6.1 INTRODUCTION

Optimization of the various process parameters of extrusion process becomes very complex due to nature of extrusion. The performance and quality of extrusion process highly relies on the few parameters which cannot be quantified directly. For example, prediction of extrusion load is mainly depends on the nature of the die geometry and friction developed between the die – billet interface. It is significant attempt to optimize the extrusion process parameters by considering it as hot extrusion. The optimization model has been extended to study the hot extrusion of SiC reinforced aluminium composite. Though there are different methods of unconventional methods of optimization techniques, very popular conventional quantitative tool like design of experiment suggested by Taguchi has been applied to study the hot extrusion of SiC/Al composite.

6.2 DESIGN OF EXPERIMENT

Among the possible methods, Taguchi’s design is one of the most powerful design of experiment method for analyzing the experiments. It is highly recognized in many fields particularly in the development of new process and product in quality control. Significant features of this method are as follows:
• A simple, efficient and systematic technique to optimize the process or product to improve the performance or to reduce the cost.

• It is scientifically developed mechanism for evaluating the optimized parameters for all kinds of processes, materials and equipment.

• Therefore, Taguchi’s method has got the pivotal role in the area of developing low cost experiments because it needs minimum number of experiment trials to yield optimized results.

• Factorial designs are powerful method to design efficient experimental designs to optimize and determine the factors that influences variability.

• But factorial designs are impractically large, whereas Taguchi design often performs better for minimum number of trials.

6.3 DEVELOPMENT OF ORTHOGONAL DESIGN

Taguchi suggested the use of orthogonal arrays (OAs) for designing the experimentally developing the concepts of linear graphs which simplifies the design of orthogonal array experiments. This orthogonal design does not require any additional statistical knowledge. The main advantage of these designs lies in their simplicity, easy adaptability to more complex experiments involving more number of factors with different number of levels. They provide the sufficient information with the least possible number of trials and yield results with adequate precision. This method are usually employed to study main effects and applied in screening the experiments.
6.4 SELECTION OF PROCESS VARIABLES AND THEIR LEVELS

There are few extrusion process variables which affected the magnitude of the extrusion force out of which ram speed, initial billet temperature and friction condition between the die and billet interface are the most dominant process parameters as far as hot extrusion is concerned. Three levels of these variables were considered to represent low, medium and high as level 1, level 2, and level 3 respectively as shown in Table 6.1.

Table 6.1 Process parameters and their levels

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Process parameters</th>
<th>unit</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Ram speed</td>
<td>mm/min</td>
<td>3</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>B</td>
<td>Billet temperature</td>
<td>℃</td>
<td>250</td>
<td>350</td>
<td>450</td>
</tr>
<tr>
<td>C</td>
<td>Friction factor</td>
<td></td>
<td>0.1</td>
<td>0.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

The experimental set up utilised for this study, cosine profiled die and the extrudate are as shown in Figure 5.2, 5.3 and 5.4 respectively in chapter 5, and the details of the experimental conditions with which the various experiments conducted as shown in Table 6.2. As far as the frictional coefficient was concerned during the experiments, complete lubrication of die with graphite powder as minimum friction factor of 0.1 as level 1 and partly lubricated as medium friction factor 0.4 as level 2 and null lubrication as maximum friction factor of 0.8 as level 3 were considered.
Table 6.2 Experimental conditions

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Press tool</td>
<td>600 KN UTM (Digital) UTE-60</td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1mm</td>
</tr>
<tr>
<td>Clearance</td>
<td>600mm</td>
</tr>
<tr>
<td>Ram stroke</td>
<td>250mm</td>
</tr>
<tr>
<td>Minimum test</td>
<td>0.1mm/min</td>
</tr>
<tr>
<td>Material</td>
<td>10% vol. SiC/Al 6061 composite</td>
</tr>
<tr>
<td>Die</td>
<td>Cosine profiled die geometry</td>
</tr>
<tr>
<td>Punch</td>
<td>10mm diaX40 mm length EN 24 rod</td>
</tr>
<tr>
<td>Heating Source</td>
<td>Muffle furnace</td>
</tr>
<tr>
<td>Billet Dimensions</td>
<td>10 mm dia X 25 mm length</td>
</tr>
<tr>
<td>Lubrication</td>
<td>Graphite powder</td>
</tr>
</tbody>
</table>

6.5 ORTHOGONAL ARRAYS

Orthogonal array (OA) based on Taguchi’s design of experiment is found to be more useful to solve the engineering problems. While designing the experiments, number of trials could be drastically reduced by the introduction of orthogonal arrays. In orthogonal arrays each column represents the main factors which attribute the response. The number of factors and its number of variation in their level would decide the degrees of freedom. For the present study, three main factors with three levels were considered thereby implementing L9 orthogonal arrays. The degrees of freedom defined as the number of combinations made between the design parameter at different level so as to determine betterment of levels.
Usual procedure to arrive the degrees of freedom is that it should be greater than the number of design parameters. But normally it is less than number of rows in orthogonal array by one in count. For the present study eight degrees of freedom were considered. Only the main factors of interest, its interaction factors were ruled out. There were nine number of experiment trials were performed, for each and every trial, the extrusion load applied was observed and recorded as response value in L9 orthogonal array as shown in Table 6.3.

