Optimization of Machining Parameters of Standard and Edge Chamfered Polycrystalline Diamond Cutting Tools using Taguchi, Entropy – GRA Approaches

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Machining the Al 7075 alloy using polycrystalline diamond (PCD) tools with a high-quality surface finish is difficult. To solve this challenge, numerous researchers across the globe are experimenting with different kinds of cutting tools and optimising machining settings to get better cutting forces and surface roughness. The authors utilised a conventional edge chamfered (80 µm) PCD cutting tool to machine Al 7075 alloy. The primary goal of this study is to use Taguchi-Entropy-Grey Relational Analysis to discover the best machining parameters, such as cutting speed, feed rate, and depth of cut. Initially, a L9 orthogonal array was created using the Taguchi technique to perform the trials. The ideal responses were determined using a grey relational analysis (GRA), which included cutting force, thrust force, shear force, ploughing force, and surface roughness. Furthermore, the GRA's weight values are assessed using an entropy approach. Finally, the GRA with entropy identifies the best combination of machining parameters for Al 7075 alloy utilising the conventional and edge chamfered PCD cutting tools. The weighted GRA with Taguchi shows that the ideal combination of machining parameters for normal PCD cutting tools is v=314m/min, f=0.10 mm/rev, and d=0.1 mm, while for chamfered PCD cutting tools is v=785m/min, f=0.10 mm/rev, and d=0.2 mm. Finally, the ideal findings were compared to Taguchi's anticipated and experimental values for weighted GRG. The results demonstrate that there is no improvement when using the regular PCD cutting tool and a 20.34% improvement when using the chamfered PCD cutting tool to machine Al 7075 alloy. It concludes that the chamfered PCD cutting tool gets superior results than the conventional PCD cutting tool while milling the Al 7075 alloy.
Keywords: Al 7075, PCD cutting tool, Taguchi, Entropy, and GRA.

1. Introduction

This alloy of aluminum 7075 finds usage in all aerospace and automobile industries due to its high index of machinability, high strength to weight ratio, and excellent corrosion resistance. In the current scenario, many researchers around the world are performing machining operations using carbide tools and found that there is excessive tool wear along with poor surface finish on Al alloys. Machining of Al alloys with conventional cutting tools and cutting speeds developed the built-up edge formations that degrade the surface quality of the component. To overcome this difficulty, some researchers have tried high-speed machining operations by utilizing a PCD tool to provide suitable tool life and better surface finish for Al alloys. Zebala et al. [1] have discussed the machining of sintered carbides using PCD tools with three different noise radius. The received cutting forces will help to define the equations for the growth of the components, machining time and tool wear. Obtained equations will help to optimize the process of WC-Co turning using PCD tools with maximal removal rate of metal. Li and Seah [2] conducted a study on the machining of AA2024 consisting of various % of silicon carbide with a different diameters. They observed that the wear of the tool due to coated carbide is acute when the % of SiC is a matrix. Dabade et al. [3] performed machining operation on AA2124/SiCp composite with PCD/CBN tool. The authors used L29 orthogonal array for conducting the number of experiments. The size and % volume of reinforcements have a significant effect on chip formation. In addition, Xu [4] established a two-step finite element model for machining and achieved the distribution of residual stresses with different cutting parameters. Furthermore, the predicted optimal cutting parameters will eventually provide good quality of machining as well as improve the performance of the machined component. Subsequently, the authors discussed optimum geometrical parameters of the PCD tool in cutting Al-Si alloys. Bhushan et al. [6] analyzed the influence of cutting speed, feed rate and depth of cut on surface roughness in machining of Al 7075 metal matrix composites by PCD tool. Davim et al. [7] performed the machining operation on Al 7075 alloy using the PCD and cemented carbide K10 tool to determine thermal and mechanical behavior. The authors found that the PCD tool has performed better compared to K10 tool under temperature, cutting, and feed forces. Manna and Bhattacharyya [8] carried out a series of turning tests on aluminum 10 vol.% SiC metal matrix composite using different tooling systems. They observed the tool wear resulting from the length of machining and cutting time and the effects of feed rate, depth of cut, cutting speed, and inclination angle of the tool on surface finish. Chen et al. [9] discussed conventional and non-conventional machining on SiC particles reinforced with aluminum matrix. Tugrul et al. [10] investigated the effect of cutting edge geometry, work piece hardness, cutting speed and feed rate on resultant force and surface roughness in the hard turning operation of AISI H13 steel. It has been inferred that the effect of cutting edge geometry, work piece hardness, cutting speed, and feed rate on surface roughness is statistically significant. Components of the resultant force depend on cutting edge geometry, work piece hardness and cutting speed. Roy et al. [11] studied the compatibility of cutting tools during the dry machining on Al-Si alloys. The authors recommended natural diamond and PCD cutting tools in the machining process of non-ferrous materials. Aluminum metal matrix composites are not easily machinable due to the abrasive hardness of silicon carbide particles. To improve machining, Kilickap et al. [12] proposed two variants of K10 cutting tools: uncoated K10 tool and TiN coated K10 cutting tool. They reported that the lower feed rate and higher cutting speed produced better surface finish for the uncoated and TiN coated tools. In addition, optimally determining machining parameters for drilling hybrid aluminum metal matrix composites is challenging. To overcome this difficulty, Rajmohan et al. [13] developed a Taguchi-based grey fuzzy algorithm. They observed that the development suggests better machining parameters, and the performance of the drilling process is improved. Rajeswari and Amirthagadeswaran [14] discussed RSM-based GRA to obtain the machinability characteristics of the end milling operation. Optimization was found to result in a minimum surface roughness, cutting force, and tool wear with the maximum value of material removal rate. Iqbal et al. [15] developed the response surface methodology for the optimization of twist extrusion process parameters of AA 7075 aluminum alloy with T6 condition. The RSM was used for establishing an empirical relationship for identifying the factor most influencing the output parameters, including tensile strength and hardness. Further, Lin et al. [16] proposed a grey Taguchi method for performing the experiments in order to get better surface finish parameters for micro-electrical discharge machining. The findings show that the grey Taguchi method perform well in clear improvements in electrode depletion and overcut. Bhaskar et al. [17] examined single-point diamond turning of mono-crystalline germanium. Optimization of the process input parameters, namely, feed rate of the tool, rotational speed, overhang of the tool, rake angle, and depth of the workpiece that lead to optimal surface finish and waviness errors is determined by means of gray Taguchi analysis. Manimaran and Pradeep [18] used Taguchi grey relational analysis for finding the optimal environmental conditions like conventional, cryogenic and dry cooling. They were of the view that the grinding performance was improved due to these optimum environmental conditions. Kamal et al. [19] put forward an integrated approach: Taguchi grey relational analysis (TGRA) with entropy for the determination of the optimal single setting process parameters for friction stir welded joint of AA 6082-T6. Martin and Jozef [20] have compared the machining edge on AA 5083 in terms of laser technology and electrical discharge machining technologies with PCD cutting edge tools. The GRA technique is adapted to optimize the input process parameters for turning operation. Raju and Suhas [21] used TGRA to optimize the parameters for high speed turning of Inconel 718 machining. The result has demonstrated the optimized machining parameters that produce better cutting forces and surface roughness. Later, Jangra et al. [22] discussed Taguchi GRA and entropy method to get the optimal multi wire electrical discharge machining characteristics. Based on the previous researcher's work, it can be observed that many researchers are working on machining various materials using PCD tool. But, very few research work has been done on machining aluminum alloys using PCD tool with the edge chamfered 0 µm and 80 µm. Further, very few researchers have used entropy GRA for determining the optimal machining parameters. Therefore, in the present research work, the authors conducting machining on Al 7075 using a PCD cutting tool with optimal machining parameters.

