A study on bi-objective optimization for end milling of Aluminium based composite

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Abstract The composites are renowned for better properties than base alloy. In general, 2-8% weight fraction of reinforcement has been researched for various industrial applications. The addition of reinforcement gives improvement in mechanical properties but badly affects ductility. Liquid route method (casting) has been employed for fabrication of SiC reinforced aluminium composites. Machining has been performed by controlling input parameters such as cutting speed, feed rate and depth of cut. Roughness parameter (R_a) and material removal rate (MRR) have been considered for evaluation of surface quality and productivity respectively. Only MRR has been given consideration for rough machining conditions. Whereas, both surface roughness and MRR have been considered for the finish machining conditions. Standard L9 orthogonal array have been employed for the experimentation. The occurrence of hard reinforcement in the base alloy creates the casted composite tough to machine. The confirmation experiments have been performed with the optimal settings of process parameters to confirm the output responses.

Keywords: Al-4032, End Milling, Composite, Roughness, Stir Casting, TGRA.

1. Introduction

Metallic and ceramics particles may be utilized for the fabrication of desired materials. El-Gallab and Sklad [1] have brought numerous functions of metal matrix composites (MMCs) such as chassis, drive shafts, pistons, and cylinder lining. The composite consists of a metal matrix and ceramic reinforcement [2-5]. MMCs fabricated by powder metallurgy and casting produces better quality than other methods. Although stir casting is normally favored, Hashim et al. [6,7] encountered a critical issue that influences the properties, and quality of MMCs is even allocation of ceramic particles. Excellence of fabricated products does not barely depend on fabrication process but also on machining performance. The machining of the composite is a difficult task for the research community [8,9]. The model obtained in present work has been tested through ANOVA to discover the statistically significant parameters. People have reported work on machining of metals, alloys, and composites over decades. Ozben et al. [10] observed improvement in the mechanical properties by altering the weight fraction of reinforcements such as SiC to Al base alloy. Results tell that both toughness and hardness expand with addition of SiC. Other literature related to fabrication and machining of aluminium based MMCs have been reported by different experts [11-17]. Machining of the MMCs is a key issue due to hard ceramic particles that results into low tool life, poor machined surface etc. [18]. Sahin [19] depicted few challenges during machining of AMCs such as less utilization of energy due to tool wear at the flank face. Surface roughness is one of the quality issues during machining of MMCs.
2. Materials and Methods

In the current study machining has been carried out for both the rough and finish machining. A logical use of the TGRA method has been described in Figure 1. Also, all other relevant details linked to applications of the TGRA in machining science have been testified in the literature [15, 20-24]. The metal matrix composite (MMC) has been casted taking Al-4032 as the base matrix and SiC (3% by weight, particle size up to 54µm) as reinforcement. All other relevant details regarding the fabrication of the composite sample have been provided in separate work carried out by the authors [18]. Milling experiments were performed on CNC vertical machining center. The process parameters are cutting speed (A): 15.70, 23.55, 31.40 m/min; depth of cut (C): 0.5, 1.0, 1.5 mm; feed rate (B): 40, 70, 100 mm/min (Table 1).

Table 1. Design matrix and experimental results

| Exp. No. | Cutting Speed: A (m/min) | Feed Rate: B (mm/min) | Depth of Cut: C (mm) | Roughness Ra (µm) | MRR (mm³/sec) |
|----------|------------------------|----------------------|---------------------|------------------|---------------|
| 1        | 15.70                  | 40                   | 0.5                 | 3.36             | 03.33         |
| 2        | 15.70                  | 70                   | 1.0                 | 3.62             | 11.66         |
| 3        | 15.70                  | 100                  | 1.5                 | 3.42             | 25.00         |
| 4        | 23.55                  | 40                   | 1.0                 | 2.99             | 06.66         |
| 5        | 23.55                  | 70                   | 1.5                 | 2.75             | 17.50         |
| 6        | 23.55                  | 100                  | 0.5                 | 3.04             | 08.33         |
| 7        | 31.40                  | 40                   | 1.5                 | 2.91             | 10.00         |
| 8        | 31.40                  | 70                   | 0.5                 | 3.18             | 05.83         |
| 9        | 31.40                  | 100                  | 1.0                 | 3.07             | 16.66         |

