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Analysis of the Influence of EDM Parameters on Material Removal Rate and Electrode Wear Ratio of Al-Cu

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ABSTRACT

الهدف من هذا العمل هو إيجاد الظروف المثلى لمتغيرات التشغيل بالتفريغ الكهربي (EDM)،وقد استخدمت سبيكة من الألومونيوم والنحاس كمعدن تشغيل بينما أداة التشغيل كانت من النحاس النقي. استخدمت طريقة (Taguchi) لتصميم عدد من التجارب، والتي أنجزت على آلة (ROBOFORM 2-LC)،ولتحليل تأثير كل متغير على خصائص التشغيل وللتنبؤ بالخيار الأمثل لكل المتغيرات مثل قطبية الشغلة، مدة تفريغ الشحنة، كثافة التيار, كفاءة الأداء. كذلك تم تحليل التباين (ANOVA) باستخدام اختبار (F) للتحقق من أي متغيرات التشغيل المؤثرة على خصائص الأداء وإيجاد النسبة المئوية لكل هذه المتغيرات على معدل إزالة المعدن (MRR)،ونسبة تآكل الآلكترود (EWR). توصل هذا العمل إلى أن كثافة التيار تؤثر بشكل ملحوظ على معدل إزالة المعدن (MRR)، بينما مدة تفريغ الشحنة تؤثر بشكل رئيسي على نسبة تآكل الآلكترود(EWR).
الكلمات المفتاحية: *التشغيل بالتفريغ الكهربائي،طريقة Taguchi،متغيرات التشغيل المثلى، معدل إزالة المعدن (MRR)، نسبة تآكل الآلكترود (EWR).*

The objective of this work is to determine the optimal setting of the process parameters on the electro-discharge machining (EDM), The Aluminium copper cast alloy were used as a work piece and pure copper were used as the electrode. The experiments were done on an FORM 2-LC machine by using Taguchi methodology. The Taguchi method is used to formulate the experimental layout and analyze the effect of each parameter on the machining characteristics, and to predict the optimal choice for each EDM parameter such as polarity, Pulse-on time, discharge currant, and duty factor. Analysis of variance (ANOVA) used F-test to investigate which process parameters significantly affect the performance characteristics and the percent contribution of these parameters on material removal rate (MRR) and electrode ware ratio (EWR). In general, it is found that the discharge currant significantly affects the MRR, while the Pulse-on time mainly affects the EWR.
Key words*: Electrical discharge machining (EDM), Taguchi method, Material Removal Rate (MRR), Electrode Wear Ratio (EWR).*

1. Introduction

Electrical Discharge Machining (EDM) is defined as the non-traditional process of material removal of electrically conductive materials to produce the part with intricate shapes and profiles. This process is done by applying high-frequency pulsed, AC, or DC current to the workpiece through an electrode or wire, which melts and vaporizes the workpiece material. Positioned very precisely near the workpiece, the electrode never touches the workpiece but discharges its potential current through an insulating dielectric fluid (distill water or oil) across a very small spark gap. The spark is reported to be in the range of 8000 to 12000°C, and it vaporizes and melts the workpiece material. This process is used when the workpiece material is too hard, or the shape or location of the detail cannot easily be conventionally machined. This makes many formerly difficult projects more practical and many times it can be the only feasible way to machine a part or material [1].

The electrical discharge machining (EDM) has become an important nontraditional machining process because it can machine the complex shapes, i.e. machining materials like die for manufacturing plastic, which cannot be machined by conventional machining processes [3]. Electrical discharge machining (EDM) is a widely accepted non-traditional material removal process used to manufacture components with intricate shapes and profiles. in the modern world today's, many kind of materials have been invented, so the best parameters need to be find in order to get the best result for machining the materials such as al alloys.

In the machining processes by using electrical discharge machining (EDM), it is involved some parameters setting and there is no fixed setting for all the materials. In traditional practical, the machining condition relying heavily on the operator's experiences or conservative technological data provided by the EDM equipment manufacturers, which is lead to the inconsistent machining performance [3].

A strategy that is done to get the optimal cutting of EDM process planning start from roughing to finishing operations. This process including the number of machining process that is done and its corresponding machining parameters setting for each operation that has been proposed. This method can produce better performance than that achieve by a well skilled operator. A good surface finish, maximum material removal rate and minimum electrode ware ratio can be achieved in less machining time.

To get the perfect result of the machining process by using the EDM it is needed to find the correct parameter setting. Until now, there is no perfect parameter setting for any type of materials. So, it is important to find the best parameter setting before start the machining process in order to achieve the maximum result in its material removal rate (MRR), electrode ware ratio (EWR) and surface roughness (Ra).

In this work, Aluminum Copper cast alloys (Al-Cu) 201.0, which is commonly used for space and aircraft application as well as high performance automotive that require materials with high corrosion resistance and strength [2], has been used as the workpiece material.

The main objective in this work is to optimize the maximum material removal rat, minimum electrode ware ratio and minimum surface roughness.

Also in this work the best combination of certain input parameters to obtain optimum performances will be determined. These parameters are selected because it is significantly can affect the machining performances. Therefore these factors are the controllable factors. The first factor is intensity (I) it represents the maximum value of the discharge current intensity. The intensity values used in the EDM machine programming are power levels of the generator, these corresponding with values of the peak intensity. The second factor is ON time which is defined as the sparks occur time generated during a pulse which to perform the machining process. The third factor is OFF time and defined as the interval time between spark in a single pulse. The fourth factor is polarity of the workpiece. The collection of data is based on these selected factors. This set of data can be used to perform the best result in

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machining Al-Cu cast alloys 201.0 by using EDM machine. All the data will be used to produce one best setting to obtain the maximum material removal rate (MRR), minimum electrode ware ratio (EWR) and minimum surface roughness (Ra).

2. Literature Review

Various experimental and theoretical conducted on the EDM which is considered as a non-traditional machining process. Jensen et al (1993) and Leu et al (1998) have shown comparisons between non-traditional electroformed electrodes and traditional machined electrodes. Jensen et al have shown a general comparison between electroformed electrodes and machined electrodes but do not give much detail into performance of the electrodes. Research by Leu et al shown a more details comparison of the different electrodes in terms of MRR, EWR and Ra [5,6].

