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Influence of process parameters in electrical discharge machining on H13 die steel

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ABSTRACT

H13 die steel is characterized by its high hardness and need for special surface features that are obtained by nontraditional machining processes. Electrical discharge machining (EDM) is used to machine hard materials and to produce complicated shapes. In this work, different EDM process parameters are investigated on H13 die steel. Several experiments are conducted to study the effect of three process parameters: peak current (I_p), pulse on-time (T_{on}) and electrode material on the machining process of H13 die steel. The machining process is evaluated by material removal rate (MRR), electrode wear ratio (EWR%) and surface roughness (SR) as indicators of the process efficiency in terms of quality and cost. Taguchi method was used to investigate the significant effect of process parameters on the performance measurements and the optimal parameters of the EDM process. For analysis and explanations Minitab version 17 software was used. Different process parameters were experimentally investigated and statistically analyzed and the results showed that the copper electrode leads to the highest MRR and lowest EWR%; whereas the brass electrode leads to the lowest SR.

1. Introduction

Die-sinking EDM is a process which is based on spark erosion to manufacture complicated shapes through electrically conductive workpieces by using an electrode. The material in EDM is removed by erosion process with repetitive spark discharges produced by pulsating DC power supply. About thousands of sparks are generated per second and each spark melts and vaporizes very small amounts of material and produces a minuscule crater [1]. Discharge energy is provided in the form of electrical pulses with short duration. A discharge is initiated where electric field is stronger. A single spark is caused by the insulation of the dielectric fluid which breaks down under high electric field [2]. A plasma zone is created and the metal quickly reaches a very high temperature in the range of 8000C^0 to 12000C^0 (and sometimes to more than 20000C^0) which lead to the instant melting of particles from the surface of the workpiece and also electrode material [3, 4].

Precision and accuracy are of great importance in the machining of die steels, which requires optimization of EDM process parameters to improve the performance of the process regarding the surface finish or roughness (SR), dimensional accuracy, electrode wear rate (EWR) and material removal rate (MRR) of the EDM process [5]. Since the process parameters are related strongly to the machined material, most of the published literature focuses on investigating the effect of EDM process parameters for machining a specific alloy. For example, Torres, A. et al. [6] examined the impact of process parameters; electric current (I_p), pulse on-time (T_{on}), duty cycle and electrode polarity on MRR, EWR% and SR in EDM of INCONEL 600 Alloy with copper as the electrode material, the dielectric liquid used was mineral oil with a flash point of 82 °C. They found that positive polarity leads to higher MRR though negative polarity leads to lower SR values. Yan Cherng Lin et al. [7] studied the impact of process parameters, including, I_p, T_{on} and gap voltage on MRR, EWR and SR in EDM of SKH 57 high speed steel with copper electrode material. Their study demonstrated that the MRR increased with the I_p, and the maximum values were achieved at T_{on} of around 100 μs, as the T_{on} increased further, the MRR was reduced. Raj, Sumit, et al. [8] observed that I_p and pulse off-time are the most significant parameters for MRR. Saindane, T. Y. et al. [9] studied the impact of process parameters for machining AISI H13 tool steel. Their results showed that the higher the value of the I_p and T_{on} increase the value of SR.

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The previous discussion shows the potential for further studies aiming at full utilization of the EDM process by considering all parameters together, as the results of one parameter varies significantly if other parameters are changed. This is owed to the stochastic nature of the process, in addition to the interrelationship among the many variables that are involved in this process. The performance in the EDM process is usually assessed in terms of material removal rate (MRR), electrode wear rate (EWR) and surface finish for a specific electrode material. However, up to our knowledge there has been no consideration for changing the parameters during the process, meaning that the suitable machining conditions may vary from the beginning of the process (roughing stages) to the end of the process (finishing stages). At the beginning and during roughing stages it is important to emphasize the performance in terms of high MRR, whilst towards the end of the process and during the finishing stages, reducing the SR and EWR become more significant.

