

ARC DETECTION IN ELECTRO-DISCHARGE MACHINING¹

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ABSTRACT

For combining high performance and security during Electro-discharge machining (ED-machining) the presence of an effective facility for detecting short-circuits and so called „arcs“ is of big importance. Especially ignitions with a tendency towards arcing are dangerous for the ongoing of the ED-process. Without an efficient module of arc detection and a strategy of arc prevention a destruction of the work piece surface due to overheating can be the result. Finally the ED-process can come to a stillstand and no further removal will happen. Strategies for arc detection have been studied already for a long time. The ignitions in ED-machining have various characteristics, depending on the material used for electrode and work piece, the current and the voltage. This fact makes it hard to develop a universal criterion for arcs. Modern generators working as a current source limit the applicability of conventional arcing criteria and create the necessity of new developments in this field. Therefore a new strategy for catching arcs was developed which easily may be applied and which causes a strong indication.

KEY WORDS: *electro-discharge machining (EDM); arc detection; process stability*

1. INTRODUCTION

Electro-discharge machining (ED-machining) uses the removal phenomenon of electrical discharges in a dielectric fluid. Two conductive electrodes, one being the tool of a predetermined shape and the other the work piece, are immersed in a liquid dielectric. A series of voltage pulses, usually of rectangular form, are applied between the electrodes, which are separated by a small gap. A 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 movement (by means of a servo mechanism) of the tool electrode towards the work piece enables metal removal along the entire surface of the electrodes [1].

Besides the ignitions with contribution to material removal, arcing pulses can happen and a dangerous situation for the process stability can occur. The overall process stability is a result of the continuous discharge process. Some single arc-pulses well distributed among regular discharges only slightly may influence the stability and removal rate. Whereas series of arcs can lead to total instability [2]. Arcs are successive discharges which ignite concentrated in a small area of the work piece. The effect of this discharge concentration is an overheating of work piece and electrode. Instead of removing material, carbon is brought up by the arcs and finally the erosion process must be aborted.

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The evolution from single well distributed arcs to total instability happens in stages and it should be the intention of the process control system to detect tendencies towards arcing in an early stage and react effectively against it.

2. REASONS FOR ARCING

In electro-discharge machining the dielectric fluid has only a limited isolating effect. This is the precondition for a pulse ignition and the whole removal process. If the dielectric isolation within one small geometrical region is reduced because removed particles pollute the dielectric fluid, ignitions will prefer this region. This concentration of ignitions will overheat the material and damage the surface.

To avoid this effect it is necessary to control the condition of the gap in a way that no regions with a concentration of ignitions can establish [3]. In order to re-establish the isolating effect of the dielectric fluid within the gap after each ignition a pause has to follow at which no energy is supplied to the gap. The amount of time that is needed for de-ionization of the gap is strongly influenced by the contamination of the dielectric fluid by removed particles. The number and size of these particles is related to the preceding burning time and the working current. The distribution of the particles is hard to estimate because of the many influencing factors. The movement of the particles is influenced by gas bubbles emerged by the evaporation and chemical reactions of the dielectric fluid at ignition as well as the geometrical gap conditions [4].

3. METHODS FOR ARC DETECTION

The problem of detecting arcs is strongly related to the determination of the conductivity of the dielectric fluid. Some methods determine the conductivity of the dielectric fluid by applying test pulses to the gap during pause time [5], [6]. From this procedure arises the problem of an additional energy supply during pause time. Therefore in this case the pause time has to be extended in order to ensure a complete de-ionization of the gap.

Most methods for arc detection determine characteristic elements of the pulse and from that indirectly conclude to the conductivity of the dielectric fluid. The ignitions during ED-processing show various characteristics depending on the materials used for work piece and electrode, the working current and the ignition voltage. This variety makes it hard to define a universal criterion for arcs and is responsible for the big number of different methods of arc detection.

Arc detection methods, which are most popular in industrial practice can be found in Table 1

critereon	interpretation	time of measuring	evaluation	reference
ignition delay time (t_d)	series of short t_d means arcs	ignition phase	not applicable if generator is working as an <u>active</u> current source like [16], [17], because the high gradient in the raising edge of the ignition voltage leads to predominantly short t_d .	[7], [8]
gradient of falling edge of ignition voltage	high falling gradient is an indication of arcs	ignition phase	not applicable if generator is working as an <u>active</u> current source like [16], [17], because the gradient in the raising edge of current (which is equivalent to gradient in the falling edge of voltage) is controlled by generator.	[9]
level of the ignition voltage	if ignition voltage doesn't reach a reference level an arc is interpreted	ionisation phase	could not be proved on our used EDM system	[10],[11],[12]
frequency spectrum of burning voltage	an arc frequency spectrum of burning voltage shows low portions of high frequencies	burning phase	applicability strongly depends upon the used material work piece/electrode	[13],[14],[15]

Table 1: comparison of arc detection methods

Many methods for arc detection are not applicable when using generators, designed as an active current source [16], [17]. This shows the need for the development of an arc detection method which is more suitable to the employed generator technology.

The basic for this development is a model that represents the dynamic electrical behaviour of the EDM system at pulse-start and -end time with the effect of applying a step function to an electrical system being terminated by a variable capacity/resistor [18].

