Review

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Advances in EDM Monitoring and Control Systems Using Modern Control Concepts

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Abstract

The EDM process performance depends on the control of the machining gap and discharge pulses parameters. The dynamic performance of the servo control system and the controllable range of pulse power generator play important roles determining the stability, productivity, and quality of the machined surface. This paper reviews the research and development activities related to EDM process monitoring and control system in last two decades. Important research activities include different EDM gap monitoring systems, servo and pulse adaptive control systems, and application of modern control theory into the EDM monitoring and control systems.

Key Words: EDM, monitoring, control, adaptive control

1. INTRODUCTION

In modern manufacturing industries, the Electrical Discharge Machining (EDM) process is rapidly becoming an effective method for machining advanced difficult-to-machine materials and complex shapes.[1),2)] To realize EDM's full application potential and integration within the future manufacturing environment, many attempts are being made to enhance the technological capabilities of ED machines.[3)-6)]

During the EDM process, the machining gap between the tool electrode and workpiece is submerged in the dielectric fluid, and the material is removed evenly around the tool electrode due to the pulsed spark discharges that shift discharge locations all over the machining gap. In die-sinking EDM process, when machining a deep cavity, the arc discharges always occur due to the poor flushing condition. Because of the low power density and fixed discharge location, the arc discharges produce thermal damage on workpiece and tool surfaces.[3),7)-11)] The arcing damage substantially reduces the machining productivity and decreases the surface quality of workpiece, and it also greatly increases the machining cost.

In order to improve the machining rate, stability, and quality, extensive efforts have been made by the researchers and manufacturers to develop advanced monitoring and control system to identify and eliminate the arc damage. This paper reviews the worldwide research activities of developing the advanced monitoring and control systems for die-sinking EDM in last two decades.

2. EDM MONITORING TECHNOLOGY

Figure 1 shows the voltage and current waveforms of five basic EDM gap states, that were collected by a high speed digital oscilloscope during the EDM process. Sound, light, and electrical radiation signals associated with EDM discharges contain information pertaining to electrical, mechanical, and thermal processes at the gap. Extensive research and development efforts have been made to analyze these

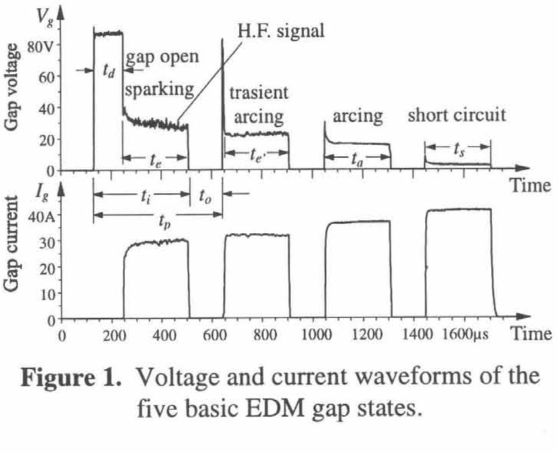

Figure 1. Voltage and current waveforms of the five basic EDM gap states.

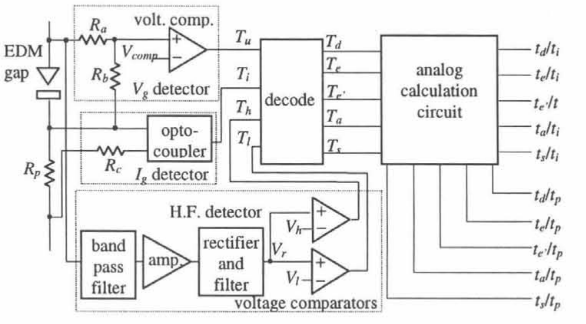

Figure 2. Circuit diagram of an EDM gap monitor.[17)]

signals seeking an effective method to distinguish the normal sparks and harmful arcs. Investigations on the identification of normal spark and harmful arc using radio, acoustic, and photo signals were reported by Bhattacharyya and El-Menshawy[12)-14)] in 1970's.

