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# Cutting Force and Surface Roughness Analysis During Turning of Al 7075 Based Hybrid Composites

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**Abstract**

This paper presents the influence of cutting parameters like cutting speed, feed rate, and depth of cut on cutting forces and surface roughness in dry turning of three hybrid composites, viz. (i) Al7075-10%SiC-0.1% $B_4C$, (ii) Al7075-10%SiC-0.1% Graphene, and (iii) Al7075-10%SiC-0.1% CNT using uncoated and Diamond-Like Carbon (DLC) coated carbide tool. The composites were fabricated via combined stir and squeeze casting method with ultrasonic vibration for homogeneity. The experimental results implied that the feed rate was the most dominant factor on the surface roughness. Lowest feed rate (0.1mm/rev) offered minimum surface roughness on three composites 1.1961µm, 0.4428 µm, and 0.5995µm respectively. Presence of graphene showed a minimum surface roughness (0.4428 µm) than that of the composites based on carbon nanotubes (CNT) and $B_4C$. Depth of cut (1.5mm) was the most influencing factor on the cutting forces on all composites. Graphene-(383.4N) and CNT-composites (318.6N) required higher cutting force than the $B_4C$ composite (264.3N) for dry turning at a depth of cut of 1.5 mm using DLC coated carbide tool. Taguchi L18 orthogonal-array decided the number of experiments. Grey relational analysis was used to optimize the cutting parameters for minimum surface roughness and cutting force.



*Keywords:* Hybrid Composites; Carbon Nanotubes; Turning; Surface Roughness; Optimization; Grey Relational Analysis

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## 1. Introduction

Metal matrix composites (MMCs) are being presently used for a number of applications in aerospace, defense and automobile industries due its basic properties such as low density, high specific strength and stiffness, higher modulus, and low expansion coefficient. [1,2]. Metal matrix nano composites (MMNCs) have a great potential than the conventional MMC for the same application areas, mostly structural, where a lower weight leads to reduce the energy requirement due to their advanced basic properties such as high specific strength, high thermal conductivity, excellent wear resistance and controllable coefficient of thermal expansion [3,4]. Commonly used nano carbon reinforcement materials are carbon nanotubes (CNTs) [5,6] and Graphene [7]. Similar to the conventional composites, the arrangement of the CNTs and Graphene, uniformity in distribution of the composite, matrix adhesion, aspect ratio and volume fraction are the major contributors on the properties of the nanocomposites. Carbon nanotubes (CNTs) and Graphene have been capable reinforcements for nano composites, due its superior mechanical and physical properties, high thermal conductivity, good electrical conductivity, high strength-to-weight ratio, and improved flexibility.

## 2. Matrix

Aluminium 7075-T6 showing superior mechanical and physical properties especially remarkable strength to weight ratio compared to other materials used for structural applications [4]. Zinc is the prime alloying component in Al7075 and it is stronger than many of steel. It possesses good fatigue strength and moderate machining characteristics. Al 7075-T6 material was purchased from M/s. Bharat Aerospace Metals, Mumbai, for experimentation.

## 3. Experimental procedure

### *3.1. Turning experiment*

Combined Stir and Squeeze casting method used for fabrication of these composites. Uncoated and Diamond-Like Carbon (DLC) coated carbide tool inserts (Grade K313) from the M/s. Kennametal Inc, used for turning experimentation. DLC-coated carbide is outstanding tool than the uncoated for machining of aluminum alloys. It improves the tool life due to the controlled wear as well as toughness and it shows resistance to the formation of build-up edge. The experimentation was carried out in dry cutting condition by using Turn 5075- SPM CNC lathe for the above mentioned composites. The cutting force measured by Kistler (9257b) multi component dynamometer. Surface roughness was evaluated by MarSurf GD 120 surface roughness tester with a traverse length of 30mm. The surface roughness data given for this evaluation was the average of three measurements taken from different position of the machined surface.

