CHAPTER 5

OPTIMIZATION OF WORK ROLL GRINDING
WITH MULTIPLE PERFORMANCE CHARACTERISTICS
USING TAGUCHI METHOD WITH FUZZY LOGICS

5.1 INTRODUCTION

The challenge in roll grinding is to restore the roll to a required surface roughness with minimum power consumption and material removal rate without visible feed and chatter marks or surface irregularities. The dualism of quality on the one hand and productivity on the other requires the development of tools by which one can completely use the rationalization potentials in roll grinding operations. 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. However, most published Taguchi applications to date have been concerned with the optimization of a single performance characteristic. Elsayed and Chen (1993) have reported that the handling the more demanding multiple performance characteristics is still an interesting research problem.

Zadeh (1965) developed the theory of fuzzy logics, has proved to be useful for dealing with uncertain and vague information. In fact, the definition of performance characteristics such as lower-the-better, higher-the-better and nominal-the-better contains certain degree of uncertainty and vagueness.
Therefore, optimization of the performance characteristics with fuzzy reasoning of the multiple performance characteristics has been developed based on fuzzy logic. As a result, optimization of complicated multiple performance characteristics can be transformed into the optimization of single Multi-Response Performance Index (MRPI). Usually, the desired grinding parameters are determined based on experience or handbook values. However, this does not ensure that the selected grinding parameters result in optimal or near optimal grinding performance for that particular roll grinding of work rolls. To solve this task in the present study, the Taguchi method with fuzzy logic is used as an efficient approach to determine the optimal machining parameters in finish work roll grinding. In this chapter, the optimization of the finish work roll grinding process with multiple performance characteristics has been investigated to illustrate this approach.

5.2 RESEARCH METHODOLOGY

Douglas C. Montgomery (1991) has described that the classical experimental design methods are too complex and not easy to use. Furthermore, 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 S/N ratio, the lower-the-better, the higher-the-better and the nominal-the-better. Regardless of the category of the performance characteristics, a larger S/N ratio corresponds to better performance characteristics. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio. Moreover, a statistical
analysis of variance (ANOVA) is performed to identify the process parameters that are statistically significant. The optimal combination of the process parameters can then be predicted based on the above analysis. Finally, a confirmation 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. Lin et al (2000) have pointed out that the usual recommendation for the optimization of a process with multiple performance characteristics is left to engineering judgment and verified by confirmation experiments. This is because, the category of each performance characteristics may not be same; the engineering unit for describing each performance characteristics may be different and the importance of each performance characteristics also may vary. As a result, the application of the Taguchi method in a process with multiple performance characteristics cannot be straightforward. In this work, the use of fuzzy logic to deal with the optimization of process with multiple performance characteristics is reported. First, several fuzzy rules are derived based on the performance requirement of the process. The loss function corresponding to each performance characteristics is fuzzified and then a single Multiple-Response Performance Index (MRPI) is obtained through fuzzy reasoning on the fuzzy rules. The MRPI can be used to optimize the process based on the Taguchi approach.

5.3 EXPERIMENT DETAILS

5.3.1 Experiment Design and Factor Levels

To perform the experiment design, three levels of the grinding parameters were selected and as shown in Table 5.1. MRR could be calculated using empirical relation (Juneja et al 2003),
MMR = πDT_s d \hspace{1cm} (5.1)

where D is the diameter of the work roll. In this study average diameter of the work roll (63mm) has been considered.

