Grey Relational Analysis-based Interactions of Machining Parameters for Optimal Process Response: An Experimental Initiative

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DOI: 10.56201/ijemt.v8.no5.2022.pg13.22

Abstract
This study, investigated the optimal combining of tool nose radius and cutting variables for the overall performance for both AISI 4140 steel and IS-2062 steel. The both materials were machined on a centre lathe and measurements were taken. The data collected was analysed through grey relational analysis. Results showed that grey relational optimal interactions of machining parameters for the overall performance were: N_R (0.35mm), U_o (0.5mm), V_w (65m/min), R_f (0.2mm/rev) for both materials. Also, grey relational grade improved by 1.2767 (24.69%) for the expected optimal design for AISI-4140 steel, and improved by 1.7417 (33.68%) for the expected optimal design for IS-2062 steel. The expected responses were: cutting power 11.157 kW, specific metal removal rate 9.710 mm3/min.kW, cutting force 173.110 N, thrust force 77.207 N, shear force 124.838 N, surface roughness 5.00 µm, and Shear work 7945.9kNm/min for AISI-4140 steel; and cutting power 5.544 kW, specific metal removal rate 19.541 mm3/min.kW, cutting force 86.074 N, thrust force 39.440 N, shear force 65.688 N, surface roughness 6.165 µm, and shear work 4158.67 KNm/min for IS-2062 steel. Grey relational analysis reduced the factors affecting on the dependent variables to feed rate and depth of cut.

Keywords: Grey Relational Analysis, Shear Force, Shear Work, Optimization, Cutting Power.

1. Introduction

Mass production of mechanical parts required the used of machines. Machine tools capable of reducing work piece to the specifications are planer, milling machine, shaping machine, drilling machine and lathe machine. Among these machines, the most versatile is the lathe machine often used for different turning operations. When this lathe is in use, the metal is held and rotated, while the cutting tool is moved across or along it and, volume of metal is being removed. Under such condition, control factors like feed rate, cutting speed, depth of cut and tool nose radius are being varied. The fluctuation of this cutting conditions and tool geometry also affected uncontrolled factors such as cutting power, rate of productivity, surface roughness, and shear force. Nowadays, when experimental results are obtained by measurement or evaluation, necessary analyses are being carried out for reasons of forecast or decision making. Many methods are available for analysis by researchers, however, on the basis of simplicity and fewer number of experiments required, grey relational analysis has received an accelerated application, especially for multi-objective optimization. This study investigated the optimal combining of tool nose radius and cutting variables for the overall performance in turning AISI 4140 steel and IS-2062 steel.

1.1 Literature Surveys

Kazancoglu *et al*. (2011) studied cutting force, surface roughness and productivity in turning process. Cutting conditions was the inputs and grey relational analysis was applied for data analysis. The results of the analysis showed that feed rate was the marked factor affected the responses. It was also found that grey relational analysis reduced influencing factors from four to two (feed rate and depth of cut). Vijaya *et al*. (2013) reported productivity and integrity of finished component as quality characteristics during CNC milling. In the report, AISI 304 specimen was used and cutting conditions was process variables considered for orthogonal series cutting tests. Grey relational analysis applied for analysis showed that cutting speed influenced the output more, followed by cut depth. Nayak *et al.* (2014) studied the influence of machining condition upon performance. Taguchi method was used for design of experiment, while grey relational analysis and ANOVA were used independently. It has been concluded that a combination of speed 45 m/min, distance per revolution 0.1mm/rev, depth of cut 1.25mm were the optimum condition for high productivity and least surface roughness in turning AISI 304. Saraswat *et al*. (2014) also reported an optimization study of cutting parameters in turning of mild steel. Taguchi method was applied to plan the nine experimental runs. The data of predicted model developed and experiments compared showed a close relation, which indicated that the model can be used to predict the surface roughness.

