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Electrode profile prediction and wear compensation in EDM-milling and micro-EDM-milling

Jacques RICHARD*, Nicola Giandomenico

hepia Geneva / Member of HES-SO University of Applied Sciences and Art Western Switzerland
4 rue de la Prairie, CH 1202 Geneva

* Corresponding author. Tel.: +41 22 546 26 02; fax: +41 22 546 25 77. *E-mail address:* Jacques.richard@hesge.ch

Abstract

EDM-milling and micro-EDM-milling aims to machine deep cavities with rotating electrode; those technologies have a great potential, nevertheless the electrode's wear has to be compensated, which is a big challenge. To achieve this, the electrode profile is of crucial importance as it has a direct impact on the part removed material, but in the same time, the wear modifies this profile. This paper will investigate how the electrode profile is related to tool-path trajectory. It will demonstrate the link between wear, trajectory and electrode profile – both from theoretical point of view and by experimental verification. In case of cylindrical shape electrode with a trajectory in full material, the electrode profile is conically self-shaped. With a zigzag pocketing trajectory the self-shaped profile is more complex but linked with the tool-path overlap in a predictable way: it depends upon the volumetric wear, upon the tool-path overlap, tool-path steepness and the EDM gap. In identical conditions, the EDM gap has for effect to more make the electrode's profile more flat. For the micro-EDM-milling (electrode diameter < 0.3mm); this fact is even more pronounced and lead to the fact that the electrode profile tends to be cylindrical. This makes much easier the tool-path strategy and electrode's wear compensation algorithm. This opens new opportunities for micro-EDM-milling technology.

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Keywords: EDM-milling; micro-EDM-milling; Rotating electrode; Wear; Electrode's profile; Tool-path strategy; Wear compensation;

1. Introduction

EDM-milling is a technology somehow in-between die EDM sinking and wire EDM cutting. EDM milling tools are tubular copper electrode rotating at high speed in the dielectric oil and removing the work piece material by sparking. By analogy to conventional milling, it is the movement of the electrodes that generates the work piece geometry by subtraction of material.

Some applications are using nonrotating electrodes. In that case the electrode is usually in hard metal and the sparking technology is adjusted in order to get minimum of wear. Engraving very small parts are possible with this technology [1], but the wear cannot be completely avoided. The electrode has to be changed and it is difficult to warranty the final part accuracy.

We will here investigate applications where the electrode is rotating. The wear combined with the rotation involves the effective tool to have revolution symmetry. EDM-milling tools are usually tubular electrodes ranging diameters from 0.8 mm to 12 mm and the machining strategies are similar to a layer by layer pocketing [2,3,4,5]. Nevertheless, to achieve the part geometrical features, the wear has to be compensated by the electrode's renewal. This is one main difficulty of this process, so we will discuss the wear in detail in this article.

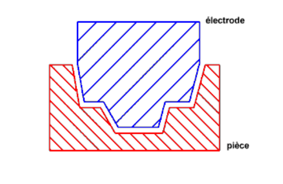

Fig.1. Conventional Die Sinking

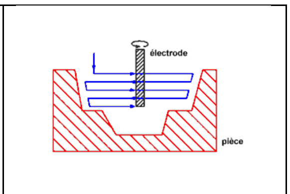

Fig.2. EDM milling

Micro-EDM-milling [c] uses basically the same ideas but for much smaller electrodes. In typical case, electrodes are

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copper wire of diameter 0.25mm and 30mm long rotating at high speed. The rotation has an effect of stabilization along the spindle axis. One particularity of this process is the absence of cutting forces, which allows machining deep cavities of high precision without any risk of tool break.

We have focused our research on a simplification of this technology: the “Light” micro-EDM-milling [d] and this article relates about some aspects of this research. Therefore the case of plain electrode will be studied in detail, even with bigger diameter.

2. EDM milling tool path strategies

We define the “effective tool” acting to remove the part material; this includes the gap and takes care of electrodes shape reduced by the wear. From an “effective tool” point of view, the machining strategies are similar to a layer by layer pocketing. In order to have the effective tool tip at constant level, (layer at Z constant) the wear has to be compensated in a sophisticated way. As the wear is function of the removed material, a way to do this is to use a pre-processor software that computes the removed material along the “effective tool” trajectory. To do this in an accurate way, it is important to have a right idea of the electrode’s profile: the material removed by a conical tool is not the same as a cylindrical tool. This is particularly important for micro-EDM-milling using plain electrode.