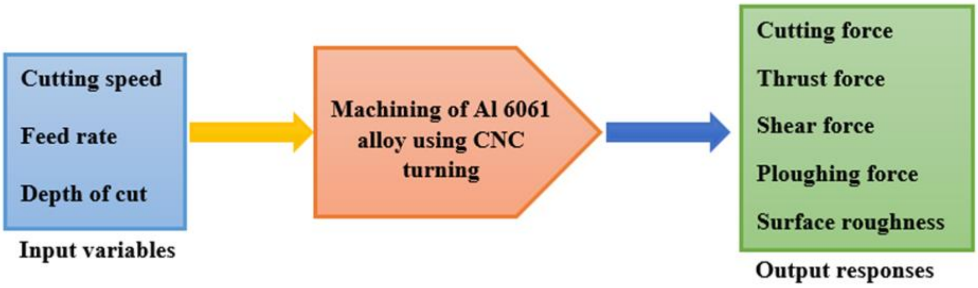


Fig.1 Schematic diagram showing the relation between the input and output responses.

2. Experimentation

In the present work, entropy GRA approach has been used to identify the correlation among input variables and their performance characteristics. Total possible nine combinations are designed by Taguchi design of experiments, which would be very useful in conducting the experiments. Further, the experiments are carried out in ACE Designed W3117 CNC turning machine at IIT Madras.

2.1 Work material

The material selected for machining in this present research work is Al 7075 Alloy. Table.1 is tabulated chemical composition of the Al 7075 alloy. A commercially purchased cylindrical Al 7075 specimen with the dimension diameter, 100mm and length,150 mm was used in this present research work for performing the machining operations.

Table 1. Chemical composition of the Al 7075 alloy.

Element	Al	Mg	Si	Fe	Cu	Cr	Zn	Ti	Mg	Others
% of composition	96.85	0.9	0.7	0.60	0.30	0.25	0.20	0.10	0.05	0.05

2.2 Cutting tool

A commercially available standard PCD and chamfered PCD tool have been used to do the machining operation on Al 7075 alloy. Nose radius is of 0.8 mm. The shape of the tool is rhombus with an included angle of 80°. Its edge length is 9 mm; insert thickness is 4 mm and shank cross-section is 13 x3 mm, respectively. An SSDCL 2525M12 tool holder is used for holding the tool. Therefore, "S" represents the cross-section shape of the holder is square, "S" represents the insert shape square, "D" represents the Damping of the tool, "C" represents the clearance angle 70, "L" represents the left-hand machining, "2525" represents cross-section of the holder 25mm*25mm, "M" represents the tool holder material is mild steel, and "12" represents the insert size is 12mm.

The tool holder back rake angle, toll inclination, side rake angle, side cutting edge angle, and clearance angle are -50 degree, 00 degree, -50 degree, 00 degree, and 70 degree, respectively.

2.3 Experiments Design

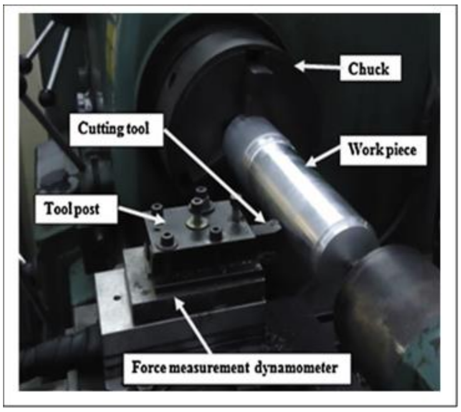
Taguchi orthogonal array has been used in designing a limited number of experiments for the machining operation. The parameters like, cutting speed, feed rate, and depth of cut have been considered to perform the machining operation on Al 7075 alloy. To generate an interaction between three levels, this present research work requires three levels and 7 degrees of freedom. Hence, in this present research work, an L9 orthogonal array is considered to carry out the experiments as it requires 8 degrees of freedom and that is higher than the 7 degrees of freedom, which is more reliable while choosing the machining parameters. The values of the machining parameters are designated in a row of the orthogonal array, and the number of the combination of the machining parameter are 9 is provided in Table 2. The output variables (responses) taken for this investigation are: cutting force, thrust force, shear force, ploughing force and surface roughness.

Table 2 Input parameters and their levels for machining of Al 7075 alloy.

