Modeling and Experimental Study of Vibration-assisted Micro-EDM of Cemented Carbide

M.P. Jahan*, M. Rahman, Y.S. Wong
Department of Mechanical Engineering, National University of Singapore,
pervej@nus.edu.sg

Abstract

The machining of deep micro-holes in difficult-to-cut materials is of prime importance in manufacturing. Present study aims to introduce the application of low-frequency workpiece-vibration in deep-hole micro-EDM drilling of difficult-to-cut cemented carbide (WC-Co). In this context, an analytical study on the mechanism of low-frequency workpiece vibration-assisted micro-EDM drilling has been presented. In addition, experimental investigation has been conducted in order to validate the model by studying the effects of workpiece vibration on machining performance, surface quality and dimensional accuracy of the micro-holes.

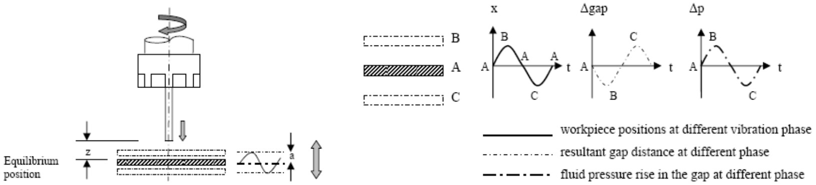
1 Introduction

Micro-electrodischarge machining (micro-EDM) is being used extensively in the field of machining micro-holes, micro-moulds, dies, cavities and even complex 3D structures at micro-level [1]. However, during the application of micro-EDM in deep-hole drilling the circulation of dielectric and removal of debris become difficult, especially when the hole or the cavity becomes deep providing low machining efficiency and lower aspect ratio [2]. Although, recently some research has been conducted on the vibration assisted micro-EDM, the authors used ultrasonic vibration for assistance. No study has reported the feasibility of applying low frequency vibration assistance during micro-EDM drilling. Moreover, most of the studies only considered experimental investigation, with little focus on analytical explanation of the mechanism. This study presents an analytical approach as well as experimental investigation on the workpiece vibration assisted micro-EDM of WC-Co.

2 Modeling of workpiece vibration-assisted micro-EDM

Assumptions:

- Low frequency vibration follows a simple harmonic motion [3].
- The plate is horizontal and vibration direction is perpendicular to the plate.
- The debris particles have same frequency, velocity and acceleration as plate.



(a) (b)

Figure 1: (a) Workpiece vibration-assisted micro-EDM drilling, (b) variation of gap distance and fluid pressure inside the gap during vibration-assisted micro-EDM

Let, the workpiece is vibrating at amplitude of ‘*a*’ with an angular frequency ‘*ω*’ [Fig. 1(a)]. The displacement of vibrating plate can be obtained as:

$$x = a\sin(\omega t + \varphi) \tag{1}$$

Where, *f* = vibration frequency (Hz), *t* = time (s) and *φ* = phase angle (rad)

The velocity and acceleration of the plate at that position of can be obtained as:

$$\dot{x} = a\omega\cos(\omega t + \varphi) \tag{2}$$

$$\ddot{x} = -a\omega^2\sin(\omega t + \varphi) \tag{3}$$

Now, if we consider the maximum acceleration is at B and C positions, then:

$\ddot{x}_{\max} = \pm a\omega^2$, At positions B and C: $\sin(\omega t + \varphi) = 1$

Therefore, the equation of maximum acceleration can be written as:

$$\ddot{x} = \pm a\omega^2\sin(\omega t + \varphi) \tag{4}$$

Where, the ± sign indicate two opposite directions from the mean position.

If the maximum acceleration along the gravitational direction is defined by ‘*c*’ and *(ωt +φ)* is replaced by *α*, then the equation of maximum acceleration becomes:

$$c = a\omega^2\sin\alpha \tag{5}$$

The position and velocity of the debris particle lying on the vibrating plate will depend on the ratio of acceleration ‘*c*’ to the gravitational acceleration ‘*g*’

$$\frac{c}{g} = \frac{a\omega^2}{g}\sin\alpha \quad => \quad K_v = K\sin\alpha \tag{6}$$

[Putting, (c/g) as K_v and $(a\omega^2/g)$ as K in eqn. (6), $K = (a\omega^2/g)$ is centrifugal effect]

For the debris to fly out of the plate, its acceleration must exceed the gravitational acceleration, therefore $c>g$, or $c/g >1$. If, $K_v = c/g >1$, i.e. $c>g$, the debris will fly out of the vibrating plate at the same velocity of the plate at that time.

