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A Design of Experiment Approach to Compare the Machining Performance of CNC End Milling

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ABSTRACT

The surface roughness is a very significant indicator of surface quality. It represents an essential exploitation requirement and influences technological time and costs, i.e. productivity. The objective of this paper is to compare the surface roughness of the two materials and to analyze the influence of end milling cutting parameters (number of revolution, feed rate and depth of cut) on the surface roughness of Aluminum alloys. In order to improve the quality and productivity the present study highlights the optimization of CNC end milling process parameters to provide good surface finish. The surface finish has been identified as one of the main quality attribute and is directly related to the productivity of a machine. In this paper an attempt has been made to optimize the process such that the best surface roughness value can be obtained in a process. Principal component analysis (PCA) and grey relational analysis are used to predict the surface roughness in end milling operation to analyse the pre measured test data. These applications can simulate the end milling process and surface roughness Ra (μm) prediction graphs against cutting conditions simultaneously.

Keywords: ANOVA, Grey Relational Analysis, End Milling, Surface Roughness.

1. INTRODUCTION

In this research the various surface roughness measurements of the product prepared by CNC end milling operation are to be studied experimentally and the results will be interpreted analytically. Quality and productivity are two important criteria in any machining operation. But it can be seen that as the quality increases the productivity seems to decrease. It is therefore essential to optimize quality and productivity simultaneously. In this case we are only considering the different surface roughness parameters. The product being machined has to have the minimum surface roughness and in order to obtain the high quality the processing time has to be compromised which directly affects the productivity. Thus it is very important to optimize both of the factors simultaneously. The interdependence and correlation among quality and productivity is very complex and difficult to understand. In most of the cases the optimization is based on a single objective function. In certain cases it has proven to be effective but in most of the cases it has adverse affects. Therefore multiple objectives have to be optimized simultaneously. Milling is a very useful machining operation and is the most widely used equipment for producing various kinds of different components. Now the conventional milling machines have been replaced with the CNC milling machines that are very flexible and very fast in their operation. Hence various research work has been done in order to optimize the milling processes and our work also involves optimizing the milling operation in order to get the most reasonable results. In end milling surface finish is one of the most important aspects. There are many roughness parameters and Ra is the most commonly used. Some parameters are used within certain industries or within certain countries.

2. GREY RELATIONAL ANALYSIS

Grey relational analysis was proposed by Deng in 1989 as cited in is widely used for measuring the degree of relationship between sequences by grey relational grade. Grey relational analysis is applied by several researchers to Optimize control parameters having multi-responses through grey relational grade. The use of Taguchi method with grey relational analysis to optimize the end milling operations with multiple performance characteristics includes the following steps:

1. To identify the performance characteristics and cutting parameters to be evaluated.
2. To determine the number of levels for the process parameters.
3. To select the appropriate orthogonal array and assign the Cutting parameters to the orthogonal array.
4. To conduct the experiments based on the arrangement of the orthogonal array.
5. To normalize the experiment results of cutting Tool life and surface roughness.
6. To perform the grey relational generating and calculate the grey relational coefficient.
7. To calculate the grey relational grade by averaging the grey relational coefficient.
8. To analyze the experimental results using the grey Relational grade and statistical ANOVA.
9. To select the optimal levels of cutting parameters.

10. To verify the optimal cutting parameters through the confirmation experiment.

2.1 Data Pre-Processing

In grey relational analysis, the data pre-processing is the first step performed to normalize the random grey data with different measurement units to transform them to dimensionless parameters. Thus, data pre-processing converts the original sequences to a set of comparable sequences. Different methods are employed to pre-process grey data depending upon the quality characteristics of the original data. The original reference sequence and pre -processed data (comparability sequence) are represented by $X_0^{(0)}$ and $X_i^{(0)}$, i =1,2,….,m; k =1,2,.....,n respectively, where m is the number of experiments and n is the total number of observations of data. Depending upon the quality characteristics, the three main categories for normalizing the original sequence: If the original sequence data has quality characteristic as 'larger-the-better' then the original data is pre-processed as
'Larger-the-best':

$$x_i^*(k) = \frac{x_i^{(0)}(k) - \min x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)} \quad (1)$$