Levels of factors	Input parameters		
	Cutting speed (v) in m/min	Feed rate (f) in mm/rev	Depth of cut (d) in mm
1	314	0.1	0.1
2	565	0.14	0.2
3	785	0.18	0.3

2.4 Experimental procedure

The machining operation is performed by IIT Madras with an ACE designed W3117 CNC turning machine. The maximum spindle speed 7of the turning machine is 6,000 rpm and takes 11 kw power. The cutting speeds are considered as 1000rpm,1800rpm & 2500rpm, the feed rates are considered as 0.1mm/rev, 0.14mm/rev & 0.18mm/rev and the depth of cuts are considered as 0.1mm, 0.2mm & 0.3 mm respectively. There are two types of side edge chafers PCD tools, namely 0 µm and 80 µm, which are applied to the machining operation on Al 7075 alloy. The cutting forces taken into consideration are ploughing force, cutting force, shear force, and thrust forces, which are measured through mounting of a three-component piezo-electric dynamometer on the tool post. The output of the dynamometer signal is amplified by using the charge amplifiers, which is acquired and sampled by a data acquisition card and Kistler dyno ware software. Further, the surface roughness on the machined components was measured using Mahr perthometer. The cut-off length and sampling length for the measurements are 0.8mm and 4.0 mm, respectively. Photographs of piezo-electric dynamometer used for force measurement are shown as figures 2 (a). Figure 2 (b)



(a) (b)

Fig 2. Schematic diagram showing the (a) dynamometer for force measurement, and (b) surface roughness measurement.

3 Grey Relational Analysis (GRA)

In the current study, for carrying out the machining operation on Al 7075 alloy authors have used Taguchi analysis and designed 9 different experiments. Hence in GRA above 9 different experiments will become 9 subsystems. Also, the impact of the developed 9 subsystems on the response variables: cutting force, thrust force, shear force, ploughing force, and surface roughness is to be investigated through the GRA technique. For optimizing output responses in this study, a grey relational analysis has been used. The following are the steps that must be performed in order to attain the multiple characteristic optimizations using GRA. In a sequence manner, apply the normalization for all the experimental values.

- Obtain the GRC after carrying out the grey relational generation.
- Utilize the entropy method to find the GRG. The entropy method will facilitate to assign the weights of each machining characteristic.
- Measure the weighted GRG to S/N ratio using the Taguchi method to extract the most significant parameters that influence the various multi-machining characteristics.
- Determine the optimal levels of the process parameters.
- Lastly, a confirmation experiments has been conducted in order to confirm the optimal processing parameters.

After statistical analysis, the highest weighted GRG will thus yield the smallest cutting force, thrust force, shear force, ploughing force and surface roughness values respectively.

To limit the five responses initially, the problem has been formulated into a multi-objective optimization problem. It is stated as Minimization: f (CF, TF, SF, PF and SR)", ranges of the independent input decision variables such as, cutting speed denoted as v (m/min); $314 \leq 565 \leq 785$, feed rate represented as f (mm/rev); $0.1 \leq 0.14 \leq 0.18$ and depth of cut indicated as d (mm); $0.1 \leq 0.2 \leq 0.3$. It can also be seen that the number of output responses is high and it is very difficult to reduce the number of responses. Overcoming this difficulty, the multi-objective optimization problem has been transformed into a single objective optimization problem by making use of GRA technique in the present study. This section has focused upon the step-wise procedure of the GRA optimization.

3.1 Data processing

At the primary stage, data needs to be processed to convert the data obtained from the original sequence into comparable sequence. For this operation, a linear normalization of the data obtained from the experiment in between 0 and 1 that is called as grey relational generation. Based on the objective function, the results obtained from the experimental procedure may be normalized in three different forms: "the larger the better", "the smaller the better", and "the nominal the better". In the present work,

At the first step of processing GRA data, after achieving S/N ratio for 9 tests, normalization of the response variables and the deviation sequences were calculated. Thereafter, the grey relational coefficients and the weighted grey relational grades for all the tests were determined.

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (1)$$

where $x_i(k)$ and $y_i(k)$ are the sequence after the data processing and original sequence of experimental values. where i = 1, 2, 3, …, m and k = 1, 2 …, n with m = 9 and n = 5; maximum of $y_i(k)$ is the largest value of $y_i(k)$ and minimum of $y_i(k)$ is the smallest value of $y_i(k)$.

Moreover, the deviation sequence is calculated by Eq.2 where, $\Delta_{0i}(k)$ is the absolute difference between the reference sequence $y_i(k)$ and the comparable sequence $x_i(k)$ after normalization.

$$\Delta_{0i}(k) = |y_i(k) - x_i(k)| \quad (2)$$

3.2 Grey relational coefficient (GRC)

In this step, the GRCs are determined to make the relationship between the best (reference) and actual normalized value. The GRC can be found using the following equation, that is, Eq).

$$\gamma_{0,i}(k) = \frac{\Delta_{min}+\zeta\Delta_{max}}{\Delta_{0i}(k)+\zeta\Delta_{max}} \quad (3)$$

here ζ is the distinguish coefficient and value can be varied between 0 to 1. The aim of introducing this coefficient is to make the relational degree between the reference sequences and comparability 9 sequences. However, in the above scenario, the value of ζ is taken as 0.5. Besides, Δ_min is the minimum value of mini mink $|y_i (k)-x_i (k)|$ and Δmax is the maximum value of $max_i\, max_k|y_i(k) - x_i(k)|$.

3.3 Grey relational grade (GRG)

The weighting sum of the GRC's is called the GRG. The entire evaluation of multiple performance characteristics is based on the GRG.

$$\Gamma_{0,i} = \sum_{k=1}^{n} w_k\, \gamma_{0,i}(k), i = 1,2, \dots \dots \dots \dots \dots m \quad (4)$$

where w_k indicates the weight of the k^{th} machining characteristics, and $\sum_{k=1}^{n} w_k = 1$.

The ranges of multiple characteristics will rely on the value of weights. The weights can be calculated either by changing the parameters setting or by change in the influence of the parameters. But, the authors in this study considered a new method called entropy weight method for assigning the weights of each machining characteristic.

