ELECTROMACHINING

Proceedings of the 7th International Symposium

Edited by Prof. J.R. Crookall

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Birmingham, UK

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Automatic Control and Supervision of the EDM-Process

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Abstract

A supervision and control system has been set up considering the disturbances on the electro-discharge process and the specific properties of individual machine elements. For identification of the current state and the actual time behaviour of process statistical procedures are used as well as computations of sample spectrum and correlation function estimates. Based on technological relationships suitable searching and adjusting strategies have been selected and adapted to the special conditions given by the spark-erosion process.

Finally experimental results are discussed which were obtained by using the control system with a series-produced electro-discharge sinking machine.

1. INTRODUCTION

To make optimum use of spark-erosion machining, it is necessary to have a suitable control system to ensure that the equipment is correctly matched to each particular task. Since the discharge process is subject to faults and disturbances, the control system should also include continuous adjustment and monitoring for possible process faults. To fulfil this need, such a control and monitoring system has been developed in the Laboratorium für Werkzeugmaschinen und Betriebslehre der RWTH Aachen. This system is built up of several individual control circuits /1/. This paper describes the two circuits "feed optimization" and "pulse interval control".

2. IDENTIFICATION OF THE PROCESS AND QUALITY CRITERION

Since it has so far not proved possible to measure the material removal and electrode wear directly, relationships must be found between the results on the piece of work and quantities whichare measurable on-line. Therefore the ignition delay time t_d is used as the parameter characterising the process /2/.

Fig. 1 shows the result of measuring the ignition delay time for successive spark pulses (set "a" of curves). This time is subject to large, apparently random variations. Statistical analysis confirms that, over limited periods, the ignition delay time is in fact a random function. However, as can be seen from fig. 1, this signal can usefully be analysed into several different frequency bands. The set "c" of curves shows the portion of the mean of the ignition delay time which can be compensated out by control of the feed system. The remaining higher-frequency components (set "d" of curves) can only be compensated out by a more rapidly responding control system, such as a pulse interval control.

Since the signal t_d by itself gives no information about the quality of the result to be expected on the workpiece, this signal is turned into the form of a frequency distribution. Initial tests confirmed a correlation between the relative frequency of discharges with a very short ignition delay time t_d and the rate of electrode wear V_E /3/. It should not, however, be assumed that a discharge with a certain ignition delay time corresponds to a particular quantity of material removed or electrode wear. Nevertheless there is a clear correlation between the results achieved on the workpiece and the shape of the frequency distribution curve. A calculation programme was therefore set up which is capable of predicting, on-line, the anticipated material removal rate and electrode wear rate to an accuracy of approximately 4 % from a classification of the frequency distribution /4/. This was initially achieved by carrying out material removal tests and measuring classified frequency distributions at regular intervals. To reduce the amount of computing needed, the ignition delay times were divided into 5 classes. Coefficients were allotted to the frequency sums in each of these five classes, which were intended to measure the contribution of each to material removal and electrode wear. There is however no case in which all gave a positive correlation, so that the calculation model is not valid for the actual physical erosion mechanism.

To optimise the model, a further data reduction must be carried out. In this, the frequency distribution is reduced to three classes, as shown in fig. 2. The division is made such that class H_I contains the discharges with very short ignition delay times: the frequency of these correlates with the electrode wear rate; Class H_{II} contains the discharges with normal ignition delay times: these carry out most of the work of material removal; and Class III contains the discharges with longer delay times and open-circuit pulses.

Fig. 3 shows an example of the relationship between frequency sums and and the workpiece result. The material erosion rate V_W has a maximum at the same point as the maximum of the frequency sum H_{II}. Since the reference voltage U_{soll} (over which these parameters are shown) has a major influence on the process, the parameter H_{II} can be used as a quality criterion for optimising the feed system. If it is desired to maximise the material removal ratio, then the ratio H_{II}/H_I can be used as the quality criterion.

3. EFFECT OF THE ADJUSTABLE PARAMETERS ON THE PROCESS

The adjustable parameters used are the pulse interval t_o, the reference voltage U_{soll}, and the amplification of the voltage regulator, U_V. To assess the dynamic response behaviour of the system, the reference voltage was changed by a discrete step and the step response of the ignition delay time to this was measured, using the "average response technique". The result of such a measurement for various pulse lengths t_i is shown in fig. 4. It is found that the response time of the control circuit descreases linearly with the length of the pulse. Therefore the optimisation should be carried out within a time grid $T = N \cdot t_o$, which for constant N is likewise proportional to the pulse length.