Experimental studies show that for most of the discharges, a certain amount of ignition delay time (t_d) can be used as an indicator of normal sparks because a longer ignition delay means that gap is well deionized before the occurrence of a discharge. The EDM gap parameters monitoring system (EDM Analyzer) reported by Snoeys and Cornellissen[15)] monitors the ignition delay t_d, and identifies four major gap states, i.e., gap open, normal spark, harmful arc, and short circuit. It provides the time ratio parameters of each identified gap states, including gap open or ignition delay (Φ_d), normal spark (Φ_e), harmful arc (Φ_a), and short circuit (Φ_s). These parameters are defined as the ratio of accumulated gap states to an accumulated cycle time t_p (i.e. recording period), as $\Phi_d=\Sigma t_d/\Sigma t_p$, $\Phi_d=\Sigma t_e/\Sigma t_p$, $\Phi_d=\Sigma t_a/\Sigma t_p$, and $\Phi_d=\Sigma t_s/\Sigma t_p$. The recording period for each data point is adjustable.

The radio or high frequency (H.F.) signal generated during EDM is believed to be a unique feature of the spark discharge. In 1979, an EDM gap monitoring system that identifies the spark and arc with the high frequency signal was reported by Crookall *et al*[16)]. This system detects the high frequency signal on the gap voltage in a frequency band from audio to 7MHz, and provides an output signal of pulse efficiency that accounts the time ratio of normal sparks.[7),16)]

A study reported by Wang[17)] investigated the high frequency (H.F.) component signals generated by sparking with various tool and workpiece material combinations under different machining conditions. This research revealed that the normal spark discharge generate H.F. signals in a very wide frequency band, from audio to 1 GHz.[18)] Based on this study, a new EDM gap monitoring system has been developed. Figure 2 shows the simplified circuit diagram of this monitoring system. This system detects the gap voltage and current and the intensity of the H.F. component signal on the discharge voltage in the frequency band of 10-500 MHz to identify the five basic EDM gap states given in Figure 1. This monitoring system can also precisely measure the time ratio of each gap state to the pulse on-time t_i, including time ratios of gap open t_d/t_i, normal spark t_e/t_i, transient arc $t_{e'}/t_i$, harmful arc t_a/t_i, and short circuit t_s/t_i, and also the time ratio of each gap state to the pulse cycle time t_p, i.e., gap open rate t_d/t_p, normal spark rate t_e/t_p, transient arc rate $t_{e'}/t_p$, harmful arc rate t_a/t_p, and short circuit rate t_s/t_p. The output signals are moving average analog voltages proportional to these parameters with a constant time of 2ms. The unique feature of this monitoring system is its capability to identify transient arcs. The transient arc occurs when the gap pollution starts. The transient arc parameter is an indicator of the onset of occurrence of harmful arcing.[18)-20)]

3. EDM ADAPTIVE CONTROL SYSTEMS

The main objective of developing advanced monitoring and control system for EDM is to adjust on-line the machine settings to improve the machining performance. The control systems using on-line optimization, self-tuning regulation and control, model reference, and fuzzy logic are described in following subsections.

3.1 Optimization for Servo and Pulse Parameters

During machining, the gap size is a random variable due to the stochastic and dynamic nature of the EDM process. The average gap width is controlled by monitoring the average gap voltage which is approximately proportional to the average gap size. A control reference voltage V_s is used to compare the feedback gap voltage, and the difference value of the comparison drives the servo mechanism to maintain average gap voltage at the level determined by the servo reference voltage.

In EDM, if the servo reference voltage V_s is set at

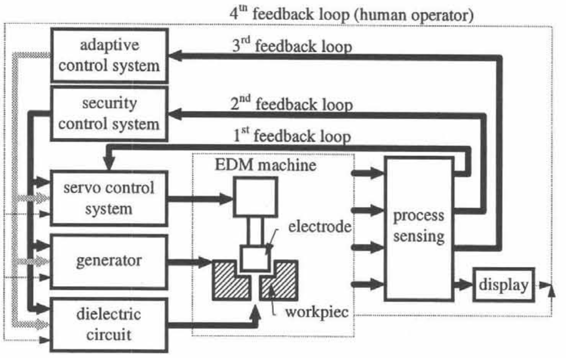

Figure 3 EDM adaptive control system proposed by Snoeys *et al.*[23)]

a very low level, the corresponding average gap size is small that increases the occurrence rate of short circuit and arcing. When servo reference voltage is set too high, the related gap is enlarged and generates more open circuit pulses to reduce the pulse efficiency.

