Influence of Force Components on Thin Wire EDM

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Abstract

Apart from the important role that Micromachining and Ultraprecision machining has provided to the development of improved or innovative miniaturised products, these techniques have also attracted the interest of the researchers to obtain the highest accuracy and a thorough analysis of the principles governing the material removing mechanisms. The present article exposes the theoretical analysis of some aspects of the thin WEDM that drop the process accuracy in terms of minimum machinable slot or corner over/undercutting. The scaled electrode dimensions and the reduced power supply with respect to the normal process causes a different influence of the process variables and contributes to obtain complementary information about the WEDM process. The different force components contributing to the wire deformation are discussed and some of them are analyzed from a theoretical point of view presenting analytical calculations to evaluate their expected magnitude and pointing out the difficulties to obtain an experimental characterisation of each phenomena.

Keywords: thin WEDM, process accuracy, process forces

1. Introduction

Wire EDM is a industrially well established machining process that provides reliability and high accuracy. Nevertheless the knowledge about the erosion mechanism, the scale of the different phenomena arising from the sparking process and the influence on the wire electrode is still limited [1].

Some usual errors like wire lag, bowing, corner accuracy, white layer depth, etc. have been partially solved with the last generation machines thanks to the application of last generation controls for path definition, wire tension, etc. and the results of the research performed in the past by several authors [2,3, 4 among others] that identified different algorithms to limit the influence of the aforementioned errors.

Since the beginning of the WEDM analysis, many authors focused their efforts in the identification of the different physical and chemical processes arising from the sparking process. Stressing the influence of the geometrical error in most applications, the research carried out until now has identified the most important force components acting on the wire: electrostatic, electromagnetic, dielectric flushing, spark generation, wire traction and wire feed. Apart from these components, the thermal effects should always been looked after. For normal wires, the values obtained by different authors provide the magnitude of the different effects with some dispersion.

All these aspects are still nowadays an important research field but the inclusion of smaller wires (down to Ø0.02mm) has introduced not only a new range of applications, but also a new field for technology analysis. The research on both scales constitutes an important chance for the better understanding of the wire EDM process.

In a previous job [5], the experimental analysis and characterisation of a Ø0.03mm thin wire performance was addressed, the present paper analyses some of the reasons for such performance, specially the effect of the force components acting on thin wires.

2. Thin Wire EDM limitations

At present wires and machining equipment for thin WEDM are not capable to perform the machining with high productivity and low errors in a reliable way because both electrical (specially current) and mechanical parameters cannot extract the highest material performance avoiding rupture. This is the reason why the operator must apply soft working conditions (low current and traction forces) in aims of reliability, hampering the process capabilities in terms of accuracy and productivity.

As it was already introduced in the past [5], the slot produced by thin wire when cutting 120~130 aspect ratio features in steel or tungsten carbide is circa 60% the wire diameter while the corner undercut/overcut can be as big as 2 times the wire diameter for small angles (10º). The magnitude of such errors can constitute an important handicap in the machining of precision punches/dies or moulds for micro-replication.

Concerning the research aspects, the process does also imply important difficulties for experimental characterisation. The measurement of some critical process variables is harder to do than that in conventional WEDM: the spark frequency is circa 1MHz; (over the acquisition rate and the minimum resolution of most commercial current probes and high speed acquisition cameras, something similar happens with the measurement of currents circa 40 mA); the ~10 times scale of the wire makes difficult to apply many of the displacement measuring techniques (illumination aspects, focal distance, depth of focus, etc. for optical systems; wire alignment for inductive or capacitive sensors, etc.; touch surface magnitude for tactile probes).

The analysis and inspection of the machined components must be carefully addressed [5,6]: specially for micro-features, even with the latest

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metrology techniques, component clamping or cleaning constitute important challenges.

3. Electrostatic force

The electrostatic force acts during the pause (OFF time) of the spark cycle due to the attraction between charges of opposite signs (wire and part surface prior to spark). The magnitude and direction can be calculated by differential integration if the charge distribution on the wire and the part surface is defined.

For thin wires, it is possible to perform some assumptions that simplify the calculation of the charge in the wire: i) electric charge in the wire is assumed to be concentrated in its axis; ii) the electric field vectors entering the wire present a radial distribution towards its axis; iii) during the OFF time the voltage decays linearly from the wire to the part surface in the radial direction (fig. 1).