N.F. Petrofes and A.M, (1995) A significant difference in the optimal machining parameters when the machining surface is drastically reduced. According to the experimental results greater the electrode [7]. J.C. Rebelo, A. Dias Morao, D. Kremer and J.L. Lebrun, (1999) Optimization of the complicated multiple performance characteristics can be greatly simplified. The optimal setting of the parameters are determined through experiments planned, conducted and analyzed using the Taguchi method. It is found that EWR reduces substantially, within the region of experimentation, if the parameters are set at their lowest values, while the parameters set at their highest values increase the MRR drastically [8]. Guu Y.H. (2001) proposed the surface morphology, surface roughness and micro-crack of AISI D2 tool steel machined by the electrical discharge machining (EDM) process were analyzed by means of the atomic force microscopy (AFM) technique [9]. C.J. Luis, I. Puertas and G. Villa, (2003) The Taguchi methodology was used to study that influence. The result of the verification test for workpiece surface roughness was a strong confirmation [10]. Guu Y.H. et al, (2003) proposed the electrical discharge machining (EDM) of AISI D2 tool steel was investigated. The surface characteristics and machining damage caused by EDM were studied in terms of machining parameters. Based on the experimental data, an empirical model of the tool steel was also proposed. Surface roughness was determined with a surface profilometer [11]. Kansal, H.K, et al., (2005) study has been made to optimize the process parameters of powder mixed electrical discharge machining (PMEDM). Response surface methodology has been used to plan and analyze the experiments [12]. Pecas, P, et al. (2008) presents on EDM technology with powder mixed dielectric and to compare its performance to the conventional EDM when dealing with the generation of high quality surfaces [13]. S.Prabhu, et al (2008) analyzed the surface characteristics of tool steel material using multiwall carbon nano tube to improve the surface finish of material to nano level [14]. Ozlem Salman, et al (2008) proposed roughness values obtained from the experiments that have been modeled by using the genetic expression programming (GEP) method and a mathematical relationship has been suggested between the GEP model and surface roughness and parameters affecting it. Moreover, EDM has been used by applying copper, copper–tungsten (W– Cu) and graphite electrodes to the same material with experimental parameters designed in accordance with the Taguchi method [15].

From the review, it was concluded that much research was still needed to understand the EDM process fully and there is an evolution on the production of copper tools for EDM that lead to saving costs and manufacturing time, and this copper was the tool material chosen for the research.

There is a consensus that in the initial stage of the discharge and transitory stage of the EDM process the tool wear rate is high. So, the influence of the input parameters on the output parameters needed to be investigated in order to evaluate if they were the sole cause of the EWR optimization. Thus, the investigation in the work reported here was therefore directed to develop techniques for improving the EDM performance of copper tools.

3. Experimental Set-Up and Procedure

Series of experiments was conducted on FORM 2-LC electrical discharge machine to examine the effects of input machining parameters such as for instance intensity (I), pulse on time (t_i), duty factor (ή), and electrode polarity. In the tests the machining characteristics, i.e. the output variables, namely the optimum selection of manufacturing condition is important in manufacturing process as surface quality (Ra), metal removal rate (MRR), and electrode wear ratio (EWR) were measured using different techniques and equipment.

3.1 Workpiece Material

The workpiece material used in this study was Al-Cu cast alloys 2010. Table 1 lists the chemical composition (wt.%) of the material, while Table 2 lists the mechanical properties of the Al-Cu cast alloys 2010 [37].

Table 1: Chemical composition of the Al-Cu cast Alloys 2010.

Elements	Al	Cu	Fe	Mg	Mn	Si	Ti	Zn
Wt. %	91.83	5.22	0.28	0.55	0.43	0.83	0.02	0.05

Table 2: Mechanical properties of the Al-Cu cast Alloys 2010.

Property	**Value in metric unit**		**Value in US unit**	
Density	2.80 x10³	kg/m³	175	lb/ft³
Modulus of elasticity	71	GPa	10300	ksi
Thermal expansion (20 ºC)	$34.7x10^{-6}$	ºC⁻¹	$19.3*10^{-6}$	in/(in* ºF)
Specific heat capacity	963	J/(kg*K)	0.230	BTU/(lb*ºF)
Thermal conductivity	121	W/(m*K)	841	BTU*in/(hr*ft²*ºF)
Electric resistivity	$5.4x10^{-8}$	Ohm*m	$5.4*10^{-6}$	Ohm*cm
Heat of fusion	$3.89*10^{5}$	J/kg	167	BTU/lb
Liquidus temperature	649	ºC	1200	ºF
Solidus temperature	571	ºC	1060	ºF
Tensile strength (T6)	485	MPa	70300	psi
Yield strength (T6)	435	MPa	63100	psi
Elongation (T6)	7	%	7	%
Shear strength (T6)	290	MPa	42100	psi
Hardness (T6)	135	HB	135	HB
Solution temperature	516	C°	960	ºF
Aging temperature	154	C°	310	ºF
Aging time	12-20	hrs.	12-20	hrs.

3.2 Electrode Material

The electrode materials investigated in this research was copper with the characteristic shown in Table 3.

Table 3: Electrode material properties [25].

Material	Copper
Composition	99% copper
Density (g/cm)	8.904
Material point (C°)	1083
Electrical resistivity (μΩcm)	9
Hardness	H_B 100

3.3 Dielectric Fluid

The dielectric fluid used in this study was Kerosene.The quality, viscosity and composition of the dielectric are important parameters

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for guaranteeing optimum spark erosion conditions. Charmilles Technologies uses FLUXELF 2. The dielectric must be changed once per year [18].

3.4 Instruments and Equipment Required

3.4.1 Balance Sensitive

The Balance sensitive used in this study was Balance Electronic Model EUROPE 500. Maximum load is 510 g and its precision is 3 digits.

3.4.2 Spectrometers

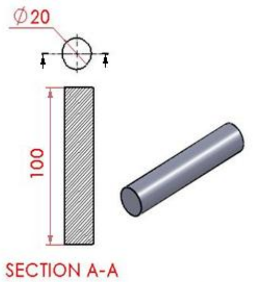
Spectrometers model (J.Y 132F) to test the chemical composition for the specimens (Al-Cu) 2010 was used.

3.4.3 Surface Roughness Measurement

Roughness measurement was done using a portable stylus type profilometer, Talysurf (Taylor Hobson, Surtronic 3+). The profilometer was set to a cut-off length of 0.8 mm, filter 2CR, and traverse speed 1mm/s and 4 mm evaluation length roughness measurements, in the transverse direction, on the workpieces were repeated four times and average off the measurements was recorded. The measured profile was digitized and processed through the dedicated advanced surface finish analysis software, Talyprofile, for evaluation of the roughness parameters.

3.5 Experimental Preparation

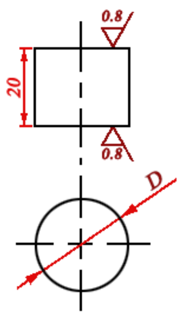
The raw materials were machined as using conventional methods such as turning and grinding. The electrode were made to a size of 20 mm diameter and length 100 mm as shown Figure 1



Diameter	Dimensions	Quantity
D	20 $\pm^{0.02}$mm	56

Fig. 1: Electrode design.