**Table 5.1 Factors and their levels**

<table>
<thead>
<tr>
<th>S.No</th>
<th>Factors</th>
<th>Levels</th>
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<tbody>
<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td>01</td>
<td>Wheel Speed in rpm (W_s)</td>
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<tr>
<td>02</td>
<td>Work Speed in rpm (J_s)</td>
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<tr>
<td>03</td>
<td>Traverse Speed in m/min(T_s)</td>
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<tr>
<td>04</td>
<td>In-feed in micron (d)</td>
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</tr>
<tr>
<td>05</td>
<td>Dress depth in micron (D_p)</td>
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<tr>
<td>06</td>
<td>Dress lead in m/min(D_s)</td>
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5.3.2 Taguchi Experiment

To select an appropriate orthogonal array for the experiments, the total degrees of freedom need to be computed. The degrees of freedom are defined as the number of comparisons between process parameters that need to be made to determine which level is better and specifically how much better it is. In this study, the interaction between the machining parameters is neglected. Therefore, there are 26 degree of freedom owing to six three-level machining parameters in the roll grinding operation. Once the degree of freedom is known, the next step is to select an appropriate orthogonal array to fit the specific task. In this study L_{27} orthogonal array was used because it has 26 degrees of freedom in grinding parameters. Each grinding parameter is assigned to columns and 27 grinding parameter combinations are required. Therefore, only 27 Experiments are needed to study the entire grinding parameter space using the L_{27} orthogonal array. The experimental combination of the grinding parameters using the L_{27} orthogonal array is presented in the Table 5.2.
In the Taguchi method, a loss function is defined to calculate the deviation between the experimental value and the desired value. Usually, there are three categories of the performance characteristics in the analysis of the signal-to-noise, i.e., the lower-the-better, the higher-the-better, and the nominal-the-better.

**Table 5.2  $L_{27}$ Orthogonal array experimental combinations**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>$W_s$ rpm</th>
<th>$J_s$ rpm</th>
<th>$T_s$ m/min</th>
<th>$D$ microns</th>
<th>$D_p$ microns</th>
<th>$D_s$ m/min</th>
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To obtain optimal machining performance, the minimum value of surface roughness, power required at grinding wheel spindle and maximum value of material removal rate are desired. Therefore, the lower-the-better surface roughness and power required should be selected. For material removal rate, the higher-the better value should be selected. The loss function \( L_{ij} \) of the lower-the-better performance characteristic can be expressed as

\[
L_{ij} = \frac{1}{n} \sum_{k=1}^{n} y_{ijk}^2
\]  

(5.2)

where \( L_{ij} \) is the loss function of the \( i^{th} \) performance characteristics in the \( j^{th} \) experiment, \( n \) the number of tests and \( y_{ijk} \) is the experimental value of the \( i^{th} \) performance characteristics in the \( j^{th} \) experiment at the \( k^{th} \) test. The loss function of the higher-the –better performance characteristic be expressed as

\[
L_{ij} = \frac{1}{n} \sum_{k=1}^{n} 1/y_{ijk}^2
\]  

(5.3)

The loss function is further transformed into an S/N ratio. In the Taguchi method, the S/N ratio is used to determine the deviation of the performance characteristic from the desired value. The S/N ratio \( \eta_{ij} \) for the \( i^{th} \) performance characteristics in the \( j^{th} \) experiment can be expressed as

\[
\eta_{ij} = -10 \log(L_{ij})
\]  

(5.4)

Table 5.3 shows the experimental results for the surface roughness, power required at grinding wheel spindle and material removal rate and their S/N ratios based on the experimental parameter combinations described in the Table 5.2. To consider the three different performance characteristics in the Taguchi method, the S/N ratios corresponding to the surface roughness, power required at spindle and material removal rate are processed by the fuzzy logic unit.
Table 5.3  Experimental results of Surface roughness, power required and material removal rate and their S/N ratios

<table>
<thead>
<tr>
<th>S.No.</th>
<th>SR Microns</th>
<th>S/N</th>
<th>P KW</th>
<th>S/N</th>
<th>MRR</th>
<th>S/N</th>
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5.4 Fuzzy Logic

A fuzzy logic unit comprises a fuzzifier, membership functions, a fuzzy rule base, an inference engine, and a defuzzifier. First, the fuzzifier uses triangular membership functions to fuzzify the S/N ratios. Next, the inference engine performs a fuzzy reasoning on fuzzy rules to generate a fuzzy value. Finally, the defuzzifier converts the fuzzy value into a MRPI.

