GAP PROFILE MODEL OF ELECTRICAL DISCHARGE MACHINING PROCESS TO PREDICT MATERIAL REMOVAL RATE

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ABSTRACT

Electrical discharge machining (EDM) is a non-traditional material removal technique using an electrical spark-erosion process in the presence of dielectric liquid where electrode and workpiece are not in physical contact. Although EDM is widely implemented in the manufacturing industry, knowledge about the process is still at an early stage, which poses many challenges for further development. Experimental analysis is time-consuming and costly due to the highly stochastic and complex nature of the process. Thus, research efforts are directed toward process modeling to study EDM behaviour by eliminating experimental difficulties. Developed models are mostly centred on only one sparking phase, especially the discharge or ignition phase. In order to achieve a complete understanding of machining behaviour, it is essential to consider all sparking phases. This research presents a mathematical model of EDM gap profile by introducing an equivalent circuit of gap spark. This is to reach precise insight into the interactive behaviour of the machining process regarding ignition, discharge and recovery phases. The equivalent circuit model is designed based on the sparking phases and pulse power generator. Buck converter and transistor-based switching circuits are used to provide suitable pulsed voltage. Spark circuit is employed to obtain mathematical equations of gap profile for studying the time-varying behaviour of the EDM process through Matlab simulation. In order to validate the model, simulated data are first compared with previous experimental data and then with data from the EDM operation manual, both in term of Material Removal Rate (MRR). It is shown that the simulated model can predict the dynamic behavior of the EDM process with an average simulated error of about 8.27% for steel workpiece and copper electrode and about 7.93% for steel workpiece and graphite electrode. Comparison with MRR from the EDM manual also showed an average error of 10.10%, which is acceptable to standardize the validation process. Besides, the consistency range of the model is confirmed at noise power $n_p \leq 10^{-5} J$ with an average error of 11.15% for steel workpiece and copper electrode. Then, a parametric study of simulated MRR is carried out to investigate the effect of pulse on-time and peak gap current on MRR. Research conducted shows that the MRR increased by increasing pulse on-time and peak gap current up to peak value of pulse on-time for each peak discharge current. Finally, based on the EDM discharge self-sustaining condition, gap discharge closed-loop structure is formed via discharge model to evaluate the discharge stability. The Influence of peak discharge current on the response time of the system is analyzed using frequency response method. It is found that increasing peak discharge current results in slower system time response and improves the discharge stability. This study can be helpful to reveal the mechanism of EDM, predict the machining time, maintain the discharge stability, and select the process parameters.

