Dynamic behaviour of EDM system through mathematical model

D Dehghani[1], A Yahya[2] and N H Khamis[1]

[1]School of Electrical Engineering, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia
[2]School of Biomedical Engineering and Health Sciences, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia

Abstract. Electrical discharge machining (EDM) is a stochastic machining process which widely used to generate dies and molds. However, information about the EDM process is still at the earlier stage which lead to experience many challenges for further developments. Experimental analysis is time consuming as well as a costly procedure, due to the highly stochastic and complex nature of the process. Therefore, process modeling is an alternative to reduce the experimental costs related to the technology. This research proposes method to design a mathematical model of electrical discharge machining (EDM) system. The model will be used to understand the effects of machining parameters into the dynamic behaviour of EDM system based on the sparking phases and pulse power generator.

Keywords: EDM, stochastic nature, process modeling

1. Introduction

With the quick development in the industrial machining procedures, electrical discharge machining (EDM) has become the important and economical method for hole manufacturing [1]. EDM is a valuable technique for variety of hole manufacturing approaches, for example, in medical, aerospace, automotive and chemical industries as well as manufacturing of hard material devices [2]. In fact, for certain machining operations, the EDM procedure may be the only possible method to meet complex hole requirements.

Although a large number of EDM devices are sold every year, current knowledge about the process is still insufficient for its more development. Nonlinear and stochastic characteristics of EDM process vary the machining situations throughout the entire machining process [3]. It is mostly a phenomenon that the machining goes to an unstable degenerate machining condition and makes it difficult to experimentally study behaviour of the EDM system. Many researches have been done in order to discover a suitable approach to change gap condition and improve the EDM performance during experimental process. Efforts have been made to optimize the process parameters [4], develop controller for gap state monitoring [5] and enhance the flushing system [2]. However, investigation the EDM process is still challenging task due to the random nature of the process. In order to overcome difficulty aspects related to real machining environment, process modeling can be an alternative way to understand the mechanism underlying the EDM procedure. Although EDM spark profile plays important role in analysis the machining process, there is no mathematical model to identify the EDM spark profile during the machining procedure. Therefore, this paper proposes mathematical model of EDM spark profile to show dynamic behaviour of machining process.

2. Working principle

Electrical discharge machining (EDM) is one of the widely used machining methods [6] which uses spark discharge to remove conductive materials regardless of their hardness. Non-contact removal principle EDM makes it feasible to process complex surfaces with high quality and machining accuracy [7]. As shown in figure 1, EDM system composes of pulse power generator, servo system, dielectric fluid, electrode and workpiece.

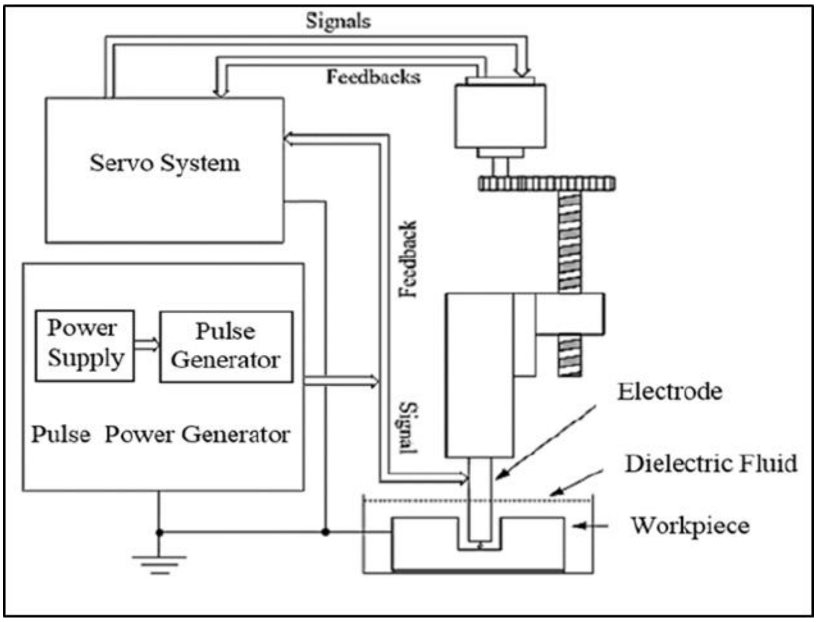

Figure 1. EDM system

Material is removed by using an accurately controlled electrical discharge (spark) that occurs between the electrode and the workpiece, which are connected to a pulse power generator and submerged in a dielectric fluid. A servo system controls the gap distance between electrode and workpiece. Equation 1 can be used to determine the energy provided by the pulse power generator, which is proportional to the amount of metal being removed. Thus from this relationship, the size of the eroded metal can be estimated [8].

