Optimization Machining Conditions on Composite Materials Using Fuzzy Logic

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Abstract— Automotive, aircraft and train companies need to replace steel and cast iron in mechanical components with lighter high strength alloys like Al metal matrix composites (MMC). Experiments were carried out on Radial Drilling Machine. A plan of experiments, based on the techniques of Taguchi was performed. In this study drilling of Aluminium Silicon Carbide (Al/SiC) was investigated. The objective of this research is to study the effect of cutting speed, feed, and volume fraction, diameter of cut machining time on metal removal rate, specific energy, surface roughness, and flank wear. The experiments were conducted using L27 orthogonal array. This paper deals with the use of Taguchi Technique with fuzzy logic to optimize drilling process in Al/SiC composites with multiple quality characteristics. The influence of each parameter on the responses is established using analysis of variances (ANOVA) at 5% level of significance. It is found that % of Vol SiC, Cutting Speed, Feed Rate, diameter of drill and machining time contribute significantly to the multiple performance characteristic index. The five responses at optimal parameter setting have been reported.

Keywords: Composite materials; drilling processes; Fuzzy Logic; ANOVA

I. INTRODUCTION

Metal Matrix Composites have found considerable applications in automotive, aircraft and manufacture of sea vehicles industries due to their improved strength, high specific strength/stiffness, microbiological attacks and increased wear resistance over unreinforced alloys. As a consequence of the widening range of applications of MMC, the machining of these materials has become a very important subject for research. The particles used in the MMCs are harder than most of the cutting tool materials.

Fuzzy logic has great capability to capture human commonsense reasoning, decision-making and other aspects of human cognition. The classes of certain objects in the real world do not have precisely defined criteria of membership. Fuzzy set was introduced by Zadeh (1965) to deal such problems and is defined as a class of objects with a continuum of grades of membership. Klar & Yuan (1998) stated that fuzzy logic involves a fuzzy interference engine and a fuzzification-defuzzification module. El-Sonbaty et al (2004) investigated the influence of cutting speed, feed, drill size and fiber volume fraction on the thrust force, torque and surface roughness in the drilling processes of fiber reinforced epoxy composite materials. However, very few researchers have used the Grey relational analysis to predict the efficient drilling process parameter for surface roughness and delamination. Latha & Senthilkumar (2009a, 2009b, 2010) analyzed the thrust force and surface roughness in drilling operation. Fuzzy rule-based model has been developed to predict the thrust force. Response surface model has been developed and comparison between fuzzy based model and response surface model has been carried out.

II. EXPERIMENTAL WORKS

In this work, LM25 –based Aluminium alloy (7 Si 0.33Mg 0.3Mn 0.5Fe 0.1Cu 0.1Ni 0.2Ti) reinforced with green bonded Silicon particles of size 25 micrometer with different volume fractions (10%, 15%, 20% in weight percentage) manufactured through stir casting route is used for experimentation.

The experiment was repeated for the various cutting conditions like % volume of SiC, feed, speed, depth of...
cut and time of machining. The variables used in this study are given in the Table 1.

Table 1 Selected Input variables and output

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Input Variables</th>
<th>Variations</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
</tr>
<tr>
<td>3</td>
<td>Feed Rate</td>
<td>0.12, 0.22, 0.40 (mm/rev)</td>
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<td>4</td>
<td>Dia of Drill</td>
<td>4, 7, 10 (mm)</td>
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</tr>
<tr>
<td>5</td>
<td>Machining Time</td>
<td>2, 4, 6 (min)</td>
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</tbody>
</table>

The Metal Removal Rate (MRR), Flankwear (Tw), Specific Energy (Es) and Surface Roughness (Ra) are considered as response for this study. The factors and their levels considered in this study are shown in Table 2

Table 2 Machining parameters and their levels

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Machining parameters</th>
<th>Unit</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
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<td>%</td>
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<td>15</td>
<td>25</td>
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<td>Cutting Speed</td>
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<td>1000</td>
<td>1500</td>
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<tr>
<td>C</td>
<td>Feed</td>
<td>mm/rev</td>
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<td>0.22</td>
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<tr>
<td>D</td>
<td>Dia of Drill</td>
<td>mm</td>
<td>4</td>
<td>7</td>
<td>10</td>
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<tr>
<td>E</td>
<td>Machining Time</td>
<td>min</td>
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<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

III. OPTIMIZATION STEPS USING FUZZY LOGIC

A fuzzy logic unit consists of a fuzzifier, membership functions, a fuzzy rule base, an inference engine and a defuzzifier. In the system of fuzzy reasoning, the fuzzifier primarily uses membership functions to fuzzify the S/N ratios. A Membership Function (MF) is a curve to determine how each input value is mapped to a membership value (or degree of membership) between 0 and 1. Next, the inference engine performs a fuzzy interface so as to generate a fuzzy value according to the membership function and fuzzy rules. Finally, the defuzzifier converts the fuzzy value into a non-fuzzy value called multi-response performance index (MRPI). In this study, the membership function adopts the trapezoidal membership function that has a flat top and a truncated triangle curve. In fuzzy logic, if–then rule statements are used to formulate the conditional statements. In the following, the concept of fuzzy reasoning is described briefly based on the two-input-one-output fuzzy logic unit, where $x_1$ and $x_2$ are the two inputs and $y$ is the output.

