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AN STUDY ON SELECTING CUTTING REGIME TO ATTAIN SUITABLE ROUGHNESS AND DIMENSIONAL PRECISION IN BOTH WHEN HARD TURNING TEMPERED ALLOY STEEL

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ABSTRACT

The paper presents an experimental study about the influence of cutting regime parameters (cutting speed, feed rate, depth of cut) on two performance characteristics: surface roughness and dimensional precision when hard turning the tempered alloy steel on the CNC lathe by PCBN tool. Taguchi technique and analysis of variance (ANOVA) in designing experiment and analyzing results has been applied to define the contribution of cutting regime parameters on the characteristics. Taguchi L_9 design matrix with nine experimental runs was conducted to define sets of optimized parameters for each under the experiment conditions. The combination of Taguchi method and grey relation analysis (GRA) was also performed to solve multi object optimization. A set of optimized cutting regime parameters have been defined, that allow to get both low surface roughness and high dimensional precision. An aplication study case is introduced, too. The optimized parameters have been applied to machine the intake valve of the internal combustion engine, effectively.

Keywords: *Taguchi method, Analysis of Variance (ANOVA), Grey Relation Analysis (GRA) hard turning, PCBN insert.*

TÓM TẮT

Bài báo trình bày một nghiên cứu thực nghiệm ảnh hưởng của chế độ cắt (tốc độ cắt, lượng chạy dao, chiều sâu cắt) đến các chỉ tiêu đầu ra là độ nhám bề mặt và độ chính xác kích thước khi tiện cứng thép hợp kim đã nhiệt luyện trên máy tiện CNC bằng dao PCBN. Kỹ thuật Taguchi và phân tích phương sai (ANOVA) được sử dụng trong thiết kế thực nghiệm và phân tích kết quả để xác định mức độ ảnh hưởng của từng thông số chế độ cắt đến các chỉ tiêu đầu ra. Ma trận thực nghiệm Taguchi L_9 với chín thí nghiệm được sử dụng để xác định bộ thông số tối ưu cho từng chỉ tiêu đầu ra. Phương pháp Taguchi kết hợp với phân tích xám (GRA) cũng được áp dụng trong nghiên cứu này nhằm thực hiện tối ưu hóa đa mục tiêu. Bộ thông số tối ưu đa mục tiêu xác định, cho phép nhận được đồng thời độ nhám bề mặt thấp và độ chính xác kích thước cao. Một nghiên cứu ứng dụng cũng được giới thiệu trong bài báo này. Bộ thông số tối ưu tìm được ở trên được sử dụng để gia công hiệu quả xuppap nạp động cơ đốt trong.

Từ khóa: *Phương pháp Taguchi, phân tích phương sai (ANOVA), phân tích xám (GRA), tiện cứng, mảnh dao PCBN.*

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1. INTRODUCTION

Hard turning is a special case of turning, in which hard metals (45 - 65 HRC) are finish machined using ceramic or polycrystalline tools [1]. Hard turning become effectively process when it is conducted on CNC lathe with high rigidity, strong PCBN tools. Very fine roughness and tolerances can be produced by the process. So it is used to replace for grinding in many cases. The use of hard turning and dry machining replacing for grinding also reduces environmental pollution, towards green production. However, how to most appropriately select its cutting regime is not clearly introduced. Some researches related to hard turning have been conducted. Here are some studies related to this issue. A study was conducted to determine the effects of cutting conditions and tool geometry on the surface roughness by using mixed ceramic inserts with different nose radii and different effective rake angles [2]. The feed is the dominant factor to determine the surface finish followed by nose radius and cutting velocity. Though the effect of the effective rake angle on the surface finish is less, the interaction effects of nose radius and effective rake angle are considerably significant. Another surface roughness model was developed on AISI 1050 hardened steels by Cubic Boron Nitride (CBN) cutting tools under different conditions, using response surface methodology [3]. Results revealed that the feed rate is the most dominant factor on the surface roughness, but it decreased with decreasing cutting speed, feed rate and depth of cut for CBN tools. In an investigation [4], different methods were employed such as OA, S/N ratio, ANOVA to investigate the effect of three parameters such as speed, feed, depth of cut, on the performance measure of surface roughness. The paper [5] presented a study on selecting cutting regime to attain suitable roughness and dimensional accuracy in both when CNC turning SUS304 stainless steel by carbide insert.

