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Determination of Optimum Cutting Parameters for Multiperformance Characteristics in CNC End Milling of Al-Si7Mg Aluminum Alloy

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***Abstract*— This paper presents an approach to determine the optimum cutting parameters leading to have best multiperformance in terms of lower surface roughness (quality) and higher material removal rates (quantity) simultaneously in CNC end milling of Al-Si7Mg (LM25). Conventional Taguchi method is applicable for optimizing single performance characteristics only. The grey relational analysis (GRA) coupled with Taguchi method called as grey-Taguchi method used here is useful and a very versatile statistical tool to manipulate the experimental data to have best multiperformance under various conditional requirements. Four process parameters, i.e. coolant environment, cutting speed, feed rate and depth of cut, each at three levels except the coolant at two levels, have been considered. The L_{18} orthogonal array best suited for such mixed levels of milling parameters is used for the experimental study. The results of confirmation tests demonstrate that grey-Taguchi method can effectively be used to get the optimum combination of milling parameters.**

***Index Terms*— Al-Si7Mg (LM25), CNC end milling, grey-Taguchi, Multiperformance**

I. Introduction

Milling with an end mill cutter is one of the fundamental, major and important material removing process in case of CNC machining. It is estimated that in average shop, milling constitutes 28% of the total number of operations and 30% of the total machining time. Because of its versatility, it is efficiently used for making slots, profiles, surface contouring, engraving, pocketing. Various factors involved in CNC milling influence the quality of the final machined part and its manufacturing economy. Tool materials, control system of the machine tool and type of the tool holder, axial capability of the machine tool and cutting parameters (spindle speed, depth of cut, feed and cooling/lubricating conditions) are the key factors directly affecting the surface quality and productivity [4]. Among these factors, the cutting parameters are suitable for any kind of modifications without altering the current installation to meet the required demands of surface finish, material removal rate and dimensional accuracy. Patel [2] presented the experimental analysis on aluminium alloy (AL 6351-T6) material with end milling operation. Taguchi parameter design was used to optimize the surface roughness. The final surface roughness might be considered as the sum of two independent effects as the ideal surface roughness is a result of the geometry of tool and feed rate and the natural surface roughness is a result of the irregularities in the cutting operation. Factors such as spindle speed, feed rate, tool diameter and depth of cut that control the cutting operation can be setup in advance [3]. It demonstrates how to use Taguchi parameter design for optimizing machining performance with minimum cost. In case of end milling of aluminium alloy (A6061P-T651) the grey-Taguchi method has been efficiently implemented to have multiperformance in terms of surface quality and material removal rate [6], [7].

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II. Experimental studies

A. Design of Experiments

A specially designed experimental procedure is required to evaluate the effects of machining parameters on performance characteristics. Conventional experimental design methods are too complex and difficult to use. Additionally, large numbers of experiments have to be carried out when number of machining parameters increases. Normally, the full factorial design would require 54 experimental runs in this study. However, the effort could be prohibitive and unrealistic. Here Taguchi method along with GRA used is a powerful tool for parameter design, to determine optimal machining parameters for minimum surface roughness and maximum MRR in milling. The milling parameters levels and ranges for final experimentation are decided from pilot experimental results.

Table I shows the test matrix for various parameters selected along with the ranges and levels for the milling parameters. L_{18} orthogonal array proposed by Taguchi is the best suitable for the study of parameters with mixed levels and has been used for final experimentation and runs were carried out with complete randomization.

Table I – Test matrix for experimentation.

Factor → Level ↓	Coolant	Cutting Speed N (rpm)	Depth of cut d (mm)	Feed rate f (mm/rev.)
1	No (D)	4400	1.3	0.015
2	Flooded(C)	5000	2	0.03
3	-	5600	2.7	0.045