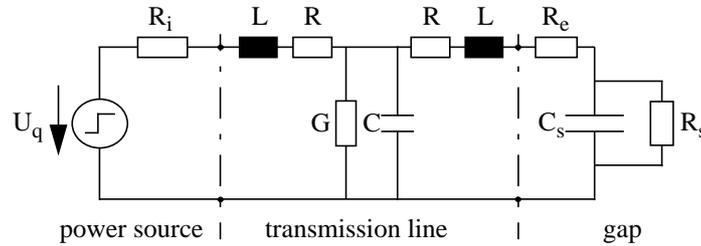


Figure 1: Discrete model of EDM system at pulse-start and -end time

The gap is represented as an „imperfect“ capacity, whose capacitive part C_s is determined by the electrode plain and the geometrical distance. Of major importance for impulse analysis is the resistor part R_s , which is representing the varying pollution of the dielectric fluid in the gap region. The resistor R_e represents the loss caused by the electrodes.

If this system is stimulated using a voltage pulse we can see voltage oscillation according to the impedance of the gap (C_s , R_s). The damping and the resulting frequency spectrum of these oscillations allow a classification of this ignition (Table 2).

oscillation	R_s	consequence
distinctive oscillation	very big	good ignition
less oscillation	medium	polluted gap, arc
collapse of gap-voltage	very small	short circuit

Table 2: Classification of ignitions by voltage oscillation [20]

This arc detection method is applied during the ignition phase immediately after pulse beginning. Thus it is possible to detect an arc already in an early stage after only a few μs and react by switching off the power.

A disadvantage of this method is the difficulty of measuring the oscillating behaviour of a pulse after starting it. The oscillating behaviour is influenced by the chosen working current and ignition voltage as well as the materials used for work piece and electrode. This complicates the universal applicability of this method. Therefore an improvement of this method is necessary.

Starting point of this development was again the already introduced model of the ED removal system (figure 1), which represents the gap as a variable impedance. This model was now transferred to the burning phase.

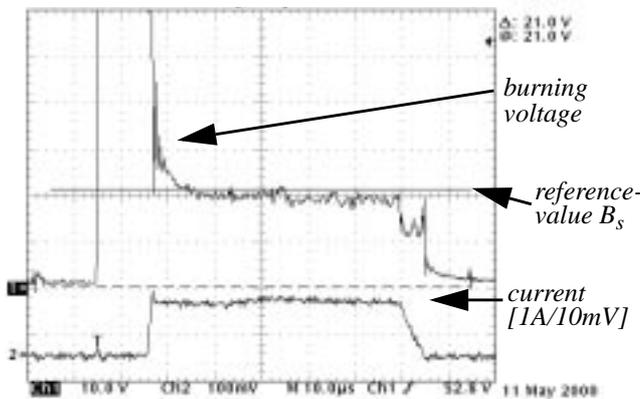
In this case the resistor R_s is of major interest. With R_s it is possible to characterize the state of the dielectric fluid inside the gap (table 3).

R_s	state of dielectric fluid inside the of gap	conclusion
medium R_s	only slightly polluted dielectric fluid inside the gap. Good working conditions	the actual ignition is <u>not</u> an arc
small R_s	strong polluted dielectric fluid inside the gap. Poor working conditions.	the actual ignition is an arc

Table 3: Classification of ignitions by gap-resistor

The gap-resistor R_s varies during the burning phase. The measurement of R_s is possible by using the burning voltage. A drop of R_s is interpreted as a turning of the ignition into an arc. This easily can be measured by comparing the burning voltage to a reference value. Contrarily to arc detection methods which work during the ignition phase this new methods allows to detect even arcs which start as a normal discharge but become an arc during the burning phase. Therefore an increased effectiveness is achieved.

From figure 2 to figure 5 different discharges are shown (machining parameters: $U_0=160V$, $I_c=12A$, $t_c=50\mu s$). At the discharges classified as arcs one can see the drop of the burning voltage below the reference value.



In figure 2 this takes place immediately after the ignition phase in spite of a distinct ignition-delay time (t_d). This discharge will be classified as an arc.

Figure 2: Burning-voltage of an arc

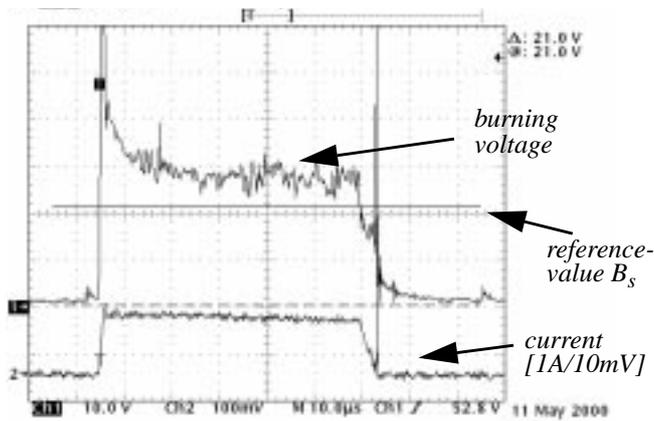


Figure 3: Burning voltage recorded from a normal discharge

In this case the burning voltage is above the reference value until the end of the pulse. So this ignition will not be classified as an arc.

