Desirability analysis and genetic algorithm approaches to optimize single and multi response characteristics in machining Al-SiCp MMC

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Abstract

Metal matrix composites (MMCs) having aluminum (Al) alloy in the matrix phase and silicon carbide (SiC) particulates/particles in reinforcement phase have been found in common use for making components in automotive and aircraft industries. Number of conventional (i.e., turning, milling, grinding, and drilling) and non-conventional machining processes are employed for manufacturing MMC components. In this work, an experimental investigation was carried out in turning Al-SiCp MMC (with less percentage of SiC particulates: 5% by weight) using polycrystalline diamond (PCD) insert. ‘Surface roughness (Ra)’ as job quality and ‘material removal rate (MRR)’ as job productivity are considered as two response parameters. A mathematical predictive models based on response surface methodology (RSM) have been developed. Feed rate is found most influencing parameter for obtaining Ra and MRR. The optimum process parameters are obtained for optimizing single and multiple response characteristics employing two different approaches of optimization: (i) statistical and mathematical approach based on desirability analysis (DA) and (ii) soft computing based genetic algorithm (GA). The results are compared. Optimal Pareto fronts are obtained using GA provides suitable combination of process parameters providing higher material removal rate at desired surface roughness.

Keywords: Turning, Metal matrix composites, Desirability analysis, Genetic algorithm.

1 Introduction

Particulate reinforced metal matrix composites (PMMCs) are finding more application due to their attractive properties such as high strength to weight ratio, stiffness, increased wear resistance over unreinforced alloys and corrosion resistance. Silicon carbide particle (SiCp) reinforced aluminium based metal matrix composites (MMCs) are among the most commonly used PMMCs. It is due to its low densities to the aluminium matrix for better dispersion, high mechanical properties, high melting point, hardness, wear resistance, higher service temperature and thermal conductivity by Jayakumar (2012). The favourable properties of Al-SiCp MMCs used to replace conventional materials in many applications especially in the aerospace, electronics, automobile, military and recreational industries.

Number of researchers have studied the effect of different machining parameters viz., spindle speed (N), cutting speed (v), feed rate (f), depth of cut (d) and work material characteristics on surface roughness (Ra) material removal rate (MRR), tool wear (VB), tool life etc. Tamang et al. (2013) reviewed the application of various computational methods in modeling and optimization of various composite machining processes. Davim (2003) has applied orthogonal array and analysis of variance (ANOVA) to investigate the cutting characteristics of MMC (A356/20/SiCp-T6) in turning with PCD cutting tool. He found that cutting velocity has the highest physical and statistical influence on the tool wear and cutting power. Feed has highest physical and statistical influence in surface roughness. Palanikumar et al. (2006) conducted machining experiments on glass fibre reinforced plastics (GFRP) composite using PCD cutting tool. They attempted to obtain machining parameters for minimum surface roughness employing Taguchi method and RSM. Antonio et al. (2008) used artificial neural network (ANN) modeling and GA optimization methodology for optimizing orthogonal turning process of PEEK composites to obtain optimum cutting conditions. Rajasekaran et al. (2011) also conducted machining experiments on CFRP composites using cubic boron nitride (CBN) cutting tool. They applied fuzzy logic (FL) technique for modeling of surface roughness and found that feed is an influencing parameter. The predictive capability of FL found better. Arokiadass et al. (2011) developed a predictive model surface roughness for end milling of LM25Al/SiCp MMC by using RSM technique. They considered cutter feed rate, spindle speed, depth of cut and SiC percentage of composite work material as model input parameters and observed that feed rate is most dominant parameter in deciding the surface roughness. Devarasiddappa et al. 2012 employed ANN for developing surface roughness
model in end milling of Al-SiCp MMC using carbide cutter. They found that the model predicts with average prediction error 0.31% when compared with experimental data. The surface roughness is mainly affected by feed rate and spindle speed while depth of cut has less influence on it. They also compared the performance of ANN model with RSM and found that ANN outperforms. Rajmohan and Palanikumar (2013) have used D optimal design using RSM to predict surface roughness, thrust force, burr height and tool wear in drilling of hybrid metal matrix composites using carbide, coated carbide and polycrystalline diamond drills. They found that the predicted value is close with the experimental results. Also, Arokiadass et. al., (2012) examined the tool flank wear (VB) during machining LM25 Al/SiCp composite using CNC vertical milling and carbide tool of 12 mm diameter with 4 flutes is used. They had taken spindle speed, feed rate, depth of cut and SiCp percentage as input parameters and output parameter is tool wear. Response surface methodology (RSM) was applied for modeling and the predictive capability of the developed model is within 5% error.

From the detailed literature survey considering the huge applicability of Al-SiCp MMC, it has been aimed for the experimental investigation, modeling and optimization on MMC turning process. In the present work, turning experiments were conducted on Al-SiCp MMC specimen using PCD tool. Taguchi L$_{27}$ orthogonal array of experimentation was employed. RSM mathematical (full quadratic) model have been developed to predict surface roughness and material removal rate. The cutting conditions are optimized in the developed model for both single as well as multi objectives. Two optimization techniques viz., desirability analysis and soft computing based genetic algorithm have been used and the results are compared.

