3. PARAMETRIC ANALYSIS AND OPTIMIZATION OF DIE CORNER ACCURACY IN SINGLE PASS CUTTING OF ALUMINIUM 5083 ALLOY

3.1. PROBLEM STATEMENT

Aluminium 5083 (AA 5083) alloy exhibits poor machinability [23] through conventional means such as turning, milling, drilling and grinding. The challenges involved in machining aluminum alloys require innovative approaches towards the design of cutting tools, especially diamond-based cutting tools. Nonetheless, the WEDM is one of the promising machining techniques to process AA 5083 to any complex two- and three-dimensional shapes with very high precision and accuracy.

WEDM is an extremely complicated process controlled by a large number of process parameters such as pulse on time ($T_{on}$), pulse off time ($T_{off}$), pulse peak current ($I_p$), peak voltage ($V_p$), wire feed rate ($WF$), wire tension ($WT$), servo spark gap set voltage ($S_v$), servo feed setting ($SF$), dielectric flow rate etc. A single parameter change will influence the process in a complex way [29]. Therefore, it is very difficult to select the optimum machine setting or cutting parameters in WEDM. Improperly selected parameters may result in serious consequences like short-circuiting of wire and wire breakage, imposing certain limits on the cutting speed and thus reducing productivity.

Several researchers [3,7,10,22,31, 36-41,47,54,55,62,67] have attempted to obtain the optimal parametric combination for WEDM process through various optimization techniques, but selection of cutting parameters for obtaining higher accuracy or cutting efficiency is not fully solved. In majority of the past research works, machining speed and surface finish have been considered. A few works [37,41,55,64] have been reported with dimensional shift. Some researchers [16,28,42,43,58] have exclusively conducted study on corner cutting and corner accuracy aspects of WEDM. In this research, an additional process criteria yield, corner accuracy which is an imperative criterion for intricate shape machining has been considered along with machining speed, surface finish and dimensional shift. Achieving specified surface finish, corner and dimensional
accuracy along with the maximum cutting speed (maximum productivity) is a matter of grave concern in the field of WEDM. This issue has been addressed in this work.

By far the most common workpiece materials in the past research are tool and die steels. No comprehensive research work has been reported so far in the field of wire electrical discharge machining of Aluminium 5083 (AA5083) alloy. No technology tables or guidelines are available for WEDM of AA 5083 alloy which is mostly used in technologically advanced industries like ship building, cryogenic, nuclear, aerospace and missile industries.

The present research work aimed at providing a customized technology table for professionals involved in machining aluminum alloys through WEDM process. Initial emphasis is placed on the influence of the parameters on the process criteria yield and the prediction of the responses through Taguchi based additive models. Later, optimization of the responses has been carried out by applying Pareto optimality approach. The optimal machining conditions proposed in this work have ample industrial applications because of the versatility of Aluminum 5083 alloy.

3.2. CHARACTERISTICS OF ALUMINIUM 5083 ALLOY

Aluminium 5083 alloy possesses:
(i) Excellent corrosion resistance,
(ii) Excellent cryogenic properties (does not exhibit ductile to brittle transition),
(iii) It has very high toughness even at cryogenic temperatures to near absolute zero, and
(iv) Good weldability and ductility.

The chemical composition of Aluminium 5083 alloy is presented in Table 3.1.

| Table 3.1 Chemical composition of Aluminium 5083 alloy (wt %) |
|----------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Element | Mg   | Mn   | Cr   | Si   | Fe   | Cu   | Al   |
| Weight (%) | 4.32 | 0.74 | 0.15 | 0.19 | 0.27 | 0.04 | balance |
The physical, mechanical, thermal and electrical properties of Aluminium 5083 alloy is given in Table 3.2.

Table 3.2 Properties of Aluminium 5083 (AA5083) alloy

<table>
<thead>
<tr>
<th>S.no</th>
<th>Properties</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Density (g/cm³)</td>
<td>2.65</td>
</tr>
<tr>
<td>2</td>
<td>Melting Point (°C)</td>
<td>570 - 630</td>
</tr>
<tr>
<td>3</td>
<td>Hardness</td>
<td>75 HV</td>
</tr>
<tr>
<td>4</td>
<td>Modulus of Elasticity (GPa)</td>
<td>72</td>
</tr>
<tr>
<td>5</td>
<td>Modulus of Rigidity (GPa)</td>
<td>26.4</td>
</tr>
<tr>
<td>6</td>
<td>Tensile strength, Ultimate (MPa)</td>
<td>275 - 300</td>
</tr>
<tr>
<td>7</td>
<td>Tensile strength, Yield (MPa)</td>
<td>195</td>
</tr>
<tr>
<td>8</td>
<td>Elongation</td>
<td>10-14 %</td>
</tr>
<tr>
<td>9</td>
<td>Poisson’s ratio</td>
<td>0.33</td>
</tr>
<tr>
<td>10</td>
<td>Mean Coefficient of thermal expansion (µm/m °C)</td>
<td>24.2</td>
</tr>
<tr>
<td>11</td>
<td>Thermal Conductivity (W/m-K)</td>
<td>121</td>
</tr>
<tr>
<td>12</td>
<td>Electrical Resistivity (µΩ-Cm)</td>
<td>5.8</td>
</tr>
</tbody>
</table>

3.3. EXPERIMENTATION

Experiments were conducted according to Taguchi’s L 18 orthogonal array, on an ELECTRA SUPERCUT 734 series wire electrical discharge machine, with Aluminum 5083 alloy plate of 15mm thickness as the workpiece (anode) and a brass wire of 250 µm diameter as the tool electrode (cathode).