$$W_e = V_{gap} \times i_{gap} \times t_{on} \tag{1}$$

where (W_e) is pulse energy (J), (V_{gap}) is gap voltage (V), (i_{gap}) is gap current (A) and (t_{on}) is discharge time (s). Generally, pulse power generator consists of two parts: power supply and pulse generator. DC voltage provided by power supply feeds to pulse generator to prepare controlled DC pulse with adjustable duty cycle D which uses by process spark to obtain discharge success with desirable gap current (i_{gap}) and gap voltage (V_{gap}) [9, 10]. As illustrated in figure 2, each spark cycle of EDM process (T_s) is divided into three phases namely ignition phase (t_d), discharge phase, (t_{on}) and recovery phase (t_{off}).

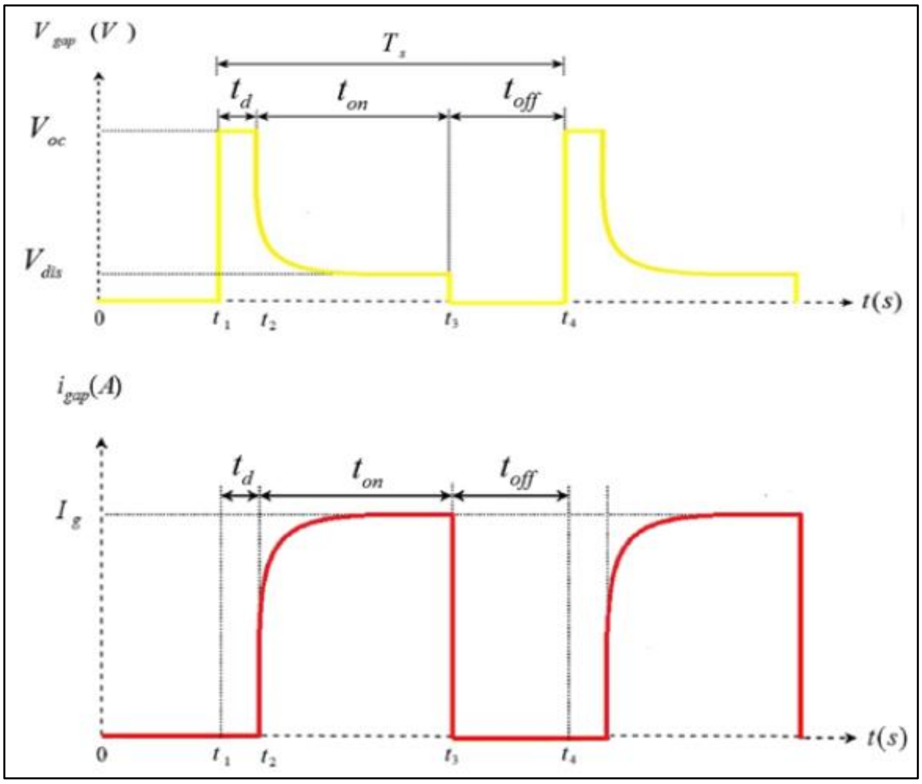

Figure 2. Spark profile of V_{gap} and i_{gap} during one machining cycle over time [11] .

Based on the spark profile illustrated in figure 2, ignition phase occurs in the time interval from t_1 to t_2. During this phase, a high gap voltage (V_{oc}) is applied between electrode and workpiece, causes a strong dielectric field. An ionization path is created through the dielectric and there is no current flow at the gap [12]. After a short ignition phase, the dielectric breaks down, gap current (i_{gap}) starts to flow while gap voltage falls to discharge voltage (V_{dis}). This phase is called as discharge phase and the time interval is from t_2 to t_3 [13]. Next phase is recovery phase which happens during the time interval from t_3 to t_4. During this phase, the flow of current is interrupted and desired insulating electric properties of the dielectric fluid are recovered [14, 15].

