A Taguchi application on optimization of process parameters for hole quality in drilling of AISI 304 stainless steel

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Abstract

In this study, Taguchi method optimized the process parameters used in the drilling of AISI 304 stainless steel with coated M35 HSS drills to provide better hole quality. L_{27} (3^{13}) orthogonal array, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA) were employed to capture the optimal levels of process parameters and their effects on surface roughness (Ra) and roundness error (Re). After 27 trials of the Taguchi technique, it was observed that the feed rate was the most influential parameter on both the Ra and Re. In addition, confirmation test results showed that Taguchi method was very powerful on optimization of process parameters for Ra and Re in drilling.

Key words: Coatings; Surface Roughness; Roundness Error; Taguchi Method

1. Introduction

The application of hard coatings to cutting tools has been proven to be one of the most significant technological advances in the development of modern tools [1]. One possible approach that can be used to obtain increased fracture resistance of the coating is to apply coatings with a multi-layered structure. In multilayer coatings, alternate layers of two or three different compounds are deposited in a certain sequence. A combination of single-layer materials with different properties and functions, on the one hand, and a specific interface to interrupt the columnar grain growth, on the other, can be realized. The numerous interfaces created between individual layers of a multilayer coating cause a dramatic increase in hardness and strength [2]. Additional improvements to cutting tools such as high toughness, corrosion resistance, and low thermal conductivity have been contributed by multilayer coatings [3-4].

TiN coatings have a wide area of application due to their high hardness, low friction coefficient, and good corrosion and oxidation resistance [5, 6]. As an alternative to TiN coatings, TiAlN coatings with high oxidation resistance [7-11] and toughness [12] were developed. TiAlN coatings are frequently used due to their lower thermal conductivity [8] and friction coefficient [10], higher hardness, and thermal stability [2], especially in dry cutting conditions at high cutting speeds [13-15]. TiAlN coatings generally show worse performance than TiN coatings in the case of low sliding speeds or interrupted cutting processes due to their brittleness and high friction coefficient [2]. TiAlN coatings were superior to TiN coatings in terms of wear resistance during the machining of SKD 11 steel. TiAlN coatings failed in terms of brittle fracture and

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oxidation resistance, while TiN coatings failed in terms of oxidation resistance and plastic deformation. However, TiN coatings showed better abrasion wear resistance than TiAlN coatings [15]. It was also observed that TiAlN coatings had advantages over TiN coatings due to their high oxidation resistance and strength at especially high cutting speeds in the machining of AISI D2 cold work steel [11]. When Inconel 718, SAE 1045, medium carbon steel, and ductile iron were machined with TiN-, TiCN-, and TiAlN-monolayer-coated cemented carbide tools at low and high cutting speeds, it was reported that TiAlN-coated tools showed the best machining performance at especially high cutting speeds due to their hot hardness and oxidation resistance [9]. TiAlN/TiAlZrN-multilayer-coated HSS drills were better than TiN- and TiAlN-monolayer-coated drills in terms of drilling performance [1, 16]. TiAlN-coated cutting tools showed the best performance in tool wear tests performed with coated ceramic cutting tools with different coating materials (TiN + TiAlSiN + AlSiTiN, TiN + TiAlSiN + TiN, TiCN + TiN, TiN + Al2O3, TiN, TiN + multiTiAlSiN + TiN, TiAlN) ~~-~~under dry cutting conditions at high cutting speeds, while TiN + multiTiAlSiN + TiN showed the best performance in the surface roughness tests [17]. The tool life of TiN- and TiAlN-coated cermet inserts were better than those of other coated and uncoated ones when compared with monolayer- and multilayer-coated cermet inserts in terms of tool life in milling operations [18].