### *3.2. Design of experiments*

Taguchi method is the dominant and prime tool to enhance the productivity as well as providing a robust design. L18 orthogonal array is used to frame the number of experiments. The cutting parameters and their levels are given in Table 1.

Table 1. Cutting parameters and their levels.

| Machining Variables | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Type of insert | uncoated | DLC coated | |
| Cutting Speed (m/min) | 50 | 70 | 90 |
| Feed (mm/rev) | 0.1 | 0.2 | 0.3 |
| Depth of Cut (mm) | 0.5 | 1 | 1.5 |

The process parameters such as cutting speed, feed and depth of cut were decided for turning experiments. The experimental parameters with L18 orthogonal array and corresponding outputs such as cutting force and surface roughness are tabulated in Table 2.

Table 2. Experimental parameters with L18 orthogonal array and corresponding results.

| Exp. No | Tool | Material (Samples) | Cutting Speed (*m/min*) | Feed (*mm/rev*) | Depth of Cut (*mm*) | Cutting Force (*N*) | Surface Roughness ($\mu m$) |
|---|---|---|---|---|---|---|---|
| 1 | Uncoated Carbide | 1 | 50 | 0.1 | 0.5 | 69.41 | 1.1961 |
| 2 | Uncoated Carbide | 2 | 50 | 0.2 | 1 | 157.3 | 1.1533 |
| 3 | Uncoated Carbide | 3 | 50 | 0.3 | 1.5 | 324.9 | 1.9209 |
| 4 | Uncoated Carbide | 2 | 70 | 0.1 | 0.5 | 301.7 | 0.5007 |
| 5 | Uncoated Carbide | 3 | 70 | 0.2 | 1 | 176.2 | 1.0477 |
| 6 | Uncoated Carbide | 1 | 70 | 0.3 | 1.5 | 254.2 | 2.2886 |
| 7 | Uncoated Carbide | 1 | 90 | 0.1 | 1 | 49.03 | 1.8108 |
| 8 | Uncoated Carbide | 2 | 90 | 0.2 | 1.5 | 337.7 | 0.9653 |
| 9 | Uncoated Carbide | 3 | 90 | 0.3 | 0.5 | 147.8 | 1.6889 |
| 10 | DLC coated Carbide | 3 | 50 | 0.1 | 1.5 | 321.7 | 0.8905 |
| 11 | DLC coated Carbide | 1 | 50 | 0.2 | 0.5 | 50.49 | 1.7941 |
| 12 | DLC coated Carbide | 2 | 50 | 0.3 | 1 | 208.1 | 2.0058 |
| 13 | DLC coated Carbide | 3 | 70 | 0.1 | 1 | 274.0 | 0.5995 |
| 14 | DLC coated Carbide | 1 | 70 | 0.2 | 1.5 | 191.1 | 2.3206 |
| 15 | DLC coated Carbide | 2 | 70 | 0.3 | 0.5 | 63.86 | 1.7691 |
| 16 | DLC coated Carbide | 2 | 90 | 0.1 | 1.5 | 203.0 | 0.4428 |
| 17 | DLC coated Carbide | 3 | 90 | 0.2 | 0.5 | 268.8 | 0.6532 |
| 18 | DLC coated Carbide | 1 | 90 | 0.3 | 1 | 51.26 | 2.9346 |

## 4. Results and Discussion

### *4.1. Microstructure*

The microstructures of the three composites with 50x and 200x magnifications are shown in Fig 1. In $B_4C$ based composite (a), dendritic growth is very clear, but it could not contribute much for grain refinement of matrix. Due to

