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Smart Generator for Micro-EDM-Milling

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Abstract

Micro-EDM-Milling has a strong innovation potential because it can perform accurate and detailed cavies with a high aspect ratio.
In this technology, the electrode wear and material removal produced by every discharge is determined by the effective power delivered by the generator during every pulse cycle.
High speed electronics make now possible the statistical analysis of sparks distributions in real time during the machining but also the measurement and modulation of the characteristics of every spark-discharge. It is now possible to measure and control in real-time the electrode wear and the material removal with extreme accuracy.
Our “Smart EDM Generator” has the functions of voltage measurement, spark analysis and process control. It can count the sparks and classified them, control the electro-erosion process and calculate the wear of the electrode.
The statistical distribution of the sparks and other parameters can be acquired by the CNC-PC from a direct Ethernet link and be visualized on a specific HMI.

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Keywords: Micro-EDM-Milling; Smart EDM generator; EDM linear current; Micro-machining; High aspect ratio; Real time sparks analysis; Frequency EDM process control

1. Introduction

Micro-manufacturing emerged in the last years as a new engineering area with the potential of increasing people’s quality of life through the production of innovative micro-devices to be used, for example, in the biomedical, micro-electronics or telecommunication sectors. The possibility to decrease the energy consumption makes the micro-manufacturing extremely appealing in terms of environmental protection.

The technology that combines EDM and Milling, called EDM-Milling (the “historical” starting point of this research) is somehow in-between Die Sinking and Wire Cutting EDM. EDM-Milling tools are very simple and inexpensive electrodes, as tubular copper, rotating at high speed in a dielectric oil and removing the workpiece material by sparking.

The appellation “Micro-EDM-Milling” uses basically the same ideas but for much smaller electrodes (diameter smaller than 1mm, in fact the same wires used in Wire EDM machine). Micro-electrodes consist essentially in cylindrical rods with diameters that can be down to 20 or 10 um. They are driven along defined paths while rotating, in a way like conventional multi-axis milling. The material is removed layer by layer, with layer thickness ranging of a few microns, depending on the diameter of the electrode and the discharge energy (fig.1). 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. Micro-EDM-Milling simplifies the machining process including the tool electrode fabrication and electrode wear compensation. Furthermore, this method can machine a freeform surface suitable for machining 3D microstructures with high aspect ratios even in high performance materials. However, it is necessary to

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integrate a CAD-CAM system to generate the tool path and an algorithm for the wear compensation, this last point is one of the critical issue of this technology.

In that context, the Micro-EDM-Milling has a strong innovation potential because today there are no machining technology that can perform accurate, fine detailed cavies with a high aspect ratio. This new technology could be positioned as an independent machining technology but also as a complement module to Die Sinking machine or to high speed milling.

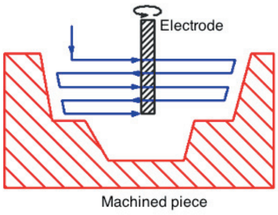

Fig. 1. Principle of the Micro-EDM-Milling

As the machining conditions are quite unconventional, the physical basis of this process has been investigated in previous research: typical hydrodynamic, sparking plasma in liquid dielectric with velocity gradient, mechanical stability of flexible rotating electrode.

In this project, the objective was to break the fast real-time loop control between the EDM process and the numerical control, existing in all the current topology of EDM machine. It permits to separate the control axis function to the EDM process: by this way, the machining stability, the wear compensation calculation and the module integration in any numerical control could be drastically simplified.

In that context, the generator must have, in addition to the sparks generation, the functions of the EDM gap voltage measurement, the spark analysis and the process control. It should count the sparks and classified them, control the electro-erosion process and calculate in real-time the wear of the electrode, hence the name "Smart".

High speed electronics make now possible the statistical analysis of sparks distributions in real time during the machining but also the measurement and modulation of the characteristics of every spark-discharge even though their time duration is on the scale of tenths of ns. As the electrode wear and material removal produced by every discharge is determined by the effective power delivered by the generator during every pulse cycle, it is now possible to measure and control in real-time the electrode wear and removal material with extreme accuracy.

