Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 11 (3): 549-554, 2011
ISSN 1812-5654 / DOI: 10.3923/jas.2011.549.554

Experimental Investigation into Electrical Discharge Machining of Stainless Steel 304

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Abstract: This study presents the experimental investigation of the machining characteristics of austenitic stainless steel 304 through electric discharge machining. The effectiveness of the EDM process with stainless steel is evaluated in terms of the removal rate (MRR), the Tool Wear Rate (TWR) and the surface roughness of the work-piece produced. The experimental work is conducted utilizing Die Sinking electrical discharge machine of AQ55L model. Cylindrical copper electrode having a size of Ø19×37 mm and positive polarity for electrode (reverse polarity) is used to machine austenitic stainless steel 304 materials. The work material holds tensile strength of 580 and 290 MPa as yield strength. The size of the work-piece was Ø22×30 mm. Investigations indicate that increasing the peak current increases the MRR and the surface roughness. The TWR increases with peak ampere until 150 μ sec pulse-on time. From the experimental results no tool wear condition is noted for copper electrode at long pulse-on time with reverse polarity. The optimal pulse-on time is changed with high ampere.

Key words: Electrical discharge machining, pulse duration, peak current, material removal rate, tool wear rate and surface roughness

INTRODUCTION

Electrical discharge machining is a thermo-electrical material removal process, in which tool electrode shape is reproduced mirror wise into a work material (Beri *et al*., 2008). The mechanism for removing material primarily turns electrical energy into thermal energy through a series of successive sparks between the electrode and the work-piece in a dielectric fluid. The thermal energy is consumed in generating high temperature plasma, eroding the work-piece material (Tsai *et al*., 2003). The recent developments in the field of EDM have progressed due to the growing application of EDM process and the challenges being faced by the modern manufacturing industries, from the development of new materials that are hard and difficult-to-machine such as tool steels, composites, ceramics, super alloys, hastalloy, nitralloy, waspalloy, nemonics, carbides, stainless steels, heat resistant steels, etc. being widely used in die and mould making industries, aerospace, aeronautics and nuclear industries (Singh *et al*., 2004).

EDM has also made its presence felt in the new fields such as sports, medical and surgical instruments, optical, dental and jewellery industries, including automotive R and D areas. The various machining characteristics used to evaluate the performance of EDM such as material removal rate (MRR), Tool Wear Rate (TWR), relative wear ratio and surface roughness (SR) (Wu *et al*., 2005). The important variables that affect the performance of EDM are peak current, pulse duration, pulse-off time, the polarity of the electrode, nozzle flushing etc. (Kansal *et al*., 2007). The thermodynamic and physical properties of the tool and the work-piece also influence the electrical discharge machining performance (Wang and Tsai, 2001).

The following studies have been carried out to investigate the performance of EDM on different type of steel work-piece. The metal removal rate depends upon the amount of energy per spark, but too much current can damage the work-piece or the electrode (Bojorquez *et al*., 2002). An experiment revealed that copper electrode gives better surface finish, high MRR and less electrode wear for tool steel work-piece followed by brass, aluminum and copper tungsten electrode (Singh *et al*., 2004). It was shown that the MRR is also controlled by the frequency of the sparks and the low discharge currents with higher frequency correspond to low stock removal using reverse polarity. At all values of current copper provide maximum MRR and minimum tool wear rate, zero whereas aluminum