### Table 6.3 Experimental layout using L9 orthogonal arrays

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Ram speed (A) Level Value (mm/min)</th>
<th>Billet Temperature(B) Level Value (°C)</th>
<th>Friction condition(C) Level Value</th>
<th>Extrusion load(tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>250</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>350</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>450</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>250</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>350</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>6</td>
<td>3</td>
<td>450</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>9</td>
<td>1</td>
<td>250</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>9</td>
<td>2</td>
<td>350</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>450</td>
</tr>
</tbody>
</table>

**6.6 EXPERIMENTAL RESULTS**

Based on Taguchi’s L9 orthogonal array, nine experiments were conducted for the different combinations of levels of process parameters. Experimental observations revealed that the force required to extrude the material found to be higher in run no 5, 4, 8 and 9. The levels of process
parameters of these runs include higher friction, lower billet temperature and higher ram speed. From the previous literature, it is very obvious that the higher magnitude of the friction would cause inhomogeneous strain distribution in central and outer part of the billet during deformation which in turn requires the higher force to extrude the material. Simultaneously, rate of decrease in billet temperature would allow the plasticity to decrease. This phenomenon requires the higher extrusion force to extrude. Prediction of exact level of extrusion process parameters to yield the lesser extrusion load is very complex in the absence of this type of useful statistical studies.

The following Table 6.4 was developed by adding the response values corresponding to each level (Level 1, Level 2 and Level 3)

**Table 6.4 Response totals for each factor and level**

<table>
<thead>
<tr>
<th>Factors</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>36.64</td>
<td>37.45</td>
<td>35.87</td>
</tr>
<tr>
<td>Level 2</td>
<td>36.82</td>
<td>37.04</td>
<td>36.65</td>
</tr>
<tr>
<td>Level 3</td>
<td>37.45</td>
<td>36.1</td>
<td>38.07</td>
</tr>
</tbody>
</table>

Average response table was constructed to assess the ranking between the factors. The response totals given in the Table 6.4 were converted into average response by dividing the number of observations made as shown in Table 6.5. The absolute difference in the average response of maximum and minimum of each factor was also recorded. This difference purely represents the effect of the factor. These differences were ranked starting with the highest difference as rank 1, the next highest difference as rank 2 and so on. The average response table with ranking of factors effect is as shown in Table 6.5.
Table 6.5  Average response and ranking of factors effect

<table>
<thead>
<tr>
<th>Factors</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>4.07</td>
<td>4.16</td>
<td>3.98</td>
</tr>
<tr>
<td>Level 2</td>
<td>4.09</td>
<td>4.11</td>
<td>4.07</td>
</tr>
<tr>
<td>Level 3</td>
<td>4.16</td>
<td>4.01</td>
<td>4.23</td>
</tr>
<tr>
<td>Max- Min</td>
<td>0.09</td>
<td>0.15</td>
<td>0.25</td>
</tr>
<tr>
<td>Rank</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 6.1  Average response graph

From Table 6.5, it was observed that factor C has the largest effect emerging as rank 1 and the grand overall mean is given by

$$\bar{Y} = \frac{T}{N} \quad (6.1)$$

Based on the objective of the experiment, the optimum condition was selected. It is well known fact that the minimization of extrusion load is
the dominant objective, therefore in order to minimization of response optimum condition was selected based on lower mean value of each factor. Accordingly from Figure 6.1, the optimum condition was given by

\[ A_1 \quad B_3 \quad C_1 \]

The predicted optimum response is given by

\[ \mu_{\text{Pred}} = \bar{Y} + (\bar{A} - \bar{Y}) + (\bar{B} - \bar{Y}) + (\bar{C} - \bar{Y}) \quad (6.2) \]

where \( \bar{Y} \) the overall mean response, \( \bar{A}, \bar{B}, \bar{C} \) are the average response at level 1, level 3 and level 1 respectively for the corresponding factors.