The Taguchi method is frequently used in many experimental studies as a method of optimization and experimental design. By means of this method, it is possible to substantially minimize the cost and time in many experimental studies [19]. Horng et al. [20] presented a model for the evaluation of machinability using response surface methodology (RSM) in the machining of Hadfield steel. The combined effects of four machining parameters, cutting speed, feed rate, depth of cut, and tool corner radius, were investigated on the basis of two performance characteristics, flank wear and surface roughness, and centered central composite design (CCD) and ANOVA were employed. Palanikumar [21] modeled the delamination factor and surface roughness in the machining of GFRP composites using RSM. Three-factor five-level CCD was employed in this study. The RSM was also adopted by Singh and Rao [22] in their study of the effects of cutting conditions and tool geometry on the surface roughness in the finish hard-turning of bearing steel (AISI 52100) with mixed ceramic tools. Asilturk and Neseli [23] presented a new method of determining multi-objective optimal cutting conditions and mathematic models for surface roughness in CNC turning. Firstly, the cutting parameters, namely cutting speed, depth of cut, and feed rate, are designed using the Taguchi method. Secondly, the model for the surface roughness, as a function of cutting parameters, is obtained using RSM. Finally, the adequacy of the developed mathematical model is proved by ANOVA. Tosun [24] used the Taguchi method to determine the optimal process parameters for surface roughness in the drilling of Al/SiCp metal matrix composite. Confirmation tests verified that the optimal combination of process parameters selected via the Taguchi design was able to achieve the desired surface roughness. Davim [25] presented a study of the influence of cutting parameters and cutting time on drilling metal–matrix composites. A series of experiments planned on the basis of Taguchi's techniques was performed on controlled machining with cutting conditions preset in work pieces. The analysis of results showed that the cutting time is the factor which has the greatest influence on the tool wear (50%), followed by feed rate (24%).

TiN and TiAlN coatings have different superior properties. Therefore, it would be logical to deposit TiAlN and TiN coating materials on HSS drills as a multilayer for evaluation of the machinability of austenitic stainless steel. This study has two objectives. The first objective is to investigate the influences of TiN- and TiAlN-monolayer and TiAlN/TiN-multilayer coatings on surface roughness and roundness error in the drilling of AISI 304 austenitic stainless steel with HSS drills. The second objective also is to optimize the process parameters to obtain better Ra and Re and to reduce cost and time in drilling of the stainless steel.

2. Materials and Method

In the present study, the work piece materials were AISI 304 austenitic stainless steel blocks. The chemical composition of AISI 304 steel considered in this work is shown in Table 1.

Table 1. Chemical composition of AISI 304 austenitic stainless steel

C	Si	Mn	P	S	Cr	Ni	Mo	Cu
0.059	0.581	1.08	0.029	0.001	18.06	8.15	0.064	0.154

The experiments were conducted on a Johnford VMC 850 model three-axis CNC vertical machine center. The experiments were carried out at three cutting speeds (10, 12 and 14 m/min) and three feed rates (0.04, 0.06, and 0.08 mm/rev) and a depth of cut (13 mm) under dry cutting conditions. The drills used were TiN- and nano-TiAlN-monolayer-coated and TiAlN/TiN-multilayer-coated M35 HSS drills with a diameter of 6 mm. Thicknesses of TiN and nano-TiAlN-monolayer-coatings and TiAlN/TiN-multilayer-coating (six layers) are 2.5 µm, 2.5 µm and 4 µm, respectively. The friction coefficients and hardness values (HV 0.05) are 2.5 - 2200 for TiN coating, 0.35 – 3400 for nano-TiAlN coating and 0.3 – 3600 for TiAlN/TiN coating. The Ra was measured using a Mitutoyo Surftest SJ-301 portable surface roughness tester. To be able to measure the Ra, steel blocks were cut by wire EDM. The Re measurements were also carried out using a Mitutoyo CRT-A C544 3D coordinate measuring machine. Surface roughness and roundness error measurements are shown in Fig. 1a, b respectively.