ABSTRAK

Pemesinan nyahcas elektrik (EDM) adalah teknik bukan konvensional yang digunakan untuk menyingkir bahan menggunakan proses percikan-hakisan dengan kehadiran cecair dielektrik, di mana elektrod dan bahan kerja tidak bersentuhan secara fizikal. Walapun EDM digunakan secara meluas dalam industri pembuatan, pengetahuan dalam pemesinan ini masih berada di tahap awal dan masih mempunyai banyak cabaran dalam perkembangan seterusnya. Analisis eksperimental memakan masa dan melibatkan kos yang mahal kerana sifat proses yang sangat stokastik dan kompleks. Oleh itu, usaha penyelidikan dilakukan dalam bentuk pemodelan proses untuk mengkaji tingkah laku proses EDM dengan mengelakkan kesukaran melakukan eksperimen. Model yang telah dibangunkan sebelum ini kebanyakannya hanya berfokus pada satu fasa percikan, terutamanya fasa nyahcas atau pencucuhan. Untuk mendapatkan pemahaman yang menyeluruh mengenai tingkah laku pemesinan, adalah penting untuk mempertimbangkan semua fasa percikan. Penyelidikan ini mempersembahkan model matematik profil jurang EDM dengan memperkenalkan litar pencucuhan jurang yang setara. Ini bagi mendapatkan gambaran dan kefahaman yang lebih jelas dan tepat mengenai tingkah laku interaktif dalam proses pemesinan berkaitan fasa pencucuhan, menyahcas dan pemulihan. Model litar setara direka berdasarkan fasafasa percikan dan penjana kuasa nadi. Litar pensuisan Buck converter dan transistor digunakan untuk memberikan denyut voltan yang sesuai. Litar percikan digunakan untuk mendapatkan persamaan matematik daripada profil jurang bagi mengkaji karektar perubahan masa proses EDM melalui simulasi Matlab. Untuk mengesahkan model, data yang disimulasikan terlebih dahulu dibandingkan dengan data eksperimen yang diperolehi dari kajian sebelum ini dan kemudian dibandingkan dengan data dari manual operasi EDM, kedua-duanya dari segi kadar hakisan bahan (MRR). Model simulasi menunjukkan tingkah laku dinamik proses EDM dapat diramal dengan ralat simulasi 8.27% bagi bahan kerja keluli dan elektrod tembaga dan 7.93% bagi bahan kerja keluli dan elektrod grafit. Perbandingan dengan MRR dari manual EDM juga menunjukkan ralat 10.10% di mana ianya dapat diterima untuk menyeragamkan proses pengesahan. Selain itu, julat konsistensi model pada kuasa gangguan, $n_p \leq 10^{-5} J$ telah disahkan dengan ralat 11.15% bagi bahan kerja keluli dan elektrod tembaga. Kemudian, kajian parametrik simulasi dijalankan untuk mengkaji kesan denyut nadi tepat waktu dan arus jurang puncak ke atas MRR. Penyelidikan yang dijalankan menunjukkan bahawa MRR meningkat dengan meningkatnya denyut nadi tepat waktu dan arus jurang puncak hingga nilai puncak denyut tepat waktu untuk setiap arus nyahcas puncak. Akhirnya, berdasarkan kelestarian nyahcas EDM, struktur gelung tertutup nyahcas jurang dibentuk melalui model penyahcas untuk menilai kestabilan cas. Pengaruh arus nyahcas puncak pada masa tindak balas sistem dianalisis menggunakan kaedah sambutan frekuensi. Didapati bahawa peningkatan arus nyahcas puncak menghasilkan sambutan masa sistem yang lebih perlahan dan meningkatkan kestabilan nyahcas. Kajian ini dapat membantu untuk mendedahkan mekanisma EDM, meramalkan masa pemesinan, menjaga kestabilan nyahcas dan memilih parameter proses.

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LIST OF ABBREVIATIONS

EDM	-	Electrical Discharge Machining
WEDM	-	Wire Electrical Discharge Machining
PMEDM	-	Powder Mixed Electrical Discharge Machining
MRR	-	Material Removal Rate
TWR	-	Tool Wear Rate
SQ	-	Surface Quality
SR	-	Surface Roughness
DC	-	Direct Current
AC	-	Alternating Current
AGIE	-	Australian Government Indigenous Expenditure
HAZ	-	Heat Affected Zone
ANN	-	Artificial Neural Network
FFANN	-	Feed Forward Artificial Neural Network
SMA	-	Shape Memory Alloy
MMC	-	Metal Matrix Composites
PH	-	Precipitation Hardening
ERFC	-	Complementary Error Function
CCM	-	Continuous Conduction Mode
DCM	-	Discontinuous Conduction Mode
BCM	-	Boundary Conduction Mode
MOSFET	-	Metal Oxide Silicon Field Effect Transistor
RMS	-	Root Mean Square
EMI	-	Electromagnetic Interference