The setting of pulse off-time t_o is also an important issue for determining the machining efficiency. When the off-time is set at a very small value, the time for deionizing the plasma channel in the dielectric fluid at the gap is insufficient, and consequently generates arc discharges. If the pulse off-time is too long, the time ratio of effective spark is reduced to decrease the machining rate. Therefore, both servo reference voltage V_s and off-time t_o have parabolic relationships with machining efficiency.[21)]

Figure 3 shows the block diagram of the EDM adaptive control system proposed by Kruth *et al*[21),22)] and Snoeys *et al*[23)]. This system uses the EDM analyzer reported by Snoeys and Cornellissen[15)] as the gap data monitoring unit. The pulse efficiency Φ_e ($=\Sigma t_e/\Sigma t_p$) is used as the controlled parameter. The system changes on-line the value of V_s and t_o seeking the highest value of Φ_e in order to achieve maximum machining rate. A two dimensional Steepest-Ascent algorithm was used to search the optimal values of V_s and t_o (Figure 4). The magnitude of the adjustments of V_s and t_o for each control step is determined with the discrete derivative values of Φ_e to V_s and t_o, as

$$\Delta V_s(k)=K_v \Delta_v \Phi_e(k) / \Delta V_s(k-1) \quad (1)$$

$$\Delta t_o(k)=K_t \Delta_t \Phi_e(k) / \Delta t_o(k-1) \quad (2)$$

where k is the time point, k=1,2,3... . $\Delta_v\Phi_e(k)$ and $\Delta_t\Phi_e(k)$ are the changes in Φ_e at time point k due to

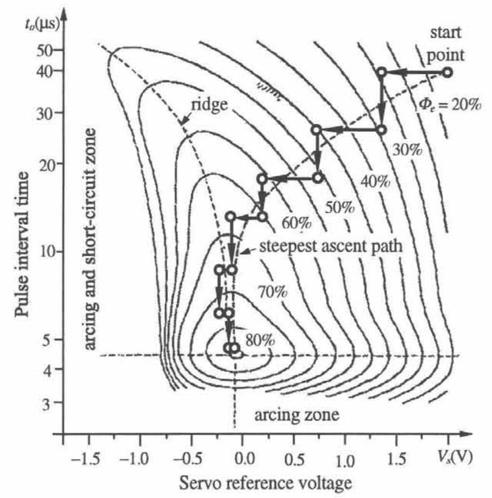

Figure 4. Optimization of servo reference voltage and pulse off-time.[21)]

adjustments ΔV_s and Δt_o at time point k−1. Properly selecting the adjusting gains K_v and K_t, the values of V_s and t_o can be smoothly converged to the saddle points to achieve the maximum Φ_e. Therefore, the machining parameters V_s and t_o are maintained at optimal levels during machining.

This system is the first application of modern control concept to the EDM monitoring and computer control system with on-line search of the optimal machining parameters during machining. This research indicated the potential benefits of using advanced monitoring and control technology to improve the EDM process performance.

3.2 Self-Tuning Control for Servo and Pulse

EDM is a stochastic and dynamic process, and, therefore, a control system using dynamic approach is expected to provide a better performance. An EDM self-tuning control system using dynamic modeling approach to adjust servo reference voltage V_s and pulse off-time t_o was reported by Wang[19)]. Figure 5 shows the transfer block diagram of this system. The EDM monitor reported by Wang[17)] is as the gap data monitoring unit. The control system was developed based on a single board computer with an 8bit and 2MHz CPU. A multiple input and output model is used to describe the dynamic relationship between the system outputs Y_v and Y_t to the control values V_s and t_o. The output variables Y_v and Y_t are used for the control of the servo reference voltage V_s and pulse off-time t_o, respectively. The output

