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Procedia CIRP 113 (2022) 143–148

www.elsevier.com/locate/procedia

ISEM XXI

Data-driven statistical analysis for discharge position prediction on Wire EDM

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Abstract

Wire-cut Electrical Discharge Machining (Wire EDM) is a machining technique widely used to cut high-precision punch tools and highly value added precision components. With increasing resource efficiency requirements and zero-defect manufacturing trend, pushing the limits of machining reliability, even at cutting speed next to the technical limits, is becoming imperative. Predicting the position of the sparks along the wire is thus needed to develop more efficient EDM processes, thanks to the suppression of discharges which are expected to happen in undesired positions. This will lead to a reduction of the number of machine stops caused by wire breaks. Motivated by this need, the paper presents a data-driven statistical analysis to get insight into the correlation between the discharge positions of two consecutive sparks, along with the relation between spark positions and discharge frequency. The underlying basis for this analysis was the possibility to obtain reliable real-time information about the position of sparks along the wire, a feature made available by a Discharge Location Tracker [4]. Results on spark position correlation are presented for cutting experiments on a steel workpiece of 50 mm in plane parallel with different machining parameters using brass wire of diameter 0.25 mm.

Keywords: Wire EDM; Predictive Model; Data-driven statistical analysis

1. Introduction

One of the main bottlenecks in the wire electrical discharge machining process, in terms of productivity, is the wire break. In literature, the main causes of a wire break are widely investigated and have been identified as the consequences of several factors, occurring also simultaneously, as mechanical stress and excessive local thermal load on wire due to discharge concentrations combined with weak flushing [1–3]. For a reliable high-speed rough cut, with given wire tension and flushing conditions, the prevention of wire breaks is today possible by controlling in real time the pulse frequency, reducing it upon the occurrence of signal pattern attributable in general terms to erosion degradation. The discharge distribution along the wire is, on a macro scale, influenced by the debris distribution, the wire oscillation, the bulk of material that needs

10.1016/j.procir.2022.09.122

to be removed on an irregular workpiece, the flushing conditions, etc. [4]. It is also known that the thermal overload of the wire is a local phenomenon, caused by a local discharge concentration in a short time lap. Said wire break prevention methods are indirectly affecting the discharge concentration on a point along the wire, but not in a deterministic way.

Recent developments [4] went a step beyond, determining the number of discharges per vertical section of the wire and reducing the pulse frequency (the energy) when a given pulse concentration has been exceeded. This method is more accurate than the previous one, but still not giving guarantee that the suppressed pulse (indirectly by reducing the frequency) had ignited in the critical position of the wire.

The purpose of this work is to get insight into the correlation between spark positions in order to predict, based on historical data, the pulse position probability of a spark to come. To this end a data-driven analysis regarding the statistical distribution of the spark's positions and its dependence on process parameters, such as discharge frequency and time occurring between two consecutive sparks, has been done. This is the first study which addresses the issue in this way and has been made possible thanks to the so called Discharge Location Tracker (DLT) [4], allowing to obtain reliable real-time information about the position of sparks along the wire.

2. State of the art (discharge position prediction)

Over the years, several studies have focused on the localization of the discharge position, developing different methods to influence and localize the discharge positions and investigating the factors determining the discharge location.

Kunieda et al. [5] described the factors affecting the discharge location on a Die Sinking machine using oil as dielectric and found out that the preceding discharge does not affect the location of the subsequent discharge, as long as the plasma formed by the preceding discharge is fully deionized during the discharge interval. The authors claim that the time interval between pulses, after which there is no longer any correlation between their positions, is 6 us. Moreover, they noticed that in a series of pulse discharges, since numerous chains of debris particles grow over the working surface, the influence of the debris particle concentration becomes more dominant than the gap width distribution, which can lead to process instability [5].

