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An Experimental Study on Electrochemical Grinding Parameters on Hardness and Material Removal Rate for Stainless Steel 316

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Abstract

Electrochemical Grinding (ECG) process is a mechanically assisted electrochemical process for material processing. The process is able to successfully machine electrically conducting harder materials at faster rate with improved surface finish and dimensional control. This research studies the effect of applied current, electrolyte concentration, spindle speed and the gap between workpiece and tool on hardness and material removal rate during electrochemical grinding for stainless steel 316. The characteristic features of the electrochemical grinding process are explored through Taguchi-design-based experimental studies. The better hardness can be obtained at 10 A of the current, 150 g/l of the electrolyte concentration, 0.3 mm of gap and spindle speed of 180 rpm, and the maximum material removal rate can be obtained at 40 A of the current, 250 g/l of the concentration, 0.2 mm of a gap and 180 rpm of spindle speed.

Keywords: *Electrochemical grinding (ECG, stainless steel 316, hardness, non-traditional machining*.

1. Introduction

Electrochemical grinding (ECG) is one of the hybrid electrochemical processes [1]. It consists of a combination of the mechanical grinding process and electrochemical machine (ECM). ECG procedure for removal metal requires a conductive grinding wheel with metal-bonded in which a negative charge as a cathode, workpiece with a positive charge as an anode, connected to DC power source and electrolyte solution in a gap between tool and workpiece. The electrolyte solution consists of water mixed with salt. The metal removal occurs in this process by electrochemical reaction which removes about (90% - 95%), on the other hand the mechanical action is responsible for removal (5% - 10%) [1]. The heat generates in this procedure is much less as compared to the traditional grinding process because most of the metal removal process occurs by electrolytic dissolution. The thermal residual stresses and heat-affected zone are not obtained during the ECG procedure [2]. Electrolysis is performed at low voltage (5-25 V) so the quality of the function is not affected by the spark [3]. This process is productive, economical and has minimal effect on the useful properties of the material of the ECM process [1]. ECG has been well applied in machining Tungsten carbide, stainless steel and metal-ceramic hard alloy of WC-Co groups for improving surface safety [4-5]. T. M. A. Maksoud [6] studied the effects of voltages and the electrolyte flow rate on material removal rate (MRR) and wheel wear. In addition to comparing it with a traditional grinding process. R. N. Goswami [7] focused on studying the effect of electrolyte concentration, electrolyte flow rate, supply voltage and cutting depth on MRR and surface finish during ECG of the Al2O3/ Al interpenetrating phase compound. Asit

Baran Puri [8]. evaluated the effect of cutting speed and voltages on composite carbide as a workpiece for finding optimum surface roughness and MRR by using response surface methodology (RSM). Furthermore, Zhang Q.L., et al [9] studied the effect of voltage, electrolyte temperature and electrode feed rate on MRR. Besides studying the use of the brazed diamond wheel instead of the diamond wheel used in the ECG process to prolong the life of the wheel. In this paper, ECG is employed to process stainless steel 316. Experiments are done to study the effects of applied current, electrolyte concentration, gap size and spindle speed on hardness and MRR and improvement the hardness and MRR. The hardness: is the resistance of a material to plastic deformation. There are several hardness scales currently in use. The most common of which are Brinell, Rockwell, Knoop, and Vickers. Rockwell hardness (HRc) is used in this experimental [10] and material removal rate: is one of the most important criterions to determine the machining efficiency in ECG process determined by

$MRR = \frac{W}{t}$, (g/min) …(1)

Where: $W = w_b - w_a$ …(2)

w_b = the weight of the workpiece before ECG operation in grams,

w_a = the weight of the workpiece after ECG operation in grams,

t = the time of operation in minutes.

2. ECG Theory

2.1. The Design of Experiment (DOE)

It is a branch of statistics which provides the experimenter with the methods for selecting the effective possible combinations or recipes of independent variables at which a limited number of experiments has been performed. There are many experimental design methods to create certain combinations of experiments. These combinations of experiments are called experimental design matrix (EDM). The results of the planned experiments are used to investigate the sensitivity of the acquired dependent quality characteristics (QC), or the response, to the independent variables [11].

