DEA-based Taguchi method for Optimization of CNC End milling Process parameters

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ABSTRACT

In any machining operations, quality and productivity are the two important conflicting objectives. In order to give assurance for high productivity, some extent of quality has to be compromised. Similarly productivity will be decreased while the efforts are channelized to enhance quality. Therefore it is essential to optimize both quality and productivity simultaneously. Surface roughness and material removal rate in end milling refer to quality and productivity respectively. In this paper, Data Envelopment Analysis based Taguchi method is employed for solving the multi-response optimization problem in CNC end milling. The application of the methodology is demonstrated through an experimental study in which end milling of aluminium is carried on CNC milling machine.

Key words: CNC End milling, Data Envelopment Analysis, Taguchi method, Multi-response optimization.

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1. INTRODUCTION

Milling is the most extensively used machining process which may be employed in at least one stage of fabrication in manufacturing industries. In the present days CNC milling machines are commonly used as they possesses versatility, flexibility and allows manufacture of products in shorter time at reasonable cost and good surface finish. End milling is one of the important milling operations, which is commonly used in manufacturing industries due to its capability of producing complex geometric surfaces with reasonable accuracy and surface finish [1]. In end milling process, surface finish and material removal rate are two important aspects, which require attention both from industry personnel as well as in Research and Development, because these two factors greatly influence machining performance [2]. CNC machines are most suitable to achieve high quality products in shorter time and to produce products at minimum cost. Yang and Chen [3] attempted to demonstrate how Taguchi parameter design could be used in identifying the significant processing parameters and optimizing the surface roughness of end-milling operations. Rehman et al. [4] conducted experimental study for evaluating minimal quantities of lubricant in end milling. Mansour and Abdalla [5] studied the roughness in end milling of EN 32 steel in terms of machining parameters using RSM. Ghani et al. [6] considered Taguchi method for optimization of cutting parameters in end milling of hardened steel AISI H13 with TiN coated P10 carbide insert tool. Yang et al. [7] stated that the machining factors affecting the tool wear and surface finish produced in the end milling process are generally the cutting speed, the feed rate, the depth of cut, etc. They also described a study that identifies the influence of the machining parameters on the groove width and the surface roughness average for the end milling of high-purity graphite under dry machining conditions. Abou-EI-Hossein et al. [8] employed response surface methodology (RSM) to develop first and second order models for predicting the cutting force produced in end milling operation of modified AISIP20 tool steel. Ibraheem et al. [9] investigated the affect of cutting speed, feed, axial and radial depth of cut on cutting force in machining of modified AISI P20 tool steel in end milling process. Huang et al. [10] studied an empirical approach to investigate surface roughness in controllable and uncontrollable factors in end milling operation. The effect of cutting tool geometry on milling of AISI 1045 steel for surface roughness model is studied. Gopalsamy et al. [11] applied Taguchi method to find optimum process parameters for end milling while hard machining of hardened steel. Oktem [12] developed an integrated study of surface roughness to model and optimize the cutting parameters when end milling of AISI1040 steel material. Moshat et al. [13] proposed principal component analysis (PCA) based hybrid Taguchi method to solve multi-objective optimization problem and they demonstrated the methodology with a case study in CNC end milling operation. Routara et al. [14] conducted experimental study on CNC end milling of UNSC34000 medium leaded brass with a view to evaluate the best process environment which could simultaneously satisfy multiple requirements of surface quality. They applied utility concept coupled with Taguchi method for solving the multi-objective optimization problem. Jaya Krishna et al. [15] adopted principal component analysis (PCA) based neural networks for predicting the surface roughness in CNC end milling of P20 mould steel. Ravi Kumar and Krishna Mohana Rao [16] studied the application of Taguchi design to optimize surface quality in end milling operation and they concluded that the Taguchi design for their experimentation is a successful in optimizing milling parameters for surface roughness. Sidda Reddy et al. [17] made an attempt to develop an accurate mathematical model for predicting the surface roughness in end milling of P20 mould steel using artificial neural networks (ANN). Zeng and Xiong [18] has been applied Taguchi optimization method coupled with Grey Relational Analysis (GRA) for determining the optimal combination of end milling process parameters. Lakshmi and Venkata Subbaiah [19] conducted experimental investigations on surface finish and material removal rate during the high speed end milling of EN24 alloy steel in order to develop an appropriate roughness prediction model and optimize the cutting parameters using RSM. Bhanu Prakash et al. [20] identified the best combination of cutting parameters to provide the lowest surface roughness for end milling of aluminium alloy 6082 with cemented carbide tooling. They found RSM is a successful technique to perform the analysis of surface roughness with respect to different combinations of machining parameters when compared to Genetic Algorithm. In the present work an attempt has been made to apply Data Envelopment Analysis (DEA) based Taguchi method to optimize the process parameters in CNC end milling of aluminium. The over view of Taguchi method and DEA are discussed below.