The specimens were made to a size of diameter 20 mm and length 20 mm as shown Figure 2. After that numbering all the workpieces and put it in the container box.



Diameter	Dimensions	Quantity
D	20 $\pm^{0.02}$mm	56

Fig. 2: Workpiece design.

3.6 Experiments Steps

The method adopted in the Kerosene experiments was as follows:

The electrode and specimen were cleaned and dried before every test, then weighed before and after every run. The electrode was tightened into the spindle chuck and passed through the jig. The machining parameters were preset on the control panel generator. Once it had been verified that the ventilation was working, the machine and timer were switched on in the same action. After the specified time had elapsed, the cycle was ended by switching off the machine.

The electrode and specimen were released, and then cleaned with dry compressed air and tissue paper. The electrode and specimen were weighed after machining and the values noted as shown in the Appendix - Table 18. The emergency switch on the machine and the mains supply were both switched off and the machine was cleaned as per scheduling. During the test, the Kerosene level was maintained so that it covered the specimen to a height of (30 – 40) mm, to prevent the spark igniting the Kerosene and the fumes becoming dissolved in it.

3.7 Measurements

The electrodes and specimens were dried by tissue paper and dry compressed air after each experiment and before weighing. Then MRR and EWR were calculated by weighing the specimen and electrode on the digital single pan balance with an accuracy of ± 0.001g and by recording the test time with a stop clock.

4. Experimental Design

Design of experiments (DOE) is used to study the effect of multiple variable simultaneously, which is a powerful statistical technique introduced by R. A. Fisher in England in 1920's [*]. Reacting to Fisher's methods in the design of experiments, Taguchi interpreted Fisher's methods as being adapted for seeking to improve the mean out come of a process. The method could be used not only to improve quality, but also to quantify the improvements made in terms of saving money. The experimental design and analyze of the results can be done with less effort and expenses by using the Taguchi method. Since the method enormously reduces the number of experiments. A well planned set of experiments, in which all parameters of interest are varied over a specified range, is a much better approach to obtain systematic data. Mathematically speaking, such a complete set of experiments ought to give desired results. In many cases, particularly those in which some optimization is required, the method does not point to the BEST settings of parameters [42,43].

4.1 Taguchi Method

Dr. Taguchi of Nippon Telephones and Telegraph Company, Japan has developed a method based on "ORTHOGONAL ARRAY" experiments which gives much reduced "variance" for the experiment with "optimum settings "of control parameters. Thus the marriage of Design of Experiments with optimization of control parameters to obtain BEST results is achieved in the Taguchi Method. "Orthogonal Arrays" (OA) provide a set of well balanced (minimum) experiments and Dr. Taguchi's Signal-to-Noise ratios (S/N), which are log functions of desired output, serve as objective functions for optimization, help in data analysis and prediction of optimum results [44,45].

4.2 The Steps in Taguchi Methodology

Taguchi Method is a process/product optimization method that is based on 8-steps of planning, Table 4, conducting and evaluating results of matrix experiments to determine the best levels of control factors. The primary goal is to keep the variance in the output very low even in the presence of noise inputs. Thus, the processes products are made ROBUST against all variations [43,44].

The Taguchi method can optimize performance characteristics through the settings of process parameters and reduce the sensitivity of the system performance to sources of variation. As a result, the Taguchi method has become a powerful tool in the design of experiment methods, the applications of DOE for EDM to optimizing process parameters to achieve low electrode wear and high machining rate.

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Table 4: Steps for conducting experimental design [42].

Step	Details
1-	Identify the main function, side effects, and failure mode
2-	Identify the noise factors, testing conditions, and quality characteristics
3-	Identify the objective function to be optimized
4-	Identify the control factors and their levels
5-	Select the orthogonal array matrix experiment
6-	Conduct the matrix experiment
7-	Analyze the data; predict the optimum levels and performance
8-	Perform the verification experiment and plan the future action

As a research, the DOE method has been used to study the performance of the EDM process using Kerosene for Al-Cu cast Alloys 2010 under different control parameters. EDM is a very complicated process. It is very difficult to monitor its working conditions effectively; there is a lack of adequate knowledge on the discharge mechanism. The statistical analysis in this experimental work consists of Taguchi approach that is applied to find the optimal combinations and the optimal parameter design; computer simulations are performed to show the control performances of operating parameters [45, 46].

4.3 Improving EDM Performance Based on the Taguchi Method

The definition of performance characteristics such as lower-the-better, higher-the-better, and nominal-the-better contains a certain degree of uncertainty and vagueness. Therefore, optimization of the performance characteristics with Taguchi method has been considered in this research.

Experimental design methods are too complex and not easy to use. Also, a large number of experiments have to be carried out as the number of the process parameters increases. To solve this important task, the Taguchi method uses a special design of orthogonal array to study the entire parameter space with only a small number of experiments. The experimental results are then transformed into a signal-to noise (S/N) ratio. The S/N ratio can be used to measure the deviation of the performance characteristics from the desired values. Usually, there are three categories of performance characteristics in the analysis of the S/N ratio. The lower-the-better, the higher-the-better, and the nominal-the-better. Regardless of the category of the performance characteristic, a larger S/N ratio corresponds to better performance characteristic. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio. Finally experiment is conducted to verify the optimal process parameters obtained from the parameter design.

Basically, the Taguchi method is designed to handle the optimization of a single performance characteristic [44,46].

4.4 Experimental Design Methods

Design of experiments is a powerful analysis tool for modeling and analyzing the influence of process variables over some specific variable. Taguchi method requires the knowledge about the domain that is examined, since the main function, side effects and failure modes have to be identified. A wrong decision in this step makes all other steps useless. The aim of experimentation is to find the significant machining parameters for the material removal rate (MRR) and electrode wear ratio (EWR) and surface roughness (Ra) and verify the optimal machining parameters. Taguchi methodology were applied to optimize the machining parameters for current intensity I, plus on time ti, duty factor ή, and Workpiece polarity when machining Al-Cu cast Alloys 2010 with copper electrode, three electrodes were used in experiments. Control factors and their levels, to reduce the number of experiments, only the most important factors should be considered. Two or three factor levels can be chosen. In the latter case, the levels should be evenly distributed. The factor levels should be placed very carefully, since the Taguchi method defines the significant and optimal parameters only within the levels.