2.2. Taguchi Approach

Taguchi's comprehensive system of quality engineering is one of the greatest engineering achievements of the 20th century [12]. This method focuses on the effective application of engineering strategies rather than advanced statistical techniques [12]. The goals of Taguchi's approach can be summarized as designing robust products or processes that are insensitive to environmental conditions (external noise factors), developing robust products that are insensitive to component variation (internal noise factors), and minimizing variation around a target value. The most important parts of Taguchi's approach are the reduction of variability and minimization of nonconformance cost. They are rational with the modern continuous quality improvement philosophy [13].

2.3. Analysis of Variance (ANOVA)

It is one of the most critical tools for analyzing data from DOE. The analysis of variance [14], which is a statistical technique is applied to reveal the level of significance of the influence of factors on a particular response. ANOVA experiments can be very complex [15]; the analysis is conducted by using Minitab 17 software that gives a table of ANOVA.

3. Experimental Procedures

Fig. 1 shows a schematic setup diagram for electrochemical grinding. When machine conditions are applied, the rotary wheel is perpendicular to the workpiece.

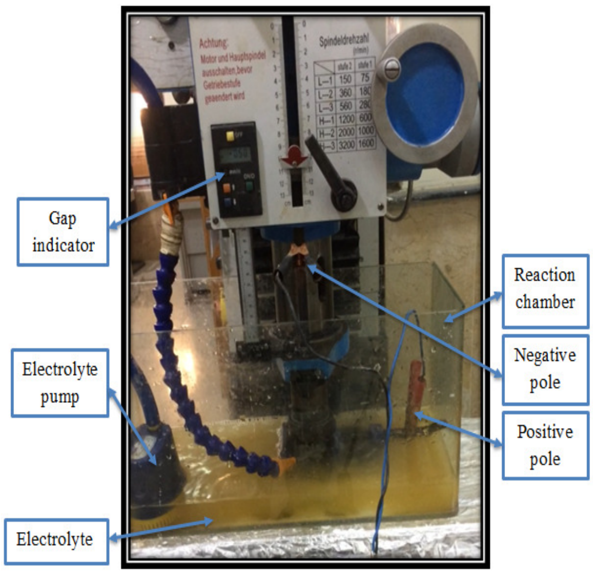

Fig. 1. Experimental set-up for ECG.

In these experiments, a cylindrical diamond grinding wheel a metal-bonded is chosen as a cathode tool as shown in fig. 2, and stainless steel 316 is chosen as anode workpiece. The dimensions of a workpiece are (60mm × 40mm × 2mm).

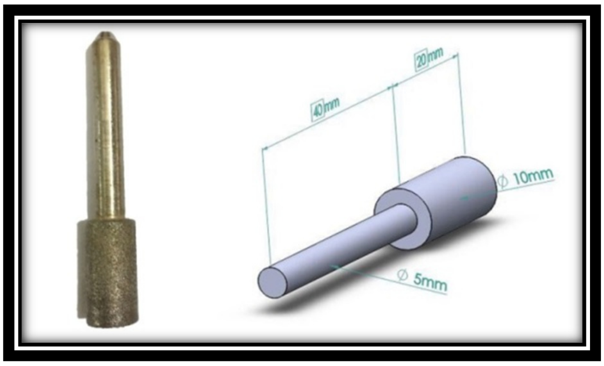

Fig. 2. Cylindrical grinding wheel.

Table 1 shows the measured chemical composition of the workpiece by (Spectrometer device in Baghdad, Iraq).

Table 1,
Chemical composition of the workpiece.

Elements	**%**	**Elements**	**%**
C	0.057	Cr	18.73
Mn	1.769	Mo	0.284
Si	0.391	Ni	8.69
P	0.035	Fe	Bal.
S	<.0005		

Table 2 shows machining conditions used in this experiment. Taguchi design used for this experimental, where sixteen experiments were conducted by using the Taguchi method design with L16 (4^4) mixed orthogonal array as shown in table 3.

