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Optimization of machining parameters of turning operations based on multi performance criteria

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A B S T R A C T

The selection of optimum machining parameters plays a significant role to ensure quality of product, to reduce the manufacturing cost and to increase productivity in computer controlled manufacturing process. For many years, multi-objective optimization of turning based on inherent complexity of process is a competitive engineering issue. This study investigates multi-response optimization of turning process for an optimal parametric combination to yield the minimum power consumption, surface roughness and frequency of tool vibration using a combination of a Grey relational analysis (GRA). Confirmation test is conducted for the optimal machining parameters to validate the test result. Various turning parameters, such as spindle speed, feed and depth of cut are considered. Experiments are designed and conducted based on full factorial design of experiment.

1. Introduction

Turning is one of the most basic machining processes in industrial production systems. Turning process can produce various shapes of materials such as straight, conical, curved, or grooved work pieces. In general, turning uses simple single-point cutting tools. Many researchers have studied the effects of optimal selection of machining parameters in turning. Tzeng and Chen (2006) used grey relational analysis to optimize the process parameters in turning of tool steels. They performed Taguchi experiments with eight independent variables including cutting speed, feed, and depth of cut, coating type, type of insert, chip breaker geometry, coolant, and band nose radius. The optimum turning parameters were determined based on grey relational grade, which maximizes the accuracy and minimizes the surface roughness and dimensional precision.

Similarly, the researchers have applied grey relational analysis (GRA) to different machining processes, which include electric discharge machining Lin et al. (2002), determining tool condition in turning (Lo, 2002), chemical mechanical polishing (Lin & Ho, 2003), side milling (Chang & Lu, 2007),

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and flank milling (Kopac & Krajnik, 2007) to compare the performance of diamond tool carbide inserts in dry turning (Arumugam et al., 2006), and optimization of drilling parameters to minimize surface roughness and burr height (Tosun, 2006). Lin (2004) implemented grey relational analysis to optimize turning operations with multiple performance characteristics. He analyzed tool life, cutting force, and surface roughness in turning operations.

Tosun (2006) reported the use of grey relational analysis for optimizing the drilling process parameters for the work piece surface roughness and the burr height is introduced. This study indicated that grey relational analysis approach can be applied successfully to other operations in which performance is determined by many parameters at multiple quality requests. Al-Refaie et al. (2010) used Taguchi method grey analysis (TMGA) to determine the optimal combination of control parameters in milling, the measures of machining performance being the MRR and SR.

Based on the ANOVA; it was found that the feed rate is important control factor for both machining responses. If there are multiple response variables for the same set of independent variables, the methodology provides a different set of optimum operating conditions for each response variable. The grey system theory initiated by Deng (1982) has been proven to be useful for dealing with poor, incomplete, and uncertain information. The grey relational based on the grey system theory can be used to solve the complicated interrelationships among the multiple performance characteristics effectively (Wang et al., 1996).

Therefore, the purpose of the present work is to introduce the use of grey relational analysis in selecting optimum turning conditions on multi-performance characteristics, namely the surface roughness, power consumption and frequency of tool vibration. In addition, the most effective factor and the order of importance of the controllable factors to the multi-performance characteristics in the turning process were determined.

2. Experimentation procedure and test results

The cutting experiments were carried out on an experimental lathe setup using a HSS MIRANDA S-400 (AISI T – 42) cutting tool for the machining of the IS: 2062, Gr. B Mild Steel bar, which is 24 mm in diameter. The percent composition of the work piece material is listed in Table 1. Mar Surf PS1 surface roughness tester was used to measure the Surface roughness R_a (µm) of the machined samples and Lathe tool dynamometer was used to measure the cutting forces and measuring cutting tool vibration using Pico Scope 2202

Table 1

Chemical composition of IS: 2062, Gr. B. mild steel

Material Composition	C	Mn	Si	S	P
Weight Percentage (%)	0.15	0.79	0.22	0.022	0.030

In the present experimental study, spindle speed, feed and depth of cut have been considered as machining parameters. The machining parameters with their units and their levels as considered for experimentation are listed in Table 2.