B. Experimental conditions, Workpiece, Tool Materials and Measurements

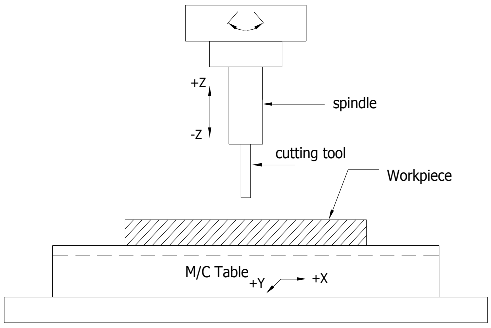

Fig.1 - Schematic diagram of Experimental setup

The experimental setup for end milling of LM25 is shown schematically in fig. 1. The experiments were performed on vertical machining centre (BMV45 TC-24 model) having CNC control system of FANUC series Oi-MD, as shown in fig.2. The maximum spindle speed is of 6000 rpm, Spindle power 5.5/7.5 kW (cont. 30 min rating) and maximum feed rate available is 10 m/min.

Fig.2 - VMC Center BMV TC24

The work piece used for experimentation was initially in the form of a rectangular plate of LM25 with the dimensions 420 x 120 x 20 mm as shown in fig.3. Actual chemical composition and mechanical properties of work material are listed in Table II. End mill cutters used for the pilot and final experimentation are of solid carbide with TiCN coating [WIDIA-HANITA make List 4103] which is best recommended for machining of aluminum alloys. The cutter is of 10 mm diameter having helix angle of 45^0 and has three numbers of flutes equally spaced.

Table II- Chemical composition and mechanical properties of work piece material

Work Material Al-Si7Mg (LM25)
Chemical composition(%wt)
91.37Al, 6.52Si, 0.33Fe, 0.99Cu, 0.18Mn, 0.31Mg, 0.08Zn, 0.01Cr, 0.02Ni, 0.09Ti, <0.00Be, 0.02Ca, 0.01Pb, 0.01Sn, 0.02Na
Mechanical properties
Density 2.7gm/cm^3, Tensile strength 150.9 N/mm^2, Elongation after fracture 2.29%, Strength to weight ratio 0.15.

Fig.3 - Workpiece LM 25 plate fixed on m/c table before machining

The material removal rate and surface roughness, taken as performance characteristics were evaluated for the analysis of multiperformance. Surface roughness (Ra) for the experimental runs have been measured using the HOMMEL-ETAMIC T8000 roughness tester with length of travel equal to 3.6 mm for cut off length of 0.6 mm. The measuring probe of tester is of TKU 300 type and the range/resolution for surface roughness measurement is 8 µm/ 1nm. The material removal rates for each experimental runs are estimated from the basic equation giving the ratio of material removed per unit time. The volume of material removed is measured in mm^3 and thus the MRR is expressed in mm^3/s. The experimental run details for milling the slots are shown schematically in fig.5. Fig.4 shows the partly machined workpiece.

The observations for material removal rates (MRR) and surface roughness (Ra) for each experimental run of L_{18} array are shown in Table III. The Run order was generated in MINITAB 15 to have complete randomization.

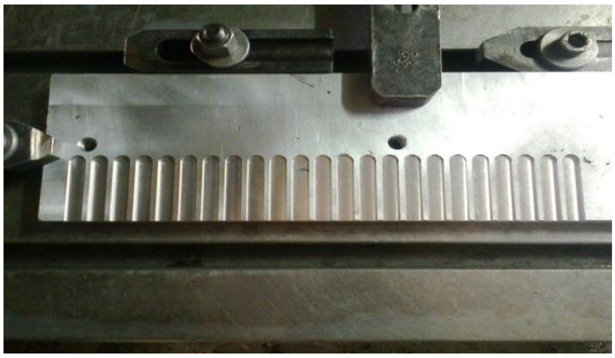

Fig.4 - Workpiece LM 25 (Partly machined)

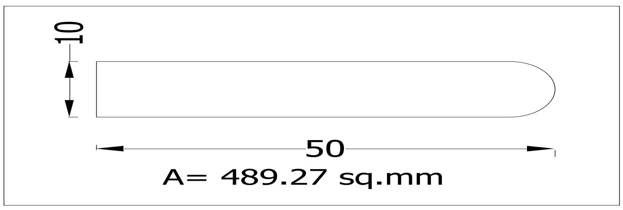

Fig.5 – End mill slot details

Table III - The observations for L_{18} Experimentation.

