# Performance Optimization of Electrical Discharge Machining (Die Sinker) for Al-6061 via Taguchi Approach

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## ABSTRACT

**This paper parametrically optimizes the EDM (Electrical Discharge Machining) process in die sinking mode for MRR (Material Removal Rate), surface roughness and edge quality of aluminum alloy Al-6061. The effect of eight parameters namely discharge current, pulse on-time, pulse off-time, auxiliary current, working time, jump time distance, servo speed and work piece hardness are investigated. Taguchi's orthogonal array L18 is employed herein for experimentation. ANOVA (Analysis of Variance) with F-ratio criterion at 95% confidence level is used for identification of significant parameters whereas SNR (Signal to Noise Ratio) is used for determination of optimum levels. Optimization obtained for Al-6061 with parametric combination investigated herein is validated by the confirmation run.**

**Key Words:** **Al-6061, Electrical Discharge Machining, Parametric Optimization, Taguchi's Method.**

## 1. INTRODUCTION

EDM is a popular non-conventional machining process that is capable of machining precise and complex shapes in electrically conductive hard materials [1-5]. Due to the superior capabilities of the process, it is extensively used in state-of-the art metal working industries such as aerospace sector, defense sector and machining of dies and molds [1,3,6].

The working principle of EDM is essentially an electro-thermal mechanism wherein, electrical energy of discrete electrical discharges between two electrodes (work piece and tool), immersed in a dielectric fluid is converted to thermal energy that produces a plasma channel of very high temperature ultimately resulting into erosion of material [7-8]. Since the tool does not come into direct contact with the work piece so certain undesirable issues pertaining to the use of other conventional machining techniques such as development of mechanical stresses in machined products, vibrations and chatter are not faced herein [9].

Fig. 1 illustrates the working principle of EDM die sinking process wherein the tool (electrode) is sunk in a controlled manner into the work piece for generating its counter profile in the work piece. A minute gap (typically in the range of 0.01-0.5mm) is maintained between work piece and tool to prevent short circuit and that is where aforementioned plasma channel gets created. The circulating dielectric fluid, in addition to

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acting as a coolant also aids in flushing of debris and bubbles generated in the gap as a result of material erosion as shown in Fig. 1 [10]

The EDM process parameters that bring about the aforementioned electro-thermal mechanism are broadly categorized as electrical and non-electrical [7-8,12]. The main electrical parameters are discharge voltage, peak current, pulse duration, pulse interval, electrode gap, polarity and pulse wave form [7-8,12]. The major non-electrical parameters on the other hand, include work piece rotation, electrode rotation and the way dielectric is flushed [7-8,12]. The involvement of these so many parameters make EDM quite complex and highly stochastic in thermal nature [13] due to which, the potential of EDM processes is not fully utilized [14]. Over the years various research efforts have been focused on optimizing the process and its variants for machining of different materials using number of parametric combinations [1,12,14-23]. In the reported work, some researchers have focused on single response parametric optimization as is the case with Chandramouli, et. al. [1], Lodhi, et. al. [14], Mohamad, et. al. [16], Ikram, et. al. [17] Vikas, et. al. [18] and Rajmohan, et. al. [19] who used Taguchi's approach for optimization of the process whereas others have carried out the multi response parametric optimization as is demonstrated by the works of Jung, et. al. [20], Dewangan, et. al. [21], Khan, et. al. [22] and Mathew, et. al. [23] who used a combined Taguchi-Grey relational approach for the purpose. Chandramouli, et. al. [1] studied the effects of three electrical parameters namely pulse on time, current and pulse off time on MRR, surface roughness and tool wear rate for nickel super alloy by employing aluminum electrode. They conclude that studied parameters have significant effect on the output measures and careful selection of parameters is needed for obtaining the desired results

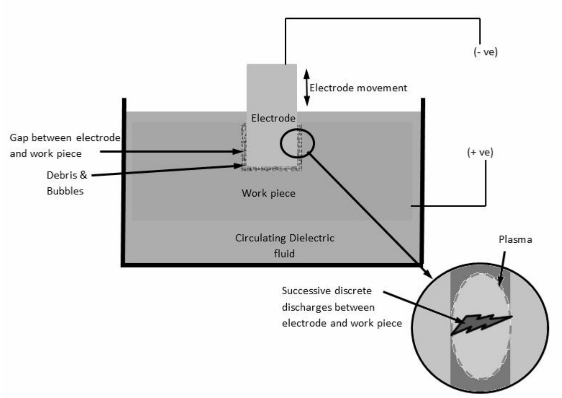



*FIG. 1. SCHEMATIC OF EDM DIE SINKING PROCESS AND ITS WORKING PRINCIPLE [11]*

for machining the material under consideration. Rajmohan, et. al. [19] while optimizing the process for 304 Stainless Steel found Taguchi to be an efficient methodology and conclude current and pulse off time to be the most significant parameters amongst the four parameters studied by them. In another study Marafona, et. al. [24] investigated the effect of work piece hardness on the premise that high heat of the process subjects work piece to localized heat treatment thus changing the metallurgical constituents and hardness in the heat affected zone, which could well be a reason of decreased MRR normally observed during the EDM cut [24]. They report that hardness & its interactions influence the MRR and surface roughness [24]. Their study provides a basis that hardness in certain cases could be included as one of the possible parameters to investigate while formulating a parametric combination.

The work presented herein is an ongoing effort to exploit full benefits of EDM process in die sinking mode for desired performance measures of MRR, surface finish (surface roughness, "$R_a$") and EQ (Edge Quality) of Al-6061 that is an important material; the material is used in the construction of yachts, bicycle components, automotive parts, aircraft wings, fuselages and as a mold material for plastic industry [25-26] wherein the intricate machining requirements can be adequately met by EDM. Taguchi's orthogonal array L18 is employed for experimentation followed by analysis of main effect, ANOVA, F-ratio criterion and SNR for analyzing and optimizing the effects of eight parameters namely discharge current "$I_D$", pulse on-time "$P_N$", pulse off-time "$P_F$", auxiliary current "$I_A$", working time "$T_W$", jump time distance "$D_J$", servo speed "$S_V$" and work piece hardness "$H_V$".

## 2. MATERIALS AND EXPERIMENT SETUP

### 2.1 Work Piece Details

A 12.7 mm (½-inch) thick plate of Al-6061 was obtained in as T-651 temper grade. The details of the chemical composition of plate as measured by X-Ray fluorescence spectrometer are given in Table 1. Three work pieces of 152.4x101.6 mm (6″x4″) were cut from the plate and two of these were subjected to two different heat treatment schedules in the furnace to achieve a total of three different hardness levels for the work pieces. Vickers hardness test was employed for measuring the hardness of the work pieces. A total of

15 reading were taken for each work piece and the average value for each work piece is reported herein. Details of the heat treatment schedules adopted along with three hardness values achieved in the work are given in Table 2.