3.3.1. CONTROL FACTORS

Based on literature survey and trial experiments, the control factors illustrated in Table 3.3 were chosen as input parameters. During trial experiments, it is observed that the corner inaccuracy in terms of uncut corner area (µm²) is more while cutting acute angles. Therefore, corner angles ranging 30 to 90 degree has been considered.
Table 3.3 Control factors and their levels

<table>
<thead>
<tr>
<th>S.no</th>
<th>Control factor</th>
<th>Symbol for coded value</th>
<th>Levels</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pulse on time (T_{on})</td>
<td>A</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>Pulse off time (T_{off})</td>
<td>B</td>
<td>14</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>Peak current (I_p)</td>
<td>C</td>
<td>20</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>Wire Tension (WT)</td>
<td>D</td>
<td>420</td>
<td>660</td>
</tr>
<tr>
<td>5</td>
<td>Servo feed setting (SF)</td>
<td>E</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>Corner angle (θ)</td>
<td>F</td>
<td>30</td>
<td>60</td>
</tr>
</tbody>
</table>

3.3.2. CONSTANT FACTORS

In WEDM process, there are other factors which are anticipated to have an effect on the measure of performance are kept constant. They are presented in Table 3.4.

Table 3.4 Constant factors

<table>
<thead>
<tr>
<th>S.no</th>
<th>Constant factors</th>
</tr>
</thead>
</table>
| 1    | Product shape and size  
       | square of size 6 mm x 6 mm               |
| 2    | Dielectric fluid                       
       | distilled water                         |
| 3    | Temperature of the dielectric           
       | 27°C                                    |
| 4    | Conductivity of the dielectric          
       | 20 mho                                   |
| 5    | Dielectric flushing pressure            
       | 8.5 kg/cm²                              |
| 6    | Servo voltage                           
       | 3V                                      |
| 7    | Pulse peak voltage                      
       | 100 V                                   |
| 8    | Wire feed rate                          
       | 6 m/min                                 |
| 9    | Threshold setting                       
       | 60%                                     |
| 10   | Angle of cut                            
       | vertical                               |

In this context, it may be pointed out that there are several noise factors associated with WEDM process as listed below:

(i) Ambient temperature of the tool room;
(ii) The structure of workpiece material matrix;
(iii) Variation in wire geometry;
(iv) The complex nature of wire vibration;
(v) Superimposition of sparks or craters at a particular point;
(vi) Variation of number of sparks from point to point between the wire and the workpiece;
(vii) Change in instantaneous conductivity of the dielectric fluid;
(viii) Variation of the controller performance; and so on.

3.3.3. PART GEOMETRY CREATION IN ELAPT

The CNC wire electrical discharge machine requires programming for the part shape and generations of path definitions for wire movement with respect to a reference point (or starting point) for making a profile. The part geometries or profiles employed in this research were created with ELAPT (Electra Automatic Programming Tool) software. ELAPT is a CAD/CAM software system for generating NC program for the ELEKTRA supercut wire cut EDM machine. The profile definition in ELAPT was performed in three simple steps as described below;

Step – I: Profile creation

The required part profile is created with the drawing elements (or construction elements) such as point, line, circle, line segment and arc. The editing comments namely erase, undo, redo, hide and transform (copy, move, mirror, rotate, scale) are available with the ELAPT to make necessary modification in the drawing.

Step – 2: Path definition

The drawing created in step-1 is connected using the comment CONNECT in order to define the actual wire path along with the cutting takes place. The wire path defined by connecting the drawing elements will act as a single entity though it contains many construction elements.
Step – 3: NC program generation

As soon as the drawing of the profile to be cut and the definition of the path of wire movement are fed to the controller, the software itself generates the NC part programming. In this step, the WEDM operator needs to input the dimensions of the product either in Inch or mm, wire compensation, taper angle (if any), corner rounding (Yes/ No), number of passes of wire, dwell time etc., The generated NC program is stored in a floppy disc which can be used by the controller for the execution, when required.

By following the above three steps, NC programs for 30°, 60° and 90° corner angles have been created through ELAPT software. The details of the part geometry are illustrated in Fig. 3.1.