Run No	Coolant	N (rpm)	d (mm)	f	Ra (μm)	MRR (mm^3/s)
3	D	1	1	1	0.63	13.99
17	D	1	2	2	0.65	43.06
9	D	1	3	3	0.71	87.19
13	D	2	1	1	0.6	15.90
11	D	2	2	2	0.63	48.93
6	D	2	3	3	0.70	99.08
16	D	3	1	2	0.59	35.62
12	D	3	2	3	0.70	82.20
2	D	3	3	1	0.61	36.99
18	C	1	1	3	0.45	41.98
14	C	1	2	1	0.33	21.53
5	C	1	3	2	0.47	58.13
8	C	2	1	2	0.42	31.80
10	C	2	2	3	0.44	73.39
15	C	2	3	1	0.34	33.03
4	C	3	1	3	0.39	53.43
1	C	3	2	1	0.34	27.40
7	C	3	3	2	0.36	73.98
				MAX	0.71	99.08
				MIN	0.33	13.99

III. Grey Relational Analysis

The word grey used for indicating between black (with no information) and white (with full and complete certain information). In a complex system with various inter relational parameters the grey relational analysis is used, as the information about the inter relationship is not fully known. When experiments are not carried out at details GRA is useful tool to predict the multiperformance of two or more performance characteristics. The steps that are followed in GRA can be summarised as follows.

a] Generating comparability sequence or data preprocess- ing (Normalization of data).
b] Deviation sequence generating.
c] Calculating grey relational coefficients for each perfor-mance characteristics.
d] Estimation of grey relational grades from grey relational coefficients.

The surface roughness (Ra) and material removal rate are taken as the two performance measures in the study. Data normalization is necessary since the ranges and units for each performance characteristics are different. The normalized results between 0 and 1 are easily comparable. So it is also called as comparability sequence generating. The equation (1) is used for normalization of surface roughness data which is expected to be "lower the better" characteristics. The equation (2) is used for normalizing the MRR values for experimental runs which is expected to be "higher the better" characteristics.

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

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

where, $\max x_i^0(k)$ = maximum value of experimental data for k^{th} performance characteristics $x_i^0(k)$, $\min x_i^0(k)$ = minimum value of same experimental data and $x_i^*(k)$ is the normalized value of i^{th} experiment of k^{th} performance characteristics. The deviation sequence can be obtained from equation (3) for each performance characteristics.

$$\Delta_{0i} = \left\| x_0^*(k) - x_i^*(k) \right\| \quad (3)$$

where, $x_0^*(k)$ is the reference sequence and $x_i^*(k)$ is the comparability sequence and Δ_{0i} is the deviation sequence value obtained for i^{th} experimental run. The grey relational coefficient for i^{th} experimental run of k^{th} performance characteristics is calculated from equation (4).

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{0i}(k) + \zeta \Delta_{\max}} \quad (4)$$

where, ζ = distinguishing coefficient (normally=0.5)

$$\Delta_{\min} = \min_{\forall j \in i} \min_{\forall k} \left\| x_0^*(k) - x_j^*(k) \right\| \quad (5)$$

$$\Delta_{\max} = \max_{\forall j \in i} \max_{\forall k} \left\| x_0^*(k) - x_j^*(k) \right\| \quad (6)$$

In real engineering application the emphasis on various performance measures is different. This can be achieved by giving different relative weights (w_k) given for each performance measure to calculate grey relational grade. The equation (7) is the general form to calculate the grey relational grade. Table IV shows the comparability and deviation sequence for measured Ra and MRR for each experimental run.

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} w_k \xi_i(k), \qquad \sum_{i=1}^{n} w_k = 1 \quad (7)$$

Table IV - The sequence after data pre and post processing

Sr. No.	Run no.	Comparability sequence x_i*(k)		Deviation sequence Δ_{0i} = IIx_0*(k) - x_i*(k)II	
		Ra	MRR	Ra	MRR
1	3	0.211	0.000	0.789	1.000
2	17	0.158	0.342	0.842	0.658
3	9	0.000	0.860	1.000	0.140
4	13	0.289	0.022	0.711	0.978
5	11	0.211	0.411	0.789	0.589
6	6	0.026	1.000	0.974	0.000
7	16	0.316	0.254	0.684	0.746
8	12	0.026	0.802	0.974	0.198
9	2	0.263	0.270	0.737	0.730
10	18	0.684	0.329	0.316	0.671
11	14	1.000	0.089	0.000	0.911
12	5	0.632	0.519	0.368	0.481
13	8	0.763	0.209	0.237	0.791
14	10	0.711	0.698	0.289	0.302
15	15	0.974	0.224	0.026	0.776
16	4	0.842	0.463	0.158	0.537
17	1	0.974	0.158	0.026	0.842