The main objective of this research is to obtain the optimal process parameters to be used in the cutting and operation of H13 die steel used for making cutting tools. Therefore, the specific wear behavior, material removal rate, and surface roughness are investigated in detail in this paper and linked to the process parameters of the different electrode material and its wear rate. In this investigation, two types of copper electrodes were used; high purity 98.5% copper and brass with 48.92% copper, in addition to, graphite. Therefore, this research will highlight the effect of changing the electrode material by using some values of I_p and T_{on} for evaluating the effect of all the combined parameters on the cutting process of the H13 die steel.

2. Experimental

2.1. Experimental materials

In the present study, the workpiece chosen was H13 die steel (200 × 20 × 4mm), which is generally utilized in hot and cold work tooling applications. Because of its phenomenal mix of high strength and fatigue resistance, its suitability comes from its distinctive hardness, resistance to abrasion and deformation and its capacity to hold a cutting edge at raised temperatures. Table 1 introduces the chemical composition of the workpiece material. Table 2 shows the material properties for both the workpiece and the electrodes.

The electrode materials in this work are copper, brass and graphite, which are commonly used in EDM. The outer and inner diameter of the electrodes are 15mm and 2mm; respectively. Table 3 presents the chemical composition of both copper and brass electrodes used in this work.

Graphite used in this study falls under the set fine graphite Grade R8340. Table 4 shows the properties of graphite Grade R8340.

The EDM machine used in this study is CHARMILLES ENGEMAQ EDM200NC with a transistor circuit, as it is more capable of controlling the process parameters. The experimental trials conducted in this work were done using kerosene as the dielectric fluid with injection flushing. The values of the process parameters (peak current (I_p), pulse on-time (T_{on}) and electrode material) are illustrated in Table 5. The experimental design included three control factors and up to three levels for each factor, the values of which were determined by Taguchi method (L9 orthogonal array), the values of which are shown in Table 6.

Table 1
Chemical composition (in weight %) of the H13 die steel.

Alloy	Chemical composition (in weight %)						
	Fe	Cr	Si	C	Mo	V	Mn
H13 Die steel	Bal.	4.85	0.964	0.385	1.163	0.807	0.335

• Analyzed by Central Metallurgical Research Institute (CMRDI).

Table 2
Typical room temp mechanical properties of the workpiece material and electrode materials.

Properties	H13 die steel	Copper	Brass
Melting point (°C)	1427	1083	927
Density (kg/m^3)	7810	8920	8770
Thermal conductivity (W/mK)	42.2	400	111
Modulus of elasticity (GPa)	207	117	102

2.2. Performance measurements

2.2.1. Material removal rate (MRR)

The MRR of the workpiece was measured by dividing the machined volume of the workpiece by the machining time that was achieved. After completion of each machining process, the workpiece was cleaned thoroughly by compressed air using air gun to ensure freedom from debris and dielectric fluid.

2.2.2. Electrode wear ratio (EWR%)

The electrode wear rate (EWR) of the electrode was measured by dividing the machined volume of the electrode by the machining time that was achieved. After completion of each machining process, the electrode was cleaned thoroughly by compressed air using air gun to ensure freedom from debris and dielectric fluid. In addition to that the graphite was roasted after each process by placing it in the oven at 180C^0 to ensure no dielectric fluid were present. The weight of the electrode was measured using a precise balance. And then the EWR% was measured by dividing the EWR by the MRR that have been previously measured.

2.2.3. Surface roughness (SR)

There are various methods available for measuring SR of the workpiece. The arithmetic surface roughness value (R_a) was adopted and measured. The SR was measured by TR200 Hand-Held Roughness tester through measuring the workpiece five times and calculating the average for each experiment. The surface roughness measurements were made at different positions on the machined surface for each EDM condition.

3. Results and discussion

3.1. Experimental data

The three output parameters were adopted and measured during Die-sinking EDM of H13 die steel. Table 7 gives the combinations of experimental machining parameters and parameter levels in the L_9. This table also gives the S/N ratio for each one.

3.2. The effect of different factors on the MRR

Fig. 1 illustrate the effect of the electrode material, the I_p, and the T_{on} on MRR. It is clear from Fig. 1 that the MRR increases by increasing the I_p value, up to a certain value which varies from one electrode material to the other. It was found that the MRR increases by increasing the T_{on}, but it was observed that at the value 150ìs of the T_{on} the MRR began to collapse.