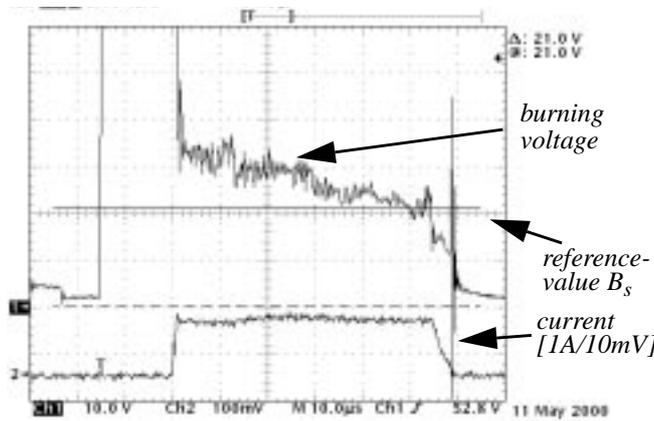


Figure 4: Burning voltage of an ignition that becomes an arc during burning phase

The burning voltage of this discharge falls under the reference value near the end of burning phase. Therefore this ignition will be classified as an arc, though the drop takes place near the end of the ignition.

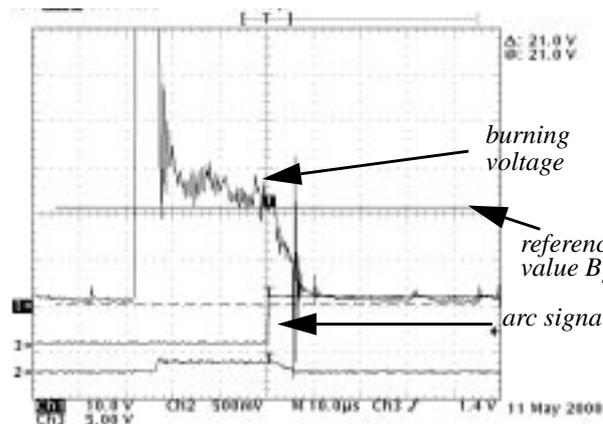


Figure 5: Reaction to a detected arc

In reaction to the detection of an arc the actual discharge is switched off. This is carried out within 1µs after detection. After switching off the rest of the pulse time is used as an additional pause time.

An additional signal is generated to inform the process control system of the appeared arc.

4. EFFECTIVENESS OF THE DEVELOPED ARC DETECTION METHOD

Many experiments have been carried out to study the effectiveness of the developed arc detection method. The value of the reference voltage (B_s), which is used to classify an arc is of high importance for the efficiency of the arc detection facility. B_s depends on the materials used for work piece and electrode as well as on the working current. The sensibility of the arc detection module is defined by the reference voltage. If the reference voltage is too low, arcs will be detected too late or even not at all. If this happens the surface of the electrodes can be affected. Often black spots are visible on the work piece. If the reference voltage B_s is adjusted too high, removal rate goes down and electrode wear is increased. In case of an increased B_s many normal discharges who would have contributed to material removal are classified as arcs and switched off. So removal rate goes down. The increased electrode wear is caused by fact, that material removal on the electrode normally (in case when electrode has positive polarity) happens during ignition phase. therefore all ignitions classified as arcs and switched off still contribute to electrode wear.

Figure 6 shows the effect of varying the reference voltage B_s on removal rate and relative electrode wear during a roughing operation.

Parameters: Cu(+) / X 210Cr 12 (-); I_e 40A; U_0 160V; t_e 200 μ s; t_0 20 μ s

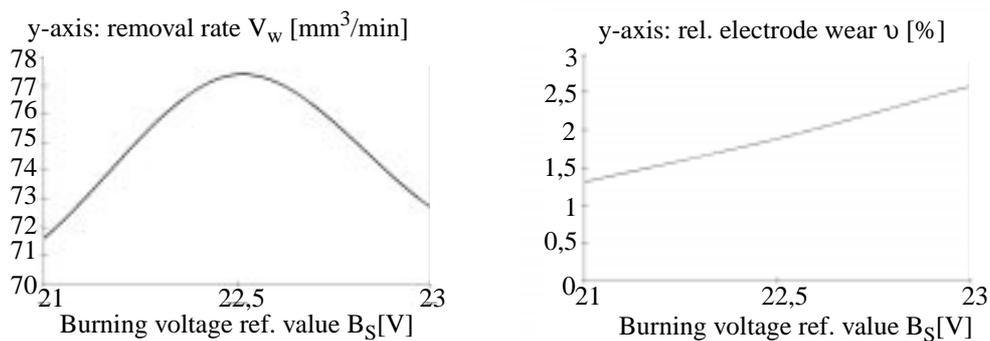


Figure 6: Variation of reference voltage in roughing operation

The removal rate shows a maximum when B_s has a value of 22.5 V. The reduced removal rate at low B_s -values indicates the effectiveness of the arc detection method, because when B_s is too low, arcs will be recognized too late or not at all. Therefore the reduction of the removal rate is caused by an increasing influence of not detected arcs on the removal process.

In a finishing operation B_s can be varied only in a small range, because otherwise black spots on the work piece occur, if B_s is too low. Figure 7 shows optimal values for the reference voltage B_s determined by large number of tests with different electrode materials.