18	7	0.921	0.705	0.079	0.295

IV. Results and Discussions

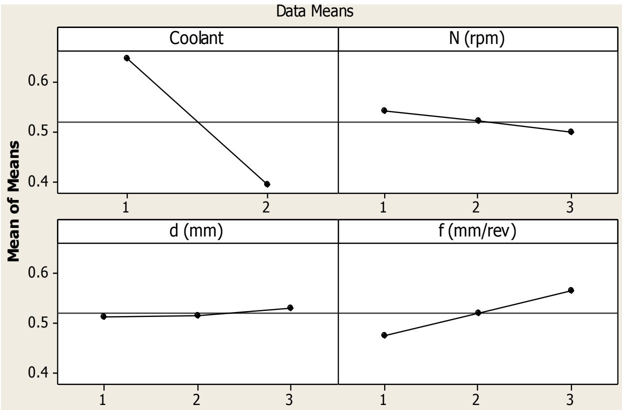

Fig.6 –Main Effect plot - milling parameters on Ra

Fig. 6 presents the main plots for data means of Ra showing the effect of each milling parameter on surface roughness. The lower surface roughness can be obtained by setting the milling parameters as N3, d1, f1 and C (flooded coolant).The surface roughness decreases as there is increment in cutting speed (N), while feed rate and depth of cut have direct relation with Ra. Also it can be seen from main plots that feed rate has more influence on Ra as compared to cutting speed and depth of cut.

The influence of selected cutting parameters on surface roughness have been assessed with the help of analysis of variance (ANOVA) applied for data means for surface roughness values obtained in L_{18} experimental runs. Table V presents the ANOVA result which shows that the surface roughness is most affected by coolant environment (C/D) followed by feed rate (f), and cutting speed (N). The depth of cut (d) is having least significance on Ra. Fig.7 presents the % contributions by C, f, N, d on surface roughness as 87.88, 7.40, 1.58, and 0.37 respectively.

The preprocessed (normalized) results along with experimental observations are shown in Table IV. Higher the better and lower the better characteristics equations are used for MRR and Ra respectively to get comparability sequence x_i*(k). The deviation sequence (Δ_{0i}) is generated by taking reference sequence (x_0*(k)) equal to 1, for both Ra and MRR. The grey relational coefficients are calculated with distinguishing coefficient value ζ = 0.5 which is most generally used.

Table V - ANOVA for surface roughness (Ra) (L_{18})

Source	DOF	SS	MS (V)	F-Ratio	Prob.
Coolant	1	0.2888	0.2888	319.7	0.000
N (rpm)	2	0.0052	0.0026	2.90	0.102
d (mm)	2	0.0012	0.0006	0.68	0.527
f (mm/rev`	2	0.0243	0.0122	13.45	0.001
Error	10	0.0090	0.0010		
Total	17	0.3286			

$F_{0.05,2,10}$ = 4.10 (F-test TABLE VALUE)