1.1. Taguchi method

Taguchi Method was proposed by Dr. G. Taguchi in the year 1950. This method explores the concept of quadratic quality loss function and uses a statistical measure of performance called signal-to-noise (S/N) ratio. In Taguchi method, the process parameters are divided into two groups such as control factors and noise factors. The control factors are the controllable parameters which affect the process significantly whereas noise factors are the variables that affect the process and are either uncontrollable or more expensive to control. Signal represents the effect on the average response while the noise is a measure of the influence on the deviation from the average response. The S/N ratio is the ratio of the mean (Signal) to the standard deviation (Noise), which indicates the scattering around a target value. This ratio helps to identify the optimum level of process parameters. The combination of parameters with the highest S/N ratio will be the optimum setting of process parameters. A high S/N ratio is desirable as the signal level is much higher than the random noise level that leads to best performance. The calculation of S/N ratio depends on the quality characteristics of the product or process to be optimized. The equation for calculating S/N ratios for “larger is better” (HB), “smaller is better” (LB) and “nominal is best” (NB) types of characteristics are as follows:

- For larger is better

$$(S/N)_{HB} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}(1/y_i^2)\right]$$

- For smaller is better

$$(S/N)_{LB} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}(y_i^2)\right]$$

- For nominal the better

$$(S/N)_{NB} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}(y_i - y_0)^2\right]$$

Where, y_i = experimental value in the i^{th} test
y_0 = target value and
n = number of replications

The signal-to-noise (S/N) ratio for each level of process parameters are computed. The optimum setting of the process parameters contributes the minimization of the effect of noise. It means that the level of process parameters with the highest S/N ratio corresponds to the optimum level of process parameters.

1.2. Data Envelopment Analysis

Data Envelopment Analysis (DEA) was developed by Charnes Cooper and Rhodes in the year 1978. It is a mathematical programming approach for evaluating the relative efficiency of a set of homogenous organizational units called decision making units [21]. These decision making units (DMUs) utilize multiple inputs to produce multiple outputs and their efficiency is measured by the ratio of multiple outputs to multiple inputs. DEA measure the relative productivity of a DMU by comparing it with other homogeneous units transforming the same group of measurable positive inputs into the same types of measurable positive outputs. The efficiency score in the presence of multiple input and output factors is obtained by the computing the ratio of weighted sum of outputs to the weighted sum of inputs. Assuming that there are *n* DMUs, each with *m* inputs and *s* outputs, the relative efficiency score of a test DMU_p is obtained by solving the following model.

$$\text{Maximize} \quad Z = \frac{\sum_{k=1}^{s} v_k y_{kp}}{\sum_{j=1}^{m} u_j x_{jp}}$$

Subject to constraints

$$\frac{\sum_{k=1}^{s} v_k y_{ki}}{\sum_{j=1}^{m} u_j x_{ji}} \leq 1 \quad \forall i$$

$$v_k, u_j \geq 0 \quad \forall k, j$$

Where k = 1 to s, j = 1 to m and i = 1 to n,

y_{ki} = amount of output k produced by DMU i,

x_{ji} = amount of input j utilized by DMUi,

v_k = weight given to output k and u_j = weight given to input j.

The above model has to be converted into a linear program so that it can be solved easily. This is done by normalization i.e., the denominator of the objective function is equated to one and the first constraint corresponding to efficiency ratios of all DMUs in the sample is also modified as shown below.