The condition for laying the debris particle on the plate can be determined in terms of phase angle. When $K_v = 1$, the total phase angle of the debris particle (α_d) just before the particle leaves the plate is given by:

$$K_v = \frac{c}{g} = \frac{a\omega^2}{g}\sin\alpha_d = 1 \quad \Rightarrow \quad \sin\alpha_d = \frac{1}{\frac{a\omega^2}{g}} = \frac{1}{K} \quad \Rightarrow \quad \alpha_d = \sin^{-1}\left(\frac{1}{K}\right) \qquad (7)$$

Therefore, the debris particle will lie on the vibrating workpiece when $0<(\omega t+\varphi)<\alpha_d$ and jumps out of the plate when $\alpha_d<(\omega t+\varphi)$.

Therefore, For $K_v > 1$:

- The debris particles will fly out of the workpiece
- The fluid pressure inside the gap is continuously changing; either positive indicating suction or negative indicating pressure increase [Fig. 1(b)].

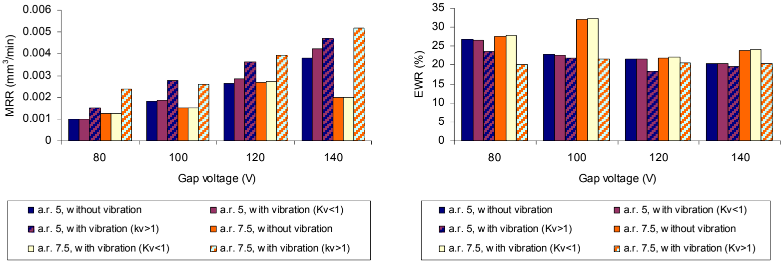
These two effects collectively help in improving the flushing conditions.

3 Experimental verification of the analytical findings

In order to validate the model, the material removal rate (MRR), electrode wear ratio (EWR), dimensional accuracy and surface quality of the micro-holes are compared for without vibration to that of with vibration for settings $K_v<1$ and $K_v>1$.

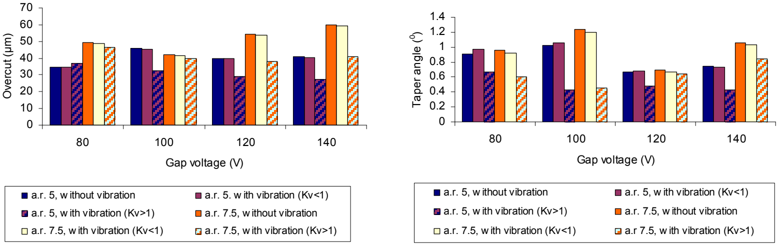
At $f = 500$ Hz, $a = 0.5$ μm: $K_v = \frac{c}{g} = \frac{a\omega^2}{g}\sin(\omega t+\varphi) = 0.5 \quad [\sin(\omega t+\varphi) = 1]$

At $f = 750$ Hz, $a = 1.5$ μm: $K_v = \frac{c}{g} = \frac{a\omega^2}{g}\sin(\omega t+\varphi) = 3.4 \quad [\sin(\omega t+\varphi) = 1]$



(a) (b)

Figure 2: Comparison of (a) MRR and (b) EWR for without vibration, with vibration ($f = 500$ Hz, $a = 0.5$ μm, $K_v<1$) and with vibration ($f = 750$ Hz, $a = 1.5$ μm, $K_v>1$) at electrical setting of voltage: 80 – 140 V, capacitance: 10 nF



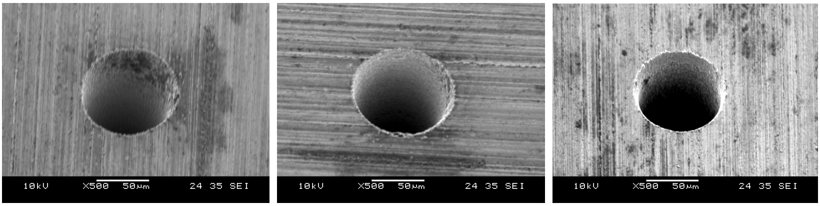
(a) (b)