Various high level programming languages are used for machining the products or parts, which does all the evaluations automatically, minimizing the total time for computation. Complex profile can also be easily defined by top and bottom profiles in two different layers and connecting those later. The salient programming features in WEDM system as used in the present research are listed as below;

(i) Exhaustive geometry definitions for point, line, circle, line segment etc;
(ii) Easy definition of the a two-dimensional wire path;
(iii) Wire path definition for a complex job in two layer or two faces of the job (top and bottom) and also facility for connecting top and bottom edges;

![Fig. 3.1 Part geometry with corner angles](image-url)
(iv) Transformation including multiple translations, multiple rotation, mirror image about a line etc;
(v) Smooth curve fitting for CAM profiles;
(vi) Involutes gear definitions with corrections; and so on.

3.3.4. RESPONSES

In the present research, the following responses were considered.

(i). Cutting speed (mm/min)
(ii). Surface finish (R_a)
(iii). Corner Inaccuracy (CI)
(iv). Dimensional shift (µm)

The cutting speed or machining speed is an important response that determines the productivity of the WEDM process, is directly obtained from the monitor of the machine tool. Surface finish plays a very critical role in determining the quality of engineering components. A good quality surface improves the fatigue strength, corrosion and wear resistance of the product. The surface finish values in terms of R_a were measured using PERTHOMETER manufactured by Mahr, Germany.

The corner inaccuracy is defined as the uncut area left between the actual profile and the desired (i.e. programmed) profile of the job as pictured in Fig. 1.7. In the present case it was measured by area. The corner inaccuracy or corner error in terms of uncut area at the corner with respect to different corner angles has been considered as response as it plays a significant role in complex shape machining. The corner accuracy is very much demanded by the technically advanced industries like aerospace, missile and nuclear industries where Aluminium 5083 alloy finds ample applications. The corner inaccuracy has been measured with the aid of OLYMPUS make, STM6 model measuring microscope. The sample corner inaccuracy measurements are illustrated in Figs. 3.2 – 3.4.
The dimensions of the square job (as shown in Fig. 3.1) produced through WEDM is undersized by the half of the width of the cut as seen from Fig. 3.5. This deviation in dimension is named as Dimensional shift. Fig. 3.5 also reveals that the dimensional shift is equal to the sum of the radius of the wire and the over cut. The dimensional shift can be defined as the half of the difference between the widths of the programmed path to the actual width of the finished product.

Dimensional shift (DS) = 0.5x (w_p-w_a) \hspace{1cm} (3.1)

Where, \( w_p \) is the width of the programmed profile and \( w_a \) is width of the actual job profile.

The actual job length (\( w_a \)) was measured by using Mitutoyo, Japan make digital micrometer having least count of 0.001mm. By using equation 3.1, the dimensional shift can be calculated.

Fig. 3.2. Corner inaccuracy (CI) for \( \theta =30^\circ \), pulse on time 1.1 \( \mu s \), pulse off time 38 \( \mu s \), peak current 70 A, wire tension 420 g and servo feed setting 40 \( v \)
Fig. 3.3. Corner inaccuracy (CI) for $\theta = 60^\circ$, pulse on time 0.8 $\mu$s, pulse off time 14 $\mu$s, peak current 70 A, wire tension 900 g and servo feed setting 20 v

Fig. 3.4. Corner inaccuracy (CI) for $\theta = 90^\circ$, pulse on time 0.8$\mu$s, pulse off time 14$\mu$s, peak current 20A, wire tension 660 g and servo feed setting 40v
The deviation of the job dimension during wire electrical discharge machining can be solved by shifting the wire by a distance equal to dimensional shift. This distance and the direction of shift of the wire can be controlled through part programming. This shift of wire through part programming is commonly termed as wire compensation or wire offset. Hence in case of rough cutting, to eliminate dimensional shift the wire offset must be equal to dimensional shift. Thus,

\[
\text{Wire offset} = \text{Dimensional shift}
\]  \hspace{1cm} (3.2)

It may be noted that the magnitude of dimensional shift and wire offset are equal, but their usage are different. The term ‘dimensional shift’ has been used as response parameter during single pass cutting experiment in WEDM with zero wire offset. But, ‘wire offset’ is a control setting in WEDM part programming to eliminate or minimize dimensional inaccuracy during actual machining. All the experiments were conducted according to Taguchi’s L-18 orthogonal array with zero wire offset and the dimensional shifts were measured along with other responses and reported in Table.3.5.
3.4. ADDITIVE MODELING OF THE WEDM PROCESS

Main feature of the Taguchi method based robust design philosophy is the use of additive model to approximate the relationship between the response variable and the factor levels. Interactions are considered as errors in the additive model. However, the relationship between (η) the S/N ratio and the process parameters, say A, B, C and D can be approximated adequately as follows [1]:

Table 3.5. Experimental results

<table>
<thead>
<tr>
<th>Exp.no</th>
<th>Control factors</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp.no</td>
<td>T_{on}</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>A</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>A</td>
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<td>6</td>
<td>2</td>
<td>A</td>
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<td>7</td>
<td>3</td>
<td>A</td>
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<td>8</td>
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<td>9</td>
<td>3</td>
<td>A</td>
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<td>10</td>
<td>1</td>
<td>A</td>
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<tr>
<td>11</td>
<td>1</td>
<td>A</td>
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<tr>
<td>12</td>
<td>1</td>
<td>A</td>
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<tr>
<td>13</td>
<td>2</td>
<td>A</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>A</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>A</td>
</tr>
<tr>
<td>16</td>
<td>3</td>
<td>A</td>
</tr>
<tr>
<td>17</td>
<td>3</td>
<td>A</td>
</tr>
<tr>
<td>18</td>
<td>3</td>
<td>A</td>
</tr>
</tbody>
</table>
\[ \eta (A_i, B_j, C_k, D_l) = m + a_i + b_j + c_k + d_l + e \]  

(3.3)

Where, \( m \) = overall mean = \( \frac{1}{n} \sum_{i=1}^{n} \frac{\eta_i}{n} \)

\( a_i \) = the deviation from ‘m’ caused by setting factor A at level \( A_i \)

The terms \( b_j, c_k, d_l \) represent similar deviations from ‘m’ caused by the settings \( B_j, C_k \) and \( D_l \) of factors B, C and D, respectively.

\( e = \text{error} \)

The error term includes the error of the additive approximation plus the error in the repeatability of measuring \( \eta \) for a given experiment. While calculating the factor effect the individual error terms are treated as independent random variables with zero mean and variance. In reality, this is only an approximation because the error term includes the error of the additive approximation so that the error terms are not strictly independent random variables with zero mean. This approximation is adequate because the error variance is used for only qualitative purposes.

It is worth mentioning that if the predicted response under the optimum conditions does not match with the observed response, then it implies that the interactions are important. If the predicted response matches with the observed one, then the same implies that the interactions are probably not important and that the additive model is a good approximation.

Additive model has been employed on the basis of matrix experiments using orthogonal arrays [1]. An additive model can be viewed as superposition model or a variable separable model. It can be noted that superposition model implies that the total effect of several factors is equal to the sum of individual factor effects. It is possible for the individual factor effects to be linear, quadratic or of higher order. In an additive model cross product terms involving two or more factors are not considered.
The predicted S/N ratio \( \hat{\eta} \) using the optimal levels of the machining parameters can be calculated as [31]:

\[
\hat{\eta} = \eta_m + \sum_{i=1}^{p} (\bar{\eta}_i - \eta_m)
\]  

(3.4)

Where \( \eta_m \) is total mean of S/N ratio \( \bar{\eta}_i \) is the mean of S/N ratio at the optimal level and \( p \) is the number of main machining parameters that significantly affect the performance. The model given in equation (3.4) was used for prediction. The additive model is verified through verification experiments and the outcome of these experiments along with the prediction error has been presented in Table 3.6. The prediction error depicted in Table 3.6 is defined [37] as:

\[
\text{Prediction error (\%)} = \left| \frac{\text{Experiment value} - \text{Predicted value}}{\text{Experiment value}} \right| \times 100
\]  

(3.5)

The prediction error reported in Table 3.6 strongly indicates that this model is plausible for prediction.

Table 3.6 Verification experiments along with the prediction error

<table>
<thead>
<tr>
<th>S. no</th>
<th>Control factor setting</th>
<th>Experiment value</th>
<th>Prediction Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CS (mm/min)</td>
<td>( R_a ) (( \mu )m)</td>
</tr>
<tr>
<td>1</td>
<td>A3B2C2D1E2F2</td>
<td>1.40</td>
<td>2.820</td>
</tr>
<tr>
<td>2</td>
<td>A1B2C3D3E1F3</td>
<td>0.54</td>
<td>1.650</td>
</tr>
<tr>
<td>3</td>
<td>A1B1C2D2E3F2</td>
<td>1.19</td>
<td>2.431</td>
</tr>
<tr>
<td>4</td>
<td>A3B1C1D3E1F1</td>
<td>0.69</td>
<td>1.924</td>
</tr>
<tr>
<td>5</td>
<td>A3B1C3D1E2F2</td>
<td>2.12</td>
<td>2.874</td>
</tr>
<tr>
<td>6</td>
<td>A2B3C2D3E2F3</td>
<td>0.82</td>
<td>2.366</td>
</tr>
</tbody>
</table>

Average prediction error 10.6 8.72 11.15 4.61
3.5. PARAMETRIC ANALYSIS BY TAGUCHI METHODOLOGY

In WEDM, the lower surface roughness (Ra), lower corner inaccuracy (CI) and the higher cutting speed (CS) are the indication of better performance. Therefore, the “Lower is better (LB)” for Ra and CI, “higher is better (HB)” for the CS were selected for obtaining optimum machining performance characteristics.

