Development of empirical relationship for surface roughness during the machining of metal matrix composite

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Abstract. The surface roughness is an important parameter that affects the mechanical properties of machined parts. In present work empirical relationship between the surface roughness and machining conditions during the end milling of Al/Al₂O₃/Gr metal matrix composites using response surface methodology based on face centered design. The effect of machining conditions on surface roughness is also investigated. The feed, cutting speed and % wt Al₂O₃/Gr seems to have significant effect on the surface roughness

Keywords. End milling; MMC; Al356, Alumina oxide; Graphite, FCD, RSM

1. Introduction

Now a day, metal matrix composites (MMCs) are widely used engineering material in several applications likes aerospace, automobile, defense, marine, sports and recreation industries [1]. Metal matrix composites (MMCs) materials offer such modified property combinations [2, 3]. In manufacturing industries, various machining processes are used for removing of extra material from workpiece to obtain finished part. Among various machining operations, the turning is widely used metal removal process [4]. Now days, due to global competitiveness, manufacturing industries are give attention towards the surface finish of products. The quality of turned surface is significantly affected by the cutting conditions, tool material, workpiece material and vibration during machining [5]. To obtain the required surface finish during turning, the turning parameters should be selected properly [6]. Therefore, it can be accomplished using mathematical modeling using design of experiments. Many researchers have examined the impact of % wt of reinforcement in aluminium alloys on surface roughness (SR) and mechanical properties of MMCs. Quan and Bangyan investigated the impact of SiC particles size and % wt of SiC reinforcement on tool wear rate in turning of SiC particle based aluminium matrix composites. It has been observed that heavier cutting tools require with large size SiC reinforcement [7]. Manna and Bhattacharayya examined the impact of basic turning parameters, inclination angle of tool holder, types of tool cutting time and machining length on tool wear and surface finish in turning of Al/SiC/MMC. The fixed rhombic tooling and fixed circular tooling have been found capable for high speed machining with small depth of cut [8]. Manna and Bhattacharayya examined the impact of turning variables on feed force and main cutting...
force in turning of LM 6 Mg 15 SiCp using uncoated tungsten carbide fixed rhombic tools. The result reveals that the main cutting force and feed force have been found maximum at low speed and decreases as speed increase [9]. Kılıçkap et al. examined the impact of machining conditions on surface quality and tool wear in machining AlSiCp MMC. Two types of K10 cutting inserts have been used for the analysis. The minimum surface roughness has been attained at higher speed and lower feed [10]. Kurt et al. examined the impact of coatings, point angle, cutting conditions on the hole quality in drilling of Al 2024 alloy. The minimum surface roughness, radial deviation of produced hole and maximum roundness are attained at minimum speed and feed [11]. Muthukrishnan and Davim used design of experiment (DOE) and artificial neural network (ANN) approaches for the optimization of cutting conditions for minimum surface roughness during the machining of Al/SiC based MMC using PCD inserts. It has been revealed that feed rate has highest impact on surface finish. A comparison has also been made between the prediction results obtain using design of experiment and ANN. It has been found that ANN predicts the surface roughness with high accuracy as compare to DOE technique [12]. Przestacki compared the laser-assisted machining with conventional machining during the turning of A359/20SiCp material using cubic boron nitride (CBN) and sintered carbide inserts. The effect of laser's beam in laser assisted turning on surfaces roughness, tool wear and cutting force has also been examined. It has been found that the laser assisted machining process shows a considerable improvement in machinability of metal matrix composite through the lower tool wear [13]. Tsao used Taguchi approach using grey relation analysis to optimize the cutting variables for desire multiple performance characteristics during the milling of A6061P-T651 aluminum alloy. The results indicated that the most vital factor affecting the wear is diameter of cutter and the feed rate has been identified as main influencing parameter for surface roughness [14]. Ramanujam et al. applied Taguchi methodology with grey relation approach to optimize multiple performance characteristics in turning MMC. The depth of cut, feed and speed are taken as machining parameters whereas specific power and surface finish as response. The results indicate that grey relation analysis with Taguchi methodology has been found effective tool for the simultaneous optimization of specific power and surface finish [15]. Rajmohan and Palanikumar used RSM to optimize the drilling parameters for burr height, thrust force and surface roughness in machining of Al-SiC-mica based MMC. The results indicated that develop models have high prediction efficiency [16]. Bhardwaj et al. studied the effect of cutting variables on surface roughness in turning of EN 353 steel. An empirical relationship is also established using RSM between cutting conditions and surface roughness. The close values are obtained for predicted and experimental values with quadratic model as compared to those values which are predicted using first order model [17]. Bhardwaj et al. formulated empirical relationship using Box-Cox technique between the cutting conditions and surface roughness based RSM during the end milling of EN 353 steel. The error in prediction of surface roughness is found less with Box-Cox based empirical model [18]. Suresh et al. (2014) used grey-fuzzy algorithm to optimize the cutting variables for multi responses in turning of Al/SiC/Gr based composite. The speed, feed and % SiC-Gr particles are used as input variables whereas surface finish, tool wear and metal removal rate (MRR) as performance function. The composite with 10% SiC-Gr shows excellent machinability as compared to other Al/SiC/Gr based composites [19]. Karabulut optimized the milling variables for minimum surface roughness and minimum cutting forces using L_{18} 2^1 x 3^2 mixed Taguchi methodology during the milling of AA7039/Al2O3 metal matrix composite. The material structure has been found the main significant factor for surface finish whereas feed rate has been found most significant factor for cutting force [20]. Kishore et al. fabricated Al6061-TiC composite with 4 wt% TiC by the reaction of halide salt K2TiF6 and C with the molten aluminium. Also, an effort is carried out to examine the effect of cutting conditions on surface finish and cutting force in the turning of MMC using Taguchi methodology. The contribution of depth of cut has been found more on cutting force while feed is found most influencing variable that affect the surface finish followed by cutting speed [21]. Boswell et al. examined the impact of machining condition on the surface finish and MRR during the end milling of aluminium/boron carbide particles based MMC. The minimum surface roughness and maximum MRR are achieved at high feed and high speed[22].
Karabulut et al. examined the impact of machining conditions on surface finish in milling of aluminium 7039-based SiC and B4Cp MMCs with uncoated carbide tool using Taguchi methodology and ANN. The speed and feed are found most significant parameters that affect the surface finish whereas depth of cut has been found insignificant parameter. The prediction accuracy of ANN model has been found excellent as compared to regression model [23].