Figure 3: Comparison of (a) overcut and (b) taper angle for without vibration, with vibration ($f = 500$ Hz, $a = 0.5$ μm, $K_v<1$) and with vibration ($f = 750$ Hz, $a = 1.5$ μm, $K_v>1$) at electrical setting of voltage: 80 – 140 V, capacitance: 10 nF

Figure 2 shows a comparison of machining performance in terms of MRR and EWR without vibration, with vibration at $f = 500$ Hz, $a = 0.5$ μm ($K_v < 1$) and with vibration at $f = 750$ Hz, $a = 1.5$ μm ($K_v >1$). It can be seen from Fig. 2(a) that for all the settings of gap voltage, the MRR is higher for vibration assisted micro-EDM drilling with $K_v >1$. On the other hand, no significant improvement has been noticed for vibration with $K_v <1$. This proves that the effect of vibration becomes effective only when $K_v >1$. The increase in MRR is due to the improvement in machining stability and improved flushing process after applying vibration. Another important reason for improving MRR during vibration assisted micro-EDM is the increase of discharge ratio after applying vibration. In addition, the EWR also reduces after applying vibration assistance with $K_v >1$. The reduction of EWR is more significant during the drilling of higher aspect ratio micro-holes with lower voltages. This is due to the fact that, the smaller spark gap at low voltage setting results in difficulties to remove the debris from machined zone. These debris particles cause arcing and short-circuiting inside the deep micro-holes increasing the EWR during machining. However, with the assistance of vibration debris can be easily flushed away from the machined zone, which reduces the EWR.

In addition to machining performance, the dimensional accuracy of the micro-holes is found to improve significantly for $K_v >1$. It has been observed from Fig. 3 that both the overcut and taper angles reduces after applying the workpiece vibration of $f = 750$ Hz, $a = 1.5$ μm ($K_v >1$). During the micro-EDM drilling of small and high-aspect-ratio holes, the evacuation of debris becomes difficult from small working gap, and this difficulty level increase with the increase of aspect ratios. If the debris cannot be removed from the machined zone properly, it will cause secondary sparking and arcing at the side walls of micro-holes. This phenomenon causes the entrance of the micro-holes to be larger, thus increasing the spark gap and taper angles. However, after applying vibration into the workpiece, the debris particles come out from the smaller working gap, which facilitate the reduction of ineffective pulses. Hence, the overall dimensional accuracy of the micro-holes improves.

Furthermore, it was observed that the surface quality of the micro-holes obtained without vibration has resolidified debris and craters attached to the rim [Fig. 4(a)]. Besides, the surface is heat-affected and contains black spots or pin holes in different positions. On the other hand, the surface obtained using vibration assisted micro-EDM (for both $K_v < 1$ *and* $K_v > 1$) is smoother and free of burr-like recast layer. However, much higher aspect ratio micro-holes with improved surface quality at the rim has been obtained using vibration with $K_v > 1$ [Fig. 4(b)].



(a) (b)

Figure 4: (a) Micro-hole [Ø 60 µm in 0.5 mm, a.r. 8.3] without vibration, (b) Micro-hole [Ø 65 µm in 0.5 mm, a.r. 7.7] with vibration ($K_v<1$), (b) micro-hole [Ø 60 µm in 1 mm, a.r. 16.7] using vibration-assisted micro-EDM ($K_v>1$)

4 Conclusions

Following conclusions can be drawn from the modeling and experimental study:

- The performance of low frequency vibration-assisted micro-EDM depends on K_v (ratio of maximum acceleration in gravitational direction to gravitational acceleration 'g'). For $K_v > 1$, the workpiece vibration becomes effective.
- The machining performance improves as MRR increases and EWR decreases significantly after applying workpiece vibration ($K_v > 1$) in micro-EDM.
- The surface quality at the rim and dimensional accuracy of micro-holes improves due to significant reduction of arcing and short-circuiting.

References:

[1] Alting, L., Kimurta, F., Hansen, H.N. and Bissacco, G., 2003, “Micro Engineering”, Ann. CIRP, 52(2), pp.635-658.

[2] Tong, H., Li, Y. and Wang, Y., 2008, “Experimental research on vibration assisted EDM of micro-structures with non-circular cross-section”, J. Mater. Process. Technol. 208(1-3), pp.289-298.

[3] Tse, F.S., Morse, I.E. and Hinkle, R.T., 1974, “Mechanical Vibration”, Prentice Hall of India Private Limited, New Delhi.