## 2.2 Machining Details

Machining on EDM die sinker was performed using square copper tool (electrode) of 17.6mm a side under different settings of discharge current, pulse on-time, pulse off-time, auxiliary current, working time, jump time distance, servo speed and hardness of the work part. Fig. 2 shows the EDM machine (EDM Die Sinker: CM 655C by CHMER) used in this work for experimentation. Kerosene oil was used as dielectric medium. Electrode had negative polarity during experimentation. Fluid pressure was a constant parameter with its value set at $4.9 \times 10^{-3}$ $N/m^2$ while jet flushing method was used for flushing of the debris. Repeatability of experiments was validated by three replications approach as is generally adopted by others [17,27]. Obtained values were within 5% of each other indicating experimental variation was not an issue. Average values of the results are reported herein.

**TABLE 1. CHEMICAL COMPOSITION OF THE WORK PIECE MATERIAL**

| Constituent | Actual | Standard [25] |
|---|---|---|
| Mg | 1.00% | 0.8-1.2% |
| Si | 0.53% | 0.4-0.8% |
| Fe | 0.187% | 0.7% max |
| Mn | 0.10% | 0.15% max |
| Cu | 0.15% | 0.15-0.4% |
| Others (incl. Ti, Zn and Cr) | 0.863% | 0.9% max |
| Al | Rem. | Rem. |

**TABLE 2. HEAT TREATMENT SCHEDULES ADOPTED**

| Work Pieces | | 1 | 2 | 3 |
|---|---|---|---|---|
| Condition | | Annealed | Solution Heat Treated | T-651 (Precipitation Heat Treated) |
| Hardness (HV) | | 47 | 64 | 132 |
| Heat Treatment Schedule Employed | Soaking Temperature | 413°C | 530°C | Obtained from Market |
| | Soaking Time | 2hrs and 45mins | 65min | |
| | Cooling rate | 28°C per hour up to final temp. of 260°C | Readily quench in water | |

## 2.3 Design of Experiments

Taguchi's orthogonal array L18 is adopted herein where one parameter (auxiliary current) has two levels and the remaining parameters have three levels each. Taguchi orthogonal array L18 is one of the many orthogonal arrays designed to accommodate number of parameters & associated levels being investigated [28]. L18 is a mixed level array that contains eighteen experiment runs to ensure the orthogonality for the number of parameters and levels considered herein [28]. Orthogonality means that the experimental design is balanced i.e. not only that a parameter within a column, has an equal number of levels but also combinations of levels between the investigated parameters are equal in numbers [28]. Considering that orthogonality produces statistically independent results, orthogonal arrays help design efficient fractional factorial designs [29-30] which reduce the number of experiment runs & thus cost and time associated with experimentation.

Table 3 lists process parameters with units and values of the levels selected herein whereas Fig. 3 shows the schematic of the work piece and the cavity dimensions. Level-1 of each parameter represents the least value whereas level-3 represents the highest value of the selected value set.


*FIG. 2. ELECTRICAL DISCHARGE DIE SINKING MACHINE USED FOR EXPERIMENTATION*

## 2.4 Measurement Procedures

Calculation of material removal rate is done by using Equation (1) [21]:

$$MRR = \frac{Mass\ (before) - Mass\ (after)}{Time \times Density} \quad (1)$$

Surface roughness is quantified by measuring surface roughness parameter "$R_a$" using surface profilometer (Surtronic S25 by Taylor Hobson) as shown in Fig. 4. Three readings with a cut-off length of 0.8mm and evaluation length of 4.0mm were taken and the average is reported.

**TABLE 3. PROCESS PARAMETERS AND LEVELS**

| Process Parameters | Units | Level-1 | Level-2 | Level-3 |
|---|---|---|---|---|
| Auxiliary Current ($I_A$) | Amp | 0.9 | 1.2 | _ |
| Hardness ($H_V$) | HV | 47 | 64 | 132 |
| Pulse on-time ($P_N$) | μ-sec | 200 | 300 | 400 |
| Pulse off-time ($P_F$) | μ-sec | 100 | 150 | 200 |
| Discharge current ($I_D$) | Amp | 8 | 10 | 12 |
| Working time ($T_W$) | Sec | 2 | 3 | 4 |
| Jump time distance ($D_J$) | mm | 1 | 3 | 5 |
| Servo speed ($S_V$) | % | 75 | 125 | 175 |

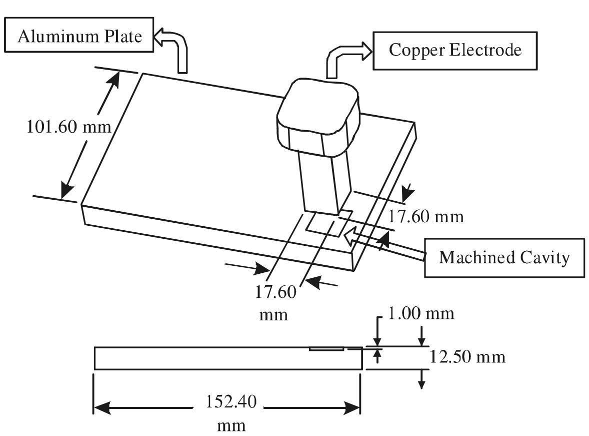



*FIG. 3. SCHEMATIC OF WORK PIECE AND CAVITY DIMENSIONS*

EQ is quantified herein by measuring the maximum depth of the pit observed. Images were captured via coordinate measuring machine at a magnification of 70X and maximum depth of the pit measured graphically, is reported. Fig. 5 shows the coordinate measuring machine CE-450DV by Precise Technology Co. Ltd. used in this work whereas Fig. 6 shows the schematic of the measurement.