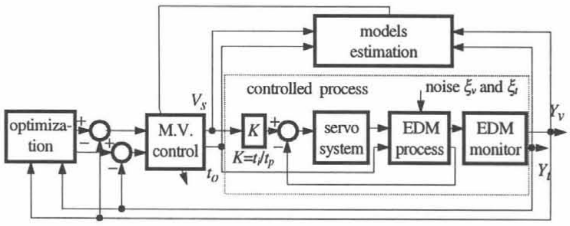

Figure 5. Self-tuning control system of servo reference voltage and pulse off-time.[19)]

variable Y_v is defined as a parameter representing gap conditions to be influenced mainly by servo reference voltage as

$$Y_v=-(t_e/t_i+2t_{e'}/t_i+2t_d/t_i+2t_s/t_i) \tag{3}$$

When the machining gap width is large and no discharge occurs, Y_v=0. If the gap is at optimal size and with excellent flushing condition, the corresponding spark ratio $t_e/t_i \approx 1$, and time ratios of other gap states are zero, therefore, Y_v=–1. When gap width is small or heavily polluted, the stable arcs or short circuits continuously occur, the value of Y_v approaches –2.

The value of Y_t is defined with the discharge parameters influenced mainly by pulse off-time as

$$Y_t=-(t_e/t_p+2t_{e'}/t_p+2t_d/t_p) \tag{4}$$

When the gap is well flushed and without the occurrence of arcing, $Y_t=t_e/t_p$. The decrease in Y_t shows the occurrence of transient arc and stable arc.

The output variables of Y_v and Y_t are modeled separately with the control values V_s and t_o (when the sampling interval is 0.1 second) as

$$Y_v(k+1)=b_{10}V_s(k)+b_{11}V_s(k-1)+b_{1c}+\xi_v(k) \tag{5}$$

$$Y_t(k+1)=b_{20}t_o(k)+b_{2c}+\xi_t(k) \tag{6}$$

During machining, a least-square identification algorithm is used to estimate the model parameters, b_{10}, b_{11}, b_{1c}, b_{20}, and b_{2c}. Based on the estimated model parameters, a minimum-variance-control (MVC) strategy generates the control value of $V_s(k)$ and $t_o(k)$ to maintain the output values $Y_v(k)$ and $Y_t(k)$ at the levels of references Y_{rv} and Y_{rt}, respectively. The reference values Y_{rv} and Y_{rt} are set manually according to given machining conditions.

Experimental analysis shows that when machining a deep cavity using a 25mm diameter copper electrode at the depth of 80mm without flushing and the reference value Y_{rv} and Y_{rt} are selected as –0.96 and –0.95, this system effectively avoids the arcing damage and increases the machining rate by 20%.

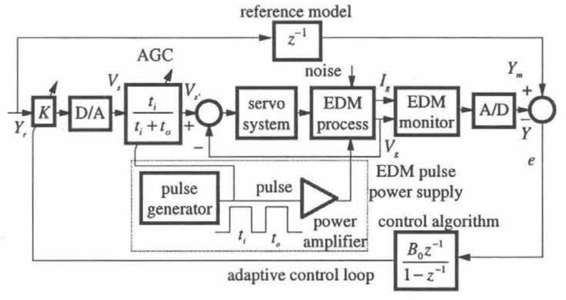

Figure 6. Block diagram of the model reference adaptive control system of EDM.[20)]

3.3 Model Reference Servo Control System

In order to simplify the structure of the EDM self-tuning control system described in previous section, a model reference control system was proposed.[20)] The transfer block diagram of the model reference control system is given in Figure 6. This system uses a modified version of the EDM monitor reported by Wang[17)] at the gap data monitoring unit. A PC 286 8MHz computer was used to produce the servo reference voltage V_s with a D/A interface. The output value Y of the controlled process is defined in the form that can be linearized with the machining gap size as

$$Y = 2t_d/t_i + t_e/t_i \tag{7}$$

When the gap is extremely large, Y equals 2 as the gap-open (t_d/t_i) is 100%. When the gap state is optimal, Y equals 1 because the normal sparking ratio t_e/t_i is close to 100%. If the gap is highly polluted, there is no gap-open and normal spark pulse in the gap, Y equals 0. Therefore, the gap state parameters can be controlled by changing Y. A control reference value Y_r is used as the target value of Y, and can be optimized by a computer or preset manually according to the machining settings.