In addition, as the sparking has a stochastic nature, a traditional EDM control adjusts the axis speed to maintain a constant gap between electrode and workpiece for stabilizing the process. The possibility of controlling and measuring the effective sparking cycle at the finest scale, means counting sparks and determining its effective power, opens the way to the control of the gap through the control of the instantaneous frequency of pulse generation, thus achieving stability independently of the axis speed. This is the basis of a new modular approach for a high-precision EDM-milling technology.

1.1. Potential of innovation

The Micro-EDM-milling has a strong innovation potential. This new technology could be positioned as an independent machining technology but also as a complement as to Die-EDM-sinking or to high speed milling.

The miniaturization of parts and components (for instance MEMS) plays an important role in today's economy. To successfully achieve this task, processes must suit the needs for micro mold manufacturing and combined with a subsequent injection-molding process to satisfy the need for large-scale production with a vast variety of possible materials.

As mentioned in [11], the micro- and nano-product market is currently influenced strongly by the following significant trends:

a) Emerging markets driven by needs from sectors such as energy, transport, healthcare and consumer electronics, which are closely linked to important societal challenges.

b) Increased introduction/utilization of materials and technology into micro-miniaturized products and devices which offers unique performance and extended life such as that used in new medical devices, implantable components, and micro-electronics products

c) Disruptive development of manufacturing technologies, which helped the development of new products.

Considering that micro-manufacturing is the bridge between high-impact technology, real-life and low-cost products, it will achieve further significant development over the next 10 years.

Nomenclature

CNC	Computer Numerical Control
CCR	Constant Current Regulator
Labview	Graphical programming language
HMI	Human machine Interface
Ethernet	Communication protocol

2. State of the art

Micro-EDM-Milling is a developing technology and there are very few results published in international journals and conferences. The main difference between this new technology and more traditional EDM-milling is the use of electrodes with smaller diameters that are suitable for micro fabrication. Therefore, the main feature of micro-EDM-milling is to achieve a very high accuracy. The accuracy of micro-EDM-drilling is studied in [1] and the research issues for this technology are surveyed in [2]. A well-known method to improve the accuracy is the use of high performance closed-loop control systems. Two major control problems have been recognized in micro-EDM-milling: vibration control and electrode wear compensation.

It is in this last issue, the wear compensation, that we find the most publications. In [3], the paper discusses a new wear compensation method, incorporating real-time wear sensing based on discharge pulse evaluation instead of wear compensation methods based on off-line prediction. The papers [4] and [5] discusses the electrode wear based on spark discharge counting and volume measurements, their influence on the accuracy and the method limitation. Specifically, the paper [5] investigates the applicability of real time wear compensation in micro EDM milling based on discharge counting and discharge population characterization. Experiments were performed involving discharge counting and tool electrode wear measurement in a wide range of process parameters settings involving different current pulse shapes. In [6], a three-dimensional geometric simulation method of micro EDM-milling processes is proposed, which introduces a Z-map algorithm to precisely represent the geometries of a machined workpiece and the evolution of the tool shape caused by tool wear during the machining. The publication [7] proposes a new electrode wear compensation method, the combination of the linear compensation method (LCM) and the uniform wear method (UWM), called the CLU method.

There are few publications about concrete machining applications using micro-EDM-Milling. The paper [8] discusses the physical basis and the industrial feasibility of micro-EDM-milling. Another paper [9], the Micro-EDM-Milling of zirconia is investigated in order to further understand the mechanisms of ceramics machining. Roughness and surface characteristics are analyzed and compared to the equivalent metal parts. Finally, the publication [10], the study reports on the production of micro flow channels in metallic bipolar plates, using Micro-EDM-Milling.

