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Short communication

Modelling and analysis of material removal rate and surface roughness in wire-cut EDM of armour materials

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ABSTRACT

The current work presents a comparative study of wire electrical discharge machining (WEDM) of armour materials such as aluminium alloy 7017 and rolled homogeneous armour (RHA) steel using buckingham pi theorem to model the input variables and thermo-physical characteristics of WEDM on material removal rate (MRR) and surface roughness (Ra) of Al 7017 and RHA steel. The parameters of the model such as pulse-on time, flushing pressure, input power, thermal diffusivity and latent heat of vaporization have been determined through design of experiment methodology. Wear rate of brass wire increases with rise in input energy in machining Al 7017. The dependence of thermo-physical properties and machining variables on mechanism of MRR and Ra has been described by performing scanning electron microscope (SEM) study. The rise in pulse-on time from 0.85μs to 1.25μs causes improvement in MRR and deterioration of surface finish. The machined surface has revealed that craters are found on the machined surface. The propensity of formation of craters increases during WEDM with a higher current and larger pulse-on time.

1. Introduction

Wire electrical discharge machining (WEDM) of armour materials such as aluminium alloy 7017 and RHA steel has been considered in this work. Al 7017 is an Al–Mg–Zn-based alloy, which is having superior impact strength, corrosion resistance and low density [1]. This alloy is potential for armour applications due to excellent properties. Armour steels [2] are the widely used metallic armour materials nowadays due to excellent strength and hardness with superior toughness making them suitable for armour applications. WEDM plays significant role in cutting conductive materials to produce intricate profiles and complex shapes. The material removal takes place due to melting and evaporation of workpiece because of the heat produced by discharges. The wire traverse is regulated by numerical controlled systems to accomplish desired accuracy and precision of components.

The most significant response variables in WEDM are material removal rate (MRR) and surface roughness (Ra) of workpiece. Spark gap voltage, discharge current and pulse duration are the machining parameters which influence the performance measures. Tosun [3] evaluated the significance machine variables on responses i.e kerf width and Ra. An optimum combination of process parameters was derived for large MRR and small Ra by applying analysis of variance (ANOVA). Tzeng et al. [4] studied the effect of machine variables on Ra by employing taguchi technique. Kumar [5] employed grey relational methodology to optimize input parameters of EDM to maximize MRR. The optimum machine variables were validated by performing confirmation experiments. Wang [6] explored the possibility of removing recast layer using etching by means of EDM. An L9 orthogonal array was selected to design experiments for attaining optimum process parameters. Somasekhar [7] presented the modelling and optimization of micro-EDM using back propagation and genetic algorithms. The neural net work model has been established and simulated using MATLAB. Lin et al. [8] attempted to improve the multiple response characteristics using taguchi technique to optimize machine variables of EDM. Tsai [9] developed a semi-empirical model of surface finish for various materials by adopting dimensional analysis in the electrical discharge machining process. Fan et al. [10] employed Buckingham pi theorem to develop a model for the erosion rate in micro abrasive air jet machining of glasses.

Limited research has been done to develop mathematical models for MRR and Ra in wire EDM based on thermo-mechanical

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approaches. Authors have made an attempt to establish the relation between these parameters by employing buckingham pi theorem and understanding the mechanism of material removal by performing microscopic study. RHA steel and aluminium 7017 are the most widely used armour materials. Using these materials, a variety of armour configurations have to be fabricated to provide ballistic protection against different threat levels. WEDM plays an important role in processing these materials to the desired sizes to accomplish the above objective. The aim of this investigation is to analyse the effect of input variables and thermo-physical characteristics of Al 7017 and RHA steel on MRR and Ra. Based on the literature survey, several preliminary experiments were performed to select the influencing factors on performance characteristics. The chosen machining variables are: pulse on-time (TON), flushing pressure (FP), peak current (IP), input power (E), thermal diffusivity (α) and latent heat of vaporization (H_v). The design of experiment technique is a dominant experimental planning tool, uses efficient and orderly approach for obtaining optimum process variables. Buckingham pi theorem is employed to develop mathematical model between process variables and performance characteristics. The complex nature of WEDM involves interaction of thermal, mechanical and physical phenomena, which makes process model difficult. The current work presents a comparative study of WEDM of Al 7017 and RHA steel using buckingham pi theorem to model the input variables and thermo-physical properties. Experiments were carried out on workpieces under various conditions.