A reference model is used to describe the desired relationship of process output (Y) and the target value of the adaptive control loop (Y_r). Y_r is simultaneously sent to both the reference model and the controlled process. The control algorithm is shown in Figure 5. During machining, the difference

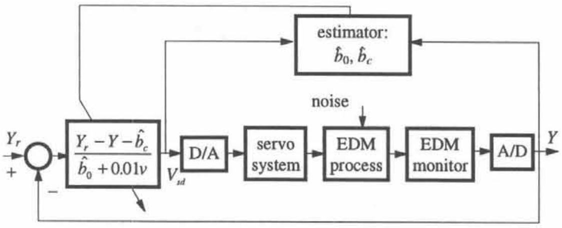

Figure 7. Block diagram of the self-tuning regulator for EDM servo adaptive control.[24)]

between Y (the output of the process) and Y_m (the output of the reference model) is controlled at minimum values. In this research, an attempt has been made to simplify the model based on the unit delay (Figure 6). The feed forward gain $K(k)$ is always changed to compensate for the changes in the process properties caused by the time variant feature of the EDM process. The system stability can be adjusted by selecting the coefficient B_0 and sampling interval. The sampling interval in this study is set at 0.1 second.

This control system has been verified with extensive experimental study to improve machining productivity by 25-200% as compared to the original control system of a conventional EDM machine when machining a deep cavity with area of 470mm^2 for the peak current (I_p) from 5 to 30A.

3.4 Self-Tuning Regulator for Servo Control

The EDM servo reference adaptive control systems only adjust the input of the servo control loop V_s, without addressing the internal dynamic characteristics of the closed loop servo system and stochastic features of the machining process. The EDM process is of stochastic nature and unstable under finish or semi-finish machining without flushing, and there are many gap-open and gap-short pulses but very few sparking pulses. The variations of system output Y may be very frequent and large.

The advancement of computer technology in the early time of 1990's provided sufficient speed of computation capability to process EDM data and mathematical model for direct servo control loop. An EDM servo adaptive control using self-tuning regulator approach was developed.[24)] A PC 386 25MHz computer system was used to directly generate the servo driving signal with an adaptive regulating strategy according to the internal dynamic features of the control system and as well as the

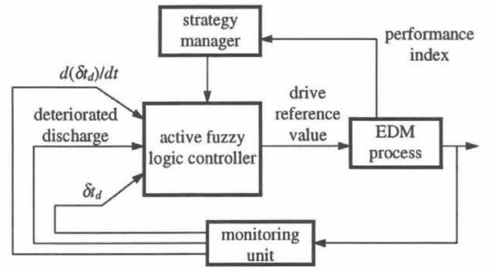

Figure 8. Block diagram of the EDM fuzzy logic control system proposed by Ethz and Dauw.[11)]

stochastic characteristic of machining process in order to achieve higher machining stability, and to provide the same merits of model reference adaptive system described in the previous section..

The block diagram of the self-tuning regulator for EDM servo adaptive control is shown in Figure 7. The input control signal (Y_r) of adaptive control loop is generated similarly to the model reference adaptive controller described in previous section. The output function Y is the same as that in equation (7). The relationship between V_{sd} and the process output Y (with a 2ms sampling interval) is described by a mathematical model as [24)]

$$Y(k+m+1)=Y(k)+b_0V_{sd}(k)+b_c+e(k+m+1) \qquad (8)$$

Where m is the number of delay steps of the transfer from V_{sd} to Y, and $e(k+m+1)$ is the process noise e at the time step $k+m+1$. The b_0 and b_c are uncertain parameters and are estimated on-line by a fast least-squares identification algorithm. The control strategy V_{sd} is generated by a minimum-variance-control (MVC) law based on the identified parameters.