The S/N ratios for MRR were calculated by Eq. (1). Taguchi method was utilized to analyze the results of response of the machining parameters as indicated by "larger is better" criteria [10]. Table 8 and Fig. 2 illustrates the factors level S/N ratios.

$$(S/N)_{LB} = -10 \log (MSD_{LB}) \quad (1)$$

Where:

$$MSD_{LB} = \frac{1}{n}\sum_{i=0}^{n}(y_i^2)$$

MSD_{LB} = Mean Square deviation for larger the better response.

Table 3
Chemical composition (in weight %) of copper and brass.

Alloy	Chemical composition (in weight %)								
	Cu	Zn	Pb	Fe	Sn	Al	Ti	Ni	Cr
Copper	98.5	0.81	0.0088	0.179	0.101	0.084	0.103	0.013	0.056
Brass	48.92	34.96	7.28	1.36	1.77	0.233	0.045	1.92	0.051

• Analyzed by Science and Technology Center of Excellence (STCE).

Table 4
Material properties of specialty graphite Grade R8340.

Properties	Value
Average grain size (μm)	15
Density (kg/m3)	1720
Open porosity (Vol. %)	15
Medium pore size (μm)	2
Specific electrical resistivity (μΩm)	12
Thermal conductivity (W/mK)	90
Young's modulus (kN/mm^2)	10.5

• SGL CARBON GROUP.

Table 5
The process parameters.

Variables	Setup Value
Electrode material	Graphite, Copper, Brass
Dielectric fluid	Kerosene
Flushing pressure (kgf/cm^2)	0.5
Peak current (A).	2, 6, 14
Spark gap (mm)	0.035
Duty cycle rate	50%
Pulse on-time (μs)	50, 150, 500
Machining time (min)	2–5
Electrode polarity	Positive

Table 6
Factors, factor levels and factor designation.

Factor		Symbol	Unit	Factor levels		
				Level 1	Level 2	Level 3
1	Peak current	I_p	A	2	6	14
2	Pulse on-time	T_{on}	μs	50	150	500
3	Electrode material			Graphite	Brass	Copper

The workpieces and the electrodes were weighed before and after each experiment using a precise balance (resolution of 0,001 g), to determine the MRR and EWR%.

n = no. of trials.

y_i = the ith measured value in a row.

The delta value is the difference between the higher average of each factor and its lower average value. Peak current, electrode material, polarity and pulse on-time are assigned as rank 1, 2, 3, and 4, respectively according to their larger value of delta as shown in Table 8. Rank 1 means highest effect factor on MRR, rank 2 comes after that and means medium effect factor on MRR, and so on.

From Fig. 2, the optimized value for MRR is found that copper electrode at I_p = 14A andT_{on} = 150ìs. At this condition, can achieve the highest MRR obtained for H13 die steel.

Analysis of Variance (ANOVA) test was utilized to test the null hypothesis with regard to the data gained through experiments. Table 9 records the outcome of the ANOVA test. In this examination, the confidence level was chosen to be 95%. So, the P-values which are less than 0.05 indicate that null hypothesis should be rejected and thus the effect of the respective factor is significant. It can be seen from Table 9 that the peak current (P = 0.021) has the most significant impact on MRR, and the electrode material and the pulse on-time do not have a significant effect on MRR.

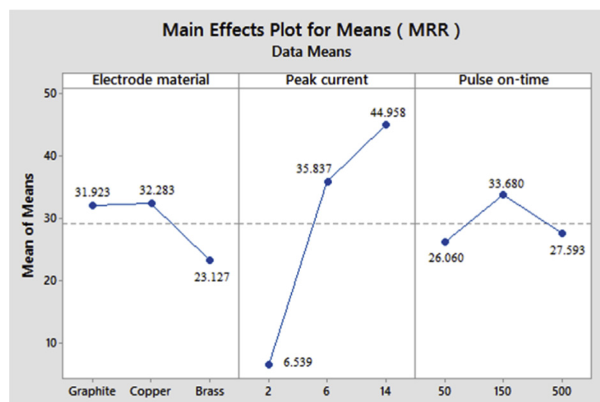

Fig. 1. Process parameters effect on MRR.