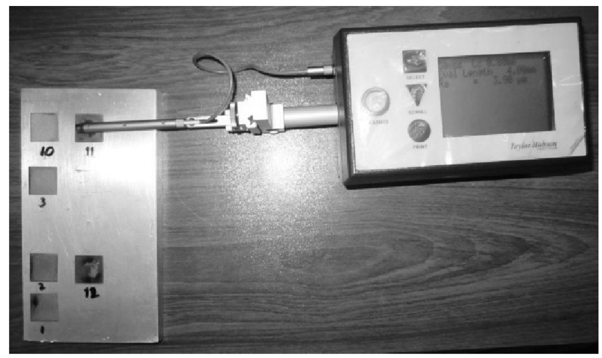


*FIG. 4. SURFACE ROUGHNESS MEASUREMENTS*

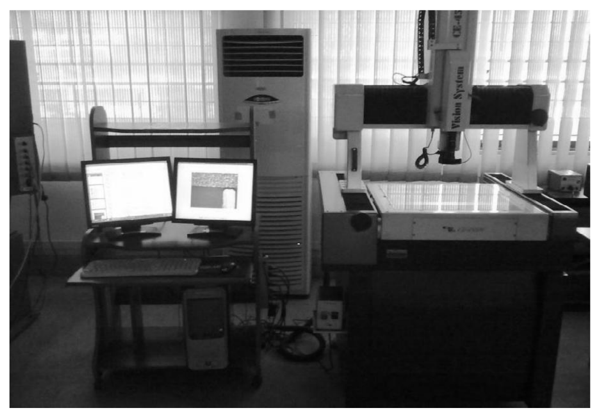


*FIG. 5. COORDINATE MEASURING MACHINE USED FOR EDGE QUALITY MEASUREMENTS*

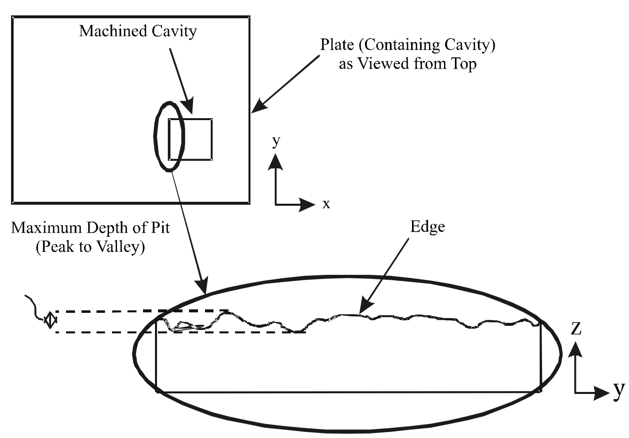



*FIG. 6. SCHEMATIC OF EDGE QUALITY (EQ) MEASUREMENT*

# 3. RESULTS AND ANALYSIS

## 3.1 Results

Table 4 lists the results for all of the experiment runs. Each row shows the results obtained for the selected performance measures along with respective treatment condition for the particular experiment as guided by Taguchi's orthogonal array L18 (already explained).

## 3.2 Main Effects and Analysis of Variance

The influences of parameters investigated herein are shown in the response Tables 5-7 and the main effect (response) plots in Figs. 7-9. ANOVA is then used for quantifying individual factor's contribution on stated performance measures with F-ratio criterion at 95% confidence level to determine the significance of a factor (a factor is significant if F-ratio > critical F). The results of ANOVA are presented in Tables 8-10.

For particular performance measures, the Tables 5-7 give the average responses (value of performance measures) against each level of the individual parameter under investigation whereas Δ is the absolute difference, a greater value of which indicates more influence of the parameter on performance measure [31]. Now it can be seen from Table 5 that maximum Δ is obtained for the case of $I_D$ so it has the maximum influence on MRR whereas $S_V$ has the minimum Δ so it has the minimum influence on its value; accordingly $I_D$ is ranked 1st whereas $S_V$ is ranked last for its influence on MRR. On the same analogy the influence of parameters for other performance measures can be seen from the presented Tables 6-7. Discharge current and pulse on time are found to be the most influential parameters for all of the performance measures investigated herein. Figs. 7-9

TABLE 4. TAGUCHI ORTHOGONAL ARRAY AND EXPERIMENTAL RESULTS FOR SURFACE ROUGHNESS, MRR AND EQ

| Experiments Runs | Parameters | | | | | | | | Performance Measures | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $I_A$ | $H_V$ | $P_N$ | $P_F$ | $I_D$ | $T_W$ | $D_J$ | $S_V$ | $R_a$ (μm) | MRR ($mm^3$/min) | EQ (μm) |
| 1 | 0.9 | 47 | 200 | 100 | 8 | 2 | 1 | 75 | 3.13 | 8.13 | 36.66 |
| 2 | 0.9 | 47 | 300 | 150 | 10 | 3 | 3 | 125 | 4.75 | 12.99 | 57.98 |
| 3 | 0.9 | 47 | 400 | 200 | 12 | 4 | 5 | 175 | 6.51 | 31.77 | 98.85 |
| 4 | 0.9 | 64 | 200 | 100 | 10 | 3 | 5 | 175 | 4.22 | 16.31 | 62.62 |
| 5 | 0.9 | 64 | 300 | 150 | 12 | 4 | 1 | 75 | 5.28 | 31.22 | 98.58 |
| 6 | 0.9 | 64 | 400 | 200 | 8 | 2 | 3 | 125 | 4.19 | 9.87 | 50.87 |
| 7 | 0.9 | 132 | 200 | 150 | 8 | 4 | 3 | 175 | 3.36 | 3.11 | 35.47 |
| 8 | 0.9 | 132 | 300 | 200 | 10 | 2 | 5 | 75 | 4.58 | 10.39 | 75.85 |
| 9 | 0.9 | 132 | 400 | 100 | 12 | 3 | 1 | 125 | 6.01 | 34.86 | 99.74 |
| 10 | 1.2 | 47 | 200 | 200 | 12 | 3 | 3 | 75 | 7.14 | 24.24 | 87.43 |
| 11 | 1.2 | 47 | 300 | 100 | 8 | 4 | 5 | 125 | 3.86 | 9.12 | 37.68 |
| 12 | 1.2 | 47 | 400 | 150 | 10 | 2 | 1 | 175 | 4.53 | 19.32 | 75.79 |
| 13 | 1.2 | 64 | 200 | 150 | 12 | 2 | 5 | 125 | 5.12 | 20.92 | 97.77 |
| 14 | 1.2 | 64 | 300 | 200 | 8 | 3 | 1 | 175 | 3.50 | 5.18 | 52.35 |
| 15 | 1.2 | 64 | 400 | 100 | 10 | 4 | 3 | 75 | 6.12 | 15.50 | 76.34 |
| 16 | 1.2 | 132 | 200 | 200 | 10 | 4 | 1 | 125 | 4.24 | 12.14 | 67.88 |
| 17 | 1.2 | 132 | 300 | 100 | 12 | 2 | 3 | 175 | 5.17 | 23.22 | 99.23 |
| 18 | 1.2 | 132 | 400 | 150 | 8 | 3 | 5 | 75 | 3.99 | 4.22 | 55.14 |

