NEW ARC DETECTION TECHNOLOGY FOR HIGHLY EFFICIENT ELECTRO-DISCHARGE MACHINING

by Prof. Dr.-Ing. A. Behrens and Dipl.-Ing. M.P. Witzak
Universität der Bundeswehr Hamburg
Laboratorium Fertigungstechnik (LFT)- Holstenhofweg 85 - 22043 Hamburg
Tel./Fax (00)49 40 6541 2839 - Email mwk@unibw-hamburg.de

Abstract.

Control of Electro-discharge machining (ED-machining) is aimed at a stable process, with maximum removal rate in combination with high quality surfaces. Electro discharge machining is known for its high statistic and non-linear nature and is therefore difficult to control. Furthermore there does not exist a complete mathematical model for the physical varieties related to the removal process. Therefore it is impossible to go through a classical identification procedure to find a transfer function permitting a controller design for stable process control. Consequently, EDM control requires multiple modules accomplished in hardware sensors and computer systems in combination with so-called „technology tables“. These technology tables that are created by the manufacturer contain users‘ experience and deliver a great spectrum of basic machining parameters. Modern EDM plants contain so-called „adaptive control optimization“ which leads to on-line adjustment of an ensemble of working parameters [1]. The basis of ED-machining however is the process stabilization that is able to detect so-called „arcs“ and „short circuits“ quickly and efficiently. This paper will present a strategy that belongs to overall process stability control and contains a new arc detection technology [3]. The resulting system enables the user to drive the EDM process under all circumstances near its physical limit i.e. maximum removal rate with regard to a defined surface quality.

Keywords: EDM process control, arc detection, removal rate. electrode wear.

I. Introduction.

In electro-discharge Machining (EDM), two metal electrodes one being the tool of a predetermined shape, and the other being the workpiece, are immersed in a liquid dielectric, such as paraffin or light oil. A series of voltage pulses, usually of rectangular form, of magnitudes of up to 400V and of frequencies of the order of 5kHz - 200kHz, applied between the electrodes, which are separated by a small gap, typically 10-100 µm. Localised breakdown of the dielectric occurs and sparks are generated across the inter-electrode gap, usually at regions where the local electric field strength is highest. Each spark erodes a small amount of metal from the surface of both electrodes. The repetitive impulse together with the feed forward movement (by means of servo mechanism) of the tool electrode towards the workpiece, enables metal removal along the entire surface of the electrodes. The process can be controlled such that substantially more material is removed from the workpiece electrode. Along with the process evolution the tool-electrode is reproduced to fine accuracy in the workpiece. As the metal removal is affected by electric sparks and not by mechanical forces the machining is not limited by the hardness of the workpiece. These attractive features of EDM have led to the known widespread use of this machining technology especially in the area of dies and molds manufacturing. In order to gain the utmost efficiency the ensemble of the process parameters has to be adjusted permanently. The range of adjustment lies within open circuit i.e. no removal rate, maximum security and short circuit i.e. no removal rate, destruction of the workpiece. An efficient process control should be able to take the process near the short circuit working point without the risk of destroying the workpiece neither through arcing nor through short curcuits.

II. The removal model of ED-machining and arcing

The objective of removing a defined quantity of metal from the workpiece with every single spark demands for controlled energy flux from the power source to the working gap. The working gap consists of the tool electrode, the gap which is between 5µm and 100µm wide and is filled with dielectric liquid and the workpiece electrode. Normally, the tool electrode carries positive polarity and the workpiece negative. Because of the non-symmetrical current density and mostly supported by different melting temperatures of the electrode materials the so-called „polarity effect“ leads to a much greater removal rate on the workpiece (99%) than on the tool electrode (1%). The working quality and efficiency is defined by the process velocity and the smoothness of the workpiece. In order to optimize the velocity and the smoothness many machines use so-called planetary cycles that allow huge removal rates at the beginning of the process by means of a large current. After this first phase the electrode is changed and a small current is applied. The cavity is then formed by orbital movements that allow very high precision compared with normal sinking erosion where the accuracy depends on the quality and precision of the electrodes. The main removal fraction is achieved after the so-called „burning phase“ in phase 4 as shown in figure 1. At that point the current is switched off. The quickly vanishing energy provokes a gas implosion because of the pressure gradient between the plasma channel and the surrounding dielectric fluid. The instantaneous pressure drop has two effects. First the already melted liquid metal of the workpiece is torn into the gap by mechanical forces. Second the pressure drop with approximately constant temperature for a very short period leads to an evaporation of liquid metal because of a lowered sublimation point. These two effects yield approximately 95% of the overall removal rate per single discharge. The removed amount of workpiece material shows a correlation with the working current amplitude and length of burning period.