Numerous studies have been conducted on controlling the discharge location. Han et al. [6] were able to influence the distribution of discharges by locally superimposing high electric fields in a dry-Wire EDM process. The natural stochastic distribution of the discharge locations has been modified by changing the electric field distribution along the wire by superimposing the open voltage (set by technology parameters) with additional voltage pulses or a series voltage pulses. The point of application of these additional pulses was at the current pick-up of the machine, the same position used for the technology pulses. The discharge distribution (location probability) was moving towards the wire contact where the high voltage pulses were applied. Okada et al. [7] proposed an alternative evaluation method of discharge location by recording the sparks generated in the working gap by using a high speed video camera. The positions of sparks were calculated by image analysis and the effects on the distribution of spark location was investigated for different servo voltages, pulse interval time and wire running speed. It has been demonstrated by them, that sparks distribution becomes uniform when the servo voltage is high, the interval time between pulses is long and the scrolling speed of the wire is low.

3. Experimental setup

All series of experiments were performed on a Wire EDM Machine on a plan parallel steel workpiece of 50 mm height and using a brass wire of diameter 0.25 mm. The dielectric used was deionized water. To ensure optimal flushing conditions, both the upper and lower heads of the machines were in contact with the workpiece surface (see Fig. 1). The data of discharge positions and the time difference between subsequent sparks have been collected using the Discharge Location Tracker (DLT).

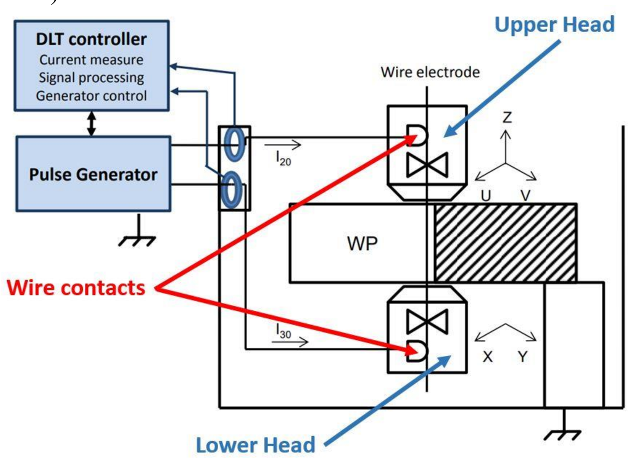

Fig. 1: Schematic representation of the DLT integration in a Wire EDM machine.

The measurement series were executed by varying the machining discharge frequency and the current amplitude in rough cut mode (cut from solid material). Flushing pressure (12 bar) and wire unwinding speed (195 mm/s) were kept constant All machine functions used for erosion optimization have been disabled, so that they could not affect the interpretation of the results.

4. Dataset acquisition

The DLT allows extracting the information of the position of the discharge along the wire and the time difference between two consecutive discharges. The discharge position is processed in real time by an FPGA (field programmable gate arrays), measuring the machining current pulses flowing to the upper wire contact and lower wire contact inside the machine heads. The discharge position is stored by dividing the workpiece height into 256 sections (positions from 0 to 255) allowing to have a resolution of 0.2 mm on the discharge position, considering the height of the workpiece of 50 mm. The dataset analyzed consists of 44 measurement series, covering a discharge frequency range from 1.5 kHz to 111.6 kHz and an impulse current amplitude of 380 A and 550 A. The accuracy of the measurement system is estimated to be +/- 0.3 mm.

For each erosion run, the cutting length was of about 2 mm allowing the data acquisition for about 3 million sparks.

5. Results

Based on the available datasets, an empirical statistical analysis has been performed to describe the discharge distribution as a function of the last observed spark position and the time occurring between two consecutive sparks. It should be noted that the results presented in this section are valid for both values of current used in the experiments. The histograms below show the distance Δs [mm] distribution between two consecutive sparks at two given discharge frequencies and for two different current amplitudes (380 A and 550 A). From these figures we can conclude that the distance between two consecutives sparks is independent from the current amplitudes used.