In this study, the hard turning of tempered alloy steel 40Cr on CNC lathe by PCBN tool is investigated. The Taguchi technique and analysis of variance (ANOVA) followed by grey relation analysis (GRA) were used to conduct the study.

The contribution of each cutting regime parameter on the roughness and dimensional precision were defined. By the way, an optimal parameter combination for roughness and dimensional precision in both was then obtained. At the end of the paper is a study case, in which the intake valve of the internal combustion engine is machined by hard turning.

2. TAGUCHI METHOD & GREY RELATION ANALYSIS

Taguchi method [6] was introduced since the late 1940s. The method is broadly accepted as a DOE which has proven to produce high quality products at subsequently low cost. Two important tools used in the method are Orthogonal Arrays (OAs) and Signal to Noise (S/N) ratios.

The orthogonal array is an experimental matrix, such that the fewest number of trials but the greatest amount of information obtained. An orthogonal array describing the inputs, the levels of those factors, the number of experiments and the configuration of those experiments. It is selected from the set of Taguchi OAs according to the number of experimental variables, levels of each variable, accuracy requirements, experimental conditions ... S/N (η, dB) is defined as the ratio of the wanted signal towards random noise and, in general, it represents quality characteristics for the observed data. Maximization of S/N is desired for parameters of the design. In design there are often many interacting design parameters. So, an exploration of the effects of the combinations of parameters is a necessity. It will, however, not be realistic if there are many numbers of parameters. The signal to noise ratio (S/N) is a measure of the magnitude of a data set relative to the standard deviation. If the S/N is large, the magnitude of the signal is large relative to the noise as measured with the standard deviation.

$$S/N = -10\lg(MSD) \tag{1}$$

Where MSD = mean squared deviation from the target value of the quality characteristic.

Consistent with its application in engineering and science, the value of S/N is intended to be the large; hence the value of MSD should be small. Thus, the mean squared deviation (MSD) is defined differently for each of the quality characteristics considered, smaller, norminal or larger.

For smaller is better:

$$MSD = \frac{y_1^2 + y_2^2 + y_3^2 + \ldots + y_n^2}{n} \tag{2}$$

Where y_1, y_2… y_n result of experiments, observations or quality characteristics such as length, weight, surface finish…

n: Number of repetitions (y_i)

Let $T = \sum_{i=1}^{n}(y_i - y_0)$ the sum of all deviations from the target value, we have the sum of squares of deviations :

$$S_T = \sum_{i=1}^{n} y_i^2 - \frac{T^2}{n} = \sum_{i=1}^{n} y_i^2 - \frac{\left[\sum_{i=1}^{n} y_i\right]^2}{n} \tag{3}$$

- The sum of squared deviations factor A is calculated by the following formula:

$$S_A = \sum_{k=1}^{L} \frac{1}{n_{A_k}} \sum_{i=1}^{n} y_{iA_k}^2 - \frac{\left[\sum_{i=1}^{n} y_i\right]^2}{n} \tag{4}$$

Here in: y_{iA_k} - The ith result of factor A at level k

n_{A_k} - Number of repetitions of factor A at level k.

If there are 3 factors A, B, C and does not take into account the interactions of the factors we can define the error sum of square:

$$S_e = S_T - S_A - S_B - S_C \tag{5}$$

- Contribution level of factors and error:

$$P_A = S_A/S_T;\ P_B = S_B/S_T;\ P_C = S_C/S_T;\ P_e = S_e/S_T \tag{6}$$

Grey relation analysis [7, 8]

Grey System theory was introduced to science world in 1982. Grey Relational Analysis (GRA) is a part of Grey System theory and used for decision making in multi attribute cases. The GRA process includes the following steps:

Step 1: Preprocessing data

Data values of target function are normalized to scalar values in the range from 0 to 1.