Table 8
Average effect response table of S/N ratio for MRR.

Level	Electrode material	Peak current	Pulse on-time
1	27.23	16.25	25.38
2	27.81	30.51	28.14
3	24.72	33.00	26.24
Delta	3.08	16.75	2.76
Rank	2	1	3

Table 7
L_9 orthogonal array with S/N ratio for the MRR, EWR% and SR.

Experiment Number	Electrode material	I_p (A)	T_{on} (μs)	MRR (mm^3/min)	S/N ratio (dB)	EWR%	S/N ratio (dB)	Ra (μm)	S/N ratio (dB)
1	Graphite	2	50	6.120	15.735	18.999	-25.575	4.371	-12.812
2	Graphite	6	150	50.021	33.983	3.874	-11.763	9.049	-19.132
3	Graphite	14	500	39.629	31.960	2.934	-9.349	11.789	-21.430
4	Copper	2	150	7.657	17.681	0.586	4.647	4.658	-13.364
5	Copper	6	500	37.311	31.437	3.185	-10.062	11.652	-21.328
6	Copper	14	50	51.882	34.300	51.557	-34.246	5.455	-14.736
7	Brass	2	500	5.839	15.327	35.934	-31.110	5.960	-15.505
8	Brass	6	50	20.179	26.098	116.798	-41.349	3.246	-10.226
9	Brass	14	150	43.363	32.742	77.133	-37.745	4.308	-12.685

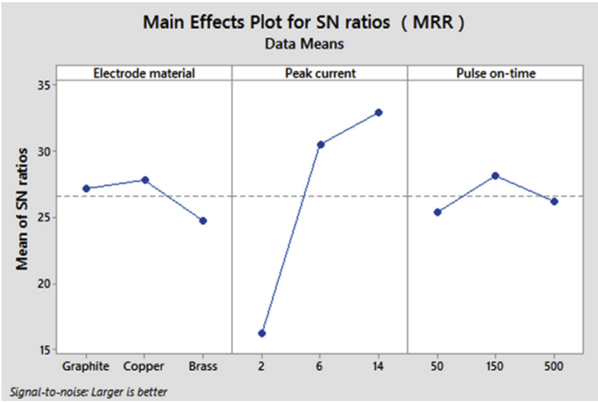

Fig. 2. S/N ratio of MRR.

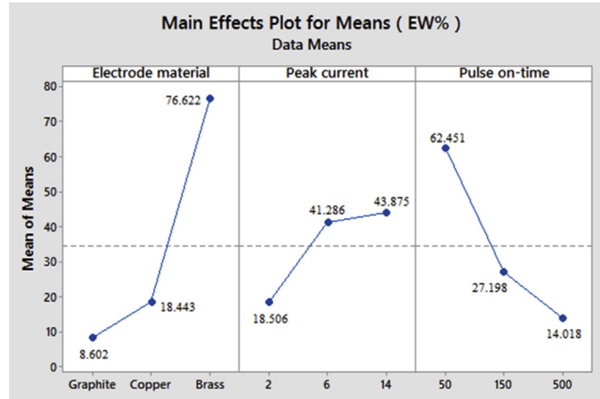

Fig. 3. Process parameters effect on EWR%.

Table 9
ANOVA table for MRR.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Electrode material	2	16.11	16.11	8.057	1.56	0.391
Peak current	2	490.20	490.20	245.099	47.42	0.021
Pulse on-time	2	11.94	11.94	5.970	1.15	0.464
Residual error	2	10.34	10.34	5.169		
Total	8	528.59				

Table 10
Average effect response table of S/N ratio for EWR%.

Level	Electrode material	Peak current	Pulse on-time
1	-15.56	-17.35	-33.72
2	-13.22	-21.06	-14.95
3	-36.73	-27.11	-16.84
Delta	23.51	9.77	18.77
Rank	1	3	2

3.3. The effect of different factors on the EWR%

It is clear from Fig. 3 that the EWR% increases by increasing the I_p value. It was also found that the EWR% decreases by increasing T_{on}.