**TABLE 5. RESPONSE TABLE FOR MRR**

| Level | 1 | 2 | 3 | Δ | Rank |
|---|---|---|---|---|---|
| $I_A$ | 17.629 | 14.874 | - | 2.755 | 5 |
| $H_V$ | 17.597 | 16.5 | 14.656 | 2.941 | 4 |
| $P_N$ | 14.144 | 15.354 | 19.256 | 5.113 | 2 |
| $P_F$ | 17.858 | 15.299 | 15.597 | 2.559 | 6 |
| $I_D$ | 6.607 | 14.441 | 27.706 | 21.099 | 1 |
| $T_W$ | 15.31 | 16.3 | 17.144 | 1.834 | 7 |
| $D_J$ | 18.476 | 14.822 | 15.456 | 3.654 | 3 |
| $S_V$ | 15.617 | 16.65 | 16.487 | 1.033 | 8 |

**TABLE 6. RESPONSE TABLE FOR SURFACE ROUGHNESS**

| Level | 1 | 2 | 3 | Δ | Rank |
|---|---|---|---|---|---|
| $I_A$ | 4.67 | 4.852 | - | 0.182 | 8 |
| $H_V$ | 4.988 | 4.736 | 4.559 | 0.429 | 7 |
| $P_N$ | 4.533 | 4.524 | 5.226 | 0.702 | 2 |
| $P_F$ | 4.752 | 4.505 | 5.026 | 0.521 | 4 |
| $I_D$ | 3.67 | 4.74 | 5.873 | 2.203 | 1 |
| $T_W$ | 4.455 | 4.935 | 4.893 | 0.48 | 6 |
| $D_J$ | 4.448 | 5.122 | 4.714 | 0.674 | 3 |
| $S_V$ | 5.039 | 4.696 | 4.548 | 0.491 | 5 |

**TABLE 7. RESPONSE TABLE FOR EDGE QUALITY**

| Level | 1 | 2 | 3 | Δ | Rank |
|---|---|---|---|---|---|
| $I_A$ | 68.51 | 72.18 | - | 3.66 | 5 |
| $H_V$ | 65.73 | 73.09 | 72.22 | 7.36 | 3 |
| $P_N$ | 64.64 | 70.28 | 76.12 | 11.49 | 2 |
| $P_F$ | 68.71 | 70.12 | 72.2 | 3.49 | 7 |
| $I_D$ | 44.7 | 69.41 | 96.93 | 52.24 | 1 |
| $T_W$ | 72.69 | 69.21 | 69.13 | 3.56 | 6 |
| $D_J$ | 71.83 | 67.88 | 71.32 | 3.95 | 4 |
| $S_V$ | 71.67 | 68.65 | 70.72 | 3.01 | 8 |

are the graphical representation of the tabulated results that highlight the trend of a particular performance measure against a process parameter. From the figures it can be seen that not only $I_D$ is the most influential factor but increase in its value contributes to an increase in MRR; same is the case for pulse on time $P_N$. It can also be seen that the increase in these parameters contribute to more surface roughness and max. pit depth observed for EQ. The reasons for the contributions and trends for the parameters are elaborated in the discussion section.

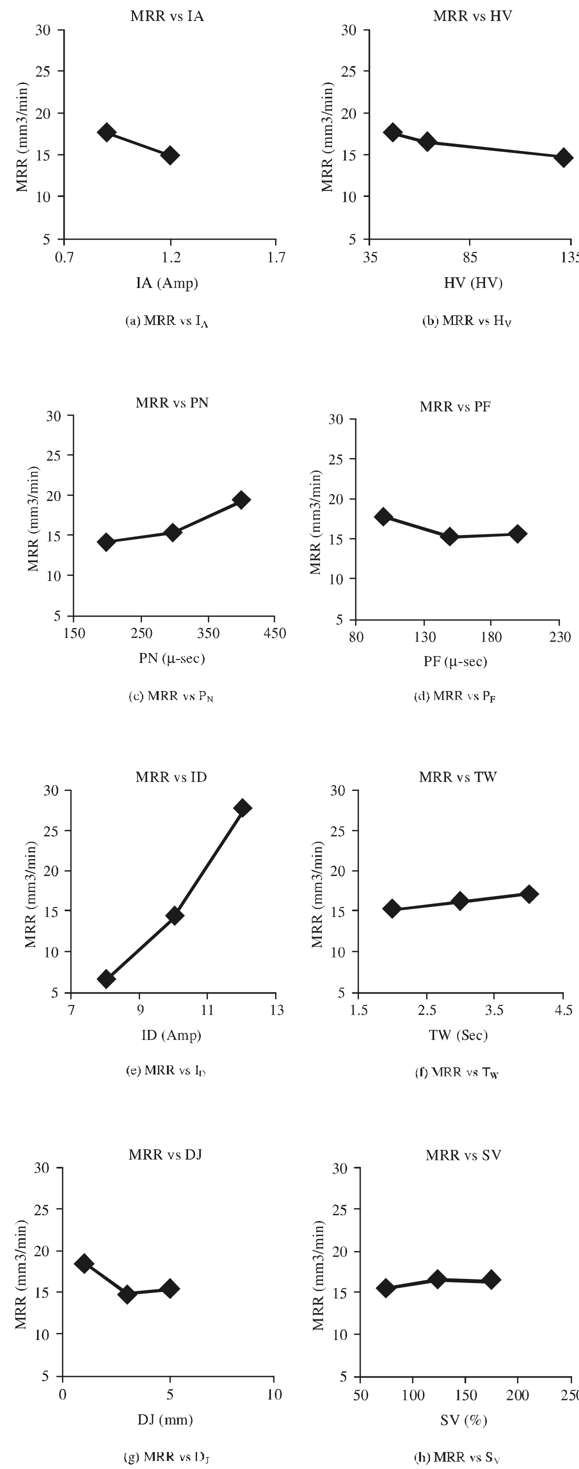



*FIG. 7. MAIN EFFECT PLOTS FOR MRR*

Once the parameters are ranked it is necessitated that their contribution is quantified and significance is determined. ANOVA is used for the purpose of quantifying individual factor's contribution on stated performance measures. ANOVA is a powerful technique to find the effect of an individual parameter on performance values in a group of parameters [32]. An F-ratio criterion of 95% confidence level is used herein to determine the significance of a factor (a factor is significant if F-ratio > critical F). The results of ANOVA are presented in Tables 8-10.