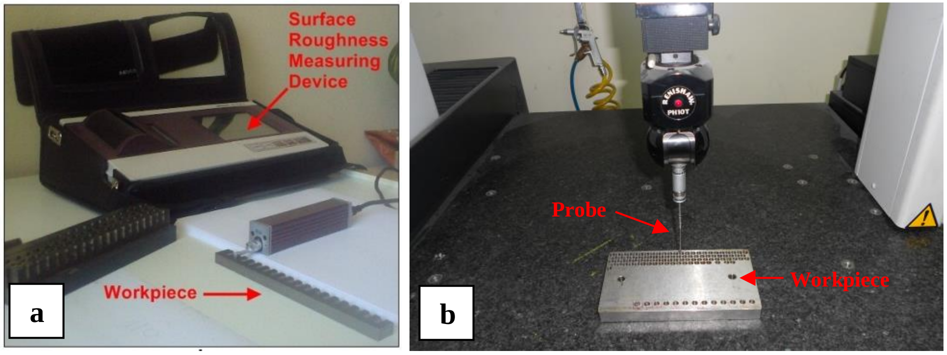

Fig. 1. a- Surface roughness measurement, **b-** roundness error measurement

3. Methodology of Taguchi method of experimental design

3.1. Taguchi method

The Taguchi method is a simple and robust technique for optimizing the process parameters in order to reduce the process variation. The aim of the analysis is to investigate how different process parameters affect the mean and variance of process performance characteristics and to determine which variables contribute significantly [26]. The Taguchi design finds optimal values of the objective function in the manufacturing process [23]. For the elaboration of the experimental plan, Taguchi's method for three factors at three levels was used. The control factors and levels used in this study are shown in Table 2.

Table 2. Control factors and levels used in the experiments

Levels	Control factors		
	A - Coating materials (Cm)	B - Cutting speed (Vc)	C - Feed rate (f)
1	TiAlN-nano	10	0.04
2	TiAlN/TiN	12	0.06
3	TiAlN	14	0.08

In the Taguchi method, as a loss function is used to calculate the deviation between the experimental value and the desired value, this loss function is further transformed into an S/N ratio [27]. There are several types of quality characteristics such as "smaller is better", "higher is better", and "nominal is the best". The surface roughness and roundness error use a "smaller is better" type of quality characteristic (the goal is always to minimize the Ra and Re). So, according to this approach, the equation given below is used in the calculation of the S/N ratio;

$$\text{S/N ratio (in dB)} = -10 \log \left(\frac{1}{n}\sum_{i=1}^{n} yi^{2}\right) \qquad (1)$$

where $\bar{y}$ is the mean of the observed data, s_y^2 is the variance of y, n is the number of observations, and y is the observed data [28].

Table 3. L_{27} (3^{13}) orthogonal array, experimental results and their S/N ratios.

Exp. no	***Designation***	***Control factors***			***Observed values***		***S/N ratio (dB)***	
		A	***B***	***C***	***Ra [μm]***	***Re [μm]***	***Ra***	***Re***
1	$A_1B_1C_1$	TiAlN-nano	10	0.04	2.37	6.7	-7.49	-16.52
2	$A_1B_1C_2$	TiAlN-nano	10	0.06	2.41	7.6	-7.64	-17.61
3	$A_1B_1C_3$	TiAlN-nano	10	0.08	3.4	8.5	-10.62	-18.58
4	$A_1B_2C_1$	TiAlN-nano	12	0.04	2.16	5.4	-6.68	-14.64
5	$A_1B_2C_2$	TiAlN-nano	12	0.06	2.21	7.3	-6.88	-17.26
6	$A_1B_2C_3$	TiAlN-nano	12	0.08	3.29	9.8	-10.34	-19.82
7	$A_1B_3C_1$	TiAlN-nano	14	0.04	2.2	5.1	-6.84	-14.15
8	$A_1B_3C_2$	TiAlN-nano	14	0.06	2.23	8.8	-6.96	-18.89
9	$A_1B_3C_3$	TiAlN-nano	14	0.08	3.4	11	-10.62	-20.82
10	$A_2B_1C_1$	TiAlN/TiN	10	0.04	2.21	7.3	-6.88	-17.26
11	$A_2B_1C_2$	TiAlN/TiN	10	0.06	2.31	7.1	-7.27	-17.02
12	$A_2B_1C_3$	TiAlN/TiN	10	0.08	3.32	8.4	-10.42	-18.48
13	$A_2B_2C_1$	TiAlN/TiN	12	0.04	2.02	4.9	-6.107	-13.80
14	$A_2B_2C_2$	TiAlN/TiN	12	0.06	2.03	6.9	-6.15	-16.77
15	$A_2B_2C_3$	TiAlN/TiN	12	0.08	3.21	8.7	-10.13	-18.79
16	$A_2B_3C_1$	TiAlN/TiN	14	0.04	2.07	4.7	-6.32	-13.44
17	$A_2B_3C_2$	TiAlN/TiN	14	0.06	2.17	7.6	-6.73	-17.61
18	$A_2B_1C_3$	TiAlN/TiN	14	0.08	3.23	10.6	-10.18	-20.50
19	$A_3B_1C_1$	TiAlN	10	0.04	2.42	5	-7.68	-13.97
20	$A_3B_1C_2$	TiAlN	10	0.06	2.74	6.8	-8.76	-16.65
21	$A_3B_1C_3$	TiAlN	10	0.08	3.57	7.7	-11.05	-17.72
22	$A_3B_2C_1$	TiAlN	12	0.04	2.34	4.7	-7.38	-13.44
23	$A_3B_2C_2$	TiAlN	12	0.06	2.38	6	-7.53	-15.56
24	$A_3B_2C_3$	TiAlN	12	0.08	3.24	8.6	-10.21	-18.68