3. Significance of process parameters affected the EDM performance measures

The machining performance of EDM such as MRR (speed) and surface quality [16, 17] are mainly depends on process parameters. Many experimental research works have been done to find the influence of process parameters on EDM procedure. Most research works reveal that the machining time and gap current have the most effect on the EDM performance measures [18].

Gostimirovic et al. [19] investigated the influences of electrical process parameters on the operations of die-sinking electrical discharge machining procedure with RC pulse generator. Manganese-vanadium steel is used as workpiece and graphite is used as electrode. It is found that the material removal rate during the EDM process is highly influenced by the pulse duration and gap current. Chandramouli and Eswaraiah [20] conducted an experimental study of EDM process parameters on 17-4 Precipitation Hardening (PH) Stainless Steel. Taguchi method applied to reduce the effect of the external noise. It is found that material removal rate improves as the gap current increase. This increase attributed to the enhancement of spark energy that simplified the melting and vaporization of the material. However, preparing and repeating each exam makes the research procedure too lengthy.

Detailed experimental investigation of the surface quality and material removal mechanisms of Al2O3–SiCw–TiC ceramic composite with EDM process is presented by Patel et al. [21]. Surface damage and material removal mechanisms are examined using a Scanning Electron Microscope

(SEM). It is found that good surface quality and gentle material removal rate obtained at a low current range due to the lower thermal spalling in comparison to the rough cutting mode. It is also seen that increasing the pulse on time led to increase the surface quality. It may be related to the expansion of the plasma channel by increasing the pulse-on time. However, the process is time consuming due to experimental procedure.

Ahmad and Lajis [22] studied the influence of gap current and pulse duration on the performance of copper electrode in Edm of Inconel 718. Experimental results show that machining at a highest gap current of 40A and the smallest pulse duration of 200 μs gives the highest material removal rate (MRR). However, This experimental investigation is also time consuming related to stochastic nature of edm. Mohan et al. [22] studied the surface quality of the SiC/6025Al composite using electrical discharge machining process along with brass as the electrode. Experimental results showed that increasing gap current increases surface roughness in the machining process.

4. Discussion

Based on previous researches explained in section 3, pulse on time and gap current are major process parameters contributing to the improvement of the machining performance. However, study related works on effect of pulse on time and gap current on EDM behaviour shows that the stochastic nature of the EDM process still causes difficulty during the investigation process. In this study, dynamic mathematical model of EDM system is proposed to reduce experimental limitations during analysis. In order to find the mathematical model of EDM system, first circuit configuration will be designed and then mathematical equation of gap voltage and gap current will be obtained based on the designed circuit configuration. Then the model can be used to study behaviour of EDM system in term of pulse on time and gap current.

4.1. Circuit design process

Circuit can be designed by dividing EDM system into three consecutive parts as shown in Figure 3. Part A is the power supply section that provides required DC voltage to feed the system. Part B is the pulse generator section that generates timed pulses for delivering the DC voltage to the EDM spark circuit during specific duration and time interval. Both the power supply and pulse generator called pulse power generator. Part C is EDM spark circuit that provides gap profile including V_{gap} and i_{gap}.

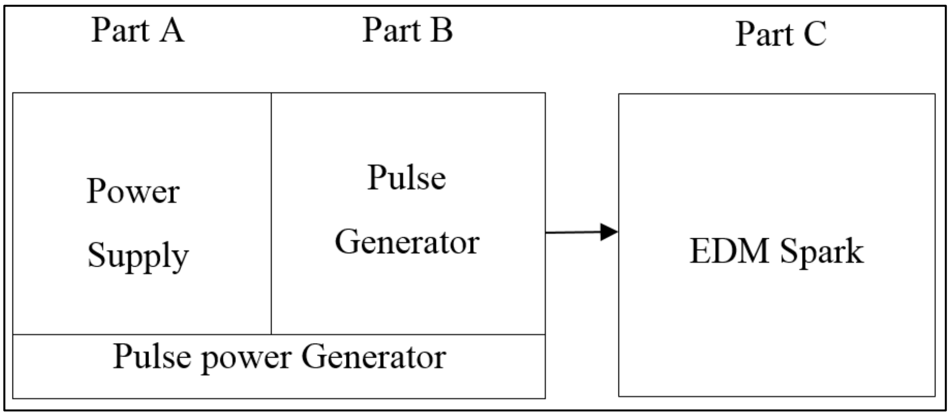

Figure 3. Block diagram for modeling EDM system

Switching power supply has some advantages such as simplicity and high efficiency [23, 24]. Also, the required V_{oc} is less than the peak voltage of the utility supply for most EDM applications. So, the Buck converter is suitable to use as switching power supply to convert the utility voltage to the lower value of DC voltage. The schematic diagram of the DC-DC buck converter is shown in figure 4.