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contributes minimum MRR and maximum TWR, around 60%. Tsai *et al.* (2003) performed the experiment on steel work-piece and they reported that EDM technology yields higher roughness with negative polarity than that obtained with positive polarity. Negative polarity machining yields a higher roughness than positive polarity machining, because the composite electrode was anode, such that a larger discharge spot results in a wide melting zone. The machining characteristics of SiC/6025 Al composite was investigated and the results evidenced the more material removal rate (~40 mm^3 min^{-1}) for aluminum alloy with 20% SiC than that of obtained (~29 mm^3 min^{-1}) for aluminum alloy with 25% SiC using brass as electrode (Mohana *et al.*, 2004). The increase in volume percentage of SiC caused to decrease in MRR and increase in Electrode Wear Rate (EWR). Maximum MRR was achieved at 180 μ sec as pulse-on time. Their results evident that EWR decreases with pulse duration and increases with peak current. The increase of peak current and pulse duration cause to increase the surface roughness. An experiment has been performed to find out the influences of EDM parameters on surface roughness for machining of 40CrMnNiMo864 tool steel (AISI P20) which is widely used in the production of plastic mold and die (Kiyak and Cakir, 2007). They investigated that when pulsed current and particularly pulse time increased, machined work-piece surface exhibited a higher surface roughness. Pulsed current had an effect on surface roughness at low pulse time, but the influence of pulse time was more significant than pulsed current at higher pulse times. Bojorquez *et al.* (2002) reported that the surface finish of the machined part depends upon the ability of the electrode to resist wear. Theisen and Schuermann (2004) investigated the influence of EDM on pseudo-elastic NiTi shape memory alloys (SMAs). Their observation revealed that increasing current intensity increases the working energy, so that discharge craters become deeper and wider, thus resulting more MRR and high surface roughness. Increase of frequency also raises surface roughness, since craters depth becomes more profound. The discharge current that principally has a significantly higher effect, than frequency. The copper and aluminum electrodes achieve the best MRR with the increase in discharge current, followed by copper–tungsten electrode. Pulse current and pulse-on duration can be utilized to significantly improve the thickness of the white layer. Experiment was conducted on EDM by using SKD 61 steel as work-piece and copper as electrode where commercial kerosene was used as dielectric fluid (Wu *et al.*, 2009). It was observed the material removal rate increases with peak current till 4A, but when peak current reaches 6A, the MRR was lower because of larger diameter of debris and tars due to the higher electrical discharge energy. It was argued that at high ampere (6A) the debris and tars in larger diameter exist in the gap between the electrode and work-piece.

Electrical discharge machining was done on stainless steel (SUS304) work-piece in the case of copper electrode and conventional EDM oil, electro-rheological (ER) fluid with different cons (Tsai *et al.*, 2008). The discharge pulse number and the surface roughness were found maximum using conventional EDM oil. Using ER fluid and the abrasive Al_2O_3 the roughness was improved 85%. Mirror-like surface can be obtained when using the smaller capacitance of 0.001 μF. It was also found that for all values of pulse duration (12.8-200 μ sec) the MRR rises with peak current up to 48 A and then dropped when machining with higher current due to inferior discharge caused by insufficient cooling of the work material (Lee and Li, 2001). Material removal is directly proportional to the amount of energy applied during the pulse-on time (Puertas and Luis, 2003). This energy is really controlled by the peak current and the length of the on time.

Stainless steel is selected as engineering materials mainly because of their excellent corrosion resistance in many environments. The corrosion resistance of stainless steels is due to their high chromium contents. Austenitic stainless steel has better corrosion resistance than ferritic and martensitic stainless steel (Smith and Hashemi, 2006). Stainless steels are used abundantly in engineering applications especially stainless steel 304 is used in chemical and food processing equipment. To enhance its machining facility it is essential to identify the performance characteristics on electrical discharge machining on SUS 304. Although various parameters influence the performance of EDM, such as peak current, pulse-on time, polarity of electrode, properties of the tool and work-piece, etc., it is perceived that peak current and pulse-on time retain great impact on EDM performance. Thus, this study has been accomplished to analyze the performance of electrical discharge machining on stainless steel 304 material considering the peak current and pulse duration variables.

MATERIALS AND METHODS

This study was conducted at Automotive Excellence Centre, Faculty of Mechanical Engineering, Universiti Malaysia Pahang, Kuantan. The duration of the project is April 2009 to August 2010.

Pulse duration or on-time refers the duration of time (μ sec) in which the current is allowed to flow per cycle (Puertas and Luis, 2003). Pulse interval or off-time is the duration of time (μ sec) between the sparks and the

Table 1: Chemical composition of stainless steel 304 work piece

Elements	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co	Cu	V	Fe
wt.%	0.0575	0.371	1.74	0.06	0.0268	17.4	0.366	9.07	0.0058	0.113	2.7	0.059	Balance