The search plane for the static case, determined by the function $H_{II} = f(U_{soll}, U_V)$ shows a shallow maximum (see fig. 5). The reference voltage has a stronger effect on the quality criterion H_{II} than has the amplification U_V. The shallow nature of the maximum means that a search algorithm with a high certainty must be employed. The algorithm used must be a compromise between statistical certainty (high N) and the desired short response time for the process (low N).

Investigation of the static adjustment of the pulse interval time show shows that the optimum pulse interval for material removal is the minimum time at which discrete sparks, rather than a continuous discharge, are still given. Trials with a search algorithm enabled this minimum period to be quickly found, and it remained unchanged during the entire trial. This result is however different when tests are carried out using short-term variations of the pulse interval time. The "average response technique" was used to determine the system's response to a single change in the pulse interval. The result is shown in fig. 6. In contrast to the static case, an increase of the pulse interval leads here to a reduction in the expectation value of the ignition delay time, whereas when the pulse interval is decreased the anticipated ignition delay time increases. This result was also checked using a different identification method. The pulse interval was changed according to a pseudo-random binary signal, and the weighting function was calculated using correlation analysis. This procedure gave the same resultant relationship as the given by the "average response technique" method /1/.

4. CONTROL STRATEGY AND INDIVIDUAL CONTROL CIRCUITS

On account of the stochastic nature of the spark erosion process, a process with a high statistical certainty must be used for optimising the feed system.

A method using a fixed step width is particularly suitable. The Simplicial method is one such method /6/. This is a so-called "evolutionary" method. The search plane (cf. fig. 5) is divided into a network of equilateral triangles. The apexes of the triangles are the possible settings for the variables U_{soll} and U_V. The method is based on allowing the one point of a triangle which has the lowest quality criterion to be mirrored on the side joining the other two points. Although this method has a high degree of statistical certainty, the system is switched over to a modified method once a point in the neighbourhood of the optimum has been reached. This modified method alters the variables in smaller steps, and alters the setting voltage several times before the amplification reacts. This ensures reliable following of the optimum.

The upper half of fig. 7 shows such a search procedure. The lower half of the figure shows the variation of the quality criterion over the same time. Before the switchover to the modified fine search it can be seen taht the quality criterion rises repidly in the region of the optimum point. If the increment in the quality criterion is too small, the search path moves in a circle, which fact is detected and is used to initiate the modified search method, which works more slowly and can follow smaller increments. This procedure is very reliable and has proved to be the best. After approximately 15 sec the direct neighbourhood of the optimum has been reached. For this method to function properly, it is necessary for it to start from a high reference voltage value and a low amplification. Disturbances, such as can be simulated by altering the maximum current $\hat{i}_e$, are regulated out within approximately 20 sec.

The pulse interval control is used to reduce the proportion of discharges with long ignition delay times, in line with the results in section 3 above. Material removal tests have shown that the smallest possible pulse interval time is the optimum. If an uninterrupted sequence of open-circuit pulses occur, the pulse interval is then temporarily increased for a few pulses. As a reaction, an increased (statistical mean) number of discharges with shorter ignition delay times occurs. This should improve the material removal rate. The algorithm is so designed that the lengthened pulse interval is only effective for a time less than that needed to affect the feed system.

5. TEST RESULTS FROM THE SYSTEM HERE DESCRIBED

To illustrate the test results, the material removal rate V_W, the electrode wear rate V_E and the relative electrode wear Θ are shown, and are compared with the results from manual operation (fig. 8). To distinguish between the various different manual settings, the mean ignition delay time (determined as the arithmetic mean over the period of the test) is stated. If the results produced by optimising the quality criterion H_{II} by continuous matching of the feed parameter (left-hand group of bars, fig. 8) are compared with those from manual setting, then the following relationship becomes clear: the material removal rate is slightly above the maximum rate achievable by manual setting. The major difference, however, appears in the electrode wear rate. The matching of setting voltage and amplification by the control succeeds in reducing the proportions both of discharges which spark too early and of open-circuit pulses which do not remove any material. This is shown particularly clearly in the relative wear ratio achieved, which is almost 50 % lower than that achieved by manual setting.

As regards potential for spark erosion machining with low wear, the automatic control system is also superior to manual setting. If the manual working point for minimum electrode wear V_E ($\bar{t}_d = 32.5\ \mu s$) is compared with the corresponding figures for automatic control operation, then the controlled system can remove more than 20 % more material for approximately the same electrode wear.

