Optimization of machining parameters in CNC turning of AA6061-B4C-CNT hybrid composites using Grey-fuzzy method

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Abstract. Aluminium hybrid composites and its machining receives a great attention due to their superior properties like good strength to weight ratio, good castability, machinability, and low cost, suitable for various applications in automotive and aerospace industries. CNC turning is considered as an ideal method for machining of aluminium hybrid composites. Nevertheless, the parameters of turning of aluminium hybrid composites need to be optimized for better and precise machining. Also, the presence of solid lubricants such as Carbon nanotube, Graphite, hexagonal Boron Nitride etc. promotes the machinability of aluminium hybrid composites. In this study, CNC turning on AA6061 matrix based hybrid composites reinforced with Boron carbide (5-15 vol.%) and Carbon nanotube (15 vol.%) was performed. Cutting Speed (rpm):60-180, feed (mm/rev): 0.10-0.20, depth of cut (mm): 0.50-1.00 and percentage of B4C (vol.%) 5-15 were the controlling parameters and responses namely tangential force (N), cutting power (W) and tool wear (mm³/min) were considered for the optimization. Experimental design was made as per Taguchi’s L27 orthogonal array and Grey-fuzzy analytical tool was applied for the optimization. The optimal setting for turning operation on this hybrid composite using Grey-fuzzy analysis were 120 rpm, 0.20 mm/rev, 0.5 mm and 15 vo.% for cutting speed, feed, depth of cut and reinforcement respectively.

1. Introduction
Aluminium alloy matrix ceramic particulates reinforced composites possess excellent combination of mechanical and physical properties; promising for structural applications. Aluminium Matrix Composites (AMCs) shows better quality characteristics due to the combined effect of properties of the matrix and ceramic reinforcements. Matrix possesses high toughness and good ductility; whereas the ceramics shows high modulus and high strength [1]. Aluminium Hybrid Composites (AHCs) are the advanced composites and are mostly preferred due to their superior properties for automotive and aerospace applications [2]. AHCs containing ceramic particles such as B4C, SiC, TiC and soft lubricants such as Carbon nanotube (CNT), hexagonal Boron Nitride (hBN) were shown much improvements in machinability, wear resistance and strength [3-4]. Stir casting is the most popular and effective method for fabricating hybrid composites as it ensures a uniform distribution of different
reinforcements [5]. Turning is considered as the feasible method for machining of cylindrical components from hybrid composites. Even though, the optimization of turning parameters for the particular hybrid composite is necessary for obtaining good quality characteristics.

Grey Relational Analysis (GRA) is a versatile method used for optimization and that analyses uncertain relations among the factors in a given system. In addition, Grey-fuzzy approach is popular for optimization as it has the combined advantages of both grey system and fuzzy logic approach. Sankar et al. applied Taguchi-Grey technique for optimizing non-conventional machining parameters for graphite solid lubricant reinforced AA6061-B4C based hybrid composites [6]. Ravinder Kumar et al. studied the feasibility on turning of AA7075/ SiC and AA7075/SiC/Graphite hybrid composite by varying the input parameters such as cutting speed, feed rate and approach angle. The machinability of the hybrid composite was better due to the presence of graphite solid lubricant [7]. Kalpesh tank et al. applied ANOVA, fuzzy and desirability function analysis in order to find the optimal combination of input parameters for finest surface finish characteristics in turning process [8]. Surendra Kumar et al. investigated the CNC turning characteristics of aluminium alloy 8011 and optimized the turning parameters by Taguchi-Fuzzy method. They ranked the parameters which significantly influenced the quality characteristics as feed, depth of cut and cutting speed [9]. Senthilkumar et al. presented an approach for optimizing the turning parameters of AISI 1045 steel using grey fuzzy logic. They found an improvement in performance of the turning process by applying hybrid techniques [10]. Palanisamy et al. applied Grey-Fuzzy approach and successfully determined the optimal parameter setting for CNC turning process [11]. Biswajit Das et al. optimized the CNC milling parameters for Al–4.5%Cu–TiC composites using grey- fuzzy logic approach and reported that cutting speed has a major role in finding the Grey Fuzzy Reasoning Grade [12].