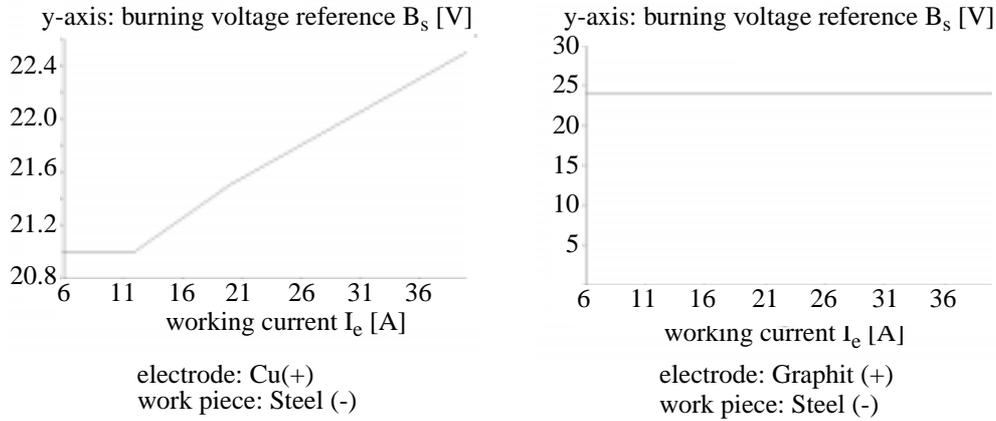


Figure 7: Burning voltage reference values for different working currents and materials

The described method for detecting arcs is able to detect an arc and to switch off the current in order to avoid any damage, but does not eliminate the reason for arcing. Therefore sequences of arcs are observed by the process control system. If an arc sequence is longer than a threshold value N_{VPL} , a long process interruption will be carried out. If in spite of that arcing will continue, the process control system carries out a flushing movement after reaching another threshold ($N_{SPÜL}$).

5. THE EVOLUTION OF A DISCHARGE INTO AN ARC

In comparison to other arc detection methods which detect arcing by looking at the ignition- or pause phase, this detection method works during the burning phase. Ignition or pause phase based methods assume that a discharge is born as an arc. Contrarily to that our method presumes that a discharge can start normally and turn to an arc during burning phase. From this arises the question:

What makes a discharge that starts normal turn into an arc?

In order to find a solution the exact point in time (t_{arc}) when a discharge „decides“ to become an arc was measured (figure 8).

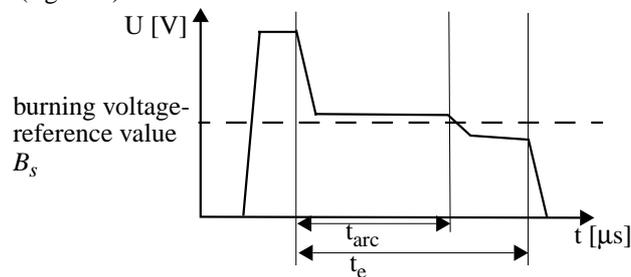


Figure 8: Exact point in time when a discharge becomes an arc

By measuring t_{arc} for each arc out of a great number of discharges and by using various pulse times (t_e), it can be seen that nearly every discharge can turn into an arc, if the pulse time is extended for too long.

Figure 9 shows the histogram of t_{arc} made up from 32.000 pulses recorded during a finishing application with a t_e of $10\mu s$. The process showed a stable behaviour during the inspected discharge duration (32.000 pulses).

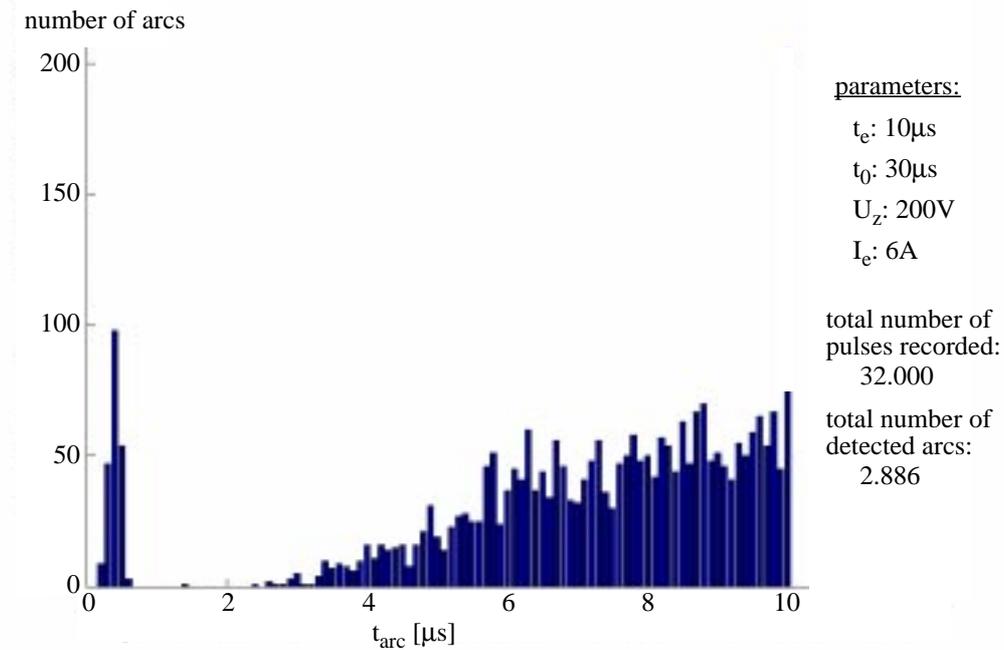


Figure 9: Histogram of t_{arc} recorded during stable process conditions

While running the ED-process with the parameters shown in figure 9 the pulse time (t_e) has been extended abrupt to a much longer value ($50\mu s$) just for recording another 32.000 pulses and then pulse time was set back to the previous value. The histogram of the arcing-time (t_{arc}) for those pulses showing extended t_e can be seen in figure 10.