The material removal rate (MRR) is calculated on the basis of material removed during by machining action and time consumed for the machining (Equations 1-3, Figure 2).

\[
\text{Table Feed, } f_m = f_t \times N \times n
\]

\[
\text{Cutting time, } CT = \frac{L}{f_m}
\]

\[
\text{MRR} = \frac{\text{volume removed}}{\text{cutting time}} = \frac{L \times W \times t}{CT} = W \times t \times f_m
\]

Researcher have preferred Ra as the roughness parameters due to its accuracy of representing the quality of the surface [25-28]. For the present work Ra parameter has been assessed with portable roughness tester (Taylor Hobson made, Figure 3).
Figure 1. Block diagram of TGRA methodology

Figure 2. Schematic for calculation of material removal rate during end milling
3. Results and Discussion

Total nine experiments have been performed based on Taguchi’s L₉ orthogonal array. Three control parameters namely cutting speed, feed rate and depth of cut have been varied during the experimentation as described in design matrix (Table 1.)

3.1 Case I: Rough machining conditions

For rough machining, only MRR has been given weightage because for rough cut worker need not to pay any attention on the quality of surface produced after the cutting operation. The MRR increased linearly with increase in each input parameters as observed by other experts. Same could be understood from equations (1-3). In other words, the machining time decreases increase in each cutting parameter.

The theoretical MRR for all value of the cutting parameter was calculated applying analysis of mean (ANOM). DOC, FR, CS (i.e., 53.86 > 39.55 > 03.33) is the significance order for optimal MRR. The preferred settings of the cutting parameters turn out to be ‘A₁ B₃ C₃’ (Table 2 and Figure 4). Equation (4) shows the relationship between the productivity and the cutting parameters for rough machining conditions using the regression analysis of the results.

\[
\text{MRR} = -7.92 - 0.1592 \text{CS} + 0.1667 \text{FR} + 11.67 \text{DOC} \tag{4}
\]

| Factor | A   | B   | C   |
|--------|-----|-----|-----|
| 1      | 13.33 | 06.66 | 05.83 |
| 2      | 10.83 | 11.66 | 11.66 |
| 3      | 10.83 | 16.66 | 17.50 |
| Delta  | 02.50 | 10.00 | 11.67 |
| Rank   | 3    | 2    | 1    |

Table 2. Main effect for rough machining
Figure 4. Main effects plot for rough machining

Analysis of variance (ANOVA)

Table 3 illustrates the concise results of ANOVA analysis. It appears that two process parameters DOC and FR are important parameter from the viewpoint of production rate. 53.86 %, 39.55 % and 03.30 % are the contribution % for DOC, FR and CS respectively.

| Parameter | Degree of Freedom | SS  | MS   | F Value | Percentage Contribution | F > F table |
|-----------|------------------|-----|------|---------|-------------------------|-------------|
| A         | 2                | 12.5| 06.25| 01.00   | 03.30 %                 | Insignificant|
| B         | 2                | 150.00| 75.00| 12.00   | 39.55 %                 | Significant  |
| C         | 2                | 204.28| 102.14| 16.34   | 53.86 %                 | Significant  |
| Error     | 2                | 12.50| 06.25|         | 03.30 %                 |             |
| Total     | 8                | 379.28|      |         |                         |             |
| F_{0.10}(2,2) | 9                |      |      |         |                         |             |
3.2 Case II: Finish machining conditions

The surface finish has been assumed more important compared to MRR considering finish machining conditions. 80% weightage to surface finish and 20% weightage to MRR has been given during the analysis for this case. Lower the better (L-B) criteria for surface roughness and higher the better (H-B) criteria for MRR have been used for conversion of response values into the S/N ratio. Moreover, it is essential to normalize/standardize the calculated S/N ratio as presented in Table 4.

