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Determination of the minute range for RSM to select the optimum cutting conditions during turning on CNC lathe †

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Abstract

Taguchi method and RSM (response surface method) are two of the most well known DOE (design of experiment) techniques. The levels of parameters are recommended to be taken far apart in the Taguchi method in order to cover a wide region to increase the chance of capturing nonlinearity of the relationship between the control and control factors. On the contrary, as long as the optimum is located within the region, RSM needs it to be as small as possible to identify the exact optimum. In this study, the Taguchi method is used to determine the rough region first, followed by RSM technique to determine the exact optimum value during turning on a CNC lathe. A new region reducing algorithm is introduced to narrow down the region of the Taguchi method for RSM. To achieve the goal, the result from the Taguchi method is fed to train the artificial neural network (ANN), whose optimum value is used to drive the region reducing algorithm. The proposed algorithm is tested under different cutting condition with different insert and work material. Data located in the literature is also used to inspect the adequacy of the region reducing algorithm. Both results show that the introduced algorithm has a good region reducing capability. In a separated experiment, it is shown that the obtained cutting condition from RSM gives a better result than that from the Taguchi method.

Keywords: Taguchi method; Artificial neural network (ANN); Response surface method (RMS); Region reducing algorithm

1. Introduction

Metal cutting is one of the most widely used manufacturing processes in engineering industries. To increase the efficiency and the productivity of the machining process, it is necessary to determine the proper feature of the cutting tool, machine tools and machining parameters. A significant improvement of the productivity and efficiency can be obtained by process parameter optimization that identifies the region of process control factors [1].

Machining process parameter optimization can be achieved either by empirical input-output parameter relationship modeling technique or by optimization tools and techniques [2]. Artificial neural network technique [3] and design of experiment (DOE) are two of the most well known methodologies in the area of empirical modeling technique and optimization tools, respectively. DOE includes the Taguchi method [4, 5], factorial design [6] and response surface design method [7].

In the Taguchi method, it is recommended that the levels of the parameters are taken to be far apart so that a wide region can be covered [4]. By choosing levels that are wide apart, the chance of capturing nonlinearity of the relationship between the control factors and the noise factors is increased and the effect of the levels is larger when compared to the experimental errors. In most cases, however, the optimum value obtained by the Taguchi method is not the exact optimum solution. Reduction of the region by half is proposed [8] for successive experiments after the previous optimization process, which takes a long time until the obtained optimum is within the tolerance bound of the true optimum. When interactions between parameters are taken into consideration, the number of the experiments is increased significantly.

Another drawback of the Taguchi method is that it uses signal-to-noise ratio to minimize the variance while obtaining a target condition on the mean. This approach has drawn much criticism [9]. A dual response approach combining the Taguchi and response surface method was proposed as an alternative to overcome the difficulty [10]. In the dual response approach, we have to be sure that the optimum is within the region that we have taken. At the same time, the selected region has to be small enough to obtain the solution as precise as possible.

The RSM technique is a dynamic and foremost important tool wherein the relationship between responses of a process

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with its input decision variables is mapped to achieve the objective of maximization or minimization of the response properties [1]. Since the RSM technique is based on series of experimentation, it may not be cost effective. Hence, the RSM technique has to be conducted only when the region of the optimum is already known or predictable. If the region is unidentified, first order RSM equations have to be obtained successively until we find the region close to the optimum point, where the experiments to obtain second order RSM equation is conducted. This procedure needs considerable number of experiments.

In this paper, a region reducing algorithm is introduced and utilized to determine the near exact optimum cutting conditions for the maximum tool life during turning on CNC lathe using both Taguchi method and RSM techniques. To achieve a goal, a relatively wide region of levels is selected using the Taguchi method. These wide regions are subsequently narrowed by the newly proposed algorithm to apply for the RSM technique. The new region reduction algorithm can be also used to determine the next region of levels when the Taguchi method is applied successively.

2. Experimental procedure

Initially, the first two experiments were conducted to derive the region reducing algorithm, experimentally. The adequacy of the determined algorithm was proved by the subsequent four experiments. In the experiments, we tried to obtain the optimum cutting condition to maximize the total cutting volume with given work materials and tool inserts during turning on a CNC lathe. The experimental procedure to determine the near exact optimum using the proposed algorithm consists of three steps-: 1) Estimation of the rough optimum cutting condition using the Taguchi method. 2) Application of the region reducing algorithm on the region used for the Taguchi method. 3) Determination of the exact optimum cutting conditions using RSM in the narrowed region obtained in step 2. Two kinds of work material and tool insert were used for the experiments.