The S/N ratios for EWR% were calculated by Eq. (2). Taguchi method was utilized to analyze the results of response of the machining parameters as indicated by “smaller is better” criteria [10]. Table 10 and Fig. 4 illustrates the factors level S/N ratios.

$$(S/N)_{SB} = -10 \log (MSD_{SB}) \tag{2}$$

Where:

$$MSD_{SB} = \frac{1}{n}\sum_{i=0}^{n}\left(\frac{1}{y_i^2}\right)$$

MSD_{SB} = Mean Square deviation for smaller the better response.

From Fig. 4, the optimized value for EWR% is found that copper electrode at $I_p = 2A$ and$T_{on} = 150$ìs. At this condition, can achieve the highest EWR% obtained for H13 die steel.

Table 11 records the outcome of the ANOVA test. It can be seen that the electrode material, the pulse on-time, and the peak current do not have a significant impact on EWR%.

3.4. The effect of different factors on the SR

It is clear from Fig. 5 that the SR increases by increasing the T_{on} value, up to a certain value which varies from one electrode material to the other. It was found that the SR increases by increasing the I_p, but it was observed that at the value 6A of the I_p the SR began to decrease.

The S/N ratios for SR were calculated by Eq. (2). Taguchi technique was utilized to analyze the results of response of the machining parameters as indicated by “smaller is better” criteria [10]. Table 12 and Fig. 6 illustrates the factors level S/N ratios.

From Fig. 6, the optimized value for SR is found that brass electrode at $I_p = 2A$ and $T_{on} = 50$ìs. At this condition, can achieve the highest SR obtained for H13 die steel.

Table 13 records the outcome of the ANOVA test. It can be seen that the pulse on-time ($P = 0.043$) has the most significant impact on SR, and the electrode material and the peak current do not have a significant effect on SR.

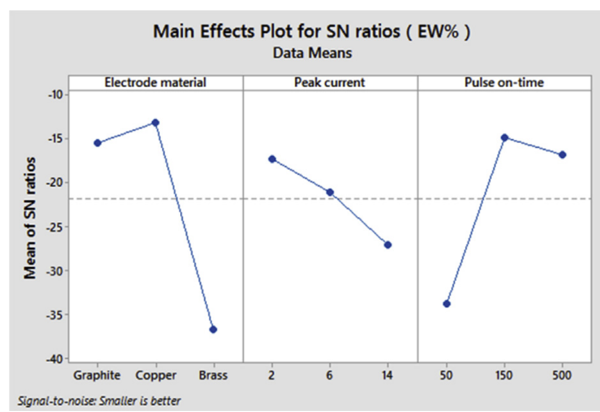

Fig. 4. S/N ratio of EWR%.

Table 11
ANOVA table for EWR%.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Electrode material	2	1006.7	1006.7	503.34	5.25	0.160
Peak current	2	145.8	145.8	72.92	0.76	0.568
Pulse on-time	2	640.9	640.9	320.44	3.34	0.230
Residual Error	2	191.8	191.8	95.90		
Total	8	1985.2				

3.5. The effect of electrode material on the performance measurements

In EDM, the electrical energy is used to generate an electrical spark possessing thermal energy. The workpiece material removal is the result of the thermal energy of the spark. The right selection of the electrode material controls the transport of the electrical current to the workpiece [11]. Thus, the selection of the electrode material plays a significant role in this process, owing to its thermo-physical properties, though the non-thermal properties are not negligible. The peak current causes the occurrence of a crater after the break down of the open circuit voltage.

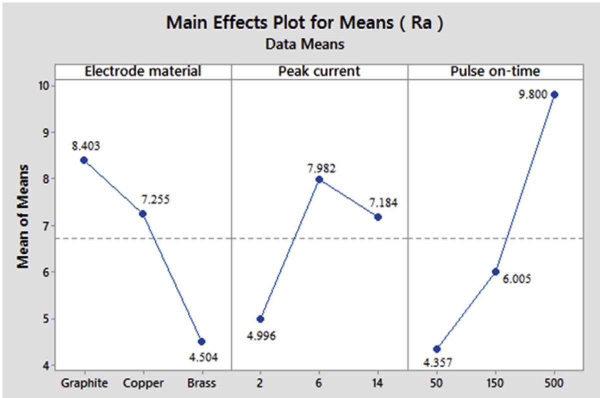

Fig. 5. Process parameters effect on SR.