Bhatt and Raval (2018) used Taguchi-based grey relational analysis and finite element analysis to investigate forces, power consumption, and formability in manufacturing process. Three levels of three operating parameters and two levels of two roller shape parameters were considered. It was found that reduction percentage, roller attack angle and roller nose radius were the major factors that influenced the resultant force. The power consumption was influenced by speed and feed rate. The reduction percentage and depth of forming were the governing factors for the formability. There was a good agreement among experimental, grey relational analysis and finite element analysis results. Puh *et al*. (2021) investigated an optimal basis of machining parameters for turning multiple quality responses. The data were analyzed with grey-based Taguchi and analysis of variance. It was concluded that minimum surface roughness and maximum metal removal rate occurred at a cutting speed of 400m/min, feed rate 0.1mm/rev, and depth of cut 12mm. It was further found that cutting speed and depth of cut were the marked influential factors

2. Materials and Methods

2.1 Specification of Work-piece Specimens

The materials utilized for this study were IS-2062 and AISI 4140 alloy steel. IS-2062 steel is widely used in industries for different applications such as hydraulic press, washers, pipes and tubes and, air receivers (Patel & Deshpande, 2014). Also, AISI 4140 alloy steel is used to manufacture axles, conveyor parts, crowbars, gears, engines, logging parts, lathe spindles, drive shafts, sprockets, studs, pinions, pump shafts, ring gear, rams, and connecting rods. It has good balance of strength, excellent toughness, and wears resistance due to its low carbon and high alloy contents (Kus *et al*., 2015)

2.2 Machining Test Arrangement and Input factors

The test specimens (AISI 4140 and IS-2062 steel) were treated on a conventional lathe. In the process, cutting power, cutting forces and surface roughness were measured with wattmeter, dynamometer and stylus respectively, while specific metal removal rate, shear force, and shear work were evaluated. The arrangement of the control factors follows thus: Tool Nose Radius (N_R) 0.15mm, 0.25mm, 0.35mm; Depth of Cut (U_o) 0.5mm, 0.70mm, 0.90mm; Cutting Speed (V_w) 65m/min, 83m/min, 101m/min; and Feed Rate (R_f) 0.2mm/rev, 0.3mm/rev, 0.4mm/rev. The cutting tool selected has a rake angle 15^0 and clearance angle 6^0 and were kept constant throughout the nine experiments.

Evaluation of SZQ, Fs and Ws

The specific metal removal rate (SZQ) can be obtained according to Equation (1) (Sharma, 2011).

$$SZQ = \frac{16.6667.Uo.Vw.Rf}{Pc} \quad (1)$$

where, SZQ is the specific metal removal rate, P_c is cutting power at the tip of the tool, and $U_{o,}$ V_w, R_f are cutting variables. The shear plane angle can also be calculated using Equation (2) to make way for the shear force (Sharma, 2011).

$$\varphi = \text{Tan}^{-1}\left\{\frac{C_{CF} Cos\propto}{1-C_{CF} Sin\propto}\right\} \quad (2)$$

where, $\propto$ represents rake angle, C_{CF} is the chip cutting factor, and φ stands for the shear plane angle.
Shear force is an unmeasurable force and can be evaluated according to Equation (3) (Sharma, 2011).

$$F_s = F_c \cos\varphi - F_t \sin\varphi \quad (3)$$

where, F_s is the shear force and F_t is the thrust force.
The shear work can be obtained using Equation (4) (Sharma, 2011).

$$Ws = F_s \frac{Cos\propto}{Cos\,(\varphi-\propto)} V_w \quad (4)$$

where, Ws is the shear work in turning operations and V_w represents cutting speed.

2.3 Grey Relational Analysis

This study will use grey relational analysis to obtain the grey relational grade and arrange the machining parameters in order of their effect on the dependent factors. The objective of this study is to maximize the specific metal removal rate and minimize the rest of the quality characteristics of machined parts. Therefore, Equations (5 and 6) can be used for Least-The-

Better and Higher-The-Better data normalization respectively (Teja *et al.*, 2013; Tamilarasan and Marimuthu, 2014; Sylajakumari *et al.*, 2018; Prakash *et al.*, 2020).