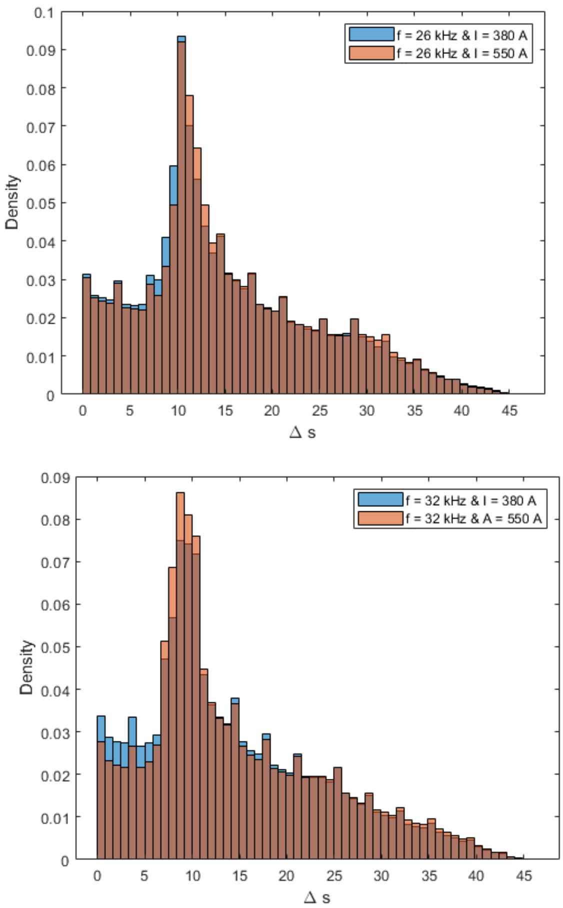

Fig. 2: Histograms of the distance of two discharges Δs for two discharge frequencies (26 kHz and 32 kHz) for two pulse amplitudes (380 A and 550 A).

Fig. 3 shows the histograms of the position of the next spark for different current spark position. The discharge frequency is fixed and equal to the average discharge frequency *f* = 56 kHz. It can be observed that two peaks in the histograms are symmetrically centered at about +/- 6 mm from the current spark position. This means that the position of the next spark is more probable at a certain distance from the current one. The same information can be also retrieved in Fig. 5, where a scatter plot shows the position of current versus next spark position. In the figure it can clearly be observed that two clouds of points are symmetrically positioned around the bisector of the plane. This shows that the sequence of sparks along the wire is not completely stochastic. Furthermore these clouds of points have a linear shape, indicating that the distance between two consecutive sparks is more likely to be constant (namely, independent of spark position along the wire) for a given frequency of discharges. For a complete analysis, the histogram of the overall of the sparks' positions is also constructed and reported in Fig. 5. In this figure we can note the tendency to an accumulation of discharges in the middle of the workpiece and a marked decrease in the upper part. This phenomenon is reflected in the size of the gap: larger in the middle of the workpiece and reduced in the upper part (from 40 to 50 mm).

Fig. 6 shows the histograms of the distance Δs between two consecutive sparks for five different values of the discharge frequency *f*. It can be observed that the distance Δs is likely to decrease when *f* increases. Note that, although the last plot in Fig. 6, corresponding to a discharge frequency *f* = 77 kHz does not show a clear peak, the mass of histogram is moved left with respect to the histograms above.

In Fig. 7 the modes of the histograms of Δs are reported for all discharge frequencies considered in this study. An inverse relationship between Δs and *f* is observed and modeled by the function $\Delta s = Af^B + C$, with parameters A = 16510, B = -0.7102 and C = -1.654 computed by minimizing the fitting error. The quality of the fit is summarized in the performance indexes reported in Tab. 1.

Tab. 1: Quality of fit

	Value
Root mean square deviation (RMSE)	0.09594
Residual sum of squares	0.1105
R-squared	0.9994

Fig. 8 shows the boxplots of the absolute distance Δs between two consecutive sparks for different values of the time Δt elapsed between the sparks. A clear trend is observed in the figure, which shows that Δs is likely to increase when Δt increases. This is in line to what has been discussed regarding the relationship between the distance between two consecutive spark positions and the average discharge frequency *f*.