Denote:

$y_0^{(0)}(k)$: Original reference sequence of the target functions values

$y_i^{(0)}(k)$: Comparable sequence of the target functions values

$y_i^*(k)$: Normalized sequence of the target functions values

With i = 1, 2, 3,…., m are experimental indicators; k = 1, 2, 3,..., n are the target functions.

- If the data have "the larger-the better" characteristic:

$$y_i^* = \frac{\max(y_{ij}) - y_{ij}}{\max(y_{ij}) - \min(y_{ij})} \tag{7}$$

- If the data have "the Smaller-the better" characteristic:

$$y_i^* = \frac{y_{ij} - \min(y_{ij})}{\max(y_{ij}) - \min(y_{ij})} \tag{8}$$

Step 2: Calculating of Grey Relational Coefficient and Grey Relational Grade

Let the deviation sequence between reference sequence $y_i^*(k)$ and comparable sequence $y_0^{(0)}(k)$ as

$$\Delta_{0i}(k):\ \Delta_{0i}(k) = \left|y_{0j} - y_{ij}\right| \tag{9}$$

Grey Relational Coefficient is calculated based on normalized sequences:

$$\gamma[y_0^*(k), y_i^*(k)] = \frac{(\Delta_{min} + \xi\Delta_{max})}{(\Delta_{0i}(k) + \xi\Delta_{max})} \tag{10}$$

$$0 < \gamma[y_0^*(k), y_i^*(k)] < 1$$

The biggest deviation and the smallest deviation are calculated as:

$$\Delta_{max} = \max\{\Delta_{0i}(k),\ i = 1,2,...,m,\ k = 1,2,..,n\} \quad (11)$$

$$\Delta_{min} = \min\{\Delta_{0i}(k),\ i = 1,2,...,m,\ k = 1,2,..,n\} \quad (12)$$

ξ is distinguishing coefficient in [0, 1] and its value is usually 0.5 in literature.

Grey Relational grade is weighted sum of Grey Relational coefficients and it can be shown as:

$$\Gamma(y_0^*, y_i^*) = \sum_{k=1}^{n} w_k \gamma(y_0^*(k), y_i^*(k)) \quad (13)$$

$$\sum_{k=1}^{n} w_k = 1 \quad (14)$$

The performances of the runs are ranked from the biggest to the smallest Grey Relational grade.

3. EXPERIMENTS, RESULTS & DISCUSSION

3.1. Experimental conditions.

The workpieces made by alloy steel 40Cr were tempered to hardness 40-42 HRC (Fig. 1). The experiment was conducted on CNC lathe CLX-350 at Center for Precision Mechanical Technology of Military Institute of Science and Technology (Fig. 2). Some main specifications of the lathe are presented in table 1.

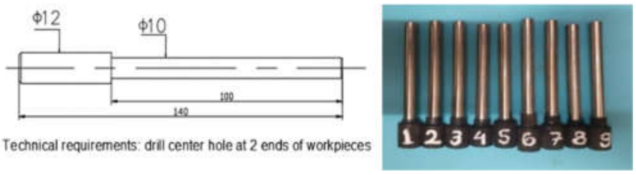

Figure 1. The workpices

Figure 2. CNC lathe CLX-350

Table 1. Specification of CNC lathe CLX-350

X-axes turret travel	270mm
Z-axes turret travel	300mm
Spindle speed	100 ÷ 6000rpm
Spindle Motor	5.5kW/7.5HP
Cutting Feed rate	1 - 10000 mm/min
X-axes Motor	1HP
Z-axes Motor	1HP
Max. tool diameter	ϕ80mm
Overall dimension	2440x1260x1830 mm
Controller	Heidenhain

The PCBN cutting tool insert is made by Kyocera (Fig. 3). The Insert has type D with one side of cutting (DCMW), size 11 and nose radius r = 0.4mm. The coating KBN05M of the insert is convenient for hard turning.