2.1 Experimental set up

Experiments were carried out on a CNC lathe (Hyundai HiT-15). Commercial inserts of P20 (tungsten carbide insert, TaeguTec) and AB30 (Ceramic insert, TaeguTec) with the specification of SNGN120408 (12.7 × 12.7 mm square, 4.76 mm thickness, 0.8 mm nose radius and 0.2 mm × 20° chamfer) were used for turning the work materials, SM45C (AISI45) and SCM440, whose chemical compositions and mechanical properties are given in Table 1. The diameter and the length of work material were 110mm and 370mm, respectively. When flank wear land length reached 0.3mm, the life of the insert was considered to have reached its end. Length of flank wear land was measured by tool microscope (Bestec vision, Xi-Cam) after each stroke of cut. The cutting force was measured by a piezo-type tool dynamometer (Kistler 9257B) and the measured force was amplified using a charge amplifier (Kistler 5011). A/D converter (NI PCI-6250) and a PC were used for data processing. Experiments during turning SM45C and SCM440 by P20 insert were conducted to derive the region reducing algorithm. After derivation of the algorithm, a combination of two kinds of inserts and work materials – the combination of P20-SM45C, P20-SCM440, AB30-SM45C and AB30-SCM440 - was exerted to prove the algorithm. All experiments were executed under dry cutting conditions.

Table 1. Chemical composition and mechanical property of SM45C and SCM440.

		SM45C	SCM440
Chemical Property (wt%)	C	0.42~0.48	0.38~0.43
	Si	0.15~0.35	0.15~0.35
	Mn	0.60~0.90	0.60~0.85
	P	0.030 Max	0.030 Max
	S	0.035 Max	0.030 Max
	Cr	-	0.90~1.20
	Mo	-	0.15~0.30
Mechanical property	Tensile strength (N/mm^2)	470.7 Min	980.7 Min
	Hardness (HRC)	11~25.6	29.8~35.5
	Yield point (N/mm^2)	343.2 Min	834 Min

Table 2. L_9 (3^4) Orthogonal array.

Expt. No.	Column			
	1 Cutting speed (m/min)	2 Feed rate (mm/rev)	3 Depth of cut (mm)	4 (Empty)
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

2.2 Taguchi method

Since the interaction between cutting parameters was not considered, an orthogonal array of L_9 (3^4) was big enough for the experiments and given in Table 2. The cutting conditions for each combination of inserts and work materials are shown in Table 3. The cutting conditions given in Table 3 were used to complete the Table 2 for the experimental plan for the Taguchi method. For example, for the experiment using the com-

Table 3. Cutting conditions for each combination of inserts and work materials for Taguchi method.

	Cutting velocity (m/min.)		Feed rate (mm/rev.)		Depth of cut (mm)	
P20-SM45C	1	100	1	0.1	1	0.2
	2	200	2	0.2	2	0.4
	3	300	3	0.3	3	0.6
P20-SCM440	1	100	1	0.1	1	0.2
	2	200	2	0.2	2	0.4
	3	300	3	0.3	3	0.6
AB30-SM45C	1	200	1	0.2	1	0.2
	2	400	2	0.5	2	0.4
	3	600	3	0.8	3	0.6
AB30-SCM440	1	300	1	0.3	1	0.3
	2	400	2	0.4	2	0.4
	3	500	3	0.5	3	0.5

Table 4. Experimental plan for RSM technique.

Number	Coded variable		
	x_1	x_2	x_3
1	-1	-1	0
2	-1	1	0
3	1	-1	0
4	1	1	0
5	-1	0	-1
6	-1	0	1
7	1	0	-1
8	1	0	1
9	0	-1	-1
10	0	-1	1
11	0	1	-1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0

bination of P20-SM45C, the number 1, 2, 3 of cutting speed in Table 2 were substituted by 100, 200, 300m/min. in Table 3.

Identical procedure was carried out for feed rate and depth of cut. Consequently, the cutting conditions for the first experiment of Table 2 using the P20-SM45C combination were 100m/min. cutting speed, 0.1mm/rev. feed rate and 0.2mm depth of cut. In the same manner, the rest of the table was filled to complete the design of experiments. Fourth column remained empty.

2.3 RSM technique

Experimental plan for the RSM technique is given in Table 4 and the cutting condition to identify the region reducing algorithm in Table 5. In this study, the Box-Behnken method [11] was used as the RSM technique. The fixed numbers, -1, 0, and 1 in Table 4, were substituted by cutting conditions given in Table 5 to complete the experimental plan.

Table 5. Cutting conditions for each combination of inserts and work materials for RSM technique.