On account of the boundary conditions which apply for achieving rapid matching of the pulse interval time, no further reduction in electrode wear can be expected from using also this individual control circuit (fig. 8, right-hand group of bars). Rather the proportion of late-igniting discharges and of open-circuit pulses, which contribute less to material removal, can be reduced, as is clearly shown by the material removal rates achieved. For comparable relative electrode wear this gives shorter machining times. In a further example (fig. 9), machining was carried out with a substantially lower energy per discharge, at only 30 % of that used in the previous example. It is true that for this case an appropriate manual setting (t_d = 25 µs) can produce a lower electrode wear rate than under automatic control, if a lower material removal rate is accepted. However, considering relative electrode wear, which is the more important parameter in practice, then, at this setting, more than 40 % must be sacrificed in material removal rate to achieve the same relative electrode wear (Θ = 17 %) as under automatic control.

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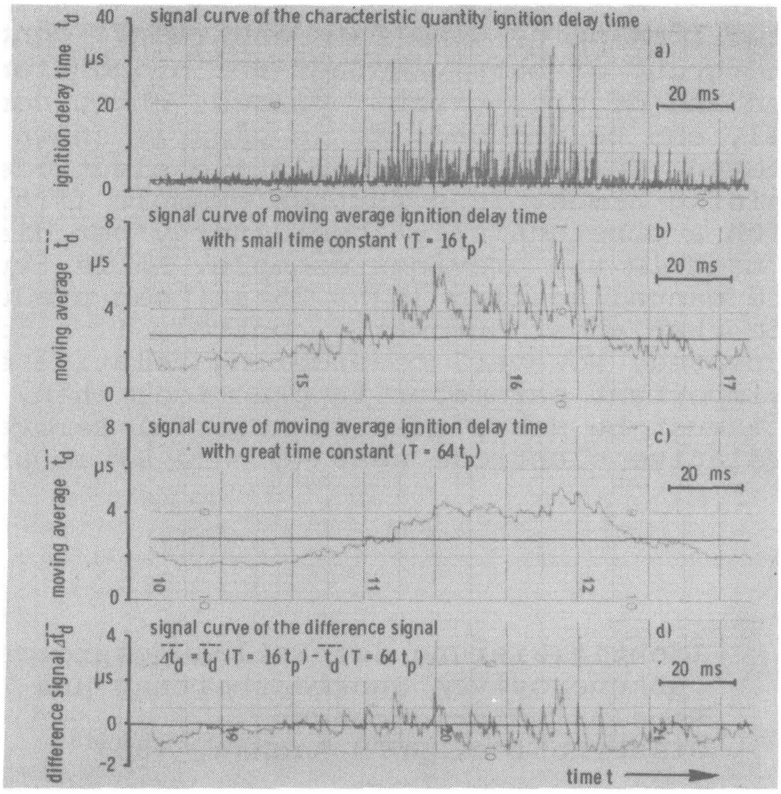