3. Electrode profile related with tool path

It is obvious that in EDM-milling the wear will modify the electrode shape. For given sparking parameters and given material couple electrode/part, it is right to consider the wear as proportional to the removed material. So once the electrode enters in the material, its shape will continuously be modified depending on the part material repartition and the electrode’s trajectory. In full generality it is a very complex and non-linear problem. We will consider simple configuration: homogenous part material repartition, linear and homogenous segments trajectory with constant steepness; in those conditions, after a transitory stage, the electrode profile reaches an asymptotic shape.

Notation

U	volumetric wear :: U = Vel / Vp
Vp	Volume removed on part
Vel	Volume removed on electrode
R	electrode external radius
r	radius (variable)
z	z coord (variable)
r::f(z)	electrode profile
p	groove depth ; layer thickness
pi	partial layer thickness
dZ	electrode segment trajectory along z axis
dX	electrode segment trajectory along x axis
m	electrode segment trajectory steepness :: m = dZ/dX
elth	electrode thickness (case flat el. elth << R)
Cte	arbitrary constant
TEfCS	Tool Efficient cross Section
gap	EDM gap

3.1. Cylindrical electrode in plain material

The Fig.3 to Fig.5 show the situation of a cylindrical electrode moving with constant steepness in plain material. At the asymptotic state the wear compensate the electrode down sinking. For the following development, the wear is supposed constant and we assume the gap to be negligible:

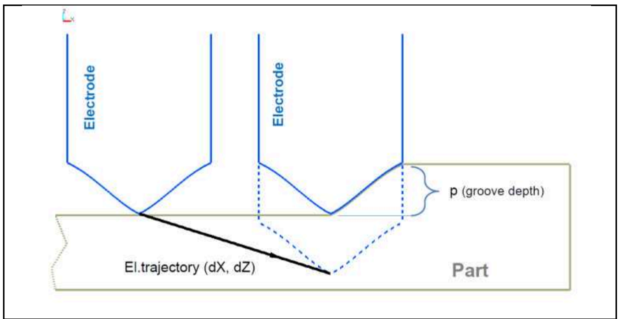

Fig.3. Cylindrical electrode in plain material (to trajectory: side section)

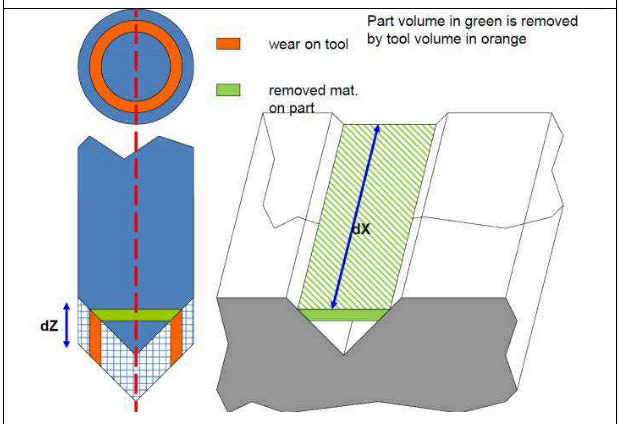

Fig.4. Cylindrical electrode in plain material (to trajectory: isometric vue,)

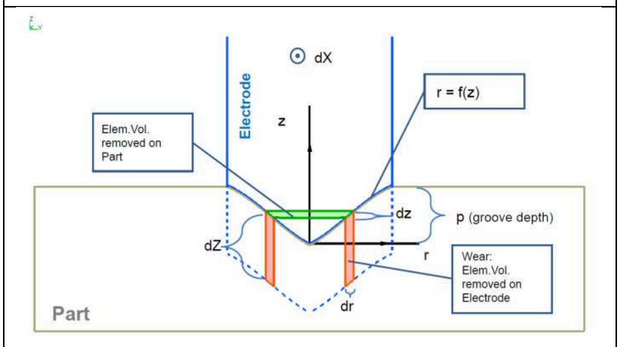

Fig.5. Cylindrical electrode in plain material (to trajectory: front section). The Elementary volume removed on part is a thin strip; the elementary wear volume of electrode is a thin cylinder

Vel = U*Vp (1)

Considering the elementary volume at a given point of the profile:

dVel = 2 π* r * dr * dZ (2)

dVp = 2 * r * dX dz (3)