In the following, the concept of fuzzy reasoning is described briefly based on the three-input-one-output fuzzy logic unit. The fuzzy rule base consists of a group of if-then control rules with the three inputs, $x_1$, $x_2$, $x_3$ and output $y$, i.e.,

- Rule 1: If $x_1$ is $A_1$ and $x_2$ is $B_1$ and $x_3$ is $C_1$ then $y$ is $D_1$ else
- Rule 2: If $x_1$ is $A_2$ and $x_2$ is $B_2$ and $x_3$ is $C_2$ then $y$ is $D_2$ else
- ………………………………………………………………………
- Rule n: If $x_1$ is $A_n$ and $x_2$ is $B_n$ and $x_3$ is $C_n$ then $y$ is $D_n$.

$A_i$, $B_i$, $C_i$ and $D_i$ are fuzzy subsets defined by the corresponding membership functions. i.e., $\mu_{A_i}$, $\mu_{B_i}$, $\mu_{C_i}$ and $\mu_{D_i}$. In this work, three subsets are assigned in the three inputs such as surface roughness, power required at grinding wheel spindle and material removal rate are shown in Figures 5.1, 5.2 and 5.3. Seven fuzzy subsets are assigned in the output Multiple Response Performance Index (MRPI) as shown in Figure 5.4.

Twenty-seven fuzzy rules as shown in Table 5.4 are derived directly based on the fact that larger is the S/N ratio, the better is the performance characteristics. Various degree of membership to the fuzzy sets is calculated based on the values of $x_1$, $x_2$, $x_3$ and $y$. 
Figure 5.1 Membership function for $R_a$

Figure 5.3 Membership function for MRR

Figure 5.2 Membership function for Power required

Figure 5.4 Membership function for MRPI
### Table 5.4  Fuzzy Rules

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<tr>
<th>Rule</th>
<th>Condition</th>
<th>Conclusion</th>
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<td>Rule 1</td>
<td>If MRR is Small and $R_a$ is Small and $P$ is Small then MRPI is Very Small.</td>
<td></td>
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<td>Rule 2</td>
<td>If MRR is Middle and $R_a$ is Small and $P$ is Small then MRPI is Small.</td>
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<td>Rule 3</td>
<td>If MRR is Large and $R_a$ is Small and $P$ is Small then MRPI is Middle.</td>
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<td>Rule 5</td>
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<td>Rule 6</td>
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<td>Rule 10</td>
<td>If MRR is Small and $R_a$ is Small and $P$ is Middle then MRPI is Small.</td>
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<tr>
<td>Rule 11</td>
<td>If MRR is Middle and $R_a$ is Small and $P$ is Middle then MRPI is Middle.</td>
<td></td>
</tr>
<tr>
<td>Rule 12</td>
<td>If MRR is Large and $R_a$ is Small and $P$ is Middle then MRPI is Large.</td>
<td></td>
</tr>
<tr>
<td>Rule 13</td>
<td>If MRR is Small and $R_a$ is Middle and $P$ is Large then MRPI is Middle.</td>
<td></td>
</tr>
<tr>
<td>Rule 14</td>
<td>If MRR is Middle and $R_a$ is Middle and $P$ is Large then MRPI is Large.</td>
<td></td>
</tr>
<tr>
<td>Rule 15</td>
<td>If MRR is Large and $R_a$ is Middle and $P$ is Large then MRPI is Very Large.</td>
<td></td>
</tr>
<tr>
<td>Rule 16</td>
<td>If MRR is Small and $R_a$ is Large and $P$ is Small then MRPI is Middle.</td>
<td></td>
</tr>
<tr>
<td>Rule 17</td>
<td>If MRR is Middle and $R_a$ is Large and $P$ is Small then MRPI is Large.</td>
<td></td>
</tr>
<tr>
<td>Rule 18</td>
<td>If MRR is Large and $R_a$ is Large and $P$ is Small then MRPI is Very Large.</td>
<td></td>
</tr>
<tr>
<td>Rule 19</td>
<td>If MRR is Small and $R_a$ is Small and $P$ is Large then MRPI is Middle.</td>
<td></td>
</tr>
<tr>
<td>Rule 20</td>
<td>If MRR is Middle and $R_a$ is Small and $P$ is Large then MRPI is Large.</td>
<td></td>
</tr>
<tr>
<td>Rule 21</td>
<td>If MRR is Large and $R_a$ is Small and $P$ is Large then MRPI is Very Large.</td>
<td></td>
</tr>
<tr>
<td>Rule 22</td>
<td>If MRR is Small and $R_a$ is Large and $P$ is Middle then MRPI is Middle.</td>
<td></td>
</tr>
<tr>
<td>Rule 23</td>
<td>If MRR is Middle and $R_a$ is Large and $P$ is Middle then MRPI is Large.</td>
<td></td>
</tr>
<tr>
<td>Rule 24</td>
<td>If MRR is Large and $R_a$ is Large and $P$ is Middle then MRPI is Very Large.</td>
<td></td>
</tr>
<tr>
<td>Rule 25</td>
<td>If MRR is Small and $R_a$ is Middle and $P$ is Small then MRPI is Small</td>
<td></td>
</tr>
<tr>
<td>Rule 26</td>
<td>If MRR is Middle and $R_a$ is Middle and $P$ is Small then MRPI is Middle.</td>
<td></td>
</tr>
<tr>
<td>Rule 27</td>
<td>If MRR is Large and $R_a$ is Middle and $P$ is Small then MRPI is Large.</td>
<td></td>
</tr>
</tbody>
</table>
By taking the maximum-minimum compositional operation, the fuzzy reasoning, the fuzzy reasoning of these rules yields a fuzzy output. Supposing that $x_1$, $x_2$, $x_3$ are the three input values of the fuzzy logic unit, the membership function of the output of fuzzy reasoning can be expressed as,