Experimental studies show that self-tuning regulator for the EDM servo adaptive control improves the process stability, and the process variance is reduced by 35% as compared to the model reference control given in previous section. Experiments were conducted by machining small holes and medium-size cavities. The improvement in the productivity ranged from 15-25% due to the self-tuning controller.

3.5 Fuzzy Logic Servo Control System

Figure 8 shows the block diagram of the adaptive fuzzy logic controller of Agie Fuzzytron control system. The servo feed control strategy is generated

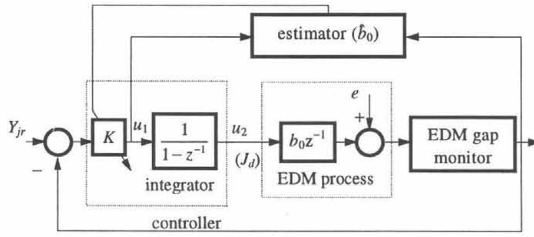

Figure 9. Self-tuning integral controller for EDM auto-jumping.[26]

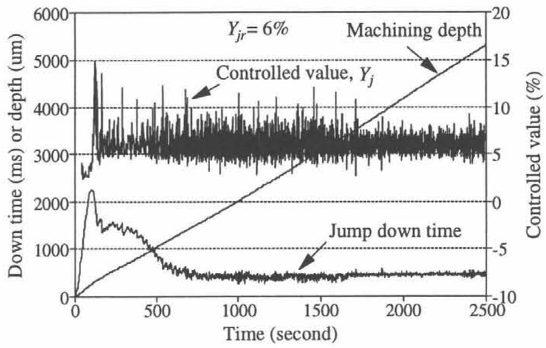

Figure 10. On-line recorded data with adaptive jumping control.[26]

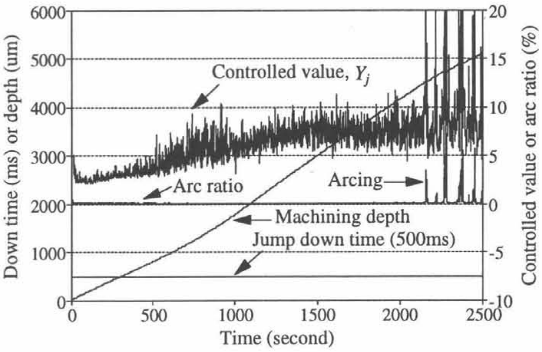

Figure 11. On-line recorded data of jumping machining without control.[26] (under same conditions in Figure 10)

by the fuzzy logic control system that encounters all measured gap parameters. Therefore, the system with a fuzzy logic control system can respond to all monitored gap signals in order to effectively avoid the arc damage, improve the machining rate and machined workpiece quality.

The servo driving signal is generated by a strategy that evaluates all monitored gap parameters, including the ignition delay time t_d, deteriorated discharge, and the change of ignition delay time δt_d. This control system is claimed to significantly improve the process stability and performance, and increase the machining rate by 20 to 300%.[11]

3.6 Self-Tuning Auto-Jumping Control System

When machining a deep cavity under extremely difficult flushing conditions, particularly using graphite electrode, the arc damage cannot completely be avoided by only adjusting servo and off-time parameters. In practical EDM applications, jumping operation is always used to periodically retract the tool electrode from the machining area to further improve the flushing condition in order to completely avoid arc damage. However, with most of the state-of-the-art EDM systems, the machining period (jump-down-time) between two jump-up-times (idle periods) is set by the operator according to previous experience. Because the control values of machining (jump-down) periods do not change in real-time to follow the change of the degree of the pollution by eroded material debris and carbon particles, machining performance can neither be optimal nor consistently stable.