Figure 3. PCBN insert made by Kyocera

Measurement equipments are device for measuring roughness HOMMEL TESTER T1000 (Fig .4) and digimatic outside micrometer MITUTOYO with resolution 0.001mm (Fig. 5).

Figure 4. Device for measuring roughness

Figure 5. Digimatic outside micrometer Mitutoyo

3.2. Experimental design

The experiment is performed according to L_9 Taguchi design. Three input variables as cutting speed (v), feed rate (s), depth of cut (t) are selected. Each variable has three selected levels as in table 2. The experimental machining process is the dry cutting process.

Table 2. Cutting parameters and their levels

N^0	Parameters	Levels		
		Low	Avarage	High
1	Cutting speed v, m/min	45	75	105
2	Feed rate s, mm/rev	0.02	0.06	0.10
3	Depth of cut t, mm	0.06	0.23	0.40

For each sample, the roughness and diameter deviation are measured 3 times. The mean value of the three roughness measurements (R_a) and the mean value of the three diameter deviations (ΔD) of each sample are recorded in table 3. According to equations (1, 2), the ratios S/N for Ra and ΔD are also determined and presented in this table.

Table 3. Orthogonal array L_9 of the experimental runs and results

N^0	v (m/min)	s (mm/rev)	t (mm)	R_a (µm)	ΔD (mm)	S/N_{Ra}	$S/N_{\Delta D}$
1	45	0.02	0.06	0.60	0.001	4.4370	60.0000
2	45	0.06	0.23	0.75	0.003	2.4988	50.4576
3	45	0.10	0.40	0.85	0.006	1.4116	44.4370
4	75	0.02	0.23	0.55	0.004	5.1927	47.9588
5	75	0.06	0.40	0.68	0.008	3.3498	41.9382
6	75	0.10	0.06	0.72	0.003	2.8534	50.4576
7	105	0.02	0.40	0.47	0.009	6.5580	40.9151
8	105	0.06	0.06	0.50	0.005	6.0206	46.0206
9	105	0.10	0.23	0.67	0.007	3.4785	43.0980

3.3. Investigating the impact of cutting regime parameters on the roughness

Main effects of v,s,t on surface roughness (Ra) are shown in Figure 6. Average S/N values of influence levels of v, s, t on Ra are presented in Table 4. When S/N is bigger, it means that Ra is smaller. Using equations (3-6) we have determined the influence of cutting parameters on surface roughness as shown in Table 5. Feed rate (s) has the greatest impact (51.24%), followed by the cutting speed (43.33%), and finally the depth of cut (4.10%). Effect of noise factors on surface roughness is 1.33%. Analysis results also showed that the predicted smallest value of Ra corresponding to the parameters of the cutting regime at (v3, s1, t1).