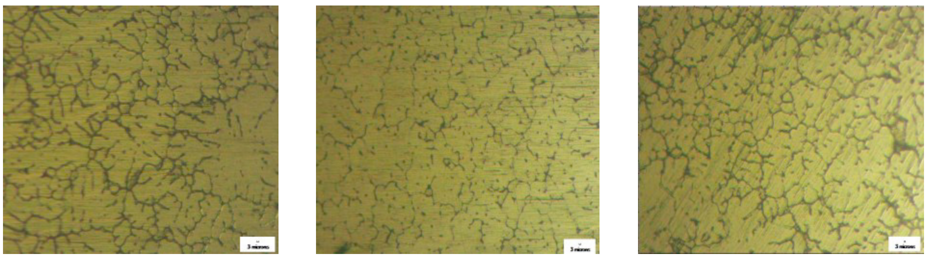


Fig.1. (a) Al7075-10%SiC-0.1% $B_4C$; (b) Al7075-10%SiC-0.1% Graphene; (c) Al7075-10%SiC-0.1% MWCNT.

the addition of Graphene in the Graphene based composite (b), dendritic structure broken into fine grain and grain boundary separation also eliminated by the Graphene grain fining effects. In CNT based composite (c), grain refining effect is not similar to Graphene based composite, but some of dendritic growth is restricted. However grain refinement is better than the $B_4C$ based composite.

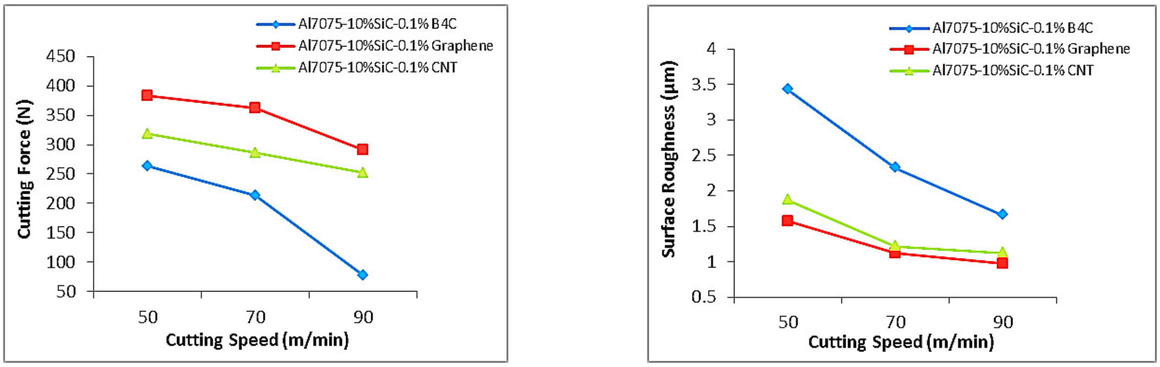
### *4.2. Hardness and Tensile strength*

Brinell hardness tests were performed based on the ASTM E10-07 standard with 10 mm ball indenter and a load of 500 kg at the room temperature (29˚C). The hardness was taken from four different locations and the average value is taken for measurement. The tensile test was carried out as per the ASTM E08-8 standards. The final value was derived based on the average values of measurements which were conducted on two samples in the INSTRON 8801 testing machine, with an extra fitment, the details of which are provided in the Table 3.

Table 3. Hardness and Tensile Strength of the composites.

| Composite | Al7075-10%SiC-0.1% $B_4C$ | Al7075-10%SiC-0.1% Graphene | Al7075-10%SiC-0.1% CNT |
|---|---|---|---|
| Hardness (BHN) | 167 | 145 | 133 |
| Tensile Strength(MPa) | 239 | 324 | 308 |