	Cutting velocity (m/min.)		Feed rate (mm/rev.)		Depth of cut (mm)	
P20-SM45C	-1	100	-1	0.1	-1	0.2
	0	200	0	0.2	0	0.4
	1	300	1	0.3	1	0.6
P20-SCM440	-1	100	-1	0.1	-1	0.2
	0	200	0	0.2	0	0.4
	1	300	1	0.3	1	0.6

Table 6. Revised cutting conditions for each combination of inserts and work materials for RSM technique.

	Cutting velocity (m/min.)		Feed rate (mm/rev.)		Depth of cut (mm)	
P20-SM45C	-1	160	-1	0.1	-1	0.34
	0	185	0	0.2	0	0.41
	1	210	1	0.3	1	0.48
P20-SCM440	-1	160	-1	0.1	-1	0.28
	0	225	0	0.2	0	0.38
	1	290	1	0.3	1	0.48
AB30-SM45C	-1	340	-1	0.28	-1	0.32
	0	410	0	0.44	0	0.37
	1	480	1	0.6	1	0.42
AB30-SCM440	-1	340	-1	0.35	-1	0.32
	0	410	0	0.5	0	0.39
	1	480	1	0.65	1	0.46

As a result, 15 experimental plans for each of P20-SM45C and P20-SCM440 were set. After the region reducing algorithm was identified, 4 experiments with cutting condition of Table 6 were carried out to prove the adequacy of the proposed algorithm.

2.4 Region reducing algorithm

The Taguchi method works particularly well in the early stage when the starting point is far from optimum. Once we get near the optimum point, we have to use the standard nonlinear programming methods to obtain the exact optimum. [4] Since nonlinear programming such as the Newton-Raphson method uses the formula that is already obtained theoretically or experimentally, and since we do not have the formula yet, it cannot be applicable. Instead of nonlinear programming method, the RSM technique was used to find the optimum. Since the region needs to be narrowed down for a more precise formula from the RSM technique, a region reducing algorithm was introduced. The artificial neural network (ANN) model was utilized to develop a region reducing algorithm. The input and output to and from the Taguchi algorithm was fed to train an ANN model. Since ANN model can

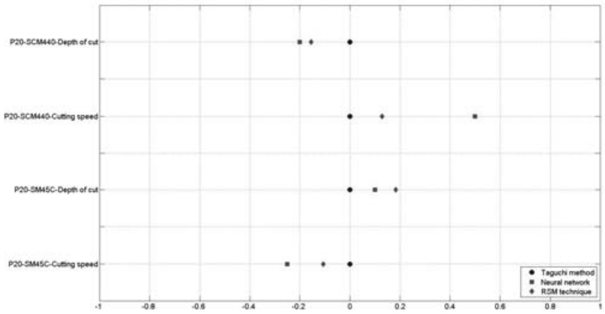


Fig. 1. Optimum values obtained from Taguchi method & neural network & RSM technique during turning SM45C and SCM440 using P20.

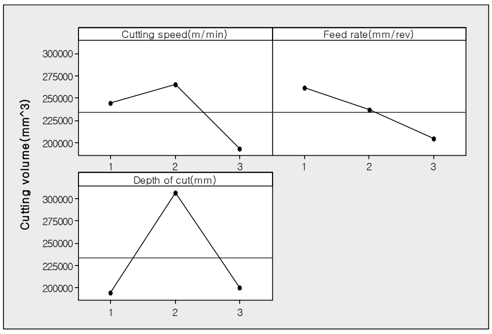


Fig. 2. Line graph obtained from Taguchi method during turning SM45C using P20.

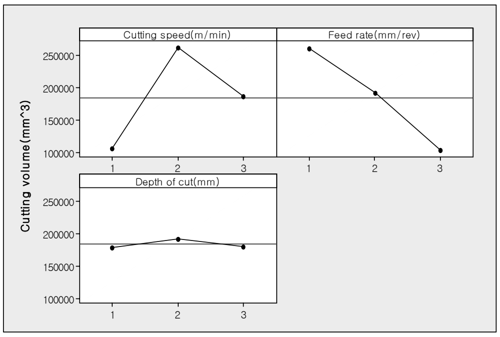


Fig. 3. Line graph obtained from Taguchi method during turning SCM440 using P20.

provide more points compared to the Taguchi method, it may possibly contain the optimum value that is closer to the actual optimum compared to the point obtained by the Taguchi method. Hence, the optimum point from the ANN model may give us a clue where the actual optimum is located. The optimum points from the Taguchi method and ANN model were compared to the optimum from the RSM tchnique to determine the reduced region experimentally. The example to determine the reduced region is given in Fig. 1. Commercial software (MINITAB 14.12.1) was used to analyze the experimental results for both Taguchi method and RSM technique.