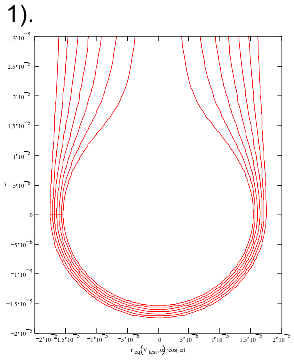

Fig. 1 Assumed distribution for voltage constant lines

The charge distribution in the wire can be calculated using the law of Gauss (1) for a close section around the electrode.

$$\int_O E \, dS = Q/\varepsilon \qquad (1)$$

Being E, the electric field (negative radial gradient of the voltage in the radial direction, which has been supposed to be linear for each radius); $\int_O dS$ the integration on loop around the wire; Q is the charge in the wire; ε is the electrical permeability of the dielectric.

Given the assumed voltage distribution, it is possible to calculate the negative voltage gradient in the orthogonal direction for each point at the surface of the machined path (electric field) and, estimate the charge distribution on the surface applying the law of Coulomb (2).

$$\Delta E(\theta) = -\Delta V/\Delta n = q(\theta)/(4\cdot\pi\cdot\varepsilon\cdot\Delta n^2) \qquad (2)$$

Being θ the polar coordinate used for integration; $\Delta E(\theta)$ the normal electric field for each differential surface; ΔV the voltage variation; Δn the orthogonal to surface distance; $q(\theta)$ the positive charge on the surface.

Each differential surface will produce a force vector acting on the wire, given by the law of Coulomb ($r(\theta)$ is the distance from each point on the surface to the wire). The electrostatic force acting on the wire can be calculated Integrating all force components. For the exposed example, the components of the force in the feed direction produce an electrostatic force attracting the wire to the part (3), while the components in the orthogonal direction are balanced.

$$F_{electrostatic} = \int_\theta [-q(\theta)\cdot Q/(4\cdot\pi\cdot\varepsilon\cdot r(\theta)^2)]\cdot \sin(\theta)\cdot d\theta \qquad (3)$$

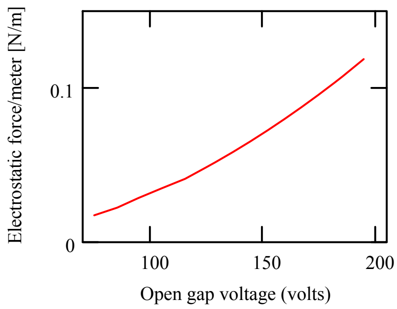

Fig. 2 Calculated Electrostatic force per unit length for a Ø0.03mm wire

The force depends specially on the open gap voltage. Figure 2 shows the analysis of the forces for a Ø0.03mm wire in a straight slot cutting a 3.6 mm height WC part, using oil as dielectric. The obtained values do not differ much to those provided by different authors, the applied voltage, gap and permeability is not very different to the normal WEDM.

4. Electromagnetic force

The electromagnetic force appears due to the creation of a magnetic field around the direction of a moving charge. In the EDM process the current will only appear during the discharge (ON time).

The direction of the current inside the part is difficult to estimate and, for the wire, it will depend on the spark location with respect to the conductivity blocks (fig 3).

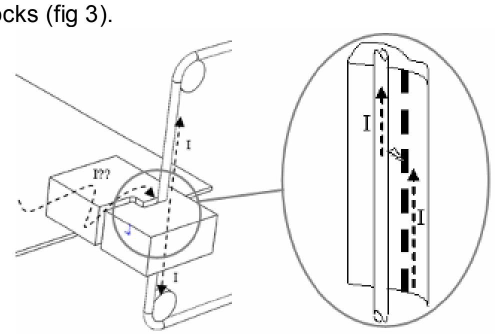

Fig. 3 Assumed path for the current in the part

The discharge will happen from the wire to a given position on the part surface, assuming that current will flow on the part surface tracing a line parallel to the wire, the wire electrode will be subjected to an attracting force between two parallel wires given by the law of Biot-Savart (4).

$$F_{electromagnetic} = \mu_{WC}\cdot\mu_0\cdot I^2\cdot L/(2\cdot\pi\cdot r_w) \qquad (4)$$

Being μ_{WC} and μ_0 the magnetic susceptibility of the part and vacuum; I the discharge current; L the part height and r_w the wire radius.

The force depends specially on the discharge current but the obtained values are negligible due to the low discharge assumed for calculations (fig.4, the adopted values are those measured in real discharges with thin wires).