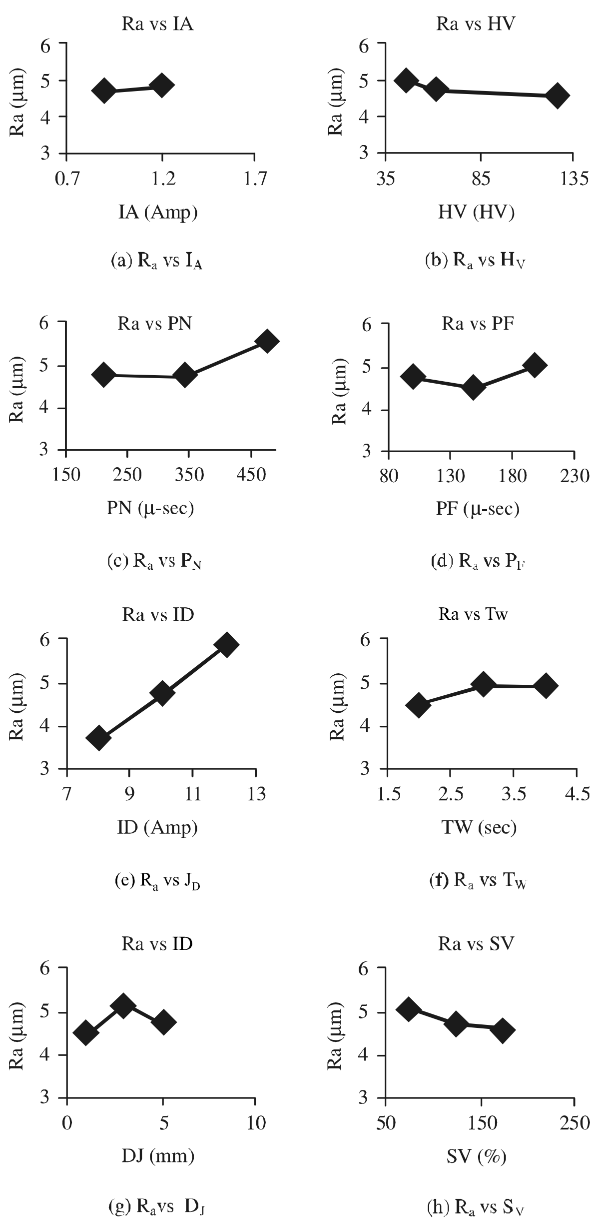



*FIG. 8. MAIN EFFECT PLOTS FOR SURFACE ROUGHNESS ($R_a$)*

In ANOVA, the total observed variation in the data is broken into accountable sources so as to determine which variation component can be attributed to error and which can be attributed to the effect of factor so that ultimately the quantification and significance of the effect of a particular parameter can be determined [31-32]. Now it can be seen in Tables 8-10 that variances "MS" associated with error is 10.19 for

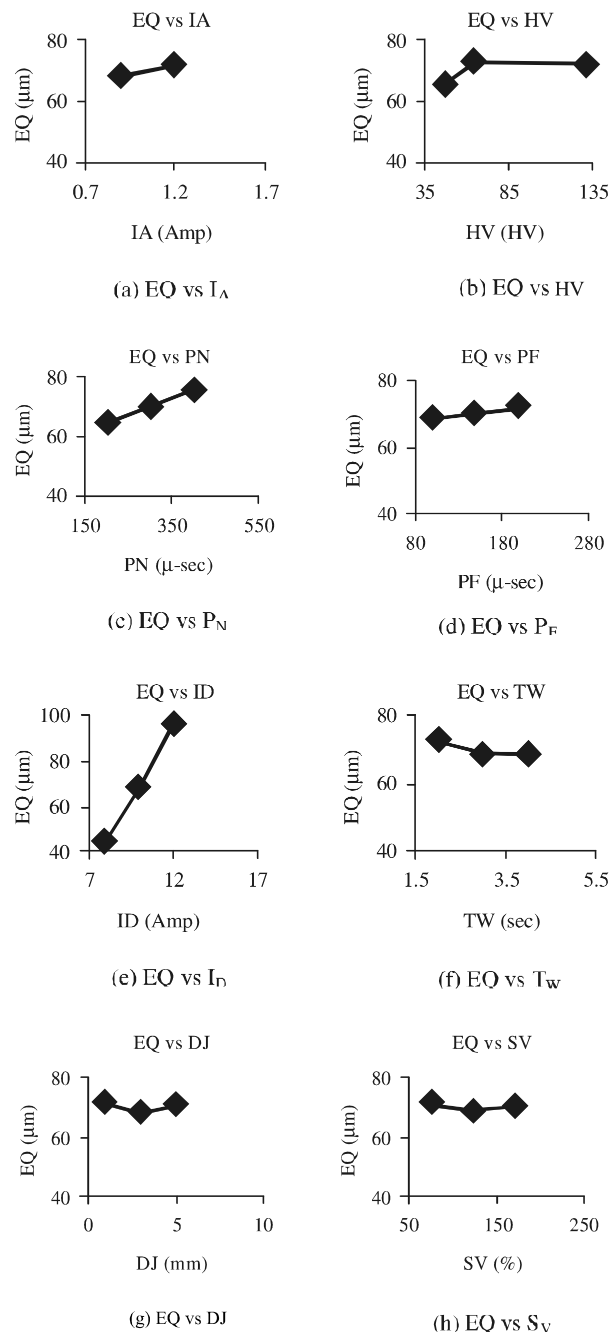



*FIG. 9. MAIN EFFECT PLOTS FOR EQ*

MRR, 0.15 for surface roughness and 2.03 for EQ. Significant factors are identified when all the variances are subjected to F-test. ANOVA results thus confirm that discharge current and pulse on-time are the most significant factors for all of the performance measures investigated with the contributions of 84.53% and 5.30% respectively in the case of MRR, 68.30% and 9.12% respectively in the case of surface roughness and 90.85% and 4.38% respectively in the case of EQ.

## 3.3 Signal to Noise Ratio Analysis

Two types of SNR are used herein to determine the optimum levels of parameters; one for MRR that is a "larger the better" performance characteristic and another for "smaller the better" characteristics which in this work, are surface roughness and max. pit depth (for EQ).

**TABLE 8. ANOVA FOR MRR**

| Process Parameter | DoF | SS | MS | F-Ratio | Critical F | Contribution (%) |
|---|---|---|---|---|---|---|
| $I_A$ | 1 | 34.15 | 34.15 | 3.35 | 4.67 | 2.11 |
| $H_V$ | 2 | 26.50 | 13.25 | 1.30 | 3.81 | 1.64 |
| $P_N$ | 2 | 85.66 | 42.83 | 4.20 | 3.81 | 5.30* |
| $P_F$ | 2 | 23.49 | 11.75 | 1.15 | 3.81 | 1.45 |
| $I_D$ | 2 | 1364.98 | 682.49 | 66.97 | 3.81 | 84.53* |
| $T_W$ | 2 | 10.11 | 5.05 | 0.50 | 3.81 | 0.63 |
| $D_J$ | 2 | 45.74 | 22.87 | 2.24 | 3.81 | 2.83 |
| $S_V$ | 2 | 3.70 | 1.85 | 0.18 | 3.81 | 0.23 |
| Error | 2 | 20.38 | 10.19 | - | - | 1.26 |
| Total | 17 | 1614.72 | 824.43 | 79.89 | 31.34 | 100 |