$$
\mu_{\text{D}_o}(y) = \left( \mu_{A_1}(x_1) \land \mu_{B_i}(x_2) \land \mu_{C_i}(x_3) \land \mu_{D_i}(y) \right) 
\lor \ldots \left( \mu_{A_n}(x_1) \land \mu_{B_n}(x_2) \land \mu_{C_n}(x_3) \land \mu_{D_n}(y) \right)
$$

(5.5)

where $\land$ is the minimum operation and $\lor$ is the maximum operation.

Finally, a defuzzification method, called the centre-of-gravity method is adopted here to transform the fuzzy inference output into a non-fuzzy value.

$$
y_0 = \frac{\sum y\mu_{C_o}(y)}{\sum \mu_{C_o}(y)}
$$

(5.6)

The non-fuzzy value $y_0$ is called the Multiple Response Performance Index (MRPI). MATLAB 7.0 software is used to carried out the fuzzy logic operations and the determination of MRPI. Based on the above discussion, the larger is the MRPI, the better is the performance characteristic. Table 5.5 shows the experimental results for the MRPI using the experimental combinations of the Table 5.2. Since the experimental design is orthogonal, it is then possible to separate out the effect of each grinding parameter at different levels. Basically, the larger is the MRPI, the smaller is the variance of the performance characteristics around the desired value. However, the relative importance amongst the machining parameters for the multiple performance characteristics still needs to be known so that the optimal combinations of the machining parameter levels can be determined more accurately. Table 5.6 shows the mean of the MRPI for each level of the roll grinding parameters is summarized and called the MRPI table.
Table 5.5  Results for the MRPI