The signal to noise (S/N) ratio for cutting speed is calculated by using equation 3.6. The S/N ratio for surface roughness and the corner inaccuracy have been computed by using equation 3.7.

\[
S/N \text{ ratio } = \eta = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right) \quad (3.6)
\]

\[
S/N \text{ ratio } = \eta = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) \quad (3.7)
\]

Where, \( y_i = i^{th} \) reading of ‘y’ in a treatment

\( n = \) total number of readings in the same treatment

From the analysis of the cutting speed data as shown in Table 3.7 it is observed that pulse on time, pulse off time, peak current and servo feed setting play significant role in determining the cutting speed. From Table 3.8 it is learnt that the pulse on time and the peak current are the predominant parameters in determining surface roughness followed by wire tension and the servo feed setting. From the analysis of corner inaccuracy data in Table 3.9, it is observed that the corner angle is the most important factor. Pulse on time, Pulse off time and Peak current are also influencing factors but their importance is much less compared to the corner angle. Table 3.10 reveals that the dimensional shift has been influenced by the Peak current, Pulse on time and pulse off time.
### Table 3.7 Analysis of Cutting Speed (CS) data

<table>
<thead>
<tr>
<th>Factor</th>
<th>Average η(CS) by factor level (dB)</th>
<th>d.f</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A: Pulse on time</td>
<td>-4.566</td>
<td>-1.530</td>
<td>0.4097*</td>
<td>2</td>
<td>75.5</td>
</tr>
<tr>
<td>B: Pulse off time</td>
<td>1.71*</td>
<td>-2.493</td>
<td>-4.901</td>
<td>2</td>
<td>134.2</td>
</tr>
<tr>
<td>C: Peak current</td>
<td>-5.456</td>
<td>-0.433</td>
<td>0.202*</td>
<td>2</td>
<td>115.3</td>
</tr>
<tr>
<td>D: Wire Tension</td>
<td>-1.346</td>
<td>-1.996</td>
<td>-2.344</td>
<td>2</td>
<td>3.1^a</td>
</tr>
<tr>
<td>E: Servo feed setting</td>
<td>-4.449</td>
<td>-1.609</td>
<td>0.372*</td>
<td>2</td>
<td>70.5</td>
</tr>
<tr>
<td>F: Corner Angle</td>
<td>-1.510</td>
<td>-2.179</td>
<td>-1.997</td>
<td>2</td>
<td>1.4^a</td>
</tr>
<tr>
<td>Error</td>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>3.38^a</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>17</td>
<td>403.38</td>
</tr>
<tr>
<td>(Error)</td>
<td></td>
<td></td>
<td></td>
<td>(9)</td>
<td>(7.88)</td>
</tr>
</tbody>
</table>

Overall mean ($\eta_m$) = **1.895**; * indicates Optimum level

d.f - degrees of freedom; SS- Sum of square; MS- Mean square; ^a Indicates the sum of squares added together to form the pooled error sum of squares shown in parentheses.

### Table 3.8 Analysis of Surface Roughness (Ra) data

<table>
<thead>
<tr>
<th>Factor</th>
<th>Average η(Ra) by factor level (dB)</th>
<th>d.f</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A: Pulse on time</td>
<td>-5.101*</td>
<td>-6.919</td>
<td>-7.737</td>
<td>2</td>
<td>21.84</td>
</tr>
<tr>
<td>B: Pulse off time</td>
<td>-6.809</td>
<td>-6.582</td>
<td>-6.367*</td>
<td>2</td>
<td>0.59^a</td>
</tr>
<tr>
<td>C: Peak current</td>
<td>-5.257*</td>
<td>-7.156</td>
<td>-7.345</td>
<td>2</td>
<td>16.01</td>
</tr>
<tr>
<td>D: Wire Tension</td>
<td>-6.922</td>
<td>-6.543</td>
<td>-6.292*</td>
<td>2</td>
<td>1.21</td>
</tr>
<tr>
<td>E: Servo feed setting</td>
<td>-6.420</td>
<td>-6.405*</td>
<td>-6.932</td>
<td>2</td>
<td>1.08</td>
</tr>
<tr>
<td>F: Corner Angle</td>
<td>-6.774</td>
<td>-6.623</td>
<td>-6.360</td>
<td>2</td>
<td>0.53^a</td>
</tr>
<tr>
<td>Error</td>
<td></td>
<td>5</td>
<td>0.48a</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>17</td>
<td>41.74</td>
<td>20.71</td>
<td></td>
</tr>
<tr>
<td>(Error)</td>
<td></td>
<td>(9)</td>
<td>(1.6)</td>
<td>(0.18)</td>
<td></td>
</tr>
</tbody>
</table>

Overall mean ($\eta_m$) = **6.586**; * indicates Optimum level

d.f - degrees of freedom; SS- Sum of square; MS- Mean square; ^a Indicates the sum of squares added together to form the pooled error sum of squares shown in parentheses.
Table 3.9 Analysis of Corner Inaccuracy (CI) data