* Significant

**TABLE 9. ANOVA FOR SURFACE ROUGHNESS (Ra)**

| Process Parameter | DoF | SS | MS | F-Ratio | Critical F | Contribution (%) |
|---|---|---|---|---|---|---|
| $I_A$ | 1 | 0.15 | 0.15 | 0.98 | 4.54 | 0.70 |
| $H_V$ | 2 | 0.56 | 0.28 | 1.84 | 3.68 | 2.61 |
| $P_N$ | 2 | 1.95 | 0.97 | 6.44 | 3.68 | 9.12* |
| $P_F$ | 2 | 0.82 | 0.41 | 2.70 | 3.68 | 3.82 |
| $I_D$ | 2 | 14.56 | 7.28 | 48.22 | 3.68 | 68.30* |
| $T_W$ | 2 | 0.85 | 0.42 | 2.81 | 3.68 | 3.98 |
| $D_J$ | 2 | 1.38 | 0.69 | 4.58 | 3.68 | 6.48* |
| $S_V$ | 2 | 0.76 | 0.38 | 2.52 | 3.68 | 3.75 |
| Error | 2 | 0.30 | 0.15 | - | - | 1.42 |
| Total | 17 | 21.33 | 10.74 | 70.09 | 30.3 | 100 |

* Significant

The formula for measuring "larger the better" and "smaller the better" SNR are given in Equations (2-3) respectively [27].

$$SNR = \eta = -10\log_{10}\left[\frac{1}{n}\times\left\{\sum_{i=1}^{n}\left(\frac{1}{y_i^2}\right)\right\}\right] \tag{2}$$

$$SNR = \eta = -10\log_{10}\left[\frac{1}{n}\times\left\{\sum_{i=1}^{n}\left(y_i^2\right)\right\}\right] \tag{3}$$

Where SNR is represented by η and $y_i$ is the $i^{th}$ reading [27].

Equation (2 and 3) are used to find the SNR values of the stated performance measures for each experiment. Table 11 lists the average SNR values for MRR, surface roughness and EQ. The SNR results of MRR, surface roughness ($R_a$) and EQ are shown in Figs. 10-12 respectively.

Considering, Taguchi approach of process optimization is based on the premises that if proper levels of the process parameters are selected then the effect of noise factors can be dampened [31] therefore the objective here is to find the level of process parameter where highest SNR is achieved. Figs. 10-12 help graphically identify the levels at which maximum SNR is obtained for a particular process parameter. For example from Fig 10 it can be seen that the optimum level for achieving maximum MRR for the process parameter

**TABLE 10. ANOVA FOR EQ**

| Process Parameter | DoF | SS | MS | F-Ratio | Critical F | Contribution (%) |
|---|---|---|---|---|---|---|
| $I_A$ | 1 | 60.43 | 60.43 | 29.78 | 4.67 | 0.669* |
| $H_V$ | 2 | 194.00 | 97.00 | 47.81 | 3.81 | 2.15* |
| $P_N$ | 2 | 395.78 | 197.89 | 97.54 | 3.81 | 4.38* |
| $P_F$ | 2 | 37.08 | 18.54 | 9.14 | 3.81 | 0.411* |
| $I_D$ | 2 | 8194.82 | 4097.41 | 2019.58 | 3.81 | 90.85* |
| $T_W$ | 2 | 49.67 | 24.83 | 12.24 | 3.81 | 0.55* |
| $D_J$ | 2 | 55.34 | 27.67 | 13.64 | 3.81 | 0.613* |
| $S_V$ | 2 | 28.46 | 14.23 | 7.01 | 3.81 | 0.315* |
| Error | 2 | 4.06 | 2.03 | - | - | 0.045 |
| Total | 17 | 9019.63 | 4540.03 | 2236.74 | 31.34 | 100 |

* Significant

namely discharge current ($I_D$), is "3" i.e. highest of the set selected herein. Similarly for other parameters the optimum levels can be identified. Tables 12-14 summarize the SNRs achieved at respective levels along with identification of optimum levels of process parameters for maximizing MRR, minimizing surface roughness and max. pit depth (maximizing quality of edge) respectively.

**TABLE 11. SIGNAL TO NOISE RATIO VALUES IN DB**

| Experiment No. | Surface Roughness | MRR | Edge Quality |
|---|---|---|---|
| 1 | -9.9081 | 18.21 | -31.283 |
| 2 | -13.5394 | 22.27 | -35.265 |
| 3 | -16.2743 | 30.04 | -39.900 |
| 4 | -12.5021 | 24.25 | -35.934 |
| 5 | -14.4477 | 29.89 | -39.876 |
| 6 | -12.4422 | 19.89 | -34.129 |
| 7 | -10.5164 | 9.86 | -30.996 |
| 8 | -13.2230 | 20.33 | -37.599 |
| 9 | -15.5833 | 30.85 | -39.978 |
| 10 | -17.0727 | 27.69 | -38.833 |
| 11 | -11.7317 | 19.20 | -31.523 |
| 12 | -13.1277 | 25.72 | -37.592 |
| 13 | -14.1871 | 26.41 | -39.804 |
| 14 | -10.8689 | 14.28 | -34.378 |
| 15 | -15.7322 | 23.80 | -37.654 |
| 16 | -12.5412 | 21.68 | -36.634 |
| 17 | -14.2765 | 27.32 | -39.932 |
| 18 | -12.0173 | 12.51 | -34.830 |