| Ex. No. | Calculated (µm) | S/N Value | Standardized | Calculated (mm³/sec) | S/N Value | Standardized |
|---------|-----------------|-----------|--------------|----------------------|-----------|--------------|
| 1.      | 3.36            | -10.52678555 | 0.728845609  | 0.33                 | 10.45931191 | 0.000000000  |
| 2.      | 3.62            | -11.17417141 | 1.000000000  | 11.66                | 21.33918396 | 0.621725155  |
| 3.      | 3.42            | -10.68052212 | 0.793237418  | 25.00                | 27.95880017 | 1.000000000  |
| 4.      | 2.99            | -9.513423766 | 0.304404001  | 0.66                 | 16.47860910 | 0.343969898  |
| 5.      | 2.75            | -8.786653877 | 0.000000000  | 17.50                | 24.86076097 | 0.822964012  |
| 6.      | 3.04            | -9.657471672 | 0.364737759  | 08.33                | 18.41706992 | 0.454742327  |
| 7.      | 2.91            | -9.277859780 | 0.205739181  | 10.00                | 20.00000000 | 0.545198119  |
| 8.      | 3.18            | -10.04854240 | 0.528535814  | 05.83                | 15.31932850 | 0.277723355  |
| 9.      | 3.07            | -9.742767510 | 0.400463502  | 16.66                | 24.43714871 | 0.798756889  |

After normalization/standardization of the S/N ratio, next step is to calculate the grey relational grade (GRG) values as presented in Table 5. A: B: C comes out to be the optimal parameters for the machining considering finish conditions. The end column in Table 6 grants the ranking for specific factor. Appropriately, the ranking order of input factor looks like CS, FR and DOC. In modern life the Al/SiC based composites are widely applied. The preferred MRR and roughness is accomplished by optimum machining of these MMCs. But then because of the excessive cutting action of reinforced SiC particulates into the Al matrix complications stand up during machining of these composites.

Figure 5 displays the GRGs regarding input machining factors. The response appears to diminish with FR throughout, but in relation to both CS and DOC, the response first grows up to level 2 and later drops. Also, both CS and FR appears to be major factors for surface machining requirements.

Equation (5) shows the relationship between the output response and the cutting parameters for finish machining conditions using the regression analysis of the results.

\[ \text{GRG} = 0.867 - 0.02368 \times \text{CS} + 0.003710 \times \text{FR} + 0.0545 \times \text{DOC} \]  \hspace{1cm} (5)
### Table 5. GRC and GRG for finish machining

| Expt. No. | Design Matrix A | Design Matrix B | Design Matrix C | GRC Ra | MRR | GRG for finish machining | Grade order |
|-----------|-----------------|-----------------|-----------------|--------|-----|-------------------------|-------------|
| 01        | 1               | 1               | 1               | 0.648378594 | 0.333333333 | 0.585369542 | 3           |
| 02        | 1               | 2               | 2               | 1.000000000 | 0.569297871 | **0.913859574** | 1           |
| 03        | 1               | 3               | 3               | 0.707451148 | 1.000000000 | 0.765960919 | 2           |
| 04        | 2               | 1               | 2               | 0.418201466 | 0.432514689 | 0.421064111 | 7           |
| 05        | 2               | 2               | 3               | 0.333333333 | 0.738513179 | 0.414369302 | 8           |
| 06        | 2               | 3               | 1               | 0.440426874 | 0.478350949 | 0.448011689 | 6           |
| 07        | 3               | 1               | 3               | 0.386320897 | 0.523668847 | 0.413790487 | 9           |
| 08        | 3               | 2               | 1               | 0.514687013 | 0.409072694 | 0.493564149 | 5           |
| 09        | 3               | 3               | 2               | 0.454737065 | 0.713019482 | 0.506393548 | 4           |