Fig. 1: Signal curves of the characteristic quantity ignitition delay time

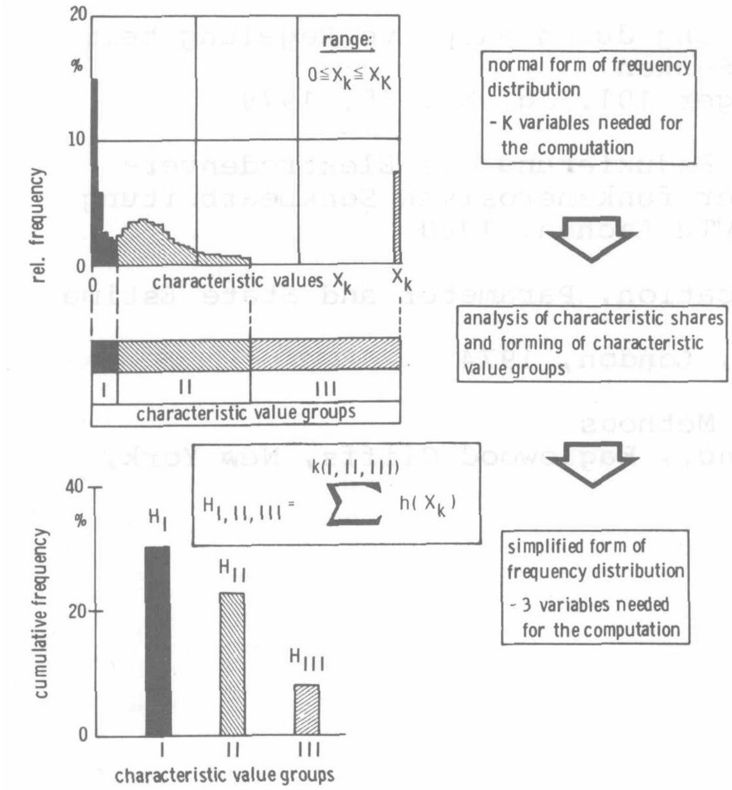

Fig. 2: Formation of the simplified description of the frequency distribution

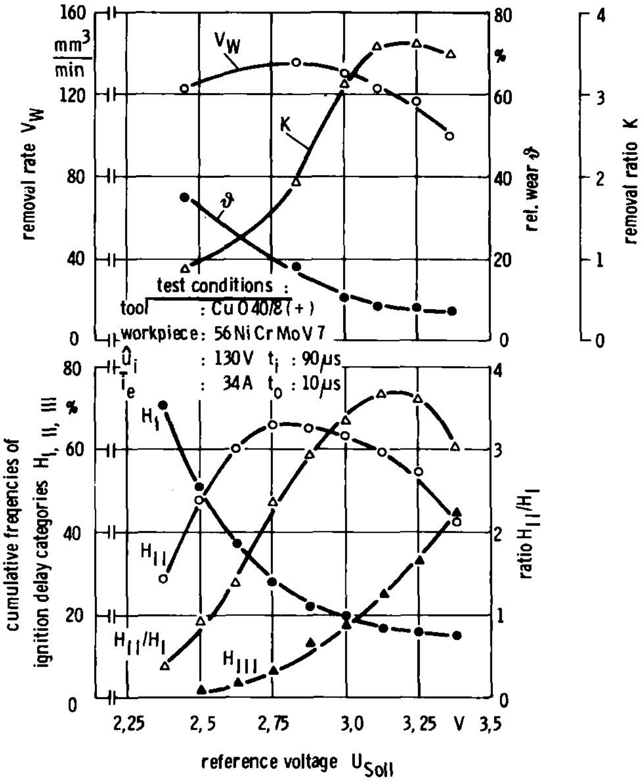

Fig. 3: Comparison between working results and shares of the ignition delay frequency distribution

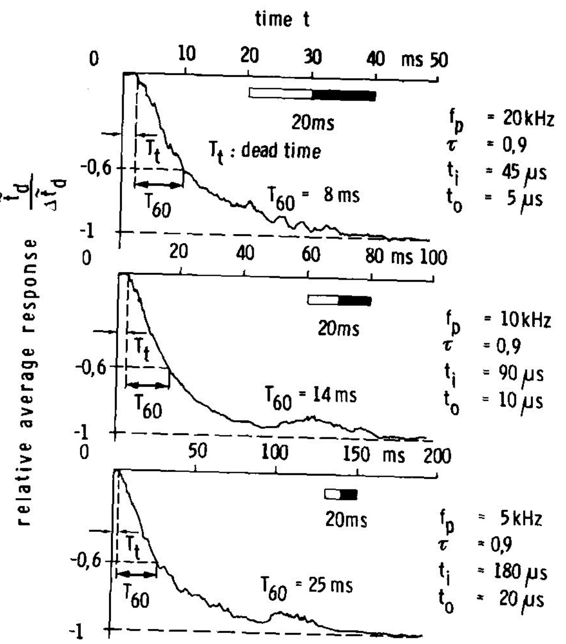

Fig. 4: Step responses of the expectation value of ignition delay time at various pulse frequencies