25	$A_3B_3C_1$	TiAlN	14	0.04	2.67	3.7	-8.53	-11.36
26	$A_3B_3C_2$	TiAlN	14	0.06	2.4	8	-7.60	-18.06
27	$A_3B_3C_3$	TiAlN	14	0.08	3.88	9.3	-11.77	-19.36
$\overline{T}_{Ra}$, overall mean of surface roughness = 2.662µm								

3.2. Selection of an orthogonal array

The first step of the Taguchi method is to select a proper orthogonal array. The Taguchi method uses a procedure that applies orthogonal arrays of statistically designed experiments to obtain the best results with the minimum number of experiments, and thus reduces the time and cost of experimentation [26]. An L_{27} orthogonal array was used for the full factorial experimental design. Thus, the effects of all the control factors can be evaluated. The total number of degrees of freedom (DOF) for three parameters each at three levels and three second-order interactions is 18. So, a three-level orthogonal array with at least 18 DOF was to be selected [25]. The selected array was the L_{27} (3^{13}). The S/N ratios were also calculated using the “smaller is better” criterion, that is, Eq. (1), for each of the 27 experimental combinations reported in Table 3. As the experimental design was orthogonal, the effects of factors were separated out in terms of the S/N ratio as well as the mean response.

4. Results and discussion

Analysis of the influence of each control factor (*Ct, Vc, f*) on the Ra and Re has been performed with a so-called response table of S/N ratios. Response tables of S/N ratios for Ra and Re are shown in Table 4. In addition to S/N analysis, the main effects of the process parameters on the mean response are also analyzed in Table 5. Therefore, the optimal level of the machining parameters is the level with the greatest value of the S/N ratio. Here, the optimum condition corresponds to the minimization of the Ra and Re.

Table 4. Response table for S/N ratios (smaller-is-better) for Ra and Re

Control	Surface roughness (Ra)				Roundness error (Re)			
	Level 1	Level 2	Level 3	Δmax-	Level 1	Level 2	Level 3	Δmax-min
Ct	-8.236	-7.80	-8.946	1.146	-17.592	-17.079	-16.094	1.498
Vc	-8.648	-7.937	-8.398	0.711	-17.095	-16.533	-17.136	0.603
f	-7.104	-7.281	-10.59	3.486	-14.290	-17.273	-19.201	4.911

*Optimum level Δ = difference between maximum and minimum Ra, Re response S/N values

Table 5. Response table for means (smaller-is-better) for Ra and Re

Control	Surface roughness (Ra)				Roundness error (Re)			
	Level 1	Level 2	Level 3	Δmax-	Level 1	Level 2	Level 3	Δmax-min
Ct	2.630	**2.507**	2.848	0.341	7.80	7.355	**6.644**	1.156
Vc	2.750	**2.542**	2.694	0.208	7,233	**6.922**	7.644	0.722
f	**2.273**	2.320	3.393	1.12	**5.277**	7.344	9.177	3.90