2. Experimental details

2.1. Material and methods

The experiments were performed using CNC WEDM make ELECTRONICA MACHINE TOOLS LTD. The Wire cut Electric Discharge Machine usually consists of a machine tool, a power supply unit and flushing unit. Wire travels through the work piece from upper and lower wire guides. In wire-cut EDM process the spark is generated between continuously travelling brass wire (0.25 mm diameter) and work piece. Aluminium alloy 7017 (0.3% Si, 0.5% Cu, 3.0% Mg, 5.00% Zn and Al remainder) and RHA steel (0.3–0.35% C, 1.5% Cr, 1.5% Ni, 0.14% V, 0.25% Si, 0.4% Mn, 0.03% Al, remaining Fe) were used as cutting materials (Table 1). A picture of the machine unit is given in Fig. 1. The cutting performance was evaluated by MRR and Ra.

The MRR was determined by equation,

$$\text{MRR}\ (\text{mm}^3/\text{min}) = \text{cutting rate} \times \text{width} \times \text{depth of work}. \tag{1}$$

The surface roughness, usually expressed as a Ra value in microns was measured by Taylor Hobson Surtronic 25 Roughness Checker.

2.2. Design of experiment

In this study, two stages of experimental work were necessary to develop mathematical models for MRR and Ra. The first stage is to recognise the machining variables by screening experiments. Two aspects employed in taguchi method are (i) S/N ratio to estimate the quality [8] and (ii) orthogonal arrays [11,12] to accommodate many factors affecting simultaneously to evaluate the machining performances. The machining parameters and corresponding values selected are furnished in Table 2. Using Taguchi technique [9], an L18 ($2^1 \times 3^3$) orthogonal arrays table was chosen. In the present study all the designs, plots and analysis have been carried out using Minitab statistical software. The effect of various WEDM machining parameters has been assessed by adopting ANOVA technique. Based on ANOVA tables (Table 3a,b) for both MRR and Ra, it was observed that TON is the influencing parameter followed by peak current. Preliminary trials were carried out by varying TON and IP, but at higher levels of IP frequent wire breakage was witnessed. Peak current, pulse-off time, flushing pressure and wire tension remain same during the experiments.


Fig. 1. Photograph of the experimental system.

2.3. Buckingham pi theorem

A correlation between n parameters (properties such as density, thermal conductivity and specific heat) can be stated as a relation between (n−m) dimensionless groups of variables, where m is the number of basic dimensions [8]. The machine parameters: pulse-on time (TON), input power (E), flushing pressure (FP) were selected as parameters. The thermal properties [13] of workpiece materials such as heat of vaporization (H_v) and thermal diffusivity (α) were chosen to establish model [14]. Variables used in the model for workpiece materials are given in Table 1. The fundamental dimensions of chosen parameters are given in Table 4. The group of significant variables and material properties for determining MRR and Ra can be expressed as:

$$\text{MRR} = f\ (\text{TON}, \text{E}, \text{FP}, \alpha, H_V) \tag{2}$$

$$\text{Ra} = f\ (\text{TON}, \text{E}, \text{FP}, \alpha, H_V) \tag{3}$$

Table 1
Properties of materials.

Properties	Al 7017	Armour steel	Units
Melting point	950	1800	°K
Density	2800	7800	kg/m^3
Thermal conductivity	210	80	w/m-k
Specific heat	950	410	J/kg-k
Heat of vaporization	10542	6230	kJ/kg

Table 2
Input process parameters and their levels.

