1 INTRODUCTION

Engineering applications require new types of materials due to the inability of the conventional materials to fulfill the requirements of the rapidly changing global market. In the past three decades, extensive research has been reported by numerous researchers with respect to mechanical property enhancement. Composite materials are mostly preferred over the conventional materials for the advanced engineering applications in the aerospace, automotive and marine industries due to their flexibility in tailoring the mechanical properties. Aluminium-matrix composites always have a firm position in the light-weight-material category due to their wide range of desirable characteristics such as low density, good wear and corrosion resistance and excellent mechanical properties over the other metal-matrix composites at reasonable costs.\(^1\)\(^.-\)\(^6\)

In the past, ceramic reinforcements were used to enhance the mechanical properties but this led to an increase in the weight and cost for the production of the composites. This shortcoming induces the quest for high-performance materials with a low density. The widely adopted method for producing low-cost composites enhance the use of inexpensive materials such as industrial and agro-wastes as secondary reinforcements.\(^7\)

Keywords: LM24 aluminium alloy, silicon carbide particles, coconut shell ash, surface roughness, Taguchi method, genetic algorithm

In any machining process, the vital part is determination of the optimum values for the process parameters to attain the highest desired quality at a low machining cost. This paper mainly focuses on the surface-roughness optimization in the turning of a hybrid aluminium-matrix (LM24-SiC\(_p\)-coconut shell ash) composite through the Taguchi method and a genetic algorithm. All composite samples for the study were prepared under the optimal squeeze-casting conditions and experimental trials were selected based on the L\(_9\) \((3)^4\) orthogonal array. The main response considered in this study related to the surface roughness, and machining parameters such as the cutting speed, feed rate, depth of cut and tool-nose radius were taken into consideration. The surface roughness was tested on the composites turned with a high-speed CNC lathe machine. From the experimental data, a regression model of the surface roughness was developed. The optimum machining conditions were obtained through the Taguchi method and a genetic algorithm and checked through confirmation experiments. In this study, it was concluded that the genetic algorithm used for determining the optimum machining conditions showed better results than the experimental outcome based on the orthogonal array and the optimum conditions obtained with the Taguchi method.

OPTIMIZATION OF MACHINING PARAMETERS IN TURNING OF HYBRID ALUMINIUM-MATRIX (LM24–SiC\(_p\)–COCONUT SHELL ASH) COMPOSITE

OPTIMIZACIJA PARAMETROV STRUŽENJA HIBRIDNEGA KOMPOZITA (LM24–SiC\(_p\)–PEPEL KOKOSOVIH LUPIN) Z MATRICO NA OSNOVI ALUMINIJA

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In the past, ceramic reinforcements were used to enhance the mechanical properties but this led to an increase in the weight and cost for the production of the composites. This shortcoming induces the quest for high-performance materials with a low density. The widely adopted method for producing low-cost composites enhance the use of inexpensive materials such as industrial and agro-wastes as secondary reinforcements.\(^7\)
The hybrid metal-matrix composites are the current research interest due to their favorable properties: high specific strength, toughness, impact strength, low sensitivity to temperature changes, etc. Usually, MMCs are fabricated through any of the following techniques: solid-state processing (powder metallurgy), liquid-state processing (stir casting, squeeze casting, compo casting) and infiltration technique. Among these methods, the stir-casting method is widely used because it is an easy and economical process compared with the other methods. Any fabrication method should ensure a few essential requirements regarding the casting such as a uniform distribution of the reinforcement particles within the matrix and better bonding between them. However, the major problems associated with the production of hybrid composites through the stir-casting method are a non-uniform dispersion, poor wettability and porosity, and these issues are minimized through the squeeze-casting method.8–12

The machining characteristics and qualities of composite parts are another major focus of research because they directly influence the functional and operational behavior. One of the major machining qualities of machined parts is their surface roughness, which plays a vital role in dynamic working conditions. Due to poor surface characteristics, fatigue-loaded components are highly prone to failure.13 The hard reinforcements (SiCp, B4Cp, TiCp and WCp) of the MMCs lead to a very complicated machining process due to a hard abrasive nature of the particles, which results in a high tool wear and poor surface finish.14–16 This problem is usually addressed by adding soft particles such as organic reinforcements like coconut shell ash or rice husk ash to hard ceramics particles.17–20