Δ = difference between maximum and minimum Ra, Re response means values

Based on the analysis of S/N ratio, the optimal Ra value is obtained with TiAlN/TiN-coated drills (level 2) with the following settings: a cutting speed of 12 m/min (level 2) and a feed rate of 0.04 mm/rev (level 1) (Fig. 2.a). In addition, according to the S/N ratio, the best drills for Re are TiAlN-coated drills (level 3) with the following settings: a cutting speed of 12 m/min (level 2) and a feed rate of 0.04 mm/rev (level 1) (Fig. 2.b). It can be observed from Table 5 that the optimum levels were $A_2B_2C_1$ and $A_3B_2C_1$ for the Ra and Re, respectively.

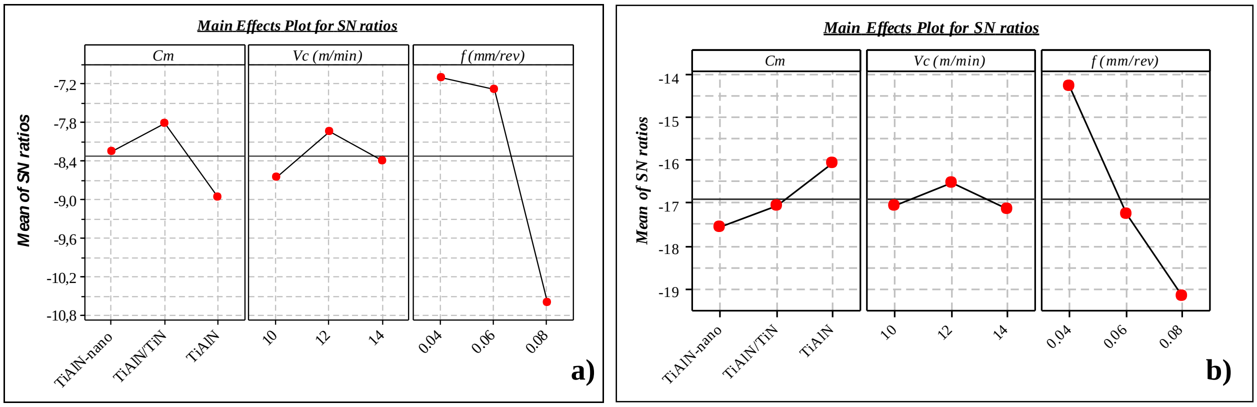

Fig. 2. Effect of process parameters on average S/N ratio for a) Ra, b) Re

The optimal Ra values were provided by TiAlN/TiN-multilayer-coated drills, respectively. The decrease in the Ra can be attributed to the lower friction coefficient (0.3) and higher hardness (3600 $HV_{0.05}$) of TiAlN/TiN-coating materials. One of the most important factors in the deterioration of the Ra is the BUE (Built-up edge) which occurs in the machining of ductile materials such as AISI 304. The coating material deposited on the substrate reduces BUE formation remarkably due to its lower friction coefficient. In addition, higher wear resistance positively affects the Ra owing to the higher hardness of TiAlN/TiN-coating materials. The best Re values were obtained using TiAlN-monolayer-coated drills as a cutting tool in the drilling experiments. The Ra values decreased with increasing cutting speed until the latter reached 12 m/min and then increased slightly. The tool–chip contact area decreased with increasing cutting speed on account of the decreasing chip curl radius. Since this led to a reduction of friction in the tool–chip contact area, the hole quality improved. But the greater tool wear which occurred at higher cutting speed (14 m/min) affected the hole quality negatively. The parameter with the greatest influence on both Ra and Re was feed rate. Ra and Re values increased notably with increasing feed rate. With increasing feed rate, as the volume of chips removed from the work piece material increased, the forces acting on the cutting tool also increased. Therefore, the hole quality deteriorated.