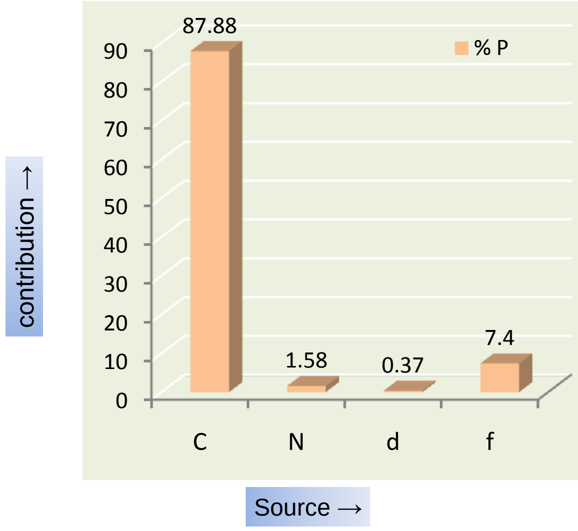

Fig.7 – Effect of milling parameters on Ra

A. *Equal weights for Ra and MRR (w1=w2=0.5)*

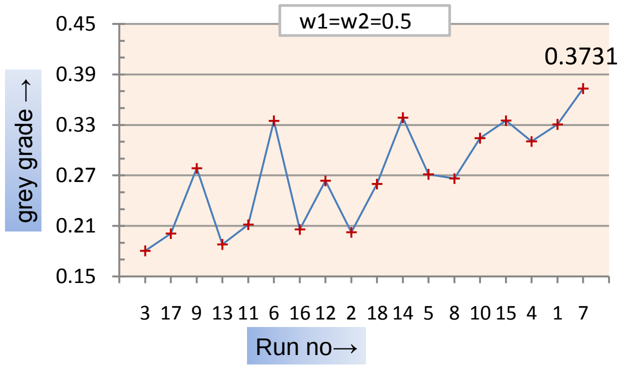

Fig.8 - Grey relational grades

Fig.8 (refer appendix Table VIII) shows the grey relational grades obtained for each experimental run. The results with equal weights are plotted as per run number. It is seen that the run no.7 has the highest grey relational grade value of 0.3731 indicating the best multiperformance in terms of lower Ra and higher MRR. Thus the initial optimum parameters setting given by run no 7 are C, N3, d3, f2 (see Table III). Further the Taguchi analysis for average grey relational grades at different levels are plotted in fig. 9 indicating the optimum setting of parameters for multiperformance as C, N3, d3, f3.

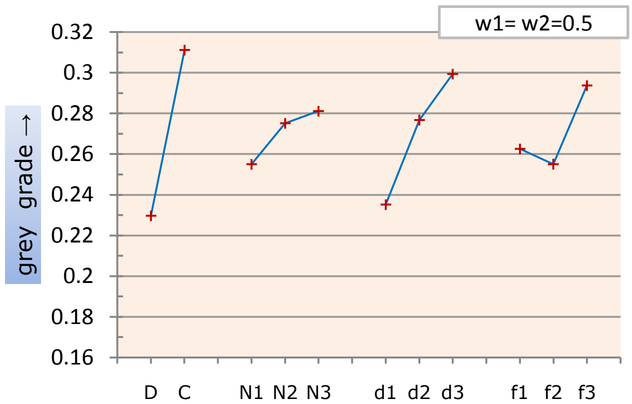

Fig.9 - Grey grade (means) for milling parameters levels

Table VI - Comparison between GRA and grey-Taguchi for grey grade prediction (L_{18})

w1=w2=0.5	Optimum by mere GRA	Grey-Taguchi prediction	Confir-mation
Parameter setting	C, N3, d3, f2	C, N3, d3, f3	C, N3, d3, f3
Ra (µm)	0.36		0.44
MRR (mm^3/s)	73.978		110.966
Grey grade	0.3731	0.3741	0.5053

Improvement in grade by 0.1322, MRR by 36.988(mm3/s)

Table VI enumerates the comparative results obtained for optimum parameter setting given by mere GRA and grey-Taguchi method. It is seen that there is improvement in Grey relational grade from 0.3731 to 0.5053 and increase in MRR from 73.978 to 110.966 mm^3/s. Here justification for level f3 can be given as; i) equal weights for Ra and MRR. ii) f3 favours the higher MRR and the surface roughness of 0.44µm is much smaller compared with the Ra obtained with dry milling runs in L_{18} array.