2 Experimental works

In the present study, turning of Al-SiCp MMC with minimum amount of SiC percentage as was carried out using poly crystalline diamond (PCD) tool. The in-house fabricated A356 with SiC particulate (5% weight) metal matrix composites was used. The diameter of the work material was 46 mm and machining length was 125 mm. Turing was performed by considering three cutting parameters: spindle speed (N), feed rate (f) and depth of cut (d) and the machining responses were surface roughness ($R_a$) and material removal rate (MRR). Experimental design based on full factorial design experiments were carried out. Table 1 shows the cutting parameters and their levels.
3 Mathematical model based on RSM

The development of predictive models relates the machining responses and their influencing factors. The developed model also facilitates to optimize the process parameters. Response surface methodology (RSM) is one of the commonly used technique for modeling and analysis of problems in which the response is influenced by number of variables. RSM is the combination of mathematical and statistical technique in which the mathematical model is developed by regression method using experimental data. The concept of a response surface involves relating the response variables and several independent variables.

In this work, two RSM models viz., surface roughness ($R_a$) and material removal rate (MRR) model are developed. The machining parameters were chosen as independent input variables while desired responses are assumed to be affected by the cutting parameters. The relationship between the cutting parameters and the machining response is given as

$$ Y = \phi(N, f, d). \quad (2) $$

where $Y$ is the desired response and $\phi$ is response function. The approximation of the response is proposed by using nonlinear (quadratic) mathematical model and the interaction effects of the parameters are studied. The RSM based second order mathematical model is given by

$$ Y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_6 + b_7 x_7 + b_8 x_8 \quad (3) $$

or

$$ Y = b_0 + \sum_{i=1}^{n} b_{i} x_{i} + \sum_{i=1}^{n} b_{j i} x_{i}^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} b_{i j} x_{i} x_{j}. \quad (4) $$

where $b_{0}$ is constant or free term, $b_{i}$, $b_{j i}$, and $b_{i j}$ represent the coefficients of linear, square, and cross product (i.e., interaction) terms. Eq (4) can be written as to build the relationship between turning parameters and responses (i.e., surface roughness and material removal rate) as

$$ R_a = b_0 + b_1 N + b_2 f + b_3 d + b_4 N^2 + b_5 f^2 \quad + b_6 d^2 + b_7 N f + b_8 N d + b_9 f d, \quad (5) $$

and

$$ MRR = b_0 + b_1 N + b_2 f + b_3 d + b_4 N^2 + b_5 f^2 \quad + b_6 d^2 + b_7 N f + b_8 N d + b_9 f d. \quad (6) $$

The quadratic model developed from the above functional relationship is found better and the obtained model equation is given as

$$ R_a = 0.3419 + 0.00033 N + 8.636 f - 0.705 d - 1.616 X 10^{-7} N^2 + 2.4793 f^2 + 0.2044 d^2 - 0.00269 Nf + 0.000313 Nd + 4.571 d f \quad (7) $$

$$ MRR = 19.97 - 0.02419 N - 77.85 f - 26.61 d - 4.7534 X 10^{-4} N^2 + 0.0612 f^2 - 0.00889 d^2 - 0.094 Nf + 0.032 Nd + 103.75 d f \quad (8) $$

4 Optimization of turning parameters

After developing the regression model the process parameters are optimized using two techniques viz., (i) a numerical optimization technique using desirability function and (ii) soft computing technique based on genetic algorithm. Single multiple as well as multiple objective optimization are performed and the results are compared.

4.1 Single objective optimization of $R_a$ and MRR

In the first method the objective of optimization is to find the best settings that minimize/maximize the particular response. Desirability value ($D$) ranges from 0 to 1 and its value increases as the “desirability” of the corresponding response optimized. Fig.1 (a) shows the optimized values of the machining parameters for achieving minimum surface roughness in turning Al-SiCp MMC using PCD tool. The coded values for the optimal solution are found as $(N, f, d)$: (1200 rpm, 0.111 mm/rev, 0.50 mm). The minimum $R_a$ obtained is 1.24 $\mu$m and experimental minimum is 1.25 $\mu$m. The value of composite desirability ($D$) obtained is 1. Fig.1 (b) shows the desirability graph for obtaining maximum $MRR$. The optimal solution obtained is 1200 rpm, 0.44 mm/rev and 0.995 mm. The predicted $MRR$ is 63.92
cm³/min and it is same as experimental maximum. The value of composite desirability is 0.9988.

The process parameters obtained for one objective does not provide good result for other objective. Therefore, simultaneous optimization of more than one objective becomes essential. In this work the multi objective optimization was performed for obtaining the optimal parameters so as to minimize $R_a$ and maximize $MRR$ in turning Al-SiCp MMC. Fig.2 shows the result of desirability analysis for multi objective optimization considering equal weightage of the objectives. The optimum process parameters are spindle speed ($N$) as 1200 rpm, feed rate ($f$) as 0.250 mm/rev, and depth of cut ($d$) as 1.0 mm. The surface roughness obtained is 2.96 $\mu$m and material removal rate is 37.79 cm³/min. The composite desirability is 0.5924 which is lower than that obtained by single objective optimization. This is due to compromise between the objectives.