3. The Micro-machine prototype

The micro machine has 4 axis : x, y, z and the spindle c (fig.2). The z-axis carries the spindle and permits the rotation of the cutting tool. The cutting tool (the electrode) is in this case an annealed wire copper.

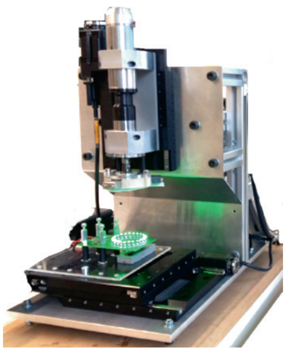

Fig. 2. Micro-EDM-Milling machine prototype

The electrode clamp holds the electrode, rotates it and permits the circulation of the current pulses coming from the Smart generator. The electrode holder is fixed in the tool shank clamp mounted on the electro-spindle

A straightening system shapes the electrode before using it for machining (fig.3). This system consists of two movable steel rollers that come to pinch the electrode. By pulling the electrode through this system, it passes from a folded state to a rectified state. After straightening the electrode is straight in rotation, it can be used as a "cutting tool".

To control the electrode and the quality of the rectification, a composite vision system of two cameras allows to check the straightening of the electrode (fig.3). A vision interface provides information on the electrode rotation. It notably makes it possible to know the beat at the end of the electrode and thus to measure the quality of the rectification.

Finally, the drivers for the axis control and the Smart Generator are fully integrated in the mechanical structure (fig.3). The vision system fulfills two functions: firstly, it allows inspecting the centering of the electrode and secondly, it makes it possible to study the lateral movements of the electrode.

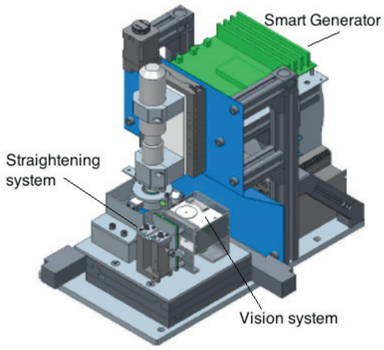

Fig. 3. The Micro-EDM-Milling machine with location of the main systems

4. The Smart Generator

This generator is said to be “Smart”, because in addition to the sparks generation, it has the functions of voltage measurement, spark analysis and process control (fig.4 and fig.5). It can count the sparks and classified them (normal, contaminated, open and short circuit discharges), control the electro-erosion process and calculate the wear of the electrode. On traditional EDM systems, these tasks are achieved on multiples electronic cards. In our development, all these elements are integrated on a single board. This integration required considerable effort and many steps to achieve this architecture.

The strength of this generator is to possess all these capacities grouped on the same platform and constitutes a main innovation.

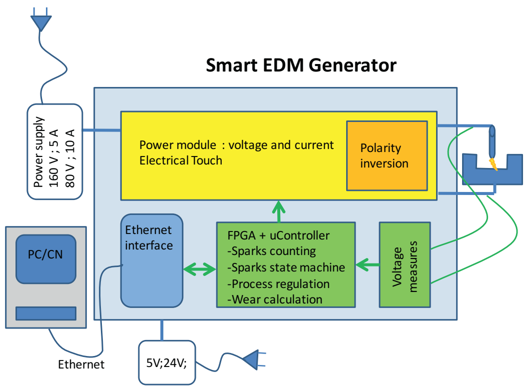

Fig. 4. Smart Generator functional diagram

The basic principle of this smart generator is to vary the spark frequency according to the machining conditions while maintaining a constant axis feed rate. This principle radically changes the way to regulate electro-erosion machining. Commonly, it is regulated in speed: instead of regulating this advance speed, one fixed it and the generator varies the frequency of the sparks according to the machining conditions. The control of the axis is simplified and the link between the CNC and the EDM process control becomes less constraining from the point of view of real time. The Smart generator can be very easily integrated in whatever numerical control, as a part of a dedicated machine or as an add-on independent module fixed in a standard Milling machine for instance.