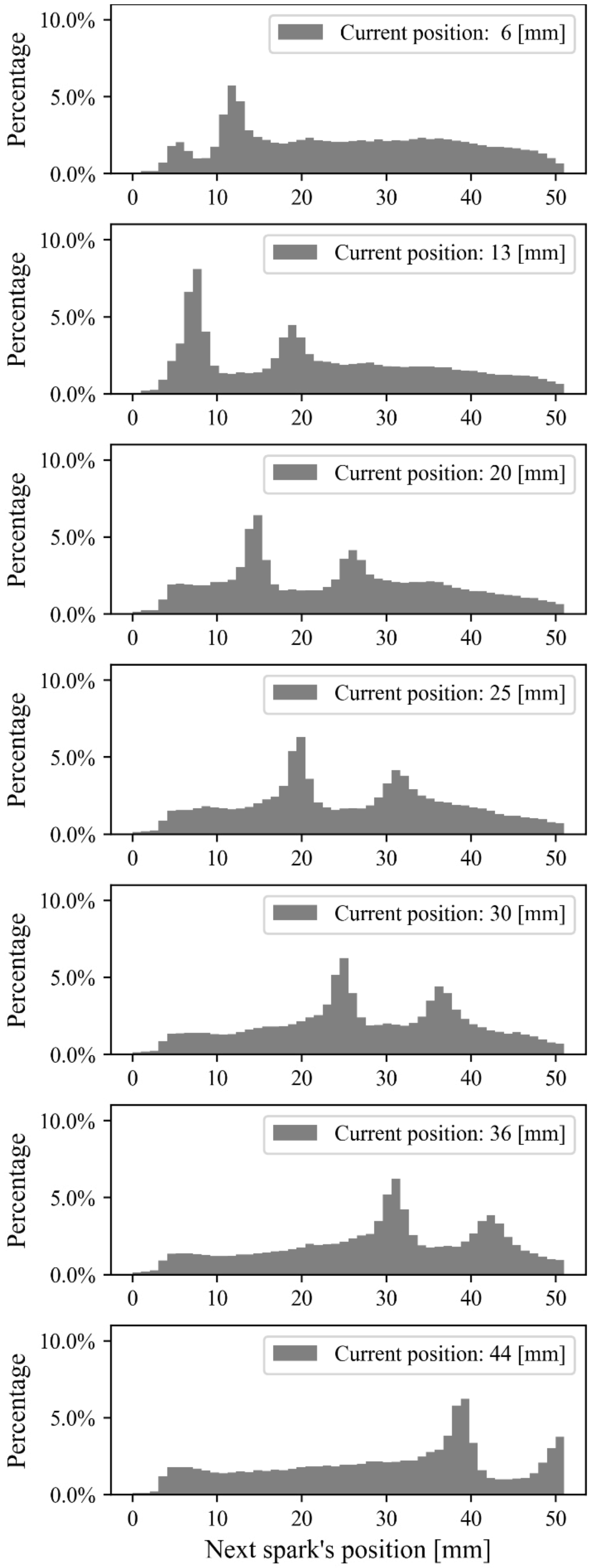

Fig. 3: Normalized histograms of next spark's positions for five different values (namely, 6, 13, 20, 25, 30, 36 and 44 mm) of current spark position. Discharge frequency $f = 56$ kHz (resolution 1 mm).

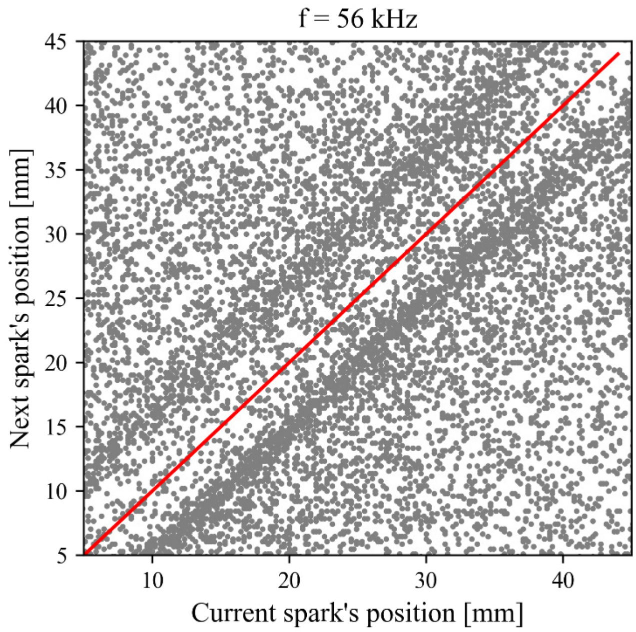

Fig. 4 Scatter plot of current spark position (x-axis) versus next spark position (y-axis) for discharge frequency f=56 kHz; bisector of the plane (red line).