The review of published literature presented above indicates that lot of research work is done to optimize the machining conditions for desirable surface finish during the machining of different MMCs. Most of the researchers used Taguchi methodology for optimization. Very few efforts are made to develop quadratic relationship between the process conditions and surface roughness. The Al/Al₂O₃/Gr metal matrix composite is substitute material in automotive and aerospace applications. Therefore, the research on this MMC is required to be more strengthened. In this research, RSM based on FCD is employed to develop quadratic relationship between the machining conditions (feed rate, cutting speed and % of Al₂O₃/Gr particles) and surface roughness during the end milling of Al/Al₂O₃/Gr metal matrix composite. Also, an attempt is made to examine the impact of machining condition on surface roughness.

2. Selection of process conditions and levels
In this research, cutting speed, percentage of Al₂O₃/Gr in MMC and feed rate are taken as process conditions, while surface roughness as a response. Among the three process conditions, cutting speed and feed rate are the basic process parameter. These parameters can be conveniently controlled by the operator at the time of machining operation. The range of machining conditions has been selected according to range specified by tool manufacturer. The levels of machining parameters have been considered according to face centered design (FCD). Table 1 shows the process parameters and process parameters levels according to FCD. The Table 2 shows the experimentation plan. The table contains total 20 experimental combinations of cutting speed, feed rate and % weight of Al₂O₃/Gr in MMC, in which a set of 8 experiments are factorial point, 6 star point and 6 center point.

| Machining Conditions                | Levels                  |
|-------------------------------------|-------------------------|
| Feed (mm/tooth)                     | 0.1, 0.15, 0.2          |
| Speed (m/min)                       | 100, 150, 200           |
| Al₂O₃/Gr particle % wt              | 5, 10, 15               |

| Table 1. Process variables and levels |
|---------------------------------------|

| Std | A: Feed | B: Cutting speed | C: % wt Al₂O₃/Gr | Surface roughness (microns) |
|-----|---------|------------------|------------------|-----------------------------|
| 1   | 0.1     | 100              | 5                | 4.365                       |
| 2   | 0.2     | 100              | 5                | 6.293                       |
| 3   | 0.1     | 200              | 5                | 2.357                       |
| 4   | 0.2     | 200              | 5                | 3.457                       |
| 5   | 0.1     | 100              | 15               | 3.126                       |
| 6   | 0.2     | 100              | 15               | 4.273                       |
| 7   | 0.1     | 200              | 15               | 0.954                       |
| 8   | 0.2     | 200              | 15               | 1.568                       |
| 9   | 0.1     | 150              | 10               | 2.872                       |
### 3. Experimentation and measurement