Table 2

Machining parameters and their limits

Symbol	Machining Parameter	Unit	Level 1	Level 2	Level 3
A	Spindle Speed	RPM	160	240	400
B	Feed rate	mm/rev	0.08	0.16	0.32
C	Depth of cut	mm	0.1	0.15	0.2

Table 3
Experimental conditions, cutting force and calculated power

Exp. No	Spindle Speed N (RPM)	Feed rate F (mm/rev)	Depth of cut d_{cut} (mm)	Response main force Fc (N)	Cutting speed V_c (m min^{-1})	Power calculated P_c (W = N * V_c) Watt
1	160	0.08	0.15	48	12.06	9.65
2	160	0.08	0.2	64	12.06	12.86
3	160	0.32	0.15	192	12.06	38.6
4	160	0.32	0.1	87.04	12.06	17.5
5	160	0.16	0.1	43.68	12.06	8.8
6	400	0.32	0.15	130.56	30.16	65.63
7	240	0.16	0.1	50.68	18.09	15.28
8	400	0.16	0.15	70.52	30.16	35.5
9	160	0.16	0.2	107.36	12.06	21.6
10	400	0.16	0.1	54.68	30.16	27.5
11	240	0.16	0.15	80.52	18.09	24.28
12	400	0.08	0.2	64	30.16	32.17
13	240	0.32	0.1	100.04	18.09	30.16
14	240	0.08	0.1	25	18.09	7.54
15	240	0.08	0.15	48	18.09	14.47
16	160	0.08	0.1	33	12.06	6.63
17	240	0.08	0.2	64	18.09	19.3
18	160	0.32	0.2	174.08	12.06	35
19	400	0.08	0.15	38	30.16	19.1
20	160	0.16	0.15	80.52	12.06	16.2
21	400	0.16	0.2	127.36	30.16	64.02
22	240	0.32	0.15	192	18.09	57.9
23	400	0.32	0.1	109.36	30.16	56
24	240	0.32	0.2	194.08	18.09	58.5
25	400	0.32	0.2	174.08	30.16	87.5
26	240	0.16	0.2	127.36	18.09	38.4
27	400	0.08	0.1	27.34	30.16	13.74

Table 4
Experimental design and collected response data

	Parameter			Response features		
Exp No.	Spindle Speed N(RPM)	Feed rate f(mm/rev)	Depth of cut d_{cut} (mm)	Power consumption P(W)	Surface roughness R_a (μm)	Frequency of tool vibration f (Hz)
1	160	0.08	0.15	9.65	1.97	270.7
2	160	0.08	0.2	12.86	2.01	281
3	160	0.32	0.15	38.6	6.84	335
4	160	0.32	0.1	17.5	6.16	322.9
5	160	0.16	0.1	8.8	2.58	295
6	400	0.32	0.15	65.63	5.46	395
7	240	0.16	0.1	15.28	2.38	326.5
8	400	0.16	0.15	35.5	1.68	362
9	160	0.16	0.2	21.6	3.02	310
10	400	0.16	0.1	27.5	2.29	347
11	240	0.16	0.15	24.28	2.20	337.7
12	400	0.08	0.2	32.17	1.66	355
13	240	0.32	0.1	30.16	6.01	350
14	240	0.08	0.1	7.54	1.59	297
15	240	0.08	0.15	14.47	1.80	321
16	160	0.08	0.1	6.63	1.88	260
17	240	0.08	0.2	19.3	1.82	327
18	160	0.32	0.2	35	6.72	347
19	400	0.08	0.15	19.1	1.54	340
20	160	0.16	0.15	16.2	3.42	302.7
21	400	0.16	0.2	64.02	2.60	384
22	240	0.32	0.15	57.9	5.84	370
23	400	0.32	0.1	56	5.82	376
24	240	0.32	0.2	58.5	6.28	375.7
25	400	0.32	0.2	87.5	5.89	420
26	240	0.16	0.2	38.4	2.84	357
27	400	0.08	0.1	13.74	1.38	322

