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Effective tool wear compensation in micro-EDM milling of 3D cavities

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Abstract

Linear tool wear compensation strategy is commonly applied in a layer-by-layer micro-EDM milling process to achieve high machining accuracy. During milling of 3D cavities, the tool path can continuously change at each machining layer, the insufficiency of traditional off-line based wear compensation method becomes more severe which generally requires more frequent off-line wear sensing. To enhance the machining efficiency and to reduce the error of the off-line tool wear compensation method, a combined off and in-line adaptive tool wear compensation method is proposed and experimentally validated. A 3D cavity has been successfully machined with only one third of the original off-line tool wear sensing frequency, while still maintaining micrometre level depth accuracy.

Key words: micro-EDM milling, machining efficiency, pulse counting and classification, off and in-line adaptive tool wear compensation

1. Introduction

In a layer-by-layer micro EDM milling process with a micron level layer depth, the frontal tool wear is a dominant component and linear tool wear compensation is commonly applied (Fig. 1). In practice, the length of the tool electrode is intermittently measured off-line to adapt the slope of compensation.

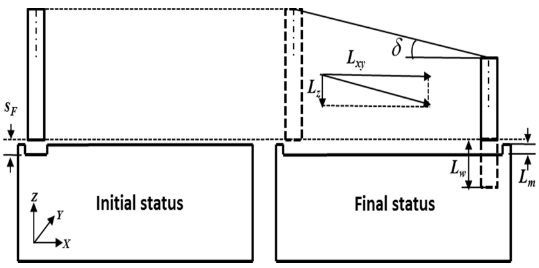

Figure 1. Principle of linear tool wear compensation [1].

During milling of 3D features, the insufficiency of off-line wear compensation becomes more severe, as the tool wear is only accessed periodically, while the tool path can be changing at each machining layer. It generally requires more often off-line wear sensing and compensation to maintain high machining accuracy, which however decreases the machining efficiency. As a solution, the concept of in-line adaptive tool wear compensation based on real-time pulse counting and classification is proposed, where the cumulative number of discharges and instant pulse frequency is continuously monitored [1]. The counted number of pulses is used to predict the tool wear and then the wear compensation factor is updated, whereby a minimum rate of updating the tanδ for every single machining layer is realized.

The feasibility of tool wear prediction based on discharge counting and characterization of the tool wear per discharge (TWD) has been studied by Bissacco et al. [2]. However, there is still no literature on implementing such an in-line adaptive tool wear compensation for machining 3D cavities where the depth accuracy is more critical. An accurate estimation of the TWD is essential for the in-line tool wear prediction and the subsequent adaptive wear compensation. But in real machining, the TWD may continuously change and it cannot be quantitatively reflected by in-line compensation only. Therefore, a combined off-line and in-line tool wear compensation method is proposed in this paper.

When machining 3D cavities, there can be multiple tool path patterns, i.e., sudden change of stepover between two adjacent layers. Fig. 2 shows an example of such change, which however can be detected by in-line pulse monitoring. To avoid a large TWD fluctuation due to the change of tool path patterns, the 3D cavity in this study is designed with specific dimension to be milled with single tool path pattern.

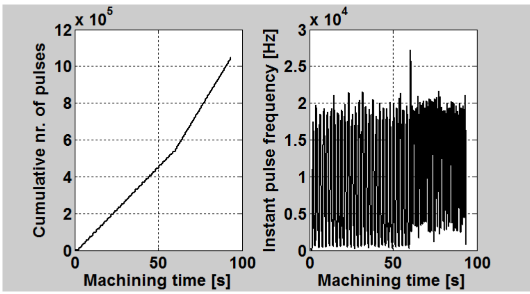

Figure 2. Change of tool path pattern detected by in-line pulse monitoring system.

To implement the proposed wear compensation method, the following iteration has been applied: the tool wear is first measured off-line after machining a certain number of layers; then a new tanδ is determined and the mean TWD is calculated by the tool volume wear divided by the number of discharges, tool wear in the next machining layers is estimated by multiplying the calculated TWD with the incremental number of counted pulses, and the tanδ is updated for the subsequent layers; in-line adaptive compensation continues till the next off-line wear sensing thereafter the TWD is updated.

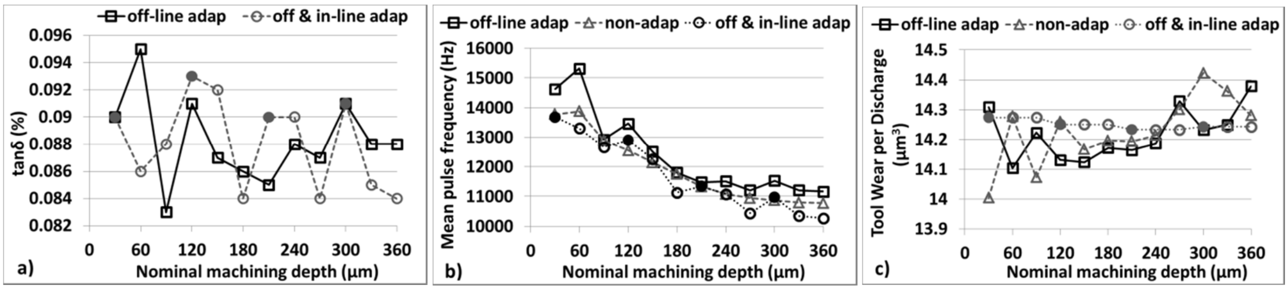

Figure 4. Comparison among three different wear compensation strategies: a) off-line, b) non-adaptive and c) off & in-line adaptive (solid circle means off-line sensing after reaching the corresponding depth and empty circle means in-line).