Table 2: Experimental conditions

Working parameters	Description
Work piece material	Stainless steel 304
Electrode material	Copper
Electrode polarity	Positive
Dielectric fluid	Kerosene
Polarity	Reverse polarity
Peak current (I_p)	2, 4, 8 and 12 (A)
Pulse duration (T_{on})	50, 100, 150 and 200 (µ sec)
Pulse-off time (T_{off})	50, 100, 150 and 200 (µ sec)
Duty factor	0.5
Working time	15 (min)

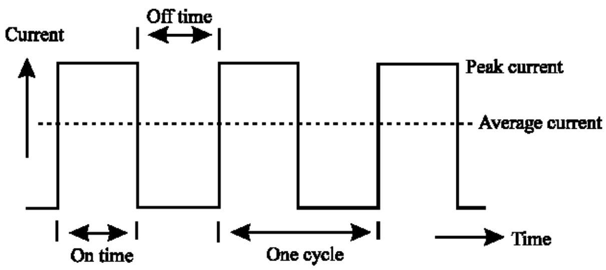

Fig. 1: Typical EDM pulse current and pulse time train for controlled pulse generator

percentage of the on-time relative to the total cycle time (on-time plus off-time) is specified as duty factor or cycle. Characteristic of pulse-on time, off time, peak current and average current are shown in Fig. 1. This experimental work is conducted utilizing die sinking electrical discharge machine of AQ55L model. Cylindrical copper electrode having a size of Ø 19×37 mm and positive polarity for electrode (reverse polarity) is used to machine austenitic stainless steel 304 materials. The work material holds tensile strength of 580 MPa and 290 MPa as yield strength (Smith and Hashemi, 2006). The size of the work-piece was Ø 22×30 mm. The chemical composition of the work-piece is tabulated in Table 1. Commercial kerosene is used as dielectric fluid and during machining kerosene is circulated in the tank. In this study, pulse duration and discharge pulse-off time were of 50, 100, 150 and 200 µ sec. The list of experimental parameters is also listed in Table 2.

The MRR is expressed as the weight of material removed from work-piece over a period of machining time in minutes (Wu *et al*., 2005). The MRR is calculated from the difference of weight of work-piece before and after machining as expressed in Eq. 1 (Mandal *et al*., 2007):

$$MRR = \frac{W_i - W_f}{\rho_s t} \text{ mm}^3 \text{ min}^{-1} \quad (1)$$

where, W_i is the weight of work-piece before machining in g; W_f is the weight of work-piece after machining in g; t is the machining time in minutes; p_s is the density of steel (7.8×10^{-3} g mm^{-3}).

The electrode wear rate is calculated from the weight difference of electrode before and after machining as expressed in Eq. 2:

$$EWR = \frac{E_i - E_f}{\rho_{cu} t} \text{ mm}^3 \text{ min}^{-1} \quad (2)$$

where, E_i is the weight of electrode before machining in gm; E_f is the weight of electrode after machining in gm; t is the machining time in minutes; ρ_{cu} is the density of copper (8.9×10^{-3} g mm^{-3}).

The SR of the work-piece can be expressed in different ways including arithmetic average (R_a), average peak to valley height (R_z), or peak roughness (R_P), etc.

Generally, the SR is measured in terms of arithmetic mean (Ra) which according to the ISO 4987: 1999 is defined as the arithmetic average roughness of the deviations of the roughness profile from the central line along the measurement (Wu *et al*., 2005). Arithmetic mean or average surface roughness is considered in this study for assessment of roughness.

RESULTS AND DISCUSSION

Influence of peak current and pulse on time on MRR: The influence of peak current and pulse on time in terms of material removal rate is discussed in this section. The contour plot and 3-D surface plot illustrate the experimental result as shown in Fig. 2 and 3. The results evidence that at all values of pulse duration the material removal rate increases as pulse current is increased. This is due to the fact that as peak current increases the discharge energy is increased consequently erodes more material from the work-piece. Thus increasing peak current causes material removal more. This phenomenon is also supported by the studies of Lee and Li (2001) and Singh *et al.* (2004). On the other hand, it is observed in this study that material removal rate is decreased with pulse on time at low discharge current. Increasing the pulse duration reduces the energy density of the discharge spots by expanding the plasma channel and therefore reduces the material removal rate. Rise in pulse on time and pulse interval (off time) decreases frequency and the higher frequencies with low discharge currents correspond to low stock removal. This outcome is also