3. Methodologies

3.1 Grey relational analysis

Original Taguchi method has been designed to optimize a single performance characteristic. The Grey relational analysis based on the Grey system theory can be used to solve complicated multiple performance parameters effectively. As a result, optimization of the complicated outputs can be converted into optimization of a single Grey relational grade. Grey relation analysis is used to find out whether there is consistency between the changing trends of two factors or not, and to find out the possible mathematical relationship among the factors or in the factors themselves.

3.1.1 Data preprocessing

Data preprocessing is normally required since the range and unit in one data sequence may differ from the others. Data preprocessing is also necessary when the sequence scatter range is too large or when the directions of the target in the sequences are different. Data preprocessing is a means of transferring the original sequence to a comparable sequence. Depending on the characteristics of a data sequence, there are various methodologies of data preprocessing available for the gray relational analysis.

If the target value of the original sequence is infinite, then it has a characteristic of the "higher is better." The original sequence can be normalized as follows:

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

When the "lower is better" is a characteristic of the original sequence, then the original sequence should be normalized as follows:

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

However, if there is a definite target value (desired value) to be achieved, the original sequence will be normalized in from:

$$x_i^*(k) = 1 - \frac{\left| x_i^0(k) - x_i^0 \right|}{\max x_i^0(k) - \min x_i^0}. \quad (3)$$

Alternatively, the original sequence can be simply normalized by the most basic methodology, i.e., let the value of the original sequence be divided by the first value of the sequence:

$$x_i^*(k) = \frac{x_i^0(k)}{x_i^0(1)}, \quad (4)$$

where *i=1,….,m; k =1,…, n. m* is the number of experimental data items, and *n* is the number of parameters. $x_i^o(k)$ denotes the original sequence, $x_i^*(k)$ the sequence after the data preprocessing, max. $x_i^o(k)$ the largest value of $x_i^o(k)$, min. $x_i^o(k)$ the smallest value of $x_i^o(k)$, and x_i^o is the desired value of $x_i^o(k)$.

3.2.2 Gray relational coefficient and gray relational grade

In gray relational analysis, the measure of the relevancy between two systems or two sequences is defined as the gray relational grade. When only one sequence, $x_o(k)$, is available as the reference sequence, and all other sequences serve as comparison sequences called a local gray relation measurement. After data preprocessing is carried out, the gray relation coefficient $\xi_i(k)$ for the kth performance characteristics in the ith experiment can be expressed as follows,

$$\xi_i(k) = \frac{\Delta_{min} + \xi \cdot \Delta_{max}}{\Delta_{oi}(k) + \xi \cdot \Delta_{max}}, \tag{5}$$

where, $\Delta_{oi}(k) = |x_0^*(k) - x_i^*(k)|$ and $\Delta_{\max} = 1.00$, $\Delta_{\min} = 0.00$

and $\Delta_{oi}(k)$ is the deviation sequence of the reference sequence $x_o^*(k)$and the comparability sequence $x_i^*(k)$. ξ is the distinguishing or identification coefficient defined in the range $0 \leq \xi \leq 1$ (the value may be adjusted based on the practical needs of the system). A value of ξ is the smaller, and the distinguished ability is the larger. The purpose of defining this coefficient is to show the relational degree between the reference sequence $x_o^*(k)$ and the comparability sequence $x_i^*(k)$. $\xi = 0.5$ is generally used.After the grey relational coefficient is derived, it is usual to take the average value of the grey relational coefficients as the grey relational grade. The grey relational grade is defined as follows:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k). \tag{6}$$

However, in a real engineering system, the relative importance of various factors varies. In the real condition of unequal weight being carried by the various factors, the grey relational grade in Eq. (1) was extended and defined as recommended by Deng (1982).