A home-made version of ANN software was also used to analyze data.

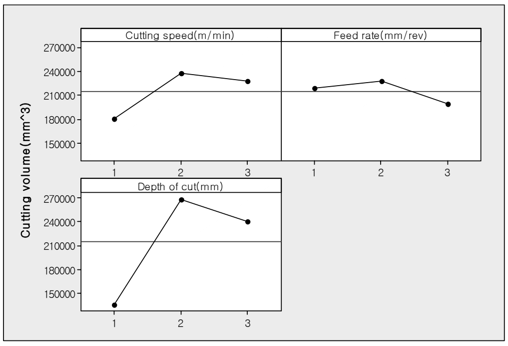


Fig. 4. Line graph obtained from Taguchi method during turning SM45C using AB30.

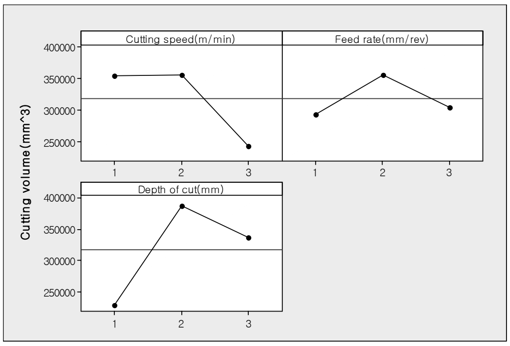


Fig. 5. Line graph obtained from Taguchi method during turning SCM440 using AB30.

3. Results

3.1 Derivation of the region reducing algorithm

3.1.1 Result of Taguchi method

We tried to find the cutting conditions that give us a maximum cutting volume under a given tool and work material. Line graphs in Fig. 2-5 were the results of experiments using the Taguchi method under the insert-work material combination of P20-SM45C, P20-SCM440, AB30-SM45C and AB30-SCM440. Out of four experiments, the first two results were used to derive the algorithm. In the figures, the curvature of cutting speed and depth of cut shows peak in the middle, meaning the optimum is located inside the selected region. In case of feed rate, the optimum is smaller than 0.1mm/rev., the minimum setting for the machine.

3.1.2 Result of ANN technique

The inputs (cutting velocity, feed rate and depth of cut) and outputs (the cutting volume) were used to train the supervised neural network. The ANN model was set to have an input layer with 10 nodes, one hidden layer with 3 nodes and an output layer with 1 node. The number of hidden layers and the nodes was determined by trial and error and the momentum and the rate of learning was set to 0.9, respectively. The ten inputs to the ANN were x_1 (cutting velocity), x_2 (feed rate), x_3 (depth of cut), and squares of x_1, x_2, x_3 (x_1^2, x_2^2, x_3^2) interaction of x_1, x_2, x_3 (x_1x_2, x_2x_3, x_3x_1) and a constant. A constant was

Table 7. Fitted curves using ANN model during machining SM45C and SCM440 with P20 and AB30.

P20-SM45C	Cutting velocity (m/min.)	$y=0.0001V^3-0.0074V^2+0.4799V-8.6253$ (*1.0e+5)
	Feed rate (mm/rev.)	$y=-0.9156V^5+1.2587V^4-0.6075V^3+0.1329V^2-0.0135V-0.0005$ (*1.0e+10)
	Depth of cut (mm)	$y=5.474V^5-6.6374V^4+1.4504V^3+0.9653V^2-0.4622V-0.0531$ (*1.0e+8)
P20-SCM440	Cutting velocity (m/min.)	$Y=0.00016V^3+0.02956V^2-2.62414V+89.73843$ (*1.0e+5)
	Feed rate (mm/rev.)	$y=2.5351V^5-2.2588V^4+0.7679V^3-0.1233V^2+0.0091V-0.0002$ (*1.0e+10)
	Depth of cut (mm)	$y=3.934V^5-5.3295V^4+2.2176V^3-0.1444V^2-0.0937V+0.0159$ (*1.0e+8)
AB30-SM45C	Cutting velocity (m/min.)	$y=-0.0003V^3+0.1437V^2-30.7657V+2598.5584$ (*1.0e+3)
	Feed rate (mm/rev.)	$y=-0.681V^5+2.0918V^4-2.3085V^3+1.1498V^2-0.262V+0.024$ (*1.0e+8)
	Depth of cut (mm)	$y=-1.1244V^5+2.5905V^4-2.2437V^3+0.9115V^2-0.1735V+0.0125$ (*1.0e+9)
AB30-SCM440	Cutting velocity (m/min.)	$y=0.0008V^4+0.6759V^3-251.7503V^2+46243.455V-3346363.18$ (*1.0e+2)
	Feed rate (mm/rev.)	$y=-2.0221V^5+5.1345V^4-5.0879V^3+2.4469V^2-0.5678V+0.0537$ (*1.0e+8)
	Depth of cut (mm)	$y=-1.4975V^5+3.9558V^4-3.8763V^3+1.8032V^2-0.4033V+0.035$ (*1.0e+10)