In 1947, Shannon and Weaver [23] proposed the entropy weight method for finding out the weights of the responses. In this technique, the uncertain information of the entropy is calculated by using the concept of probability theory. It computes the significance of each response without any consideration of the preference of the decider, who may be an engineer or a manager. The working principle of EWM will provide superior weight indicator information is more constructive than the lower indicator information. The proposed method will include first deciding objectives (decision matrix) and then determination of the normalized decision matrix. Therefore, to compute the objective weights the following steps are considered. Step 1 Objective Alternatives/experiments are worked out with suitable evaluation criteria/responses allied with it (e.g., design of experiments). Step 2 Decision Matrix

The decision template is given in Eq. (5). Every row of a decision template or matrix is allocated to one experiment and all columns to one response, such as Cutting force, Thrust force, Ra etc. Therefore the contributions for the decision template or matrix, eij of the decision template 'DT' [eij; i ¼ 1, 2, …, a no. of experiments (n), j ¼ 1,2, ., no. of responses (m)].

$$DT = \begin{bmatrix} q_{11} & q_{12} & \cdots & q_{1j} & \cdots & q_{1m} \\ q_{21} & q_{22} & \cdots & q_{2j} & \cdots & q_{2m} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ q_{i1} & q_{i2} & \cdots & q_{ij} & \cdots & q_{im} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ q_{n1} & q_{n2} & \cdots & q_{nj} & \cdots & q_{nm} \end{bmatrix} \quad (5)$$

Step 3 Normalization

The linear normalization technique is employed in order to make the experimental results of 'DT' dimensionless because there are several units of the responses. For a favorable response, Eq. (6) is used and for a non-favorable reaction, for example, Ra and it is observable that normalized decision matrix NDM € (0;1).

$$NDM_{ij} = \frac{q_{ij}}{Maxq_{ij}}\ (Beneficial) \quad (6)$$

$$NDM_{ij} = \frac{Minq_{ij}}{q_{ij}}\ (Non - beneficial) \quad (7)$$

Step 4 Probabilities and Entropy

The probability of the response (Pr_{ij}) to occur, be computed by Eq. (8) and Eq. (9) is utilized to attain the Entropy (En_j) of the jth response.

$$Pr_{ij} = \frac{NDM_{ij}}{\sum_{i=1}^{n} NDM_{ij}} \quad (8)$$

$$En_j = -\Upsilon \sum_{i=1}^{n} \mathrm{Pr_{ij}} \log_e(\mathrm{Pr_{ij}}) \quad (9)$$

It can be noted that if $\Upsilon = \frac{1}{\log_e(n)}$ is a stable expression, n indicates number of experiments and value of ***En**j* lies between zero and one.

Step 5 Divergence and Entropy Weights

The degree of divergence of (Div_j) is calculated by using Eq. (10), and the entropy weight of the j_{th} response E_w is acquired using Eq. (11).

$$\mathrm{Div_j} = |1 - En_j| \quad (10)$$

$$\mathrm{EW_j} = \frac{\mathrm{Div_j}}{\sum_{j=1}^{m} \mathrm{Div_j}} \quad (11)$$

Finally, optimum levels of the process parameters were computed taking into account the signal to noise (S/N) ratio for the grey relational grade using Taguchi method. In this way, "larger is better" condition was utilized for attaining the optimum process parameters for multi-response optimization since the larger GRG was intended. So, the signal to noise ratio has been considered by Taguchi for obtaining the "larger is better" quality from responses.

$$S/N = -10 \log\left[\frac{1}{n}\sum_{1}^{n}\frac{1}{y_i^2}\right] \quad (12)$$

where n is the number of measurements in each experiment and yi as the ith measurement of the experimental result, respectively. From the above method, maximum S/N ratio shows that which process parameter is the best to obtain the response.

Finally, the confirmation experiments of the process parameters at optimum levels were done to confirm the multi-response optimization. Hence, the predicted WGRG (ηpredicted) at optimum process parameters can be presented as:

$$\eta_{predicted} = \eta_m + \sum_{i=1}^{n}(\eta_i - \eta_m) \quad (13)$$

where $\eta_{predicted}$, represents the predicted optimum WGRG process parameters, η_m indicates the total mean of GRG, η_i denotes the mean of GRG at optimum levels, and *n* indicates the number of process parameters significantly affecting quality characteristics.

4. Results & Discussion

In the present research work, after machining the responses cutting force, thrust force, shear force, ploughing force, and surface roughness at various machining parameters are given in Table 3 (a) and 3 (b).

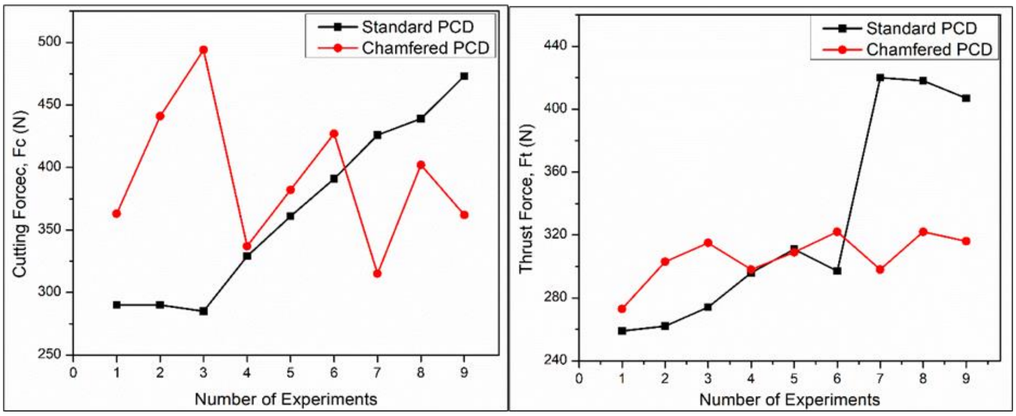
Table 3 (a). Experiments designed using L_9 orthogonal array for standard PCD cutting tool.

Exp. No	Cutting speed (v) mm/rev	Feed rate (f) m/min	Depth of cut (d) mm	Cutting force (F_c) N	Thrust force (F_t) N	Shear force (F_s) N	Ploughing force (F_p) N	Surface roughness (Ra)
1	314	0.1	0.1	290	259	83	306	0.692
2	314	0.14	0.2	290	262	105	286	0.702
3	314	0.18	0.3	285	274	115	280	0.769
4	565	0.1	0.1	329	296	98	345	0.794
5	565	0.14	0.2	361	311	140	336	0.525

6	565	0.18	0.3	391	297	151	344	0.486
7	785	0.1	0.1	426	420	139	459	0.595
8	785	0.14	0.2	439	418	172	434	0.604
9	785	0.18	0.3	473	407	154	470	0.995

Table 3 (b). Experiments designed using L_9 orthogonal array for chamfered PCD cutting tool.