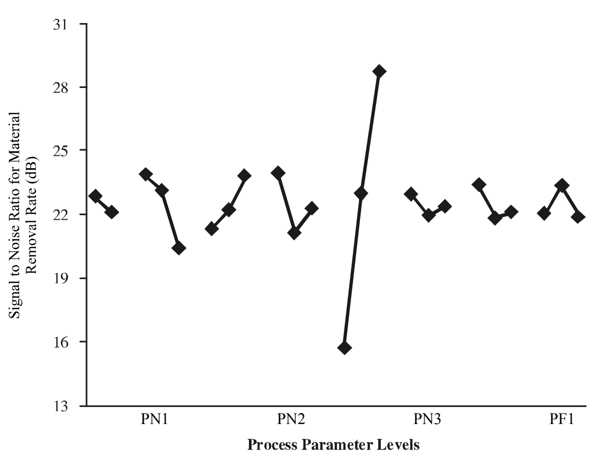



*FIG. 10. MEAN SNR FOR MRR*

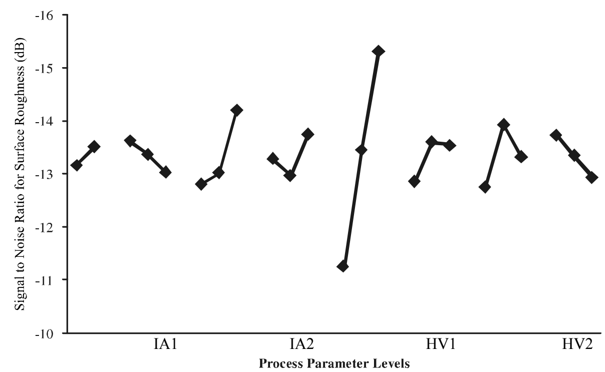



*FIG. 11. MEAN SNR FOR SURFACE ROUGHNESS*

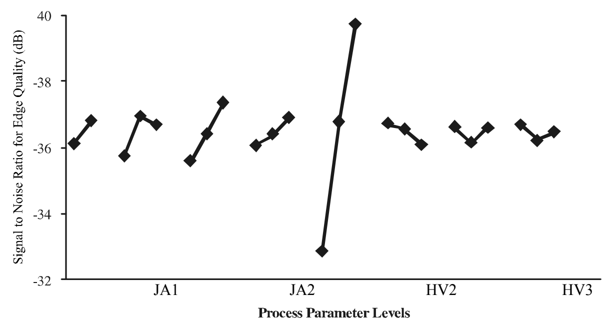



*FIG. 12 MEAN SNR FOR EDGE QUALITY*

**TABLE 12. DETERMINATION OF OPTIMUM LEVELS FOR MRR**

| Parameter | Level 1 | Level 2 | Level 3 | Optimum Level |
|---|---|---|---|---|
| $I_A$ | 22.84 | 22.07 | - | 1 |
| $H_V$ | 23.86 | 23.09 | 20.42 | 1 |
| $P_N$ | 21.35 | 22.22 | 23.8 | 3 |
| $P_F$ | 23.94 | 21.11 | 22.32 | 1 |
| $I_D$ | 15.66 | 23.01 | 28.7 | 3 |
| $T_W$ | 22.98 | 21.97 | 22.41 | 1 |
| $D_J$ | 23.44 | 21.81 | 22.12 | 1 |
| $S_V$ | 22.07 | 23.38 | 21.91 | 2 |

**TABLE 13. DETERMINATION OF OPTIMUM LEVELS FOR SURFACE ROUGHNESS**

| Parameter | Level 1 | Level 2 | Level 3 | Optimum Level |
|---|---|---|---|---|
| $I_A$ | -13.16 | -13.51 | - | 1 |
| $H_V$ | -13.61 | -13.36 | -13.03 | 3 |
| $P_N$ | -12.79 | -13.01 | -14.2 | 1 |
| $P_F$ | -13.29 | -12.97 | -13.74 | 2 |
| $I_D$ | -11.25 | -13.44 | -15.31 | 1 |
| $T_W$ | -12.86 | -13.6 | -13.54 | 1 |
| $D_J$ | -12.75 | -13.93 | -13.32 | 1 |
| $S_V$ | -13.73 | -13.34 | -12.93 | 3 |

Looking at Tables 12-14, it can be deduced herein that the single response parametric optimization for Al-6061 is attained for greatest MRR when auxiliary current, hardness, pulse off-time, working time and jump time distance are at level 1; pulse on-time and discharge current are at level 3 and servo speed is at level 2. The optimization for better surface finish would require auxiliary current, pulse on-time, discharge current, working time and jump time distance at level 1; hardness and servo speed at level 3 and pulse off-time at level 2. Maximization of EQ however is achieved by selecting the auxiliary current, hardness, discharge current, pulse on-time and pulse off-time at level 1, jump time distance and servo speed at level 2 and working time at level 3.

## 3.4 Confirmatory Experiment

To validate the conclusions drawn from the analysis, this confirmatory run involves prediction and verification of the performance measures under optimal levels of process variables. The predicted SNR ($\eta_{pre}$) using the optimal process variables is given by Equation (4) [33].

$$\eta_{pre} = \eta_m + \sum_{q=1}^{r} (\eta_q - \eta_m) \qquad (4)$$

Where $\eta_m$ denotes the total mean of the SNR, $\eta_q$ gives mean SNR at the optimum levels and r is the number of process parameters investigated herein.

Confirmatory experiments were performed with the optimum levels of process parameters and results were compared to both, predicted and those obtained with a random set of starting machining parameters. Results of confirmatory experiments for MRR, surface roughness and EQ are shown in Tables 15-17 respectively. It can be seen from the tables that experimentation with a random set of starting machining parameters yields an MRR of 21.31 $mm^3$/min whereas the experimentally obtained value of MRR at optimum levels result in an MRR of 59.44 $mm^3$/min. The corresponding improvement in SNR is 8.91 dB. For surface roughness improvement in SNR w.r.t. starting parameters is 6.65 dB and for EQ this improvement is 10.14 dB. The confirmation runs show very good agreement (error ~3%) between predicted and experimental results. Any possible interactions for the selected parametric combination are not investigated separately considering the good level of agreement and the fact that the use of orthogonal array L18 distribute the interactions (if any) to all the columns and treat them as equivalent to noise [24].

The results of the confirmatory run thus validate the single response parametric optimization obtained for Al-6061 with parameters investigated herein.

**TABLE 14. DETERMINATION OF OPTIMUM LEVELS FOR EDGE QUALITY (EQ)**

| Parameter | Level 1 | Level 2 | Level 3 | Optimum Level |
|---|---|---|---|---|
| $I_A$ | -36.11 | -36.8 | - | 1 |
| $H_V$ | -35.73 | -36.96 | -36.66 | 1 |
| $P_N$ | -35.58 | -36.43 | -37.35 | 1 |
| $P_F$ | -36.05 | -36.39 | -36.91 | 1 |
| $I_D$ | -32.86 | -36.78 | -39.72 | 1 |
| $T_W$ | -36.72 | -36.54 | -36.1 | 3 |
| $D_J$ | -36.62 | -36.14 | -36.6 | 2 |
| $S_V$ | -36.68 | -36.22 | -36.46 | 2 |

**TABLE 15. RESULTS OF CONFIRMATORY EXPERIMENT FOR MRR**

| | Level | MRR ($mm^3$/min) | SNR (dB) |
|---|---|---|---|
| Starting Machining Parameters | $I_{A2}H_{V3}P_{N3}P_{F3}I_{D3}T_{W3}D_{J3}S_{V3}$ | 21.31 | 26.57 |
| Prediction | $I_{A1}H_{V1}P_{N3}P_{F1}I_{D3}T_{W1}D_{J1}S_{V2}$ | 61.28 | 35.75 |
| Experimental | $I_{A1}H_{V1}P_{N3}P_{F1}I_{D3}T_{W1}D_{J1}S_{V2}$ | 59.44 | 35.48 |