The literature survey reveals that, no research works has been reported particularly on the optimization of CNC turning parameters for AA6061-B4C-CNT hybrid composites using Grey-Fuzzy logic method. Therefore, the main research objective of this work is to find an optimal combination of turning parameters over the responses such as tangential force, cutting power and tool wear by applying Grey-fuzzy tool.

2. Materials and Methodology

2.1. Materials

AA6061 was chosen as the matrix material as it is the most commonly used precipitation-hardened aluminium alloy and due to its favorable properties like good mechanical properties and wettability. Boron Carbide (B4C) is a hard ceramic commonly used as particulate reinforcements in aluminium to improve the wear resistance and strength. Carbon nanotube (CNT) is well known for its excellent lubricating properties, uniform dispersion with AMMC and improved mechanical properties. B4C and CNT particles with sizes 35-40µm and 30nm respectively were used as the reinforcements. The details of composition are shown in table 1. The volume of B4C is varied at 5, 10 and 15% and the volume of CNT kept constant at 15%. Thus, three different compositions were considered in this study so as to examine the cutting performance at different volume of reinforcements. The hybrid composites were fabricated through liquid metallurgy route (stir casting).

| S. No. | AA6061 (Vol.% ) | B4C (Vol.% ) | CNT (Vol.% ) |
|-------|-----------------|--------------|--------------|
| 1     | 80              | 5            | 15           |
| 2     | 75              | 10           | 15           |
| 3     | 70              | 15           | 15           |
2.2. Parameters and levels
The fabricated composites were machined using CNC turning center (Make: Jobber XL). Cutting speed, feed and depth of cut were considered as the parameters of the CNC machine. The details of factors and levels considered for the optimization are given in Table 2. The design and conduct of experiments were based on Taguchi’s L_{27} orthogonal array.

| S. No. | Parameters              | Low  | Medium | High |
|--------|-------------------------|------|--------|------|
| 1      | Cutting speed (rpm)     | 60   | 120    | 180  |
| 2      | Feed (mm/rev)           | 0.1  | 0.15   | 0.2  |
| 3      | Depth of cut (mm)       | 0.5  | 0.75   | 1    |
| 4      | Reinforcement (Vol. %)  | 5    | 10     | 15   |

Tangential force (R_1), tool wear (R_2) and cutting power (R_3) were considered as the responses. Tangential force and tool wear values were directly obtained from the CNC turning machine. The cutting power was calculated using the equation 1.

\[ P_c = \frac{D \times F \times S \times K_c}{60 \times 1000 \times \eta} \]  

Where, \( P_c \)-Cutting power; \( D \)-Depth of cut; \( F \)-feed; \( S \)-Cutting speed; \( K_c \)-Specific cutting force and \( \eta \)-Machine Coefficient.

2.3. Grey Relational Analysis (GRA)
In GRA, the S/N ratio is calculated initially to reduce the variability in the process by minimizing the effects of uncontrollable factors. As our objective is minimizing all the three responses, the “smaller the better” was implied. In GRA, the normalizing of values was done using equation 2. Further, equation 3 was used to determine the Grey Relational Coefficient (GRC).

\[ x_i^*(k) = \frac{\text{max. } x_i(k) - x_i(k)}{\text{max. } x_i(k) - \text{min. } x_i(k)} \]  

Where, \( x_i^*(k) \): normalized data and \( x_i(k) \): observed data for the \( i \)th experiment by using \( k \)th response.

\[ \xi_i(k) = \frac{\Delta \text{min} + \Delta \text{max}}{\Delta i(k) + \Delta \text{max}} \]  

Where, \( \Delta i(k) \): absolute value of the difference between \( x_i^* \) (k) and \( x_0(k) \), \( \Delta \text{max} \): global maximum values, \( \Delta \text{min} \): global minimum values.