Table 2,
Machining conditions

Parameter	**Value**
Electrolyte	NaCl
Applied current (A)	10, 20, 30, 40
Electrolyte con. (g/l)	100, 150, 200, 250
Gap size (mm)	0.2, 0.3, 0.4, 0.5
Spindle speed (rpm)	75, 150, 180, 280
Electrolyte flow rate (l/s)	0.28
Electrolyte temperature (°C)	28

Table 3,
Distribution of parameters in the experiment

Exp. no.	**Con. (g/L)**	**Current (A)**	**GAP (mm)**	**Speed (rpm)**
1	100	10	0.2	75
2	100	20	0.3	150
3	100	30	0.4	180
4	100	40	0.5	280
5	150	10	0.3	180
6	150	20	0.2	280
7	150	30	0.5	75
8	150	40	0.4	150
9	200	10	0.4	280
10	200	20	0.5	180
11	200	30	0.2	150
12	200	40	0.3	75
13	250	10	0.5	150
14	250	20	0.4	75
15	250	30	0.3	280
16	250	40	0.2	180

Maintaining hardness after an operation is necessary in the production environment and for higher productivity in the grinding process, a highest MRR is desirable; therefore, the hardness and MRR were classified as "larger is better" and the signal to noise ratio was calculated in this case as in the equation following [16]:

$$\text{SNR} = -10\log\frac{1}{n}\left(\sum_{i=1}^{n}\frac{1}{y^2}\right) \quad \ldots(3)$$

Where: i = (1 to n), y is observed response value at each trail, n = number of observations in each trail.

4. Results and Discussion

Based on the experimental result presented in table 4, the effect of different process parameters on hardness and MRR was analyzed.

Table 4,
Taguchi L_{16} orthogonal array and experimental result for hardness and MRR and their SNR

Exp. no.	Con. (g/L)	Current (A)	GAP (mm)	Speed (RPM)	Hardness HRc	Hardness SNR	MRR (g/min)	MRR SNR
1	100	10	0.2	75	44.3	33,1602	0.09906	-20.0820
2	100	20	0.3	150	22.0	28,2995	0.23532	-12.5668
3	100	30	0.4	180	31.3	31.5957	0.26620	-11.4058
4	100	40	0.5	280	22.4	28.9432	0.32234	-9.8337
5	150	10	0.3	180	45.7	33.1602	0.10052	-19.9550
6	150	20	0.2	280	20.5	27.7833	0.26572	-11.5115
7	150	30	0.5	75	19.5	26.2351	0.22668	-12.8917
8	150	40	0.4	150	26.0	29.5424	0.36380	-8.7827
9	200	10	0.4	280	45.0	33.1602	0.10062	-19.9463
10	200	20	0.5	180	37.0	32.0412	0.18732	-14.5483
11	200	30	0.2	150	24.0	29.5424	0.28616	-10.8678
12	200	40	0.3	75	26.5	28.4649	0.36144	-8.8393
13	250	10	0.5	150	45.6	33.1793	0.10172	-19.8519
14	250	20	0.4	75	32.0	30.8814	0.21838	-13.2157
15	250	30	0.3	280	27.1	29.5424	0.26732	-11.4594
16	250	40	0.2	180	14.7	28.0280	0.57466	-4.8118

4.1. Results for Hardness

Fig. 3 shows variations in hardness with applied current, electrolyte concentration, gap and spindle speed for four-level. From table 4, it appears that the better hardness can be obtained is 45.7 at 10A of the current, 150 g/l of the electrolyte concentration, 0.3 mm of gap and spindle speed of 180 rpm, It is preferable in manufacturing to maintain the value of hardness after operations.
Table 5 shows the ANOVA and "F-test" values of contribution where it is noted the current as the most significant parameter on Hardness. Additionally, a gap size is the next significant parameter on Hardness, and then electrolyte concentration.

Table 5,
Analyses of variance for hardness

Source	DF	Seq SS	Adj SS	Adj MS	F
concentration	3	65.43	65.43	21.81	0.60
Current	3	804.15	804.15	268.05	7.39
Gap size	3	80.92	80.92	26.97	0.74
Spindle speed	3	75.02	75.02	25.01	0.69
Residual Error	3	108.77	108.77	36.26	
Total	15	1134.30			

where: *DF*=Degree of Freedom, *Seq SS*= Sum of a square, *Adj SS*=Adjacent Sum of Square, *Adj MS*=Adjacent mean Square, F=Fisher's test.