The values obtained for conventional EDM are similar to those provided by other authors, nevertheless, the experimental validation of this component is difficult to perform. The force values, if compared to other forces arising form the spark, are negligible and it is difficult to design a test to separate the influence of this force.

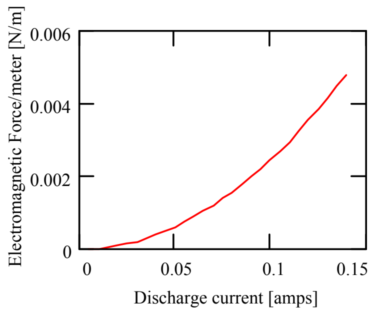

Fig. 4 Calculated Electromagnetic force per unit length for a Ø0.03mm wire

5. Dielectric flushing

The dielectric fluid surrounds all the erosion zone because both part and wire are submerged in thin WEDM. At the same time, the dielectric is injected from the top and bottom guides with a higher pressure (~6 bar for high aspect ratios) in order to clean the debris and cool the part. Oil and deionised water are used as dielectrics in market available systems but, according to the experience of the authors in machines using any of these dielectrics, the differences are minimum in terms of gap size, machining feed or machining parameters.

Trying to estimate the effect that dielectric causes on the wire: from a empirical point of view, it is possible to obtain higher cutting rates and cut wider components with higher pressures but generally this implies larger gaps. Doing an analytical estimation of the pressure executed by the dielectric is not an easy task. The problem of two opposite jets running inside a microchannel (formed by the wire and the part) and submerged in a fluid is a state of the art problem which is being analysed even for simple symmetric cavities.

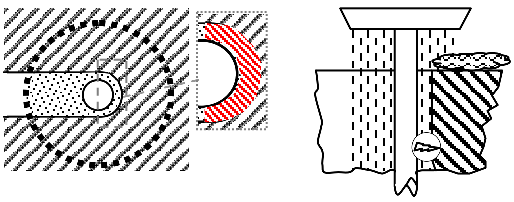

Fig. 5 Dielectric flushing scheme: top view (left); section (right)

Considering the discharge gap as a micro-channel closed by the diameter of the wire and the part (fig. 5, detail) the hydraulic diameter is too reduced, obtaining very low Reynolds numbers (<20). It is also possible to assume the microchannel as the fraction of the flow leaving the upper guide and entering the part (fig.5, left), in this case the flux is also laminar but the obtained Reynolds numbers are bigger (~100).

The Darcy-Weisbach equation can be used to calculate pressure drops in micro-channels [7]. Considering any of both sections, the pressure drop is excessive for the flow to reach the centre of thick workpieces (fig. 6).

This is probably the reason why some authors have reported that it is possible to assume that sparks occur in a dry plasma [7] (the high spark rate creates bubbles around the wire and new sparks appear in the absence of dielectric), neglecting the influence of the dielectric force[8].

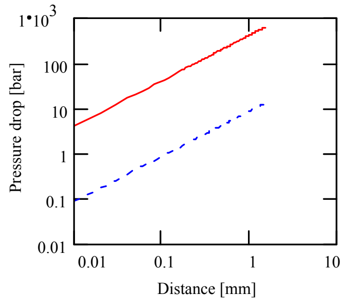

Fig. 6 Pressure drop caused by a constant flow inside a microchannel constrained by the discharge area (red); machined slot area (blue)

At the same time, the higher fluid pressure will make the dielectric jet get deeper into the machined slot to remove debris and cool the part. This effect, together to a second dielectric pumping effect caused by the plasma bubbles pushing the dielectric inwards/outwards the spark area can be the reason why lower wire breakage, higher productivity or wider components machining can be achieved with higher dielectric pressures. In this case the bigger gaps can be due to the dragging force executed by the dielectric on the wire and the turbulences caused by the plasma bubbles.

6. Spark force

The force caused by the spark on the electrode has been considered as an impulse or a travelling pressure wave by several authors in the past. It is not really well understood what happens when the spark appears: the appearance of bubbles, debris, instantaneous thermal sources, etc. at the same time in random locations at a very high repetition rate makes of the process analysis a difficult challenge.

Recent jobs [8,9] have brought some light on the problem. They consider the force as that cause by the generation of a plasma bubble that expands and collapses creating the force on the electrode.