<table>
<thead>
<tr>
<th>Factor</th>
<th>Average η(CI) by factor level (dB)</th>
<th>d.f</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A: Pulse on time</td>
<td>-86.6*</td>
<td>-88.64</td>
<td>-88.96</td>
<td>2</td>
<td>19.6</td>
</tr>
<tr>
<td>B: Pulse off time</td>
<td>-89.18</td>
<td>-87.50</td>
<td>-87.51</td>
<td>2</td>
<td>11.2</td>
</tr>
<tr>
<td>C: Peak current</td>
<td>-87.04*</td>
<td>-88.90</td>
<td>-88.25</td>
<td>2</td>
<td>10.7</td>
</tr>
<tr>
<td>D: Wire Tension</td>
<td>-89.91</td>
<td>-88.13</td>
<td>-87.16</td>
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<td>9.3^a</td>
</tr>
<tr>
<td>E: Servo feed setting</td>
<td>-87.21</td>
<td>-88.13</td>
<td>-88.85</td>
<td>2</td>
<td>8.1^a</td>
</tr>
<tr>
<td>F: Corner Angle</td>
<td>-94.94</td>
<td>-86.30</td>
<td>-82.95*</td>
<td>2</td>
<td>459.5</td>
</tr>
</tbody>
</table>

Error 5 10.56^a 2.1 | Total 17 528.96 261.2 | (Error) (9) (27.96) (3.1)

Overall mean (η_m) = -88.06; * indicates Optimum level

d.f - degrees of freedom; SS- Sum of square; MS- Mean square; ^a Indicates the sum of squares added together to form the pooled error sum of squares shown in parentheses.

Table 3.10 Analysis of Dimensional Shift (DS) data

<table>
<thead>
<tr>
<th>Factor</th>
<th>Average η(DS) by factor level (dB)</th>
<th>d.f</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A: Pulse on time</td>
<td>-49.42*</td>
<td>-49.76</td>
<td>-50.09</td>
<td>2</td>
<td>1.354</td>
</tr>
<tr>
<td>B: Pulse off time</td>
<td>-49.98</td>
<td>-49.73</td>
<td>-49.56*</td>
<td>2</td>
<td>0.549</td>
</tr>
<tr>
<td>C: Peak current</td>
<td>-49.24*</td>
<td>-50.01</td>
<td>-50.02</td>
<td>2</td>
<td>2.445</td>
</tr>
<tr>
<td>D: Wire Tension</td>
<td>-49.77</td>
<td>-49.74</td>
<td>-49.76</td>
<td>2</td>
<td>0.004^a</td>
</tr>
<tr>
<td>E: Servo feed setting</td>
<td>-49.72</td>
<td>-49.7</td>
<td>-49.85</td>
<td>2</td>
<td>0.077^a</td>
</tr>
<tr>
<td>F: Corner Angle</td>
<td>-49.82</td>
<td>-49.57</td>
<td>-49.88</td>
<td>2</td>
<td>0.334^a</td>
</tr>
</tbody>
</table>

Error 5 0.534^a 0.107 | Total 17 5.297 2.489 | (Error) (11) (0.949) (0.086)

Overall mean (η_m) = -49.76; * indicates Optimum level

d.f - degrees of freedom; SS- Sum of square; MS- Mean square; ^a Indicates the sum of squares added together to form the pooled error sum of squares shown in parentheses.

The cutting speed shows an increasing trend with the increase of pulse on time, peak current and servo feed setting at the same time it decreases with the increase of pulse off time, as illustrated in Fig.3.6 This ascertains that the cutting speed is not only
proportional to the energy content of the spark but also the rate of energy applied during sparking. The pulse on time and the peak current constitutes the energy content of a spark whereas the pulse off time controls the rate of sparking. The servo feed setting decides the servo speed of the work table in proportion with the gap voltage. Therefore increase in servo feed setting increases the cutting speed.

![Graph showing factor effects on S/N ratio for cutting speed (CS)](image)

From Figs. 3.6 and 3.7 it is observed that surface roughness as well as dimensional shift increases with increase in pulse on time and peak current. It reveals that both the surface roughness and dimensional shift value increase if the energy contained in a pulse increase. This is due to the enhanced crater size manifested by the higher energy pulse. Fig. 3.9 depicts that the corner inaccuracy diminishes with the increase in corner angle. This is due to the fact that the higher corner angle offers less geometrical constraint to wire movement.

![Graph showing factor effects on S/N ratio for surface roughness (Rₐ)](image)
The task of finding optimal parameters is extremely difficult when multiple responses are present. Careful examination of Fig. 3.6, 3.7 and 3.9 along with Tables 3.7 to 3.9 reveals that the best level of significant factors for cutting speed (CS), surface roughness ($R_a$) and corner inaccuracy (CI) are $A_3B_1C_3E_3$, $A_1B_3C_1D_3E_2$ and $A_1B_3C_1F_3$ respectively. From this, it is confirmed that the level of significant parameter setting for the CS, $R_a$ and CI are completely contradictory. Therefore it is hardly possible to have single parameter combination that could be the optimal choice for all the responses. Hence, it is required to explore a suitable strategy for optimization of this process.
3.6. ANALYSIS OF SEM MICROGRAPHS OF MACHINED SURFACE

Apart from the machining criteria like cutting speed, surface finish, corner accuracy etc., the features of WEDMed surface is one of the important subjects of research. A study on surface characteristics of WEDMed surface of AA 5083 alloy is very much essential from the point of industrial applications particularly in aerospace industry which requires components free from recast layer and subsurface damages [4].