set to 1. The output of the ANN model was cutting volume (mm^3) until the flank wear land length reached 0.3mm. Once the ANN model was formulated, then could get cutting volume under the condition that is not given by the Taguchi method. Six data of each cutting condition were newly created from the ANN model and used to fit a 5th order polynomial for each cutting condition (Table 7). The optimal value obtained from the fitted curve was used to derive the region reducing algorithm.

3.1.3 Result of RSM technique to determine region reducing algorithm

The optimum cutting conditions and the numerical formula obtained from RSM during machining SM45C and SCM440 by P20 under the cutting condition of Table 5 are given in Table 8. Since the optimum from RSM was considered to be

Table 8. Optimal cutting condition obtained RSM technique.

Insert-Material	Factor	Optimum point
P20-SM45C	Cutting velocity	189.425m/min
	Feed rate	0.149mm/rev
	Depth of cut	0.437mm
	Regression Equation	$Y=286130+1156.9x_1-18041.2x_2+4336.58x_3-24485.6x_1^2-33433.0x_2^2-24321.1x_3^2-12842.7x_1x_2-28766.1x_1x_3-35907.1x_2x_3$
P20-SCM440	Cutting velocity	212.831m/min
	Feed rate	0.146mm/rev
	Depth of cut	0.369mm
	Regression Equation	$Y=251340-27165.2x_1-28835.0x_2-9680.84x_3-54871.6x_1^2-23698.9x_2^2-78457.9x_3^2-11944.1x_1x_2-4457.15x_1x_3+10107.1x_2x_3$
AB30-SM45C	Cutting velocity	424.925m/min
	Feed rate	0.519mm/rev
	Depth of cut	0.384mm
	Regression Equation	$Y=258913+17875x_1+19146.9x_2+10530x_3-37770.5x_1^2-18177.9x_2^2-20532.1x_3^2-6146.4x_1x_2-1082.2x_1x_3+2086.7x_2x_3$
AB30-SCM440	Cutting velocity	465.174m/min
	Feed rate	0.5121mm/rev
	Depth of cut	0.467mm
	Regression Equation	$Y=347373+41602.0x_1-28798.5x_2+19653.8x_3-27611.2x_1^2-103402.0x_2^2-50390.3x_3^2-56186.8x_1x_2-17675.7x_1x_3-4980.37x_2x_3$

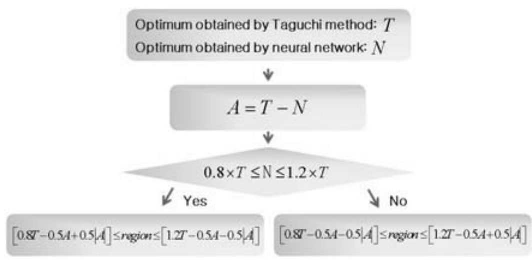


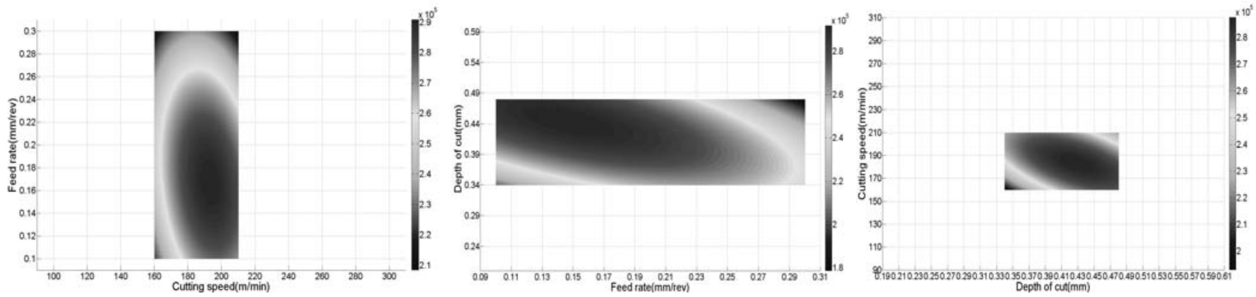
Fig. 6. Flow chart of the algorithm to determine the reduced region.

closer to the true optimum than that from other methods, they were used as standard values. Verification of the optimum obtained from RSM was accomplished by experiments in 3.2.3.