6.7 ANALYSIS OF VARIANCE

The ultimate objective of the analysis of variance is to determine the degree of significance over the total effect of response. This was achieved by separating the total mean from the sum of the squared deviations contributed by each parameter. The total sum of squared deviations (SST) is given by

\[ SS_{\text{Total}} = \sum_{i=1}^{a} \sum_{j=1}^{n} (Y_{ij} - \bar{Y})^2 \quad (6.3) \]

\[ SS_{T} = \sum_{i=1}^{a} \frac{T_i^2}{n} - CF \quad (6.4) \]

\[ SS_e = SS_{\text{Total}} - SS_{T} \quad (6.5) \]
The total sum of the squared deviations was decomposed into two sources as sum of the squared deviations due to individual parameters like $SS_A$, $SS_B$ and $SS_C$. The percentage of contribution of each process parameter in the total sum of the squared deviations can be availed to evaluate the importance of each process parameters over the performance. The Fischer’s test was also used to investigate the degree of significance of each process parameter over the performance. Usually, the largest value of F recorded the most significant process parameter. The rank of significance was assigned based on the F value, larger the value higher the rank. Table 6.6 shows the results of ANOVA.

### Table 6.6 ANOVA table

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of squares</th>
<th>Means squares</th>
<th>F value</th>
<th>% Contribution</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ram speed</td>
<td>2</td>
<td>0.36</td>
<td>0.18</td>
<td>2.18</td>
<td>14.87</td>
<td>3</td>
</tr>
<tr>
<td>Billet temperature</td>
<td>2</td>
<td>0.37</td>
<td>0.185</td>
<td>2.24</td>
<td>15.28</td>
<td>2</td>
</tr>
<tr>
<td>Friction condition</td>
<td>2</td>
<td>1.69</td>
<td>0.845</td>
<td>10.24</td>
<td>69.85</td>
<td>1</td>
</tr>
<tr>
<td>Error</td>
<td>8</td>
<td>0.66</td>
<td>0.0825</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>14</td>
<td>3.08</td>
<td></td>
<td></td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

It is well comprehended from the ANOVA table that the friction between the die billet interface emerged as the chief extrusion parameter with rank 1 followed by the billet temperature and ram speed in second and third influential rank respectively.

### 6.8 UPPER BOUND ANALYSIS

Upper bound mathematical model has been constructed as suggested at chapter No 4. Knowing the velocity and strain components of material flow at cosine die profile, the volume integral was carried out using
Simpson’s one third rule to determine the force required to extrude the Al-SiC composite. The approximate yield value of the material at the optimized temperature ($\sigma_Y$) at $B_3$, optimized ram speed as inlet velocity ($V_0$) of $A_2$ and the optimized friction factor ($m$) of $C_1$ has been substituted in the following equation to determine the extrusion force required. The determined power can be converted to the average extrusion load ($P_{ave}$)

$$P_{ave} = \frac{W_l}{nR_1^2 V_0}$$

6.9 CONFIRMATION EXPERIMENTS

The confirmation experiment was conducted based on the optimum levels arrived from the average response method. Actual extrusion force required to deform the billet under these levels has been observed and recorded as the experimental response value and as shown in Table 6.7. Additionally, extrusion force required was analytically manipulated through the upper bound technique which was developed using various velocity field and strain gradients. Theoretical force required to extrude the given billet under the optimized level of process parameters has been shown in Table 6.7 as the theoretical response value.

Table 6.7 Comparisons of confirmation experiment results with predicted and UBT

<table>
<thead>
<tr>
<th>Level</th>
<th>Initial process parameters</th>
<th>Optimal process parameters</th>
<th>Prediction</th>
<th>Experiment</th>
<th>UBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion force(tons)</td>
<td>12.59</td>
<td>11.63</td>
<td>12.18</td>
<td>12.04</td>
<td></td>
</tr>
<tr>
<td>Level</td>
<td>$A_2 B_2 C_3$</td>
<td>$A_1 B_3 C_1$</td>
<td>$A_1 B_3 C_1$</td>
<td>$A_1 B_3 C_1$</td>
<td></td>
</tr>
<tr>
<td>Level</td>
<td>$A_2 B_2 C_3$</td>
<td>$A_1 B_3 C_1$</td>
<td>$A_1 B_3 C_1$</td>
<td>$A_1 B_3 C_1$</td>
<td></td>
</tr>
</tbody>
</table>
The various results arrived from nine experiments using both Taguchi’s method and UBT has been compared with help of bar chart as shown in Figure 6.2 and Figure 6.3. The most influence parameters such as frictional condition, billet temperature were considered for the comparison. Effect of billet temperature and frictional condition with response has been shown in Figure 6.2 and Figure 6.3 respectively.