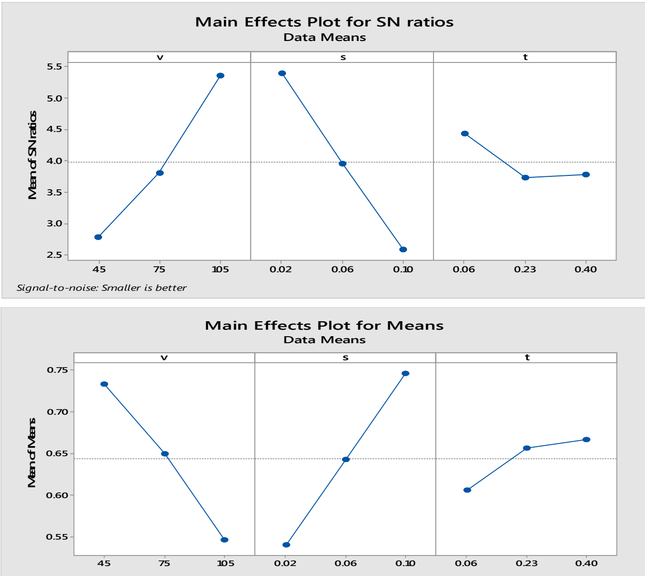

Figure 6.The effect of machining parameters (v, s, t) on R_a

Table 4. Average S / N values of influence levels of V, S, t to R_a

S/N			
Level	v	s	t
1	2.782	5.396*	4.437*
2	3.799	3.956	3.723
3	5.352*	2.581	3.773

Table 5. Contribution of factors to R_a

N⁰	Parameter	Percentage contributions, %
1	Cutting speed (v)	43.33
2	Feed rate (s)	51.24
3	Depth of cut (t)	4.10
4	Error	1.33

3.4. Investigating the impact of cutting regime parameters on the dimension accuracy

Main effects of v,s,t on diameter deviation (ΔD) are shown in Figure 7. Average S/N values of influence levels of V, S, t on ΔD are presented in Table 6. When S/N is bigger, it means that ΔD is smaller. Using equations (3-6) we have determined the influence of cutting parameters on diameter deviation as shown in Table 7. Depth of cut (t) has the greatest impact (50.96%), followed by the cutting speed (v) (37.32%), and finally Feed rate (s) (9.08%). Effect of noise factors on diameter deviation is 2.62%. Analysis results also showed that the predicted smallest value of ΔD corresponding to the parameters of the cutting regime at (v1, s1, t1)

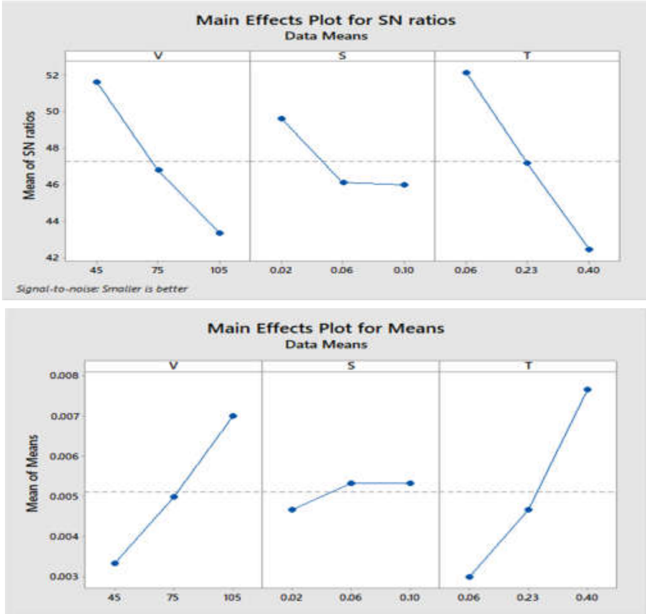

Figure 7. The effect of machining parameters (v, s, t) on ΔD

Table 6. Average S / N values of influence levels of V, S, t to ΔD

S/N			
Level	v	s	t
1	51.63*	49.62*	52.16*
2	46.78	46.14	47.17
3	43.34	46.00	42.43

Table 7. Contribution of factor to ΔD

N⁰	Parameter	Percentage contributions, %
1	Cutting speed (v)	37.32
2	Feed rate (s)	9.08
3	Depth of cut (t)	50.96
4	Error	2.64

3.5. Multi-object optimization for suitable roughness and dimensional precision in both

Firstly, with the measurement data R_a and ΔD of nine samples, using formula (8) to normalize the data of two target functions R_a and D, the values of columns 1 and 2 in table 8 are determined. The deviation sequences between reference sequences and comparable sequences are found by (9), and the results are shown in column 3 and column 4 of the table. Next, using formulas (11, 12), the values of gray coefficient for each experiment (column 5, column 6 in the table 8) are determined. And finally, The Grey relational coefficients for each response are accumulated by using formulas (13, 14) to evaluate Grey relational grade, which is the overall representative of all the features of cutting process quality. After the gray relational grade are determined, the efficiency level of each test for both roughness and machining accuracy is ranked.