If the original data has the quality characteristic as 'smaller the better', then original data is pre-processed as 'smaller the best':
However, if the original data has a target optimum value (OV) then quality characteristic is 'nominal-the-better' and the original data is pre-processed as 'nominal-the-better':

$$x_i^*(k) = 1 - \frac{|x_i^{(0)}(k) - OV|}{\max\{\max x_i^{(0)}(k) - OV, OV - \min x_i^{(0)}(k)\}} \quad (2)$$

Also, the original sequence is normalized by a simple method in which all the values of the sequence are divided by the first value of the sequence.

$$x_i^*(k) = \frac{x_i^{(0)}(k)}{x_i^{(0)}(1)} \quad (3)$$

Where max $X_i^{(0)}(k)$ and min $X_i^{(0)}(k)$ are the maximum and minimum values respectively of the original sequence $X_i^{(0)}(k)$.Comparable sequence $X_i^*(k)$ is the normalized sequence of original data.

$$x_i^*(k) = \frac{\max x_i^{(0)}(k) - x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)} \quad (4)$$

2.2 Grey Relation Grade

Next step is the calculation of deviation sequence, $\Delta oi\ (k)$ from the reference sequence of pre-processes data $X_i^*(k)$ and the comparability sequence $X_i^*(k)$.The grey relational coefficient is calculated from the deviation sequence using the following relation:

$$\gamma(x_0^*(k), x_i^*(k)) = \frac{\Delta \min + \xi \Delta max}{\Delta oi(k) + \xi \Delta max} \quad 0 < \gamma(x_0^*(k), x_i^*(k)) \le 1 \quad (5)$$

Where $\Delta oi\ (k)$ is the deviation sequence of the reference sequence $x_0^*\ (k)$ and comparability sequence $x_i^*\ (k)$.

$$\Delta oi(k) = |x_0^*(k) - x_i^*(k)|$$

$$\Delta max = \max_{\forall j \in i} \max_{\forall k} |x_0^*(k) - x_i^*(k)| ;$$

$$\Delta min = \min_{\forall j \in i} \min_{\forall k} |x_0^*(k) - x_i^*(k)|$$

ξ is the distinguishing coefficient $\xi \in [0, 1]$. The distinguishing coefficient (ξ) value is chosen to be 0.5. A grey relational grade is the weighted average of the grey relational coefficient and is defined as follows:

$$\gamma(x_0^*, x_i^*) = \sum_{k=1}^{n} \beta k \gamma((x_0^*(k), x_i^*(k)), \sum_{k=1}^{n} \beta k = 1 \quad (6)$$

The grey relational grade (x_0^*, x_i^*) represents the degree of correlation between the reference and comparability sequences. If two sequences are identical, then grey relational grade value equals unity. The grey relational grade implies that the degree of influence related between the comparability sequence and the reference sequence. In case, if a particular compalrability sequence has more influence on the reference sequence than the other ones, the grey relational grade for comparability and reference sequence will exceed that for the other grey relational grades. Hence, grey relational grade is an accurate measurement of the absolute difference in data between sequences and can be applied to appropriate the correlation between sequences.

