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Taguchi approach with multiple performance characteristics for burr size minimization in drilling

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This paper presents application of Taguchi optimization method for simultaneous minimization of burr height and burr thickness influenced by cutting conditions and drill geometry. The approach of Taguchi design for multi-objective optimization problem is based on the introduction of a new concept of fitness function for each trial of orthogonal array. The fitness function is derived through mapping the objective functions of the drill optimization problem. In present work, optimal values of cutting speed, feed, point angle and lip clearance angle are determined for a selected drill diam to minimize burr height and burr thickness during drilling of AISI 316L stainless steel workpieces. The effectiveness of proposed method is demonstrated through simulation results and experimental verifications.

Keywords: Burr size, Drilling, Fitness function, Taguchi method

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Introduction

Formation of exit burr on part edges during drilling has several undesirable features on product quality and functionality and hence it requires significant attention in the industrial research. Burrs pose reliability problems and performance degradation in precision parts, thus affecting quality[1]. Exit burrs are injurious during machining and cause groove wear[2], hence strongly affect the productivity and assembly process. When exit burr is formed inside a cavity, there are no tools available for deburring. It is estimated that deburring and edge finishing on precision components constitute as much as 30% of the cost of the finished parts[3]. The edge finishing and secondary finishing operations are difficult to automate and hence bottleneck in a production line[4,5].

The formation of exit burr and factors affecting are well studied[6-13]. Finite element models for analyzing burr formation in drilling were proposed by several researchers[14-16]. Kim *et al*[17,18] developed empirical drilling charts to choose suitable cutting conditions for different materials in order to reduce burr size over limited ranges of drilling through a single layered material. Investigations on drilling optimization of mild steel and medium carbon steel work pieces using Genetic Algorithms (GA) [19,20] revealed that point angle and lip clearance angle have major contributions in controlling burr size. However, GA optimization requires an accurate model describing complex and non-linear relationship that exists between the process parameters and the burr size.

Taguchi based optimization technique has produced a unique and powerful optimization discipline that differs from traditional practices[21]. However, original Taguchi technique was designed to optimize a single performance characteristic and the same was employed in the past for optimization in different processes[22,23]. Several modifications were suggested to the original Taguchi method for multi response optimization[24] such as Principal Component Analysis (PCA), Data Envelopment Analysis (DEA), and Grey Relational Analysis (GRA). However, all these modifications increase computational process complexity and require proper engineering judgement.

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Table 1— Factors and levels

Code	Factors	Levels		
		1	2	3
A	Cutting speed (v), m/min	8	16	24
B	Feed (f), mm/rev	0.04	0.08	0.12
C	Point angle (θ), °	118	126	134
D	Lip clearance angle (ψ), °	8	10	12

Table 2 — L_9 Orthogonal array

Trial No.	Levels of input parameters			
	A	*B*	*C*	*D*
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

This paper introduces a simple modification to Taguchi method for multi-objective drilling process optimization. The proposed modification involves introduction of a new concept of fitness function for each trial of orthogonal array for simultaneous minimization of burr height and burr thickness. Modified Taguchi technique determines the optimal values of cutting speed (v), feed (f), point angle (θ) and lip clearance angle (Ψ) for a given drill diam to minimize burr height (B_h) and burr thickness (B_t) during drilling of AISI 316L stainless steel workpieces using HSS twist drills.

Problem Formulation

It is required to determine the optimal values of v, f, θ and Ψ for a specified drill diam (d) that simultaneously minimizes the two objective functions, B_h and B_t. Since, Taguchi technique is suitable for the optimization of only one objective function, it is necessary to modify the technique for multi-objective problems. This modification is to obtain "fitness function" (*fit*) by mapping the two objective functions for each trial of orthogonal array, given as:

$$fit = M_p\{B_h,\ B_t\} \quad \ldots (1)$$

where, M_p is a mapping function.