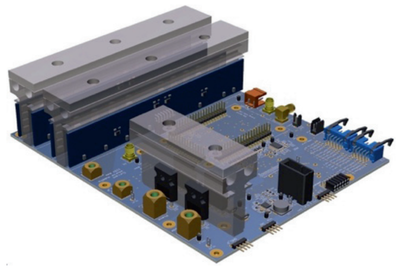

Fig. 5. The Smart Generator board

During the machining at constant axis speed, sparks are generated at a certain frequency and as soon as the electrode encounters a front of matter, two cases can occur:

-the material front is too far, in which case the generator will lower the sparking frequency. This will bring the front of material closer to the electrode, because less material will be removed per unit of time.

-on the contrary, if the material front is too close, the generator will increase the sparking frequency. This will cause the front of material to move away because there will be more material removed per unit of time.

The frequency control is based on a real-time calculation of the waiting time average (average of TD, the time until the sparks occur after applying the voltage).

All the sparks occurring during the machining are counted and classified in 4 different types. Some of them produce the material removal. By knowing the number of sparks and their nature, one can calculate the electrode wear.

The removal of material from the cutting tool and the workpiece occurs in discrete units corresponding to each discharge and, for a given combination of tool and workpiece materials and dielectric fluid, is proportional to the discharge energy. The discharge energy therefore determines the resolution of the process and thereby the minimum of machinable size and the surface roughness as well as the electrode wear per discharge. Additionally, electrode wear must be effectively compensated to achieve the required accuracy of the machined features. Since milling EDM is performed in very thin layers compared to the tool diameter, the tool profile stabilizes rapidly and wear correction can be done by a one-dimensional motion parallel to the electrode axis. Electrode wear compensation in conventional milling EDM can be based on estimation of the volumetric wear ratio and continuous compensation proportional to the in-plane displacements (anticipated wear compensation), real-time wear sensing, or on a combination of the two. Real-time sensing requires estimation of the electrode wear per discharge.

The electrode wear calculation is one of the fundamental and critical issue (see paragraph 2). Thanks to the new approach of the process regulation introduced in this project, the capacity to control very finely the shape of the current pulses and the representation of the sparks distribution (computed in the Smart generator), a new approach of the calculation of the wear compensation has been theoretically studied.

The axis control and the EDM process can be visualized on a specific HMI developed under Labview.

The statistical distribution of the sparks (fig.6) and other parameters can be acquired by the CNC-PC from a direct Ethernet link.

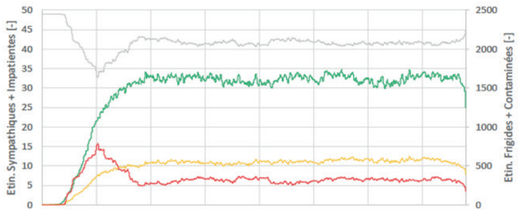

Fig. 6. Example of sparks distribution during machining

4.1. The new linear current source

The specifications for the current source have been the following:

- For currents from 0.3 [A] to 5 [A], the current ripple must be extremely low to prevent extinction and improve the results in terms of wear electrode and uniformity of the surface
- A servo system to generate precise current shape pulses with flexible forms and, somehow to sculpt the sparks of current (eg make a pedestal, ramps, stairs...)

The two main technics to generate current are:

a) Hard Switching mode: the power dissipation is lower than the linear mode but a very low current ripple is very difficult to achieve, specifically for low currents, less than 2 A. The “Ripple Current Cancellation Circuit” (RCC) has been tested during the project but it doesn’t prove to be applicable to rapid changes of varying load conditions.

b) Linear mode: in this case, there is no ripple. But the big problem is the power dissipation and the servo control of the current. For the latter, the main technique is to use a MOSFET transistor in their linear region mode but to control the generated current, it needs a current measure and a feedback control with all the problems of time reaction and stability.

An innovative and flexible solution has been found, designed and implemented in the scope of the project (fig.7).