Parameters	Symbol	Level 1	Level 2	Level 3	Units
Pulse On time	Ton	0.85	1.35	–	µs
Pulse off time	Toff	18	36	56	µs
Peak current	IP	10	13	16	A
Spark voltage	SV	10	15	20	Volt

Table 3
(a) Analysis of Variance for MRR. (b) Analysis of Variance for Surface roughness (Ra).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
(a)						
Ton	1	1.478	1.478	0.478	8.28	0.016
Toff	2	0.00541	0.0054	0.00271	0.02	0.985
IP	2	2.939	2.939	1.469	8.23	0.008
SV	2	1.0936	1.0934	0.5468	3.06	0.092
Error	10	1.7864	1.7864	0.17865		
Total	17	7.303				
(b)						
Ton	1	18.453	18.453	18.452	8.15	0.017
Toff	2	1.26	1.260	0.6299	0.28	0.763
IP	2	67.339	67.339	33.669	14.86	0.001
SV	2	2.674	2.674	1.337	0.59	0.572
Error	10	22.653	22.653	2.265		
Total	17	112.37				

Table 4
Dimensions of parameters in WEDM.

Parameters	Dimensions
Melting point	θ
Density	ML^{-3}
Thermal conductivity	$MLT^{-3}\,\theta^{-1}$
Specific heat	$L^2\,T^{-2}\,\theta^{-1}$
Heat of vaporization	$L^2\,T^{-2}$
Pulse-on time	T
Input power	$ML^2\,T^{-3}$
Surface roughness	L
Material removal rate	$L^3\,T^{-1}$
Thermal diffusivity	$L^2\,T^{-1}$
Flushing pressure	$ML^{-1}\,T^{-2}$

Based on theory of WEDM, the material removal takes place significantly by evaporation. Thermal properties [15] like specific heat (Cp), thermal conductivity (K) and density (ρ) can be written in one parameter i.e. called thermal diffusivity (α). Input power (E) is expressed as the product of applied voltage and current. As the non-dimensional homogeneous equations of performance measures have six variables and only three basic dimensions, the solution can be expressed as a product of three terms (π_1, π_2 and π_3).

The π variables can be expressed for estimating MRR as follows.

$$\pi_1 = E^{a1}\,TON^{b1}\,\alpha^{c1}\,MRR \tag{4a}$$

$$\pi_2 = E^{a2}\,TON^{b2}\,\alpha^{c2}\,FP \tag{4b}$$

$$\pi_3 = E^{a3}\,TON^{b3}\,\alpha^{c3}\,H_V \tag{4c}$$

π_2 and π_3 can be expressed as a function of π_1 as $\pi_1 = f(\pi_2, \pi_3)$

By comparing the powers of basic units on both sides, the following expressions are derived. Equations (1) and (2) are deduced as (4) and (5) respectively.

Table 5
Coefficients of the model of MRR.

	Al 7017	Armour steel
R^2	0.99	0.97
RMSE	0.3201	1.195
A_1	1.89	2.818
B_1	−0.6846	−0.8067
C_1	1.008	0.7836

Table 6
Coefficients of the model of Ra.

	Al 7017	Armour steel
R^2	0.99	0.96
RMSE	0.3955	1.102
A_2	2.443	1.824
B_2	0.1962	−0.578
C_2	1.74	0.968

$$MRR = A_1 \times (TON^{1/2} \times \alpha^{3/2}) \times (\alpha^{3/2} \times TON^{1/2} \times FP \times E^{-1})^{B1} \times \left(TON \times HV \times \alpha^{-1}\right)^{C1} \tag{5}$$

$$Ra = A_2 \times (TON^{1/2} \times \alpha^{1/2}) \times (\alpha^{3/2} \times TON^{1/2} \times FP \times E^{-1})^{B2} \times \left(TON \times HV \times \alpha^{-1}\right)^{C2} \tag{6}$$

where A_1, B_1 and C_1 are power indexes of MRR model.

A_2, B_2 and C_2 are power indexes of Ra model.

The power indices of model for MRR and Ra are presented in Tables 5 and 6.