### *4.3. Effect on Cutting Force and Surface Roughness*



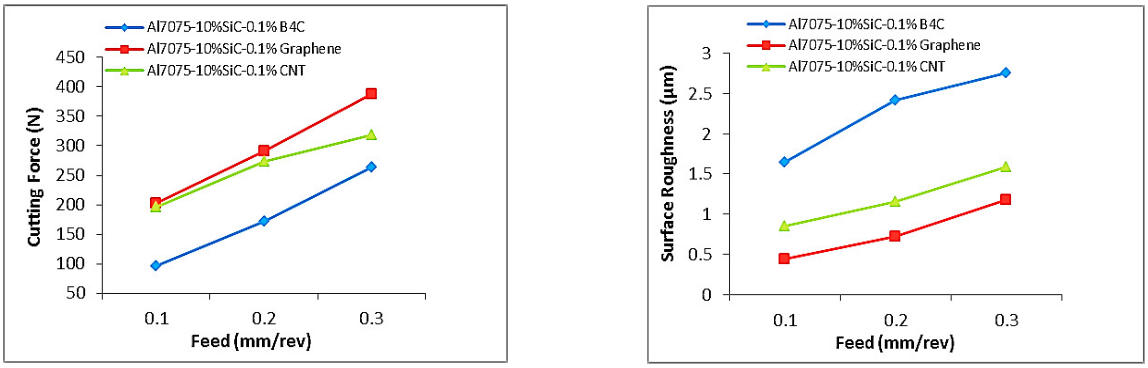

(a) (b)

Fig. 2. (a),(b) The effect of cutting speed on cutting force and surface roughness at feed rate 0.3 mm/rev and depth of cut 1.5 mm using DLC coated carbide tool.

The effect of cutting force and surface roughness has been investigated in dry turning of three hybrid composites, viz. (i) Al7075-10%SiC-0.1% $B_4C$, (ii) Al7075-10%SiC-0.1% Graphene, and (iii) Al7075-10%SiC-0.1% CNT using DLC coated carbide tool with selected parameters of cutting speed, feed rate and depth of cut.

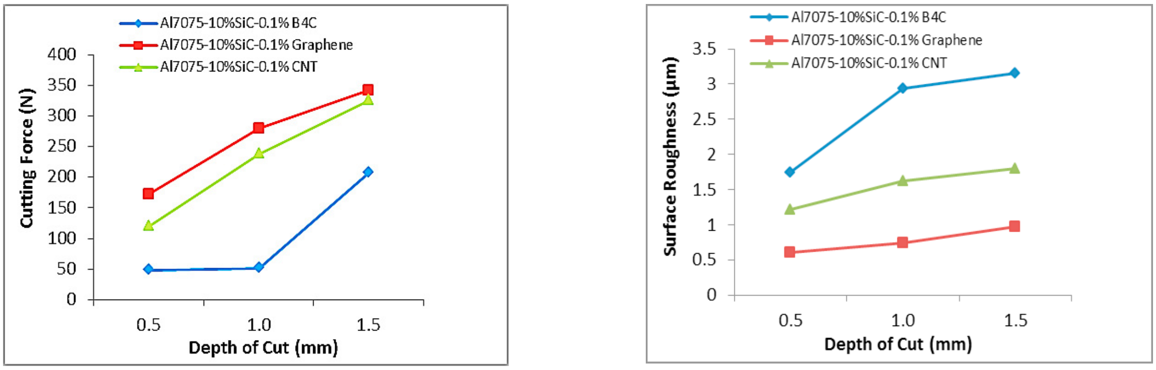
The effect of cutting speed on cutting force in turning operation performed with the constant feed rate of 0.3 mm/rev and depth of cut of 1.5 mm is shown in Fig.2.(a). The experiment results reveal that the cutting force was high at low cutting speed (50 m/min) and gradually decreases with increase in cutting speed for the three composites. It was also noted that, Graphene based composite required more cutting force than the $B_4C$ based and CNT based composites. However $B_4C$ based composite shows the lowest cutting force at the mentioned parameters level. The microstructure of the composite reinforced with $B_4C$ shows that there are sharp edges on the grain boundaries which makes it brittle and at higher speeds, areas of stress concentration due to these sharp edges leads to a steep drop in the cutting force.