<table>
<thead>
<tr>
<th>No.</th>
<th>MRPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.400</td>
</tr>
<tr>
<td>2</td>
<td>0.382</td>
</tr>
<tr>
<td>3</td>
<td>0.365</td>
</tr>
<tr>
<td>4</td>
<td>0.505</td>
</tr>
<tr>
<td>5</td>
<td>0.600</td>
</tr>
<tr>
<td>6</td>
<td>0.598</td>
</tr>
<tr>
<td>7</td>
<td>0.508</td>
</tr>
<tr>
<td>8</td>
<td>0.464</td>
</tr>
<tr>
<td>9</td>
<td>0.450</td>
</tr>
<tr>
<td>10</td>
<td>0.740</td>
</tr>
<tr>
<td>11</td>
<td>0.653</td>
</tr>
<tr>
<td>12</td>
<td>0.620</td>
</tr>
<tr>
<td>13</td>
<td>0.600</td>
</tr>
<tr>
<td>14</td>
<td>0.552</td>
</tr>
<tr>
<td>15</td>
<td>0.584</td>
</tr>
<tr>
<td>16</td>
<td>0.565</td>
</tr>
<tr>
<td>17</td>
<td>0.580</td>
</tr>
<tr>
<td>18</td>
<td>0.500</td>
</tr>
<tr>
<td>19</td>
<td>0.730</td>
</tr>
<tr>
<td>20</td>
<td>0.724</td>
</tr>
<tr>
<td>21</td>
<td>0.732</td>
</tr>
<tr>
<td>22</td>
<td>0.620</td>
</tr>
<tr>
<td>23</td>
<td>0.650</td>
</tr>
<tr>
<td>24</td>
<td>0.650</td>
</tr>
<tr>
<td>25</td>
<td>0.580</td>
</tr>
<tr>
<td>26</td>
<td>0.617</td>
</tr>
<tr>
<td>27</td>
<td>0.625</td>
</tr>
</tbody>
</table>
5.5 RESULTS AND DISCUSSION

Since the experimental design is orthogonal, it is then possible to separate out the effect of each process parameter at different levels. The mean of the MRPI for each level of the process parameters is calculated and given in the Table 5.6. Figure 5.5 shows the mean Multiple Response Performance Index graph. The dashed line indicated in Figure 5.5 is the value of the total mean of the multiple response performance grade. The larger is the MRPI, the better is the multiple process response.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Level</th>
<th>Max-Min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>W_s</td>
<td>0.474</td>
<td>0.599</td>
</tr>
<tr>
<td>J_s</td>
<td>0.594</td>
<td>0.596</td>
</tr>
<tr>
<td>T_s</td>
<td>0.524</td>
<td>0.615</td>
</tr>
<tr>
<td>d</td>
<td>0.522</td>
<td>0.614</td>
</tr>
<tr>
<td>D_p</td>
<td>0.583</td>
<td>0.580</td>
</tr>
<tr>
<td>D_s</td>
<td>0.567</td>
<td>0.596</td>
</tr>
</tbody>
</table>
5.5.1 Analysis of Variance

The purpose of the ANOVA is to investigate which process parameters significantly affect the performance characteristics. This is accomplished by separating the total variability of the multi-response performance indexes, which is measured by the sum of the squared deviations from the total mean of the MRPI, into contributions by each of the process parameter and the error. The percentage contribution by each of the process parameter in the total sum of the squared deviations 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 characteristics.

The results of ANOVA as shown in the Table-5.7 indicates that wheel speed, In-feed and Traverse speed are the significant grinding
parameters in affecting the multiple performance characteristics, with wheel speed being the most significant. This is mainly due to grinding wheel contribution on the requirement of spindle power and its self-sharpening characteristics during the grinding process. Higher in-feed cause more grinding force on work roll, which leads to wear on grinding edges. This causes grinding wheel consume more power on obtaining the required surface finish. Traverse speed has more influences on obtaining required surface finish than its influences on grinding wheel spindle power. The dress depth, which is significant on obtaining surface finish on work rolls but it is less contribution on consumption of grinding power requirement.