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (5)$$

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (6)$$

where, i = 1, 2,3, 4, …, N; $\mathfrak{H}_i(k)$ is the grey relational coefficient of k^{th} response in i^{th} experiment, n is the number of responses. From the normalized experimental data, the grey relational coefficient can be established according to Equation (7).

$$\mathfrak{H}_i(k) = \frac{\Delta min + \S\Delta \max}{\Delta oi(k) + \S\Delta max} \quad (7)$$

where, $\Delta di(k) = \|x_o(k) - xi(k)\|$ stand for the difference of absolute value $x_o(k)$ and $x_i(k)$. $x_o(k)$ is the reference sequence k^{th} quality response, $\S$ represent the distinguishing coefficient whose value is from 0 to 1, generally set to 0.5 since it can ensure stability, Δmin stands for the smallest value of Δdi, and Δmax represents the largest value of Equations (8 and 9).

$$\Delta di = \forall j^{min} \in i\ \forall k^{min} \| x_o(k) - xi(k) \| \quad (8)$$

$$\Delta di = \forall j^{max} \in i\ \forall k^{max} \| x_o(k) - xi(k) \| \quad (9)$$

The grey relational coefficient values are applied to obtain the grey relation grade. The average grey grade for the i^{th} experimental runs for all n responses can be obtained according Equation (10).

$$\mathcal{H}_i = \frac{1}{n}\sum_{i=1}^{n} \mathfrak{H}i(k) \quad (10)$$

where, i = 1, 2, 3, …, 9.
$\mathfrak{H}i(k)$ is the grey relational coefficient of k^{th} response in i^{th}experiment, n is the number of responses. $\mathcal{H}_i$ is the average grey grade for the i^{th} experimental runs for all n responses. The higher grey relational grade implies that the corresponding parameter combination is closer to the optimal.

2.4 Expected Responses and Improvement in Grey Relational Grade

The estimated response (grey relational grade) using the optimal setting of the machining parameters can be obtained by Equation (11) (Mgbemena *et al.*, 2016; Baskaran *et al.*, 2017; Basar *et al.*, 2018). The higher the value of the Grey relational grade is, so the corresponding machining parameter combination is said to be close to the optimal.

$$E_R = \lambda a + \sum_{i=1}^{q}(\lambda i - \lambda a) \quad (11)$$

where, E_R is the expected response, ⅄a stands for the total mean of the grey relational grade, ⅄i is the mean of the grey relational grade at the optimal setting, and q represent the number of machining parameters that affect the dependent factors significantly.

3. Results and Discussion

In this study, the dependent variables were cutting power, specific metal removal rate, main cutting force, thrust force, shear force, shear work, and surface roughness. The actual data from experiments performed are presented in Table 1. The data was necessary for grey relational generation.

Table 1: Results of machining AISI 4140 Steel

Treatments	Pc	SZQ	Fc	Ft	Fs	Ws	RY
1	11.157	9.710	173.110	777.208	124.838	7945.94	8.33
2	28.368	10.241	343.004	143.127	243.625	19194.67	18.75
3	57.659	10.510	569.928	223.221	408.539	40140.85	33.33
4	27.998	9.868	337.068	148.672	241.375	19672.06	20.00
5	23.086	10.208	228.670	95.459	162.417	16168.61	5.00
6	27.893	10.487	427.447	167.002	301.155	19376.31	11.25
7	23.997	10.522	237.549	93.598	167.364	16731.38	8.04
8	29.635	10.236	457.340	191.717	324.837	20808.87	14.28
9	23.689	10.511	284.963	113.561	200.769	16495.18	3.57

Table 2: Results of machining IS-2062 Steel

Treatments	Pc	SZQ	Fc	Ft	Fs	Ws	RY
1	5.544	19.5409	86.074	39.440	65.688	4158.87	11.833
2	15.209	19.1009	182.013	82.682	137.887	11146.79	24.375
3	31.590	19.1837	313.079	141.709	236.377	23254.40	41.100
4	14.491	19.0927	174.360	78.826	131.375	10620.36	26.000
5	12.270	19.2071	120.012	54.671	91.924	9042.56	6.165
6	15.186	19.2616	233.259	106.358	177.283	11223.79	15.975
7	13.172	19.1698	130.711	59.161	98.532	9692.59	9.908
8	15.614	19.4273	240.084	110.286	183.849	11639.48	20.286
9	12.757	19.5191	153.040	70.772	118.189	9552.03	4.643

3.1 Optimization of Multiple Responses using Grey Relational Analysis

Grey relational grade technique was used for multi-response optimization as the performance index. The data acquisition processes (normalization of experimental data, computation of grey relational coefficient, and grey relational grade) were performed for AISI-4140 and IS-2062 work piece materials. The performance characteristics based on the grey relational grade are presented in Tables (1 and 2) for the respective materials. From Tables (1 and 2), it is clear, the multiple responses optimization has been converted to a single grey relational grade.