2. Experimental setup and 3D feature design

Experiments have been performed on a Sarix® micro-EDM milling machine (SX-100-HPM). A Ø500 μm tungsten carbide rod, was used as tool electrode and a block of stainless steel as workpiece.

The design and dimension of the 3D cavity is shown in Fig. 3, which is a cylindrical cavity with a hemisphere in the middle. Concentric out milling strategy has been chosen to machine the cavity with a machining layer depth of 1 μm and the machining took about 28 min.

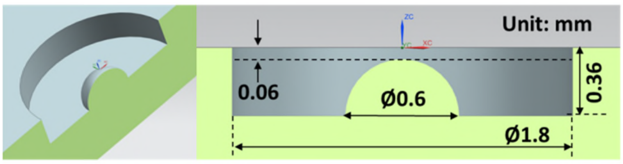

Figure 3. Section view and dimensions of the 3D feature.

Table 1 Machining depth error accumulation for three different wear compensation strategies (Unit: μm).

Target depth	Non-adap measure	Off-line adap predict	Off-line adap measure	Off & in-line adap predict	Off & in-line adap measure
30	2.4*	-1.1*	0	0.6	-0.3
60	2.1	2.1	2	0.4	
90	4.1	-0.6	0.6	-0.7	
120	3.9	0.6	2	0.0	0.8
150	4.1	0.8	2.4	1.5	
180	5.8	0.5	1.7	0.3	
210	6.8	-0.3	1.6	0.3	1.6
240	7.5	0	1.9	1.2	
270	7.7	-1.2	-0.3	-0.2	
300	7.2	-0.1	1.6	1.0	1.5
330	7.2	0	1.4	0.8	
360	7.7	-1.2	0.8	-0.2	-0.5

*: positive value means over machining and negative values means under machining.

3. Combined off and in-line tool wear compensation

12 was chosen as the frequency of off-line tool wear sensing and compensation to mill the cavity shown in Fig. 3, as a good compromise between depth accuracy and machining efficiency, while only 4 for the combined method. In order to illustrate the difference, a non-adaptive machining has also been tested. An initial tanδ of 0.09% is applied and each scenario has been repeated three times. One set of the machining results is shown in Table 1 and Fig. 4. It can be seen that the tanδ is fluctuating for both wear compensation methods, and that the mean pulse frequency is decreasing due to reduced stepover at higher machining depth. Regarding the tool wear per discharge (TWD), the maximum deviation is below 3% and the mean TWD used for the combined method lies in the middle.

As for the cumulative depth error, it continues to deteriorate in the non-adaptive machining case while it is maintained within 2 μm for both the off-line and the combined method. Please note that the difference of the predicted and measured error comes from the inaccuracy of the in-line wear prediction, as well as from the inaccuracy of tool wear sensing.

Fig. 5 shows the pictures of the machined cavity, the diameter of the hemisphere is measured to be between 595 μm and 603 μm (Mitutoyo® Quick Vision Pro 202).

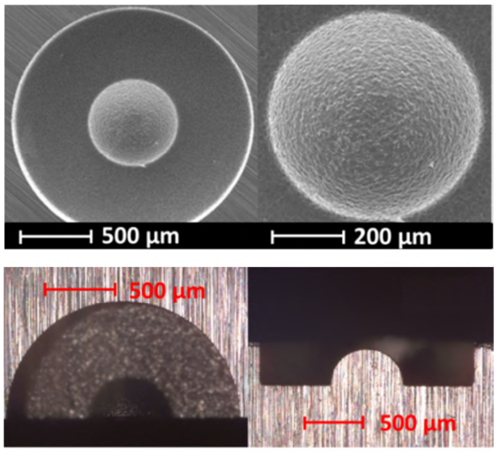

Figure 5. SEM (top, FEI® XL30 FEG) and optical microscope (bottom, ZEISS® SteREO Discovery. V20) images of the milled cavity.

4. Conclusion

A combined off and in-line tool wear compensation method is proposed and experimentally validated. A 3D cavity has been successfully machined with one third of the original off-line tool wear sensing frequency, while still maintaining micrometre level depth accuracy. With special workpiece preparation, the form accuracy is also measured to be in the same order of magnitude. Further research is on-going to further enhance the machining efficiency by maximizing the in-line compensation and minimizing the off-line compensation, without losing the machining accuracy which is critical for 3D cavities (highlighted in EU projects MIDEMMA and Hi-Micro).

References

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