3.EXPERIMENTAL DETAILS

Design of Experiments (DOE) techniques enables designers to determine simultaneously the individual and interactive effects of many factors that could affect the output results in any design. DOE also provides a full insight of interaction between design elements; therefore, it helps turn any standard design into a robust one. Simply put, DOE helps to pin point the sensitive parts and sensitive areas in designs that cause problems in Yield. Designers are then able to fix these problems and produce robust and higher yield designs prior going into production. Al 6061 and Al 6463 was chosen to be the Specimen materials in the proposed work in order to study the effect of four different parameters (Depth of cut, Feed & Spindle Speed) on the Surface Roughness of the finished specimens using L9 orthogonal design. Therefore the milling Operations and measurements of surface roughness have been done 9 times on each workpiece for each of the following cases in student's Workshop department of mechanical engineering, Shepherd school of engineering and technology, SHIATS, Allahabad. The workpieces were machined by HSS cutting tool wet the cutting conditions respectively. The objective was to obtain the combinations of the optimal levels of the parameters using Principal Component Analysis and Grey Relational Approach and to compare the obtained results. The experiment were conducted with Al 6061alloy and Al 6463 grade as work piece material and HSS cutting tool. The process parameters were given different values and were optimized for minimum surface roughness on the work material. The used Al 6061 is a precipitation hardening aluminum, containing magnesium and silicon as its major alloying elements. Originally called "Alloy 61S," it was developed in 1935. It has good mechanical properties and exhibits good weld ability Aluminum alloy 6463 is a medium strength alloy. Often referred to as a decorative alloy and can be chemically brightened to enhance this use. is typically used in commercial and is highly suitable for anodizing and polishing, or brightening. This makes it suitable for retail applications like shop fittings and trims.

Table 1: Material Composition

Material	Al (%)	Cr (%)	Cu (%)	Fe (%)	Mn (%)	Mg (%)	Si (%)	Ti (%)	Zn (%)
Al 6061	96.89	0.28	0.27	0.56	0.12	1.00	0.60	0.09	0.18
Al 6463	98.57	-	0.20	0.15	0.05	0.67	0.30	-	0.05

The cutter used was an end milling cutter of diameter 16 mm. In full factorial design, the number of experimental runs exponentially increases with the increase in the number of factors as well as their levels. This results in huge experimentation cost and considerable time period.So, in order to compromise these two adverse factors and to search for the optimal process condition through a limited number of experimental runs L9 orthogonal array consisting of 9 sets of data was selected to optimize the multiple performance characteristics of the end milling. Experiments were conducted with the process parameters as given in Table 2:

Table 2: Factors at different levels for End Milling Operation

Factors	Level 1	Level 2	Level 3
Depth of cut (A)	0.15	0.30	0.5
Feed (B)	50	70	90

The spindle speed would be taken for **Al 6061 is 800 rpm** and for **Al 6463 is 1000 rpm.**
The Initial Dimensions of the Specimen Al 6061 for Milling Operation:

Length (mm) =75±0.5
Breath (mm) = 70±0.5
Height (mm) = 25±0.5

The Initial Dimensions of the Specimen Al 6463 for Milling Operation:

Length (mm) =100±0.5
Breath (mm) =100±0.5
Height (mm) = 35±0.5

All these data are used for the analysis and evaluation of the optimal parameters combination.

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Table 3: Standard L9 Orthogonal Array for both workpiece Al 6061 and Al 6463

Experiment No.	Depth of Cut, A	Feed Rate, B
1.	1	1
2.	1	2
3.	1	3
4.	2	1
5.	2	2
6.	2	3
7.	3	1
8.	3	2
9.	3	3

The response variables measured were surface roughness of the machined workpiece. Surface roughness tester TR 110P is used to measure the surface roughness for end milling operation. The single generated value is measure after working.