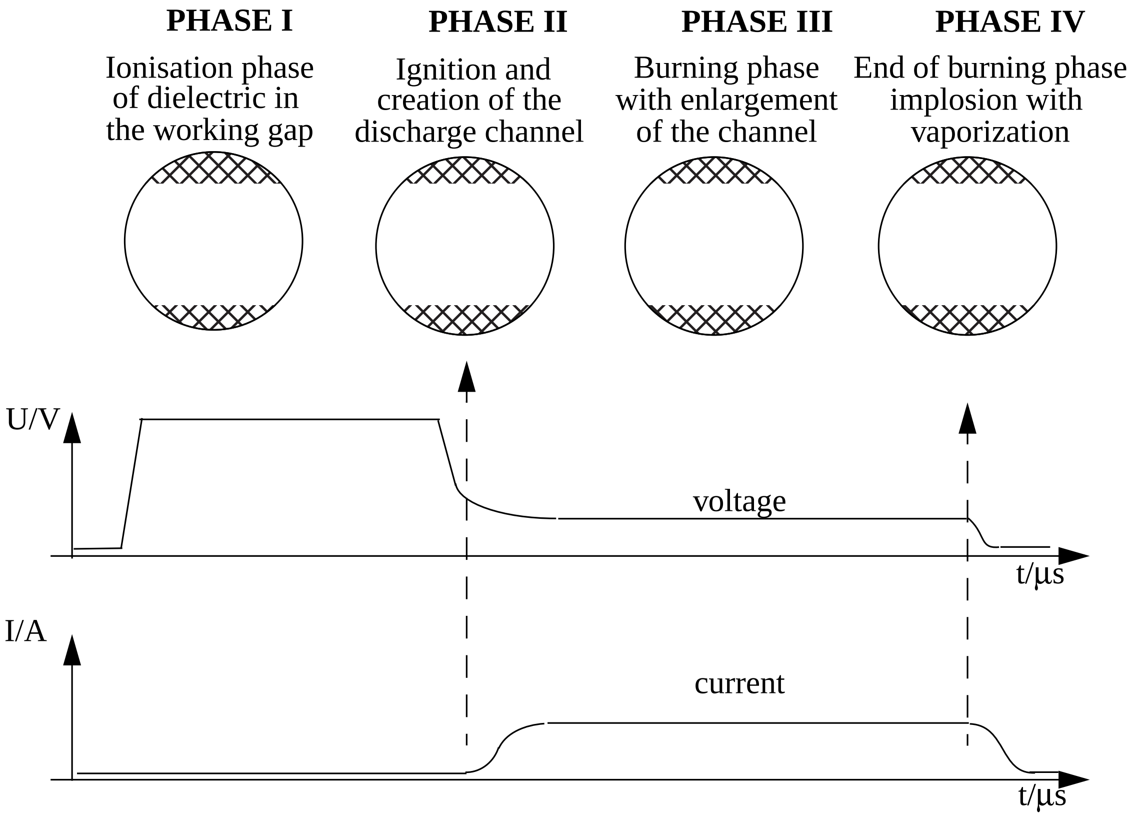
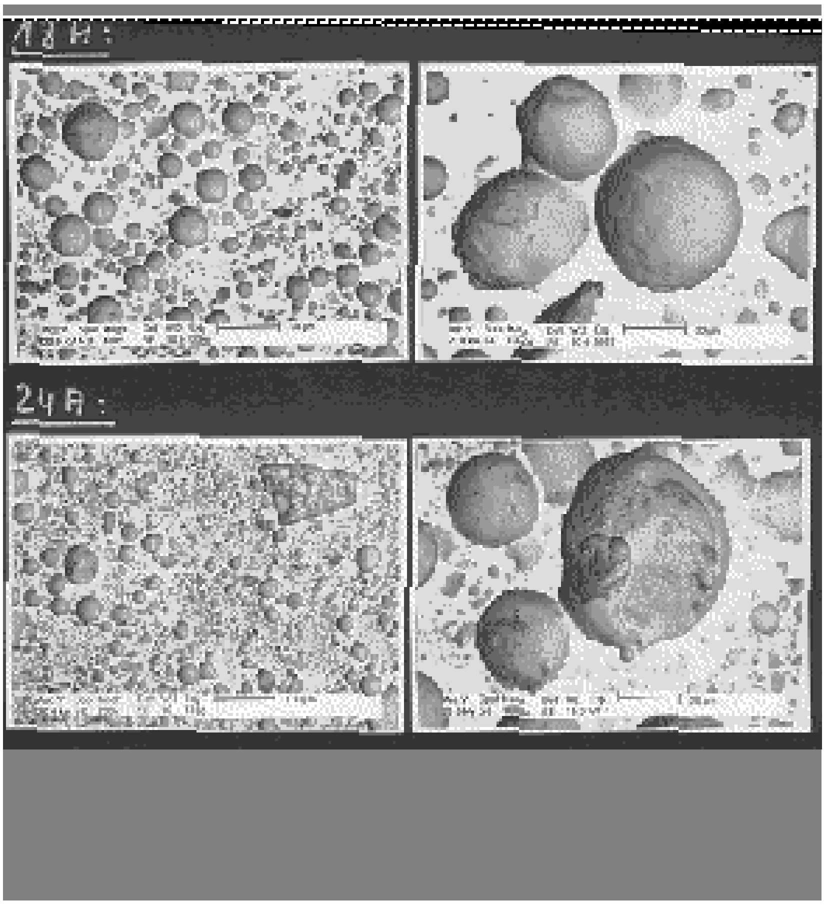


