two main reasons. One is that several sequential cuts clean up the previous tool marks and the other is the periodical separation between the tool and workpiece improves the cutting performance.



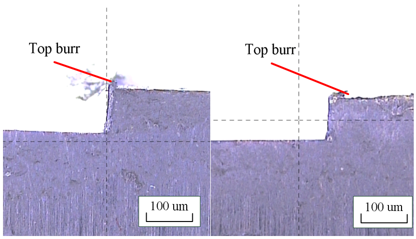
(a) without vibration (b) with vibration

Figure 2: Images of the machined surface taken at a Zygo 3D surface profiler

The surface roughness will decrease with the increment of the amplitude and frequency substantially, as increasing the amplitude and the frequency can add the no-contact time between the tool and the workpiece[1].

2.2 Top burrs

Fig. 3 shows the photos of top burrs in micro end milling without and with vibrations respectively. Without vibrations, larger top burrs and geometrical error in the slot shape can be found as shown in Fig. 3(a). On the contrary, with the help of vibrations, perfect rectangular shape can be obtained and top burrs are less serious and more evenly distributed along the edge, as shown in Fig. 3(b).



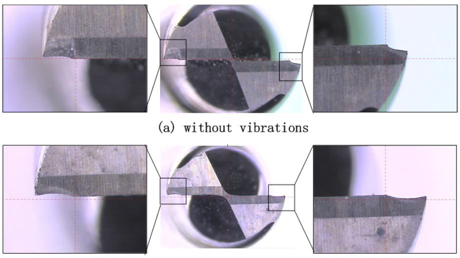
(a) Micro end milling (b) 2-D VAMEM

Figure 3: Photos of top burrs generated without and with vibrations applied

In micro milling, the size effect is a pivotal factor affecting top burrs formation[2]. When the undeformed chip thickness is less than the minimum chip thickness, the workpiece material is not removed as a chip but formed as a burr. In 2D VAMEM, with the help of two-dimensional vibrations, the undeformed chip thickness can rapidly exceed the minimum chip thickness to remove materials at the moment when the tool engages in or out of the workpiece, which can minimize the size effect so as to suppress burr generation.

2.3 Tool wear

Fig. 4 shows the wear patterns on the micro cutting tool for (a) without vibrations and (b) with vibrations. The photos demonstrate chipping and flank wear modes. Flank wear is measured at the bottom face of the micro tool. The length of flank wear without vibrations is 65 μm larger than that with vibrations (54 μm). The results show that the tool wear with two dimensional vibrations can be reduced by approximately 5-20% compared to that in traditional micro end milling. Larger amplitude and higher frequency are generally useful for reducing the tool wear.



(a) without vibrations

(b) with vibrations

Figure 4: Photos of the tool wear

3 Conclusions

In this paper, the cutting mechanisms and physics in 2D VAMEM are thoroughly analysed and corresponding experiments are undertaken to further validate the scientific understanding and findings. It is found that applying two dimensional vibrations to micro end milling can improve its cutting performance by improving machining accuracy, burr reduction and tool life extension. Therefore, 2-D VAMEM is an effective method for mechanically micromachining micro and miniature parts and has great potential for micro manufacturing of moulds and dies in a range of engineering materials.

References:

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