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

where $\sum_{k=1}^{n} w_k = 1$ and w_k denotes the normalized weight of factor k.

Here, the grey relational grade γ_i represents the level of correlation between the reference sequence and the comparability sequence. If the two sequences are identical by coincidence, then the value of grey relational grade is equal to 1.

The grey relational grade also indicates the degree of influence that the comparability sequence could exert over the reference sequence. Therefore, if a particular comparability sequence is more important than the other comparability sequences to the reference sequence, then the grey relational grade for that comparability sequence and reference sequence will be higher than other grey relational grade. Grey relational analysis is actually a measurement of absolute value of data difference between sequences, and it could be used to measure approximation correlation between sequences.

4. Results and discussion

4.1 Optimal parameter combination

We know from the analysis of machining process that the lower power consumption and surface roughness as well as lower value of frequency of tool vibration provides better quality of the machined surface. Thus, the data sequences power consumption, surface roughness and frequency of tool vibration both have "smaller-the-better" characteristics. Table 5 lists all of the sequences following data pre-processing of power consumption, surface roughness and frequency of tool vibration by using Eq. (2). Then, the deviation sequences, $\Delta_{oi}(k) = |x_0^*(k) - x_i^*(k)|$ has been determined and are shown in Table 6. Grey relational coefficient and Grey relational grade values of each experiment of the full factorial design were calculated by applying equation 5 and 6 and Table 7 and table 8 shows the Grey relational coefficient and grey relational grade for each experiment using full factorial design.

Table 5
Grey relational generation of each performance characteristics

Exp. No.	Power consumption P(W)	Surface roughness R_a (μm)	Frequency of tool vibration f (Hz)
Ideal sequence	1.000	1.000	1.000
1	0.693	0.892	0.933
2	0.923	0.885	0.869
3	0.605	0.000	0.531
4	0.866	0.124	0.607
5	0.973	0.780	0.781
6	0.270	0.253	0.156
7	0.893	0.817	0.584
8	0.643	0.945	0.362
9	0.815	0.699	0.688
10	0.742	0.833	0.456
11	0.782	0.850	0.514
12	0.684	0.949	0.406
13	0.709	0.152	0.438
14	0.989	0.961	0.769
15	0.903	0.923	0.619
16	1.000	0.908	1.000
17	0.843	0.919	0.581
18	0.650	0.022	0.456
19	0.846	0.970	0.500
20	0.882	0.626	0.733
21	0.290	0.776	0.225
22	0.366	0.183	0.3125
23	0.389	0.187	0.275
24	0.359	0.102	0.277
25	0.000	0.174	0.000
26	0.607	0.733	0.394
27	0.912	1.000	0.612

The multi- response optimization problem has been transformed into a single equivalent objective function optimization problem using this approach. The higher grey relational grade is said to be close to the optimal. According to performed experiment design, it is clearly observed that experiment no. 16 has the highest Grey relation grade. Thus, the sixteenth experiment gives the best multi-performance characteristics of the turning process among the 27 experiments.

Table 6
Evaluation of deviation sequence Δ_{oi} (*k*) for each of the responses

Exp. No.	Power consumption P(W)	Surface roughness R_a (μm)	Frequency of tool vibration f (Hz)
Ideal sequence	1.000	1.000	1.000
1	0.037	0.108	0.067
2	0.077	0.115	0.131
3	0.395	1.000	0.469
4	0.134	0.876	0.393
5	0.027	0.220	0.219
6	0.73	0.747	0.844
7	0.107	0.183	0.416
8	0.357	0.055	0.638
9	0.185	0.301	0.312
10	0.258	0.167	0.544
11	0.218	0.150	0.486
12	0.316	0.051	0.594
13	0.291	0.848	0.562
14	0.011	0.039	0.231
15	0.097	0.077	0.381
16	0.000	0.092	0.000
17	0.157	0.081	0.419
18	0.350	0.978	0.544
19	0.154	0.030	0.500
20	0.118	0.374	0.267
21	0.710	0.224	0.775
22	0.634	0.817	0.688
23	0.611	0.813	0.725
24	0.641	0.898	0.723
25	1.000	0.826	1.000
26	0.393	0.267	0.606
27	0.088	0.000	0.388