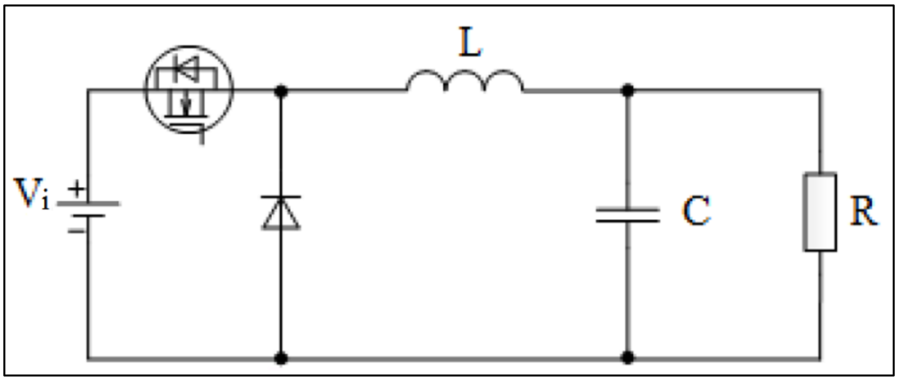

Figure 4. Topology of DC-DC buck converter [25].

Pulse generator is developed according to the transistorized switching circuit designed in the 1970's [26] as illustrated in figure 5. The transistor works as a high-speed switching device to control current from the capacitor to the gap. The voltage across the capacitor is retained by a DC supply and the transistor is controlled by using a low power pulse generator. In this design, MOSFET will be used as a high-speed switch due to its more efficient switches.

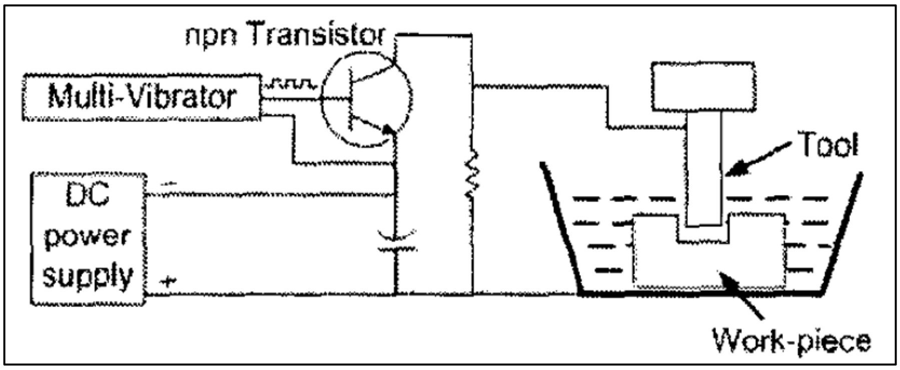

Figure 5. EDM system using transistorized switching circuit as pulse generator [26].

EDM spark is important part to model the EDM system. Dynamic behaviour of gap voltage and gap current will be studied in each machining phase of EDM system including ignition, discharge and recovery phases. Then, electrical circuit configuration for EDM spark will be obtained based on the spark profile. EDM spark profiles over one sparking cycle (T_s) as shown in figure 2.

4.2. Mathematical equation

Figure 6 shows proposed model of EDM spark circuit using buck converter as power supply and transistorised switching circuit as pulse generator. Mathematical equations will be derived to describe time variation of the gap voltage and gap current in each phase, separately. In this way, Kirchhoff's law and ohm's law will be applied to the EDM spark circuit shown in figure 4. Matlab software will be used to simulate model of EDM system using experimental data as variable parameters. Simulations will be done for different setting of variable parameters, experimental data will be selected from the work of A. Yahya [11] . For each set of selected variable parameters, the corresponding diagram presenting the gap current and gap voltage versus time will be obtained. After simulation shows good agreement with ideal spark profile, simulated model will be validated by comparing simulation results with experimental results from previous researcher [27] in the form of MRR.