#### 3.1. Workpiece

In the present research MMCs have been fabricated in the form of flat plate of 100mm X 20mm X 50 mm by means of stir casting technique at optimal speed and optimum temperature which ensure homogeneous mixture of reinforcement materials in matrix material. For the fabrication of composite, the Aluminium alloy Al 356 has been selected as a matrix material while aluminum oxide and Graphite particles in equal weight fraction of 5%, 10% , 15% is used as a reinforcement materials. The table 3 shows the chemical composition of Aluminium alloy Al 356 as obtained by spectral analysis.

#### 3.2. Tool and equipments

In the present research, all the end milling trials, as shown in table 2, have been carried out on CNC machine using Physical Vapor Deposition (PVD) cutting inserts. The detail of experimental setup is presented in table 3. A portable surface roughness tester is engaged to record the centerline average surface roughness values ($R_a$) of machined specimens. For each finished specimen, the surface roughness value is recorded at three different positions along the tool movement direction. Then, the mean value of all three recorded centerline average surface roughness is taken as final value for that particular trial [4]. The measured value of surface roughness is represented in table 2.

#### Table 3. Experimental details

| Test specimens                  | Al 356/5Al₂O₃/5Gr, Al 356/10Al₂O₃/10Gr, Al 356/15Al₂O₃/15Gr, in the form of flat plate of dimension 100mm X 20 mm X 50 mm. |
|---------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| Chemical composition of Al 356 (%) weight | Si 7.21%, Fe 0.24%, Mg 0.41% Mn 0.012%, Zn 0.023%, Cu 0.014%, Ti 0.187%, Cr 0.009%, Ni 0.012%, Sr 0.017%, B 0.007%, Rest is Al |
| CNC Machine                     | LEADWELL V 40 CNC machine.                                                                                                                                                     |
| Surface roughness tester        | SE 1200 surf coder                                                                                                                                                            |
| Cutting inserts                 | PVD coated insert AXMT0903R05 EML                                                                                                                                               |
| End mill                        | Two-flute end mill of 18 mm diameter                                                                                                                                              |

### 4. Result and analysis

To achieve the aim of present research, the measurement results as obtained from the experiments (table 2) according to design matrix, have been fed into the software (Design Expert 8.0.4.7).
4.1 Development of surface roughness prediction empirical relationship
ANOVA is employed to test the adequacy of developed model. It depends on, (1) assumption of normality of population, (2) assumption of constant variance, and (3) assumption of independence.

The normality plot for residuals is used for testing the population normality, i.e. first assumption of ANOVA. If the distribution of residuals is normal, most of the residuals must fall on the straight line. It is clear from the figure 1 that mostly residuals are laying on the straight line i.e. the residuals for surface roughness are normally distributed.

To validate the second assumption of ANOVA i.e. assumption of constant variance, the residuals versus predicted plot should not follow any recognizable patterns. The figure 2 indicate that residuals for surface roughness following unusual structure i.e. data is following second assumption of ANOVA. Figure 3 shows the run order vs. residual plot. It is used for testing the third assumption of ANOVA i.e. assumption of independence. A positive or negative correlation represents the violation of third assumption. The figure 3 indicates that data does not show any definite pattern that indicated that data is following third assumption of ANOVA.

Figure 1. Normality plot of residuals
Figure 2. Residuals v/s predicted plot

Figure 3. Residuals vs run order for surface roughness

Table 4. Reduce ANOVA table for surface roughness model

| Source    | Sum of squares | df | Mean square | F – Value | p-value |
|-----------|----------------|----|-------------|-----------|---------|
| Model     | 25.476         | 7  | 3.639       | 191.164   | 0.0001  |
In the present research, ANOVA is conducted at the confidence level of 95%. The ANOVA for reduce surface roughness prediction model after forward elimination method is represented in table 4.

As shown in table, “Prob.>F” for model is 0.0001, which is lower than 0.05, which shows that the developed empirical model is significant, that implies the terms in the model affects the surface roughness. The “Prob. > F” for speed, feed rate, % Al2O3-Gr, interaction term of cutting speed & feed, feed rate & % Al2O3-Gr; and quadratic term of feed rate, cutting speed are less than 0.05, indicating that these are significant model terms.