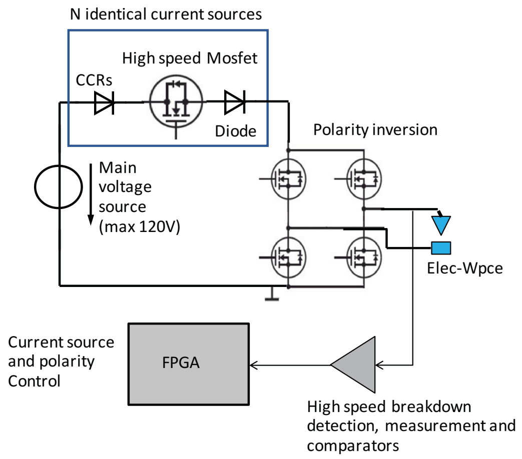

Fig. 7. Topology using CCRs

The novelty can be summarized with this citation: "small streams make big rivers".

The start point was the idea to use standard and cheaper components used for the lightning application, called "Constant current regulator" (or abbreviation CCR). In the figure 8, we can see the characteristic: if the voltage across anode and cathode is higher than the voltage threshold (around 7 volts), the component can be considered as a self-regulated current source.

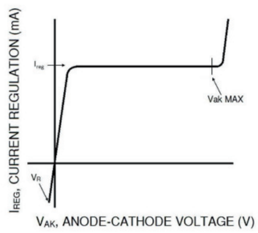

Fig. 8. Example of CCR characteristic

The great advantages are the following:

-No need to complementary electronics and regulation system because the current is internally limited to the specified value. And even if there is a tolerance of +/- 15% of the regulated output current, because the granularity is very low, the final current can be compensated and calibrated by adding or removing one or more branches (fig.9). The final current is the addition of independent CCRs current sources.

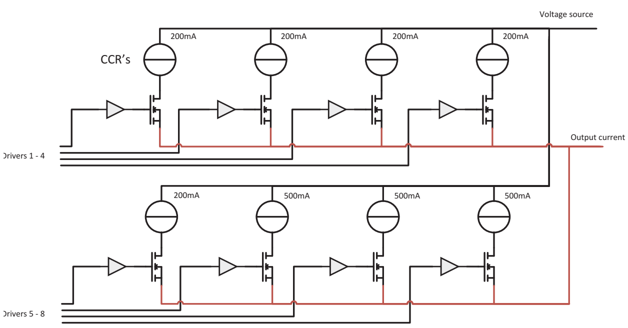

Fig. 9. Linear current source topology using CCRs

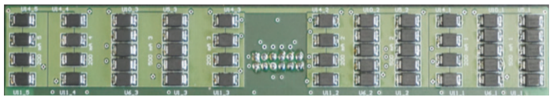

Fig. 10. CCR's electronic board

-Even this solution is the same in terms of power dissipation than traditional linear mode technics, the dissipated power is distributed over all the CCR components and thus makes it easiest cooling (fig.10).

-Compared to hard switching solution, there is no power dissipation in the system when no sparks occur

-The transition between no current delivered and the generation of the current for the spark is very fast with neglected delay and very reduced current overshoot (fig.11a)

-Because the current is low per branches (fig.9), low cost and high speed MOSFET can be used as a switch component per branch. Since then, the output pulse of current can be very short and high repetition frequency pulses can be achieved. The consequence is that higher frequency machining can be obtained

-Generation of current pulses with slopes or definition of any kind of shapes become easy: by driving the selected transistors, we can synthetize the final output current (fig.11b).

-Because there are no ripples, very low current can be maintained during the machining and thus avoiding or limiting extinctions

As we can see in the figure 11a, the final output current is generated by addition of the selected chosen CCR's channels. In our generator, we have 2 kinds of values for the CCR branch: 200 mA which is the minimum step and 500 mA.