The process of determining the optimum machining parameter is usually achieved through selected methods known as the optimization techniques. A number of techniques have been adopted for optimizing the process parameters and they may be categorized as conventional tools (Taguchi method, response-surface method, grey-relationship analysis) and soft-computing tools (genetic algorithm, artificial neural network, particle-swarm optimization, fuzzy logics).21–23 Generally, regression models are developed by relating the process parameters to the desired output and are obtained with the conventional tools, whereas the soft-computing tools are adopted for obtaining the correct solution. Many researchers attempted to optimize the machining parameters to achieve certain response criteria such as the surface roughness, metal-removal rate and tool wear. The turning process is the basic machining process performed on most of the fundamental machine elements. The major influencing parameters, reported in the literature for the turning process, are the cutting speed, feed rate, depth of cut, workpiece variables, cutting-tool variables and cutting fluids.24

Turning parameters for Al-SiC-Gr hybrid metal-matrix composites were optimized using a grey-fuzzy algorithm. Researchers investigated the effects of the spindle speed, depth of cut, feed rate and mass fraction of SiCp on the tool-flank wear, and they further optimized the parameters using the response-surface methodology. The optimization of the machining parameters of the hybrid composite materials directly affects the production cost and life of the components.25–27

Agro-wastes such as rice husk, red mud, fly ash, coconut shell ash, corncob ash etc. can serve as promising reinforcements for aluminium-matrix composites. Coconut shell ash as one of the potential reinforcements for aluminium-matrix composites has not been studied adequately due to its machinability characteristics. The LM24 aluminium alloy, widely used to fabricate automotive parts like cylinder blocks, pistons, piston rings, camshafts etc., was used as the matrix material in this study. The purpose of the present study was to investigate the effects of high-speed turning parameters like the cutting speed, feed rate, depth of cut and tool-nose radius on the surface roughness of hybrid aluminium-metal-matrix composites. The Taguchi method and genetic algorithm were employed to predict the optimum cutting conditions for obtaining the optimum surface roughness on the turned hybrid composite components.

### 2 MATERIAL AND THEIR CHARACTERISTICS

#### 2.1 Materials used

The LM24 aluminium alloy was used as the matrix material and its chemical composition is shown in Table 1. SiCp with the average particles size of 150 μm and coconut-shell-ash particles (150 μm) were used as reinforcement materials. The fabricated hybrid metal-matrix composite had fixed shares of the reinforcements: 2.5 % of the coconut-shell-ash particles and 7.5 % of SiCp. However, the resulting percentage of the reinforcement particles decreased the mechanical properties.28

An LM24 aluminium alloy ingot was melted in an electric furnace capable of heating up to 1200 °C. The reinforcement particles including 2.5 % of coconut shell ash and 7.5 % of SiCp were preheated at 500 °C in a separate crucible furnace. The molten metal was degassed using hexachloroethane (C2Cl6) tablets to remove the entrapped gases and other impurities present.

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Ni</th>
<th>Zn</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>JIS (w%)</td>
<td>7.5–9.5</td>
<td>≤ 3</td>
<td>3.0–4.0</td>
<td>≤ 0.5</td>
<td>≤ 0.3</td>
<td>≤ 0.5</td>
<td>≤ 0.5</td>
<td>≤ 3</td>
<td>Balance</td>
</tr>
<tr>
<td>Ingot (w%)</td>
<td>7.848</td>
<td>0.785</td>
<td>3.433</td>
<td>0.14</td>
<td>0.15</td>
<td>0.025</td>
<td>0.049</td>
<td>1.334</td>
<td>86</td>
</tr>
</tbody>
</table>
The use of hexachloroethane (C₂Cl₆) tablets is probably the most common method of degassing in foundries. Even though it may be the oldest technique, C₂Cl₆ tablets normally provide for effective degassing in the case of a small amount of aluminium melt. The preheated reinforcement particles were gradually added into the pure molten metal while maintaining the constant stirring speed at 500 min⁻¹ for 10 min. The optimum squeeze-casting parametric conditions are given in Table 2.

Table 2: Squeeze casting process parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squeeze pressure</td>
<td>200 MPa</td>
</tr>
<tr>
<td>Pouring temperature</td>
<td>690 °C</td>
</tr>
<tr>
<td>Die preheating temperature</td>
<td>500 °C</td>
</tr>
<tr>
<td>Mold temperature</td>
<td>211 °C</td>
</tr>
<tr>
<td>Pressure duration</td>
<td>15 s</td>
</tr>
</tbody>
</table>

2.2 Microstructure analysis

The specimens were prepared for a microstructure analysis; they were polished and the surfaces were cleaned with Keller’s reagent. The casting samples obtained under the optimal squeeze-casting parametric conditions showed a homogeneous dispersion of the reinforcement particles in the matrix phase and good wettability. The quality of the castings was determined in terms of porosity, agglomeration of reinforcement, shrinkage defects etc., which were not visible in the micro-examination of the specimens, exposing the quality of the castings. A sample microstructure is shown in Figure 1.