Table 12
Average effect response table of S/N ratio for SR.

Level	Ra		
	Electrode material	Peak current	Pulse on-time
1	-17.79	-13.89	-12.59
2	-16.48	-16.90	-15.06
3	-12.81	-16.28	-19.42
Delta	4.99	3.00	6.83
Rank	2	3	1

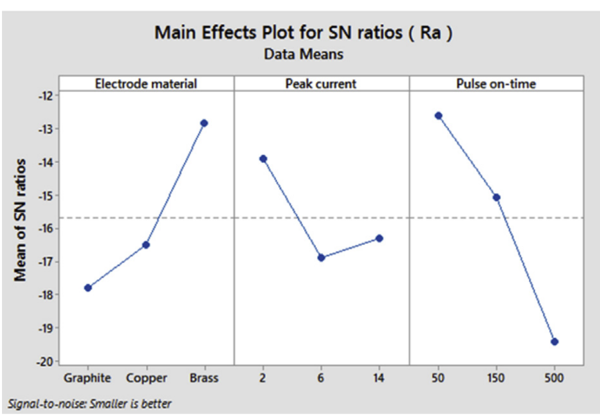

Fig. 6. S/N ratio of SR.

Table 13
ANOVA table for SR.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Electrode material	2	40.063	40.063	20.032	12.57	0.074
Peak current	2	15.097	15.097	7.548	4.74	0.174
Pulse on-time	2	71.753	71.753	35.877	22.51	0.043
Residual error	2	3.188	3.188	1.594		
Total	8	130.101				

The occurrence of this phenomenon is only possible when the cathode electrode starts to emit electrons, when the emitted electrons from the cathode collide with the molecules of the dielectric fluid releasing more electrons together with the positive ions. This causes the vaporization of the dielectric fluid and the formation of a high energy plasma channel [11].

According to the results obtained in this work, the optimal combination levels of process parameters that maximize the MRR for H13 die steel are as follows: copper electrode material, 14A peak current and 150µs pulse on-time as shown in Fig. 2. Whereas, the process parameters that minimize the EWR% are as follows: copper electrode material, 2A peak current and 150µs pulse on-time as shown in Fig. 4. Finally, the process parameters that minimize the SR are as follows: brass electrode material, 2A peak current and 50µs pulse on-time as shown in Fig. 6. The previous findings suggest that the optimized process parameters should be related to the process type. In EDM manufacturing processes for machining H13 die steel, the following conditions are recommended for optimal use: (1) copper electrode material with 14A peak current and 150µs pulse on-time, for roughing process in order to increase the MRR and (2) brass electrode with 2A peak current and 50µs pulse on-time, for finishing processes in order to reduce SR and EWR.

4. Conclusions

This work examined the impact of the process parameters for die-sinking EDM of alloyed die steel on the performance measurements (material removal rate (MRR), electrode wear ratio (EWR%) and surface roughness (SR)), for different electrode materials with injection flushing method. The following conclusions are found:

1. Analysis of Variance (ANOVA) of the obtained data shows that according to significance, the peak current (I_p) is the most important factor affecting both EWR% (using Cu electrode) and MRR, the type of electrode material and the pulse on-time (T_{on}) has a negligible effect on the MRR. While the T_{on} is the most important factor affecting the SR using brass electrode, the type of electrode material and the I_p has a negligible effect on the SR.
2. The optimal process parameters for die-sinking EDM of H13 die steel are as follows: copper electrode with 14A peak current and 150µs pulse on-time, for the highest MRR; copper electrode with 2A peak current and 150µs pulse on-time, for the lowest EWR%; brass electrode with 2A peak current and 50µs pulse on-time for produces the high surface quality.

Declarations

Author contribution statement

A. Y. Shash: Conceived and designed the experiments; Wrote the paper.
M. M. Bahgat: Performed the experiments; Wrote the paper.
M. Abd-Rabou: Analyzed and interpreted the data.
I. S. El-Mahallawi: Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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