Table 1: Grey Relational Grade for Multi-Responses for AISI-4140 Work Piece Material and Ranking.

Experiment Runs	$\mathcal{H}_i$ ($\mathfrak{H}_i$)	Ranking
1	6.0191	1
2	3.8576	6

3	2.9711	9
4	3.6185	7
5	5.1707	4
6	4.0789	5
7	5.4008	2
8	3.4966	8
9	5.2352	3

Table 2: Grey Relational Grade of multi-Responses for IS-2062 Work Piece Material and Ranking.

Experimental Runs	$\mathcal{H}_i$ ($\mathfrak{H}_i$)	Ranking
1	6.7171	1
2	3.5903	6
3	2.3853	9
4	3.6755	5
5	4.9506	3
6	3.5131	8
7	4.5777	4
8	3.5879	7
9	5.0620	2

The comparison of the grey relational grade values for AISI-4140 steel and IS-2062 steel specimens is presented in Figure 2. From the plot, the grey relational grades for AISI-4041 and IS-2062 steel specimens turned on the lathe, it was found that, both materials had their maximum grey relational grade at the first experimental run. However, IS-2062 steel specimen had higher grade. Similarly, it was found that the least grey relational grade for both materials occurred at the third experimental runs, but that of IS-2062 steel specimen was low.

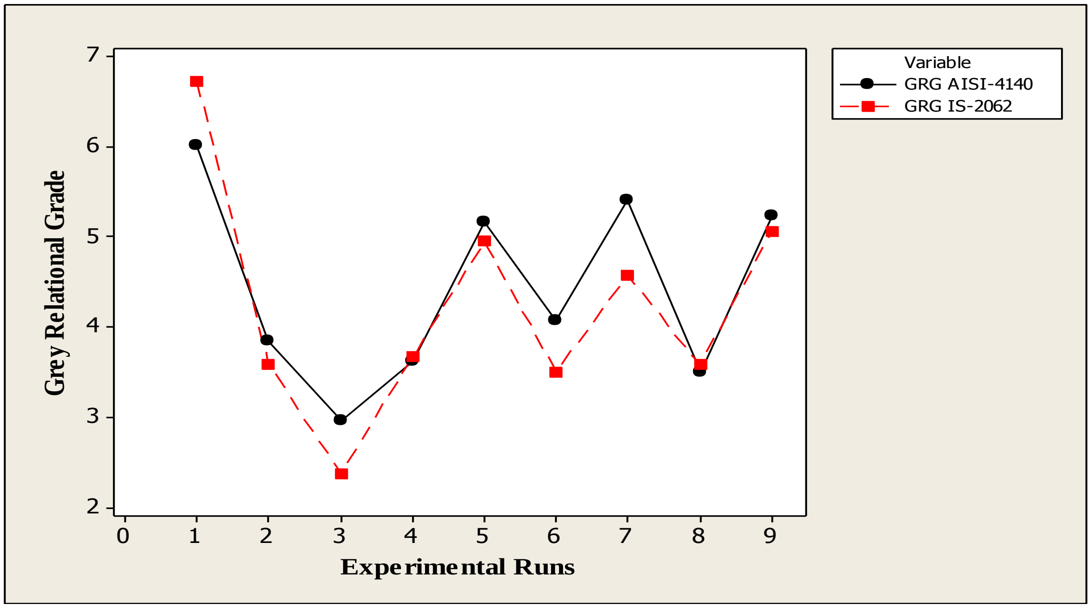

Figure 1: Grey Relational Grade for AISI-4041 and IS-2062 Steel Specimens versus Experimental Runs

The grey relational optimal combination of cutting conditions and tool geometry for the overall effect for both materials are illustrated in Tables (3 and 4). From Table 3, the overall mean of the grey relational grade for AISI-4140 steel is 4.4276 and the optimal set for efficient machining was found to be R_f (0.2mm/rev), N_R (0.35mm), V_w (65m/min), Uo (0.5mm). Also, from Table 4, the overall mean of the grey relational grade for IS-2062 steel is 4.2307 and the optimal set for efficient machining is R_f (0.2mm/rev), N_R (0.35mm), V_w (65m/min), and Uo (0.5mm).