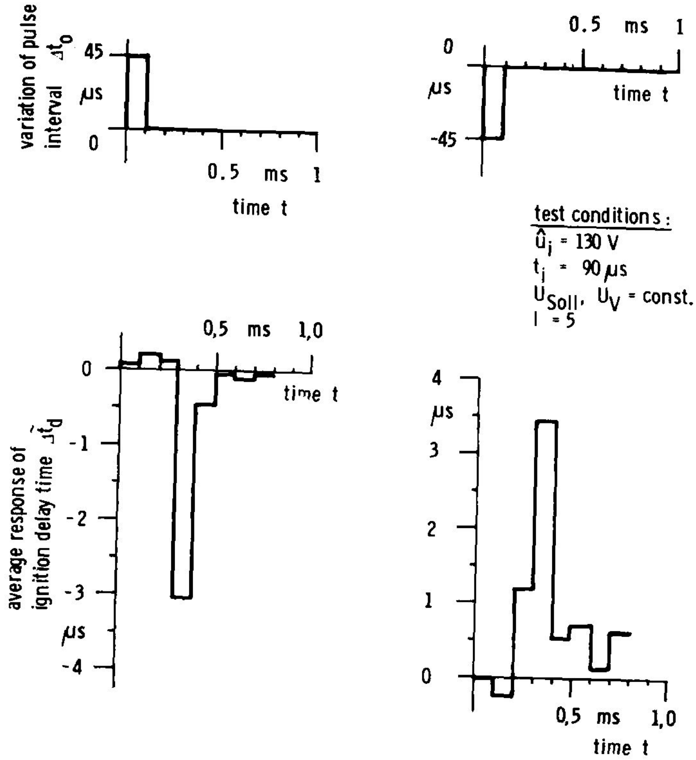

Fig. 6: Impulse responses of the expectation value of ignition delay time forced by pulse interval impulses