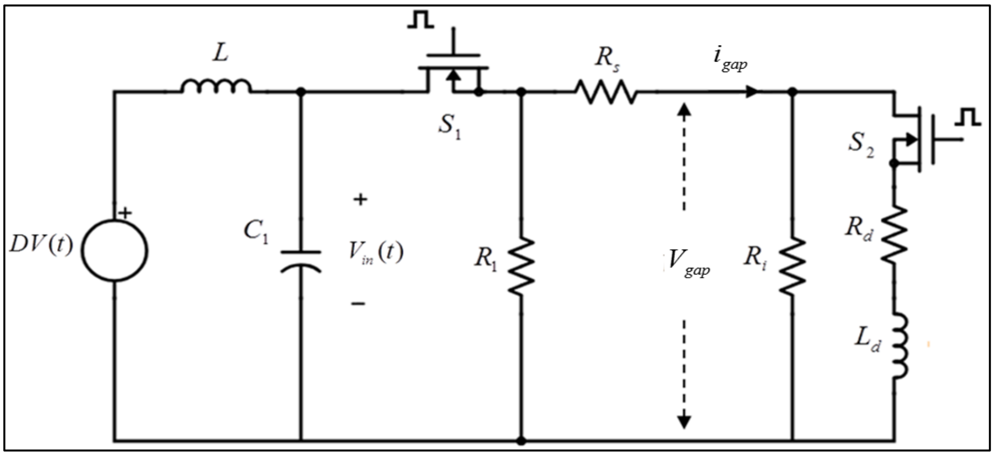

Figure 6. Proposed model of EDM spark circuit.

4.3. Validation of the EDM model

To validate the simulated model, simulated values of process parameters will be used to obtain simulated MRR. Simulated MRR will be then compared with experimental MRR obtained by former researcher [11]. To compare the simulated results with the experimental ones in the form of MRR, following Equation 2 is used which obtained in Ref [11].

$$MRR = C\alpha V_{dis} I_g t_{on} F_s [RERF] \tag{2}$$

where C is dimensionless constant, α is material properties factor and [RERF] is reduced erosion rate factor. To generate [RERF], The experimental data of different EDM process listed in table 1 were utilized to examine the average value of [RERF] with V_{arc}=25V, $\alpha = 2\times10^{-12}$ and C=1.74. Figure 7, shows plotted average value of [RERF] in term of $\frac{t_{on}}{t_d}$.

Table1. Experimental MRR for different EDM process parameters [11].

Process	$t_{on}(\mu s)$	$t_{off}(\mu s)$	$F_s(KHz)$	$\dot{V}\ (mm^3/\min)$							
				$I_{gap}=4A$	$I_{gap}=6A$	$I_{gap}=8.5A$	$I_{gap}=12.5A$	$I_{gap}=18A$	$I_{gap}=25A$	$I_{gap}=36A$	$I_{gap}=50A$
1	2	4	125	4	7	-	-	-	-	-	-
2	3	4	111.11	6	9	11	16	-	-	-	-
3	4	4	100	8	11	16	20	16	46	-	-
4	6	4	83.33	10	12	21	31	42	60	72	82
5	12	4	55.55	13	19	23	43	54	81	111	143
6	25	4	32.25	15	23	31	48	68	99	137	170
7	50	6	17.24	17	26	36	52	79	126	181	218
8	100	12	8.77	19	23	38	54	86	126	175	250
9	200	25	4.41	13	21	33	47	72	110	151	221
10	400	50	2.21	12	19	29	43	65	90	141	200

