The Iraqi Journal For Mechanical And Material Engineering, Vol.15, No3, 2015

TAGUCHI BASED GREY RELATIONAL ANALYSIS FOR MULTI-OBJECTIVE OPTIMIZATION OF CUTTING PARAMETERS IN HARD TURNING

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ABSTRACT :

In this paper, the combination between Taguchi method and grey relational analysis was applied as a key solution for multi objective optimization problem in turning of hard metal. The variable were; cutting speed, feed rate, depth of cut, and tool nose radius. These parameters were optimized with respect to surface roughness and metal removal rate. The surface roughness was to be minimized; on the other hand the metal removal rate is to be maximized. This problem was solved by converting the multi objective optimization to single objective optimization by applying the grey relational grade analysis. L16 Taguchi orthogonal array is used in this paper. The confirmation results show that the grey relational grade analysis is an effective tool to improve the multi quality objective process.

Keywords Taguchi, Grey Relational Analysis, Hard Turning, Surface Roughness, Metal Removal Rate, S/N ratio

تحليل الامثلية متعددة الاهداف لعوامل عملية القطع للخراطة الصلدة باستخدام طريقة تاكوجي مع طريقة التحليل الرمادي

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الخلاصة :

في هذا البحث تم الدمج بين طريقة تاكوجي وطريقة التحليل الرمادي لغرض تحديد الامثلية متعددة الاهداف في عملية الخراطة للمعادن الصلدة. ضروف القطع التي تم اعتمادها هي سرعة القطع، معدل التغذية، عمق القطع، ونصف قطر تقوس اداة القطع. تم دراسة هذه المتغيرات لتحديد الضروف المثلى التي تؤدي الى اقل خشونة سطحية واعلى معدل ازالة للمعدن وهذين الضرفين متعارضان. تم التغلب على هذه المشكلة من خلال تحويل عملية الامثلية متعددة الاهداف الى عملية تحقيق الامثلية ذات الهدف الواحد من خلال تطبيق مفهوم تحليل درجة العلاقة الرمادية. تم استخدام طريقة تاكوجي و بواقع 16 تجربة. اضهرت النتائج فاعلية دمج الطريقتين في تحديد الامثلية وتقليل الخشونة السطحية وزيادة معدل ازالة المعدن.

1. INTRODUCTION

In turning of hard material it is difficult to improve the surface finish and at the same time increasing the metal removal rate. In order to achieve the above goal, optimized cutting parameters and proper selection of these parameters are to be employed. Steel type AISI 4340 is one of such hard material. Taguchi method is one of the most powerful optimization methods that used in the engineering problems. In this method the parameters factors which can be controlled and noise factors which can't be controlled which influences the product quality are considered 2007. Asilturk, I. Akkus, H.2011 focuses their study on optimizing turning parameters based on the Taguchi method to minimize surface roughness. Experiments have been conducted using the L9 orthogonal array in a CNC turning machine on hardened AISI 4140 (51 HRC) with coated carbide cutting tools. The statistical methods of signal to noise ratio (SNR) and the Analysis of Variance (ANOVA) are applied to investigate effects of cutting speed, feed rate and depth of cut on surface roughness. Suresh, R.2012 established a correlation between cutting parameters such as cutting speed, feed rate and depth of cut with machining force, power, specific cutting force, tool wear and surface roughness) for machining of hardened AISI 4340 steel to analyze the effects of process parameters on machinability aspects using Taguchi technique. Pontes, F. et al.2012 studied applicability of radial base function (RBF) neural networks for prediction of Roughness Average (Ra) in the turning process of SAE 52100 hardened steel, with the use of Taguchi's orthogonal arrays as a tool to design parameters of the network. Aslan, E. et al, 2007 outlines their work on experimental study to achieve hard steel turning employing Taguchi techniques. Combined effects of three cutting parameters, namely cutting speed, feed rate and depth of cut on two performance measures, flank wear (VB) and surface roughness (Ra), were investigated employing an orthogonal array and the Analysis of Variance (ANOVA).

In this work, steel AISI 4340 was machined using CNC lathe with different cutting parameters, cutting speed, feed rate, depth of cut, tool nose radius. Experimental details on Taguchi via grey relational grade have been employed for multi objective optimization such as metal removal rate and surface roughness.