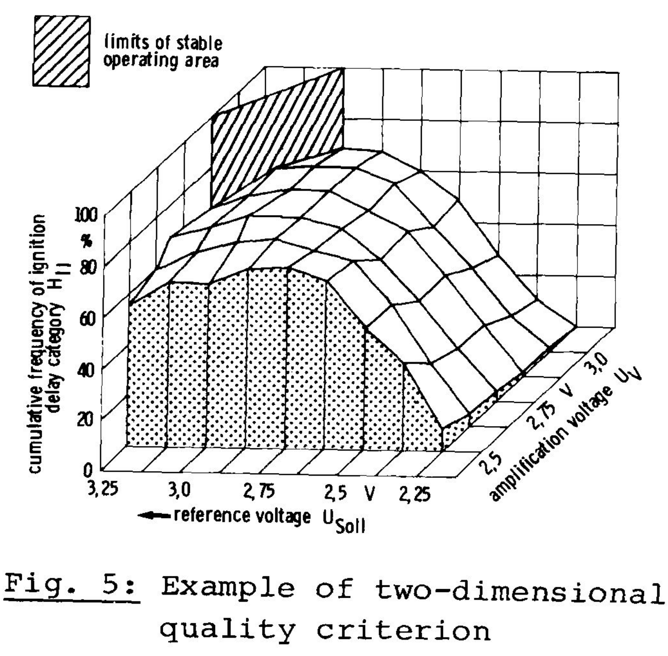

Fig. 5: Example of two-dimensional quality criterion

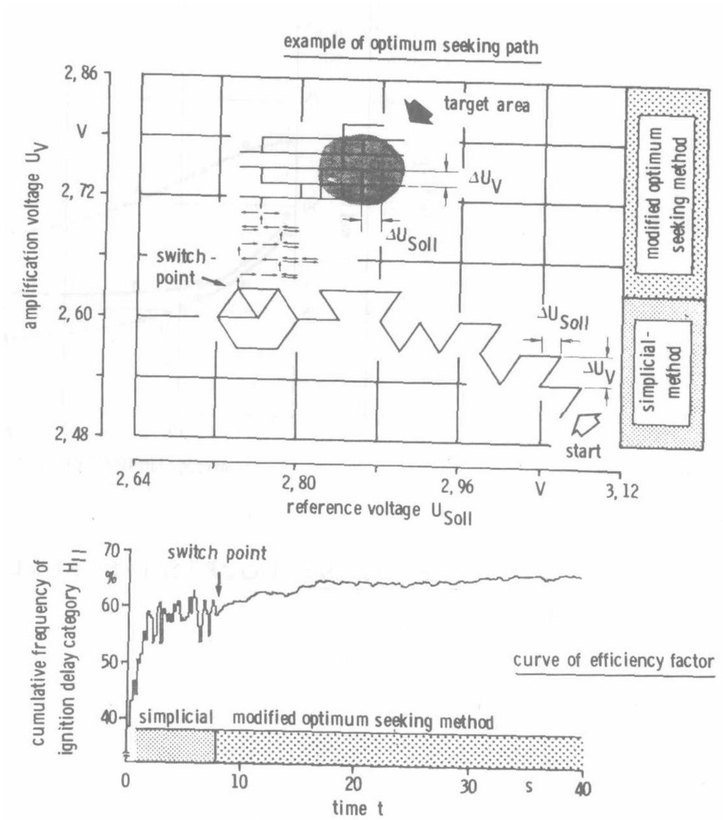

Fig. 7: Optimum seeking path and curve of quality criterion

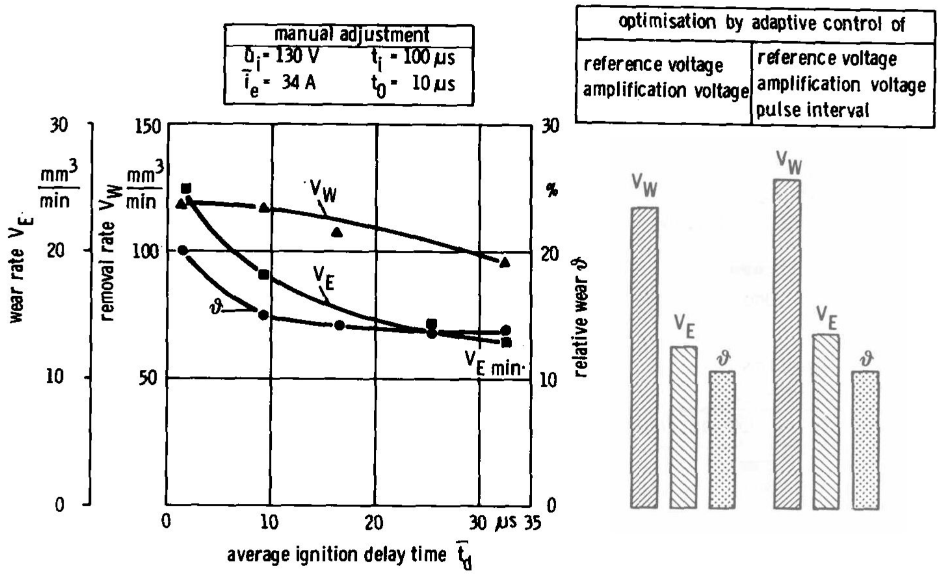

Fig. 8: Comparision of working results between manual adjustment and adaptive control