Table 7
Grey relational coefficients of each performance characteristics for 27 comparability sequences

Expt. No.	Power consumption P(W)	Surface roughness R_a (μm)	Frequency of tool vibration f (Hz)
1	0.931	0.822	0.882
2	0.867	0.813	0.792
3	0.559	0.333	0.516
4	0.789	0.363	0.560
5	0.949	0.694	0.695
6	0.406	0.400	0.372
7	0.824	0.732	0.546
8	0.583	0.900	0.439
9	0.730	0.624	0.616
10	0.659	0.749	0.479
11	0.696	0.769	0.507
12	0.613	0.907	0.457
13	0.632	0.370	0.470
14	0.978	0.928	0.684
15	0.837	0.866	0.567
16	1.000	0.844	1.000
17	0.761	0.860	0.544
18	0.588	0.338	0.479
19	0.764	0.943	0.500
20	0.809	0.572	0.652
21	0.413	0.690	0.392
22	0.440	0.379	0.420
23	0.450	0.380	0.408
24	0.438	0.358	0.409
25	0.333	0.377	0.333
26	0.559	0.652	0.452
27	0.850	1.000	0.563

Table 8
Evaluated grey relational grades for 27 groups

Expt. No.	Grey relational grade	Rank
1	0.898	2
2	0.824	4
3	0.469	21
4	0.570	17
5	0.779	6
6	0.393	26
7	0.700	10
8	0.640	15
9	0.656	14
10	0.629	16
11	0.657	13
12	0.659	12
13	0.490	20
14	0.863	3
15	0.757	7
16	0.948	1
17	0.722	9
18	0.463	22
19	0.736	8
20	0.678	11
21	0.498	19
22	0.413	23
23	0.412	24
24	0.402	25
25	0.348	27
26	0.554	18
27	0.804	5

Table 9 shows the response table and graph of grey relational grade for each turning parameter at different levels, respectively. As shown in Table 9, the important rank in sequence for various turning parameters in machining of mild steel. The order of importance of the controllable factors to the multi-performance characteristics in the turning process, in sequence can be listed as: factor B (Feed rate), A

(Spindle speed), C (Depth of cut). Factor B (Feed rate) was the most effective factor to the performance. This indicates that the turning performance was strongly affected by the feed rate

Table 9
Response of grey relational grade

Symbol	Turning parameters	Grey relational grade Level I	Level II	Level III	Max - Min	Rank
A	Spindle speed	0.698*	0.617	0.569	0.129	2
B	Feed rate	0.801*	0.643	0.440	0.361	1
C	Depth of cut	0.688*	0.627	0.569	0.119	3

** optimal turning parameters*

Total mean Grey relational grade = 0.628
Optimum set of parameters are A in first level, B in first level and C in first level respectively ($A_1B_1C_1$).