Table 3: Mean Grey Relational Grade (GRG) for AISI-4140 Work Piece Material

Setting	**R_f**	**N_R**	**V_w**	**U_o**
1	4.4750*	4.2856	4.5315*	4.9901*
2	4.4458	4.2894	4.2371	4.1750
3	3.3621	4.7109*	4.5142	4.0951
Delta	2.1129	0.4253	0.2944	0.9177
Rank	1	3	4	2

Table 4: Mean Grey Relational Grade (GRG) for IS-2062 Work Piece Material

Setting	**R_f**	**N_R**	**V_w**	**U_o**
1	5.5766*	4.2309	4.6060*	5.0128*
2	3.8937	4.0464	4.1093	4.0429
3	3.2162	4.4092*	3.9712	3.6535
Delta	2.3604	0.3628	0.6348	1.3593
Rank	1	3	4	2

3.2 Expected Response and Improvement in Grey Relational Grade

The expected responses and improvement in grey relational grade for AIAI 4140 steel and IS-2062 steel were determined and reported in Tables (5 and 6) accordingly. From Table 5, it was found that there was a reduction in all the quality characteristics except, specific metal removal rate for AISI-4140 steel specimen that experienced an increased, which is desirable. The grey relational grade also increased by 24.69%. This showed that GRA is an ideal tool for improvement of multiple objective problems. Also, from Table 6, it was found that reduction occurred in all the quality characteristics, except specific metal removal rate for IS-2062 steel specimen, which is needed. It was found that was an increased in grey relational grade by 33.68%, which justifies the adequacy of the tool for improvement of multiple objectives issue, however, the approach was more feasible for IS-2062 steel material.

Table 5: Expected Response and Improvement in Grey Relational Grade for AISI-4140 Work Piece Material

Outputs Variable/ Setting	Original Design	Experiment Optimal Design	Expected Grey Optimal Design
Setting	$R_f1N_R2V_w3U_o2$	$R_f1N_R3V_w1Uo1$	$R_f1N_R3V_w1U_o1$
Pc	23.086		11.157
SZQ	10.208		9.710
Fc	228.670		173.110
Fs	162.417		124.838
Ft	95.459		77.207
Ws	16168.60		7945.90
RY	8.88		5.00
Grey Relational Grade (GRG)	5.1707	6.0191	6.4474
Improvement in GRG		0.8485 (16.42%)	1.2767 (24.69%)

Table 6: Expected Response and Improvement in Grey Relational Grade for IS-2062 Work Piece Material

Outputs Variable/ Setting	Original Design	Experiment Optimal Design	Expected Grey Optimal Design
Setting	$R_f1N_R2V_w3U_o2$	$R_f1N_R3V_w1Uo_1$	$R_f1N_R3V_w1U_o1$
Pc	12.270		5.544
SZQ	19.207		19.541
Fc	120.084		86.074
Fs	91.924		65.688
Ft	54.640		39.44
Ws	9042.56		4158.67
RY	11.833		6.165
Grey Relational Grade (GRG)	5.1709	6.7171	6.9125
Improvement in GRG		1.5462 (29.9%)	1.7417 (33.68%)

Conclusion

i. The grey relational optimal set of machining parameters for the overall performance were: N_R (0.35mm), U_o (0.5mm), V_w (65m/min), R_f (0.2mm/rev) in turning both materials.

ii. There is an improvement in grey relational grade by 1.2767 (24.69%) for the expected grey optimal design for AISI-4140 steel material, and 33.68% for the expected grey optimal design for IS-2062 steel material.

iii. The expected responses were as follows: cutting power 11.157 kW, specific metal removal rate 9.710 mm3/min.kW, cutting force 173.110 N, thrust force 77.207 N, shear force 124.838 N, surface roughness 5.00, and Shear work 7945.9kNm/min in machining AISI-4140 steel; and cutting power 5.544 kW, specific metal removal rate 19.541 mm3/min.kW, cutting force 86.074 N, thrust force 39.440 N, shear force 65.688 N, surface roughness 6.165 µm, and shear work 4158.67 KNm/min in turning IS-2062 steel.

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