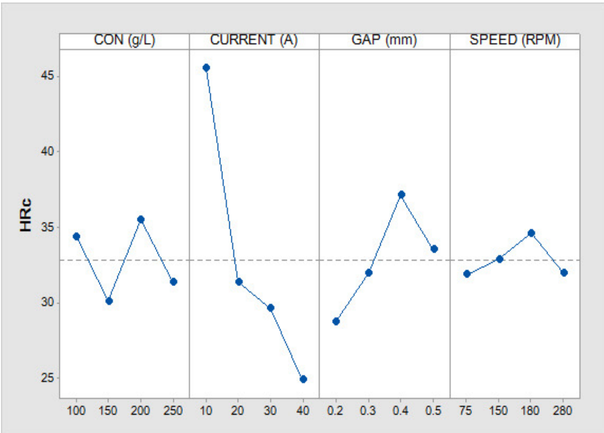

Fig. 3. Mean graph for HRc.

It is observed from Fig. 3 that the applied current had the most influence on hardness values. Increasing current leads to a decrease in hardness, as increasing current leads to increased temperature in the reaction area that affects the microstructure of the workpiece. This eventually leads to a decrease in hardness of the workpiece. The effect of the electrolyte concentration and spindle speed are less than the current on hardness. Fig. 4, Fig. 5 and Fig. 6 shows the effect of the current with the concentration, gap size and spindle speed on hardness. Fig. 4 shows that the highest hardness can be maintained with the lowest applied current and the highest concentration. Fig. 5 shows that the hardness decreases by reducing the gap when the current is stabilized. Reducing the gap size causes increasing the machining current and fast anodic dissolution in the gap between the workpiece and the tool, as a result, the MRR increases. While Fig. 6 shows that speed has limited effect or even lacking the effect on hardness at constant current.

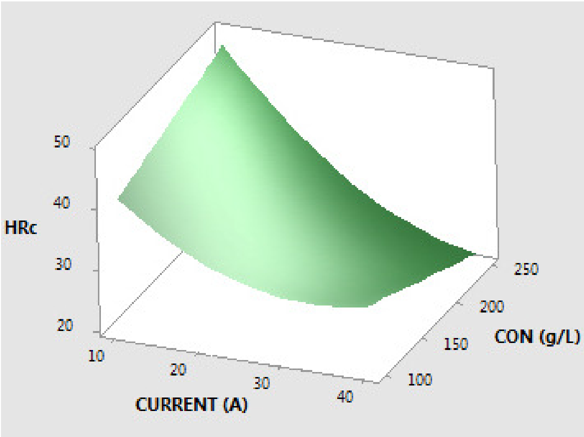

Fig. 4. Surface of HRc vs Con; Current

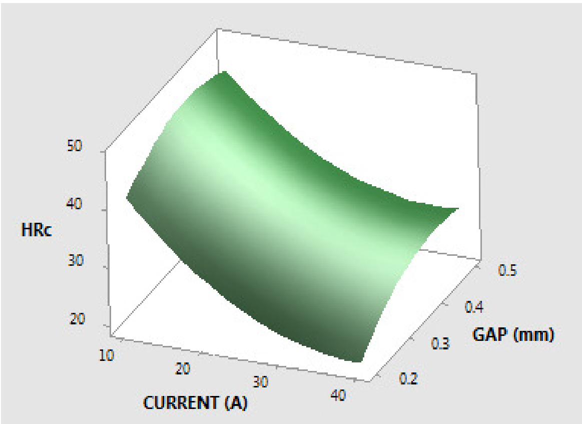

Fig. 5. Surface of HRc vs Gap; Current

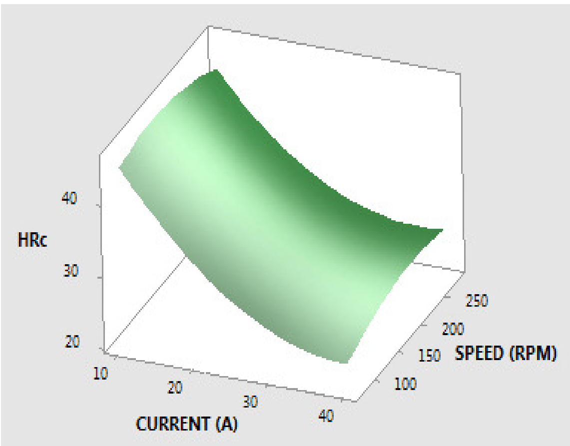

Fig. 6. Surface Plot of HRc vs Speed; Current

4.2. Results for MRR

Fig. 7 shows the variations of MRR (g/min) with applied current, electrolyte concentration, gap and spindle speed for four-level. From table 4, it is showed that the maximum MRR is 0.57466 g/min at a 40 A of current, concentration of 250 g/l, 0.2 mm of gap and spindle speed of 180 rpm. Table 6 presents the ANOVA and "F-test" values of contribution as it is noted that the current is the most significant parameter for maximum MRR and gap size as the next significant parameter for maximum MRR and then electrolyte concentration.