Exp. No	Cutting speed (v) mm/rev	Feed rate (f) m/min	Depth of cut (d) mm	Cutting force (F_c) N	Thrust force (F_t) N	Shear force (F_s) N	Ploughing force (F_p) N	Surface roughness (Ra)
1	314	0.1	0.1	363	273	134	320	0.671
2	314	0.14	0.2	441	303	217	318	0.669
3	314	0.18	0.3	494	315	284	302	0.598
4	565	0.1	0.2	337	298	125	325	0.596
5	565	0.14	0.3	382	309	169	322	0.568
6	565	0.18	0.1	427	322	163	372	0.724
7	785	0.1	0.3	315	298	129	305	0.702
8	785	0.18	0.2	402	322	168	347	0.781
9	785	0.14	0.1	362	316	114	367	0.776



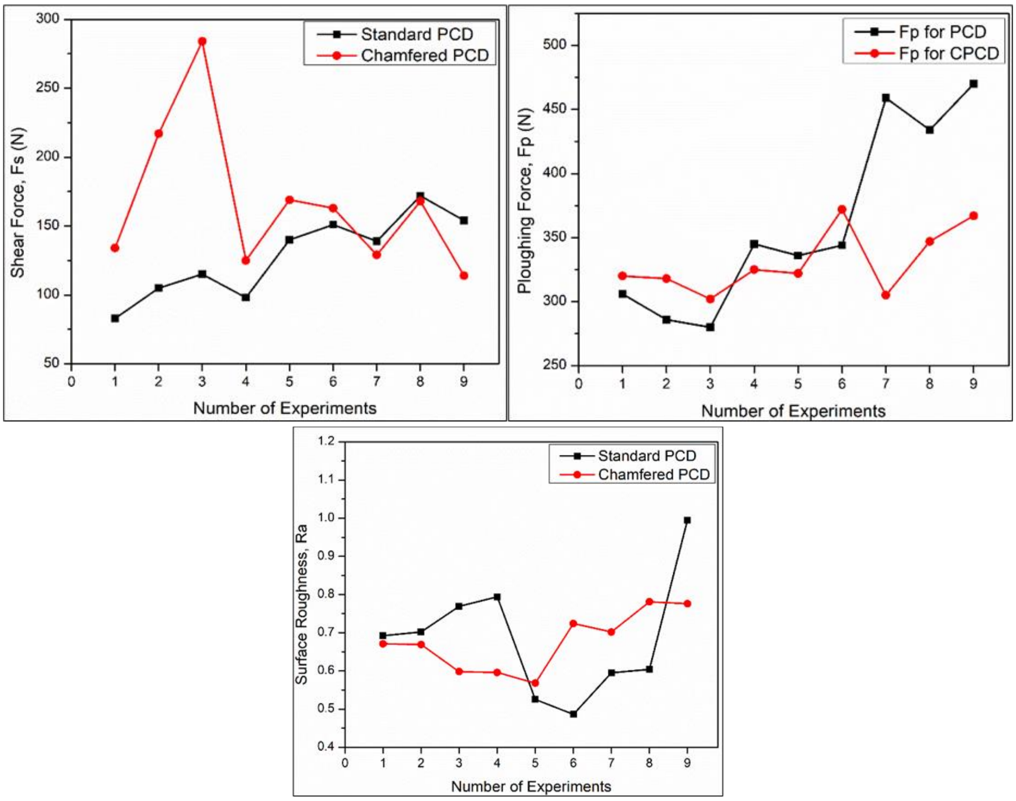


Fig. Schematic diagram showing the number of experiments with output responses (a) cutting force, (b) thrust force, (c) shear force, (d) ploughing force, and (e) surface roughness.

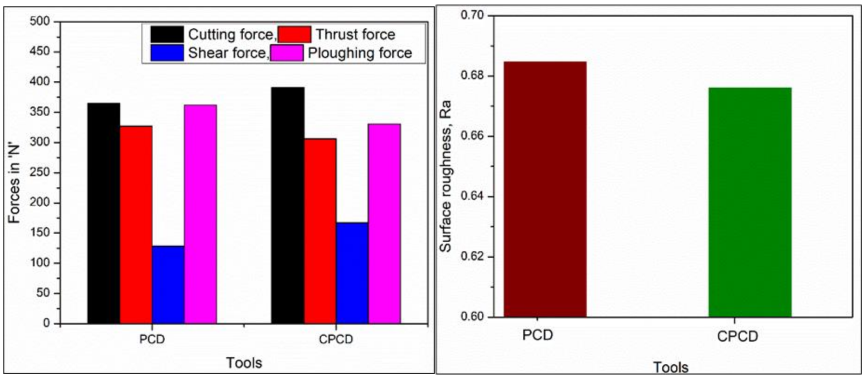


Fig. Schematic diagram showing the tools vs average output responses (a) forces, and (b) surface roughness.

To conduct the machining operation on Al 7075 alloy using standard PCD and Chamfered PCD tools lower cutting force, thrust force, shear force, ploughing force and surface roughness are performing better. Therefore, while evaluating data pre-processing in GRA the all output responses are considered as the “lower is better” (LB) and the normalized values of the output responses of the standard PCD and chamfered PCD cutting tools are given in Table 4 (a) and (b).

Table 4 (a) Normalized values for various output responses of the standard PCD cutting tool.

Exp. No	Normalized Values (PCD Insert)				
	Cutting Force(Fc) N	Trust force(Ft) N	Shear Force(Fs) N	Ploughing Force(Fp) N	Surface Roughness Ra
1	0.9734	1.0000	1.0000	0.8632	0.5953

2	0.9734	0.9814	0.7528	0.9684	0.5756
3	1.0000	0.9068	0.6404	1.0000	0.4440
4	0.7660	0.7702	0.8315	0.6579	0.3949
5	0.5957	0.6770	0.3596	0.7053	0.9234
6	0.4362	0.7640	0.2360	0.6632	1.0000
7	0.2500	0.0000	0.3708	0.0579	0.7859
8	0.1809	0.0124	0.0000	0.1895	0.7682
9	0.0000	0.0807	0.2022	0.0000	0.0000

Table 4 (b) Normalized values for various output responses of the chamfered PCD cutting tool.