Trying to apply a similar point of view for WEDM from a theoretical point of view, the bubble is a plasma that contains a mixture of gases created during the ablation of electrode, dielectric and part material. The cooling of this material will form the debris and the re-solidified layer of the WEDM process.

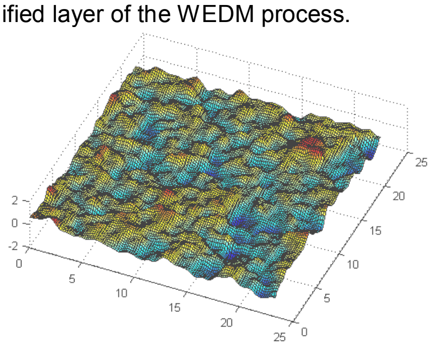

Fig. 7 Surface sparked by thin WEDM (X100 Confocal microscopy)

Identifying the portion of electrode and part material that is ablated during the process can be done by analysing the crater on both of them. For single spark tests this is easier than for real machining conditions, but the obtained values are hardly ever the same even if the same conditions are applied. The real machining process modifies the energy distribution within the dielectric (the spark is ramified by debris, etc.), part and electrode.

Just as some authors [10] have made in the past, a crater mean size can be obtained analysing the sparked surface. Optical microscopy (fig. 7) reveals a high heterogeneity in the dimensions of the craters that makes difficult to achieve the desired value.

Despite the random nature of the EDM process, if FFT filtering techniques are applied to different slides in radial and Cartesian directions, a mean value can be defined for the crater diameter and depth (fig. 8).

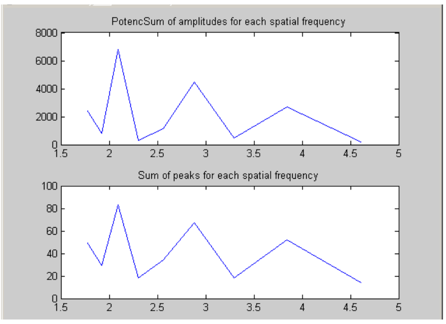

Fig. 8 Sum of all peaks (amplitudes on the top and unitary below) at different spatial frequencies for the different slices in the Cartesian and radial directions

The values obtained for the crater diameter under different conditions agree with those intuitive values guessed by the operator in the microscope. These values can be used to filter the surface and, comparing the filtered surface to the measured surface, define a volume for the sparked volume and the re-solidified volume. Dividing the measured area by the crater area, the number of craters per unitary surface and the re-solidified volume per crater are estimated.

The crater dimensions can be also used to estimate a initial bubble volume (considering the crater as part of a sphere).

If re-solidified volume and crater volume on both wire and part are assumed as ablated, the ablated number of mols for each material (electrode and part) can be calculated (5)

$$N_{mol} = V_{part} \cdot \rho_{WC} / MW_{WC} + V_{wire} \cdot \rho_W / MW_W \qquad (5)$$

Being N_{mol} the number of mols; V_{part} and V_{wire} the calculated crater and resoldified layer volume per aprk in part and wire; MW the molecular weight on the part (assumed to be tungsten carbide) and the wire (assumed to be tungsten). If the plasma is assumed to be a perfect gas, the volume per mol in normal conditions (273.15 K and 1 atm) will be 22.4 litters.

In order to achieve ablation, the temperature should be high enough to change the state of the materials of the electrodes (6203 K for WC). At that temperature the bubble volume should be that calculated out of the crater dimensions.

For a perfect gas, the partial pressure of the bubble at the temperature in which the part material is ablated can be calculated out of the conditions of pressure, volume and temperature at normal conditions. For Ø0.03mm WEDM, the obtained crater dimensions are Ø1.92~2.88µm and 0.12~0.38µm depth for both pat and wire. The calculated pressures range from 30 to 140 atm. Values that fit results obtained by other authors [11].

7. Conclusions

The present job introduces an effort to analyse the scale and the influence of different forces on thin wires in the WEDM process. Electrostatic and spark forces are definitely important in thin wires while the low current applied in the process seems to reduce the effect of electromagnetic force with respect to normal WEDM. The influence of dielectric flushing is difficult to analyse because the large pressure drop in microchannels seems to make the influence different to the conventional process. FFT filtering can be used to analyse scanned surfaces and estimate mean values for crater dimensions in EDM for different calculations.

The proposed analysis solutions are compared to results obtained by other authors in normal WEDM but a thorough experimental validation should be perform in the future job.

Acknowledgements

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