Research activities on EDM adaptive jumping control have been recently reported by Zhao and Masuzawa [25] and Wang, *et al* [26]. Figure 9 shows the block diagram of one approach of these systems. A digital EDM gap monitor modified from the monitor reported by Wang and Rajurkar[20] was used within this system. This control system is developed on the basis of self-tuning integral control approach with multiple input gap state signals. The controlled value Y_j is defined as

$$Y_j = (\Sigma\tau_{e'} + 2\Sigma\tau_a) / \Sigma\tau_i \tag{9}$$

Where $\Sigma\tau_{e'}$, $\Sigma\tau_a$, and $\Sigma\tau_i$ are the accumulated time (in a control cycle) of transient arc ($\Sigma\tau_{e'}$), stable arc ($\Sigma\tau_a$), and pulse on-time ($\Sigma\tau_i$), respectively. Y_{jr} is the reference value for the control of Y_j. J_d is the machining time (jump-down-time) in a retraction (jumping) cycle. z is the operator of z-transform. The controlled process is modeled as b_0z^{-1} in extensive experimental analysis.[25),26] The control gain K is modified in real-time with the on-line identified model parameter $\hat{b}_0$. Figures 10 and 11 indicates the on-line recorded data of machining parameters with

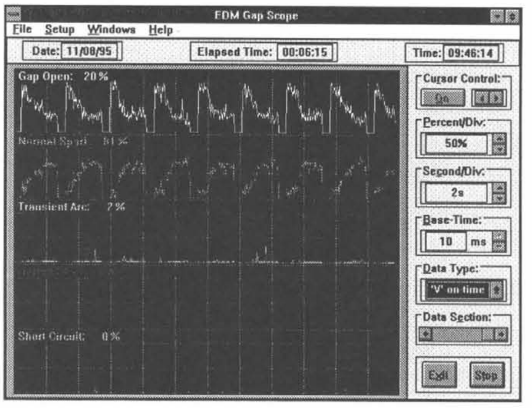

Figure 12 . EDM Gap Scope window.

and without adaptive control strategy, respectively, during machining a deep cavity.

As shown in Figure 10, in the beginning of machining, the flushing is good, thus the jump-down-time J_d is controlled at a higher value. When the machining depth increases, the flushing condition becomes poor, and the jump-down-time is gradually reduced to the level about 500ms. The machining depth smoothly increases without arcing damage (the controlled value y_j is kept at the level of y_{jr}). In Figure 11, the jump-down-time J_d is fixed at 500ms without adaptive control. Since the control parameter (jump-down-time J_d) is fixed and can not follow the change in machining conditions, the value of arc time ratio drastically increases when machining 2100 seconds (35 minutes). This result adequately proves the effectiveness of the control strategy.

3.7 Windows Software Package for EDM

The Agile Manufacturing is a new concept of the future generation manufacturing systems. The integration of EDM into Agile Manufacturing Systems requires the EDM control system to have capabilities of high level automatic and remote operation, strong network access capability, standard software interface, and ability to share CAD/CAM resources with remote EDM systems, and other remote manufacturing facilities.

A preliminary study of developing advanced software for next generation EDM system has been reported by Rajurkar and Wang[27)]. A die-sinking EDM monitoring and control software, entitled as *EDM Monitor & Controller* for Windows has been developed in this research. This software provides a platform for operating or testing different monitoring and control strategies, and can be used with any hardware interface and EDM machines for all EDM monitoring and control purposes, and are able to flexibly integrate with any monitoring and control algorithms programmed as DLL files, including data processing, fuzzy logic and neural-network control and analysis, servo control and modeling, identification of machining area, power generator control, and other adaptive control algorithms. Integration with an EDM monitoring system, this software package can be used to diagnose the machining process. Figure 12 shows the *EDM Gap Scope Window* in this software package that displays the continuous (scanning) values of gap parameters in the manner as an oscilloscope.

4. CONCLUSIONS

The capability and performance of EDM monitoring and control systems is continuously improving with the development of computer system and increasing knowledge of the EDM process. The increasing application area of EDM and future development of Agile Manufacturing System require the capability for machining diverse advanced materials with complicated shapes and high level automatic and remote operation, strong network access capability. In order to fulfill the future needs, the advancement in EDM monitoring and control system is continuing.

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