LIST OF SYMBOLS

V_{gap}	-	Gap voltage
V_{dis}	-	Gap discharge voltage
V_{oc}	-	Highest gap voltage
V_{rms}	-	RMS value of rectified input voltage
V_{R_s}	-	Voltage across current limiting resistor
V_m	-	Maximum AC voltage
V_{L}	-	Voltage across inductor
V_{in}	-	Pulsed input voltage
V_{Int}	-	Voltage of intermediate node
V_t	-	Inter-electrode voltage at *t* second
V	-	Rectified utility voltage
V_{pp}	-	Minimum ripple of DC voltage
v_s	-	AC input voltage
U	-	Output voltage of buck converter
$u_{C\mathrm{e}}$	-	discharge capacitor voltage
U_{sum}	-	Sum of the gap voltage, the workpiece voltage, and the sampling resistor voltage.
u_{ch}	-	Equivalent voltage of plasma channel
u_e	-	Spark maintaining voltage
u_{R_x}	-	Voltage across the equivalent resistance of workpiece
u_{R_s}	-	Voltage across the sampling resistor
I_{gap}	-	Gap current
I_{dis}	-	Peak discharge current
$I_{R_{ig}}$	-	Current through equivalent ignition resistor
$I_{R_{dis}}$	-	Current through equivalent discharge resistor
i_e	-	Peak current
I_L	-	Inductor current
T_s	-	Period of Switch *S*

T_b	-	Boiling temperature
T_0	-	Ambient temperature
T	-	Temperature distribution
t	-	Time
t_{on}	-	Pulse on-time
t_{off}	-	Pulse off-time
t_{on_s}	-	Switch *S* on-time duration
t_{off_s}	-	Switch *S* off-time duration
t_{opt}	-	Optimum pulse on-time
t_e	-	Pulse duration
t_d	-	Delay time
$t_{d,ave}$	-	Average delay time
t_{mach}	-	Spark machining cycle
F_s	-	Spark frequency
f_s	-	Frequency of the utility supply
f_{s_1}	-	Switching frequency of buck converter
$f(x)$	-	Probability density function
x_a	-	Value of vertical height
area	-	machining area
a_w	-	Thermal diffusivity
W_e	-	Pulse energy
W_{pc}	-	Phase cut-off frequency
W_{gc}	-	Gain cut-off frequency
Gm	-	Gain margin
Pm	-	Phase margin
N	-	Number of single pulse discharge
n	-	Number of discharges which did not occur
n_p	-	Noise power
R	-	Resistor
R_{ch}	-	Equivalent resistance of plasma channel
R_g	-	Gap equivalent resistor
R_p	-	Cable resistor

R_g - Gap equivalent resistor

R_s - Current limiting-resistor

R_{d1} - Wire-distributed resistance

R_{ig} - Equivalent ignition resistor

R_{dis} - Equivalent discharge resistor

R_{ci} - Resistance of discharging circuit

R_{melt} - Radius of the eroded cavity

R_{P_p} - Resistance of positive pole

R_{N_p} - Resistance of negative pole

r_c - Radial coordinate

r - Debris particles diameter

RC - Resistor-capacitor

$conc$ - concentration of debris particles

C - Capacitor

C_e - Discharge capacitor

C_g - Gap equivalent capacitor

C_t - Heat capacity

C_p - Sum of the parasitic capacitances

C_d - Distributed capacitance

S_{N_p} - Surface area of the discharge plate

d - Gap width

D - Diode

D_s - Duty cycle of MOSFET switch S

D_{t_0} - Diameter of the electrode

D_{peak} - Number of surface peak

S - MOSFET switch

ρ - Density of the workpiece material

P_w - Control signal applied to the switch S

P_{curr} - Average height of peak

ΔP_{anode} - Power toward anode

Q - Heat flux

L	-	Inductor
L_g	-	Gap equivalent inductor
L_m	-	Latent heats of melting
L_P	-	Cable inductor
L_d	-	Distributed inductance
L_v	-	Latent heats of vaporization
L_{dis}	-	Equivalent discharge inductor
L_g	-	Gap of discharging
Q	-	Transistor switch
E	-	Electric field intensity
E_t	-	Inter-electrode electric-field strength at the time t
$E_{t_{ch}}$	-	Electric–field intensity at the moment that discharge channel formed
ε_p	-	Medium dielectric constant before field emission
ε_0	-	Vacuum dielectric constant
λ_v	-	Effective machining time ratio
κ_t	-	Thermal conductivity
κ	-	Dimensionless constant
κ_{avg}	-	Average value of κ
α	-	Material properties factor
σ	-	Standard deviation
∞	-	Infinity