Compared to figure 9 the number of arcs is about 5 times higher. The histogram of t_{arc} in figure 10 shows that:

- Nearly all discharges had decided to become an arc until a maximum burning time of $50\mu s$ (Note: from the recorded 32000 pulses 16690 pulses were classified as open-circuits).
- For the t_{arc} values between $1\mu s$ and $50\mu s$ a bell-shaped curve can be seen that shows a maximum at $12\mu s$.

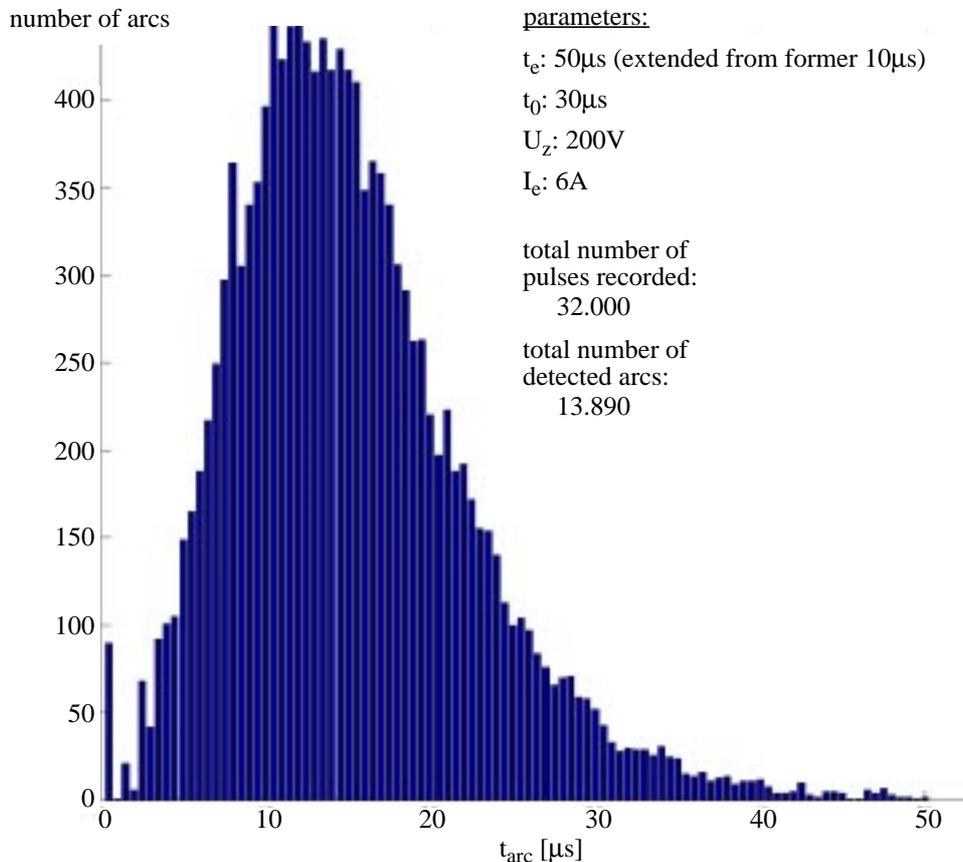


Figure 10: Histogram of t_{arc} for pulses during extended pulse time

Comparing the histograms of figure 9 and figure 10 it can be seen, that the probability of a discharge turning into an arc depends on its pulse time t_e . If t_e is set too long (this is the case in figure 10), the probability of arcing is very high. From the t_{arc} -histogram of arcs with long t_e (figure 10) one can see that most arcs occur after a burning time of 12 μ s (t_{arc}).

The conclusion out of figure 10 is that most of the arcs can be avoided, if t_e is chosen smaller than 12 μ s (as it is in figure 9). Of course the removal rate is reduced, if t_e is assigned a small value, but process stability can be increased if arcing is avoided. The introduced arc detection method makes it possible to run the process with an increasing number of arcs, but there will be no improvement in removal rate. In case of a longsome t_e most discharges get switched off because of their turning to arcs within the pulse duration time. As pointed out earlier this will result in a raised electrode wear.

Up to now extensive technological experiments must be carried out in order to find secure working parameters which combine reduced arcing and acceptable removal rates [19]. With the developed arc detection method and by looking at the t_{arc} time it is possible to derive working parameters without many experiments directly from the process.

The process tells which maximum of burning-time t_e is acceptable

The procedure of deriving optimal t_e -values out of the process uses the new arc detection method and the t_{arc} -histogram. The procedure can be described as follows:

1. Start the process with a small t_e -value that provides stable process conditions and a low number of arcs (the pause-time t_0 must be chosen high enough to avoid arcing due to insufficient de-ionization).
2. Based on stable process conditions provided by the small t_e and a sufficient t_0 the time of the burning phase t_e must be suddenly extended to a high t_e -value. This extended t_e should be kept only for a limited number of pulses in order to avoid process corruption.
3. Recording the time t_{arc} for all of the arcs occurring during the extended t_e interval will provide the data for further statistical analysis.
4. The histogram of the t_{arc} -values provides the information for the optimal t_e . The optimal t_e -value is identical to the t_{arc} -value just before reaching the maximum in the histogram.

This experiment has to be repeated for different values of working current I_e , because secure and efficient t_e -values are strongly dependent on the working current. Figure 11 and figure 12 show histograms with extended t_e recorded for different values of working current I_e .