Exp. No	Normalized Values (Chamfered PCD Insert)				
	Cutting Force(Fc) N	Trust force(Ft) N	Shear Force(Fs) N	Ploughing Force(Fp) N	Surface Roughness Ra
1	0.7318	1.0000	0.8824	0.7429	0.5164
2	0.2961	0.3878	0.3941	0.7714	0.5258
3	0.0000	0.1429	0.0000	1.0000	0.8592
4	0.8771	0.4898	0.9353	0.6714	0.8685
5	0.6257	0.2653	0.6765	0.7143	1.0000
6	0.3743	0.0000	0.7118	0.0000	0.2676
7	1.0000	0.4898	0.9118	0.9571	0.3709
8	0.5140	0.0000	0.6824	0.3571	0.0000
9	0.7374	0.1224	1.0000	0.0714	0.0235

After determining the normalized values, the deviation sequence of each experiment value was calculated using Eq. (3). Further, the grey relational coefficient of the both standard PCD and chamfered PCD tools for each experiment of the L9 orthogonal array were calculated by using Eq. (3) and given in table 5(a) and (b).

Table 5 (a) Grey relational coefficients of the standard PCD cutting tool.

Exp. No	Grey Relational Coefficients (PCD Insert)				
	Cutting Force(Fc) N	Trust force(Ft) N	Shear Force(Fs) N	Ploughing Force(Fp) N	Surface Roughness Ra
1	0.9495	1.0000	1.0000	0.7851	0.5527
2	0.9495	0.9641	0.6692	0.9406	0.5409
3	1.0000	0.8429	0.5817	1.0000	0.4735
4	0.6812	0.6851	0.7479	0.5938	0.4524

5	0.5529	0.6075	0.4384	0.6291	0.8671
6	0.4700	0.6793	0.3956	0.5975	1.0000
7	0.4000	0.3333	0.4428	0.3467	0.7001
8	0.3790	0.3361	0.3333	0.3815	0.6832
9	0.3333	0.3523	0.3853	0.3333	0.3333

Table 5 (b) Grey relational coefficients of the chamfered PCD cutting tool.

Exp. No	Grey Relational Coefficients (Chamfered PCD Insert)				
	Cutting Force(Fc) N	Trust force(Ft) N	Shear Force(Fs) N	Ploughing Force(Fp) N	Surface Roughness Ra
1	0.6509	1.0000	0.8095	0.6604	0.5084
2	0.4153	0.4495	0.4521	0.6863	0.5133
3	0.3333	0.3684	0.3333	1.0000	0.7802
4	0.8027	0.4949	0.8854	0.6034	0.7918
5	0.5719	0.4050	0.6071	0.6364	1.0000
6	0.4442	0.3333	0.6343	0.3333	0.4057
7	1.0000	0.4949	0.8500	0.9211	0.4428
8	0.5071	0.3333	0.6115	0.4375	0.3333
9	0.6557	0.3630	1.0000	0.3500	0.3386

Further, the weights required to determine the GRG are obtained from the entropy method. The weights calculated from Eq. (5) to Eq. (11) are required to calculate the GRG for the outputs cutting force, thrust force, shear force, ploughing force and surface roughness of the standard PCD and chamfered PCD cutting tool. The weights recommended for the standard PCD tool are found to be 0.17, 0.17, 0.28, 0.17 and 0.21 respectively shown in Table 6(a), and for the chamfered PCD tool are found to be 0.17, 0.02, 0.64, 0.05 and 0.12 respectively shown in Table 6(b). The grey relational grade is to be calculated after inserting the above weights in Eq. (4). Table 7(a) and (b) shows the GRG for the standard PCD cutting tool and chamfered PCD cutting tool.

Table 6(a) Entropy Weight values of the standard PCD cutting tool.

Probability					Pr_ij log_e (Pr_ij				
Cutting Force(Fc) N	**Trust force(Ft) N**	**Shear Force(Fs) N**	**Ploughing Force(Fp) N**	**Surface Roughness Ra**	**Cutting Force(Fc) N**	**Trust force(Ft) N**	**Shear Force(Fs) N**	**Ploughing Force(Fp) N**	**Surface Roughness Ra**
0.1352	0.1354	0.1634	0.1270	0.1052	-0.2705	-0.2707	-0.2960	-0.2621	-0.2369
0.1352	0.1338	0.1292	0.1359	0.1037	-0.2705	-0.2692	-0.2643	-0.2712	-0.2350

0.1375	0.1280	0.1179	0.1388	0.0947	-0.2729	-0.2631	-0.2521	-0.2741	-0.2232
0.1191	0.1185	0.1384	0.1127	0.0917	-0.2535	-0.2527	-0.2737	-0.2460	-0.2191
0.1086	0.1127	0.0969	0.1157	0.1387	-0.2411	-0.2461	-0.2261	-0.2495	-0.2740
0.1002	0.1181	0.0898	0.1130	0.1498	-0.2306	-0.2522	-0.2164	-0.2464	-0.2844
0.0920	0.0835	0.0976	0.0847	0.1224	-0.2195	-0.2073	-0.2271	-0.2091	-0.2571
0.0893	0.0839	0.0788	0.0896	0.1206	-0.2157	-0.2079	-0.2003	-0.2161	-0.2551
0.0829	0.0862	0.0881	0.0827	0.0732	-0.2064	-0.2112	-0.2140	-0.2061	-0.1914
			$\sum_{i=1}^{n} Pr_{ij} \log_e(Pr_{ij})$		-2.1806	-2.1804	-2.1700	-2.1806	-2.1762
			$Y = \frac{1}{\log_e(n)}$		0.45512				
			En_j		0.9924	0.9924	0.9876	0.9924	0.9904
			$Div_j = \lvert 1 - En_j \rvert$		0.0076	0.0076	0.0124	0.0076	0.0096
					0.0448				
			EW_j		0.17	0.17	0.28	0.17	0.21

Table 6(b) Entropy Weight values of the chamfered PCD cutting tool.