4.ANALYSIS OF RESULTS

A.Experimental Process

4.1: Grey Based Analysis Results for End Milling Operation of 'Workpiece Al 6061'

The experimental come out result for surface roughness (Ra) are given in the Table no. 4, Values of Ra are desirable. Thus the data sequences have the smaller-the-better characteristic, the smaller-the-best methodology, i.e**.** Equation (2), was employed for data pre-processing. The values of the Ra are set to be the reference sequence X0(0) (K) the results of nine experiments were the comparability sequences Xi(0) (k), ki=1,2... 9, k =1–5 Table 5 given all of the sequences after implementing the data pre-processing using Equation (2). The reference and the comparability sequences were calculate as X0*(k) and Xi*(k), respectively. The **Spindle speed** for all these nine experiments is taken as **800 rpm** while performing the end milling operation on the **'workpiece Al 6061'.**

Table 4: Results of Experimental Trial Runs for End Milling Operation of 'Workpiece Al 6061'

Experiment No.	Depth of Cut	Feed Rate	Surface roughness(Ra)
1.	0.15	50	0.267
2.	0.15	70	0.263
3.	0.15	90	0.243
4.	0.30	50	0.210
5.	0.30	70	0.243
6.	0.30	90	0.380
7.	0.50	50	0.286
8.	0.50	70	0.270
9.	0.50	90	0.236

Table 5: Data Pre-processing result for End Milling Operation of 'Workpiece Al 6061'

Run No.	Surface Roughness(Ra)
1.	0.6647
2.	0.8820
3.	0.8058
4.	1.0000
5.	0.8058
6.	0.0000
7.	0.5529
8.	0.6470
9.	0.8470

Table 6: Experimental factors and their levels for End Milling Operation of 'Workpiece Al 6061'

Symbol	Cutting parameter	Unit	Level 1	Level 2	Level 3
A	Depth of cut	Mm	0.15	0.30	0.50
B	Feed rate	mm/min	50	70	90

Also, the deviation sequences ∇oi, ∇oi max (k) and ∇oi min (k) for can be calculated. The deviation sequences $\Delta_{01}(1)$ using Equation (6) can be calculated as follows:
$\Delta_{o1}(1) = |x_{0*}(1) - x_{1*}(1)| = |1.0000 - 0.6647| = 0.3353$

Table 7: Deviation Sequence for End Milling Operation of 'Workpiece Al 6061'

Run No.	Surface Roughness, Ra
1.	0.3353
2.	0.3118
3.	0.1942
4.	0.0000
5.	0.1942
6.	1.0000
7.	0.4471
8.	0.3530
9.	0.1530

Table 8: Calculated Grey Relational Coefficients and Grey Relational Grade for End Milling Operation of 'Workpiece Al 6061

Exp No.	Orthogonal Array			Grey Relational Coefficient, Ra	Grade
	A	B	C		
1	1	1	1	0.5980	0.598
2	1	1	2	0.6159	0.6159
3	1	1	3	0.7202	0.7202
4	1	2	1	1.0000	1.0000
5	1	2	2	0.7202	0.7202
6	1	2	3	0.3333	0.3333
7	1	3	1	0.5279	0.5279
8	1	3	2	0.5862	0.5862
9	1	3	3	0.7657	0.7657

The response Table was used calculate the average Grey relational grades for each factor level, as listed in Table 8. Since the Grey relational grades show the level of correlation between the reference and the comparability sequences, the larger Grey relational grade means the comparability sequence exhibiting a stronger correlation with the reference sequence. Based on this study, one can select a combination of the levels that provide the largest average response. In Table 9, the combination of A_2 and B_1 shows the largest value of the Grey relational grade for the factors A and B respectively. Therefore surface roughness is the optimal parameter combination for the end milling operation.

Table 9: Response Table for Grey Relational Grade for End Milling Operation of 'Workpiece Al 6061

Levels	Factors	
	A	B
1.	0.6447	0.7086
2.	0.6845	0.6408
3.	0.6266	0.6064

B. Very effective Factor

Grey relational analysis was used to find the most Effective factor among the milling process parameters that affects the surface roughness. The values of the factor level in nine experimental runs are set to be the comparability sequences for two controllable factors as shown in Table no. 10. Data pre-processing was calculate from Equation (4), and the normalized results were tabulated in Table no. 10. The deviation sequences were calculated using the same method above with the help of Equation (6). To obtain the grey relational coefficients, the deviation sequences and the distinguishing coefficient were substituted in Equation (5). Additionally, the grey relational coefficients averaged to obtain grey relational grade.