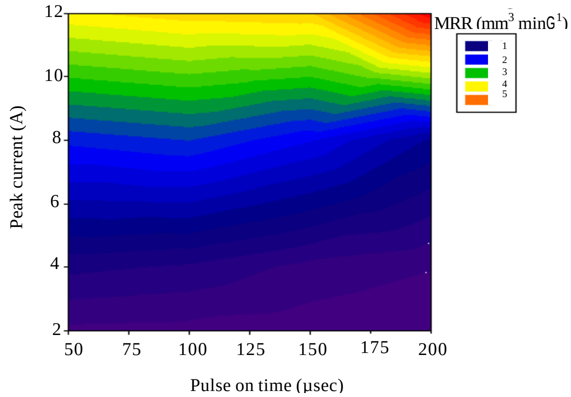

Fig. 2: Effect of peak current and pulse on time on MRR

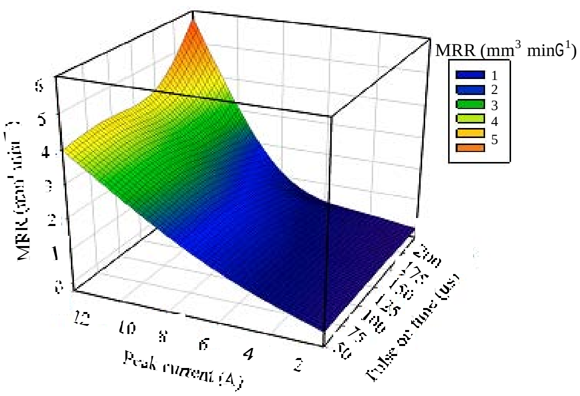

Fig. 3: 3-D plot of the effect of peak current and pulse on time on MRR

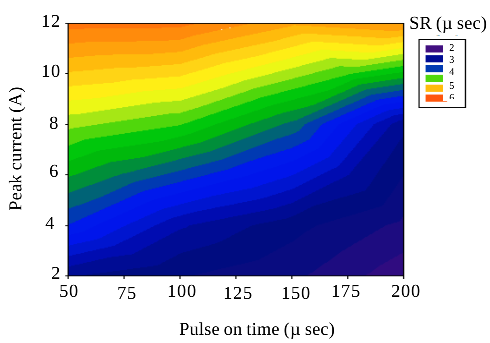

Fig. 4: Effect of peak current and pulse on time on SR

supported by the study of Singh *et al*. (2004). It is also investigated that combination of high discharge ampere (12A) and high pulse on time (200 µ sec) originates more MRR. The reason can be explained as the discharge current comprised electron and ion currents. The ion current represents a large fraction of the total current

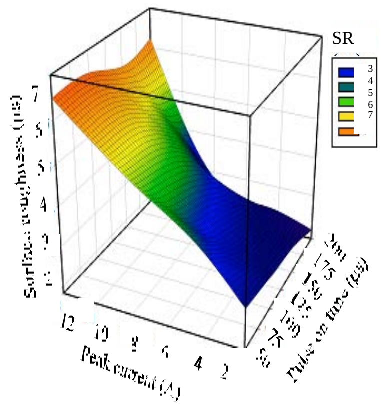

Fig. 5: 3-D plot of the effect of peak current and pulse on time on SR

when the pulse duration is long and that causes more MRR (Chow *et al*., 2008). Thus, 12 A with long pulse duration allows more ion current and produces more MRR. Another reason is that long pulse duration decreases frequency and the low frequency with high power results more metal removal (Dorf and Kusiak, 1994). So, it can be reported that the influence of pulse duration is more significant on MRR than pulse current at long pulse duration. This phenomenon is also supported by the study of Kiyak and Cakir (2007).