Table 8. Results of grey relational analysis

Runs	Normalization		Deviation Sequence		Grey relational coefficient		Grade	Rank
	Roughness R_a	Diameter Error ΔD	Roughness R_a	Diameter Error ΔD	Roughness R_a	Diameter Error ΔD		
1	0.658	1	0.342	0	0.594	1	0.797	**1**
2	0.263	0.75	0.737	0.25	0.404	0.667	0.536	**6**
3	0	0.375	1	0.625	0.333	0.444	0.389	**9**
4	0.789	0.625	0.211	0.375	0.703	0.571	0.637	**4**
5	0.447	0.125	0.553	0.875	0.475	0.364	0.420	**8**
6	0.342	0.75	0.658	0.25	0.432	0.667	0.550	**5**
7	1	0	0	1	1	0.333	0.667	**3**
8	0.921	0.5	0.079	0.5	0.865	0. 5	0.683	**2**
9	0.474	0.25	0.526	0.75	0.487	0.4	0.444	**7**

The rank shows that the most optimal set of machining parameters in the experimental domain is v1s1t1. It mean that, when hard turning tempered alloy steel 40Cr on CNC lathe by PCBN tool, the optimal parameters for roughness and dimensional precision in both are v = 45m/min, s = 0.02mm/rev, t = 0.06 mm.

3.6. A case study

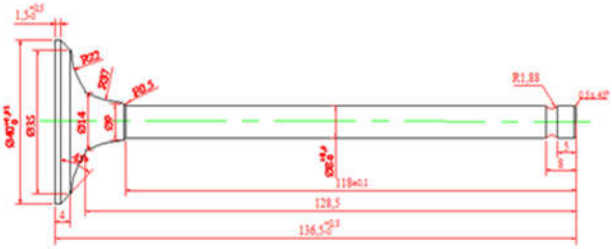

Figure 8. Intake valve of the Hyundai D4-Ab internal combustion engine

Figure 9. An sample of fabricated intake valves

Valve is an important part of the internal combustion engine. It works in hard conditions under high pressure and high temperature. To withstand the abrasion during working, valves are usually made of alloy steels and heat treated. They are then ground to ensure dimensional accuracy and surface roughness. The manufacturing process of valves is therefore often quite complicated and takes a lot of time. With the application of hard turning technology, the manufacturing process can be shortened as follows: roughing, shaping the structure of valves on the CNC lathe → heat treatment → straightening → finishing by hard turning on CNC lathes. Using this proposed process, with the optimal parameters presented above, the authors have carried out experimentally fabricating the intake valve of the Hyundai D4-Ab internal combustion engine (Fig. 8). The valve is made of heat-treated 40Cr steel reaches hardness 40-42 HRC. After the fabrication was completed, the stem of the valve was measured. The measurement results show that the fabricated valve meet technical requirements on roughness as well as dimensional accuracy (Fig.9).

4. CONCLUSIONS

In this study, the Grey based Taguchi method was applied for the multiple performance characteristics of hard turning the tempered alloy steel 40Cr on the CNC lathe by PCBN tool. By Taguchi method and analysis of Variance (ANOVA) the authors have defined the influence of each cutting parameter such as cutting speed, feed rate and depth of cut on the roughness and dimensional precision. Two sets of optimal parameters for each output criteria have been found, too. A Grey relational analysis of the surface roughness and dimensional precision obtained from the experiment data allowed multi optimization for minimum surface roughness and high dimensional precision, simultaneously. Futhermore, the hard turning with the optimal parameters of multi optimization has been effectively applied to fabricate the intake valve of the Hyundai D4-Ab internal combustion engine.

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