Figure 1. Schematic illustration of the discharge phases

The sizes of the melted and removed particles with the applied working current amplitude are given in the following figure 4. The applied working currents were 12A, 18A, 24A and 30A. The last three have been analysed (Ton=100µs, Toff=20µs, Cu^+, 56NiCrMoV7).



a
working current 18A
particel size found
maximum size 50 µm

b
working current 24A
particel size found
maximum size 60 µm

Figure 2. Raster electrode pictures of removed material by different working currents

Obviously there does exist a weak proportional relation between working current and radius of the removed particles. In all cases the particles are of nearly ideal sphere shape with very smooth surfaces. All probes show a variety of different sizes that indicate that the implosion of liquid workpiece metal is somehow unsteady. There seems to be a maximum particel size for all currents. The working current is therfore proportional to the number of particles and related to their maximum sizes to be found among the removed particles.

With the background of the removal model the central questions with respect to arcing are:
When does a ordinary spark deteriorate to an arc and what about its removal efficieny ?
In which phase of the evolution of a single discharge can an arc be detected ?
Is a single discharge a reliable indicator for arc tendency in the EDM process ?

Besides the destruction as a consequence of arc series the relation of electrode wear to workpiece removal gets worse when single arcs occur. The reason is that the electrode removal, or electrode wear takes place at the beginning of the discharge when the gap current consists mainly of electrons and the plasma channel is still contracted at its anode end (tool electrode positively poled). The workpiece removal is achieved to a large percentage in phase 4. Discharges that are considered as arcs show a significantly short ignition delay time, under 1 µs or no ignition delay time at all (no phases 1, 2) . Second, the arcing discharges occur under bad working conditions mostly in combination with polluted dielectric or very small gap widths or both The phenomenons imply that arcs are successive discharges that ingnite concentrated in a small area of the workpiece. The effect of discharge concentration must be a overheating of the workpiece and of the electrode respectively. For absolute electrode wear the discharge as arc or as regular spark makes not much difference. But for the relative wear referred to removal rate it becomes worse. The quantity of removed material decreases because the discharges remain in a relatively small area, so the overall removal rate over the workpiece surface decreases and the relative wear increases. The exact point in time when a discharge „decides“ to become an arc cannot be determined. It seems logical that an arc is in most cases a product of the „removal history“ taking into account the previous 2 to 20 discharges. This corresponds to the idea that the removal system with dielectric, gap and electrodes can work as an energy storage unit with various mechanisms of energy losses. So the arc detection should be able to recognize an arcing discharge in phase 1 or 2 or it should already be aware of an arc probability before the start of the discharge i.e. in the previous Toff time. The overall process stability is a result of the continous discharge process. There some single arcs well distributed among regular discharges may effect stability and removal rate very slightly. Whereas series of arcs of about 5 to 100 can ruin an electrode or lead to total instability. Therefore the strategy to treat every single arc detected by interrupting the discharge seems to be inefficient but guarantees a continous stable process. Nevertheless a mechanism to distiguish between single arc events and subsequent arcs is very useful to gain a picture of process evolution for process control and optimization which will not be discussed in this paper.