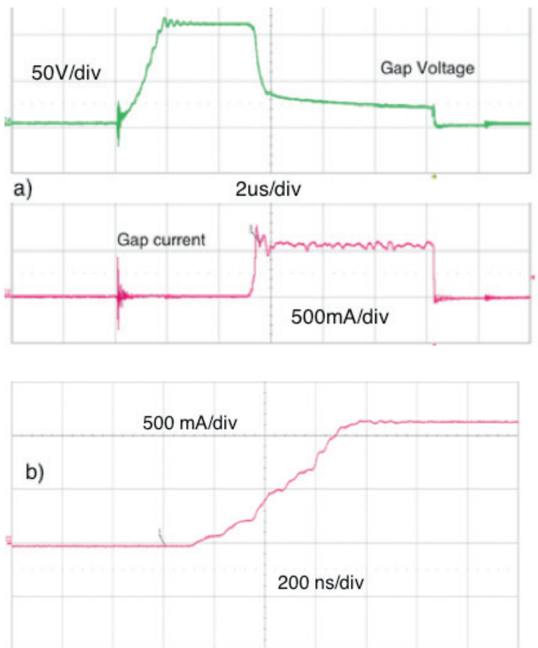

Fig. 11. a) Example of 500 mA current generation b) Generation of a rising current slope

5. Exploratory machining tests

The tests were carried out in several phases during the development of the generator. They have been able to characterize little part of the machine's capacities and have been give us an overview of machining possibilities.

The first step of testing was carried out as soon as the control of the axes was under control and the smart generator could count the sparks.

The second stage of the tests allowed to characterize the maximum z-axis speeds with a current of 2A over a frequency range from 10kHz to 40kHz. In addition, it has also been used to measure the average waiting times and will be used to set up the regulation of the spark frequency.

The third step was performed as soon as the frequency regulation was in operation.

The fourth and final stage of the tests enabled to machining a square. This last phase allowed to analyze the sparks as a function of the movements of the tool path as well as the removal of material and the wear on the electrode.

In the example below, one can see the result of a square of 2 mm with a machining depth of 200 um (fig. 12a) and the corresponding sparks distribution (1= normal discharge, 2= contaminated discharge and 3=short-circuit) for a single machining pass (fig 12b).

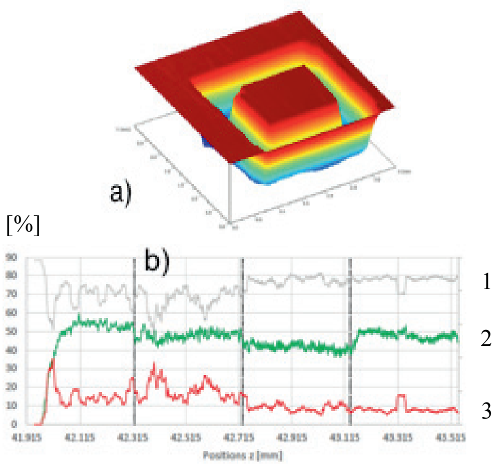

Fig. 12. a) Square profilometer reconstitution b) sparks distribution

There is a matching between the measurements made with the profilometer and the sparks distribution during the machining. It is possible to relate the number of sparks that remove the material to the evolution of the machining depth. The interpretation of the data is not easy. Indeed, in the angles there are some variations that must be explained but certainly due to an overcompensation of wear in connection during the change of direction of the electrode.

6. Conclusions

In this study, we have developed a new EDM generator, calibrated for the Micro-EDM-Milling.

This generator is an "all in one" system, where the functions of voltage measurement, spark analysis, linear current shape generation, EDM process control, electrode wear calculation and communication with the CNC have been integrated in a unique board.

It has been integrated in a EDM-Milling prototype machine and a new principle of EDM regulation has been tested with success during the first exploring tests.

At the time of the paper redaction, we have been able to perform only some machining tests. It will take time to explore all the capabilities. Further tests must be done to evaluate the machining performance and accuracy of complex shapes.

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