4.1. Analysis of variance (ANOVA) and effect factors

In order to quantify the influence of process parameters and interactions on the selected machining characteristic, ANOVA was performed [29]. ANOVA helps in formally testing the significance of all main factors by comparing the mean square against an estimate of the experimental errors at specific confidence levels [30]. The optimal combination of process parameters was predicted by both S/N and ANOVA analysis. The ANOVA results obtained for Ra and Re at the confidence level of 95% are shown in Table 6.

Table 6. Results of ANOVA for surface roughness and roundness error

Surface roughness (Ra)

Sourc	***Degree of***	***Sum of***	***Varianc***	***F-***	***Prob.***	***Contribution***
A	2	0.537	0.268	19.27	0.001*	6.54
B (*Vc*)	2	0.208	0.104	7.47	0.015*	2.529
C (*f*)	2	7.225	3.612	259.04	0.000*	87.75
A*B	(4)	0.076	0.019	1.37	0.327	0.923
A*C	(4)	0.003	0.007	0.06	0.991	0.036
B*C	(4)	0.072	0.018	1.30	0.347	0.874
Error	8	0.111	0.0138	-	-	1.348
Total	26	8.232	-	-	-	100

*Significant at %95 confidence level. Tabulated F-ratio at %95 confidence level:

Roundness error (Re)

Sourc	***Degree of***	***Sum of***	***Varianc***	***F-***	***Prob.***	***Contribution***
A	2	6.115	3.057	3.057	0.002*	6.59
B (*Vc*)	2	2.362	1.181	1.181	0.027*	2.549
C (*f*)	2	68.52	34.26	34.26	0.000*	73.94
A*B	(4)	0.582	0.145	0.145	0.599	0.628
A*C	(4)	0.651	0.162	0.162	0.552	0.702
B*C	4	12.81	3.202	3.204	0.001*	13.82
Error	8	1.604	0.2005	-	-	1.731
Total	26	92.66	-	-	-	100

*Significant at %95 confidence level. Tabulated F-ratio at %95 confidence level:

According to the ANOVA results at a confidence level of 95%, all control factors had a significant effect on The Ra and the most influential parameter was the feed rate (*C*), with a percentage contribution of 87.75%. This was followed by coating material (*A*) and cutting speed (*B*), with percentage contributions of 6.53% and 2.52% respectively. It was observed that the effect of interactions of the factors on the Ra was insignificant. Similarly, according to the ANOVA results conducted for the Re, both coating material (*A*) and feed rate (*C*) had a significant effect on the Re but the cutting speed (*B*) was insignificant. The parameter with the greatest influence on the Re was the feed rate, with a percentage contribution of 73.94%. This was followed by the interaction of cutting speed with feed rate, coating material, and cutting speed, which had percentage contributions of 13.82%, 6.59%, and 2.54% respectively.

4.2. Estimation of Mean and Confidence Interval

In order to obtain estimates of the mean value under the interaction effect, trials which include specific treatment conditions should be averaged [31]. When using the Taguchi optimization technique, it is necessary to perform a confirmation experiment to validate the optimized condition [25]. The estimated mean of the response characteristic (surface roughness) can be calculated as [32]:

$$\overline{\mu}_{Ra} = \overline{A}_2 + \overline{B}_2 + \overline{C}_1 - 2\overline{T}_{Ra} \qquad (1)$$

where, $\overline{\mu}_{Ra}$, the estimated mean of the response characteristic, is the prediction of average surface roughness under optimal conditions. $\overline{A}_2$, $\overline{B}_2$, and $\overline{C}_1$ give the mean of the Ra values for the cutting parameters at the optimal level (Table 7), and $\overline{T}_{Ra}$ represents the mean (2.622 μm) of all Ra values measured (Table 3).

Table 7. Means values for each factor at each level for Ra and Re parameters.