Thus, the drill optimization problem can be stated as:

Determine the values of v, f, θ and Ψ for a specified d

So as to optimize *fit*

Subject to constraints $X_{min} \leq X \leq X_{max}$ for $X = v, f, \theta, \Psi$.

Taguchi Multi-objective Optimization

Taguchi optimization procedure begins with selection of orthogonal array[21] with distinct number of levels (L) defined for v, f, θ and Ψ. Minimum number of trials in the array is:

$$N = (L-1)F + 1 \quad \ldots (2)$$

where, F =number of factors = 4

In the present study, three levels are defined for each factor (Table 1). This gives N=9, and hence L_9 orthogonal array was selected (Table 2). Thus, nine experiments were conducted for a specified drill diam and B_h and B_t were measured.

Experimental Details

Tests were carried out on a three-axis CNC vertical machining center (YCM-V116BVMC), which was equipped with a maximum feed rate (5000 mm/min) and variable spindle speed (45-4000 rpm). The material used was AISI 316L stainless steel having following chemical composition: C, 0.026; Si, 0.37; Mn, 1.6; P, 0.029; S, 0.027; Cr, 16.55; Ni, 10; Mo, 2.02; Co, 0.16; and N, 0.036 %. Workpieces (25 mm thick) were polished on the exit surface before drilling to prepare for burr measurement. HSS twist drills (28 mm diam) having 30-degree helix angle were utilized and the drill geometry was ground as per the orthogonal array. Cut60EP was used as coolant.

The B_h and B_t were measured on toolmakers microscope (RPP-400). Burr size values were recorded at four equally spaced locations around the circumference and average reading was taken as process response (Table 3).

Fitness Mapping

Objective functions B_h and B_t of a trial in the L_9 array are suitably mapped to obtain a *fit*. The following mapping methods are employed:

Linear Mapping

Fitness function combining the two objective functions is defined by linear relation as:

$$fit_l = 0.5(fit_1 + fit_2) = 100 - (50B_h + 142.85B_t) \ldots (3)$$

This linearly maps burr height values (0-1 mm) into fitness (fit_1) range [100:0.0]. Similarly, burr thickness values (0-0.35 mm) into fitness (fit_2) range [100:0.0].

Table 3 — Tabulation of measured response, fitness and S/N ratio

Trial No.	Measured responses		Linear mapping		Non-linear mapping	
	B_h, mm	B_t, mm	fit_l	η_l, dB	fit_{nl}	η_{nl}, dB
1	0.561	0.059	63.52	36.058	72.23	37.174
2	0.242	0.121	70.61	36.978	88.36	38.925
3	0.210	0.307	45.64	33.187	78.90	37.941
4	0.657	0.294	25.15	28.011	52.51	34.404
5	0.319	0.049	77.05	37.735	88.07	38.896
6	0.791	0.120	43.30	32.731	54.65	34.751
7	0.362	0.162	58.75	35.381	78.46	37.892
8	0.983	0.181	24.99	27.956	42.46	32.559
9	0.526	0.036	68.55	36.721	75.99	37.615

Table 4— ANOVA for linear and non-linear mapping

Factors	DOF	Sum of squares		Mean squares		% Contribution	
		Linear	Non-linear	Linear	Non-linear	Linear	Non-linear
A	2	11.168	7.951	5.585	3.976	10.08	19.87
B	2	2.282	0.170	1.142	0.085	2.06	0.43
C	2	15.234	17.895	7.616	0.947	13.74	44.73
D	2	82.182	13.993	41.090	6.997	74.12	34.97
Error	0	0	0	-	-	-	-
Total	8	110.866	40.009	13.858	5.001	100	100

Non-linear Mapping

Fitness function is obtained by mapping two objective functions through a non-linear relation:

$$fit_{nl} = \frac{100}{1+(B_h + B_t)^2} \qquad \dots (4)$$

This method maps B_h (0-1 mm) and B_t (0-0.35 mm) into fitness (fit_{nl}) in the range [100: 35].