B. Unequal weights (w_{Ra}=0.65, w_{MRR}=0.35)

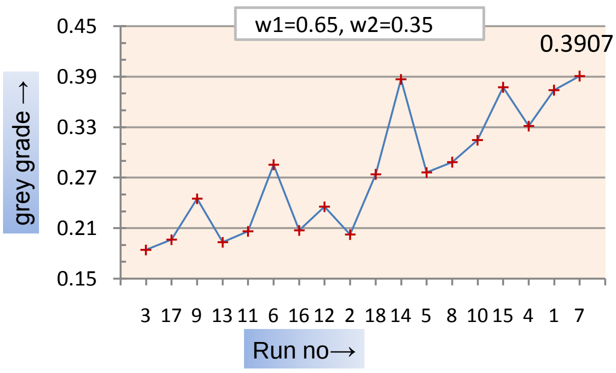

Fig.10 - Grey relational grades

The effect of relative unequal weights has been analyzed giving more weight for Ra as compared to MRR. With the given weights the optimum setting of milling parameters for best multiperformance by mere GRA prediction remains same i.e. run no. 7 as best with grey relational grade = 0.3907 (fig.10). But the grey-Taguchi analysis for grades gives the optimum parameter setting as C2, N3, d3, f1 as shown in fig 11. This is because of more emphasis is given on Ra as compared to MRR (more weight is attached to Ra) The shifting of level f3 to f1 is justified as from main plots (fig. 6) the lower Ra favours f1 as compared to f3, secondly feed rate (f) is more influencing on Ra than N and d. Thus results obtained by mere GRA and grey-Taguchi approach listed in Table VII shows that there is improvement (lowered) in Ra from 0.36 to 0.33 µm and grey relational grade is improved by 0.0055.

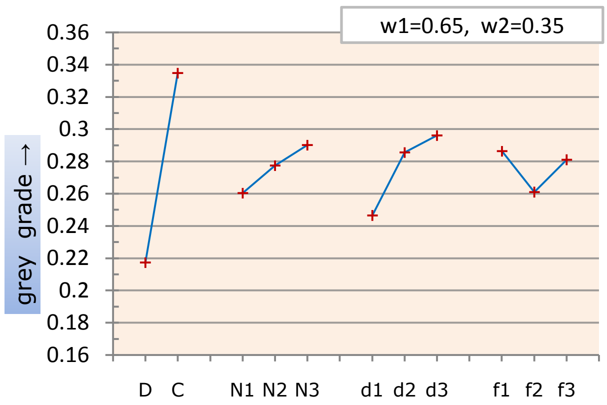

Fig.11 - Grey grade (means) for milling parameters levels

Table VII - Comparison between GRA and grey-Taguchi for grey grade prediction (L_{18})

w1=0.65 w2=0.5	Optimum by mere GRA	Grey-Taguchi prediction	Confir-mation
Parameter setting	C, N3, d3, f2	C, N3, d3, f1	C, N3, d3, f1
Ra (µm)	0.36		0.33
MRR (mm^3/s)	73.978		36.989
Grey grade	0.3907	0.3699	0.3962

Improvement in grade by 0.0055, Ra by 0.03 µm.

V. Conclusion

The grey relational analysis based on Taguchi method is applied for the observations obtained from milling experimental runs on LM25 with TiCN coated solid carbide end mill cutter. The surface roughness and material removal rate are taken as the two performance characteristics. The optimum milling parameters for multiperformance in terms of lower Ra and higher MRR given by grey-Taguchi method are C, N3, d3, f3 for selected ranges. From confirmative test results it is seen that there is improvement in MRR from 73.978 to 110.966 mm^3/s with grey relational grade improvement from 0.3731 to 0.5053. The results obtained with equal weights (importance) to Ra and MRR.

A comparative study for relative unequal weights for Ra and MRR has been carried out. More emphasis is given for Ra by giving weights of 0.65 and 0.35 to Ra and MRR respectively. The optimum parameter setting by grey-Taguchi method have resulted into C, N3, d3, f1 with improvement in grey relational grade by 0.0055. The confirmative test has shown that there is reduction in Ra also (from 0.36 to 0.33µm). From above results it is finally concluded that the Grey-Taguchi approach applied here is a very efficient and versatile tool to manipulate the experimental data in order to have best multiperformance under various conditional requirements.