Table 10: Sequence after data pre- processing for reference and comparability sequence for End Milling Operation of 'Workpiece Al 6061'

Run no.	Comparability sequence			Surface roughness , Ra
1	1	1	1	1.0000
2	1	1	1.4	0.9850
3	1	1	1.8	0.9101
4	1	2	1	0.7856
5	1	2	1.4	0.9101
6	1	2	1.8	1.4232
7	1	3.33	1	1.0711
8	1	3.33	1.4	1.0112
9	1	3.33	1.8	0.8838

Table 11: Response Table for signal to noise ratios (Smaller is better) for 'Workpiece Al 6061'

Level	Depth of Cut (mm)	Feed Rate (mm/min)
1	11.79	11.97
2	11.42	11.75
3	11.60	11.08
Delta	0.37	0.89
Rank	2	1

Table 12: Response Table for Means for 'Workpiece Al 6061'

Level	Depth of Cut (mm)	Feed Rate (mm/min)
1	0.2577	0.2543
2	0.2777	0.2587
3	0.2640	0.2863
Delta	0.0200	0.0320
Rank	2	1

Table 13: Analysis of Variance for 'Workpiece Al 6061'

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Depth of Cut(mm)	2	0.2057	0.1028	0.03	0.973
Feed Rate (mm/min)	2	1.2904	0.6452	0.17	0.848
Error	4	14.9715	3.7429		
Total	8	16.4676			

Table 14: Analysis of Variance for 'Workpiece Al 6061'

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Depth of Cut (mm)	2	0.000627	0.000313	0.08	0.926
Feed Rate (mm/min)	2	0.001808	0.000904	0.22	0.808
Error	4	0.016079	0.004020		
Total	8	0.018514			

4.2: Grey Based Analysis Results for 'Workpiece Al 6463'

The spindle speed for all these Nine experiments is taken as 1000 rpm while performing the end milling operation on the 'workpiece Al 6463'.

C.Experimental Process

Table 15: Experimental Result for End Milling Operation of 'Workpiece Al 6463'

Exp. No.	Depth of cut (mm)	Feed (mm/min)	Surface roughness (Ra)
1.	0.15	50	0.7066
2.	0.15	70	1.290
3.	0.15	90	2.096
4.	0.30	50	2.190
5..	0.30	70	1.4566
6.	0.30	90	1.2466
7.	0.50	50	1.2566
8.	0.50	70	1.183
9.	0.50	90	1.0933

The experimental come out results for surface roughness (R_a) are given in the Table no.15, Values of R_a are desirable. Thus the data sequences have the smaller-the-better characteristic, the smaller-the-best methodology, i.e. Equation (2), was employed for data pre-processing. The values of the Ra are set to be the reference sequence $X_{0(0)}$ (K) the results of twenty seven experiments were the comparability sequences $X_{i(0)}$ (k), k_i=1,2... 9, k =1–5 Table IV given all of the sequences after implementing the data pre-processing using Equation (2). The reference and the comparability sequences were calculate as X_{0^*}(k) and X_{i^*}(k), respectively.

Table 16: Data Pre-processing results for End Milling Operation of 'Workpiece Al 6463'

Comparability Sequence	Reference Sequence
Run No.	**Ra**
1.	1.0000
2.	0.6067
3.	0.0633
4.	0.0000
5.	0.4944
6.	0.6359
7.	0.6292
8.	0.6788
9.	0.7393

Also, the deviation sequences ∇oi, ∇oi max (k) and ∇oi min (k) for can be calculated. The deviation sequences Δ_{01} (1)

Comparability Sequence	Reference sequence
Run No.	**Ra**
1.	0.0000
2.	0.3933
3.	0.9367
4.	1.0000
5.	0.5056
6.	0.3641
7.	0.3708
8.	0.3212
9.	0.2607

using Equation (6) can be calculated as follows:

$\Delta_{01}(1) = |x_{0*}(1) - x_{1*}(1)| = |1.0000 - 1.000| = 0.0000$

Table 17: Deviation Sequence for End Milling Operation of 'Workpiece Al 6463'

Table 18: Calculated Grey relational coefficient and grey relational grade for End Milling Operation of 'Workpiece Al 6463'

Exp. No.	A	B	Grey Relational Coefficient
1	1	1	1.0000
2	1	2	0.5597
3	1	3	0.3480
4	2	1	0.3333
5	2	2	0.4972
6	2	3	0.5786
7	3	1	0.5741
8	3	2	0.6088
9	3	3	0.6572

The response Table was used calculate the average Grey relational grades for each factor level, as listed in Table no.18. Since the Grey relational grades show the level of correlation between the reference and the comparability sequences, the larger Grey relational grade means the comparability sequence exhibiting a stronger correlation with the reference sequence. Based on this study, one can select a combination of the levels that provide the largest average response. In Table no.19, the combination of A_2 and B_1 shows the largest value of the Grey relational grade for the factors A and B respectively. Therefore surface roughness is the optimal parameter combination for the end milling operation.

Levels	Factors		
	A	B	C
1.	0.5730	0.6359	0.6358
2.	0.5730	0.4697	0.5552
3.	0.5730	0.6134	0.5280

B. Very effective Factor

Grey relational analysis was used to find the most Effective factor among the milling process parameters that effects the surface roughness. The values of the factor level in nine experimental runs are set to be the comparability sequences for two controllable factors as shown in Table no. 20. Data pre-processing was calculate from Equation (4), and the normalized results were tabulated in Table no 20. The deviation sequences were calculated using the same method above with the help of Equation (6). To obtain the grey relational coefficients, the deviation sequences and the distinguishing coefficient were substituted in Equation (5). Additionally, the grey relational coefficients averaged to obtain grey relational grade.

Table 20: Sequence after data pre–processing for reference and comparability sequence for End Milling Operation of 'Workpiece Al 6463'

Exp.no.	Comparability sequence		Reference sequence
	A	B	Ra
1.	1	1	1.0000
2.	1	2	1.8256
3.	1	3	2.9663
4.	2	1	3.0933
5.	2	2	2.0614
6.	2	3	1.7642
7.	3	1	1.7783
8.	3	2	1.6742
9.	3	3	1.5473

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Table 21: Response Table for Signal to Noise Ratios (Smaller is better) of 'Workpiece Al 6463'

Level	Depth of Cut (mm)	Feed Rate (mm/min)
1	-1.876	-1.926
2	-3.997	-2.314
3	-1.407	-3.040
Delta	2.590	1.114
Rank	1	2

Table 22: Response Table for Means for 'Workpiece Al 6463'

Level	Depth of Cut (mm)	Feed Rate (mm/min)
1	1.364	1.384
2	1.631	1.310
3	1.178	1.479
Delta	0.453	0.169
Rank	1	2

Table 23: Analysis of Variance for 'Workpiece Al 6463'

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Depth of Cut (mm)	2	0.31151	0.15575	0.43	0.675
Feed Rate (mm/min)	2	0.04299	0.02150	0.06	0.943
Error	4	1.43532	0.35883		
Total	8	1.78982			

Table 24: Analysis of Variance for 'Workpiece Al 6463'

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Depth of Cut (mm)	2	11.429	5.7143	0.41	0.691
Feed Rate (mm/min)	2	1.920	0.9598	0.07	0.935
Error	4	56.373	14.0932		
Total	8	69.721			

a) Graph for 'Workpiece Al 6061'