The formation of craters on the workpiece surface is the result of discharge action in WEDM and is also affected by the dielectric fluid used and by the electrode materials. When the temperature of the discharges reaching 8000 to 12000°C, metallurgical changes occur in the surface layers of the workpiece. The surface of the workpiece material is melted and quickly re-hardened by the cooling action of the dielectric so that a thin re-cast epitaxial layer is formed. Hence, the components produced by WEDM are having metallurgically damaged surface layers and it often require fine, conventional finishing before they are put into service.

The geometric shape of the crater produced by EDM especially in single discharge model was studied by many researchers and concluded that the depth and width of the crater is affected by the applied discharge energy. It is already established that micro cracks and re-cast layer are also affected by higher discharge temperature and sudden cooling during the operation.

The surface generated by WEDM is random in nature. Therefore the study of the surface is to be done not only from the metallurgical aspects but also from the point of view of its topography. A few attempts [24,32,53,61] have been made to characterize the random surfaces.

The selection of process parameters determines the efficiency and cutting speed in WEDM. Machining at higher cutting speed requires high energy pulses that generally cause low surface integrity. This section presents the qualitative analysis of effects of
process parameters on surface integrity during single pass cutting of Aluminium 5083 alloy through WEDM. Attention has been focused to obtain scanning electron microscope (SEM) pictures for aggressive pulse parameters settings selected from Table 3.5 (i.e. experiment number 16) where the pulse on time = 1.1 μs, pulse off time = 14 μs, peak current = 120A, wire tension = 660g, servo feed setting = 60. The SEM micrograph for aggressive parameter setting is shown in Fig. 3.10. In this picture bigger craters and higher thickness of recast layer are observed due to the spark erosion of larger amount of molten work-material. The SEM micrograph for lower pulse parameter setting (experiment no. 11 of Table 3.5) reveals that the considerable reduction in crater size and recast layer thickness on the surfaces machined with pulse on time = 0.5 μs, pulse off time = 26 μs, peak current = 20 A, wire tension = 420g and servo feed setting = 60, as shown in Fig. 3.11.

Fig. 3.10 SEM photograph of the wire-EDM cut surface of a sample machined under the following machine settings: pulse on time = 1.1 μs, pulse off time = 14 μs, peak current = 120A, wire tension = 660g, servo feed setting = 60.
3.7. OPTIMIZATION OF THE PROCESS

In the present work in all 729 ($3^6 = 729$) machining combination exists, among which the optimal parameter combination has to be selected. The optimal parameter setting specified through Taguchi methodology for cutting speed ($A3B1C3E3$), surface roughness ($A1B3C1D3E2$) and corner inaccuracy ($A1B3C1F3$) do not have any practical value as they dealt with only one response. In practice, the WEDM industry needs to produce components with the specified surface roughness, geometrical and corner accuracy demanded by the customers. But the productivity of machining depends on the cutting speed. Therefore, it is imperative to fabricate a handy technology table for optimal processing of AA 5083 alloy.

The corner angle ($\theta$) is not an actual process parameter in WEDM. However it plays a crucial role in intricate shape machining. Therefore, the total machining combinations have been grouped according to the corner angle. Now there are 243...
parametric combinations available for each corner angle are to be concurrently optimized.

The most viable Pareto optimality approach has been adapted for searching optimal solutions. It gives a set of solutions that are non-dominated with respect to one another. In other words the optimum point is graphically located with respect to its coordinates on CS (x-axis), $R_a$ (y-axis) and CI (z-axis) axis. The optimum points will have higher coordinate value in x-axis and lower coordinate values in y and z axis with respect to other (inferior) points. If any two optimal points have same coordinate value, both will be considered.

A computer program was generated to find out these optimum points from the set of all 243 points. After executing the program, 44 Pareto optimal points were obtained for 30° corner angle. They were graphed in Fig.3.12 and visibly marked by filled circle. Similar manner the Pareto optimal solutions for 60° and 90° corner angles have been identified and reported in Table 3.11. It is quite interesting to note that the searched Pareto optimal solutions for different corner angle i.e. 30°, 60° and 90° are having the same parametric combinations as shown in Table 3.11. The group representing corner angle 30° and 90° are having 44 optimal solutions and the remaining group stand out for 60° has 43 optimal solution points.