III. Arcing and its detection techniques

First , as alread y mentioned, arcs are discharges that show a significantly short ignition delay time, typically under 1 µs or no ignition delay time at all. Second, the arcing discharges occur under bad working conditions due to polluted dielectric or very small gap widths or both. The phenomenons imply that arcs are successive discharges that ignite concentrated in a small workpiece area. The effect of discharge concentration must be a overheating of the workpiece and of the electrode respectively. The results are damaged electrodes and workpieces of bad quality. Especially when hard-metal is elaborated arcing causes so called micro cracks that must be removed with very expensive polishing treatment after the erosion.

As a matter of fact all erosion processes produce arcing i.e. subsequent discharges located in a very small area. Most of the known arc detection techniques

- classify the ignition delay time [7],
- compare the level of the ignition voltage to a reference level [8],
- judge the falling voltage gradient [9] or
- take into account the burning voltage with its amplitude or spectrum [10].

Ignition delay time (t_d) is definitely not a convenient parameter to detect arcs with. Many discharges ignite with very low t_{ds} but cannot be considered as harmful. Therefore the only way to use t_d is to count subsequent numbers of small t_{ds} - where immediately the question arises what small is - and to react with extra pauses. This strategy leads for some erosion tasks to relatively safe erosion but even there it is not competitive because the removal rate is too small.

The comparison of the ignition voltage level has some advantages concerning its simplicity. On the other hand it cannot be used as general method for arc detection. Test have shown that e.g. graphite erosion without arcing shows discharges with very small levels of ignition voltage. For a first method and under some assumptions the ignition voltage level can be used but it is by far not convienient.

There are a number of methodologies that take into account various gradient voltage drops. These methods seem to be of more academic interests. The discharge spark or arc shows especially in its flanks superposition of effects that do not allow a clear judgement. There might be some information in the falling flank of the ignition voltage that is correlated with arcing. The use of this information seems to be a problem of developing a reliable measuring devices.

Finally the burning voltage can be detected using the amplitude information or the spectral distribution. The amplitude information can be a hint for arcing. It is definitely for short circuits. Here we have made some tests that measure during a time window (3 MHz AD Converter) and then calculate the maximum, minimum and variance of the burning voltage. So far it is not possible to derive reliable correlations from the measurements. We have found typically burning voltages between ca. 20 Volts and 27 Volts showing distributions similiar to a Gaussian distribution. The frequency information gives a hint about arcing. Here the calculation time plays a very important role. The maximum number of points for the applied FFT (Fast Fourier Transformation) was 64 points when discharge time was 100µs. So, for the frequency domain of arc detection, there seems to be a problem of measurement and calculation for industrially reliable use.

In order to avoid harming arcing the arc should be detected and the reaction should be triggered as fast as possible. The best solution would be a methodology to forecast arcing, i.e. to judge the state of the gap before the beginning of the next discharge. It is known that there exist methods that measure certain dielectric values as e.g. conductivity or apply very short test pulses or steady currents to obtain information about the current state of the dielectric fluid. which indicates the electrical stability or resistance against discharges. If the forecasting does not work the second best solution would be to detect an arc reliably in the first phase of burning (phase 1) and to react with switching off the energy source in order to avoid the overheating on the workpiece. The most convenient solution would be to combine the two methodologies which would then indeed lead to practically 100% arc-free erosion process. Such a newly developed technique of arc forecast and detection will be presented in the next paragraph.

IV. A new arc strategy

As described a safe arc strategy should contain components for forecasting arcs and for quick reaction mechanisms that effect directly the energy source in order to prevent the workpiece from overheat. First the physical background of the technology will be described.