3. Results and discussion

A mathematical model for MRR and Ra has been developed with process variables of pulse-on time, input power, flushing pressure and other thermal properties. The coefficients and power indexes of models were evaluated for different workpiece materials by employing various optimization methods. By noticing the coefficient of the models, the B_1 and C_1 are smaller than A_1. This study corroborates the results from design of experiment that the thermal properties are also prominent on MRR and Ra. It is observed that R^2 values of RHA steel are less than aluminium alloy due to variation in thermal properties. Hence these metals can be distinguished by different set of power indexes. Figs. 2–3 depict comparison between experimental and modelling results. It is noticed from the above figures that the average prediction error is less than 10%. This model is different from the earlier, since it mainly concentrates on thermal end electrical properties of the selected materials.

Total input energy transported between wire and workpiece is distributed into three main components namely wire, work piece

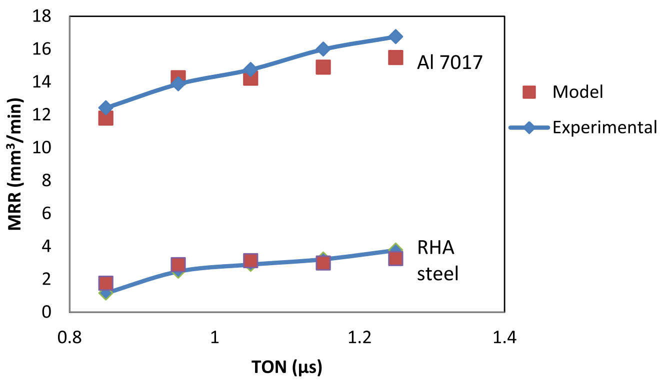


Fig. 2. Comparison between experimental results and model predictions of MRR.

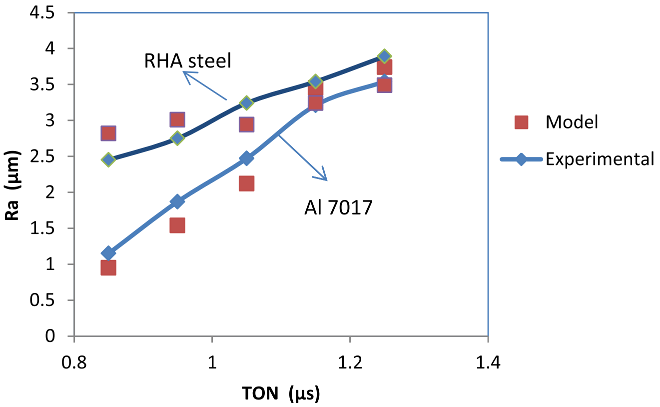
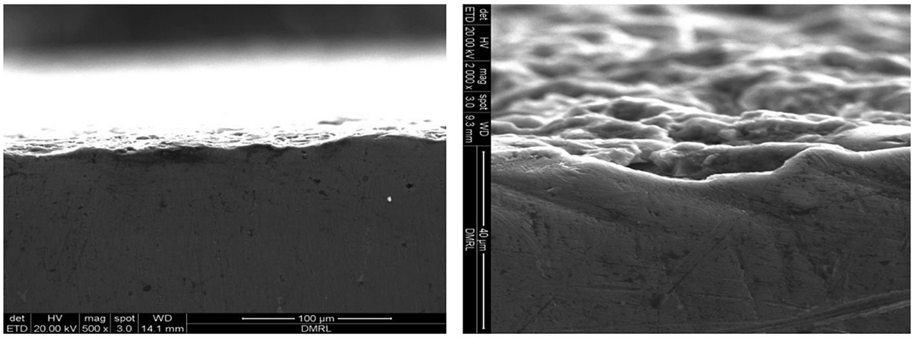


Fig. 3. Comparison between experimental results and model predictions of Ra.