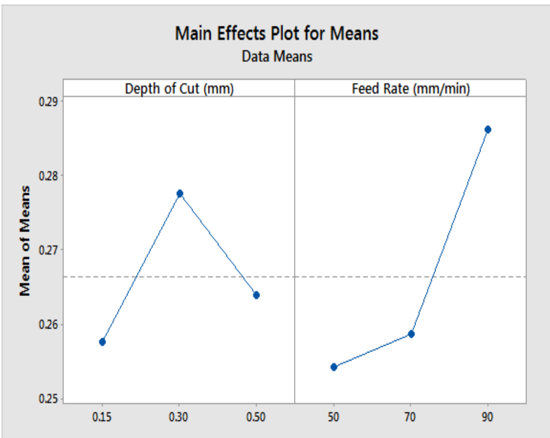

Fig1: Main Effects plot for Means (Data Means)

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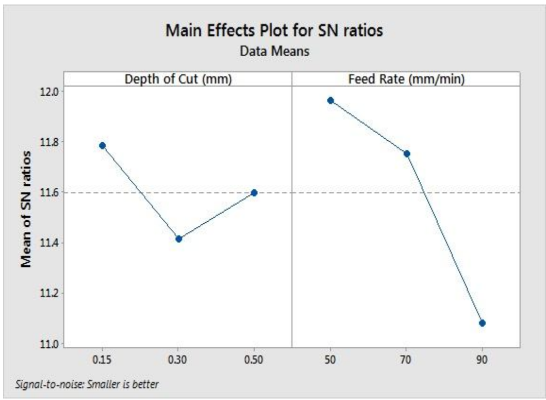

Fig 2: Main Effects plots for S/N ratios (Data Means)

a) Graph for 'Workpiece Al 6463'

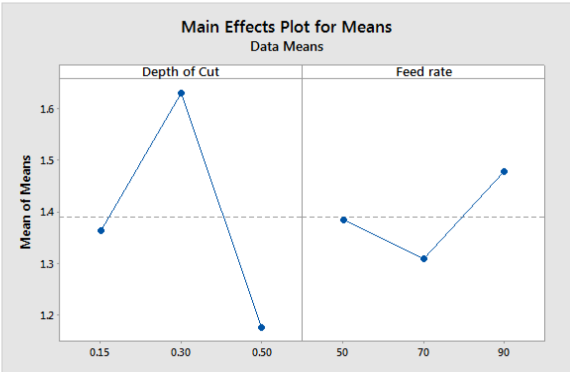

Fig 3: Main effects plot for Means (Data Means)

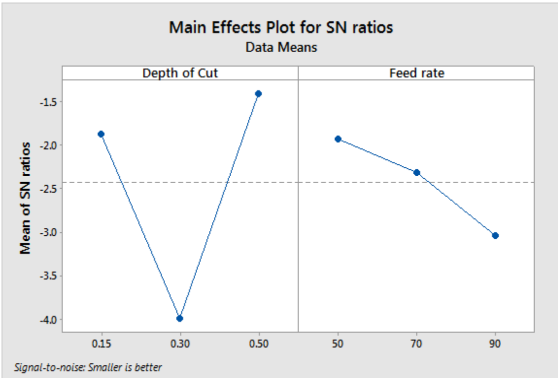

Fig 4: Main effects plot for S/N ratios (Data Means)

5.CONCLUSION

The present work successfully demonstrated the application of Grey relational analysis for optimization of process parameters in end milling of the two materials as Al 6061 and Al 6463 (aluminum alloys). The conclusions can be drawn from the present work were as follows:

1. The highest Grey relational grade of 1.0000 was observed for the experimental Process, shown in response Table (Table no. 8 and Table no. 18) of the average Grey relational grade, which indicates the combination of control factors.
2. The order of importance for the controllable factors to the minimum surface roughness, in sequence, are the feed rate and depth of cut.

3. However, it is observed through ANOVA that the spindle speed is the most influential control factor among the four end milling process parameters investigated in the present work, when minimization of surface roughness is considered

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