Objective function:

$$\text{Maximize} \quad Z = \sum_{k=1}^{s} v_k y_{kp}$$

Subjected to constraints:

$$\sum_{k=1}^{s} v_k y_{ki} - \sum_{j=1}^{m} u_j x_{ji} \leq 0 \qquad \forall i \neq p$$

$$\sum_{j=1}^{m} u_j x_{jp} = 1$$

$$v_k, u_j \geq 0 \quad \forall k, j$$

As per the efficiency scores, the DMUs are ranked. In this paper DEA is employed to measure the relative efficiency of decision making units as multiple inputs and outputs are involved in end milling process. The DEA coupled with Taguchi technique is proposed in the work to determine the optimum process parameters for CNC end milling of aluminium. The experimentation and analysis of the data are discussed in the following sections.

2. EXPERIMENTATION

The present work is carried out with a view to observe the response variables such as material removal rate and surface roughness during CNC end milling of aluminium with the change of cutting parameters at different levels. In any experimental work, it is difficult to consider all these factors that affect the quality and productivity. From the literature it is observed that the parameters such as depth of cut, spindle speed and feed rate are the three predominant cutting parameters influencing on quality and productivity in any machining operation. These three cutting parameters are considered to investigate their affect on material removal rate and surface finish. All the work pieces are taken with 150mm length and 32mm diameter. Selecting the appropriate cutting tool material for a specific application is crucial in achieving efficient operations. The solid carbide tool is used to perform the experimentation work. The design of experiments technique permits us to carry out the modeling and analysis of the influence of process variables (design factors) on the response variables. In the present experiment depth of cut (*d*, mm), spindle speed (*N*, rpm) and feed rate (*f*, mm/min) have been selected as design factors while other parameters have been assumed to be constant over the experimental domain. The process variables (design factors) with their values on different levels are listed in table 1.

Table 1. Design factors (Input parameters) and their levels

Factors	Units	Levels		
		Level 1	Level 2	Level 3
Cutting speed, *N*	RPM	750	1000	1500
Feed rate, *f*	mm/min.	50	150	200
Depth of cut, *d*	mm	2	3	5

In the present investigation, Taguchi's L_9Orthogonal Array (OA) design shown in table 2 has been considered for experimentation. The Agni BMV 45 T20 CNC milling machine has been used to carry out the experiment.

Table 2. Taguchi L_9 orthogonal array

Experiment No.	Factorial combination (coded form)		
	N	*f*	*d*
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

The experimentation has been conducted through the following step by step procedure.
Step 1: Cutting the aluminium bar to the desired size by power hack saw and performing initial turning operation in Lathe to get desired dimension of the work pieces.
Step 2: The work piece is clamped in milling-vice on the working table of CNC milling machine using T-clamps, bolts, jigs and fixture.
Step 3: Select the suitable CNC end milling cutter and their axis is selected. The selected cutter is fixed in the main spindle using different collets.
Step 4: Performing milling operation on specimens in involving various combinations of input parameters such as cutting speed, feed and depth of cut. A manual part programming is developed for CNC end milling. A coolant of same kind is employed during the milling of all the work pieces. The figure 1(a) shows the milling operation and the finished aluminium bars with single slot shown in figure 1(b), which are ready for testing surface finish.

Fig. 1: (a) Milling of aluminium work piece; Fig.1 (b): Finished aluminium bars with single slot

Step 5: Measure the surface roughness with the help of a portable stylus-type Talysurf TR200.
Step 6: Calculate the material removal rate using the following formula

$$\text{Material removal rate (MRR)} = \frac{\text{Intial weight} - \text{Final weight}}{\text{Density of aluminium} \times \text{Machining time}}$$

The experimental results are analyzed and are discussed in the following section.

3. RESULTS OF THE EXPERIMENT AND ANALYSIS OF THE DATA

After performing all the nine experiments, the material removal rate and surface roughness are determined. The normalized data of material removal rate (mm^3/min.) and surface roughness (μ m) are shown in table 3.