Level	Surface roughness (Ra)			Roundness error (Re)		
	A	B	C	A	B	C
1	2.630	2.750	**2.273**	7.8	7.223	**5.277**
2	**2.507**	**2.542**	2.320	7.35	**6.922**	7.344
3	2.848	2.263	3.393	**6.64**	7.644	9.177

$$\overline{\mu}_{Ra} = \overline{A}_2 + \overline{B}_2 + \overline{C}_1 - 2\overline{T}_{Ra}$$

$$\overline{\mu}_{Ra} = 2.507 + 2.542 + 2.273 - (2 \times 2.662)$$

$$\overline{\mu}_{Ra} = 1.998\ \mu m$$

If the reliability of the condition is assumed to be 95%, then the confidence interval (C.I.) can be calculated using the following equation [28]:

$$CI_{Ra} = \sqrt{F_{\alpha,1,fe} V_{error} \left(\frac{1}{n_{eff}} + \frac{1}{R}\right)} \qquad (2)$$

where $F_{\alpha}(1,f_e)$ is the F ratio required for α, α is risk, f_e is error DOF, V_{error} is error variance, n_{eff} is the effective number of replications, and R is the number of replications of confirmation experiments (3). $F_{0.05;2;26} = 3.49$, and $V_{error} = 0.0138$ (obtained from Table 6). Equation 3 is used to calculate the effective number of replications. N is the total number of experiments (9 × 3 = 27), and T_{dof} is the total DOF associated with the mean optimum (3 × 2 = 6).

$$n_{eff} = \frac{N}{1+[Total\ DOF\ in\ items\ in\ used\ in\ \overline{\mu}\ estimate]} \qquad (3)$$

$$n_{eff} = \frac{27}{1+6} = 3.8571$$

The calculated CI_{Ra} is:

$$CI_{Ra} = \pm 0.168$$

The confidence interval of 95% of the predicted optimal surface roughness is:

$[\overline{\mu}_{Ra} - CI] < \overline{\mu}_{Ra} < [\overline{\mu}_{Ra} + CI]$, that is, $[1.998 - 0.168] < \overline{\mu}_{Ra} < [1.998 + 0.168] = 1.83 < \overline{\mu}_{Ra} < 2.166$

Similarly, the calculation of the confidence interval for Re is:

$\overline{\mu}_{Re} = \overline{A}_3 + \overline{B}_2 + \overline{C}_1 - 2\overline{T}_{Ra}$

$\overline{T}_{Re} = 7.266$ (from Table 2)

$\overline{\mu}_{Re} = \overline{A}_3 + \overline{B}_2 + \overline{C}_1 - 2\overline{T}_{Re}$

$\overline{\mu}_{Re} = 6.644 + 6.922 + 5.277 - (2 \times 7.266)$

$\overline{\mu}_{Re} = 4.311\ \mu m$

When $F_{0.05;2;26} = 3.49$ and $V_{error} = 0.2005$, it can be found from Table 6 that

$CI_{Re} = \pm 0.643$

The confidence interval of 95% of the predicted optimal roundness error is:

$[\overline{\mu}_{Re} - CI] < \overline{\mu}_{Re} < [\overline{\mu}_{Re} + CI]$, that is, $[4.311 - 0.643] < \overline{\mu}_{Re} < [4.311 + 0.643] = 3.668 < \overline{\mu}_{Re} < 4.954$

4.3. Confirmation tests

In this study, optimal results were determined for Ra and Re and the confidence interval was calculated using the Taguchi technique. The confirmation tests showed that the results are very satisfactory. The results of the confirmation tests conducted for surface roughness and roundness error are shown in Table 8.

Table 8. Results of confirmation tests for Ra and Re

	Optimal drilling parameters		
	Experiment	***Prediction***	***Difference***
Level	$A_2B_2C_1$	$A_2B_2C_1$	-
Ra (μm)	2.02	2.0322	0.0092
S/N ratio for Ra (dB)	6.113	6.107	0.006
Level	$A_3B_2C_1$	$A_3B_2C_1$	-
Re (μm)	4.7	4.322	0.378
S/N ratio for Re (dB)	-13.44	-12.794	0.646

When Table 8 is analyzed, it is observed that the predicted value of surface roughness is 2.0322 and the optimal Ra values are in the range of $1.83 < \overline{\mu}_{Ra} < 2.166$ with a confidence interval of 95%. Similarly, it is found that the predicted value of roundness error is 4.322 and optimal Re values are in the confidence interval of $3.668 < \overline{\mu}_{Re} < 4.954$.