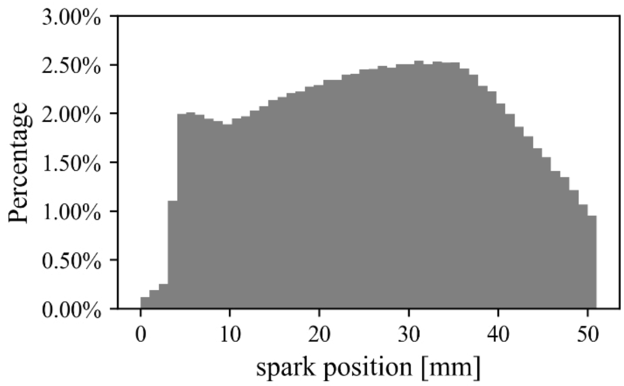

Fig. 5 Normalized histogram of overall sparks' position [mm] (resolution 1 mm).

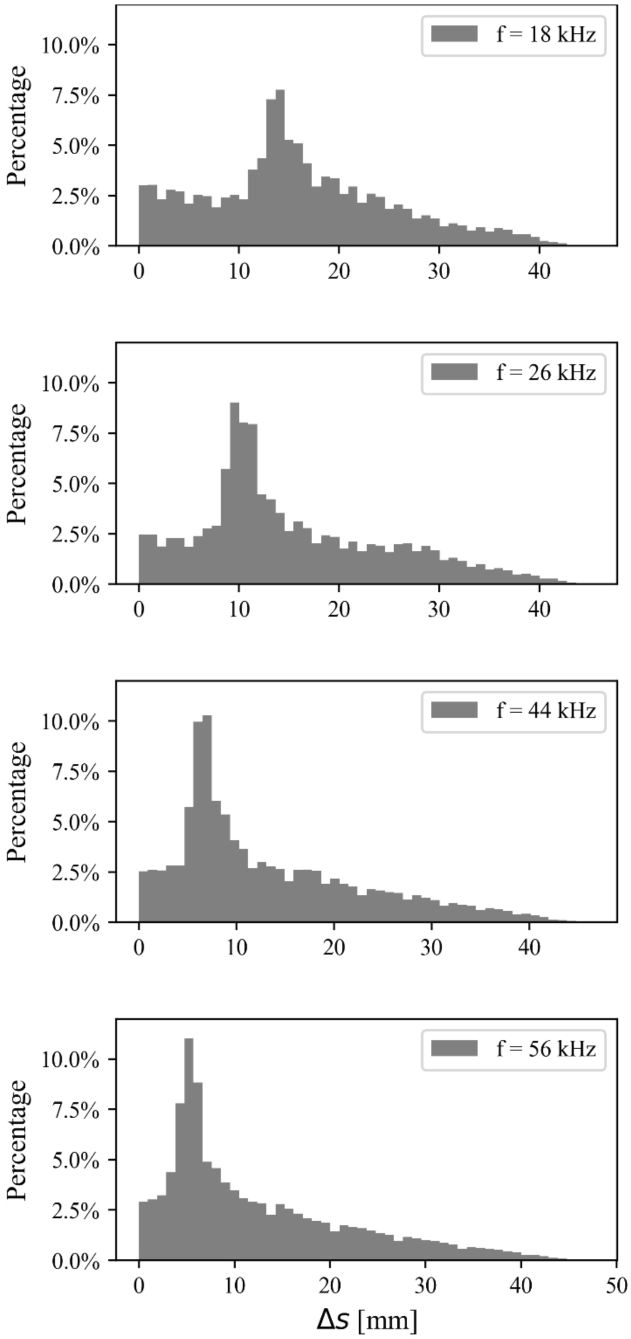

Fig. 6: Normalized histograms of the distance Δs [mm] of the position between two consecutive sparks for different discharge frequencies f. (resolution 1 mm)