3.1.4 Derivation of the region reducing algorithm

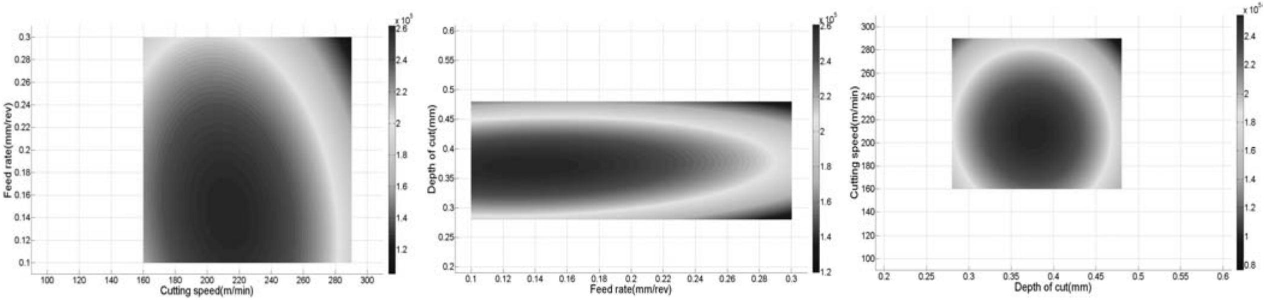
We tried to determine the region that covers the RSM optimum from the optimums obtained by the Taguchi method and ANN model, by trial and error. The identified algorithm is as follows.

$$0.8T-0.5A+0.5|A| < \text{reduced region} < 1.2T-0.5A-0.5|A|$$



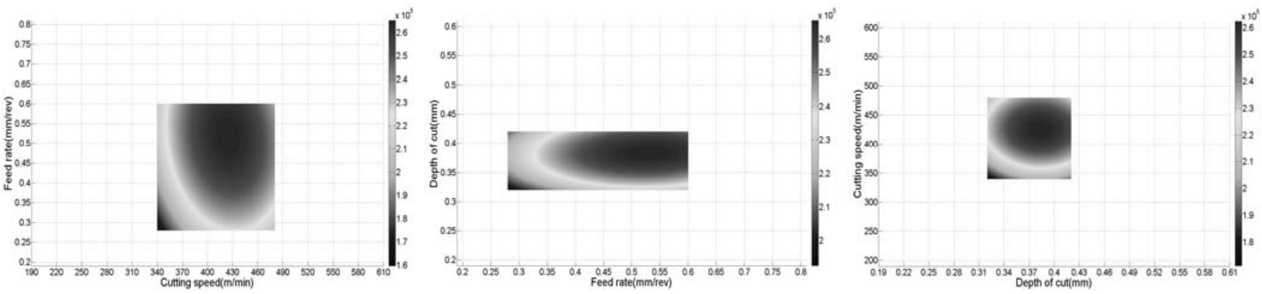
(a) Cutting speed-Feed rate (b) Feed rate- Depth of cut (c) Depth of cut-Cutting speed

Fig. 7. Optimum of RSM and the reduced region in turning SM45C with P20.



(a) Cutting speed-Feed rate (b) Feed rate- Depth of cut (c) Depth of cut-Cutting speed

Fig. 8. Optimum of RSM and the reduced region in turning SCM440 with P20.



(a) Cutting speed-Feed rate (b) Feed rate- Depth of cut (c) Depth of cut-Cutting speed

Fig. 9. Optimum of RSM and the reduced region in turning SM45C with AB30.

$$\text{when } 0.8T < N < 1.2T$$
$$0.8T\text{-}0.5A\text{-}0.5|A| < \text{reduced region} < 1.2T\text{-}0.5A\text{+}0.5|A|$$
$$\text{when } 0.8T > N \text{ or } N < 1.2T \tag{1}$$

where T: optimum obtained by Taguchi method
N: optimum obtained by neural network
A: difference between T and N (T-N)

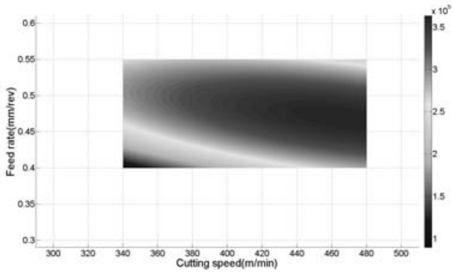
The basis of the new region was the optimal value obtained by the Taguchi method. The lower bound of the new region was set to 0.8T-0.5A, while the upper bound to 1.2T-0.5A. When the difference between optimum from the Taguchi method and ANN model was close enough for the optimum of ANN to be located between 0.8T and 1.2T, we reduced the region by 0.5|A| at both end of the bound. Otherwise, we expanded the region by 0.5|A| at both ends of the bound to include the optimum of RSM within the reduced region.