With 1) it comes:

dVel = 2 * π* r * dr * dZ = Vp = U * 2 * r * dX dz (4)

Supposing the profile is given by the function: r = f(z)

dr = δ(f(z))/δz *dz (5)

it comes the differential equation:

δ(f(z))/δz = (U * dX) / (π * dZ) = U / (π *m) (6)

Setting k = U / (π * m)

Solving this differential equation: δ(f(z)/δz = k

The profile is then given by:

r = f(z) = k * z + Cte (7)

Initial Condition: f(0) = 0 => Cte = 0 thus the profile is:

r = (U/ (π*m))*z (8)

This demonstrates that in plain material the electrode reaches a conical profile. The cone's height (or groove depth) is related to the trajectory steepness and to the wear by:

p = π*R*m/U (9)

This fits with the experimental situation.

3.2. Thin flat electrode in plain material

To check this dependence of the electrode profile with trajectory steepness and the wear, we have investigated the case of flat electrode rotating while machining [e]. It can be demonstrated with the same assumption than in 3.1 leading to solving the differential equation:

δ(f(z))/δz = k * f(z) (10)

with k = U / (elth * m)

the profile can be expressed as:

r=f(z) = R * e^{kz} where k = -U / (elth * m) (11)

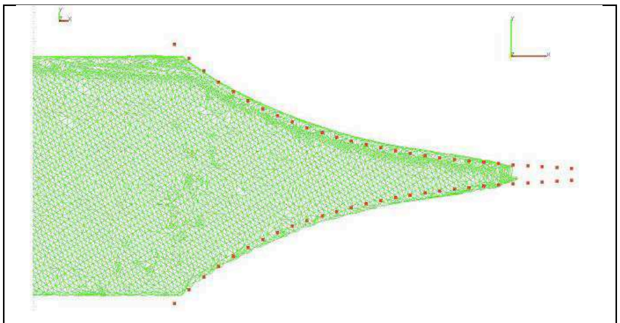

Fig.6. Thin flat electrode in plain material – experimental result superposed to theoretical function

Even if this case has no practical application, it brings a good experimental proof of the theoretical approach linking electrode profile with its trajectory.

3.3. Pocketing strategy with cylindrical electrode

To machine a cavity, at each layer a pocketing strategy is applied similar to 2.5 axis machining. We chose the following strategy: contouring the border of the pocket and then hollow up the remaining material by zigzag hatching. The contouring is in full material, the zigzag hatching is partially in material depending of the path overlap.

In case of path overlapping from the tool radius the situation is the following:

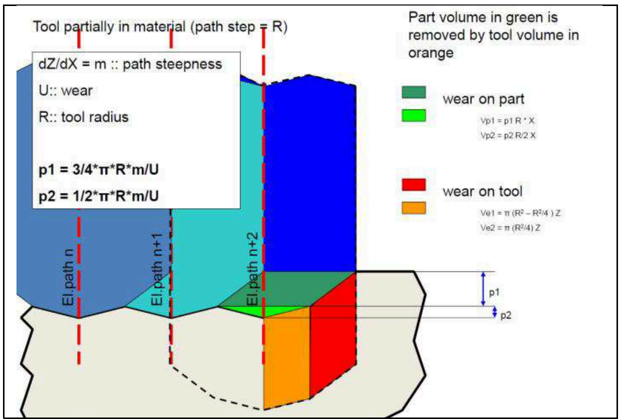

Fig.7. Cylindrical electrode with overlapping path (front section) the removed volume on part is the green area swept normal to front section; the electrode's wear is the revolution volume of the orange area around its rotation axis

With the hypothesis that the path length is much greater than the tool radius, the electrode profile is generated by the material left by the previous path; it can be predicted considering the respective volumes of removed material and electrode wear. The electrode profile have successive conical portions.