Fitness values calculated using above two methods are summarized in Table 3. Thus, simultaneous minimization of B_h and B_t requires maximization of fitness function, and hence the "larger the better type category"[21] of Taguchi optimization was selected for each trial.

Analysis of Means

Analysis of Means (ANOM)[21] is the process of estimating main effects of each factor and the effect of a factor level is the deviation it causes from the overall mean response. Taguchi optimization requires maximization of Signal to Noise ratio (η) associated with the fitness of each trial of the orthogonal array and is calculated as[21]:

$$\eta = -10\log_{10}(fit^{-2}) \qquad \dots (5)$$

Calculated values of η_l and η_{nl} for each trial of L_9 array corresponding to the linear and non-linear mapping are demonstrated (Table 4). Overall mean of η associated with 9 trails is given by:

$$m = \frac{1}{9}\sum_{k=1}^{k=9}\eta_k \qquad \dots (6)$$

Effect of a factor level i for a parameter j is defined as:

$$(m)_{i,j} = \frac{1}{L}\sum_{i=1}^{L}(\eta_i)_j \qquad \dots (7)$$

Optimum level of a factor is the level that gives the highest signal to noise ratio. Maximization of the fitness function is determined by the ANOM to give the optimum level associated with each process parameter as:

$$j_{i,opt} = \max\{(m)_{i,j}\} \qquad for\ \ j = v, f, \theta, \psi\ and\ i = 1,2,3 \qquad \dots (8)$$

Analysis of Variance

Analysis of variance (ANOVA)[21] is performed on signal to noise ratios to obtain the contribution of each of the factors. The total sum of squares (SS_T) is given as:

$$SS_T = \sum_{k=1}^{9} (\eta_k - m)^2 \quad \dots (9)$$

SS_T is used to measure the relative influence of factors on the response.

Sum of squares due to factor *j* is given by:

$$SS_j = \sum_{i=1}^{3} 3[(m_j)_i - m]_i^2 \quad for\ j = v, f, \theta, \psi\ and\ i = 1,2,3 \quad \dots (10)$$

A factor *j* with largest *SS* value will have more influence in controlling the response. Sum of the squares of error (SS_e) is given by:

$$SS_e = SS_T - \sum_{j=1}^{4} SS_j \quad \dots (11)$$

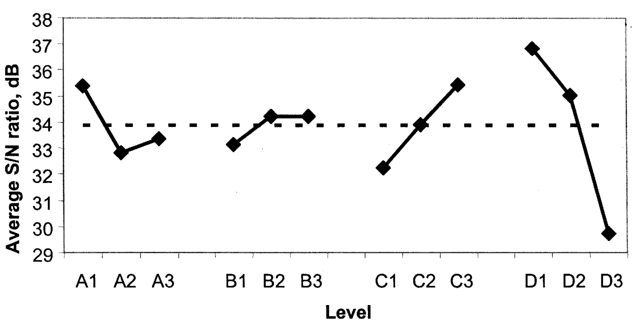

Fig. 1 — Response graph of S/N ratio for linear mapping

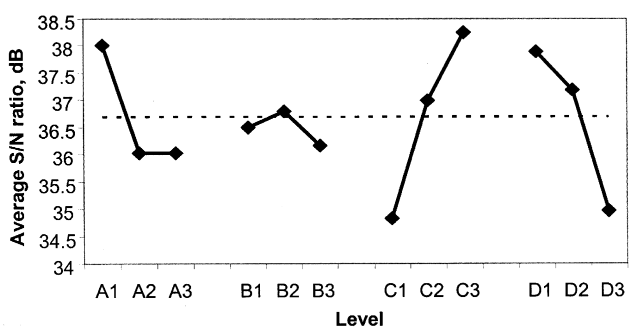

Fig. 2 — Response graph of S/N ratio for non-linear mapping

Mean square of each factor *j* is:

$$MS_j = \frac{SS_j}{L-1} \quad \dots (12)$$

Percentage contribution of each factor *j* is calculated as:

$$Q_j = \frac{SS_j - (L-1)V_e}{SS_T} \quad \dots (13)$$

where, V_e is the variance of the pooled error.