The flowchart to determine the reduced region is given in Fig. 6.

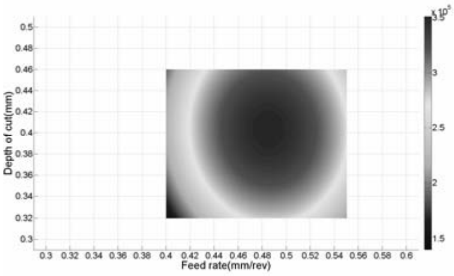
3.2 Results of application of the region reducing algorithm

3.2.1 Verification of the algorithm

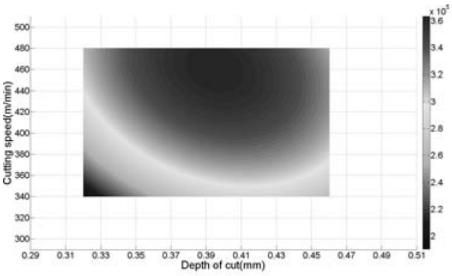
The region reducing algorithm was applied to four kinds of experiments. Out of a combination of P20-SM45C, P20-SCM440, AB30-SM45C and AB30-SCM440, we set the cutting condition for AB30-SM45C as very harsh to prove that the algorithm works regardless of the given input conditions. The reduced regions obtained by the proposed algorithm are shown in Fig. 7-10. In the figures, the optimum of the cutting condition is all within the boundary calculated by the reduced region algorithm. An exceptional case happened when we



(a) Cutting speed-Feed rate



(b) Feed rate- Depth of cut



(c) Depth of cut-Cutting speed

Fig. 10. Optimum of RSM and the reduced region in turning SCM440 with AB30.

determined the reduced boundary of the feed rate. The proposed algorithm gave a full range of region of the Taguchi method as a reduced region as shown in Fig. 7(b) and Fig. 8(b). In these cases, however, the curvature from the Taguchi method did not have a peak within the region which means that the region does not cover the optimum. In both cases, the optimum feed rate was less than 0.1mm/rev. which was below the minimum setting of the machine. Hence, the optimal feed rate was set to be 0.1mm/rev.

3.2.2 Verification of the algorithm using published data

The proposed region reducing algorithm was also proved by using the data in the literature [12]. Since not many researchers conducted experiments by using both the Taguchi method and RSM simultaneously in the machining area, this is the best that we have been able to locate in the literature. The purpose of the experiment was to study the effect of cutting condition (wheel speed, table speed, depth of cut, grain size) on surface methodologies for geometric error. The Taguchi method and RSM technique were used to find the cutting condition for the smoothest surface. The cutting condition for the Taguchi method along with the result is given in Table 9.

We used these data to determine the reduced region, which

Table 9. Cutting condition for Taguchi method smoothest surface.

Factors	Units	Levels of factors		
		1	2	3
Wheel speed	Rpm	1500	1800	2100
Table speed	m/min	7.5	10	12.5
Depth of cut	um	10	15	20
Grain size	mesh	46	120	200

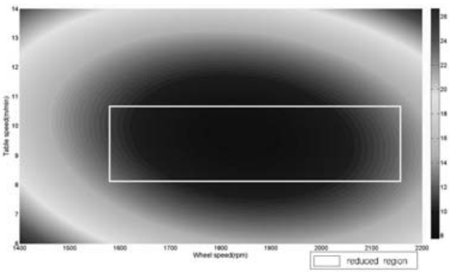


Fig. 11. Optimum of RSM and the reduced region [from data in the literature].

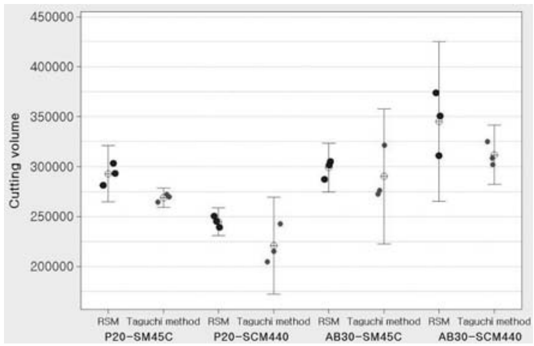


Fig. 12. Comparison of the maximum cutting volume under cutting conditions obtained from Taguchi method and RSM technique.

was drawn on a fitted response surface and given in Fig. 11. As shown in the figure, the reduced region (white box) covers the optimum value, which proves the adequacy of the proposed algorithm.