The influence of cutting speed on surface roughness of the three studied composites at constant feed rate of 0.3 mm/rev and depth of cut of 1.5 mm is shown in Fig.2.(b). It was seen that the surface roughness was improved with increase in cutting speed from 50 m/min to 90 m/min. The $B_4C$ based composite shows highest surface roughness (3.4182µm) than the Graphene based (1.5674µm) and CNT (1.8643µm) based composite at lowest cutting speed of 50 m/min. The hardness of the $B_4C$ makes the surface rough during machining which reduced the surface finish in $B_4C$ composite. It was also due to the plucking effect of the $B_4C$ particles while machining.




(a) (b)

Fig. 3.(a),(b).The effect of feed rate on cutting force and surface roughness at cutting speed 90 m/min and depth of cut 1.5 mm using DLC coated carbide tool.




(a) (b)

Fig. 4.(a),(b) The effect of depth of cut on cutting force and surface roughness at cutting speed 90 m/min and feed rate 0.3 mm/rev using DLC coated carbide tool.

The influence of feed rate on cutting force of the investigated MMCs indicated in Fig 3(a). It was observed that the cutting force increases sharply when the feed rate increases from 0.1 mm/rev to 0.3 mm/rev for all studied composites at constant cutting speed of 90 m/min and depth of cut of 1.5mm using DLC coated carbide tool in dry turning condition. For every 0.1mm/rev increment of feed rate, the measured cutting force increased linearly.

The effect of feed rate on surface roughness was presented in Fig 3(b). It was evident from the figure, the surface roughness is low at low feed rate (0.1 mm/rev) and high at high feed rate (0.3 mm/rev) for three mentioned MMCs at constant speed of 90 m/min and depth of cut of 1.5 mm. The vibration while machining with increased feed rate and thrust force was also a reason for higher surface roughness. The surface roughness of Graphene based composite is better due to the lubricating effect of Graphene present in the machined surface. This lubrication effect leads to an improved surface finish when graphene is used.

Based on the optimization results, depth of cut was the most influencing parameter on cutting force of the analysed MMCs. The effect of depth of cut on cutting force is illustrated in Fig 4(a). It was noted that at constant cutting speed (90 m/min) and feed rate (0.3 mm/rev), the cutting force increases linearly with increase in depth of cut. The $B_4C$ based composite involves less cutting force than the other two MMCs. The Graphene based composites showed highest cutting force (342.7N) at the mentioned machining conditions. This is due to its high tensile strength (324Mpa) and hardness (145BHN) at the composition which was studied.

The grain distribution of $B_4C$ based composite is continuous with inter bonding which can be the reason for the sudden spike in the cutting force requirement when the depth of cut was increased from 1 to 1.5 mm, as the continuous bonds also need to be broken due to the increase in depth of cut in case of $B_4C$. It can also be due to the crack initiation for fracture due to the presence of sharp edges. Similarly increase in metal removal rate due to the increase in depth of cut contributes to rise in cutting force. Since $B_4C$ is present as spherical granules when compared to Graphene and CNT where it is continuous sheets and cylindrical tubes, which makes Graphene and CNT based composites difficult for machining in the initial stage of depth of cut from 0.5 mm to 1 mm. Since the surface cohesive bonding of $B_4C$ is less, the machining doesn't require as extra force to be added.

The effect of depth of cut on surface roughness at constant speed of 90 m/min and feed rate of 0.3 mm/rev is represented in Fig 4(b). It was observed that the surface roughness increases with increase in depth of cut from 0.5 mm to 1.5 mm for all studied composites. Graphene based composite showed low surface roughness (0.5982µm) at depth of cut of 0.5 mm. Higher depth of cut contributes increase in cutting force and metal removal rate. The variation in different parameters of $B_4C$ based composite as shown in Fig 2, 3 and 4 can be attributed to the increased hardness and the reduced tensile strength which is mentioned in Table 3.