The “Prob.> F” for lack of fit is 0.5815, that’s mean lack of fit is insignificant, which is required. The R² and adjusted R² values are 0.991 and 0.986 respectively, which is almost close to each other. The final surface roughness empirical model is shown in equation (1)

\[
R_a = 3.931 + 0.008 \times \text{Cutting speed} + 27.718 \times \text{Feed rate} - 0.34 \times \% \text{Al2O3 - Gr particles} - 0.068 \times \text{Cutting speed} \times \text{Feed rate} - 0.633 \times \text{Feed rate} \times \% \text{Al2O3 - Gr particles} - 0.000075 \times \text{Cutting speed}^2 + 0.0135 \times (\% \text{Al2O3 - Gr particles})^2
\]  

(1)

4.2 Impact of machining variables on surface roughness

The figure 4 shows 3D graph for the surface roughness at constant 10% Al2O3-Gr. As shown in the figure, the surface roughness linearly increases with increase in feed because rapid motion takes place between the tool and specimen which deteriorate the surface of specimen. Also, surface roughness decreases with increase in speed because at high speed, high temperature generated which soften the workpiece and improve the cutting performance, hence reduce surface roughness [14].

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| Variable                   | Coefficient | Standard Error | Prob.>F |
|----------------------------|-------------|----------------|---------|
| A-feed rate                | 3.123       | 1              | 3.123   |
| B-cutting speed            | 14.755      | 1              | 14.755  |
| C-Al2O3/Gr particles       | 6.801       | 1              | 6.801   |
| AB                         | 0.232       | 1              | 0.232   |
| AC                         | 0.201       | 1              | 0.201   |
| B^2                        | 0.113       | 1              | 0.113   |
| C^2                        | 0.364       | 1              | 0.364   |
| Residual                   | 0.228       | 12             | 0.019   |
| Lack of Fit                | 0.126       | 7              | 0.018   |
| Pure Error                 | 0.103       | 5              | 0.021   |
| Cor Total                  | 25.704      | 19             |         |
| Std. Dev.                  | 0.138       |                | R²      |
| Mean                       | 3.213       |                | Adj R²  |
| C.V. %                     | 4.294       |                | Pred R² |
| PRESS                      | 0.522       |                | Adeq. Precision |

In the present research, ANOVA is conducted at the confidence level of 95%. The ANOVA for reduce surface roughness prediction model after forward elimination method is represented in table 4.
Figure 4. 3D graph of surface roughness in terms of feed rate and cutting speed

Figure 5. 3D graph of surface roughness in terms of feed rate and % wt Al₂O₃-Gr particles

The figure 5 indicates 3D surface roughness plot with feed and % wt Al₂O₃-Gr particles. The figure explains that surface roughness decreases with increase in % wt Al₂O₃-Gr particles. It is due to increase in brittleness and subsequent disappearance of BUE (Karthikeyan et al,
2000). Also, the addition of graphite particles act as a solid lubrication at the interface of tool and workpiece, which further decrease the surface roughness (Palanikumar, and Karthikeyan, 2007).

Figure 6 indicates the surface roughness cube plot. The plot indicates that minimum surface roughness (Ra = 1.018 microns) is achieved at feed rate 0.1 mm/tooth, cutting speed at 200 m/min and the % wt Al$_2$O$_3$-Gr particles at high level (15%).

![Surface roughness cube plot](image)

**Figure 6.** Cube plot for surface roughness

5. Conclusion

In this research, RSM based on FCD is employed to develop empirical relationship between machining conditions and surface roughness. Also, an attempt is made to investigate the impact of process conditions on surface roughness using 3D plots. The following major conclusions are concluded:

- A linear effect is obtained between feed rate and surface roughness while non linear effect is obtained between cutting speed & surface roughness and % wt Al$_2$O$_3$-Gr particles & surface roughness.
- An interaction effects have been observed between the feed and speed, feed and % wt Al$_2$O$_3$-Gr particles.
- The feed rate, speed and % wt Al$_2$O$_3$-Gr particles have been found significant conditions for surface roughness.
- The R$^2$ value for empirical model is found to be 0.991, which shows the excellent prediction ability of develop model.
- The surface roughness increases with increase in the feed and decreases with increase in the speed and % wt Al$_2$O$_3$-Gr particles.
- The minimum surface roughness (Ra = 1.018 microns) is achieved at 0.1 (mm/tooth) feed, at (200 m/min) speed and at 15% wt Al$_2$O$_3$-Gr parici
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