Probability					log_e (Pr_ij				
Cutting Force(Fc) N	**Trust force(Ft) N**	**Shear Force(Fs) N**	**Ploughing Force(Fp) N**	**Surface Rougness Ra**	**Cutting Force(Fc) N**	**Trust force(Ft) N**	**Shear Force(Fs) N**	**Ploughing Force(Fp) N**	**Surface Rougness Ra**
0.1177	0.1243	0.1284	0.1143	0.1106	-0.2519	-0.2592	-0.2636	-0.2479	-0.2436
0.0969	0.1120	0.0793	0.1150	0.1110	-0.2262	-0.2452	-0.2010	-0.2488	-0.2440
0.0865	0.1078	0.0606	0.1211	0.1241	-0.2117	-0.2401	-0.1699	-0.2557	-0.2590
0.1268	0.1139	0.1376	0.1126	0.1246	-0.2619	-0.2474	-0.2730	-0.2459	-0.2595
0.1119	0.1098	0.1018	0.1136	0.1307	-0.2451	-0.2426	-0.2326	-0.2471	-0.2660
0.1001	0.1054	0.1056	0.0983	0.1025	-0.2304	-0.2372	-0.2373	-0.2281	-0.2335
0.1357	0.1139	0.1334	0.1199	0.1057	-0.2710	-0.2474	-0.2687	-0.2544	-0.2376
0.1063	0.1054	0.1024	0.1054	0.0951	-0.2383	-0.2372	-0.2334	-0.2372	-0.2237
0.1181	0.1074	0.1509	0.0997	0.0957	-0.2522	-0.2396	-0.2854	-0.2298	-0.2245
			$\sum_{i=1}^{n} Pr_{ij} \log_e(Pr_{ij})$		-2.1887	-2.1960	-2.1648	-2.1948	-2.1913
			$Y = \frac{1}{\log_e(n)}$		0.45512				
			En_j		0.9961	0.9994	0.9852	0.9989	0.9973
			$Div_j = \lvert 1 - En_j \rvert$		0.0039	0.0006	0.0148	0.0011	0.0027
					0.0231				
			EW_j		0.17	0.02	0.64	0.05	0.12

Table 7(a) Weighted GRG of the standard PCD cutting tool.

Exp. No	Weighted GRC (PCD Insert)					WGRG
	Cutting Force(Fc) N	Trust force(Ft) N	Shear Force(Fs) N	Ploughing Force(Fp) N	Surface Roughness Ra	
1	0.1606	0.1707	0.2768	0.1329	0.1183	0.1719
2	0.1606	0.1646	0.1853	0.1592	0.1158	0.1571
3	0.1691	0.1439	0.1610	0.1693	0.1014	0.1489
4	0.1152	0.1170	0.2070	0.1005	0.0969	0.1273
5	0.0935	0.1037	0.1214	0.1065	0.1856	0.1221
6	0.0795	0.1160	0.1095	0.1011	0.2141	0.1240
7	0.0676	0.0569	0.1226	0.0587	0.1499	0.0911
8	0.0641	0.0574	0.0923	0.0646	0.1463	0.0849
9	0.0564	0.0601	0.1067	0.0564	0.0714	0.0702

Table 7(b) Weighted GRG of the chamfered PCD cutting tool.

Exp. No	Weighted GRC (PCD Insert)					WGRG
	Cutting force (Fc) N	Trust force (Ft) N	Shear force (Fs) N	Ploughing force (Fp) N	Surface Roughness Ra	
1	0.1100	0.0246	0.5183	0.0320	0.0599	0.1489
2	0.0702	0.0111	0.2894	0.0332	0.0604	0.0929
3	0.0564	0.0091	0.2134	0.0484	0.0919	0.0838
4	0.1357	0.0122	0.5668	0.0292	0.0932	0.1674
5	0.0967	0.0100	0.3887	0.0308	0.1177	0.1288
6	0.0751	0.0082	0.4061	0.0161	0.0478	0.1107
7	0.1691	0.0122	0.5442	0.0446	0.0521	0.1644
8	0.0857	0.0082	0.3915	0.0212	0.0392	0.1092
9	0.1108	0.0089	0.6402	0.0169	0.0399	0.1634

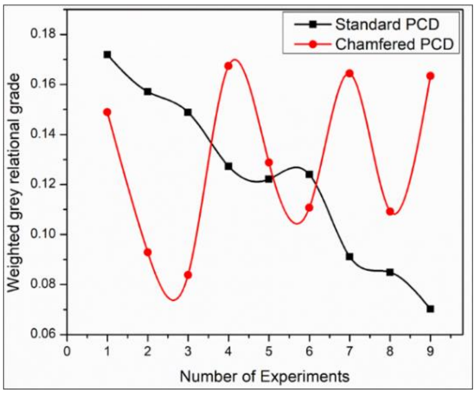


Fig. Results showing the number of experiments vs weighted GRG.

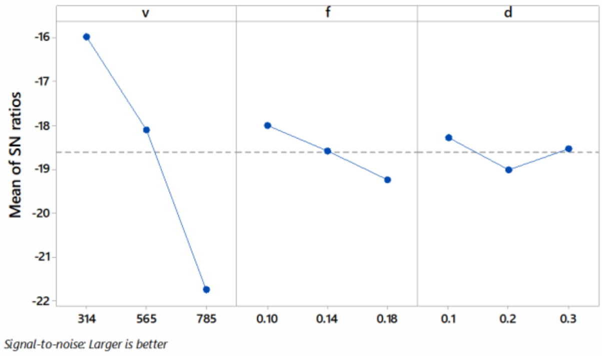


Fig. 3(a) S/N ratios for the weighted GRG of the standard PCD cutting tool.

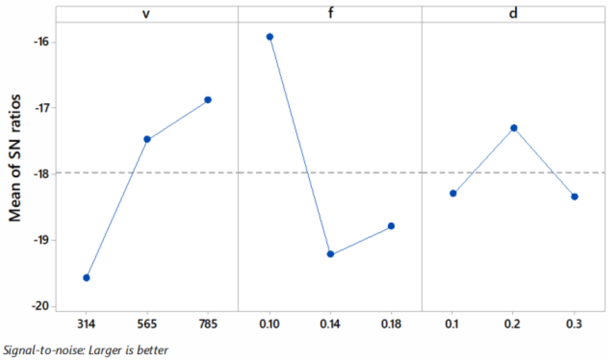


Fig.3(b) S/N ratios for the weighted GRG of the edge chamfered PCD cutting tool.