4.5 Design Factors and Technological Response Variables Analyzed

Electrical discharge machining (EDM) has been used effectively in the machining of hard, high-strength, and temperature-resistant materials. Material is removed by means of rapid and repetitive spark discharges across the gap between the tool and the workpiece. In electrical discharge machining, it is important to select machining parameters for achieving optimal machining performance. Usually, the desired machining parameters are determined based on experience. However, this does not ensure that the selected machining parameters result in optimal or near optimal machining performance for that particular electrical discharge machine and environment. To solve this task in the present research, the Taguchi method is used as an efficient approach to determine the optimal machining parameters in the electrical discharge machining process. Solid copper electrodes with outer diameter of 20 mm were used. The schematic diagram of the experimental set-up is shown in Figure 3. The workpiece and electrode were separated by a moving dielectric fluid (Kerosene). In the experiments, kerosene was used as the dielectrics for comparison. Machining experiments for determining the optimal machining parameters were carried out by setting:

(A) Polarity (-,+) of the workpiece,

(B)A pulse-on time in the range of (800, 1600, 2400) µsec,

(C)A discharge current in the range of (9, 12.5, 23) A, and

(D)A duty factor in the range of (0.5, 0.8, 0.95).

The Four initial parameters and three levels, which were related to the EDM working conditions, as in Table 5, which presents the relationship between the design factors and their corresponding selected variation levels: workpiece polarity, pulse-on time, discharge current and duty factor.

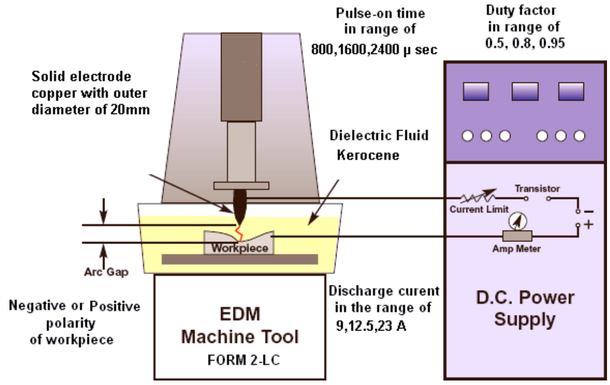

Fig.3: Schematic diagram of the EDM experimental arrangement.

Table 5: Machining parameters and their levels

Symbol	Control factor	Level			Observed values
		1	2	3	
		Minimum	Intermediate	Maximum	
A	Workpiece polarity	Negative	Positive	-	1. MRR 2. EWR 3. Ra
B	Pulse on time, µsec.	800	1200	2400	
C	Discharge current, A	9	12.5	23	
D	Duty factor	0.5	0.8	0.95	

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4.6 Calculation of the Optimal Control Parameters

The use of the Taguchi approach to determine the machining control parameters with optimal machining performance in the EDM process is illustrated in Figure 4 [46].

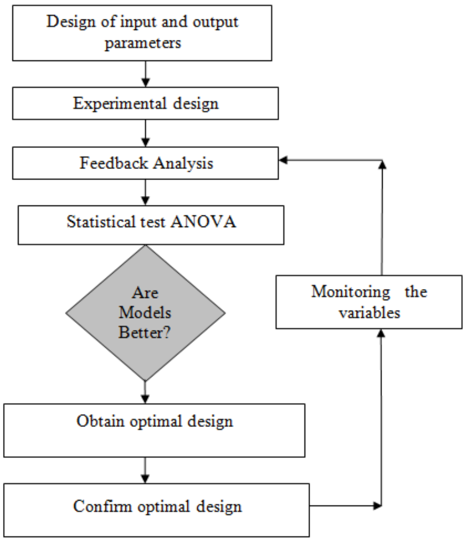

Fig. 4: Procedure of the experiments

4.7.1 Orthogonal Array (OA) Experiment

The experimental procedure using the Taguchi approach can be explained as follows:

(a) The number of factors and interactions to be considered in the experiment and the number of levels of the factors were found.
(b) The appropriate orthogonal array was selected (OA) to:-
- The required degree of freedom Design Of Experiments (DOF) from the factors and interactions was determined, the degrees of freedom of a factor are one less than the number of levels of the factor. The DOF of a particular orthogonal array is obtained by the sum of the individual DOF for each column in the array [47,48].
- The appropriate orthogonal array is the one whose DOF is equal to or more than the required DOF of the factors. The smallest array satisfying this requirement is normally chosen for efficiency.

(c) With the appropriate orthogonal array chosen, and the linear graph that fits the relationships of the factors of interest was choose. The factors can then be assigned to the columns of the orthogonal array according to the linear graph.
(d) The experiments and analyses the results was conducted. And a confirmation experiment was run finally by using the results obtained.

Hence, the selection of the appropriate OA, assigning factors to columns and the total degrees of freedom need to be computed, describing each trial condition and deciding the order and repetitions of trial conditions. The total number of DOF needs to be determined to select an appropriate orthogonal array for the experiments. The DOF are defined as the number of comparisons that need to be made to determine which level is better, and specifically how much better it is. A two-level parameter has one degree of freedom. The present analysis does not include the interaction between process parameters, so there are two DOF due to three process variables. The selection of the OA is subject to the condition that the DOF for the orthogonal array should be greater than or at least equal to those for the process parameters. In the present study, the interaction between the machining parameters is neglected. Therefore, there are 11 DOF arising from one two-level machining parameter and three three-level machining parameters in the EDM process. Once the DOF are known, the next step is selecting an appropriate OA to fit the specific task. The DOF for the OA should be greater than or at least equal to those for the process parameters. In this study, a L18 OA was chosen because it has 11 degrees of freedom, more than the 7 degrees of freedom in the machining parameters. This array has 4 columns and 18 rows. Each machining parameter is assigned to a column and 18 machining parameter combinations are required. Therefore, only 18 experiments are needed to study the entire machining parameter space using the L18 OA. The experimental combinations of the machining parameters using this array are shown in Table 6[47, 48].

Table 6: Design of experimental layout using an L18 orthogonal array.