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Electrical Discharge Machining (EDM) is the most extensively used method for hole making among other known manufacturing processes with applications on the production floor . Non-contact character of EDM makes it 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 [1]. 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 [2]. It is mostly a phenomenon that the machining goes to an unstable degenerate machining condition and makes it difficult to experimentally study the effects of process parameters on the different performance measures of EDM. So, modeling is required to provide a deep understanding of the EDM process by removing experimental challenges. Numerous models have been presented in order to study different aspects of EDM performance. Models are designed to predict the material removal rate [3, 4] and surface quality [5, 6] , to describe and analyze the discharge process in pulse time [7], to determine the discharge location [8] as well as to identify the erodibility and optimal value of pulse time [9]. It has been seen that there is a lack of a model to describe the EDM process throughout all machining phases of spark. EDM process is mainly composed of three phases, including ignition, discharge and recovery. Although these phases are physically different, they affect each other significantly which influences the machining performance [10].

Material Removal Rate (MRR), Tool Wear Rate (TWR) and Surface Quality (SQ) are some of the EDM performance measurement. In this study, Material Removal Rate (MRR) considered as the dominant performance measurement, since it directly affects the cost of production even though it is not the only indicator to measure the EDM performance. MRR is achieved due to the thermal action of electrical discharges in the gap between the electrode and the workpiece [11]. The process depends on the various machining parameters such as gap current, pulse on-time, gap voltage, dielectric and electrode materials [12]. However, the stochastic nature of the EDM process is an obstacle to understanding the influence of these parameters on MRR.

Material removal only takes place in discharge phase. In this phase, the thermal behavior is affected by a discharge channel produced as the dielectric gap breaks down [13]. The breakdown is occurred by an electric field which is higher than the dielectric breakdown field strength [14]. After breakdown, the whole discharge process occurs in the gas environment [15]. Based on the gas break down theory of townsend [16], strength of the electric field is positively correlated with maintaining discharge stability. Gap current plays an important rule to maintain the electric field strength during discharge. Thus, study the influence of the gap current on the stability of maintaining discharge is necessary to improve the process efficiency.

This study seeks to focus on the mathematical modeling and simulation of the EDM process via spark generator design. Mathematical model is developed on the basis of the sparking phases and pulse power generator. Pulse power generator is used to provide required DC voltage for EDM spark utilizing buck converter and transistor based switching circuit. Spark circuit also designed to provide gap profile based on the ignition, discharge and recovery phases. The mathematical model first without noise and then with the maximum noise power, which still results in the consistent model, is implemented using Matlab software. Model validation is conducted by comparing simulation results with the experimental results carried out by the previous scholar and standard data from Antronic EDM manual in term of MRR. The Simulated model is then used to analyze the effect of pulse on-time and gap current as two important process parameters on MRR in the absence of environmental noise. Since concern on machining stability has been rising, this study also investigated the effect of peak discharge current on discharge stability employing the frequency analysis method. This research is important to reveal EDM mechanism and to select optimal process parameters by reducing the cost and time related to the experimental operations.

1.2 Problem Statement

Study the EDM process is necessary to improve its performance. Although material removal occurs in discharge phase, a good description of EDM process requires knowledge of time and spatial condition existed in gap profile including ignition, discharge and recovery phases [17, 18]. However, EDM process has dynamic and highly stochastic nature. So, during machining, the gap size changes randomly cause abnormal discharges including open circuit and short circuit pulses which effect on gap profile. Therefore, during experimental trail, it is necessary to set up the optimum conditions for EDM operation. But, this setting procedure is an iterative and time consuming process.

So, modeling is an alternative way to understand the mechanism underlying the EDM process by removing difficulties related to the real machining experience. Researchers have proposed various models with the aim of predicting EDM behaviour in different forms. Most of the models are suggested based on the discharge process to investigate machining characteristics [6, 19, 20]. Studies of ignition mechanism have also been conducted to give more insight on chaotic nature of EDM process [21]. From previous studies it can be concluded that existing models are focused on the prediction of EDM behaviour only during one sparking phase and less attention are given on the model to study EDM process regarding all of its sparking phases. The shortcoming of these models is that they are not able to explain the dynamic behaviour of the process thoroughly. Therefore, due to the lack of such model, this thesis proposes a mathematical model of the EDM process according to its sparking phases for investigation on the machining mechanism. Matlab's simulated model is then used to study the effects of pulse on-time and gap current on MRR. Also, influence of peak discharge current on maintaining stability of discharge is analyzed.