To expand or compress the range of GRC, the distinguishing coefficient (\( \zeta \)) was taken as 0.5. Finally, Grey Relational Grade (GRG) values were calculated by taking the average of GRCs. The G-fuzzy is the combination of Grey relational approach and fuzzy logic theory. In this approach, GRA technique effectively utilized to convert the multi-objective problem in to a single-objective. The highest GRG represents the minimum value for input parameters. However, fuzzy logic theory effectively reduces the degree of uncertainty in the obtained GRG values. Each input variable has low, medium, high subsets in its membership function as shown in table 3. The range of output has Extremely Large (EL), Extremely Small (ES), Very Large (VL), Very Small (VS), Large (L), Medium (M), Small (S), Large Medium (LM) and Small- Medium (SM) in its membership function as show in table 4.
Table 3. Range of fuzzy subsets for input membership functions.

| Condition | Range   | Membership function |
|-----------|---------|---------------------|
| Low       | -0.5 – 0.5 | Triangular          |
| Medium    | 0 – 1    | Triangular          |
| High      | 0.5 – 1.5 | Triangular          |

Table 4. Range of fuzzy subsets for output membership functions.

| Condition          | Range           | Membership function |
|--------------------|-----------------|---------------------|
| Extremely large    | 0.8672 – 1.126  | Triangular          |
| Extremely small    | -0.125 – 0.125  |                     |
| Very large         | 0.75 – 1        |                     |
| Very small         | 0 – 0.125       |                     |
| Large              | 0.625 – 0.875   | Triangular          |
| Medium             | 0.375 – 0.625   |                     |
| Small              | 0.125 – 0.375   |                     |
| Large medium       | 0.5012 – 0.7512 |                     |
| Small-medium       | 0.25 – 0.5      |                     |

Figures 1 (a) and (b) indicate the fuzzy rule editor and membership functions for output GFRG (Grey Fuzzy Reasoning Grade) respectively. For fuzzification of the GRC, the input and output variables are created in the Fuzzy Inference System (FIS). Fuzzy rule was constructed by simple IF-THEN rule with condition and conclusion. The centroid method was chosen to calculate the GFRG from the fuzzy multi-response output.

Grey relational coefficients are η₁, η₂, η₃. GRC of tangential force, cutting power, tool wear are taken as η₁, η₂, η₃ respectively. Multi-response output is taken as ξ.

Rule 1: if η₁ is A₁₁, η₂ is A₁₂ and η₃ is A₁₃, then ξ is D₁,
else
Rule 2: if η₁ is A₂₁ η₂ is A₂₂ and η₃ is A₂₃, then ξ is D₂
else

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Rule n: if η₁ is Aₙ₁, η₂ is Aₙ₂ and η₃ is Aₙ₃, then ξ is Dₙn.

Figure 1. (a) Fuzzy rule editor; (b) Typical membership functions for output GFRG.
3. Result and Discussion

The composites as per the volumetric composition were successfully fabricated through stir-bottom pouring casting process. Three specimens of each composition were prepared as shown in figure 2(a). CNC turning was performed on the composite specimens as per the structured L 27 orthogonal array. Sample specimens after CNC turning process are shown in figure 2(b). The experimental results were shown in the below table 5.

![Figure 2. (a) Sample specimens (as-cast), (b) Samples after CNC turning process.](image)

The S/N ratio, normalized S/N ratio, corresponding GRC values and GRG of all 3 responses were calculated for the different experimental trials and are shown in table 6. The single representation of all the three responses corresponding to each trial is shown by the GRG value and a higher value of GRG is always desirable. The peak value of GRG is observed for the 23rd trial, (0.851). This demonstrates the closeness of optimum parameter setting.