No.	Workpiece Polarity (A)	Pulse-on Time (B)	Discharge Current (C)	Duty Factor (D)
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	1
5	1	2	2	2
6	1	2	3	3
7	1	3	1	2
8	1	3	2	3
9	1	3	3	1
10	2	1	1	3
11	2	1	2	1
12	2	1	3	2
13	2	2	1	2
14	2	2	2	3
15	2	2	3	1
16	2	3	1	3
17	2	3	2	1
18	2	3	3	2

4.7 Signal-To-Noise Ratio

Optimization of the observed values was determined by comparing the S/N ratio, which was also based on the Taguchi method. The higher observed values such as MRR are called "**the higher the better**" (HB), while the lower observed values such as EWR and Ra are "**the lower the better**" (LB). Calculating the deviation of the performance characteristic from the desired value, the S/N ratio η_{ij} for the i^{th} performance characteristic in the j^{th} experiment can be expressed as:

$$\eta_{ij} = 10\log L_{ij} \quad \cdots\cdots\cdots\cdots \quad (1)$$

As mentioned earlier, there are three categories of quality characteristics, i.e. the-lower-the-better, the-higher-the-better, and the-nominal-the-better. The loss function of the higher-the-better performance characteristic can be expressed as:

$$\text{HB:} \quad L_{ij} = \frac{1}{n}\sum_{k=1}^{n}\frac{1}{y_{ijk}^2} \quad \cdots\cdots\cdots\cdots (2)$$

On the other hand, the-lower-the-better quality characteristics for the loss function L_{ij} of the lower-the-better performance characteristic can be expressed as:

$$\text{LB:} \quad L_{ij} = \frac{1}{n}\sum_{k=1}^{n} y_{ijk}^2 \quad \cdots\cdots\cdots\cdots (3)$$

Where L_{ij} is the loss function of the i^{th} performance characteristic in the j^{th} experiment, n the number of tests, and y_{ijk} is the experimental value of the i^{th} performance characteristic in the j^{th} experiment at the kth test [43,44,45].

4.8 Statistical Test – Analysis Prediction Confidence

Once the optimal level of the process parameters has been selected, the final step is to predict and verify the improvement of the performance characteristics using the optimal level of the process parameters. The estimated S/N ratio $\acute{\eta}$ using the optimal level of the process parameters can be calculated as:

$$\acute{\eta} = \eta_m + \sum_{i=1}^{q} (\eta_i - \eta_m) \quad \cdots\cdots\cdots\cdots (4)$$

Where η_m is the total mean of the MRR, EWR, Ra, η_i the mean of the MRR, EWR and Ra at the optimal level, and q is the number of the process parameters that significantly affect the performance characteristics. The estimated MRR, EWR and Ra using the optimal machining parameters can then be obtained. Tables8-12show the results of the confirmation experiment using the optimal machining parameters.

4.9 Analysis Of Variance (ANOVA)

The purpose of the ANOVA and the F test(standard analysis) is to investigate which process parameters significantly affect the performance characteristics. This is accomplished by separating the total variability of the performance indexes, which is measured by the sum of the squared deviations from the total mean of the MRR, EWR and Ra, into contributions by each of the process parameter and the error. First, the total sum of the squared deviations SST from the total mean of the MRR, EWR, Ra can be calculated as[48,49]:

4.9.1 Total Variation

$$SST = SSA + SSW \quad \cdots\cdots\cdots\cdots (5)$$

SST=Total Sum of Squares (Total variation).

SSA=Sum of Squares among Groups (Among-group variation).

SSW=Sum of Squares within Groups (Within-group variation).

Total Variation = the aggregate dispersion of the individual data values across the various factor levels (*SST*).

Among-Group Variation = Dispersion between the factor sample means (SSA).

Within-Group Variation = Dispersion that exists among the data values within a particular factor level (*SSW*).

$$SST = \sum_{j=1}^{c} \sum_{i=1}^{nj} (X_{ij} - \bar{\bar{X}})^2 \quad \cdots\cdots\cdots\cdots (6)$$

Where:

SST = Total sum of squares.

c = number of groups (levels or treatments).

n_j = number of observations in group *j*.

X_{ij} = i^{th} observation from group *j*.

$\bar{\bar{X}}$ = grand mean (mean of all data values).

$$Mean\ Square\ Total = \frac{SST}{Degrees\ of\ Freedom}$$

$$MST = \frac{SST}{n-1} \quad \cdots\cdots\cdots\cdots \quad (7)$$

$$SSA = \sum_{j=1}^{c} n_j (\bar{X}_j - \bar{\bar{X}})^2 \quad \cdots\cdots\cdots\cdots (8)$$

Where:

SSA = Sum of squares among groups.

c = number of groups or populations.

n_j = sample size from group *j*.

$\bar{X}_j$ = sample mean from group *j*.

$\bar{\bar{X}}$ = grand mean (mean of all data values).

$$Mean\ Square\ Among = \frac{SSA}{Degrees\ of\ Freedom}$$

$$MST = \frac{SSA}{c-1} \quad \cdots\cdots\cdots\cdots \quad (9)$$

$$SSW = \sum_{j=1}^{c} \sum_{i=1}^{nj} (X_{ij} - \bar{X}_j)^2 \quad \cdots\cdots\cdots\cdots (10)$$

Where:

SSW = Sum of squares within groups.

c = number of groups.

n_j = sample size from group *j*.

$\bar{X}_j$ = sample mean from group *j*.

X_{ij} = i^{th} observation in group *j*.

$$Mean\ Square\ Within = \frac{SSW}{Degrees\ of\ Freedom}$$

$$MSW = \frac{SSW}{n-c} \quad \cdots\cdots\cdots\cdots (11)$$

4.9.2 Test Statistic

In this study, the analysis of variance (ANOVA) and *F*-test were performed to see statistically significant process parameters and the percent contribution of these parameters on MRR, EWR and Ra. Larger *F* value indicates that the variation of the process parameters makes a big change on the performance characteristics.

$$F = \frac{MSA}{MSW} \quad \cdots\cdots\cdots\cdots (12)$$

MSA= mean squares among variances.

MSW=mean squares within variances.

The percentage contribution by each of the process parameter in the total sum of the squared deviations *SST* can be used to evaluate the importance of the process-parameter change on the performance characteristics. In addition, the *F*-test can also be used to determine which process parameters have a significant effect on the performance characteristic. Usually, the change of the process parameter has a significant effect on the performance characteristic when the *F* value is large.

5. Results and Discussions

The optimization of EDM performance requires the maximum material removal rate (MRR), minimum electrode wear ratio (EWR) and good surface finish (Ra) are attained.

The mean effects plots of the S/N ratios for the output measures are obtained using Minitab 15 software. Plots with the steeper slope along with longer lines shows that the factor has significant impact on the output parameter.

5.1 EDM Performance Evaluation

As mentioned earlier, there are four input parameters whose affect EDM performance. Some of these are likely to have a much more significant effect on the output process parameters than others and the first set of experiments was designed using the Taguchi method to determine which parameters could likely improve the EDM performance.

An Ll8 orthogonal array was chosen because the aim of the study was optimization; according to Taguchi this is done using two and three-level parameters. The values for the input process parameters from A to D were allocated using the EDM cut values.

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The levels of each setting used and results obtained are shown in Appendix - Table 17.

The MRR and EWR results were obtained from the measured values of change in weight. Detailed results are given in Appendix - Table 18. The Ra values were obtained from directly measured data as shown in Appendix -Table 18.