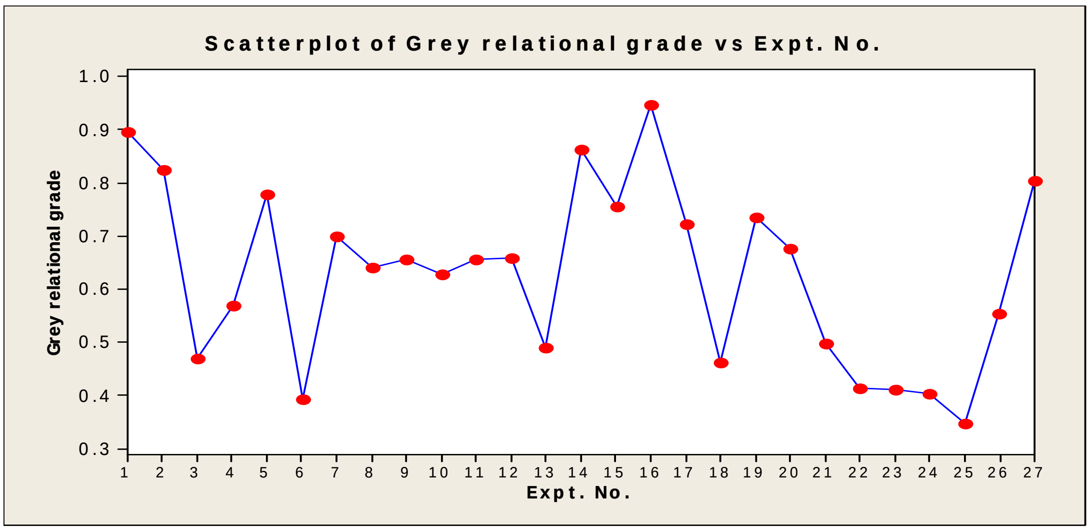

Fig. 1. Grey relation grades for the power consumption, surface roughness and frequency of tool vibration

4.2 Confirmation Test

After obtaining the optimal level of the machining parameters, the next step is to verify the improvement of the performance characteristics using this optimal combination. The estimated grey relational grade using the optimum level of the `parameter is the total mean of the grey relational grade is the mean of the grey relational grade at the optimum level and o is the number of machining parameters that significantly affects the multiple performance characteristics.

$$\hat{\gamma} = \gamma_m + \sum_{i=0}^{o} (\overline{\gamma_j} - \gamma_m), \qquad (8)$$

where γ_m is the total mean of the grey relational grade, $\overline{\gamma_j}$ is the mean of the grey relational grade at the optimum level and o is the number of machining parameters that significantly affects the multiple performance characteristics. Based on equation 8 the estimated grey relational grade using the optimal machining parameters can then be obtained. Table 10 shows the results of the confirmation experiment using the optimal machining parameters The Power consumption P is greatly reduced from 9.65 to 6.63 W, Surface roughness R_a is improved from 1.97to 1.88 µm and the frequency of tool vibration f is greatly reduced from 270.7 to 260 Hz. It is clearly shown that multiple performance characteristics in turning process are greatly improved through this study.

Table 10
Results of machining performance using initial and optimal machining parameters

	Initial machining parameters	Optimal machining parameters	
		Prediction	Experiment
Setting Level	$A_1B_1C_2$	$A_1B_1C_1$	$A_1B_1C_1$
Power consumption P(W)	9.65		6.63
Surface roughness R_a(μm)	1.97		1.88
Frequency of tool vibration f(Hz)	270.7		260
Grey relational grade	0.898	0.931	0.948

Improvement in grey relational grade = 0.05

Therefore, a comparison of the predicted values of the power consumption, surface roughness and frequency of tool vibration with that of the actual parameters by using the optimal machining conditions is shown in the above table. An improvement of 5.00% is observed in the grey relational grade. A good agreement between the two has been observed. This ensures the usefulness of grey relational approach in relation to product/process optimization, where multiple quality criteria have to be fulfilled simultaneously.

5. Conclusion

Experiments are designed and conducted on lathe machine with High speed steel MIRANDA S-400 (AISI T – 42) and IS: 2062, Gr. B Mild Steel bar as work material to optimize the turning parameters. Power consumption, surface roughness and frequency of tool vibration are the responses. Full factorial design of experiments and Grey relational analysis is constructive in optimizing the multi responses. Based on the results of the present study, the following conclusions are drawn:

- The optimum combination of turning parameters and their levels for the optimum multi-performance characteristics of turning process are $A_1B_1C_1$ (i.e. Speed—180 RPM, Feed rate—0.08 mm/rev and Depth-of-cut—0.1 mm).
- Confirmation test results prove that the determined optimum condition of turning parameters satisfy the real requirements.

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