APPENDIX

Table VIII – Grey relational grades and ranks for various weights combinations L_{18}

Run no.	grey relational coefficient		grey relational grade $\gamma i = 1/n \sum wi .\zeta i^*(k)$			
	Ra	MRR	w1=w2=0.5	Rank	w1,w2 (0.65,0.35)	Rank
3	0.3878	0.3333	0.1803	18	0.1844	18
17	0.3725	0.4316	0.2010	16	0.1966	16
9	0.3333	0.7816	0.2787	8	0.2451	11
13	0.4130	0.3384	0.1879	17	0.1935	17
11	0.3878	0.4590	0.2117	13	0.2063	14
6	0.3393	1.0000	0.3348	4	0.2853	8
16	0.4222	0.4013	0.2059	14	0.2075	13
12	0.3393	0.7159	0.2638	11	0.2356	12
2	0.4043	0.4066	0.2027	15	0.2025	15
18	0.6129	0.4270	0.2600	12	0.2739	10
14	1.0000	0.3542	0.3386	2	0.3870	2
5	0.5758	0.5095	0.2713	9	0.2763	9
8	0.6786	0.3874	0.2665	10	0.2883	7
10	0.6333	0.6235	0.3142	6	0.3149	6
15	0.9500	0.3918	0.3354	3	0.3773	3
4	0.7600	0.4824	0.3106	7	0.3314	5
1	0.9500	0.3725	0.3306	5	0.3739	4
7	0.8636	0.6289	0.3731	1	0.3907	1
confirmation			0.5053		0.3962	
			C,N3,d3,f3		C,N3,d3,f1	

A. *Calculation of Grey Relational Grade*

Sample calculation for **run no. 7**

1) Comparability sequence / Data preprocessing/ Normalization

For lower the better characteristics (Ra)

$$x_7^*(1) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)}$$

From Table III $\max x_i^0(k) = 0.71$ and $\min x_i^0(k) = 0.33$ and $x_7^*(1) = 0.36$

$$\therefore x_7^*(1) = \frac{0.71 - 0.36}{0.71 - 0.33} = 0.92105$$

2) Deviation sequence (Δ_{0i})

$$\Delta_{0i} = \left\| x_0^*(k) - x_i^*(k) \right\|$$

where, $x_0^*(k)$ =1 (reference sequence)

$$\therefore \Delta_{07} = \left\| 1 - 0.92105 \right\| = 0.07894$$

3) Grey relational coefficient

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{0i}(k) + \zeta \Delta_{\max}}$$

where, $\zeta = 0.5$ (std. value)

$$\Delta_{\min} = \min_{\forall j \in i} \min_{\forall k} \left\| x_0^*(k) - x_j^*(k) \right\|$$

$$\Delta_{\min} = \left\| 1 - 1 \right\| = 0$$

$$\Delta_{\max} = \max_{\forall j \in i} \max_{\forall k} \left\| x_0^*(k) - x_j^*(k) \right\|$$

$$\Delta_{\max} = \left\| 1 - 0 \right\| = 1$$

$$\therefore \xi_7(1) = \frac{0 + 0.5 \times 1}{0.07894 + 0.5 \times 1} = 0.86364$$

4) Grey relational grade (for w1=w2=0.5)

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} w_k \xi_i(k)$$

$$\therefore \gamma_7 = \frac{1}{2}(0.5 \times 0.86364 + 0.5 \times 0.6289) = 0.37314$$

Grey coefficient for MRR= $\xi_7(2)$ can be calculated in similar way. It is further used to estimate grey relational grade. From Table VIII it is = 0.6289.

B. *Calculation for Grey-Taguchi grade prediction ($\hat{\gamma}$)*

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{q} \bar{\gamma}_i - \gamma_m$$

where, γ_m = Total mean grey grade and $\bar{\gamma}_i$ = mean grey grade at optimum level of i^{th} parameter

From table IX, $\bar{\gamma}_1 = 0.311$, $\bar{\gamma}_2 = 0.281$

$\bar{\gamma}_3 = 0.299$, $\bar{\gamma}_4 = 0.294$, *and* $\gamma_m = 0.270$

$\therefore \hat{\gamma} = 0.374$

Table IX – Response table for grey relational grade
Means

Level	coolant	N(rpm)	d(mm)	f (mm/rev)
1	0.230	0.255	0.236	0.263
2	0.311	0.276	0.277	0.255
3	-	0.281	0.299	0.294
Delta	0.081	0.026	0.063	0.039
rank	1	4	2	3

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