1.3 Objectives

This research will require to complete the following objectives:

(a) To determine time domain mathematical model of EDM process during its sparking phases including ignition, discharge and recovery.

(b) To analyze the impact of pulse on-time and peak discharge current on Material Removal Rate (MRR) through simulated model of EDM process.

(c) To characterize the effect of peak discharge current on the system response and discharge stability via frequency response analysis of the EDM discharge model.

1.4 Scope of Research

The objectives of this study can be met conforming to the research scope as follows:

(a) A critical literature review of the EDM system and its working principle. The review covered on pulse power generator, process parameters and machining performance measures, several theoretical models in predicting different aspects of EDM behaviour, effect of process parameters on machining performance, and different attempts to maintain discharge self-sustaining condition.

(b) Mathematical modeling and simulation of the EDM process by considering sparking phases and pulse power generator. As a preliminary aim of the model is to investigate dynamic behaviour of the process, in this thesis, the environmental noise is not considered. However, besides the simulation without noise, simulation is also conducted with maximum noise intensity that the system remains stable. The reason for simulation by applying the noise source is to show the stability range of the model.

(c) A comparative study between simulated and experimental data [22] in order to determine validity of the simulated model in the form of Material Removal Rate (MRR). Although EDM process has stochastic nature, as mentioned in part (b), the proposed model in this study did not consider the noise. So, conduct the experimental test would not result in fair comparison between simulated and experimental data.

Therefore, the experimental data extracted from previously published work is applied to validate the model. The experimental system used gap control method to maintain an optimal gap distance during erosion process which is essential to recover from unstable machining condition. Robustness of the gap control method to overcome disturbances caused the comparability of the experimental data with simulated one in this thesis. Furthermore, adjustment have been done to reach constant value of delay time for achieving normal spark which makes the experimental data qualified for validation purpose in this thesis. Predicted MRR in present of noise is also compared with same experimental data using steel workpiece and copper electrode.

(d) Confirmation of model validation process by comparing simulated data with dataset from [23] in term of MRR.

(e) Analyze the effect of pulse on-time and peak discharge current on MRR based on the parametric study through the simulated model of the EDM process.

(f) Study the influence of peak discharge current on stability of discharge via simulated discharge model of EDM process.

1.5 Research Novelty

This work has main approaches in the following aspects:

(a) For the first time, an equivalent gap state model is introduced by considering all sparking phases to provide great contribution for studying EDM behaviour by removing experimental challenges.

(b) Typically, discharge phase is considered to analyze effect of two main process parameters on MRR and to analyze effect of peak discharge current on its stability as well.

1.6 Limitation

The limitations of this thesis are as follows:

(a) Validation of the model is limited according to the experimental data of previous researchers and data from operation manual.

(b) In design the EDM model, output of power supply is limited to the almost similar value of highest gap voltage.

(c) Modeling and simulation of the EDM process is limited to the noise-free environment.

1.7 Significance of Study

Electrical Discharge Machining (EDM) system is widely used in hole manufacturing, thus study on dynamic behaviour of EDM process is important to design better system in the future. Modeling is an effective way to understand the machining procedure as well as to saving time and cost related to experimental work. Study of EDM phases including ignition, discharge and recovery are significant to comprehend EDM performance. Simulated model is helpful to predict dynamic behaviour of the EDM process through its sparking phases.

MRR is main EDM performance attribute which is strongly affected by process parameters. Pulse on-time and peak discharge current are most important parameters effected on MRR. So, the study on their influence on MRR adds knowledge to improve machining performance. This thesis also aims to study influence of peak discharge current on stability of discharge self-sustaining stage through designed EDM model during discharge. This investigation is essential to select peak discharge current in order to maintain discharge stability and improve the process efficiency.

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