Figure 6.2 Billet temperature and response chart
Figure 6.3 Frictional condition and response chart

6.10 RESULTS AND DISCUSSIONS

Nine experiments were performed based on Taguchi’s design of experiment instead of full factorial design. Response value for each and every trial with specific combinations of levels of the process parameters was observed and recorded and is shown in Table 6.3. Based on average response graph method and their rankings of factors effect, it has been concluded that the optimum level of the process parameters for the current study are A₁ B₃ C₁. From the Table 6.5, it is well comprehended that the effect of friction plays a major role in entire deformation process by achieving rank 1 followed by an initial temperature of the billet and ram speed which influenced the response in considerable amount with rank 2 and 3 respectively. The same hypothesis was reinstated through analysis of variance (ANOVA) which
utilized the sum of squared deviation, mean square, error sum of squared deviations and correction factors to plot the results. ANOVA table shows the effect factor in the percentage of contribution as a measure of degree of significance.

Study and analysis of extrusion process is always a complex task due to the influence of various process parameters. The entire statistical study through the Taguchi’s design of experiment implements the result that the minimum ram speed ($A_1$), maximum billet temperature ($B_3$) and minimum friction condition ($C_1$) ensures the lesser extrusion force required to deform the given composite billet. Existence of higher frictional force between the die and billet region causes the outer layer of the billet to deform very slowly than the central zone. This unbalanced strain gradient during the deformation apparently increases the extrusion force required thereby registering the impact of frictional condition over the process. At elevated temperature, the molecular bonding between inter molecules becomes distorted thereby allowing faster deformation or higher strain gradient by consuming lesser extrusion force than at cold condition. This phenomenon clearly indicated in ANOVA table which shows the percentage of contribution of billet temperature in total process to the next significant level. Though the impact of ram speed influences the response to the minimal level, higher ram speed would impart higher strain rate followed by higher flow stress which naturally increases the load required to extrude.

In previous study Cunsheng Zhang et al (2012), they considered ram speed, die temperature, billet temperature, container temperature and billet diameters are the process parameters but they did not include the friction parameter. They have carried out number of numerical simulation experiments rather the actual experiments as per Taguch’s method and concluded that the ram speed was chief significant process parameters. But in
present study, the friction between the die and billet included as one of the parameter because experimentally friction is a most influencing parameters as far as extrusion process is concerned. Both study assures the fact that the temperature parameter as secondary role.

The predicted optimum response value from the recommended optimum process levels has been tested rigorously with double deck validation, one through the confirmation experiment and another through the pure analytical mode. The value of the optimized process levels has been substituted in the upper bound equation which was derived from various velocity fields and strain gradients. The final response value manipulated from the upper bound model does not deviate much with either predicted response value or the response value observed from the confirmation test. This comparison has been shown in Table 6.7.

6.11 CONCLUSIONS

The present study deals with the objective of finding the optimised process parameters to yield the optimised extrusion force during extrusion of SiC/Al composite. Ram speed, initial billet temperature and friction condition were considered as the key process parameters under the three levels of low, medium and high. The Taguchi’s design of experiment was used to obtain the optimum process parameters. Additionally, the experimental data were statistically processed through ANOVA. The various conclusion earned from this study are listed below

1. L9 orthogonal array was selected using Taguchi method of experimental design for three process parameters like ram speed, initial billet temperature and friction between the die billet region with three levels as low, medium and high.
2. Experimental response values were analyzed with average response method. Average response graph revealed that the optimum level of extrusion process parameters were ram speed of 3mm/min, initial billet temperature of 450° C and friction factor of 0.1 designated as A1 B3 C1.

3. Predicted average response value for the recommended optimum level of process parameters to extrude SiC/Al composite was 11.63 tons.

4. Analysis of variance (ANOVA) was also executed to determine the degree of significance of each parameter. ANOVA table revealed that the friction between the die billet regions has the highest significance followed by the billet temperature which has got second significance ranking. The effect of third parameter ram speed was felt as lesser in impact than the rest of other parameters.

5. Result of confirmation test conducted to extrude the SiC/Al composite under the recommended optimum level of parameters assures that the predicted response is very closer to the experimental one.

6. Additionally, as a measure of analytical validation, very famous UBT model was developed and the optimum extrusion force was manipulated by substituting the recommended level of process parameters in specially developed UBT equations.

7. It has been concluded that the optimum response predicted from the average response method does not deviate much with either the results of confirmation test or the response value calculated from the UBT analysis.