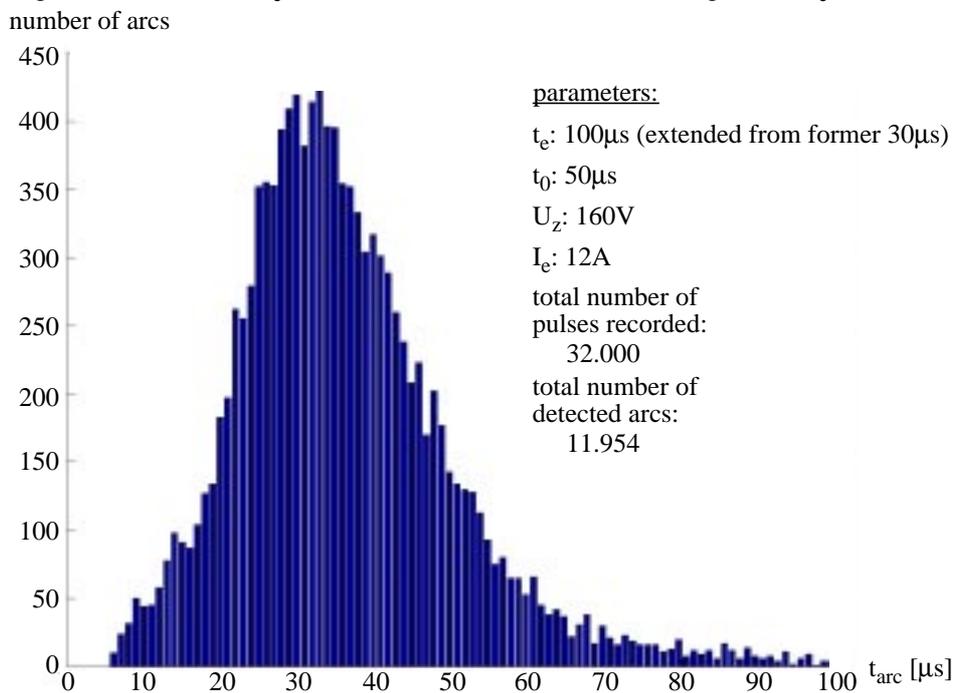


Figure 11: Histogram of t_{arc} for pulses during extended pulse time recorded for $I_e=12A$

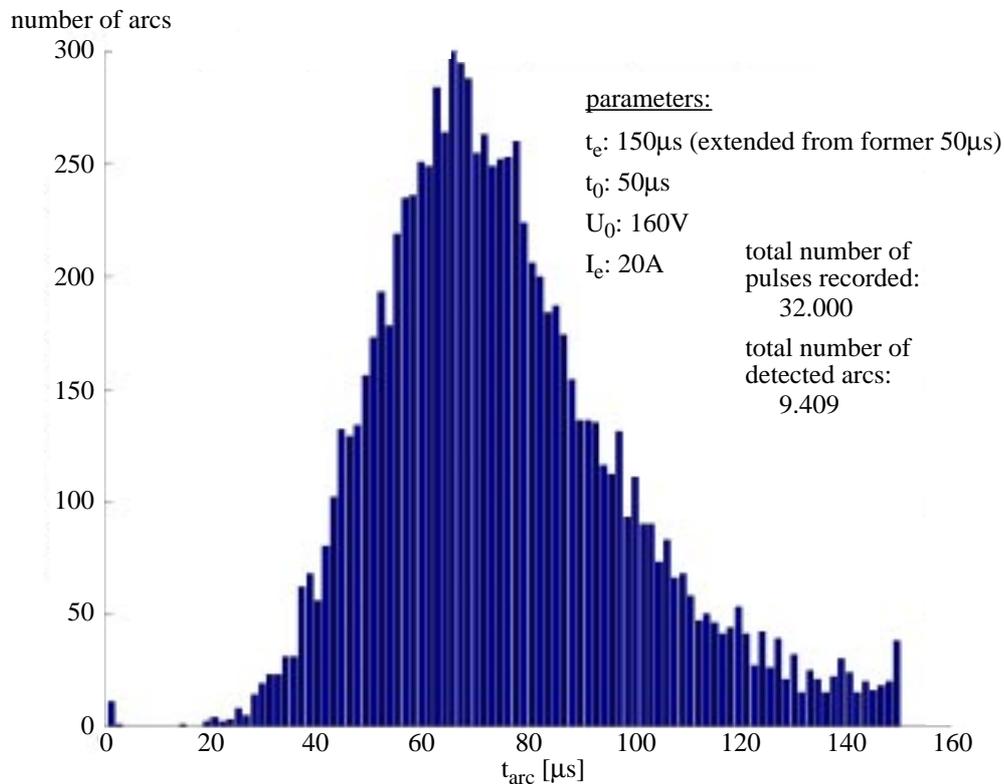


Figure 12: Histogram of t_{arc} for pulses during extended pulse time recorded for $I_e=20A$

The histogram in figure 11 shows that when using 12A working current a secure value for burning time t_e is 30 μ s. From figure 12 one can see that if running the process using 20A working current t_e should be chosen to 65 μ s in order to have secure process conditions.

The procedure of deriving optimal t_e -values out of the process using the t_{arc} histograms reduces the amount of experiments to achieve technological data for different values of current and material combinations.

6. COMPARISON WITH OTHER METHODS OF ARC DETECTION

To compare the developed arc detection strategy with other methods, already applied in industrial practice, pulses were recorded and statistically analysed. So the new developed arc detection method can be compared to other methods regarding to sensibility and equivalence.