(a) TON 0.85 μsec (b) TON 1.25 μsec

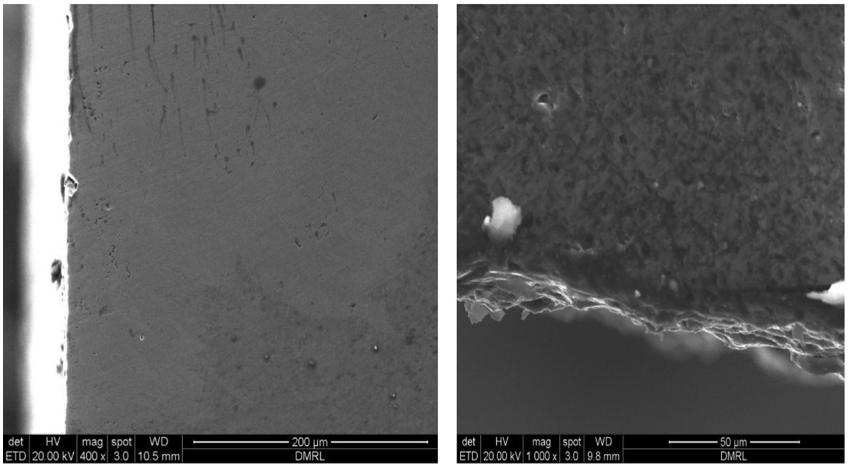
Fig. 4. Micrographs of machined surface of Al 7017.

and gap between them. The energy loss comprises heat carried away by the debris by conduction and heat loss due to convection and radiation.

The maximum MRR was obtained for cutting of Al 7017 than RHA steel. The reason may be due to lower melting point. Heat of vaporization and thermal conductivity were found to be important characteristics of the material for ascertaining MRR. Reduction in MRR is attributed to larger heat capacity and thermal conductivity.

At a large current, a stronger discharge generates more heat energy. By virtue of the size of workpiece, some amount of heat is absorbed by it. The remaining portion of energy is accumulated at the wire resulting into higher wear rate, this leads to frequent wire breakages.

Higher thermal conductivity of Al 7017 helps easy energy dissipation and its low melting point facilitates larger MRR. At low input power, a small amount of thermal energy is produced and a significant portion is absorbed by the surroundings, this makes available energy will be less. But the rise in input power generates intense discharge, which impacts the surface of the workpiece and causes more molten material to be driven out of the crater. The SEM images of Al 7017 machined surface are shown in Fig. 4. The machined surface revealed that discharge craters were large at higher peak current and pulse duration. The Increase in TON from 0.85 to 1.25 μsec resulting into creation of larger craters on the surface. This is reason for the increase in Ra with input power and pulse-on time. The higher the input power, the smaller is the machining time, as the machining rate is proportional to input power. It directly depends on the number of sparks generated per second. Flushing pressure (FP) has a significant influence on MRR. Higher MRR can be achieved by supplying dielectric fluid at low velocity into the spark gap, thereby short-circuit effect is negligible. This enhances improvement in efficiency and thus increases MRR.



(a) High surface finish machined surface (b) Cross sectional view of machined surface

Fig. 5. Micrographs of machined surface of RHA steel.

Higher FP hampers creation of ionized bridges across the gap and reduces spark energy and diminishes MRR. Fig. 5(a) shows the SEM micrograph of RHA steel machined surface observed at minimal surface roughness condition. Fig. 5(b) shows cross sectional view of specimen, depicts the outer layer called recast layer which cooled too quickly to and were cast to the material.

4. Conclusions

An application of buckingham pi theorem to model the input variables of WEDM on MRR and Ra of Al 7017 and RHA steel alloy has been studied. The dependence of thermo-physical parameters on mechanism of MRR and Ra has been interpreted. The conclusions are as follows:

- Mathematical models were developed using buckingham pi theorem for MRR and Ra to establish the relationship between machine variables and performance measures. Results predicted by the model are well matching with experiment results.
- Owing to thermal properties of WEDM, MRR of machining is higher for materials with a low melting temperature and specific heat.
- The rise in pulse-on time from 0.85μs to 1.25μs causes improvement in MRR and deterioration of surface finish. The machined surface revealed that craters are found on the machined surface. The propensity of formation of craters increases during WEDM with a higher current and larger pulse-on time.
- Wear rate of brass wire increases with increase in input energy leads to wire breakage.

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