| Trial No. | Cutting speed (rpm) | Feed (mm/rev) | Depth of cut (mm) | Reinforcement cement (Vol. %) | Tang. force (N) | Cutting power (W) | Tool wear (mm³/min) |
|-----------|---------------------|---------------|------------------|-------------------------------|----------------|------------------|---------------------|
| 1         | 60                  | 0.1           | 0.5              | 5                             | 12             | 3.72             | 0.14                |
| 2         | 60                  | 0.1           | 0.5              | 10                            | 13             | 4.03             | 0.23                |
| 3         | 60                  | 0.1           | 0.5              | 15                            | 15             | 4.65             | 0.21                |
| 4         | 60                  | 0.15          | 0.75             | 5                             | 6              | 1.86             | 0.16                |
| 5         | 60                  | 0.15          | 0.75             | 10                            | 10             | 3.1              | 0.26                |
| 6         | 60                  | 0.15          | 0.75             | 15                            | 17             | 5.27             | 0.16                |
| 7         | 60                  | 0.2           | 1                | 5                             | 16             | 4.96             | 0.15                |
| 8         | 60                  | 0.2           | 1                | 10                            | 12             | 3.72             | 0.19                |
| 9         | 60                  | 0.2           | 1                | 15                            | 20             | 6.2              | 0.19                |
| 10        | 120                 | 0.1           | 0.75             | 5                             | 13             | 8.06             | 0.2                 |
| 11        | 120                 | 0.1           | 0.75             | 10                            | 11             | 6.82             | 0.31                |
| 12        | 120                 | 0.1           | 0.75             | 15                            | 11             | 6.82             | 0.27                |
| 13        | 120                 | 0.15          | 1                | 5                             | 12             | 7.44             | 0.23                |
| 14        | 120                 | 0.15          | 1                | 10                            | 13             | 8.06             | 0.27                |
| 15        | 120                 | 0.15          | 1                | 15                            | 20             | 12.4             | 0.25                |
| 16        | 120                 | 0.2           | 0.5              | 5                             | 11             | 6.82             | 0.21                |
| 17        | 120                 | 0.2           | 0.5              | 10                            | 12             | 2.48             | 0.19                |
| 18        | 120                 | 0.2           | 0.5              | 15                            | 23             | 14.26            | 0.18                |
| 19        | 180                 | 0.1           | 1                | 5                             | 10             | 9.3              | 0.23                |
MATLAB R2016a software was used for fuzzy Logic analysis to find the GFRG values. Three triangular membership functions were applied to the GRC of Tangential force, cutting power and tool wear. Figure 3 shows triangular membership functions that are applied to the responses. For FIS, rules are framed and applied for the prediction of GFRG’s for all 27 experiments. A comparison of GFRG values with GRG values is shown in figure 4. While comparing the GRG with GFRG values, the GFRG values are improved.

Table 6. S/N ratio, GRC and GRG values.
Table 7 shows the GFRG values of corresponding parameter levels. The highest GFRG values corresponding to the parameter level are: cutting speed (level 2), feed (level 3), depth of cut (level 1) and % reinforcement (level 3). Accordingly, the optimal parameters setting for the CNC turning operation of hybrid composites by G-Fuzzy method is cutting speed, feed, depth of cut and % of reinforcement are 120rpm, 0.2mm/rev., 0.5mm and 15 Vol.% respectively.

**Table 7. GFRG values and optimum parameter levels.**

| Parameters     | GFRG    | Corresponding Optimum value |
|----------------|---------|-----------------------------|
|                | Level 1 | Level 2 | Level 3 |
| Cutting speed  | 0.4860  | **0.5973** | 0.5497 | 120 rpm |
| Feed           | 0.5162  | 0.5380  | **0.5546** | 0.2 mm/rev |
| Depth of cut   | **0.5623** | 0.5147  | 0.5317 | 0.5 mm |
| Reinforcement  | 0.4615  | 0.5547  | **0.5926** | 15 Vol.% |
4. Conclusion

The fabrication of AA6061-B4C-CNT hybrid composites and CNC turning operation as per Taguchi’s L27 orthogonal array were done successfully. Grey Relational Analysis and Fuzzy logic were combined to find out the optimum setting parameters. Grey relational coefficient, Grey relational grade and Grey fuzzy reasoning grade were calculated accordingly for G-Fuzzy analysis. The optimum combination of turning parameters for AA6061-B4C-CNT hybrid composites was cutting speed - 120 rpm, Feed - 0.20mm/rev, Depth of cut - 0.5mm and Reinforcement - 15Vol. %.

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