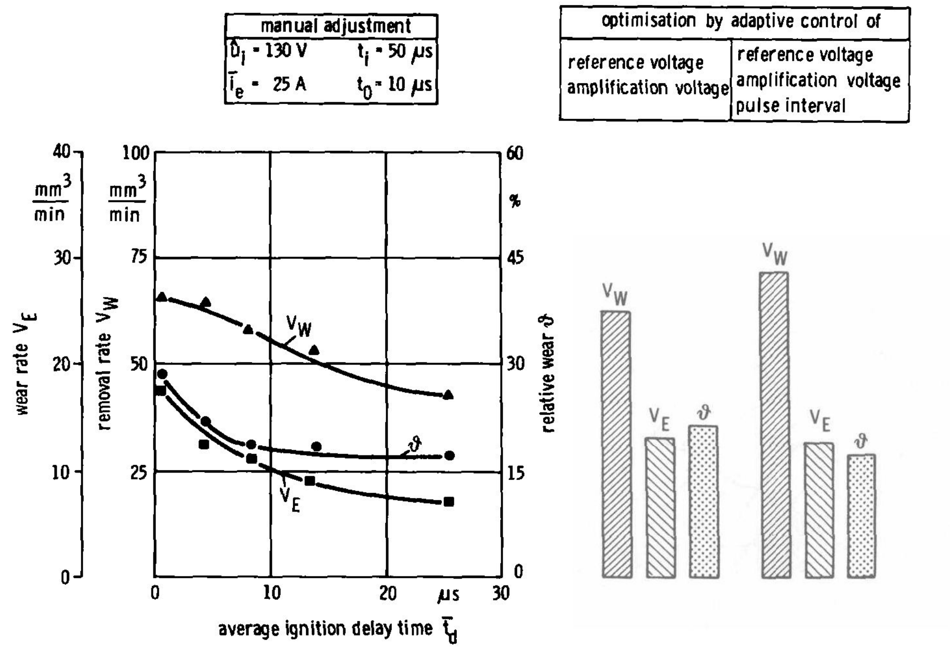

Fig. 9: Working results at lower pulse energy

HIGH SPEED PULSE DISCRIMINATION FOR REAL-TIME EDM ANALYSIS

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Reliable real time evaluation of the EDM process is essential when control techniques are applied to achieve stable and efficient machining outputs.
A common way of EDM-process evaluation consists in tracking certain gap phenominae, e.g. mean or instantaneous gap voltage, pulse current, noise generated by the process itself, etc. It has been shown that either the instantaneous gap voltage, gap current, or a combination of both can be taken as a reliable process informer. An EDM-Pulse Discriminator (EDM-PD) based upon these principles has been developed and designed capable for process analysis on deep sinking and wire-cutting machines.
The major aim of this discriminator is to end up with a detailed EDM analysis being used for on-line Adaptive Control.
This paper deals with some observations related to various pulse types occuring during EDM-processes. General functioning principles of the EDM-Pulse discriminator are highlighted and some preliminar results obtained with this new analysis device are presented.

* IWONL Grant Holder

INTRODUCTION

Optimization of the EDM-process can only be achieved by fast modification of adequate control parameters. To reach a maximal removal rate for example, the occurance of "effective" discharges should be favourized; a very fast detection system must be available for that purpose. "In-process" control of EDM requires an evaluation of machining objectives: maximal material removal rate, minimal electrode wear, acceptable surface roughness levels or a combination of suchlike requirements. The on-line measurement of these machining results is quite difficult, if not impossible. Hence, on-line monitoring of EDM-operations has to be based on an evaluation of other parameters of the process, so called "sensing parameters", correlated with some of the machining objectives.

As sensing parameter, the gap voltage signal turns out to be quite sensitive for process alterations.
The information in discharge signals (e.g. ignition delay time t_d, rise time t_r of the voltage level, fall time t_f of the voltage just after breakdown, instantaneous voltage level U_e, and so on) is traditionally used in many EDM-Process controls. For instance :

- The mean or instantaneous discharge voltage U_e used for servo feed control, (1).
- Ignition delay time t_d applied in generator systems as gap sensor (2), (3).
- Voltage noise levels might indicate some process perturbations. (4) and (5).

In order to classify EDM pulses, the CIRP STC-E derived some specifications for EDM-Pulse Analysers. Four distinct pulse types have been identified, v.i.z. normal sparks, arcs, open circuits, and short circuits (6) have been identified. Further research proved that additional pulse types may be recognized and seem to be usefull in EDM-control applications.

Therefore, a detailed investigation was carried out to identify various pulse types occuring in die-sinking EDM-operations as well as typical pulse types associated with wire-cutting operations.

As a result of those preliminar pulse identification investigations, a Pulse Discrimination system has been built at the K.U.Leuven enabling to classify systematically 15 different types of pulses. The EDM-PD may be connected with both types of spark erosion machines.
Initial results obtained with this new evaluation device are reported at the end of this paper.

PRIOR INVESTIGATION OF PULSE CHARACTERISTICS

To establish pulse type-criteria, a survey of various pulse types occuring in practice was made.

Frequency Contents of Wire-EDM-Discharges

This investigation has been concentrated only upon static pulse generators (die-sinking as well as wire-cutting applications).

A first problem to be solved was to determine the frequency contents of pulse signals. For this purpose a very high frequency, programmable waveform analyser (Tektronix 7912 A/D 500 Mhz waveform recorder) was used. (Fig.1). This 1-channel analogue transient recorder was used to track potential high frequency spikes on either the voltage or the current signal by writing an ultra fast single shot signal on a silicon diode target matrix. Afterwards the matrix could be scanned at a much slower rate either vertically or horizontally (i.e. digital mode or T.V.mode).

The digitised data were than transfered to a monitor or a controller, and sent to a digital plotter. Signals up to 100 MHz (bandwidth limited by voltage or current probes) could be captured by single shot. The experiments showed that no particular high frequency disturbances occured and that a 12.5 MHz digitising rate of the 468 Tektronix digital oscilloscope (cfr. next section) was sufficient to identify and discriminate different pulse types occuring even on short pulses of the wire-cutting machine. Some typical recordings on a Charmilles-Andrew wire-cutting machine with this 500-MHz waveform analyser are represented in Fig.2. All the typical characteristics that are used in the EDM-PD to classify the different pulse types can be found in the voltage and current measurements obtained with a 12.5 MHz digital oscilloscope as described in the following section.