## 5. Determination of multi performance characteristics

### *5.1. Grey Relational Analysis (GRA)*

GRA used for the optimization of multi performance characteristics. In order to normalize the parameters, raw data is pre-processed. In this study, linear normalized parameters for cutting force and surface roughness along with the generating range between zero to one are shown in Table.4. These parameters will be normalized based on 'smaller-the-better' condition. The pre-processing results $y_i(j)$ can be expressed as:

$$y_i(j) = \frac{\max yi(0)(j) - yi(0)(j)}{\max yi(0)(j) - \min yi(0)(j)} \tag{1}$$

Where: $yi(0)(j)$ is the value attained from experiment, $\max yi(0)(j)$ is the maximum value of the data obtained from the experiment, $\min yi(0)(j)$ is the minimum value of data. Next, the data after the deviation are shown in Table 4 and it will be determined by the following equation;

$$\Delta y_{i(j)} = |y_0(j) - y_i(j)| \tag{2}$$

Next, to compute the grey relational coefficient, the following equation is used and it forms the relationship between the best and actual pre-processed experimental results.

$$\lambda_{0,i}(j) = \frac{\Delta_{\min} + \lambda\Delta_{\max}}{\Delta y_{i(j)} + \lambda\Delta_{\max}} \tag{3}$$

Where; $\Delta_{\min}$ is the lowest value of data after deviation, $\Delta_{\max}$ is the highest value of data after deviation, and $\lambda$ is the characteristic coefficient, which is in the range between zero to one. In this study the value considered as 0.5. Finally, the grey relational grade is calculated by averaging the entire grey relational coefficient belonging to each performance characteristics. The overall assessment of multi performance characteristics is depends on the grey relational grade ($\eta_j$) and it is expressed as:

$$\eta_j = \frac{1}{x}\sum_{i=1}^{x}\lambda_{0,i}(j) \tag{4}$$

Table 4. Performance characteristics after normalization and deviation.

| Performance characteristics | | | | | |
|---|---|---|---|---|---|
| after normalization | | | after deviation | | |
| Exp No | Cutting Force ($N$) | Surface Roughness ($\mu m$) | Exp No | Cutting Force ($N$) | Surface Roughness ($\mu m$) |
| 1 | 0.9294 | 0.6977 | 1 | 0.0706 | 0.3023 |
| 2 | 0.6249 | 0.7149 | 2 | 0.3751 | 0.2851 |
| 3 | 0.0443 | 0.4068 | 3 | 0.9557 | 0.5932 |
| 4 | 0.1247 | 0.9768 | 4 | 0.8753 | 0.0232 |
| 5 | 0.5595 | 0.7572 | 5 | 0.4405 | 0.2428 |
| 6 | 0.2893 | 0.2593 | 6 | 0.7107 | 0.7407 |
| 7 | 1.0000 | 0.4510 | 7 | 0.0000 | 0.5490 |
| 8 | 0.0000 | 0.7903 | 8 | 1.0000 | 0.2097 |
| 9 | 0.6578 | 0.4999 | 9 | 0.3422 | 0.5001 |
| 10 | 0.0554 | 0.8203 | 10 | 0.9446 | 0.1797 |
| 11 | 0.9949 | 0.4577 | 11 | 0.0051 | 0.5423 |
| 12 | 0.4490 | 0.3727 | 12 | 0.5510 | 0.6273 |
| 13 | 0.2207 | 0.9371 | 13 | 0.7793 | 0.0629 |
| 14 | 0.5078 | 0.2464 | 14 | 0.4922 | 0.7536 |
| 15 | 0.9486 | 0.4677 | 15 | 0.0514 | 0.5323 |
| 16 | 0.4666 | 1.0000 | 16 | 0.5334 | 0.0000 |
| 17 | 0.2387 | 0.9156 | 17 | 0.7613 | 0.0844 |
| 18 | 0.9923 | 0.0000 | 18 | 0.0077 | 1.0000 |

Higher grey relational grade shows better machinability. From the Table 6, it was noted that the second level of insert (DLC coated), third level of cutting speed (90 m/min), first level of feed rate (0.1 mm/rev) and first level of depth of cut (0.5 mm) were the optimal machining parameters for the three studied composites. It was also found from the table, feed rate was the most influencing parameter for the investigated machining process. After feed rate, the other influencing parameters are depth of cut, cutting speed and insert type respectively.