4.4. Regression analysis of surface roughness and roundness error

Regression analysis is performed for the modeling and analysis of several variables where there is a relationship between a dependent variable and one or more independent variables [33]. The correlations between the parameters coating materials, cutting speed, and feed rate and the dependent variables surface roughness and surface error were obtained by multiple linear regression. Through the backward elimination process, the final quadratic models of the response equation in terms of actual factors are presented as follows:

$$\mathrm{Ra} = 4.71222 - 0{,}8955\, Cm - 0.8894\, Vc - 1.523\, f + 0.2316\, Cm^2 + 0.18\, Vc^2 + 0.5133\, f^2 \qquad (4)$$

$R^2 = 97.21\%$ $\quad R^2(\mathrm{adj}) = 95.74\%$

$$\mathrm{Re} = 8.766 - 3.727 Vc + 0.9833\, Vc{*}f + 0.5166\, Vc^2 \qquad (5)$$

$R^2 = 95.66\%$ $\quad R^2(\mathrm{adj}) = 93.36\%$

The coefficient of determination (R^2) defines the correlation between experimental and predicted results. The differences between the real responses which were measured after the experiments and the estimated responses that were calculated with the above equations are given in Fig. 3.

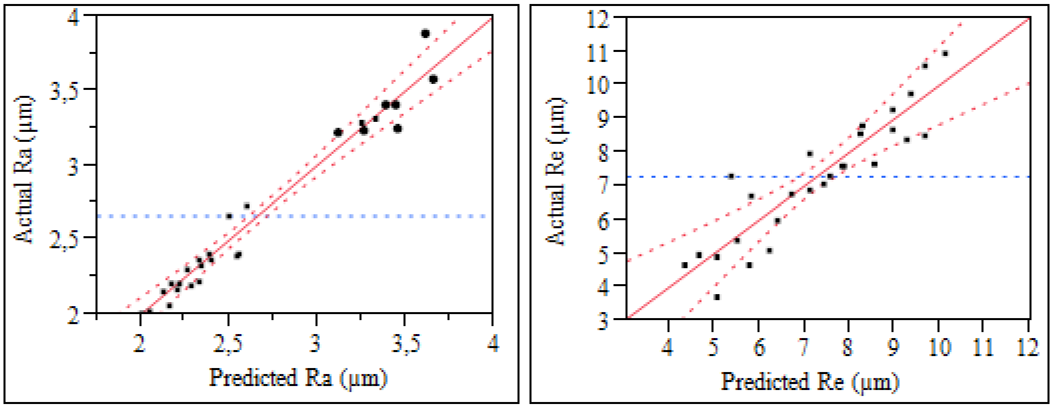

Fig. 3. Relationships between actual and predicted response values

5. Conclusions

This study has discussed an application of the Taguchi method for investigating the effects of cutting parameters on the Ra and Re values in the drilling of AISI 304 austenitic stainless steel. The experimental results were evaluated using ANOVA. According to the results, the following conclusions could be drawn:

- After the experimental trials, the parameter with the greatest influence on both the Ra and Re was feed rate *(C)*, with percentage contributions of 87.75% and 73.94%, respectively, according to ANOVA and F test analyses performed at a confidence level of 95%.
- S/N analysis was used in the determination of the optimal combination of process parameters to obtain a better Ra and Re. From the S/N analysis, the optimal process parameters for the Ra were found to be $A_2B_2C_1$, namely the TiAlN/TiN-multilayer-coated drill (A_2), cutting speed of 12 m/min (B_2), and feed rate of 0.04 m/rev (C_1). Similarly, the optimal process parameters for the Re were $A_3B_2C_1$, namely the TiAlN-monolayer-coated drill (A_2), cutting speed of 12 m/min (B_2), and feed rate of 0.04 m/rev (C_1).

- It was observed that the confirmation test results were within the confidence interval of 95%. Hence, it can be said that the Taguchi technique successfully optimized the process parameters in the drilling of AISI 304 stainless steel blocks with coated drills.

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