5.2 Analysis of Material Removal Rate (MRR)

The average values of S/N ratios for MRR at different levels are plotted in Figure 5 keeping the objective as “larger is better”. In order to study the significance of the parameters in effecting the quality characteristic of interest i.e. Table 7 shows initial machining condition. The comparison of the S/N ratios between the initial machining parameters and the optimal machining parameters is also shown in Table 8. It is shown clearly that the MRR and S/N ratios are greatly improved through this study.

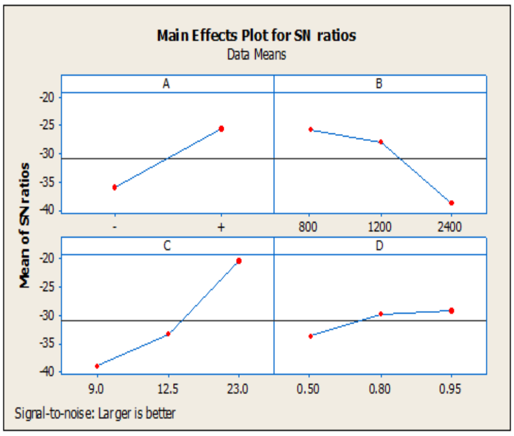

Fig. 5: Mean effect plot for S/N ratios for material removal rate, (MRR).

It is clear from Figure 5 that MRR is maximum at the 2nd level of parameter A, 1st level of parameter B, 3rd level of parameter C and 3rd level of parameter D. The S/N ratio analysis suggests the same levels of the parameters (A2, B1, C3and D3) as the best levels for maximum MRR.

Table 7: Initial machining condition based on result of EWR.

Factors	Level	Level Description	MRR g/min	S/N Ratio
A	2	+	0.2494	-12.0620
B	1	800		
C	3	23		
D	3	0.95		

Table 8: Optimum machining condition: MRR Predicted values.

Factors	Level	Level Description	MRR g/min	S/N Ratio
A	2	+	0.3871	-8.2435
B	1	800		
C	3	23		
D	3	0.95		

5.3 Analysis of Electrode Ware Ratio (EWR)

The average values of S/N ratios for EWR at different levels are plotted in Figure 6 keeping the objective as “minimum is better”. In order to study the significance of the parameters in effecting the quality characteristic of interest i.e. Table 9 shows initial machining condition. The comparison of the S/N ratios between the initial machining parameters and the optimal machining parameters is also shown in Table 10. It is shown clearly that the EWR and S/N ratios are greatly improved through this study.

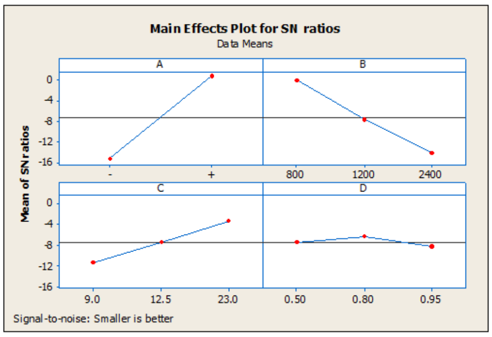

Fig. 6: Mean effect plot for S/N ratios for electrode ware ratio (EWR).

It is clear from Figure 6 that EWR is minimum at the 2nd level of parameter A, 1st level of parameter B, 3rd level of parameter C and 2nd level of parameter D. The S/N ratio analysis suggests the same levels of the parameters (A2, B1, C3and D2) as the best levels for maximum EWR.

Table 9: Initial machining condition based on result of EWR.

Factors	Level	Level Description	EWR%	S/N Ratio
A	2	+	0.204	13.8073
B	1	800		
C	3	23		
D	2	0.8		

Table 10: Optimum machining condition: EWR Predicted values.

Factors	Level	Level Description	EWR%	S/N Ratio
A	2	+	0.1866	14.5817
B	1	800		
C	3	23		
D	2	0.95		

5.4 Analysis of Surface Roughness (Ra)

The average values of S/N ratios for Ra at different levels are plotted in Figure 7 keeping the objective as “smaller is better”. In order to study the significance of the parameters in affecting the quality characteristic of interest i.e. Table 11 shown initial machining condition. The comparison of the S/N ratios between the initial machining parameters and the optimal machining parameters is also shown in Table 12. It is shown clearly that the Ra and S/N ratios are greatly improved through this study.

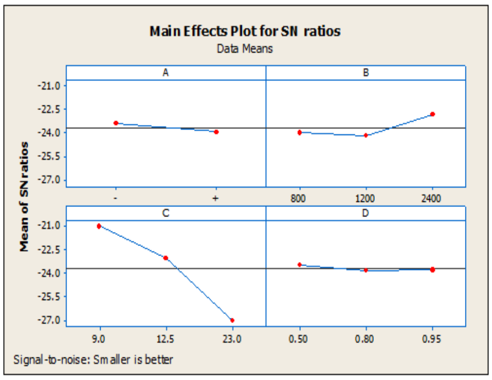

Fig. 7*:* Mean effect plot for S/N ratios for Surface Roughness (Ra).

It is clear from Figure 7 that Ra is minimum at the 1st level of parameter A, 3rd level of parameter B, 1st level of parameter C and 1st level of parameter D. The S/N ratio analysis suggests the same levels of the parameters (A1, B3, C1and D1) as the best levels for maximum Ra.

Table 11: Initial machining condition based on result of Ra.

Factors	Level	Level Description	Ra (µm)	S/N Ratio
A	1	-	9	-19.0848
B	3	2400		
C	1	9		
D	1	0.5		

Table 12: Optimum machining condition: Ra Predicted values.

Factors	Level	Level Description	Ra (µm)	S/N Ratio
A	1	-	8.33	-18.4129
B	3	2400		
C	1	9		
D	1	0.5		

5.5 Data analysis

In this study, all the analysis based on the Taguchi method is done by Taguchi DOE software (Minitab15) to determine the main effects of the process parameters, to perform the analysis of variance (ANOVA) and to establish the optimum conditions. The main effects analysis is used to study the trend of the effects of each of the factors, as shown in Figures 5-7. The machining performance (ANOVA-significant factor) for each experiment of the L18 can be calculated by taking the observed values of the MRR as an example from Table 17. Table 13 lists the ANOVA and *F* test results for MRR. $F_{0.05;\ n1,n2}$ is quoted from "Statistical Tables" [50]. If the calculated F_z values exceed $F_{0.05;\ n1,n2}$ (Table 13), then the contribution of the input parameters, such as discharge currant, is defined as significant. Thus, the significant parameters can be categorized into two levels which are significant and sub significant. All of them are based on the fact that the F_z values are much larger than $F_{0.05;\ n1,n2}$ and denoted as ** and *, respectively. For instance, to evaluate the MRR, the significant parameter is discharge currant. The remaining parameters only slightly contribute to the evaluation of the MRR. Similar calculations are also applied in evaluating the EWR and Ra. Tables 14, 15 and 16 summarized the correlated results, indicating the significant parameters in evaluating the EWR and Ra, respectively, and Figures 8-10 graphically, has been explicate the percent of control Parameters on MRR, EWR and Ra.