Basic idea of the arc detection

The idea takes into account the energy transport from the generator to the working gap with its „natural behaviour“. The working gap consists of the tool electrode, the gap (filled with dielectric) and the workpiece electrode. Between gap and generator there is a energy transmission line (two double shielded lines, sometimes twisted lines). The erosion energy is delivered via voltage pulses of 100V to 300 V and following current pulse of 1A to 100 A. The following figure 3 illustrates the energy flow. In fact the pulses begin with a „step-function“ with nearly rectangular form. The voltage gradients depends on the generator. In our case a completely new generator technology [4, 5] leads to voltage gradients of approximately 400V/µs and current flanks of ca. 60A/µs. Obviously the resulting pulses show nearly rectangular form. The sensor device measures the gap voltage directly at the tool electrode and workpiece. According to our experience it would also be possible to detect the dynmaic voltage signal on the generator side of the line or to add a passive network that is capable of filtering or dumping frequencies that do not match the interesting spectrum for arc detection.

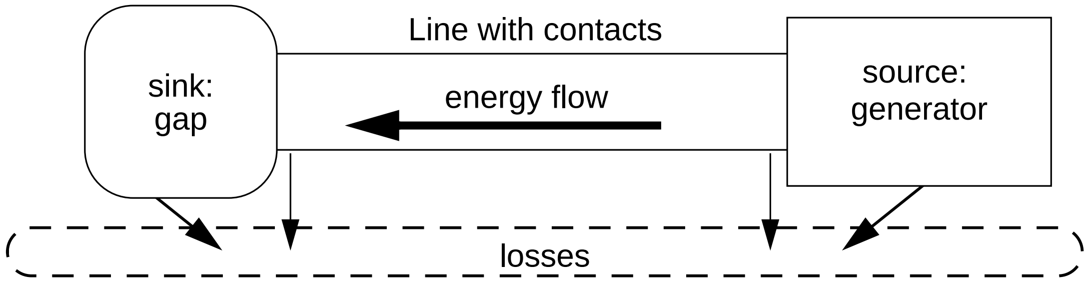


Figure 3. Block diagram of the basic energy flow in ED-machining

The effect of applying a step function or a rectangular pulse to a electrical system that contains capacitive and, inductive elements is a characteristic step response that represents the dynamic behaviour of the electrical system [6]. To close the loop to ED-machining the only problem is to identify the dominating energy storages in the gap-line-system. In figure 4 a discrete model shows the discrete line elements and the probable gap elements. The parameters which change is the inner generator resistance, that depends on the type of power source. Furthermore the gap capacity and resistance are mirroring the state of the gap concerning its conductivity and resistance against applied voltages.

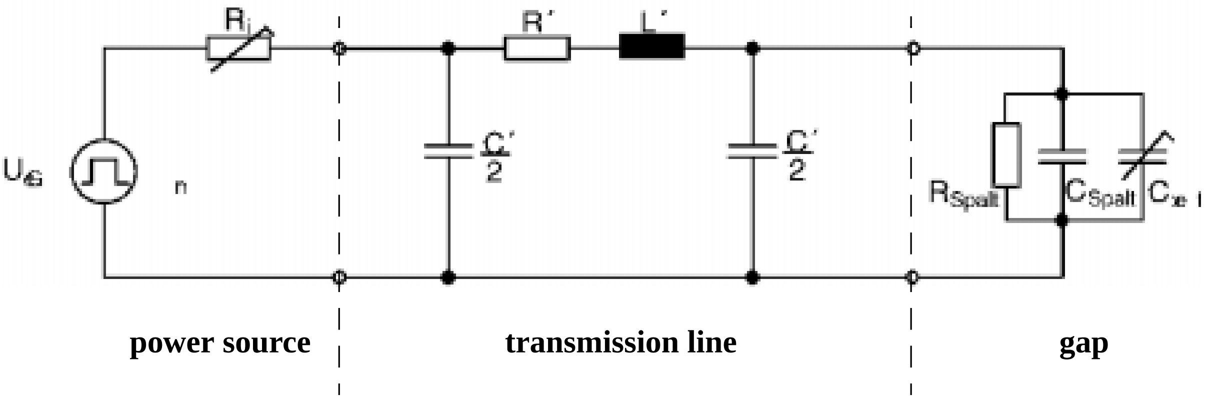


Figure 4. A Discrete model of the EDM energy transfer from EDM source to EDM sink

This first model can explain some of the static effects of the discharge behaviour but it does not cover the dynamic aspects of the energy pulse transfer. This problem asks for a model derived from the transmission line theory. The basic assumption is that any signal, that contains enough energy and that is conducted over any transmission line shows typical wave characteristics.

These behaviour leads to:
- reflections of the signal wave at the generator input
- reflections of the signal wave at the line end
- dumping of the signal at the generator input

Now the question is how the state of the gap is correlated with the characteristic reflection ?