Table 5. Evaluated Grey relational coefficients and Grade for each turning experiment.

| Exp No | Grey relational coefficient | | Grey relational grade |
|---|---|---|---|
| | Cutting Force ($N$) | Surface Roughness ($\mu m$) | |
| 1 | 0.8763 | 0.6232 | 0.7497 |
| 2 | 0.5714 | 0.6368 | 0.6041 |
| 3 | 0.3435 | 0.4574 | 0.4004 |
| 4 | 0.3636 | 0.9556 | 0.6596 |
| 5 | 0.5316 | 0.6732 | 0.6024 |
| 6 | 0.4130 | 0.4030 | 0.4080 |
| 7 | 1.0000 | 0.4766 | 0.7383 |
| 8 | 0.3333 | 0.7045 | 0.5189 |
| 9 | 0.5937 | 0.5000 | 0.5468 |

| Exp No | Grey relational grade | Grade order |
|---|---|---|
| 1 | 0.7497 | 1 |
| 2 | 0.6041 | 10 |
| 3 | 0.4004 | 18 |
| 4 | 0.6596 | 6 |
| 5 | 0.6024 | 11 |
| 6 | 0.4080 | 17 |
| 7 | 0.7383 | 3 |
| 8 | 0.5189 | 14 |
| 9 | 0.5468 | 12 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 10 | 0.3461 | 0.7357 | 0.5409 | 10 | 0.5409 | 13 |
| 11 | 0.9900 | 0.4797 | 0.7348 | 11 | 0.7348 | 4 |
| 12 | 0.4757 | 0.4436 | 0.4596 | 12 | 0.4596 | 15 |
| 13 | 0.3908 | 0.8883 | 0.6396 | 13 | 0.6396 | 8 |
| 14 | 0.5040 | 0.3989 | 0.4514 | 14 | 0.4514 | 16 |
| 15 | 0.9068 | 0.4844 | 0.6956 | 15 | 0.6956 | 5 |
| 16 | 0.4839 | 1.0000 | 0.7419 | 16 | 0.7419 | 2 |
| 17 | 0.3964 | 0.8555 | 0.6260 | 17 | 0.6260 | 9 |
| 18 | 0.9848 | 0.3333 | 0.6591 | 18 | 0.6591 | 7 |

Table 6. Mean response for the grey relational grade.

| Machining Variables | Level 1 | Level 2 | Level 3 | Max-Min | Rank |
|---|---|---|---|---|---|
| Insert type | 0.5809 | **0.6165** | | 0.0356 | 4 |
| Cutting Speed | 0.5816 | 0.5761 | **0.6385** | 0.0624 | 3 |
| Feed | **0.6783** | 0.5896 | 0.5283 | 0.1500 | 1 |
| Depth of Cut | **0.6688** | 0.6172 | 0.5103 | 0.1585 | 2 |

## 6. Conclusion

The recommended optimal cutting parameters of the machining process are 90 m/min for cutting speed, 0.1mm/rev for feed rate, 0.5mm for depth of cut with DLC coated insert in dry cutting conditions. The experiment conducted revealed that the feed rate was the most influential parameter on the surface roughness. Lowest feed rate (0.1 mm/rev) offered minimum surface roughness on three composites 1.1961µm, 0.4428 µm, and 0.5995µm respectively. Addition of graphene based composite showed an improved surface roughness viz. 0.4428µm than that of the composites based on carbon nanotubes (CNT) and $B_4C$. Depth of cut was found to be the most influencing factor on the cutting forces with $B_4C$ composite (264.3N) showing the least cutting force followed by CNT-composites (318.6N) and Graphene- (383.4N) at a depth of cut of 1.5 mm. The highest cutting force was required for Graphene based composite, CNT based required second highest and $B_4C$ based required least. Graphene based and $B_4C$ based composites have the least and the highest surface roughness respectively.

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