Table 13: Analysis of Variance for MRR.

Parameter	DOF	Sum of Square	Mean Square	*F*	$F_{0.05;n1,n2}$	Contribution (%)
A	1	0.014959	0.014959	14.08*	4.96	20.35
B	2	0.007678	0.003839	3.61	4.10	10.44
C	2	0.034716	0.017358	16.34**	4.10	47.24
D	2	0.005509	0.002754	2.59	4.10	7.49
Error	10	0.010625	0.001062			14.45
Total	17	0.073487				100

Table 14: Analysis of Variance for EWR.

Parameter	DOF	Sum of Square	Mean Square	*F*	$F_{0.05;n1,n2}$	Contribution (%)
A	1	44.579	44.579	5.59*	4.96	19.08
B	2	77.972	38.986	4.89**	4.10	33.38
C	2	29.324	14.662	1.84	4.10	12.55
D	2	1.948	0.974	0.12	4.10	0.83
Error	10	79.727	7.973			34.13
Total	17	233.55				100

Table 15: Analysis of Variance for Ra.

Parameter	DOF	Sum of Square	Mean Square	*F*	$F_{0.05;n1,n2}$	Contribution (%)
A	1	5.227	5.227	1.86	4.96	1.12
B	2	16.041	8.021	2.86	4.10	3.45
C	2	412.374	206.187	73.48**	4.10	88.87
D	2	2.271	1.136	0.40	4.10	0.48
Error	10	28.062	2.806			6.01
Total	17	463.976				100

Table 16: Summarization of significant parameters on the machinability of EDM.

Parameter	MRR	EWR	Ra
A	*	*	
B		**	
C	**		**
D			

**Significant parameter;*Sub significant parameter.

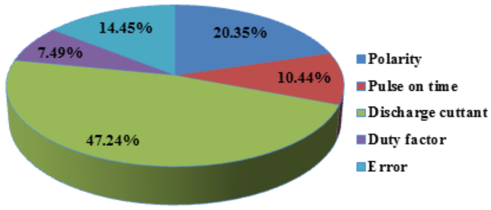

Figure 8: percent of control Parameters on MRR.

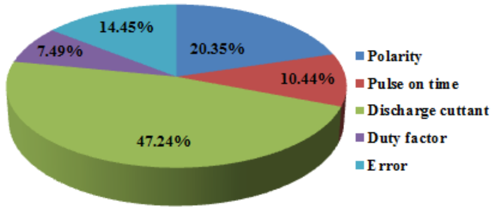

Figure 9: percent of control Parameters on EWR.

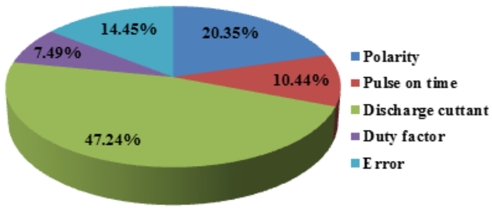

Figure 10: Percent of control Parameters on Ra.

6. Conclusion

From the experiments concerned with electrical discharge in kerosene as a dielectric, it was found that:

(1) Taguchi method indicate optimal experimental from all experiments, the experimental results for the (MRR) number twelve is the best through the higher signal to noise ratio which calculate (-12.0620), and there machining parameters was [Workpiece polarity(+), Discharge current (23 A), Pulse-on time (800 µs) and Duty factor (0.95)]. And the experimental results for the (EWR) number twelve is the best through the higher signal to noise ratio which calculate (13.8073), and there machining parameters was [Workpiece polarity(+), Discharge current (23 A), Pulse-on time (800 µs) and Duty factor (0.8)].

(2) By using Taguchi Analysis Predicted values:

- Improve the MRR from 0.2494 g/min to 0.3871 g/min by increase 55.2% improve the EWR from 0.204% to 0.1866% decreases by 8.5%
- Improve signal to noise ratio (S/N) MRR from -12.0620 to -8.2435 by increase 31% and signal to noise (S/N) EWR from 13.8073to 14.5817 by increase 5.6%

(3) Analysis of variance (ANOVA) investigate the process parameters significantly affect the performance characteristics. The most effective parameters the discharge

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currant of EDM mainly affects the MRR. The Pulse-on time largely affects the EWR.

(4) The electrode wear ratio is close to zero at any pulse duration or discharge current because the energy absorbed by the anode is greater than that absorbed by the cathode.

(5) Due the experiments it was found that the surface roughness is quit rough, and to improving the quality of this surface roughness is possible by using rough and finishing machining stages.

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Table 17: Orthogonal array L18 with the levels result and its *S/N* ratio.

No.	Workpiece Polarity (A)	Pulse-on Time (B)	Discharge current (C)	Duty Factor (D)	MRR		EWR		Ra	
					Observed Value of MRR [g/min]	S/N Ratio [dB] Decibel	Observed Value of EWR [%]	S/N Ratio [dB] Decibel	Ra [µm]	S/N Ratio [dB] Decibel
1	-	800	9	0.5	0.0085	-41.4116	4.891	-13.7879	10.8	20.6684-
2	-	800	12.5	0.8	0.0259	-31.7340	5.007	13.9915-	14.1	22.9843-
3	-	800	23	0.95	0.0956	-20.3908	5.096	-14.1445	24.4	27.7477-
4	-	1200	9	0.5	0.0072	-42.8533	5.456	-14.7374	11.1	20.9064-
5	-	1200	12.5	0.8	0.0206	-33.7226	4.824	-13.6681	13.7	22.7344-
6	-	1200	23	0.95	0.0802	-21.9165	5.804	-15.2745	23.1	27.2722-
7	-	2400	9	0.8	0.0022	-53.1515	10.920	-20.7644	10.3	20.0206-
8	-	2400	12.5	0.95	0.0045	-46.9357	4.992	-13.9654	13.2	22.4114-
9	-	2400	23	0.5	0.0231	-32.7277	7.539	-17.5462	19.1	25.6206-
10	+	800	9	0.95	0.0691	-23.2104	0.207	13.6805	12.9	22.2117-
11	+	800	12.5	0.5	0.0521	25.6632-	0.210	13.5556	16	24.0824-
12	+	800	23	0.8	0.2494	-12.0620	0.204	13.8073	20.7	26.3184-
13	+	1200	9	0.8	0.0287	-30.8423	3.387	-10.5963	14	- 22.9225
14	+	1200	12.5	0.95	0.0985	-20.1312	0.815	1.7768	15.9	24.0279-
15	+	1200	23	0.5	0.1215	-18.3084	0.515	5.7638	24	27.6042-
16	+	2400	9	0.95	0.0080	-41.9382	12.624	-22.0239	9	-19.0848
17	+	2400	12.5	0.5	0.0084	-41.5144	7.801	-17.8430	12.5	21.9382-
18	+	2400	23	0.8	0.1510	16.4206-	0.439	7.1507	24.5	-27.7833

WRW: Workpiece Removal weight [grams].
EWW: Electrode Wear Weight [grams].
MRR: Material Removal Rate [mm^3/hr].
EWR: Electrode Wear Ratio.