In figure 5 the three major cases are illustrated. First the generator has 0 ohms output impedance and is connected to an „open line“. The resulting signal at the start of the line a simple step signal whereas at the end of the line there is a 100% reflection we can see voltage oscillation which would be in theory a rectangular pulse. The second diagram shows a „real“ generator with a correctly terminated line. The result is correct step function that shows the natural delay at the line end. The last case is a real generator with a shorted line i.e. short circuit at its end. Here the signal at the line end is a 100% absorbed.

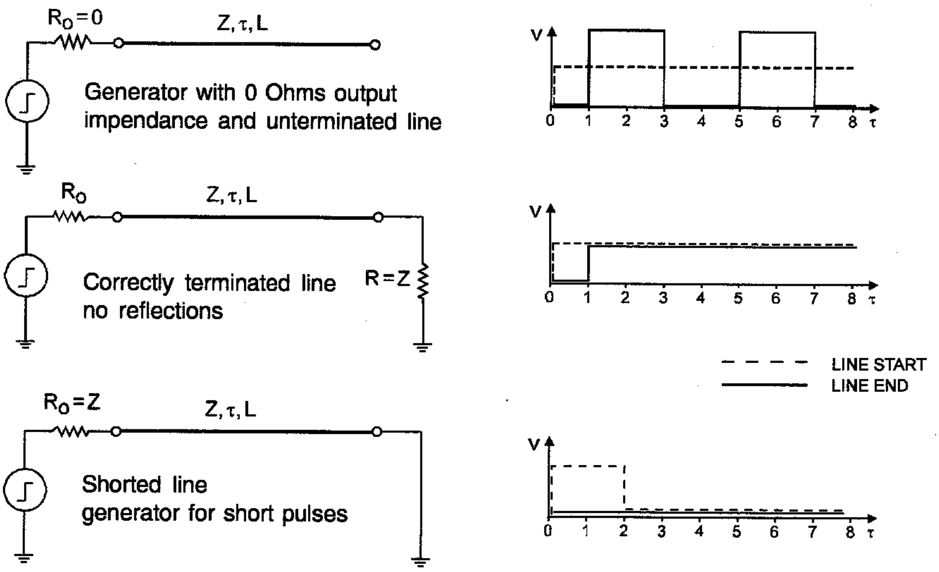


Figure 5. Special cases of line reflections derived from transmission line theory

The very last step is to define the correlation of the line end and the current gap state. Provided that a voltage step is applied to the line-gap-system and the erosion gap represents the line end the voltage signal measured over the gap identifies the current gap state.

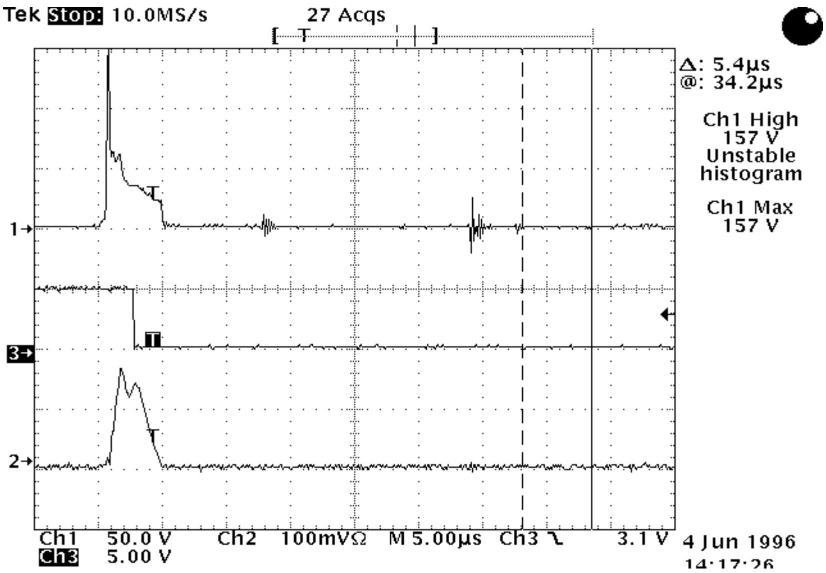
Line theory	EDM gap	Consequences
Open circuit unterminated line	Stable, well isolating gap, with very high resistance	The current spark can be classified as ok
Terminated line	Not isolating, still conductive with a measurable resistance	The current spark can be dangerous, an arc is probable
Short circuit shorted line	Short circuit with minimum resistance or no resistance	The current spark is a short circuit, the energy must be switched off

Table 1. Analogy of EDM discharge and transmission line termination model

Based on the analogy of transmission line theory and EDM discharge characteristic at the beginning of the discharge (phase 1) it is possible to classify each single spark according to the schema presented in table 1. If the spark is a short circuit or an arcing discharge the energy i.e. the working current is switched off immediately. The effect of this strategy is that the energy flow stops immediately when there is any risk of damage indicated.