2. EXPERIMENTAL CAMPAIGN AND PROOCEDURE

The experimental campaign was conducted to study the effect of four different cutting conditions on the surface roughness and material removal rate in hard turning of AISI 4340 in dry environment and a wide range of levels. The chemical composition of the work piece material is shown in **Table 1**. The hardness of the used AISI 4340 steel was 47 HRC.

2.1 TEST WORKPICE

The material used as a workpiece for hard turning was AISI 4340 steel of a 25mm diameter and 400mm length. The chemical composition of the workpiese material is shown in **Table1**. This type of workpiece material have a wide range of engineering applications such as gear shafts, crank shafts of heavy vehicles, spindles, cam shafts, spline shafts, etc.

2.2 utting tools and machine tool

In tests, grade MTKB5625 four CBN inserts have been used for experimentation. The four inserts have the same material, which contain 50% CBN and TiC binder, but of different nose radii as will be explained later. The machining experimental campaign was implemented on CNC lathe.

2.3 design of experiments

In this experimental investigation, experiments were planned by varying four different cutting parameters namely: cutting speed, feed rate, depth of cut, and tool nose radius. Ranges of cutting parameters except tool radius were selected based on machine tool capability, literature review and tool manufacturer's recommendations 2012. The tool nose radius was decided on the basis of availability. In order to explore the effect of cutting parameters, each cutting parameter was studied over four levels as shown in **Table2**.

Based on the full factorial design of experiment, the minimum number of experimental combination (N) is given by $N=\ell^{n}$, where ℓ is the number of levels, and n is the number of factors. Accordingly, full factorial design of experiments requires ($4^4=256$) experiments. It is tedious and unfeasible to conduct all the experiments, consequently, Taguchi method is used instead of FFD method to reduce the number of experiments without sacrificing the expected results of full factorial design Tong et. al 1997. Taguchi method is a very popular method used for wide range of engineering applications to design an efficient experiment Htlya Atil 2000. The optimum parameter combination for a given quality characteristic can be determined by using the signal to noise ratio (S/N) proposed by Taguchi which considered both mean and variability. The minimum number of experiments as per Taguchi's technique to be conducted for parametric optimization is calculated as Tong et. al 1997:

$$N=(\ell-1)n+1 \qquad (1)$$

Hence 16 experiments have to be conducted for four levels and four parameters. In this work, the L16 orthogonal array with four levels and four parameters is used as given by **Table3**.

3. PERFORMING EXPERIMENTS

The 16 tests were conducted based on L16 Taguchi orthogonal array on CNC lathe on dry environment. The optimization functions of this work are conflict so that to minimize surface roughness R_a and to maximize the metal removal rate MMR. Surface roughness was measured by using a surface roughness tester, the cutoff length was fixed as 1.25mm. The direction of roughness measurements was perpendicular to the direction of the cutting velocity. The measurements were taken at eight locations (45^o) around the circumference of the work piece and the average roughness was recorded for each test. The metal removal rate MRR was calculated as follows S.Ranganathan 2011:

$$MRR=V_c f\ a \qquad (2)$$

Where MRR is the metal removal rate in cm^3/min, V_c is the cutting speed (m/min), f is the feed rate (mm/rev), a is the depth of cut (mm). **Table 4** shows the results of the experimental campaign as per the Taguchi L16 orthogonal array.

4. ANALYSIS METHOD

The analysis method adopted in this paper was based on Taguchi and grey relational method. The Taguchi method is an effective technique to specify the effect of each factor and to find the optimal parameter combination.

The grey relational analysis is used for multi-objective optimization of more than one quality characteristic especially when these quality characteristics are conflicts in nature like surface roughness and metal removal rate.