### Table 6. Main effects on GRGs for finish machining

| Factor | A | B | C |
|--------|---|---|---|
| 1      | 0.8071 | 0.5054 | 0.6154 |
| 2      | 0.6295 | 0.6385 | 0.5867 |
| 3      | 0.4354 | 0.7281 | 0.6699 |
| Delta  | 0.3717 | 0.2226 | 0.0832 |
| Rank   | 1   | 2   | 3   |
8

Analysis of variance (ANOVA)

Table 7 illustrates the concise results of ANOVA analysis. It appears that both CS and FR are important parameter from the viewpoint of finish machining conditions. 67.52%, 24.51 %, and 03.48 % are the contribution % for CS, FR and DOC respectively. The result can be realised considering the process of machining operation. The elevated FR normally produce vibrations between the composite material and cutting tool. This causes an increase in intensity of surface roughness for the duration of cutting operation [29]. Likewise, expanding the FR results a rise in the machined sign owing to more contact area creation that leads to additional forces and consequently R, parameter emerges considerably [30].

Table 7. ANOVA table for finish machining

| Parameter | Degree of Freedom | SS     | MS       | F value | % Contribution | F > F_table |
|-----------|-------------------|--------|----------|---------|---------------|-------------|
| A         | 2                 | 0.20743| 0.103716 | 15.06   | 67.52 %       | Significant |
| B         | 2                 | 0.07529| 0.037643 | 05.47   | 24.51 %       | Significant |
| C         | 2                 | 0.01070| 0.005352 | 00.78   | 03.48 %       | Insignificant |
| Error     | 2                 | 0.01377| 0.006887 |         | 04.48 %       |             |
| Total     | 8                 | 0.30720|          |         |               |             |

F_{0.05 (2,8)} = 4.45
The μ at the best combination is calculated applying Equation (6) where A₁, B₂ and C₂ denotes the mean GRG at the most favourable settings, and T̅GRG is the overall mean GRG [31]. The Confidence interval is found employing Equation (7).

\[ \mu = A_1 + B_2 + C_2 - 2T_{GRG} \]  
\[ CI = \sqrt{F_0(1, f) \times \frac{V_e}{N_e}} \]

Where

- \( F_0(1, f) \) = \( F \) critical
- \( f = 8 \)
- \( F_{0.10}(1, f) = 4.45 \)
- \( V_e = 0.0068 \)
- \( N_e = \) Effective number of replications

\[ N_e = \frac{\text{Total} \text{ number} \text{ of} \text{ result}}{\text{DOF of mean} \times \text{DOF of all factors included} \text{ in} \text{ the estimate of the mean}} = N_e = \frac{9}{1 + 6} = 1.285 \]

Validation through confirmation experiment

The validation is performed with the optimal settings of process parameters to confirm the output responses. The optimal solution for the forecasted machining parameters was tested experimentally in duplicate. The confirmed results are close with the expected ones (Table 8). The outcomes recommended that the bi-objective process has been adequately improved applying the Taguchi based grey relational analysis.

| Predicted | Confirmed | Range |
|-----------|-----------|-------|
| Optimal level | GRG | Test level | GRG |  |
| A₁ B₂ C₂ | 0.8733 | A₁ B₂ C₂ | 0.9138 | 0.7471 ≤ \( \mu \) ≤ 0.9995 |

4. Conclusion

Optimization of machining of AMC has been studied for individual rough and finish machining conditions. The influence of three parameters has been investigated on the two output characteristics using \( L_9 \) orthogonal array. The occurrence of hard reinforcement in the base alloy creates this composite material difficult to cutting operation. But at high CS and low FR, machining turn out to be somewhat easier producing superior finish. Two parameters namely DOC (53.86%) and FR (39.55%) appear to be important for rough machining. Best level for the rough machining seems to be CS 15.7 m/min, FR 100 mm/min, and DOC 1.5 mm. Whereas, CS (67.52%) and FR (24.51%) looks to be the major influences for finish machining conditions. The most favorable level for finish machining found to be CS 15.7 m/min, FR 70 mm/min, and DOC 1 mm.

Conflict of Interest

The authors have no conflicts of interest to declare.

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