Rule 1: if $x_1$ is $A_1$ and $x_2$ is $B_1$ then $y$ is $C_1$

Rule 2: if $x_1$ is $A_2$ and $x_2$ is $B_2$ then $y$ is $C_2$

Rule n: if $x_1$ is $A_n$ and $x_2$ is $B_n$ then $y$ is $C_n$.

$A_i$, $B_i$, and $C_i$ are fuzzy subsets defined by the corresponding membership functions, i.e., $\mu_{A_i}, \mu_{B_i}$ and $\mu_{C_i}$. In this work, to obtain fuzzy sets, trapezoidal membership function was used for fuzzification. In fuzzification, numerical input and output values are converted into linguistic terms such as low, medium and high etc. The value of membership function ranges between 0 and 1, and it shows how much a variable matches a fuzzy set.

IV. RESULTS AND DISCUSSION

Membership functions and their ranges of input parameters were shown in Figure 1. A total of 27 rules were formed as shown in Figure 2. In this study, spindle speed, feed rate, drilling diameter, machining time and % volume of silicon carbide were considered as input parameters. Flank wear, specific energy, surface roughness and metal removal rate were considered as output parameters.
The better is the information that larger is the S/N ratio and the better of these rules fetches a fuzzy output. Supposing that \( x_1 \) and \( x_2 \) are the two input values of the fuzzy logic unit, the membership function of the output of fuzzy reasoning can be expressed as in Equation (1).

\[
\mu_{C_0}(y) = (\mu_{A_1}(x_1) \Lambda \mu_{B_1}(x_2) \Lambda \mu_{C_1}(y)) V... (\mu_{A_n}(x_1) \Lambda \mu_{B_n}(x_2) \Lambda \mu_{C_n}(y))
\]

where \( \Lambda \) is the minimum operation and, \( V \) is the maximum operation.

\[
y_0 = \frac{\sum y \mu_{C_n}(y)}{\sum \mu_{C_n}(y)}
\]

A defuzzification method, called the centroid method, is taken on here to transform the fuzzy inference output into a non-fuzzy value, called MRPI. Based on the above discussion, the larger is the MRPI, the better is the performance characteristic. Applying the fuzzy rules listed in Table 3 and the membership values for the fuzzy sets it is clear in Figure 4. The defuzzified output that gives the final Multi Performance Characteristics indices (MPCIs) value is calculated as 0.5 from the combined darkness area shown in the bottom of MPCIs column in Figure 4. The MRPI value of the corresponding machining parameters is shown in the Table 4. The effect of each machining parameters at different levels is calculated and summarized in the MRPI table (Table 5).

<table>
<thead>
<tr>
<th>S. No</th>
<th>MRR (mm/mmin)</th>
<th>Surface Roughness microns</th>
<th>Flank Specitic Heat W/m²K</th>
<th>SN Ratio of MRR</th>
<th>SN Ratio of Surface Roughness</th>
<th>SN Ratio of Flank Wear</th>
<th>SN Ratio of Specific Energy</th>
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<td>7.23</td>
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<td>2205</td>
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<td>0.91</td>
<td>50,347</td>
<td>66.87</td>
<td>-9.86</td>
<td>0.82</td>
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</table>

A defuzzification method, called the centroid method, is taken on here to transform the fuzzy inference output into a non-fuzzy value, called MRPI. Based on the above discussion, the larger is the MRPI, the better is the performance characteristic. Applying the fuzzy rules listed in Table 3 and the membership values for the fuzzy sets it is clear in Figure 4. The defuzzified output that gives the final Multi Performance Characteristics indices (MPCIs) value is calculated as 0.5 from the combined darkness area shown in the bottom of MPCIs column in Figure 4. The MRPI value of the corresponding machining parameters is shown in the Table 4. The effect of each machining parameters at different levels is calculated and summarized in the MRPI table (Table 5).
TABLE 5 MRPI values obtained based on the S/N ratio.

<table>
<thead>
<tr>
<th>Exp.No</th>
<th>SN Ratio of MRR</th>
<th>SN Ratio of Surface Roughness</th>
<th>SN Ratio of Wear</th>
<th>SN Ratio of Specific Energy</th>
<th>MRPI</th>
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</table>

The effect of each machining parameter at different levels is calculated and summarized in the MRPI table (Table 6). Table 6 depicts an optimal combination of process parameter for higher metal removal rate, lesser surface roughness, flank wear and specific energy with %vol of SiC (level 1), machining speed (level 3), feed rate (level 1), diameter of drill (level 3) and machining time (level 1). The total mean of all 15 values are calculated and presented in Table 6. The MRPI graph is shown in Figure 5. Larger values of the MRPI in the graph (or in the MRPI table 5) indicate that the smaller is the variance of the performance characteristics around the desired value. Moreover, the relative importance between 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 exactly.