F-ratio for each factor *j* is given as:

$$F_j = \frac{MS_j}{V_e} \quad \dots (14)$$

Results and Discussion

ANOM for linear (Fig. 1) and non-linear (Fig. 2) mapping functions shows that both fitness mappings yield same optimum parameter levels (A1, B2, C3 and D1). Point angle and lip clearance angle have major contributions in controlling burr size (Table 4). Cutting speed has moderate effect on burr size. Both methods indicate that the percentage contribution due to feed is negligible.

Since ANOVA has resulted in zero degree of freedom for error term, it is necessary to pool the factor having less influence for correct interpretation of results. It is observed that the pooled error is less than 10%, indicating that important factors are not omitted from the experiments (Table 5).

After selecting the optimal level of process parameters for the selected diam values, the final step is to predict and verify the adequacy of the model for determining the optimal burr size. The predicted optimum value of signal to noise ratio (η_{opt}) can be determined as:

$$\eta_{opt} = m + \sum_{j=1}^{p} [(m_{i,j})_{\max} - m] \quad \dots (15)$$

Table 5— Pooled ANOVA for linear and non-linear mapping

Factors	DOF	Sum of squares		Mean squares		Pure sum		% Contribution		F-ratio	
		Linear	Non-linear	Linear	Non-linear	Linear	Non-linear	Linear	Non-linear	Linear	Non-linear
A	2	11.168	7.951	5.585	3.976	8.885	7.782	8.01	19.45	4.889	46.980
C	2	15.234	17.895	7.616	8.947	12.947	17.726	11.68	44.30	6.667	105.733
D	2	82.182	13.993	41.090	6.997	79.896	13.824	72.07	34.55	35.971	82.681
(Error)	(2)	(2.282)	0.169	(1.141)	0.085	-	-	8.24	1.70	-	-
Total	8	110.866	40.009	13.858	5.001	-	-	100	100	-	-

Table 6 — Confirmatory test results

Performance measures	Linear mapping	Non linear mapping
Levels (A, B, C, D)	1, 2, 3, 1	1, 2, 3, 1
S/N predicted (η_{opt}), dB	39.956	40.784
B_h measured, mm	0.197	0.197
B_t measured, mm	0.048	0.048
S/N observed (η_{obs}), dB	38.560	39.494
Prediction error of S/N ratio, dB	1.396	1.290
Confidence limits (2σ), dB	±3.376	±1.762

where, $(m_{i,j})_{\max}$ is the signal to noise ratio of optimum level i of factor j and p is the number of main design parameter that affect the burr size.

The measured values of B_h and B_t under the optimal process conditions were used to determine the observed values of signal to noise ratio (η_{obs}). In order to judge the closeness of observed value of signal to noise ratio with that of the predicted value, the variance of prediction error is determined and the corresponding two-standard deviation confidence limits for the prediction error of the signal to noise ratio are calculated. Calculated value of prediction error (Table 6) has been observed within the confidence limit for all selected drill diam for the mapping functions. This indicates that the additive models of burr size are adequate. The optimal parameter settings obtained by modified Taguchi approach are as follows: *v,* 8 m/min*; f,* 0.08 mm/rev*;* θ, 134°; and Ψ, 8°.

Conclusions

Taguchi optimization for multi-objective drilling problem to minimize burr size is based on the introduction of a new concept of mapping the various objective functions for each trial of orthogonal array to obtain the fitness function. Effectiveness of proposed approach is demonstrated through detailed analysis to give optimal process setting levels, which simultaneously minimize burr height and burr thickness. Optimal process parameters were confirmed with verification experiments.

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