**TABLE 16. RESULTS OF CONFIRMATORY EXPERIMENT FOR SURFACE ROUGHNESS ($R_a$)**

| | Level | Ra (μm) | SNR (dB) |
|---|---|---|---|
| Starting Machining Parameters | $I_{A2}H_{V3}P_{N3}P_{F3}I_{D3}T_{W3}D_{J3}S_{V3}$ | 6.48 | -16.23 |
| Prediction | $I_{A1}H_{V3}P_{N1}P_{F2}I_{D1}T_{W1}D_{J1}S_{V3}$ | 2.93 | -9.3 |
| Experimental | $I_{A1}H_{V3}P_{N1}P_{F2}I_{D1}T_{W1}D_{J1}S_{V3}$ | 3.01 | -9.58 |

**TABLE 17. RESULTS OF CONFIRMATORY EXPERIMENT FOR EDGE QUALITY (EQ)**

| | Level | EQ (μm) | SNR (dB) |
|---|---|---|---|
| Starting Machining Parameters | $I_{A2}H_{V3}P_{N3}P_{F3}I_{D3}T_{W3}D_{J3}S_{V3}$ | 99.76 | -39.98 |
| Prediction | $I_{A1}H_{V1}P_{N1}P_{F1}I_{D1}T_{W3}D_{J2}S_{V2}$ | 30.29 | -29.63 |
| Experimental | $I_{A1}H_{V1}P_{N1}P_{F1}I_{D1}T_{W3}D_{J2}S_{V2}$ | 31.05 | -29.84 |

# 4. DISCUSSION

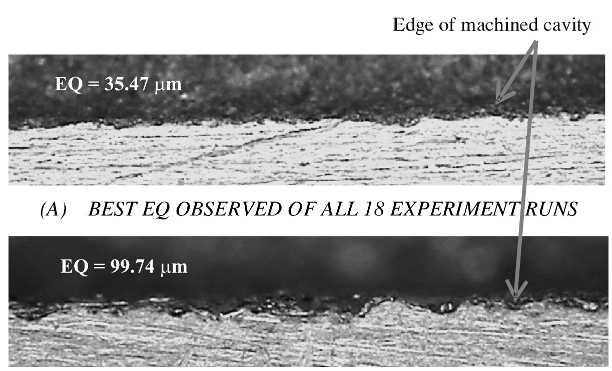
The results are analyzed in the light of physical phenomenon that exists in the gap. As indicated by the results, discharge current and pulse on-time are the two major contributors for all of the performance measures investigated herein; the greatest MRR can be obtained when pulse on-time and discharge current are at level 3 (maximum) whereas the surface roughness and EQ are improved if both of these parameters are at level 1 (minimum). It can be explained on the basis, that, both discharge current and time through which this current is discharged during the working cycle (i.e. pulse on time) would contribute directly to the spark energy [34] responsible for material erosion. A higher discharge current and pulse on time would result into larger spark energy and consequently a larger localized temperature that would remove large chunks of metal in each working cycle. Though it would increase the material removal rate however the surface finish would be deteriorated [35]. Another significant parameter in the context of surface finish is found to be jump time distance where a higher value of jump time distance supports better surface of the machined cavity. It can be explained, considering, that more jump time distance would allow the eroded debris to be flushed in a more appropriate manner thus avoiding the unwanted sparking of the eroded particles that otherwise could negatively affect the finish of the surface. As for initial hardness of the work piece, although its effect is not found to be significant for MRR and surface roughness as is the general consensus [6-8,34], however it is found to be third largest contributor as well as statistically significant for the case of EQ with the lower value of work piece hardness supporting the better quality of the edge. Supposition for the role of hardness in EQ is that lack of mechanical support at edges of the cavity for the reasons of non-existent surrounding material would make a brittle and hard material more prone to uneven and excessive erosion; which could explain why poorer EQ is observed herein for heat treated hardened material. It is, however, important to realize that though hardness is seen to be a contributor in quality of the edge however discharge current and pulse on time remain the most significant contributors owing to their central role in the dynamics of the process as explained earlier and therefore their affect would be more dominant. This could be seen by Table 4, wherein experiment runs 1 and 7, the EQs are the best amongst the rest. These are the runs where the two most significant contributors i.e. discharge current and pulse on-time are both at the optimum levels, though in one of the experiment runs (i.e. experiment run 7) the hardness is at a non-optimal level. On the other hand the worst EQ is observed when both of these main contributors are at the most undesirable levels i.e. experiment run 9. The situation is depicted in Fig. 13 that shows the comparison between the best and the poorest EQ observed of all of the eighteen experiment runs. It is important to realize that experiment 1 and 7 only show the "best" EQ of the experiments conducted in the original experiment design whereas the optimal would be obtained when all the parameters are at their optimal levels.

# 5. CONCLUSIONS

This research investigated the effect of selected parameters on EDM process and optimized the process in die sinking mode for material removal rate, surface roughness and EQ of aluminum alloy Al-6061. Eight parameters namely discharge current, pulse on-time, pulse off-time, auxiliary current, working time, jump time distance, servo speed and work piece hardness were considered herein using Taguchi's approach.

It has been found that, discharge current and pulse on time are the most significant parameters (amongst those investigated herein) for the three response variables (material removal rate, surface roughness and EQ); wherein the contribution of discharge current and pulse on-time is 84.53% and 5.30% respectively for MRR, 68.30% and 9.12% respectively for surface roughness and 90.85% and 4.38% respectively for EQ. It can also been deduced that for EQ, though work piece hardness is found to be statistically significant but its percentage contribution is meager in comparison to discharge current and pulse on time and thus the results for EQ are again dominated by these two factors.

Summarizing the findings for single response parametric optimization of the process, it is concluded that if the objective is to maximize MRR then pulse on-time and




*(B) WORST EQ OBSERVED OF ALL 18 EXPERIMENT RUNS*
*FIG. 13. IMAGES OF MACHINED EDGES AT 70X MAGNIFICATION*

discharge current should be kept at their highest value (level 3) keeping the servo speed at level 2 and other parameters namely auxiliary current, hardness, pulse off-time, working time and jump time distance at their least values (level 1); on the other hand best surface finish is achieved when hardness and servo speed are at their highest value (level 3), pulse off-time is at level 2 and other parameters (auxiliary current, pulse on-time, discharge current, working time and jump time distance) are at their least value (level 1); moreover, EQ can be optimized by selecting auxiliary current, pulse on-time, pulse off-time, discharge current and work piece hardness at their least values (level 1), jump time distance and servo speed at level 2 and working time at its highest value (level 3).

The findings of the presented research are validated by the confirmation run and are well supported by the physical phenomenon that exists in the gap between work piece and tool.

## ACKNOWLEDGMENTS

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