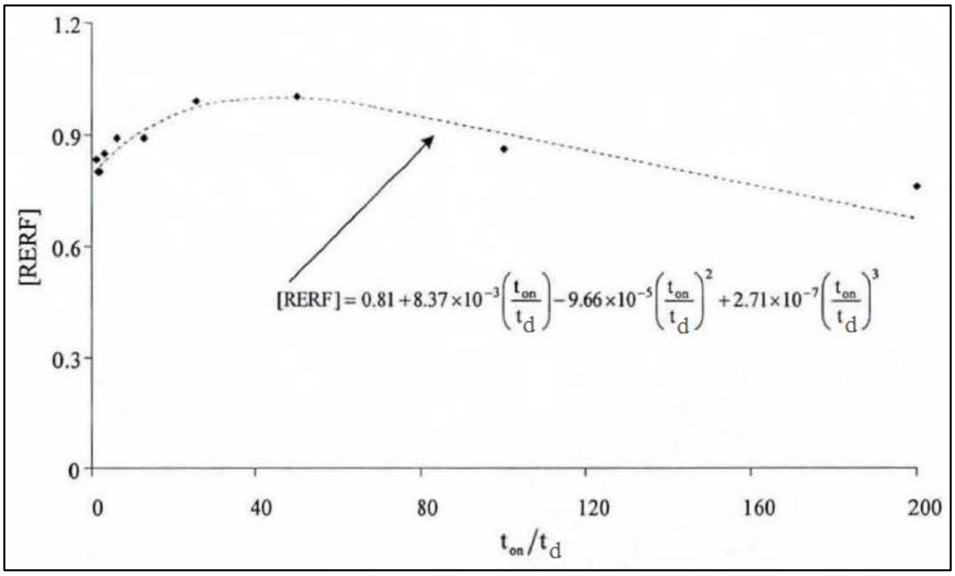

Figure 7. Value of [RERF] in term of $\frac{t_{on}}{t_d}$ [11]

In this study, simulated values of variable parameters including I_g, T_{on}, T_{off} and F_s as input data, will be measured using time scope contained several measurements. Measured values will be the substituted into the Equation 3 to obtain simulated MRR. A series of Matlab simulations will be conducted using experimental data from A. Yahya [11]. After obtaining the simulated MRR, the proposed model will be verified by comparing simulated MRRs with experimental MRRs carried out by the same researcher in Ref [27]. For each simulated process, the deviation in the prediction of the MRR will be evaluated using following error function.

$$\%error = \left|\frac{Actual.value - \Pr edicted.value}{Actual.value}\right| \times 100 \quad (3)$$

Then, average of prediction error for each electrode material will be obtained.

4.4. System Analysis

The simulated model of EDM system can be used to analyse influence of process parameters on machining performance by removing practical challenges. Pulse on time and gap current will be considered as important process parameters effected on machining behaviour [15, 18]. While, material removal rate (MRR) and surface quality will be considered as significant machining performance measures [28]. Collected data for model validation will be used to assess effect of pulse on time and gap current on machining speed (MRR).

In the case of the surface quality, only equivalent EDM model in the discharge phase considered. The fact that spark takes place in the discharge phase [29], is the main reason for this consideration. The methodology steps for study and analysis the surface quality can briefly present as following.

Step one, the mean node voltage method will be applied to simplify the proposed equivalent EDM model. Step two, the transfer function of the simplified model at the discharge phase will be derived from the rectified input voltage to the gap current. Step three, theoretical transfer characteristics of the EDM system including gain margin and phase margin will be determined from derived transfer function in step two. Step four, these stability margins are calculated for series of process parameters with different pulse on time and gap current. For each set of process parameter discharge stability is determined based on the following stability criterion: For a minimum-phase system, both the gain and phase margins must be positive to ensure the system stability [30]. Step five, to validate the frequency analyse, theoretical and simulated bode plots will be obtained and compared for selected values of pulse on time and gap current. Step six, after validation of frequency analysis, calculated stability margins obtained in step 4 along with their corresponding values of process parameters will be used to examine the effect of pulse on-time and gap current on surface quality.

5. Conclusion

This paper proposes a strategy to design the mathematical model for the EDM system. The proposed model consisted of power supply, pulse generator and EDM spark circuit. Buck convertor and transistorized switching circuit are considered as power supply and pulse generator, respectively. Time-domain mathematical equations of the gap voltage and gap current will be obtained to describe ignition, discharge and recovery phases. The model will be validate by comparing simulated MRRs and experimental MRRs from previous researcher. Pulse on time and gap current are considered as important parameters effected on EDM performance. All steps to analyse the effect of pulse on time and gap current on machining speed (MRR) and surface quality are explained. It is expected that the mathematical model of the EDM system in predicting dynamic behaviour of EDM system can be achieved to understand the effects of machining parameters of EDM behaviour.

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