4.1 Signals-to-Noise Ratio

Taguchi proposed the signal-to-noise ratio as a measure of performance characteristic. The "signal" represents the desirable value and the noise represents the undesirable value. Consequently, the largest S/N ratio is desired for any quality characteristic. In the engineering analysis, there are three types of quality characteristic namely, the larger-the-better, smaller-the-better, and nominal-the-best. The S/N ratio of the surface roughness R_a is represented by smaller-the-better characteristic that can be represented as:

$$\eta_{ij}=-10\log\left(\frac{1}{n}\sum_{j=1}^{n} Ra_{ij}^{2}\right) \quad (3)$$

The S/N ratio of the metal removal rate MRR is represented by larger-the-better characteristic that can be represented as:

$$\eta_{ij}=-10\log\left(\frac{1}{n}\sum_{j=1}^{n} \frac{1}{MRR_{ij}^{2}}\right) \quad (4)$$

where i is the ith experiment, j is the jth test, and n is the total number of the tests. The results of the S/N ratios for the surface roughness and metal removal rate are shown in **Table 5**.

4.2 Multi-Objective Optimization of Hard Turning Based on Grey Relational Analysis

Based on Taguchi optimization method, the level of the highest S/N ratio represents the optimum level. This approach can be successfully implemented when the manufacturing process has a single objective function or multi objective functions having the same goals. In this study, two conflict objective functions "surface roughness" and "metal removal rate" are to be optimized. The surface roughness objective function is the smaller the better STB, on the other hand the larger the better objective function is dedicated for metal removal rate that is why the optimization of multiple objective functions is complex. The key solution adopted in this study is the incorporating the grey relational analysis method with the Taguchi method simultaneously.

The two idealize conditions in real engineering problems is the full of information (white) and lack of information (black). The grey, in between them, represents in complete information which gives diversity of applicable solutions. The grey system theory is especially suited for the problems of multi objective optimization by simplifying these problems into the optimization of single grey relational grade.

The multi-objective optimization using grey relational analysis has the following steps:

i. Normalization the experimental results of surface roughness and metal removal rate
ii. Calculation the grey relational coefficient
iii. Calculation the grey relational grade

iv. Analyzing the experimental results using the grey relational grade
v. Select the optimum levels
vi. Verification of the optimal solution

4.2.1 Experimental results normalization

The first step in the GRA is the normalization of the random results with different measurement units in the range between zero and one. This step is also called grey relational generation.

For the surface roughness objective function which is smaller the better STB, the normalized S/N ratio η_{ij}^{norm} for the i[th] objective function in the j[th] experiments is given by:

$$\eta_{ij}^{norm} = {max\,\eta_{ij} - \eta_{ij}} \Big/ {max_j\eta_{ij} - min_j\eta_{ij}} \quad (5)$$

Where η_{ij} is the original sequence of S/N ratio, $max\ \eta_{ij}$ is the largest value of η_{ij}, and $min\ \ \eta_{ij}$ is the smallest value of η_{ij}.

For metal removal rate MRR objective function which is greater the better GTB, the normalized S/N ratio is given by:

$$\eta_{ij}^{norm} = {\eta_{ij} - \min\eta_{ij}} \Big/ {max_j\eta_{ij} - min_j\eta_{ij}} \quad (6)$$

Table 6 shows the normalized S/N ratio for surface roughness and metal removal rate

4.2.2 Calculation of grey relational coefficient

To explore the relation between the ideal and actual normalized S/N ratio, the grey relational coefficient α_{ij} has to be calculated for each experiment as follows:

$$\propto_{ij} = \frac{min_i\,min_j|\eta_i^{bes} - \eta_{ij}| + \beta\,max_i max_j|\eta_i^{bes} - \eta_{ij}|}{|\eta_i^{bes} - \eta_{ij}| + \beta\,max_i max_j|\eta_i^{bes} - \eta_{ij}|} \quad (7)$$

Where η_i^{bes} is the best normalized result. $\eta_i^{bes} = 1$ for the j[th] objective function, and β is a distinguishing coefficient which is ranging from zero to one and it is set to 0.5 in this work. **Table 7** shows the grey relational coefficients of the 16 experiments.

4.2.3 Calculation of grey relational grade

Grading the grey relational coefficients is a simple weighting method used for integration the grey relational coefficients of each experiment into the grey relational grade. The grey relational grade is calculated as follows:

$$\gamma_j = \frac{1}{m} \sum_{i=1}^{m} w_i \propto_{ij} \qquad (8)$$

Where γ_j is the GRG for the jth experiment, w_i the weighting value for the ith objective function, m is the number of objective function. The weighting value is selected as a weighting ratio of the two objective functions according to the importance of these objective functions. Assuming that the two functions have equal importance, the weighting value is set to 1. **Table 8** shows the grey relational grad of each experiment of the L16 orthogonal array.