A. Analysis of Variance (ANOVA)

The MRPI values, determined from the experimental values are statistically studied by ANOVA to investigate the effects of each machining parameter on the observed values and to clarify which machining parameters significantly affects the observed values. In addition, the F-test named after Fisher can also be used to determine which process parameters have a significant effect on the performance characteristics (Montgomery DC., 1997). Usually, the change of the process parameter has a significant effect on the performance characteristics when the F value is large. Table 7 shows the calculated F-values of the ANOVA for machining rate and overcut respectively to determine the relative significances of different control factors. From the calculated F value, it is observed that cutting speed and machining time have significant effect in metal removal rate and surface roughness. From the ANOVA test, it is also clear that cutting speed have a high percentage of contribution on different machining criteria compared to other parameters.

TABLE 6 MRPI Table

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<th>Symbol</th>
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<th>Level 3</th>
<th>Maximum</th>
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<td>4.542</td>
<td>3.786</td>
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<td>Cutting Speed</td>
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<td>Feed</td>
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</table>

TABLE 7 Results of ANOVA

<table>
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<th>Level 2</th>
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<th>Maximum</th>
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<td>3.786</td>
<td>5.126</td>
</tr>
<tr>
<td>B</td>
<td>Cutting Speed</td>
<td>3.626</td>
<td>4.696</td>
<td>5.132</td>
<td>5.132</td>
</tr>
<tr>
<td>C</td>
<td>Feed</td>
<td>4.86</td>
<td>4.462</td>
<td>4.132</td>
<td>4.86</td>
</tr>
</tbody>
</table>
B. Validation

After identifying the optimal level of the process parameters, the last step is to predict and verify the improvement of the performance characteristic using the optimal level of the process parameters. The purpose of the confirmation test is to validate the conclusions drawn during the analysis phase. The predicted or estimated MRPI value using the optimal level of the process parameters can be calculated as per the Equation (3).

\[ \eta = \eta_m + \sum_{i=1}^{q} (\eta_i - \eta_m) \]  

(3)

Where \( \eta_m \) is the total mean of the MRPI, \( q \) is the number of significant parameters, \( \eta_i \) is the mean of the MRPI at the optimal level.

The MRPI was predicted based on the Equation (3) and new experiment has been designed and conducted with the optimal levels of the machining parameters to verify the improvement of the multiple performance characteristics. Table 8 shows the confirmation test table using optimal machining parameters. This table evaluates the predicted and actual MRPI value and MRPI is increased from 0.784 to 0.8637. It is shown clearly that MRPI is greatly improved. The metal removal rate is (MRR) is improved from 192 to 3002 mm/min and surface roughness (SR) is improved from 9.02 to 4.0185μm. It is clearly shown that the multiple performance characteristics in the Al-SiC machining process are greatly improved through this study.

<table>
<thead>
<tr>
<th>Setting Level</th>
<th>Initial Machining parameters</th>
<th>Optimal machining parameters</th>
<th>Prediction</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal Removal Rate (MRR)</td>
<td>A1B1C1D1E1</td>
<td>A1B1C1D1E1</td>
<td>192</td>
<td>3002</td>
</tr>
<tr>
<td>Surface Roughness (SR)</td>
<td>9.02</td>
<td>4.0185</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flank Wear (FW)</td>
<td>0.141</td>
<td>0.3576</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Energy (SE)</td>
<td>38.157</td>
<td>40.575</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MRPI</td>
<td>0.784</td>
<td>0.8637</td>
<td>0.8530</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 8 Confirmation Test**

**V. CONCLUSION**

A hybrid optimization technique fuzzy along with Taguchi’s design is proposed to find out the optimal setting of process parameters to simultaneously improve four responses. In this experimental study, it is found that the hardness of MMC is increasing with the increasing weight% of SiC in the composite and mesh size. A fuzzy reasoning of the multiple performance characteristics has been performed by the fuzzy logic unit. As a result, the performance characteristics such as MRR, SR, FW and SE can be improved through this approach. An experiment was conducted to confirm this approach. Based on the experimental results and confirmation test the conclusion can be drawn as follows

1. The recommended levels of drilling parameters for minimizing flank wear, surface roughness and specific energy for increase in metal removal rate (at exit condition) simultaneously are the content of SiC at level 1 (10%), Spindle speed at level 3 (1500m/min), feed rate at level 1 (0.12 mm/rev), Drill diameter at level 3 (10 mm) and Machining time at level 1 (2 min). Among the tested parameters, the machining time, cutting speed and % vol of SiC shows the strongest correlation to the flank wear, surface roughness, specific energy and Metal removal rate at exit condition.

2. An increase in the value of predicted (MRPI) from 0.784 to 0.8637 confirms the improvement in the performance of drilling of metal matrix composites when using the optimal values of process parameters.

3. The experimental results for optimal settings show that there is a considerable improvement in the performance characteristics of machining process. This technique is more convenient and economical to predict the effect of different influential combinations of the parameters within the levels studied.

**REFERENCES**