3.2.3 Verification of the optimum obtained by RSM technique

We compared the cutting volume under the conditions from RSM and Taguchi method in Fig. 12 and showed that the result from RSM was superior to the one from the Taguchi method. The experimental results were also compared with the theoretical estimation. Three experiments were conducted for each of P20-SM45C, P20-SCM440, AB30-SCM440 and AB30-SM45C combination and shown in Fig. 12. The experimental results were within 1σ (standard deviation) range of theoretical estimation, which showed that the model works well.

3.2.4 Comparison of cutting force

We measured the cutting force, trust force and feed force of

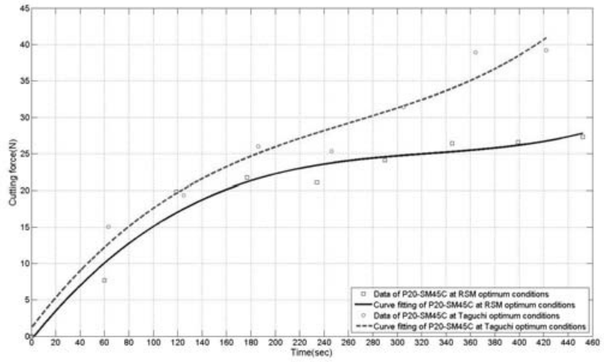


Fig. 13. Comparison of cutting force under optimal cutting condition obtained from Taguchi method and RSM technique.

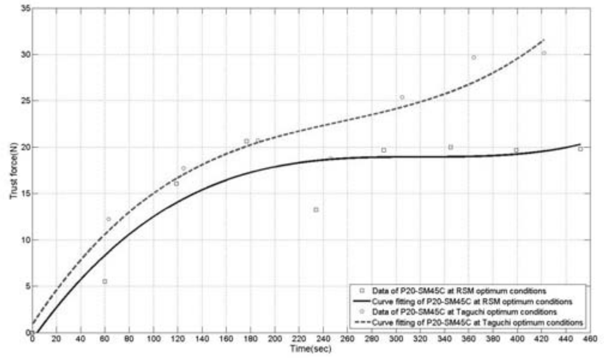


Fig. 14. Comparison of cutting force under optimal cutting condition obtained from Taguchi method and RSM technique.

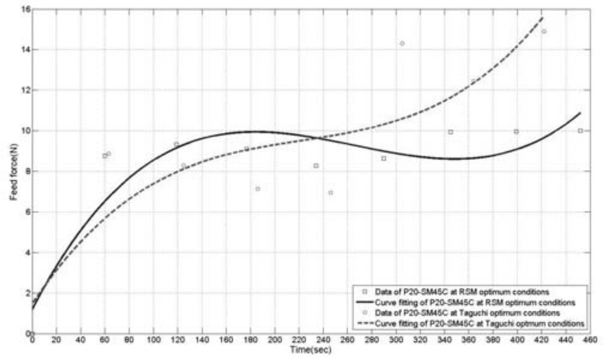


Fig. 15. Comparison of cutting force under optimal cutting condition obtained from Taguchi method and RSM technique.

P20-SM45C under the optimum conditions from RSM and the Taguchi method in Fig. 13-15. The measured force from the Taguchi method was bigger than the one from RSM and we could get the same phenomenon from P20-SCM440, AB30-SCM440 and AB30-SM45C, respectively. Smaller cutting force means a smaller flank wear land length, which leads to a longer tool life. This fact matched the result of Fig. 12 very well.

4. Conclusions

Both the Taguchi method and RSM were used to determine the optimum cutting condition for the maximum cutting volume during machining SM45C and SCM440 using P20 (tungsten carbide insert) and AB30 (ceramic insert). The Taguchi method was used to find the wide region where the optimum was located within. Once the rough region was found, then RSM was used to locate the exact optimum. To obtain a more precise solution, it was needed to find a narrower region where the optimum was located within. A new region reducing algorithm was proposed in this study. The results from the Taguchi method, artificial neural network and RSM were used to derive the region reducing algorithm, experimentally. The derived algorithm worked well during machining SM45C and SCM440 using P20 (tungsten carbide) and AB30 (ceramic insert). It was also applied to the example located in the literature and proved to work well.

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