Table 5.7 Analysis of Variance

<table>
<thead>
<tr>
<th>Parameters</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>Percent cont.</th>
</tr>
</thead>
<tbody>
<tr>
<td>W_s</td>
<td>2</td>
<td>0.160</td>
<td>0.080</td>
<td>64.36*</td>
<td>55.75</td>
</tr>
<tr>
<td>J_s</td>
<td>2</td>
<td>0.0162</td>
<td>0.0081</td>
<td>6.14</td>
<td>4.85</td>
</tr>
<tr>
<td>T_s</td>
<td>2</td>
<td>0.0403</td>
<td>0.0202</td>
<td>16.21*</td>
<td>13.38</td>
</tr>
<tr>
<td>d</td>
<td>2</td>
<td>0.0426</td>
<td>0.0213</td>
<td>17.11*</td>
<td>14.20</td>
</tr>
<tr>
<td>D_p</td>
<td>2</td>
<td>0.00079</td>
<td>0.00039</td>
<td>0.32</td>
<td>0.02</td>
</tr>
<tr>
<td>D_s</td>
<td>2</td>
<td>0.00465</td>
<td>0.00232</td>
<td>1.87</td>
<td>1.01</td>
</tr>
<tr>
<td>Error</td>
<td>14</td>
<td>0.0174</td>
<td>0.001246</td>
<td>10.79</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>26</td>
<td>0.28259</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* significant at 95% confidence level

Based on the above discussion, the optimal machining parameters are the Wheel speed at level 3, Work speed at level 2, Traverse speed at level 2, In-feed at level 2, Dress depth at level 1 and Dress lead at level 2.
5.5.2 Confirmation of Experiment

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 $\bar{\eta}$ using the optimal level of the process parameters can be calculated as

$$\bar{\eta} = \eta_m + \sum_{i=1}^{q} (\eta_i - \eta_m)$$  \hspace{1cm} (5.7)

where $\eta_m$ is the total mean of the MRPI, $\eta_i$ the mean of the MRPI at the optimal level, and $q$ (in this case it is three) is the number of the process parameters that significantly affect the multiple performance characteristics.

Based on equation (5.7) (Lin et al 2000), the estimated MRPI using the optimal grinding parameters can then be obtained. Table 5.8 shows the results of the confirmation experiment using optimal grinding parameters (obtained from the Table 5.6) such as wheel speed at 500rpm, work speed at 110 rpm, traverse at 1.0 m/min, in-feed at 15 microns, dress depth at 10microns and dress lead at 0.15 m/min. It is observed that the performances such as surface roughness value is reduced to 0.067 microns from 0.073 microns, the power required is reduced to 2.87 kw from 3.18 kw and material removal rate is increased to 4635 mm$^3$/min from 989.6 mm$^3$/min .The comparison of MRPI is shown in the Table-5.8 also indicated that work roll grinding conditions are improved through this study.
Table 5.8 Result of Confirmation of Experiment and comparison of MRPI

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial parameter (A1B1C1D1E2F2)</th>
<th>Optimal parameter (A3B2C2D2E1F2)</th>
<th>Predicted</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface roughness in μm</td>
<td>0.073</td>
<td>0.065</td>
<td>0.067</td>
<td></td>
</tr>
<tr>
<td>Power required in kw</td>
<td>3.18</td>
<td>2.68</td>
<td>2.86</td>
<td></td>
</tr>
<tr>
<td>MRR in mm³/min</td>
<td>989.6</td>
<td>4848.5</td>
<td>4635.2</td>
<td></td>
</tr>
<tr>
<td>MRPI</td>
<td>0.382</td>
<td>0.771</td>
<td>0.764</td>
<td></td>
</tr>
</tbody>
</table>

5.6 CONCLUSION

This Chapter presents the use of fuzzy logic to the Taguchi method for the optimization of roll grinding of D2 steel work rolls with multiple performance characteristics. The fuzzy logic unit has performed a fuzzy reasoning of the multiple performance characteristics. As a result, the performance characteristics such as surface roughness, power required at wheel spindle and material removal rate can be optimized through this approach. An experiment was conducted to confirm the approach. As a result, the optimization methodology developed in this study is used to optimize the multiple performance characteristics in the work roll grinding.