2.3 High-speed turning

A high-speed turning operation was performed on the casting samples using a computer-numerical-control (CNC) turning center (ECOTURN-25) manufactured by Geedee weiler pvt ltd., Coimbatore, India, shown in Figure 2. The dimensions of the casting samples used for the turning operation were 25 mm in diameter and 100 mm in length. Tool holder PDJNL 1616H11 and uncoated carbide-insert 332-SF H13A cutting tool were used in the turning operation as shown in Figure 3. The surface roughness ($R_{avg}$) of the turned casting samples was measured with a surface-roughness tester (Mitutoyo SJ-210).

Table 3: Experimental parameters and their levels

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed (min⁻¹)</td>
<td>A</td>
<td>3250</td>
</tr>
<tr>
<td>Feed rate (mm rev⁻¹)</td>
<td>B</td>
<td>0.1</td>
</tr>
<tr>
<td>Depth of cut (mm)</td>
<td>C</td>
<td>0.1</td>
</tr>
<tr>
<td>Tool-nose radius (mm)</td>
<td>D</td>
<td>0.4</td>
</tr>
</tbody>
</table>
2.4 Design of experiments

The most influential parameters affecting the surface roughness, namely, the cutting speed (A), feed rate (B), depth of cut (C) and tool-nose radius (D) were considered and their levels are given in Table 3.

3 RESULTS AND DISCUSSION

3.1 Taguchi method

The Taguchi method is a powerful statistical tool, widely applied to improve the performance of machining processes with an extensive reduction of the time for conducting experiments; it also considerably reduces the machining cost and improves the product quality.27,28 The orthogonal array developed for the set of experiments and the importance of the signal-to-noise (S/N) ratio, which together determine how the average value (signal) of the input variables was attained, and the amount of variability (noise) were examined.

3.1.1 S/N ratio response

The surface roughness was treated as the output response and the category of quality characteristics was the smaller-the-better. The S/N ratio for this response was estimated using Equation (1) for each experimental condition and their values are given in Table 4.

\[
S/N (\text{dB}) = -10 \log_{10} \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{R_i^2} \right) \quad (1)
\]

where \(i = 1, 2, \ldots, n\) (here \(n = 4\)) and \(R_i\) is the response value for an experimental condition. The mean value (\(\bar{Y}\)) of the S/N ratios was also calculated using Equation (2) and the results are given in Table 5.

\[
\text{Mean, } \bar{Y} = \frac{1}{N} \left( \sum_{i=1}^{N} Y_j \right) \quad (2)
\]

where \(j = 1, 2, \ldots, N\) (here \(N = 9\)) and \(Y_j\) is the S/N ratio for the \(j^{th}\) parametric setting.

In order to find the optimum level of the process parameters, the average S/N ratio response was estimated for every level of the parameters and the corresponding details are given in Table 6. Based on the highest value of the S/N ratio, the optimum level for each parameter (A: 2nd level; B: 3rd level; C: 1st level; D: 2nd level) was noted.29–32 Thus, the optimum parametric setting \(A_2B_3C_1D_2\) (cutting speed: 3500 min\(^{-1}\), feed rate: 0.2 mm/rev, depth of cut: 0.1 mm and nose radius: 0.8 mm) was obtained for the output response.

3.2 Genetic algorithm

Genetic algorithm (GA) is a soft-computing tool for solving both constrained and unconstrained optimization problems based on boundary conditions. The optimum machining conditions were created using the GA tool in the MATLAB software. GA is a faster and more efficient tool than the other soft-computing tools.30 The GA optimization tool is based on machining-performance-prediction models based on experimental results and numerical methods. The GA tool provided the optimum machining conditions in a short time.