The best multi response objective function is corresponding to the experiment of the highest grey relational grade, because of the result of this experiment is closer to the ideally normalized value (1).

Accordingly, the experiment number 8 with grey relational grade equal to 0.6688 has the best multi-response characteristics among the 16 experiments. By utilizing the orthogonality property of the Taguchi L16 orthogonal array, the effect of each cutting parameters in different levels based on grey relational grade can be evaluated and tabulated in **Table 9**.

Since that "the larger the grey relational grade is, the better the multi characteristic are" A_2 B_4 C_3 D_2 is the optimum level of cutting parameters of the experiment #8 according to the multi objective characteristics.

4.2.4 Selecting the Optimal Factor Level

Figure 1 show the grey relational grade graph, this graph is based on the results of table 9. The best values of hard turning process parameters for maximizing the grey relational grade can be gathered from grey relational graph **Fig.1**. Based on this graph, the optimal setting is to maintain cutting speed at level 3 (A=228 m/min), feed rate at level 4 (B=0.25 mm/rev), depth of cut at level 4 (C=0.31 mm), and tool nose radius at level 4 (D=1.4 mm) for maximizing metal removal rate and minimizing surface roughness.

4.2.5 Confirmation tests

In order to confirm the results of grey relational grade method, three confirmation tests are performed and the average results are taken and tabulated as shown in Table 10. Based on the confirmation tests, an improvement up to 7% in metal removal rate, the MRR increased from 11.57 to 12.39 cm^3/min. On the other hand the surface roughness improvement up to 30.7 %, the surface roughness decreased from 4.965 to 3.798 um.

5. CONCLUSIONS

In this paper, the optimization of hard turning process parameters based on Taguchi method with grey relational analysis using multi objective optimization characteristics. The multi objective optimization process has been simplified and converted to single objective optimization method using the grey relational analysis. The results shows a significant improvements in metal removal rate up to 7% and in surface roughness up to 23% when using the adopted optimization method. Accordingly the grey relational grade method is recommended as an effective method for the optimization of process parameters concerning the hard turning process.

Table 1

The chemical composition of the AISI 4340 steel in weight %.

C	Si	Mn	P	S	Cr	Mo	Ni	W	Cu	Fe
0.389	0.379	0.687	0.04	0.031	1.098	0.008	1.587	0.581	0.219	**94.981**

Table 2

Cutting parameters and levels used in the experiments.

Symbol	Parameter	Unit	level1	level2	level3	level4
A	Cutting Speed	m/min	128	178	228	**278**
B	Feed Rate	mm/rev	0.1	0.15	0.2	**0.25**
C	Depth of Cut	Mm	0.16	0.21	0.26	**0.31**
D	Tool Nose Radius	Mm	0.5	0.8	1.1	**1.4**

Table 3

L16 orthogonal array as per Taguchi

	Parameters (coded)				Parameters (real)			
Experiments	A	B	C	D	A	B	C	**D**
1	level1	level1	level1	level1	128	0.1	0.16	**0.5**
2	level1	level2	level2	level2	128	0.15	0.21	**0.8**
3	level1	level3	level3	level3	128	0.2	0.26	**1.1**
4	level1	level4	level4	level4	128	0.25	0.31	**1.4**
5	level2	level1	level2	level3	178	0.1	0.21	**1.1**
6	level2	level2	level1	level4	178	0.15	0.16	**1.4**
7	level2	level3	level4	level1	178	0.2	0.31	**0.5**
8	level2	level4	level3	level2	178	0.25	0.26	**0.8**
9	level3	level1	level3	level4	228	0.1	0.26	**1.4**
10	level3	level2	level4	level3	228	0.15	0.31	**1.1**
11	level3	level3	level1	level2	228	0.2	0.16	**0.8**
12	level3	level4	level2	level1	228	0.25	0.21	**0.5**
13	level4	level1	level4	level2	278	0.1	0.31	**0.8**
14	level4	level2	level3	level1	278	0.15	0.26	**0.5**
15	level4	level3	level2	level4	278	0.2	0.21	**1.4**
16	level4	level4	level1	level3	278	0.25	0.16	**1.1**