Influence of peak current and pulse on time on SR: Figure 4 and 5 exhibit the variation of surface roughness against peak current and pulse on time. It can be noticed that the surface roughness increases almost linearly with peak current for different pulse on time. The increase of discharge current increases discharge energy that promotes melting and vaporization of the work-piece material and generate larger and deeper craters, thus contributing to a greater surface roughness. In previous studies it is also found that surface roughness increases with peak current (Mohana *et al*., 2004; Singh *et al*., 2004; Kiyak and Cakir, 2007). The results reveal that low peak ampere stimulate fine surface finish. The surface roughness of the machined work-piece turns down as the pulse on time increased. Rise in pulse on time reduces frequency that produces a decreased surface roughness, since discharge craters become superficial and thinner. The results can be supported by several studies (Theisen and Schuermann, 2004; Kansal *et al*., 2007; Wu *et al*., 2009). The long pulse duration decreases frequency and the low frequency creates rough surface. Dorf and Kusiak (1994) report the similar phenomenon. It is obvious in this research that the combination of low ampere and high pulse duration provides finest surface finish. It can be

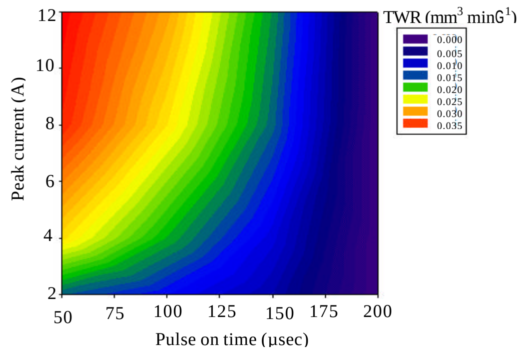

Fig. 6: Effect of peak current and pulse on time on TWR

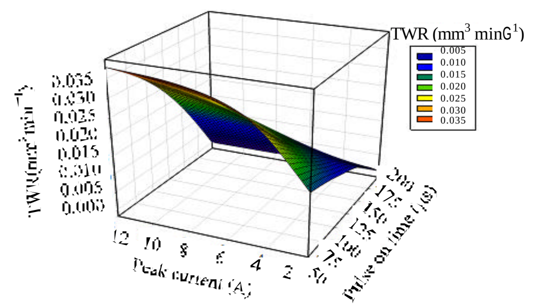

Fig. 7: 3-D plot of the effect of peak current and pulse on time on TWR

concluded also that the pulse on time has less impact on surface roughness at high peak current.

Influence of peak current and pulse on time on TWR: The effect of tool wear rate versus peak current at various pulse duration is presented in Fig. 6 and 7. Tool wear rate is increased as peak current increases, till about 175 µ sec pulse on time. Increasing the peak current increased discharge energy and sparking, removing more melted material from both work-piece and tool which increases the TWR. This result coincides with the outcome of Mohana *et al.* (2004). It is seemed that at all values of peak ampere, as the pulse on time increase the TWR trends to decrease. The minimum TWR, zero is found at 200 µ sec pulse duration for all amperes. This can be argued as the and high pulse duration facilitates no tool wear for copper electrode remaining the polarity as reverse and work-piece as steel material. Singh *et al.* (2004) also claimed the same circumstance.

CONCLUSIONS

It was attempted to investigate the effect of the peak current and pulse duration on the performance characteristics of the EDM. In roughing operations using positive polarity, the following conclusions can be drawn:

- The pulse on time and peak current greatly influenceon material removal rate, tool wear rate and surface roughness
- It is found that at all values of pulse duration the material removal rate increases almost linearly with increases of discharge current. The combination of long pulse on time and high discharge current permits more material removal. It can be represented that the impact of pulse duration is more significant on MRR than pulse current at long pulse on time
- This experiment exhibits that the surface roughness increases linearly with peak current for different pulse on time. Conversely surface roughness decreases as the pulse duration is increased. The product of long pulse duration and high discharge current causes rough surface. Finest surface finish can be achieved by utilizing low peak ampere and long pulse on time combination
- As peak current increases, the TWR increases and the impact of pulse on time on tool wear is contrary of peak current. As the pulse on time increase the tool wear rate decrease and the TWR reaches minimum (zero) at 200 µ sec spark on time for all values of peak amperes. Accordingly, it can be recommended that long pulse duration with reverse polarity provoke no tool wear on stainless steel work-piece retaining copper as electrode

ACKNOWLEDGMENTS

The authors would like to express their deep gratitude to Universiti Malaysia Pahang (UMP) for provided the laboratory facilities and financial support under project No. RDU 090394 and Doctoral Scholarship scheme (GRS 090335).

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