3.2.1 Mathematical model

The empirical relationship between the surface roughness (\(R_{\text{avg}}\)) and turning of the LM24 aluminium
Alloy reinforced with SiCₚ and coconut-shell-ash particles was a function of the machining parameters such as the cutting speed (A), feed rate (B), depth of cut (C) and tool-nose radius (D) that can be indicated as:

\[ R_{avg} = f(A, B, C, D) \] (3)

The relationship between the control parameters and their effects on the average surface roughness \( R_{avg} \) was modeled using a second-order polynomial regression analysis with the help of statistical software MINITAB 14.

\[ R_{avg} = 6.3500 - 4.03333 A - 0.43333 B - 0.55000 C - 0.56667 D + 1.03333 A^2 + 0.03333 B^2 + 0.18333 C^2 + 0.13333 D^2 \] (4)

For this regression model, it was found that \( r^2 = 0.99 \) where \( r \) is the coefficient of correlation. The value of \( r^2 \) indicates the accuracy of the model representing the process. As \( r^2 \) is nearing unity, this model can be taken as an objective function for the application of the genetic algorithm.

3.2.2 Inputs into the GA

The genetic-algorithm solver available in the MATLAB software was used to find the optimum parametric settings for the minimization of the average surface roughness of the squeeze castings \( R_{avg} \) from this study. The regression model given in Equation (3) was used as the fitness function (objective function). The following values of the genetic parameters were taken as the inputs into the MATLAB solver.

- Population type: double vector
- Number of variables: 04
- Bounds (lower): [3250 0.1 0.1 0.4]
- Bounds (upper): [3750 0.2 0.3 1.2]
- Selection function: stochastic
- Crossover fraction: 0.8
- Mutation rate: 0.03
- Migration: forward
- Total number of iterations: 53
- Level of display: iterative

It was observed that the fitness value decreased through generations as shown in Figure 5 and the optimized average surface roughness (0.399 μm) was obtained in the 53rd generation. The optimum parametric settings of the last generation are given in Table 5.

### Table 5: Optimum parametric settings

<table>
<thead>
<tr>
<th>Control parameter</th>
<th>Coded condition</th>
<th>Uncoded condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed</td>
<td>2</td>
<td>3500 min⁻¹</td>
</tr>
<tr>
<td>Feed rate</td>
<td>3</td>
<td>0.2 mm rev⁻¹</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>1.5</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>Tool-nose radius</td>
<td>2.126</td>
<td>0.8 mm</td>
</tr>
</tbody>
</table>

3.3 Confirmation experiments

Confirmation experiments were conducted for the optimum parametric conditions suggested by the Taguchi method and genetic algorithm. The average surface-roughness values (predicted and tested) are given in Table 6. It is evident that there is good agreement between the predicted average surface roughness and actual surface roughness since the error is less than 4 %. The optimum settings for the cutting speed (3500 min⁻¹) and feed rate (0.2 mm rev⁻¹) were found to be same in the Taguchi method and genetic algorithm. According to the percentage-contribution analysis, the effects of depth of cut and nose radius on the surface roughness are minimum compared to the other machining parameters. The confirmation experiments proved that the genetic algorithm gives better results than the Taguchi method with respect to the surface quality and also, indirectly, with respect to energy savings and production time.

### Table 6: Confirmation-test results

<table>
<thead>
<tr>
<th>S. no.</th>
<th>Optimization technique</th>
<th>Average surface roughness, ( R_a ) (μm)</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Predicted</td>
<td>Tested</td>
</tr>
<tr>
<td>1</td>
<td>Taguchi method</td>
<td>0.467</td>
<td>0.450</td>
</tr>
<tr>
<td>2</td>
<td>Genetic algorithm</td>
<td>0.399</td>
<td>0.386</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS

The conclusions drawn were based on the surface-roughness tests conducted on a hybrid aluminium-metal-matrix composite during a turning operation. From the percentage-contribution analysis, it was noted that the cutting speed (51.3 %) and feed rate (23.4 %) were the most important parameters influencing the surface roughness, while the depth of cut (15.4 %) and tool-nose radius (9.8 %) were the least important parameters for the surface roughness. It is evident that there is good agreement between the predicted average surface roughness and actual average surface roughness since the error is less than 4 %. The recommended levels for the turning parameters of the CNC lathe, minimizing the surface roughness, were the cutting speed at level 2 (3500 min⁻¹), feed rate at level 3 (0.2 mm rev⁻¹), depth of...
cut at level 1 (0.1 mm) and tool-nose radius at level 2 (0.8 mm). The optimum settings of the high-speed turning process parameters regarding the optimum surface roughness can be used wherever aluminium-metal-matrix composites require a high degree of surface finish. Confirmation experiments proved that the genetic algorithm gives better results than the Taguchi method with respect to the surface quality and also, indirectly, with respect to energy savings and production time.

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