Table 3. Normalized data of Material removal rate (MRR) and Surface roughness (SR)

Work piece	1	2	3	4	5	6	7	8	9
MRR	0.12900	0.16393	0.27586	0.16326	0.88888	0.46168	0.34782	0.47063	1.0000
SR	1.00000	0.3839	0.1393	0.9744	0.1962	0.3921	1.2000	0.2737	0.6965

In order to achieve better surface finish and higher material removal rate simultaneously, DEA based Taguchi method is employed. The DEA method gives the relative efficiency scores. The LINGO 8.0 is used to solve the DEA relative efficiency problem for the normalized data shown in table 3.The relative efficiency scores are presented in table 4. The Taguchi method is employed using MINITAB 14.0 for the relative efficiency scores to obtain the corresponding S/N ratios. The S/N ratios are also presented in the table 4.

Table 4. Relative efficiency scores and S/N ratios

Experiment No	Relative Efficiency scores	S/N ratios
01	1.0000	− 4.3594
02	0.5346	− 5.4403
03	0.4789	− 6.3954
04	0.9135	− 0.7858
05	1.0000	− 3.3454
06	0.9809	− 0.1678
07	1.0000	0.00000
08	0.9413	− 0.5248
09	1.0000	− 9.3954

From the table 4, it is observed that the combination of speed, feed and depth of cut employed in experiment 7 possesses higher S/N ratio. Therefore to achieve both good surface finish and better material removal rate, the speed and depth of cut should be in higher level and feed has to be taken at lower level. The main effect plots for S/N ratios are shown in figure 2. The table 5 shows the mean response table.

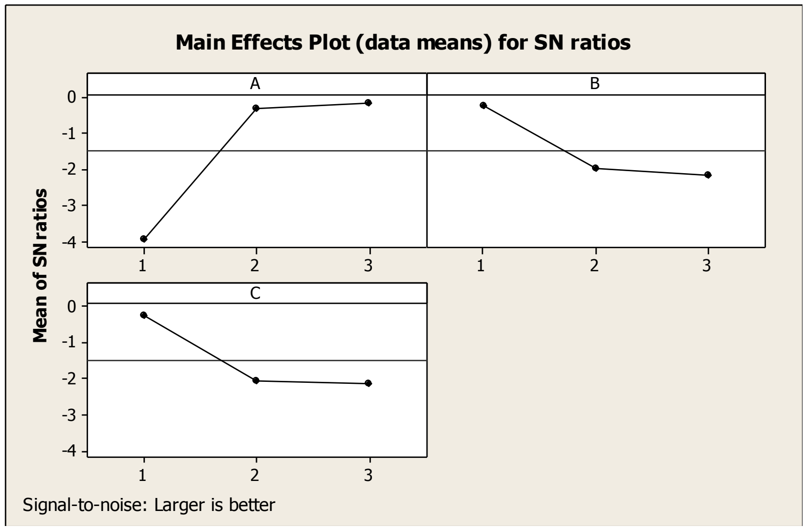

Fig. 2: Main effects plot for S/N ratios

Table 5. Mean response table

Level	Speed	Feed	Depth of cut
1	−3.9452	−0.2619	−0.2312
2	−0.3179	−1.9887	−2.0754
3	−0.1753	−2.1877	−2.1318
Delta	3.7699	1.9258	1.9006
Rank	1	2	3

The table 5 reveals that the speed, feed and depth of cut orderly influences on achieving good surface finish and higher material removal rate.

4. CONCLUSIONS

The quality and productivity are the important objectives in any machining process. Surface finish and material removal rate represents quality and productivity respectively. Taguchi method helps to optimize surface roughness and material removal rate individually. But DEA based Taguchi technique helps to solve the multi – response optimization problem. In the present work experimental investigation is carried to study the effect of cutting parameters such as speed, feed and depth of cut during CNC end milling of aluminum. The signal to noise ratios is calculated under multi-response optimization. On comparing the signal to noise ratio, the optimum levels of speed, feed and depth of cut are identified. In end milling of aluminium, the cutting speed and depth of cut have to be maintained at higher level and feed in lower level yields better material removal rate and good surface finish.

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