Table 4

Experimental results for hard turning of AISI 4340 steel

	Parameters (coded)					
Experiments	A	B	C	D	R_a	**MRR**
1	128	0.1	0.16	0.5	1.0178	**2.048**
2	128	0.15	0.21	0.8	1.2968	**4.032**
3	128	0.2	0.26	1.1	1.7398	**6.656**
4	128	0.25	0.31	1.4	1.9038	**9.92**
5	178	0.1	0.21	1.1	11.9938	**3.738**
6	178	0.15	0.16	1.4	16.5598	**4.272**
7	178	0.2	0.31	0.5	39.9108	**11.036**
8	178	0.25	0.26	0.8	44.9658	**11.57**
9	228	0.1	0.26	1.4	1.3048	**5.928**
10	228	0.15	0.31	1.1	1.5418	**10.602**
11	228	0.2	0.16	0.8	1.7178	**7.296**
12	228	0.25	0.21	0.5	6.0088	**11.97**
13	278	0.1	0.31	0.8	1.4408	**8.618**
14	278	0.15	0.26	0.5	1.8498	**10.842**
15	278	0.2	0.21	1.4	4.0578	**11.676**
16	278	0.25	0.16	1.1	8.7868	**11.12**

Table 5

S/N ratios for the hard turning of AISI 4340 steel

Ex.Nr.	Ro	MRR	S/N Ro	S/N MRR
1	1.0178	2.048	-0.1532	**6.2266**
2	1.2968	4.032	-2.2575	**12.1104**
3	1.7398	6.656	-4.81	**16.4643**
4	1.9038	9.92	-5.5924	**19.9302**
5	11.9938	3.738	-21.5791	**11.4528**
6	16.5598	4.272	-24.3811	**12.6126**
7	39.9108	11.036	-32.0218	**20.8562**
8	44.9658	11.57	-33.0576	**21.2667**
9	1.3048	5.928	-2.3109	**15.4582**
10	1.5418	10.602	-3.7606	**20.5078**
11	1.7178	7.296	-4.6995	**17.2617**
12	6.0088	11.97	-15.5758	**21.5619**
13	1.4408	8.618	-3.1721	**18.7081**
14	1.8498	10.842	-5.3425	**20.7022**
15	4.0578	11.676	-12.1658	**21.3459**
16	8.7868	11.12	-18.8766	**20.9221**

Table 6

Normalized S/N ratio for surface roughness and metal removal rate

	Ro	**MRR**	**Nor Rou**	**Nor MRR**
1	1.0178	2.048	0	**1**
2	1.2968	4.032	0.0639	**0.6163**
3	1.7398	6.656	0.1415	**0.3324**
4	1.9038	9.92	0.1653	**0.1064**
5	11.9938	3.738	0.6512	**0.6592**
6	16.5598	4.272	0.7363	**0.5836**
7	39.9108	11.036	0.9685	**0.046**
8	44.9658	11.57	1	**0.0193**
9	1.3048	5.928	0.0656	**0.398**
10	1.5418	10.602	0.1096	**0.0687**
11	1.7178	7.296	0.1382	**0.2804**
12	6.0088	11.97	0.4687	**0**
13	1.4408	8.618	0.0917	**0.1861**
14	1.8498	10.842	0.1577	**0.0561**
15	4.0578	11.676	0.3651	**0.0141**
16	8.7868	11.12	0.569	**0.0417**

Table 7

Grey relational coefficients of the 16 experiments

	Ro	MRR	GRC Rou	GRC MRR
1	1.0178	2.048	0.3333	**1**
2	1.2968	4.032	0.3482	**0.5658**
3	1.7398	6.656	0.3681	**0.4282**
4	1.9038	9.92	0.3746	**0.3588**
5	11.9938	3.738	0.589	**0.5947**
6	16.5598	4.272	0.6547	**0.5456**
7	39.9108	11.036	0.9408	**0.3439**
8	44.9658	11.57	1	**0.3377**
9	1.3048	5.928	0.3486	**0.4537**
10	1.5418	10.602	0.3596	**0.3493**
11	1.7178	7.296	0.3672	**0.41**
12	6.0088	11.97	0.4848	**0.3333**
13	1.4408	8.618	0.355	**0.3805**
14	1.8498	10.842	0.3725	**0.3463**
15	4.0578	11.676	0.4406	**0.3365**
16	8.7868	11.12	0.5371	**0.3429**