Table 6,
Analyses of variance for MRR

Source	DF	Seq SS	Adj SS	Adj MS	F
concentration	3	0.0095	0.0095	0.0031	1.24
Current	3	0.1889	0.1889	0.0629	24.52
Gap size	3	0.0202	0.0202	0.0067	2.62
Spindle speed	3	0.0068	0.0068	0.0022	0.89
Residual Error	3	0.0077	0.0077	0.0025	
Total	15	0.2332			

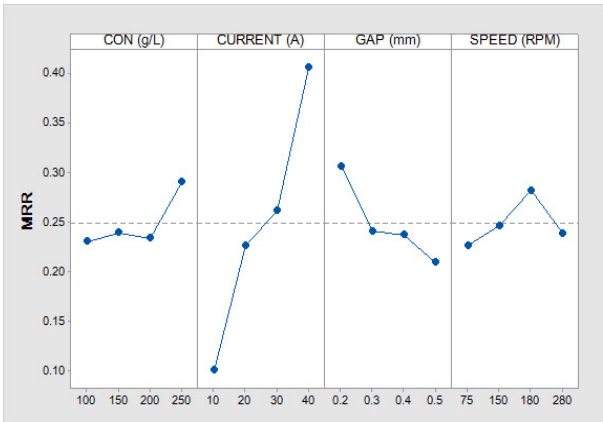

Fig. 7. Mean graph for MRR.

It is found that the applied current and the gap has a highest significant effect on MRR while the concentration of electrolyte and spindle speed does not have a significant effect on material removal rate. MRR increases by increasing the current and concentration of the electrolyte while decreasing with increasing the amount of gap. Increasing the speed to a certain level leads to increase MRR and then begins to decrease with the continued increase of spindle speed. The reason is the speed increased from (180 to 280) rpm with used constant other parameters leading to reduce in reaction dissolution.

5. Conclusions

In this research, ECG is employed to machine stainless steel 316. Conclusions could be summarized as follows:

1. The applied current has the most significant effect on the hardness and MRR while the other parameter has less effect on the hardness.
2. Hardness decrease with increasing current and reducing the value of the gap.
3. MRR increases with increasing current, concentration of electrolyte and reducing the value of the gap.
4. The better hardness can be obtained is 45.7 at 10A of the current, 150 g/l of the electrolyte concentration, 0.3 mm of gap and spindle speed of 180 rpm.
5. The maximum MRR can be obtained is 0.57466 (g/min) at 40 A of the current, 250 g/l of the concentration, 0.2 mm of a gap and 180 rpm of spindle speed.

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دراسة تجريبية في عوامل التنعيم الكهروكيميائية على الصلادة ومعدل إزالة المواد للفولاذ المقاوم للصدأ ٣١٦

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الخلاصة

تعد عملية القطع الكهروكيميائية عملية كهروكيميائية بمساعدة ميكانيكية لتشغيل المادة. اذ انها قادرة على تشغيل المواد الصلبة ذات التوصيل الكهربائي بمعدل أسرع مع تحسين السطح والتحكم في دقة الأبعاد. يدرس هذا البحث تأثير التيار وتركيز الإلكتروليت والسرعة الدورانية والفجوة بين المشغولة والأداة على الصلادة ومعدل إزالة المادة أثناء عملية التنعيم الكهروكيميائية للفولاذ المقاوم للصدأ ٣١٦ حيث تم دراسة الخواص لعملية التنعيم الكهروكيميائية من خلال دراسة تجريبية مستندة إلى تصميم تاكوجي وتم الحصول على أفضل صلادة عند تيار ١٠ أمبير و١٥٠ غم/لتر من تركيز الإلكتروليت و٠,٣ ملم من الفجوة وبسرعة دورانية ١٨٠ دورة في الدقيقة وكما تم الحصول على اعلى معدل لإزالة المادة عند التيار ٤٠ امبير و ٢٥٠ غم/لتر من تركيز الإلكتروليت و ٠,٢ ملم من الفجوة وبسرعة الدوران ١٨٠ دورة في الدقيقة.