Table 18: Sample for experimental result for the MRR and EWR.

No. of Experiment	Control Factors	Workpiece Weight Before Expr. [g]	Workpiece Weight after Expr [g]	WRW [g]	Average WRW [g]	Electrode Weight Before [g]	Electrode Weight After [g]	EWW [g]	Average EWW [g]	Average MRR [g/min]	Average EWR
1	1 A	17.8983	17.6380	0.2603	0.2576	105.2960	105.2846	0.0114	0.0126	0.0085	4.891
	1 B	17.9120	17.6526	0.2594		103.5217	103.5079	0.0138			
	1 C	17.6424	17.3892	0.2532		112.4561	112.4433	0.0128			
2	2 A	18.0245	17.2196	0.8049	0.7789	0.0392	103.4811	103.5203	0.039	0.0259	5.007
	2 B	17.8978	17.1322	0.7656		0.0462	108.7075	108.7537			
	2 C	17.9545	17.1881	0.7664		0.0316	113.0141	113.0457			
3	3 A	2.8642	15.0453	17.9095	2.8687	0.1317	109.0891	109.2208	0.1426	0.0956	4.970
	3 B	2.8876	14.7823	17.6699		0.1647	111.0183	111.1830			
	3 C	2.8545	15.0036	17.8581		0.1314	113.2570	113.3884			
4	4 A	0.2452	17.7859	18.0311	0.2181	0.0127	105.2719	105.2846	0.0119	0.0072	5.456
	4 B	0.2029	17.6065	17.8094		0.012	103.4959	103.5079			
	4 C	0.2062	17.6579	17.8641		0.011	112.4323	112.4433			
5	5 A	0.6305	17.1737	17.8042	0.6198	0.030	103.4511	103.4811	0.0299	0.0206	4.824
	5 B	0.6232	17.0079	17.6311		0.0296	108.6779	108.7075			
	5 C	0.6059	17.1593	17.7652		0.0302	112.9839	113.0141			
6	6 A	2.3651	15.4056	17.7707	2.4086	0.1367	108.9524	109.0891	0.1398	0.0802	5.804
	6 B	2.4424	15.0223	17.4647		0.141	110.8773	111.0183			
	6 C	2.4184	15.4688	17.8872		0.1418	113.1152	113.2570			
7	7 A	0.1884	17.7908	17.9792	0.2271	0.0238	105.2481	105.2719	0.0248	0.0022	10.920
	7 B	02010	17.4235	17.6245		0.0252	103.4707	103.4959			
	7 C	0.2920	17.3061	17.5981		0.0254	112.4069	112.4323			
8	8 A	0.1429	17.7872	17.9301	0.1362	0.0081	103.4430	103.4511	0.0068	0.0045	4.992
	8 B	0.1249	17.6066	17.7315		0.0063	108.6716	108.6779			
	8 C	0.1409	17.7901	17.9310		0.0061	112.9778	112.9839			
9	9 A	0.7054	17.2237	17.9291	0.6937	0.0528	108.8996	108.9524	0.0523	0.0231	7.539
	9 B	0.6917	16.6068	17.2985		0.0519	110.8254	110.8773			
	9 C	0.6842	16.9778	17.6620		0.0524	113.0628	113.1152			
10	10A	17.9193	1.9948	15.9245	2.0759	0.0046	105.2479	105.2525	0.0043	0.0691	0.207
	10B	17.6340	2.0358	15.5982		0.0036	103.4704	103.4740			
	10C	17.6983	2.1971	15.5012		0.0048	112.4021	112.4069			
11	11A	17.6467	1.6298	16.0169	1.5657	0.0033	103.4430	103.4463	0.0033	0.0521	0.210
	11B	17.7120	1.581	16.1310		0.003	108.6716	108.6746			
	11C	17.7390	1.4864	16.2526		0.0036	112.9778	112.9814			
12	12A	17.9648	6.8431	11.1217	7.4833	0.0193	108.8803	108.8996	0.0153	0.2494	0.204
	12B	17.5426	7.2188	10.3238		0.0051	110.8203	110.8254			
	12C	17.9932	8.3882	9.6050		0.0217	113.0411	113.0628			
13	13A	17.8793	0.6326	17.2467	0.8619	0.0471	105.2008	105.2479	0.0292	0.02873	3.387
	13B	17.4994	1.134	16.3654		0.0165	103.4539	103.4704			
	13C	17.8983	0.8192	17.0791		0.024	112.3781	112.4021			
14	14A	17.6939	2.6127	15.0812	2.9552	0.022	103.4210	103.4430	0.0241	0.0985	0.815
	14B	17.8751	3.2886	14.5865		0.0257	108.6459	108.6716			
	14C	17.6116	2.9643	14.6473		0.0246	112.9532	112.9778			
15	15A	17.6567	3.8984	13.7583	3.6459	0.0116	108.8687	108.8803	0.0188	0.1215	0.515
	15B	17.8402	3.2587	14.5815		0.0369	110.7834	110.8203			
	15C	17.6975	3.7807	13.9168		0.0079	113.0332	113.0411			
16	16A	0.2421	17.3214	17.5635	0.2408	0.0258	105.1750	105.2008	0.0304	0.0080	12.624
	16B	0.2378	17.7847	18.0225		0.0154	103.4385	103.4539			
	16C	0.2425	17.6594	17.9019		0.0501	112.3280	112.3781			
17	17A	0.2427	17.5062	17.7489	0.2538	0.0138	103.4072	103.4210	0.0198	0.0084	7.801
	17B	0.2684	17.7280	17.9964		0.0287	108.6172	108.6459			
	17C	0.2505	17.4230	17.6735		0.0171	112.9361	112.9532			
18	18A	6.4884	11.1526	17.6410	4.5319	0.0170	108.8517	108.8687	0.0199	0.1510	0.439
	18B	2.3512	15.6313	17.9825		0.0206	110.7628	110.7834			
	18C	4.7561	13.1435	17.8996		0.0222	113.0110	113.0332			