Technical accomplishment of the arc sensory device

The accomplishment of the arc sensor is based on the gap voltage. The gap voltage itself is thereby divided in order to get an amplitude that can be handled (5V to 15V). The most important innovation is that the signal representing the dynamic gap voltage is differentiated in order to gain only the „ac components“ of the signal. This simple trick makes it very easy to get the exact characterisation of the discharge. A subsequent electronic device transfers the detected oscillation into countable pulses that are then elaborated with a programmable logic device. The reaction on detected arcs is that the power source is immediately switched off. The whole process of detecting, classifying and reacting needs approximately 5 µs after the impulse has been implied to the working gap. The process control also gets the result of the arc sensor in order to judge the current process state. In an evolutionary model of the arc sensory device we integrated an up and down counter (40MHz) that detects the extremely dangerous sequences of arcs. This device is able to command the feed motor directly if a maximum sequence of arcs is reached. The next step is to integrate an automatic adaptation to the corresponding machine type and to the erosion parameters ignition voltage and working current. This is evident because the device uses the oscillation of applied energy to the gap. The energy is mainly determined by the ignition voltage and the working current with its flank and amplitude. Therefore an automatic adjustment of the arc sensor is mandatory. In order to realize the automatic adjustment we have integrated a calibration logic that takes samples during a calibration open circuit cycle and adjusts the detection circuit according to the measured energy oscillation. The rule of adjustment is quite simple, it says that during open circuit all impulses must be classified as ok. With lowering the sensitivity of the detection circuit as much as possible i.e. as long as the basic rule remains true the adjustment guarantees maximum sensitivity and utmost reliability. To realize a forcasting arc detection we use the same principle at the end of the discharge i.e. in phase 4. The assumption here is that a well deionizing gap must show more oscillations than a still conductive gap. According to the once again counted numbers of oscillations the Toff time will be increased[1]. In figure 6 a oscillogram shows the effect of the arc sensor device in the real erosion process. Here the arc is detected after approximately 3 µs, the current flow and the voltage is zero in the working gap after a total time of 5 µs.



a
Gap voltage,
switched off after 5µs

b
Trigger signal:
„arc detected“

c
Working curent
switched off after ca. 5µs

Figure 6. Oscillogram (a-c) of arc sensor effect in EDM

---

[1] The forecast part of the arc detection is tested in a prototype but not yet implemented in the machine, so the test results are entirely based on the arc detection unit without forecast..

Practical case study: Machining small deep cavities

Finally a case study will be presented that serves as an internal benchmark for the new arcing technology. Without the arc sensor the erosion of the described work piece was impossible on our research machine. With the arc sensor we have been capable of accomplishing the erosion task within a acceptable time limit. The workpiece diagram is presented in figure 7. In table two the erosion task is summed up.

.