The multi objective optimization is also solved by GA. The conflicting objective functions of minimizing $R_a$ and maximizing $MRR$ have been solved. The optimal Pareto fronts are obtained and is shown in Fig.3. It is used for obtaining the possible optimal solutions which can be selected based on the requirements. The optimum process parameters are spindle speed ($N$) as 1186 rpm, feed rate ($f$) as 0.246 mm/rev and depth of cut ($d$) as 0.97 mm.
5 Results and discussions

The response surface obtained in modeling of surface roughness in turning Al-SiCp MMC is presented in Fig. 4. The effect of spindle speed at different feed rates with the variation of surface roughness is shown in Fig. 4 (a). The increase in feed increases the value of $R_a$. It is possibly due to higher rate of tool feed worsen the surface generated. The increasing effect of spindle speed at $f=0.4$ mm/rev slightly reduces the $R_a$. This is because at lower cutting load with higher spindle speed smoothen the surface roughness. The increase in surface roughness is noticed with increase in depth of cut (Fig. 4 (b)). This is due to increases tool work piece contact length.

Fig. 5 (a and b) shows the effect of different process parameters on $MRR$. The material removal rate linearly increases with increase in feed rate, depth of cut and spindle speed. Maximum $MRR$ is obtained at higher levels of process parameters. The increased depth of cut and feed rate enhances chip cross section and thus volume rate of material removal.

In optimizing parameter for single objective case, the result obtained by both desirability analysis and genetic algorithm are very closer. For multi objective optimization i.e., simultaneously minimizing $R_a$ and maximizing $MRR$, the optimization by desirability analysis found better than genetic algorithm. Desirability analysis provides minimum $R_a$ of 2.96 $\mu m$ and maximum $MRR$ of 37.91 cm$^3$/min for the combination of $(N, f, d): 1200$ rpm, 0.25 mm/rev, 0.99 mm). However, optimal Pareto fronts obtained by genetic algorithm provide suitable combination of process parameters for higher material removal rate for desired surface roughness to be obtained. Table 3 shows the comparison of results by two optimization techniques for single and multi objective cases.

### Table 3. Comparison of optimization result

<table>
<thead>
<tr>
<th>Method</th>
<th>Optimization objective</th>
<th>Optimization technique</th>
<th>Optimal parameter combination</th>
<th>Optimal responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single objective optimization</td>
<td>Minimize $R_a$</td>
<td>Desirability analysis</td>
<td>$N=1156$, $f=0.12$, $d=1.32$</td>
<td>$R_a=2.96$ $\mu m$, $MRR=37.91$ cm$^3$/min</td>
</tr>
<tr>
<td>Multiobjective optimization</td>
<td>Minimize $R_a$, Maximize $MRR$</td>
<td>Genetic algorithm</td>
<td>$N=1156$, $f=0.12$, $d=1.32$</td>
<td>$R_a=2.96$ $\mu m$, $MRR=37.91$ cm$^3$/min</td>
</tr>
<tr>
<td>Minimize $R_a$</td>
<td>Desirability analysis</td>
<td>$N=1200$, $f=0.11$, $d=0.99$</td>
<td>$R_a=2.96$ $\mu m$</td>
<td></td>
</tr>
<tr>
<td>Maximize $MRR$</td>
<td>Genetic algorithm</td>
<td>$N=1200$, $f=0.11$, $d=0.99$</td>
<td>$MRR=37.91$ cm$^3$/min</td>
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6 Conclusions

The turning experiments on machining Al-SiCp (5%) MMC were successfully conducted. The RSM predictive models for surface roughness and material removal rate have been developed. The process parameters are optimized using desirability analysis (a numerical technique) and genetic algorithm (a soft computing technique). Optimization was performed for single and multi objectives for minimizing $R_a$ and maximizing $MRR$. The comparisons of the results show closer prediction. Based on experimental study and analysis of the result the following conclusions can be obtained.

- The quadratic model developed using RSM is reasonably accurate and can be used for prediction.
of surface roughness and material removal rate within the limits of the parameters investigated.

- Feed ($f$) is found to be most significant effect over surface roughness and material removal rate followed by depth of cut ($d$) and spindle speed ($N$).

- Maximum MRR is obtained at higher level of process parameters that increases volume rate of material removal per unit time. However the higher tool feed rate produces poor surface roughness. The minimum surface roughness (for better job quality) is obtained at moderate speed, low feed and low depth of cut.

- A compromise among the objectives for obtaining good surface finish and better MRR is moderate selection of feed rate. For multi objective optimization by desirability analysis found better than genetic algorithm. Desirability analysis provides minimum $R_a$ of 2.96 $\mu$m and maximum MRR of 37.91 cm$^3$/min for the combination of ($N$, $f$, $d$: 1200 rpm, 0.25 mm/rev, 0.99 mm).

- The optimal Pareto fronts obtained by GA, based on which optimal process parameter could be selected for industrial requirements. For the desired value of surface roughness, suitable combination of process parameters providing higher material removal rate could be selected.

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References