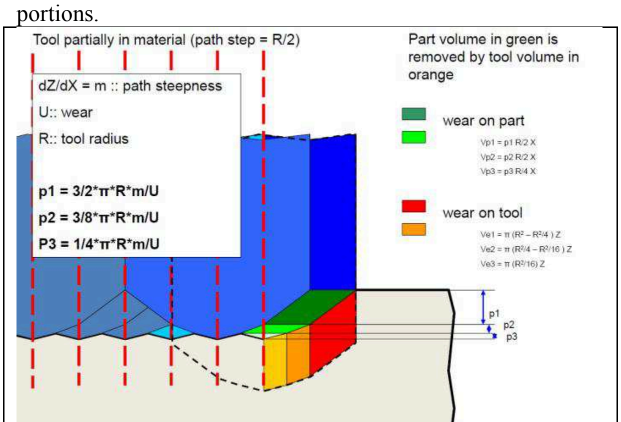

Fig.8. Cylindrical electrode with overlapping path R/2

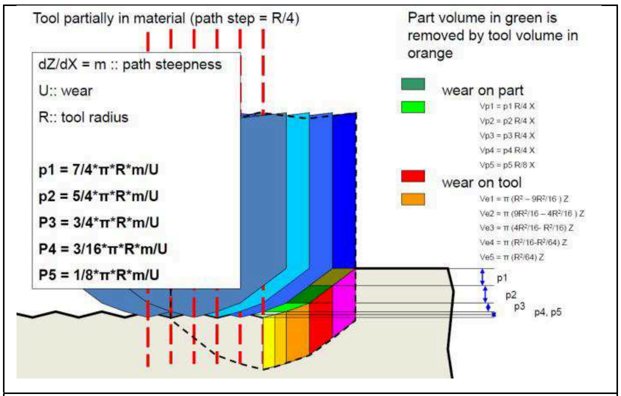

Fig.9. Cylindrical electrode with overlapping path R/4

The next figures give the situation when reducing the path step.

The remaining scallop height is given by:

Table 1.

Path Overlap	2R	R	1/2R	1/4R
pi scallop	p	p2	p3	p5
pi scallop /p	1	0.4	0.118	0.031

So even if the electrode profile is still basically conical, it is possible to obtain flat pocket bottom according to a given accuracy.

3.4. Influence of the electrode profile on the Tool Efficient Cross Section

The electrode profile has an influence on the Tool Efficient Cross Section "TEfCS" defined by:

$$\text{TEfCS} = \frac{\text{area swept in part by electrode}}{\text{reference tool swept area}} \qquad (12)$$

In conventional milling for a cylindrical tool TEfCS = 1 in full material and TEfCS = 0.5 for path step of the tool radius.

It is different with electrode of EDM-milling as the tool is profiled by the wear.

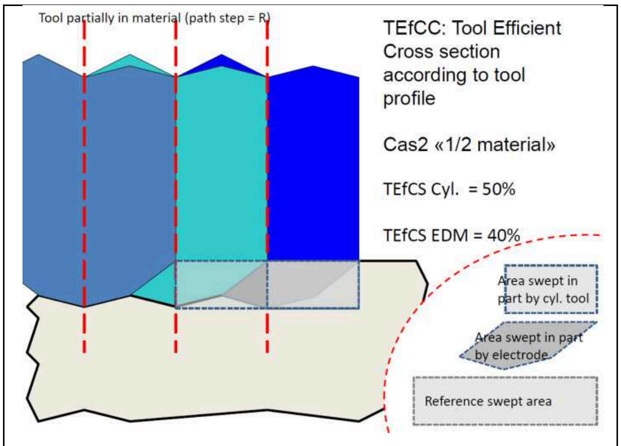

Fig.10. Cylindrical electrode with overlapping path R

The following table gives the values for several path overlap:

Table 2.

Step (/R tool)	TEfCS EDM	TEfCS conventional
2	50.0%	100.0%
1	40.0%	50.0%
0.75	32.9%	37.5%
0.5	23.5%	25.0%
0.25	12.3%	12.5%

We can observe that EDM-milling tool is much different in full material, but it tend to conventional milling tool while overlapping path.

4. Influence of the Gap on the Electrode profile

To fit more to physical reality, the EDM gap has to be taken into consideration; in the previous development it has been neglected. In the following we will study the implication on the electrode profile, assuming that the gap is still small compared to the electrode radius. The layer thickness between the pocketing levels is also supposed to be quite small.

4.1. Cylindrical electrode in plain material

The following figure schematizes the situation. The gap volume surrounding the electrode also participates to part material removal.