The developed arc detection facility consists of programmable modules. Therefore it is possible to implement other arc detection and arc suppression methods for purposes of comparison. Furthermore the integrated time- and threshold-measurement is capable of registering the needed characteristic values (figure 13). It is even possible to build combinations of the different characteristic values in order to detect arcs. This Information can be recorded for a longer period of pulses.

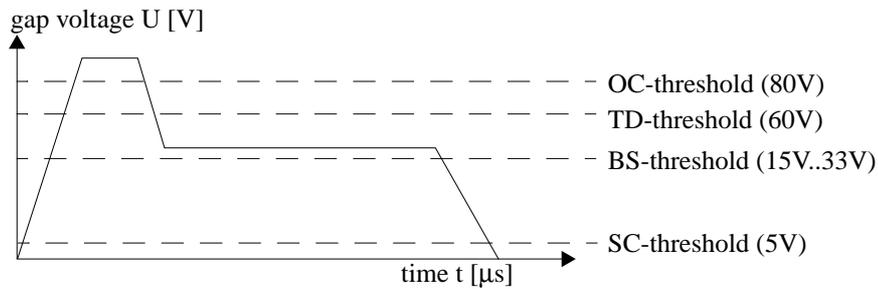


Figure 13: Thresholds detected and recorded by arc sensor

As mentioned before we propose a criterion based on the burning voltage going below the B_s -threshold (figure 13). Another often applied arcing criterion is to inspect whether the voltage level at ignition phase does not reach the ignition voltage level U_0 . In this case the discharge is assumed to be an arc [10], [11], [12]. For the following investigations this arcing criterion was implemented by detecting if the gap-voltage reaches the OC-threshold. A third very simple criterion for arcing is to look at the ignition-delay time t_d . If t_d is shorter than e.g. $3\mu s$, the discharge is assumed to be an arc [7], [8].

Experiments have been carried out in order to compare the output of the different arc detection methods for various process situations. In all experiments no external flushing was used. Only the movement of the electrode triggered by arcing was responsible for gap cleaning. Table 4 shows the comparison. The used process conditions may be taken from the mentioned figures.

process conditions/ experiment	process stability	arcs by B_s	arcs by OC-threshold	arcs by $t_d < 3\mu s$	arcs by B_s and OC-threshold	arcs by B_s and $t_d < 3\mu s$
figure 9	good	2.886	3	40	3	0
figure 10	bad	13.890	34	0	34	0
figure 11	bad	11.954	1.004	595	1.004	369
figure 12	bad	9.409	1.470	478	1.470	323
figure 14	poor	13.274	12.733	4	12.729	4

Table 4: Comparison of different arc detection methods

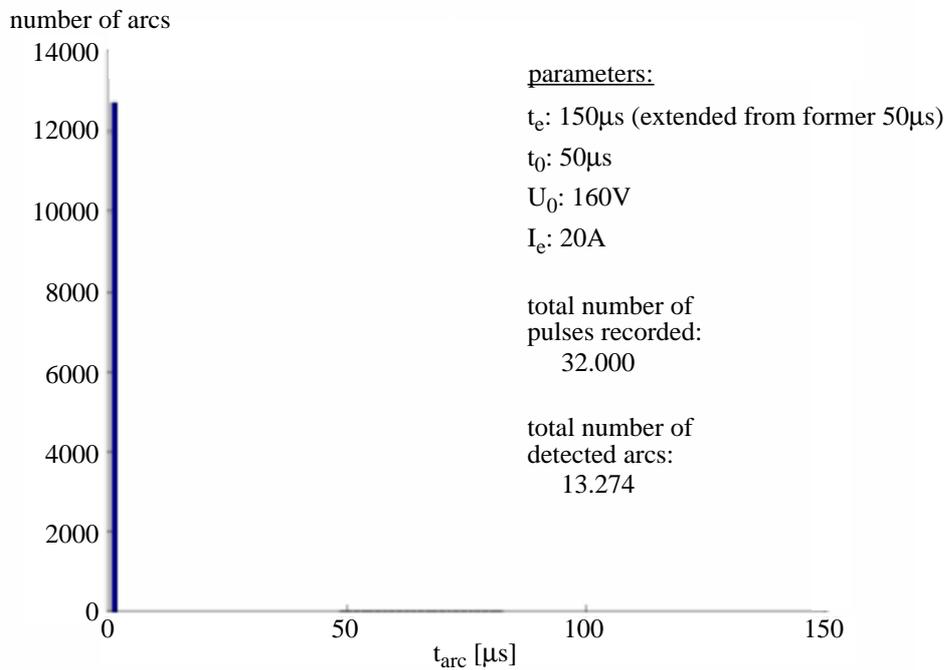


Figure 14: Process showing poor stability

As proposed the process stability classified as „bad“ could be improved when t_e was shortened. The experiment in figure 14 showed a „poor“ process stability. It could not be stabilized any more. Black spots on the work piece were visible that indicate a thermal influence. Noticeable is the huge amount of arcs showing a very small t_{arc} -time in figure 14 for this experiment.

When looking at table 4 it can be seen, that the new developed arc detection method shows the highest sensibility. No other arc detection method discovers so many arcs. The equivalence of the different arc detection methods seems to be very small. Only in case of the process shown in figure 14 there is a very high equivalence between arc detection by B_s and arc detection by OC-threshold. The process in figure 14 already corrupts directly after ignition. Therefore the strong arcing indication coming from the OC-threshold criterion comes too late. On the other hand the weakest method of arc detection seems to be the way of using ignition-delay time t_d . This isn't surprising because the employed generator technology reduces the significance of t_d .