In the present study, to maintain a strong relationship between the experimental and normalized values, a high value of GRG is taken into consideration. Those relevant parameters obtained at a higher grey relational grade are considered as optimized process parameters. Further, the multi-response S/N ratio were measured using Eq. (12). Thus, the high S/N ratio showed an optimum level of output parameters in the Taguchi method. Table 8(a) and (b) shows response table for signal to noise ratio of standard PCD cutting tool and edge chamfered PCD cutting tool. The data used for table 8(a) and (b) were calculated by finding average of each controllable factor at different respective levels. The delta column mentioned the differences that signify feed rate was the most influential factor out of all the control parameters. Thus, the optimal setting of process parameters of standard PCD cutting tool as well as edge chamfered PCD cutting tool were found to be by taking Fig. 3 (a) and (b) of the response table. Subsequently, the optimum level of parameters determined for the standard PCD cutting tool was cutting speed (1st level), feed rate (2nd level) and depth of cut (3rd level) and for the edge chamfered PCD cutting tool cutting speed (2nd level), feed rate (1st level) and depth of cut (3rd level). Finally, the overall weighted GRG mean for 9 experiments of the standard and edge chamfered PCD cutting tool were found to be

0.1219 and 0.1299, as shown in Table 8 (a) and (b). Table 8(a) Response table for the signal to noise ratios of the standard PCD cutting tool

Level Cutting speed (v) in m/min Feed rate (f) in mm/rev Depth of cut (d) in mm1 -15.97 -18.00 -18.28 2 -18.10 -18.59 -19.02 3 -21.77 -19.25 -
18.54 Delta 5.80 1.25 0.74 Rank 1 2 3
Table 8(b) Response table for the signal to noise ratios of the edge chamfered PCD cutting tool

Level	Cutting speed (v) in m/min	Feed rate (f) in mm/rev	Depth of cut (d) in mm
1	-19.57	-15.92	-18.30
2	-17.48	-19.23	-17.30
3	-16.88	-18.80	-18.34
Delta	2.69	3.31	1.04
Rank	2	1	3

Confirmation Experiment: Finally, a confirmation experiments have been performed three times and repeated at the optimum level of control parameters for standard PCD cutting tool (v1-f1-d1) and chamfered PCD cutting tool (v3-f1-d2) to obtain the improvement of responses.

The predicated weighted grey relational grade was obtained from Eq. (13) and the experimental value obtained from the experiments at optimum parameters. Table 9 indicates the summarized data of the predicted and experimental grey relational grade. Table 9 From Table 9, it has been observed that a good agreement between the predicted and experimental value. Table 10 is further used to represent the percentage of improvement of between the initial and optimal machining parameters of the standard PCD and Chamfered PCD cutting tool in terms of weighted grey relational grade. It has also found that there is no improvement between the predicted and experimental value of the standard PCD cutting tool. Because, the initial machining parameter setting (v1-f1-d1) and the optimal machining parameter setting (v1-f1-d1) are same. In the case of chamfered PCD tooling, an improvement has been shown to be there in between the values predicted and experimental values. The initial setting of machining parameter (v1-f1-d1) weighted grey relational grade is 0.1489 while the optimized machining parameter setting is (v3-f1-d2) weighted grey relational grade is 0.1792. The percentage improvements of the grey relational grade of the initial and optimal machining parameters of the standard PCD cutting tool are 0%, and those of the chamfered PCD cutting tool are 20.34%. The chamfered PCD cutting tool performs comparatively better than the standard PCD cutting tool where the optimal machining parameters encompassing a cutting force, thrust force, shear force, ploughing force, and surface roughness are determined through entropy GRA based on Taguchi's method.

Table 9. Conformation experiments.

Tool	Optimal Settings	Taguchi Predicted Value	Experimental value
PCD	v_1-f_1-d_1	0.1719	0.1719
CPCD	v_3-f_1-d_2	0.1812	0.1792

Table 10. WGRG at initial and optimal machining parameter settings.

WGRG	Initial machining parameter settings (v_1-f_1-d_1)	Optimal machining parameter settings		% Improvement
		PCD (v_1-f_1-d_1)	CPCD (v_3-f_1-d_2)	

WGRG for PCD	0.1719	0.1719		0%
WGRG for CPCD	0.1489		0.1792	20.34%

3. Conclusions

This paper obtained optimal machining parameters using Taguchi entropy grey relational analysis. The chosen quality targets were cutting force, thrust force, shear force, ploughing force, and the surface roughness of the machined specimens. For the work presented, 9 experiments were designed by making use of Taguchi design of experiments. The GRA technique has converted the given problem into a single objective optimization problem. The weights of the grey relational grade of the standard PCD and Chamfered PCD cutting tools are calculated by the entropy method. From the conclusions of the present work, the following have been observed:

1. Optimum setting parameters for performing the machining operation using standard PCD cutting tool: v=314 m/min, f=0.10 mm/rev and d=0.1 mm and using chamfered PCD cutting tool: v=785 m/min, f=0.10 mm/rev and d=0.2 mm to yield the optimum values for cutting force, thrust force, shear force, ploughing force, and surface roughness.
2. Among all the tested parameters, cutting force is more influenced when employing standard PCD cutting tool, while feed rate is more influenced on the chamfered PCD cutting tool to obtain the optimal cutting force, thrust force, shear force, ploughing force, and surface roughness.
3. There is no enhancement in the value of calculated and experimental weighted grey relational grade of the standard PCD cutting tool. Values of calculated weighted grey relational grade are improved from 0.1489 to 0.1812 and experimental weighted grey relational grade value from 0.1489 to 0.1792. It confirms that the improvement of the machining process performance with optimal values of process parameters is true.
4. The conclusion is that to machine Al 7075 alloy, the chamfered PCD cutting tool gives a better optimal result than a standard PCD cutting tool..

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