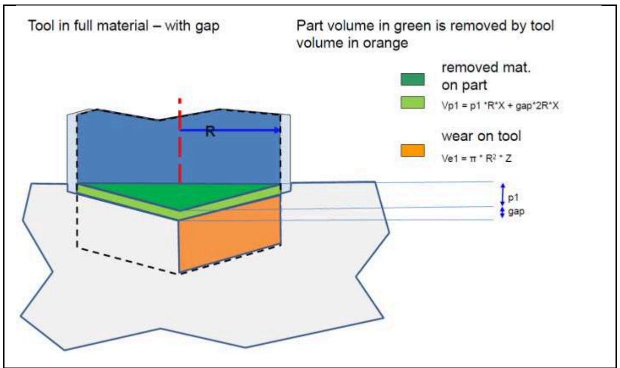

Fig.11. Cylindrical electrode in full material + Gap. The removed volume on part is the green area swept normal to front section; the electrode's wear is the revolution volume of the orange area around its rotation axis

The conical electrode profile can be characterized by p1 (cone's height):

$$p1 = (\pi * R * m / U) - 2*gap \quad (13)$$

So, for a given gap (the gap and wear depending mainly of sparks parameters), p1 may be null choosing a convenient trajectory steepness. This means that the electrode is cylindrical. With typical steepness:

$$m = (2 * gap * U) / (\pi * R) \quad (14)$$

So the electrode tip becomes flat.

4.2. Pocketing strategy with cylindrical electrode

The following figure schematizes the situation for a simple zigzag trajectory overlapping from electrode radius.

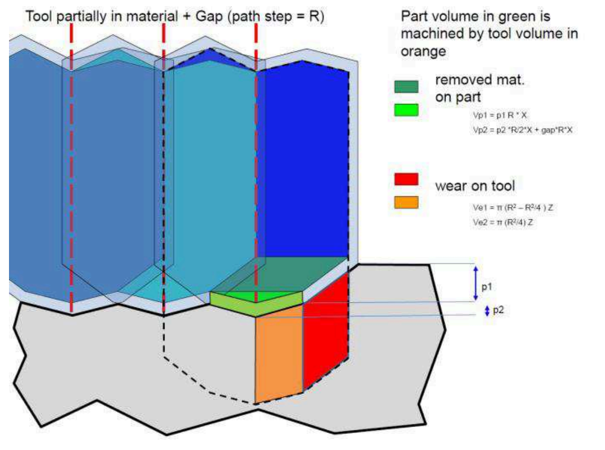

Fig.12. Cylindrical electrode + Gap with overlapping path R

The conical electrode profile can be characterized by p1 and p2:

$p1 = 0.75*\pi * R * m /U$ (15)
$p2 = (0.5*\pi * R * m /U) – 2*gap$ (16)

Here also, for a given gap p2 may be null choosing convenient trajectory steepness.

Going further with this development we obtain this graph for the electrode profile:

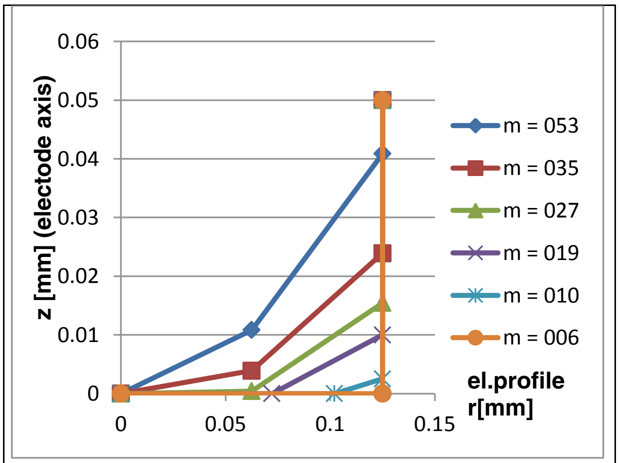

Fig.13. Cylindrical electrode profile for several tool path steepness

Electrode diameter: 0.25 mm; Path Overlap: 0.125mm; Gap:0.005mm; Wear: 50%; m = 0.53 to m = 0.006;

This also means that the trajectory steepness can be set in order to get a cylindrical electrode. With this, the Tool Efficient Cross Section EDM-milling could stay identical to conventional milling and the transitory steps are highly restricted.

5. Experimental aspect of EDM-milling and micro-EDM-milling

Although micro-EDM-milling is the motivation of this study, a series of experiments have been made with larger electrodes to make the geometrical study easier.