These set of Pareto-optimal solutions are very much useful because a manufacturing engineer can adapt to different optimal solutions, as and when required. This is the major advantage of this approach over other optimization techniques employed in the literature [3,10,22,31,36,39,40,47,54,62,67]. Once the optimal set is available there is no need to run the computer program again. Just by referring the technology table of optimal solutions one can readily find out the optimum parametric combinations for a surface finish, dimensional and corner accuracy requirements. Table 3.11 can be used as handy technology guideline for optimal machining of AA5083 as briefed below.
For instance, a customer demands components with $R_a \leq 1.8\mu m$ and corner inaccuracy (CI) $\leq 40,000\mu m^2$ for 30°. The optimal parameter setting for this circumstance can be selected from Table 3.11 (S.no:38) as pulse on time of 0.5μs, pulse off time of 26 μs, peak current of 20 Amps, wire tension of 900 g and servo feed setting of 60 yields the cutting speed of 0.45 mm/min and surface roughness of 1.553 μm and Corner inaccuracy of 38784 μm². The obtained dimensional shift (wire offset), 281 μm has been duly considered as control factor along with other control factors. This value of wire offset has been passed to the CNC part program to enhance the dimensional accuracy of the machined part.

Fig. 3.12 Pareto solutions along with the inferior solutions for 30° corner angle
Table 3.11 Technology setting for optimum machining of Aluminum 5083 alloy

<table>
<thead>
<tr>
<th>S.no</th>
<th>Control factors</th>
<th>Wire offset (μm)</th>
<th>Ave CS (mm/min)</th>
<th>Ave Rₚ (μm)</th>
<th>Corner inaccuracy (μm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pareto optimal combinations</td>
<td></td>
<td></td>
<td></td>
<td>θ =30° θ =60° θ =90°</td>
</tr>
<tr>
<td>1</td>
<td>A3B1C3D1E3</td>
<td>342</td>
<td>2.79</td>
<td>2.952</td>
<td>86719 32076 21799</td>
</tr>
<tr>
<td>2</td>
<td>A3B1C2D1E3</td>
<td>346</td>
<td>2.65</td>
<td>2.883</td>
<td>93519 ** 23508</td>
</tr>
<tr>
<td>3</td>
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<td>2.826</td>
<td>79223 29304 19915</td>
</tr>
<tr>
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<td>2.746</td>
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</tr>
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<td>5</td>
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<td>2.572</td>
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<tr>
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<tr>
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<td>32</td>
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<td>33</td>
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<td>0.61</td>
<td>1.544</td>
<td>48413 17908 12170</td>
</tr>
<tr>
<td>34</td>
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<td>296</td>
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<td>41053 15185 10320</td>
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Table 3.11 Technology setting for optimum machining of Aluminum 5083 alloy

<table>
<thead>
<tr>
<th>S.no</th>
<th>Control factors</th>
<th>Wire Offset (μm)</th>
<th>Ave CS (mm/min)</th>
<th>Ave Rₐ (μm)</th>
<th>Corner inaccuracy (μm²)</th>
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<tbody>
<tr>
<td></td>
<td>Pareto optimal combinations</td>
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<td></td>
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<td>0° =30°</td>
</tr>
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<td><strong>38784</strong></td>
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** indicates that the A3B1C2D1E3 is an inferior solution for 60° corner angle

3.8. CONCLUDING REMARKS

The experimental investigation presented in this work proved that wire electrical discharge machining (WEDM) is adequate to machine Aluminum 5083 alloy to any complex shape with desired dimensional and corner accuracy. The process has been successfully modeled using additive model. The predicted response parameter from the model fits well with that of the experimental result. It was observed that the cutting speed is mostly influenced by pulse on time, pulse off time, peak current and servo feed setting and the surface finish is mostly influenced by pulse on time and the peak current. The corner angle itself is the most predominant factor in determining the corner accuracy. The significant factor for dimensional shift has been the peak current and pulse on time.

The dimensional accuracy of the product was improved by predicting dimensional shift for every machining combination and passing the same to the CNC program as wire off set (wire compensation) value. The corner inaccuracy and the surface roughness were independent of pulse off time. This observation is very important under certain critical machining condition such as acute angle cutting etc., pulse off time can be varied as per requirement to achieve better stability and corner accuracy with the sacrifice of little
cutting speed. Nonetheless, varying pulse off time will not affect the dimensional accuracy and the surface finish significantly.

The SEM micrographs were analyzed for aggressive and low parameters settings. The crater size observed during lower parameter setting was quite lesser than that of aggressive parameters settings. The lower parameter setting is desired for better surface finish, corner accuracy and surface morphology. But, this will drastically reduce the productivity (cutting speed) of the WEDM process. Hence, Multi-pass cutting (i.e. one rough cut followed by one or more finish cut) will be an appropriate choice to enhance the productivity along with better surface morphology, better surface finish, and other accuracy features. Finally, based on the additive model predictions and Pareto-optimality approach, a handy technology table was reported with its industrial usage for optimal processing of Aluminium 5083 alloy.