Table 8

Grey relational grad of each experiment of the L16 orthogonal array

	Ro	MRR	GRG
1	1.0178	2.048	**0.6667**
2	1.2968	4.032	**0.457**
3	1.7398	6.656	**0.3981**
4	1.9038	9.92	**0.3667**
5	11.9938	3.738	**0.5919**
6	16.5598	4.272	**0.6002**
7	39.9108	11.036	**0.6423**
8	44.9658	11.57	**0.6688**
9	1.3048	5.928	**0.4011**
10	1.5418	10.602	**0.3545**
11	1.7178	7.296	**0.3886**
12	6.0088	11.97	**0.4091**
13	1.4408	8.618	**0.3678**
14	1.8498	10.842	**0.3594**
15	4.0578	11.676	**0.3885**
16	8.7868	11.12	**0.44**

Table 9

Response table based on grey relational grade

	level 1	level 2	level 3	level4	Delta	Rank
A	0.472125	0.6258	0.388325	0.388925	0.237475	**1**
B	0.506875	0.45235	0.454375	0.47115	0.054525	**4**
C	0.523875	0.461625	0.45685	0.432825	0.09105	**2**
D	0.519375	0.47055	0.446125	0.439125	0.08025	**3**

Table 10 (Results of Confirmation experiments)

		optimal parameter setting based on GRG	**MRR**	**Ra**	**optimal parameter setting based on GR graph**	**MRR**	***Ra***
Level		A2B4C3D2			A3B4C4D4		
Cutting Speed	m/min	178			228		
Feed Rate	mm/rev	0.25	11.57	4.965	0.25	12.395	***3.798***
Depth of Cut	mm	0.26			0.31		
Tool Nose Radius	mm	0.8			1.4		

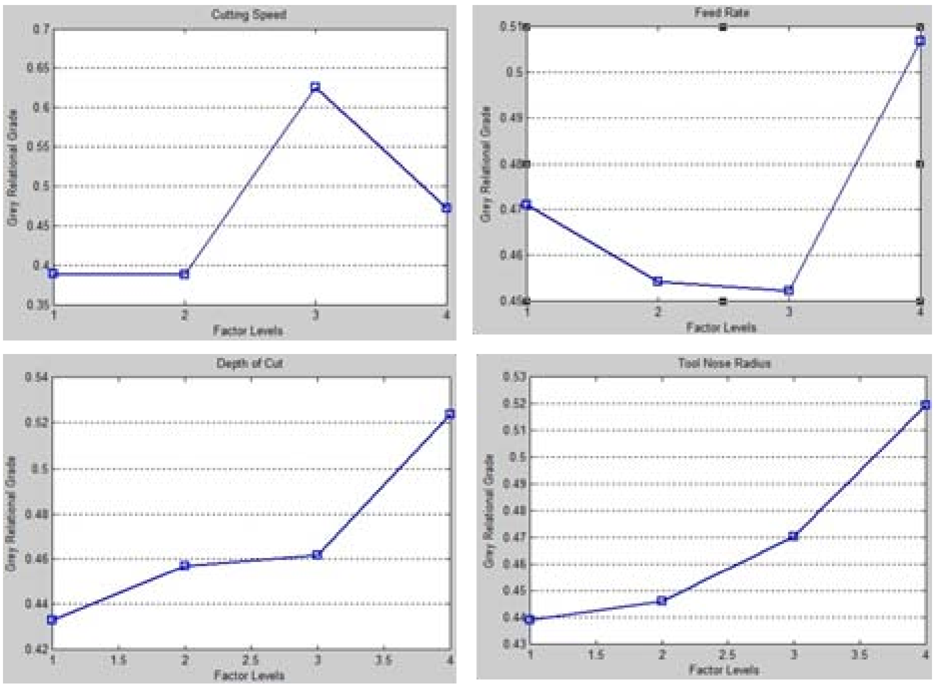

Figure 1: grey relational graph of the four variables

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