5.1. Influence of the gap on the electrode profile

The link between electrode profile wear and trajectory has been experimentally studied with copper electrode diameter 6mm machining part of steel. The resulting profile and 3D scan of the cavity has been measured. As can be seen on Fig.14

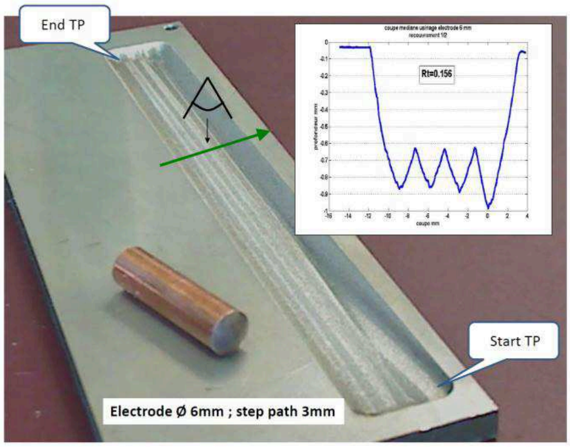

Fig.14. Experimental investigation with cylindrical electrode

It is clear that after a transitory stage (which is not so negligible), the electrode profile reaches an asymptotic shape.

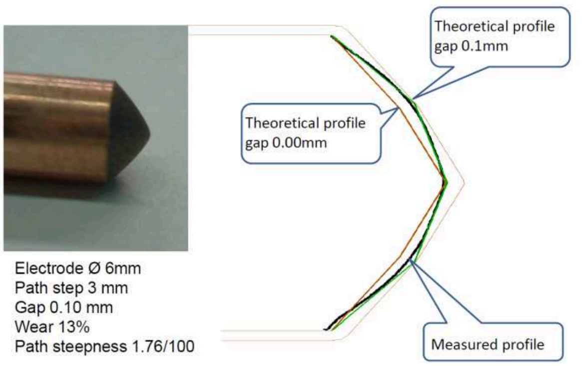

Fig.15. Cylindrical electrode + Gap with overlapping path R; m =0.0176

It is also clear that the gap has for effect to flatten the electrode conical profile. The measurements are in perfect agreement with theoretical approach.

5.2. Spark Monitoring & material removal

We have used a "Smart Generator" a new sparks generator dedicated to "light" micro-EDM-milling that is able to monitor in quasi-real time the material removal by counting the efficient sparks [d].

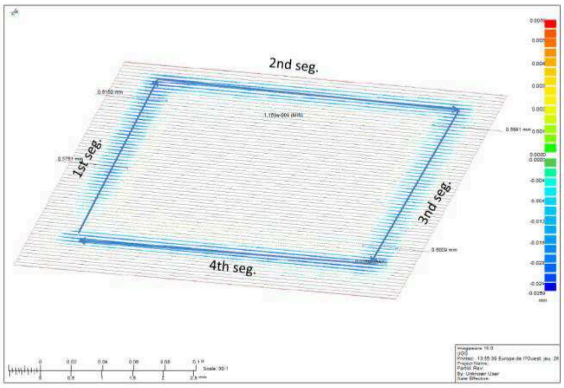

Fig.16 Square engraved by micro-EDM-milling (electrode 0.25mm) – depth map

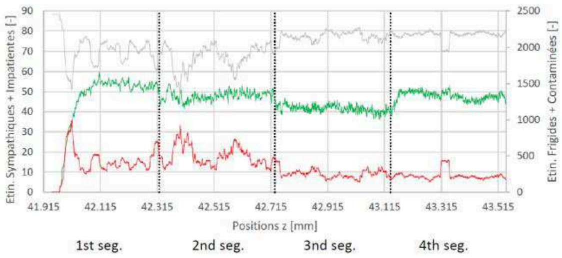

Fig.17 Square engraved by micro-EDM-milling – spark monitoring – in green the counting of spark removing material.

Fig.16 and Fig.17 clearly show the correlation between spark monitoring and material removed. This is also related to the Tool Efficient Cross Section. In this experiment, no particular wear compensation (except constant steepness tool trajectory) has been applied. Thus, choosing tool trajectory parameters that maintain the electrode tip flat will make easy the computation of the removed material along the tool trajectory. In conjunction with "Smart Generator" it enables to develop new algorithms to compensate the wear.

6. Conclusion

In EDM-milling and micro-EDM-milling, the electrode profile is related by the wear to tool-path trajectory, the EDM gap and the initial material repartition in a complex way.

Nevertheless, in carefully chosen conditions the electrode profile tends to be cylindrical. With this, the transitory stage that makes the process very difficult to manage can be avoided. This will also make the pre-computation which has been used up to now to compensate the wear much easier. This opens new possibilities for micro-EDM-milling technology.

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