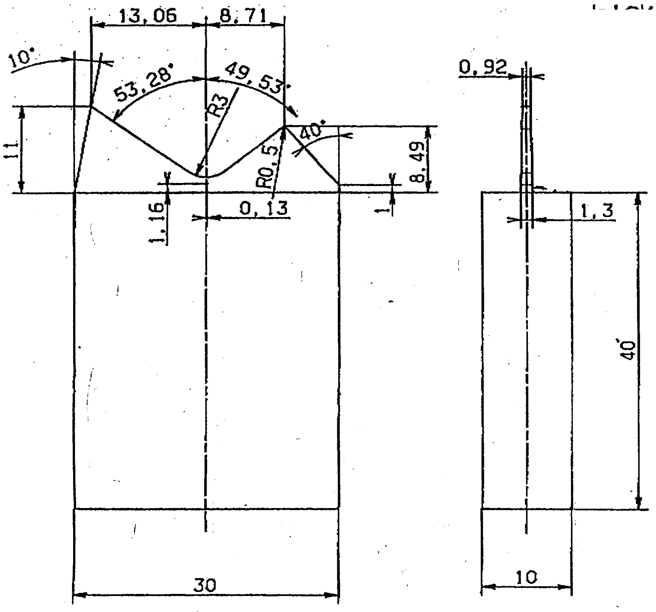


Figure 7. Reference workpiece for EDM tests in LFT, Hamburg

Materials	Erosion technology	Ignition voltage working current	Pulse timing	Geometry	Results
CU^+, 56NiCrMoV7	no flushing	180V, 12A	Ton=80µm Toff=10µs	straight forward 10mm	duration 45min Ra>4µm
CU^+, 56NiCrMoV7	micro oszillating flushing[1]	180V, 12A	Ton=80µm Toff=10µs	straight forward 10mm	duration 23min Ra=3,4µm

1. The micro oszillation technology for EDM die sinking was developed for deep cavities in the Laboratory of Production Engineering. It serves as a flushing mechanism that cleans the gap efficiently while the erosion process is running whereas conventional movement flushing interrupts the discharge process completely. Here we are at the beginning with our investigations in order to optimize this new flushing technology for higer performance in fine erosion. The results will be published as soon as possible.

Table 2. Reference erosion task, parameters and results.

V. Summary

The paper presents a new arc detection technology that is based on the transmission line theory applied to the gap-line system of the EDmachining process. The main idea is to use the analogy between the gap state concerning its electrical stability and the transmission line termination.

This approach has already demonstrated new perspectives concerning removal rate and surface quality. The next step will be the investigation of hard metal erosion which is known for its micro cracks that demand for expensive polishing after erosion. There we expect a significant decrease of micro cracks because the energy in the case of arcing is switched off immediately so that the dangerous overheating tendency is drastically reduced. Another step will the full integration of forecast and detection of arcs to avoid the 5µs of arcing that are now still necessary to detect an arc and to react by switching off the power source.

Literature.

1	Behrens, A., Witzak, M.P.	Integrating Fuzzy Technology in EDM Process Control International Symposium for Electro-discharge machining Lausanne April 17-20, 1995, Proc. 11th Int. Symp for Electro-Machining (ISEMXI), Lausanne, 1995, S. 287-294.
2	Behrens, A., Witzak,M.P.	Entwicklungspotentiale funkenerosiver Senkanlagen aus Sicht der anwendungsorientierten Forschung VDI-Z SPECIAl Werkzeug- und Formenbau November 1995 VDI Verlag, Düsseldorf; S. 40-42.
3	Behrens A. Witzak M.P. Bruhns F.L.	„Verfahren und Schaltung zur Überwachung und Vorhersage eines Funkenerodierprozesses in einer Funkenerodiermaschine“; Patentanmeldung Deutsches Patentamt München unter DE 195 12 291.7 vom 05. April 1995
4	Thyssen TLT/ Redline Aachen	Bedienhandbuch: Geregelte Prozeßstromquelle für die Senkerosion Thyssen Laser Technik, Redline Technologies Aachen 1994.
5	Knöll H. Thyssen Ind.	Patentschrift DE 34 27 520 C2: „Schaltung zur Speisung eines Verbraucherzweipols“. Patentinhaber: Thyssen Industrie AG.
6	Janzen G.	Kurze Antennen: Entwurf u. Berechnung verkürtztrt Sende- und Empfangantennen, Franckh‘sche Verlagshandlung W.Keller&Co Stuttgart 1986.
7	Marendaz, G.-A.	Patentschrift DE 22 14 486: „Funkenerosionsverfahren“. Patentinhaber Charmilles Technologies, Genf, 1983.
8	Saito, N Kobayashi K., Olizumi, T.	Patentschrift DE 23 62 251: „Verfahren und Vorrichtung zur Elektro erosionsbearbeitung“; Mitsubishi Denki K.K., Tokio, (J) 1982.
9	Dauw, D.F.	On-line identification and optimization of Electro-Discharge Machining. Diss. Kath. Universität Leuven, 1985.
10	Best, J.A. Avenarius, E. Zeeuw,J.W.	Patentschrift DE 21 257 49: „Vorrichtung zum Erkennen von Lichtbögen bei Funkenerosionsbearbeitung“, Naamloze Vennootschap, Philips Gloeillampenfabrieken, Eindhofen, Holland, 1981.