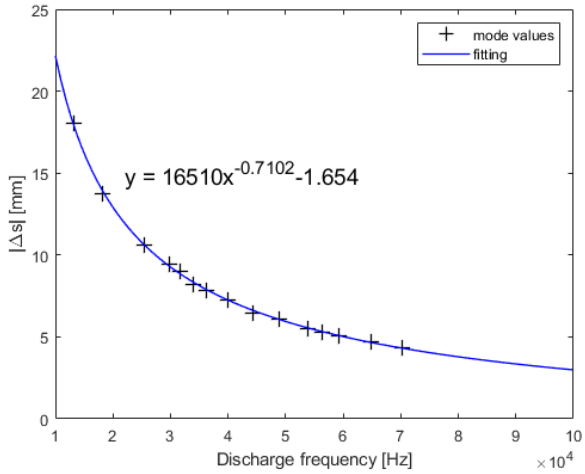

Fig. 7: Mode values of the empirical probability distribution of the absolute distance Δs between two consecutive sparks (black markers) versus discharge frequency f; computed exponential fitting function (blue line).

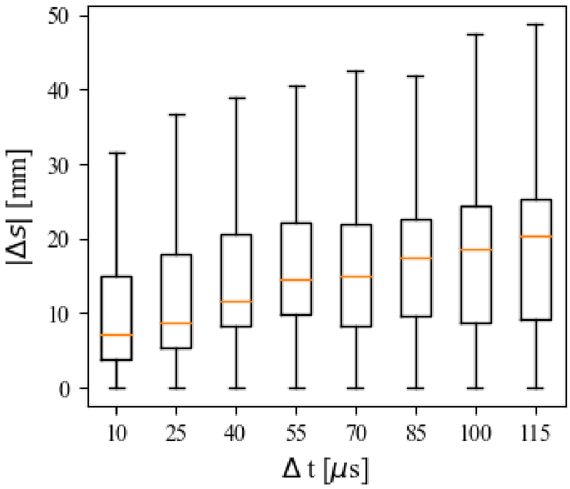

Fig. 8: Boxplots of the distance Δs [mm] of the position between two consecutive sparks versus time Δt [μs] between the sparks. Orange line represents the median of the probability distribution. Outliers are not plotted.

6. Outlook and Conclusions

The paper proposed an approach based on data-driven statistical analysis to determine the correlation between two consecutive EDM discharges. Experimental data were determined by machining on Wire EDM machine a 50 mm high steel workpiece with a 0.25 mm diameter brass wire. The dielectric used was deionized water. It has been shown that, contrary to what other authors mention [5] for Die Sinking discharges in oil, the sequence of sparks along the wire is not completely stochastic for a time between pulses form 7 to 665 us, but has peaks of distance probability between sparks in the order of several millimeters, on both directions with respect to the position on the wire of the current spark. An inverse relationship between this distance and the frequency of erosion pulses was also observed. This last phenomenon is explainable and in line with what also in [5] is stated, namely that the stochastic nature of the position of the pulses is evident only when the ionization of the gap, caused by a pulse, has had time

to extinguish completely, before the arrival of a subsequent pulse. A residual ionization from a current pulse promotes the ignition of the next spark in its proximity. This may be the reason explaining the reduction of the distance between two subsequent sparks, when increasing the pulse frequency.
Preliminary analyses have shown that the current position of the spark influences the next pulse, while no remarkable influence of the whole history of the previous pulses is observed in the statistical distribution of the next spark position. Nevertheless, current studies are focused on the development of end-to-end machine learning models, such as deep neural networks, to discover hidden patterns in the whole past history of the pulses, that might be useful to make an accurate inference of the positions of the future sparks along the wire.

Acknowledgements

This work has been supported by Innosuisse, the Swiss Innovation Agency (Project 44050 IP-ENG).

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