7. CONCLUSION

Based on a discrete model of the energy transfer from EDM source to EDM sink a new arc detection method has been developed and applied in practice. This arc detection method is characterized by a simple measuring method and a high sensibility compared to other well known arc detection strategies. In contradiction to other detection methods which are based on the assumption that a discharge is born as an arc, this new method takes into account that every discharge can evolve to an arc. By measuring the exact point in time when a discharge decides to „become“ an arc, the foundations for a much more efficient way of acquiring secure machining parameters is built.

An explanation of the physical phenomena taking place in case of arcing were not given. Here further research work can follow.

BIBLIOGRAPHY

- [1] W. König: „*Fertigungsverfahren; Band 3 - Abtragen*“, VDI-Verlag, Düsseldorf, 1990
- [2] M. P. Witzak: „*Verbesserung der Prozeßführungssysteme für funkenerosive Senkanlagen unter Einbeziehung von Fuzzy-Technologien*“, Dissertation, Universität der Bundeswehr Hamburg, 1997
- [3] B. Bommeli: „*Étude de l'influence de la contamination sur l'amorçage des décharges dans les diélectriques liquides*“, Dissertation, Université de Genève, 1979
- [4] D. Bichsel, M. Kocher: „*Contamination Evolution in EDM Die Sinking*“, Proc. 12th International Symposium for Electro-discharge machining (ISEMXII), Aachen, pp. 351-357, 1998
- [5] Deutsches Patent DE 3117 814: „*Verfahren und Schaltung zum Bestimmen des elektrischen Widerstandes im Arbeitsspalt einer funkenerosiven Werkzeugmaschine*“
Inventor: J. V. Vailiev, M. S. Otto, M. L. Levit; ENIMS, Moskau, 1981
- [6] H. Peuler: „*Identifizierung des Entladungsprozesses bei der funkenerosiven Senkbearbeitung und Auslegung von Regelungseinrichtungen*“, Dissertation, RWTH Aachen, 1981
- [7] M. Slomka: „*Funkenerosives Senken - adaptive Vorschubregelung und Planetärbewegung*“, Dissertation, RWTH Aachen, 1989
- [8] J. M. Dehmer: „*Prozeßführung beim funkenerosiven Senken durch adaptive Spaltweitenregelung und Steuerung der Erodierimpulse*“, Dissertation, RWTH Aachen, 1992
- [9] D. F. Dauw: „*On-line Identification and Optimization of Electro-Discharge Machining*“, Dissertation, Katholieke Universiteit Leuven, 1985

- [10] Europäisches Patent EPA 0099613: „*Method of prevention of arcing in a spark erosion process*“, Inventor: H. E. de Bruyn, Sticing Steunfonds Laboratorium voor werkplaatstechniek en Organisatie van de technische Hogeschool Delft, 1983
- [11] H. Timm: „*Elektronische Stromquellen für das funkenerosive Schneiden von elektrisch schlecht leitfähigen Werkstoffen*“, Dissertation Otto-von-Guericke-Universität Magdeburg, 1996
- [12] R. P. Raabe: „*Prozeßoptimierung für das funkenerosive Senken mit Neuro-Fuzzy-Control*“, Dissertation RWTH Aachen, 1999
- [13] Deutsches Patent DE 2125749: „*Vorrichtung zum Erkennen von Lichtbögen bei Funkenerosionsbearbeitung*“, Inventor: J. A. Best, E. Avenarius, J. W. Zeeuw, Naamloze Vennootschap Philips Gloeilampenfabrieken; 1981
- [14] Deutsches Patent DE 2214486: „*Funkenerosionsverfahren*“, Inventor: G. A. Marendaz, Ateliers des Charmilles, S. A., 1983
- [15] Deutsches Patent DE 3327900: „*Elektrische Entladungsvorrichtung*“, Inventor: T. Itoh, Mitsubishi Denki K.K., 1984
- [16] Deutsches Patent DE 19513593: „*Tiefendeionisierung des Arbeitsspaltens und Unterdrückung von parasitären Kurzschlußströmen für geregelte Prozeßstromquellen mit Spaltkurzschlußschalter zur Stromkommutierung im Bereich von Funkenerosionsmaschinen*“, Inventor: A. Behrens, M.P. Witzak, F.-L. Bruhns; 1995
- [17] A. Behrens, J. Ginzel: „*Neuartige Konzepte für Prozeßführungssysteme funkenerosiver Senkanlagen*“, Proc. Fachtagung Leistungselektronik und intelligente Bewegungssteuerungen, Magdeburg, pp. 198 - 203, 1999
- [18] G. Janzen: „*Kurze Antennen: Entwurf u. Berechnung verkürzter Sende und Empfangantennen*“, Franckh'sche Verlagshandlung W.Keller&Co, Stuttgart 1986
- [19] U. Busack, K. Schmidt: „*Auf Statistik basierende Methoden reduzieren den Aufwand für Versuche zum Senkerodieren*“, Maschinenmarkt 101, Würzburg, pp. 42 - 47, 1995
- [20] Patentanmeldung, Deutsches Patentamt DE 195 12 291 A1
 „*Verfahren und Schaltung zur Überwachung und Vorhersage eines Funken-erodierprozesses in einer Funken-erodiermaschine*“
 Inventor: A. Behrens, M.P. Witzak, F.-L. Bruhns; April 1995