Observations of Pulse Types

A voltage attenuator probe was connected near the gap (Fig.3). To measure pulse current simultaneously, a current probe was mounted on the generator connection cables. Both signals were fed into a Tektronix 468 digital oscilloscope and sampled at 12.5 MHz/channel (chopped sampling).

- External triggering was performed by the generator pulse time t_i signal. Digitized pulse data (voltage and current) were then read by an H.P.85 personal computer for analysis and plotting.

Fig.4 shows part of a discharge pulse train captured during a test on a Charmilles Isopulse 80 machine. The upper graph represents the gap voltage, the lower one the corresponding pulse current. From the former to the latter, it is clear that the discharge voltage varies substantially. Even during the discharge duration t_e, the gap voltage does show some substantial changes.

- The voltage after breakdown drops from very smooth to steep. By minute comparison of several discharge evolutions and by the proper combinations of pulse describing features, a set of 15 distinguished pulse types could be uniquely defined. These results were applied to determine selection criteria on the EDM-PD. A summary of the 15 pulse types and their specific features is given in Table 1 and Fig.9.

TABLE 1 : Pulse Type Characteristics for Deep Sinking Machining.

Description	Pulse nr.	H.L.	t_d > 200 ns	t_f			U_e			U_s			Remarks
				S	N	H	H	N	L	H	N	L	
Normal spark	1	x	x		x			x			x		
Normal spark	2	x	x	x				x			x		t_f small
Normal spark	3	x	x			x		x			x		t_f large
Less eff.spark	4	x	x		x		x				x		U_e high
Less eff.spark	5	x	x			x		NCF		x			t_d large
Arc	6	x	NO		NCF			x			NCF		H.L.arc
Arc	7	NO	NO		NCF			x			NCF		
Arc	8	NO	NO		NCF				x			x	
Short circuit	9	NCF	NCF		NCF			NCF					
Short circuit	10	NCF	NCF		NCF			NCF				x	Carb.br.
Contam. pulse	11	x	x			x	x				x		U_e high
Less eff. spark	12	x	x	x				NCF		x			t_d large
Contam. pulse	13	NO	NO		NCF		x				x		U_e high

Description	Pulse nr.	H.L.	t_d >	t_f			U_e			U_s			Remarks
			200 ns	S	N	H	H	N	L	H	N	L	
Open circuit	14	x	x	NCF			NCF			S.B.			No disch.
Remainders	15	N.C.	NCF	NCF			NCF						Spec.arc
Summation	16	N.C.	NCF	NCF			NCF						Check

Notes :(see Fig.8).

H.L. : high level detection (i.e. whether or not the open generator voltage was reached)
t_d : ignition delay time
t_f : fall time off discharge voltage after breakdown
U_e : measured discharge voltage after breakdown
U_s : overall discharge voltage of the pulse during at least 50% of t_i
S : small fall time t_f (fast drop of discharge voltage after breakdown
N : normal situation
H : high value for considered function
L : low value for considered function
NCF : not considered function
S.B. : special detection bit for open circuits

- As an example, Fig.5 represents four typical pulse types. The first pulse (1) is a normal spark (type 3), with a rather long ignition delay t_d at the open circuit generator voltage (80 V) and a large voltage fall-time t_f (voltage drop measured between two predefined levels). The discharge voltage is also considered and determined as normal. Pulse (2) satisfies same conditions, except that the ignition delay t_d lasts for more than 50 percent of the generator pulse time t_i (type 5) Pulse (3) is an arc (type 15) with an overall voltage level not beyound a chosen voltage range. No ignition delay was observed. Finally pulse (4) is an open circuit pulse (type 14); no breakdown occured.

By setting other pulse discribing features on the Pulse Discriminator (i.e. selection criteria), other pulse types can easily be searched. Once a particular pulsetype can be discriminated, the impact of it on the process can be evaluated.

Typical pulse recordings noticed on a Charmilles-Andrew wire-cutting machine are plotted in Fig.6. Compared with die-sinking, very short pulse durations are used; discharges with and without ignition delay exist here too.
For die-sinking applications, arcs are considered as undesirable though, it is not quite sure that this is also true for wire-cutting machining.
Further detailed analysis with the EDM-PD is required to verify this statement.
Short circuit current is limited by internal generator resistances.

As a result, a carefull analysis of the gap voltage versus time allows to distinguish several pulse types. Some of them are effective, others less effective or even harmful.

EDM-PULSE DISCRIMINATOR (EDM-PD)

The discrimination of pulses is based on electrically detectable signals:
- voltage levels
- time periods