The Determination of Empirical Model for Surface Roughness in Turning Process Using Design of Experiment

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Abstract: - The purpose of this research is to determine the empirical model for surface roughness in a turning process. This process is performed in the final assembly department at a manufacturing company which supplies fluid dynamic bearing (FDB) spindle motors for hard disk drives (HDDs). The workpieces used were the sleeves of FDB motors made of ferritic stainless steel, grade AISI 12L14. A 2^k factorial experiment was used to characterize the effects of machining factors, depth of cut, spindle speed and feed rate on the surface roughness of the sleeve. The results show that the surface roughness is minimized when the spindle speed and feed rate are set to the highest levels while the depth of cut is set to the lowest level. Even though the results from this research are process specific, the methodology deployed can be readily applied to different turning processes. As a result, practitioners have guidelines for achieving the highest possible performance potential.

Key-Words: - Fluid dynamic bearing (FDB), Full factorial experiment design, Hard disk drives (HDDs), Spindle motor sleeve, Surface roughness, Turning process

1 Introduction

Hard disk drives (HDDs) are storage devices that store encoded data on rotating platters, which are turned by spindle motors or spindle shafts. Today, most HDDs on the market, especially in desktop computers and servers, use the spindle motor technology known as the ball bearing (BB) design. However, the usage of HDDs is swiftly expanding to consumer electronics products, such as mobile devices, which require higher performance HDDs. For this reason, the old bearing design in HDDs has shifted to a new technology, fluid dynamic bearing (FDB), because HDDs with FDB technology can effectively reduce acoustical noise. Other advantages of FDB include higher capacity, faster spindle speed and improved reliability [3]. One of the key components of the FDB design is the sleeve of the spindle motor, which contains ester oil to lubricate the rotating shaft of motors. The contact stress (source of acoustical noise) between the shaft and sleeve can be significantly reduced if there is a conformance between these two components. The FDB sleeve is manufactured by a turning process, and the surface quality of sleeve is known to depend on the irregularities of materials resulting from machining operations or surface roughness, which is a critical quality characteristic. Therefore, if the relationship between turning process parameters and the surface quality is fully recognized, the surface roughness can be effectively minimized.

2 Literature Review

Among the most basic operations performed by machine tools are drilling, milling, grinding and turning or lathing. The turning process is a machining method that removes material from the surface using a rotating cutting tool that moves to a workpiece. The surface quality, which is measured in terms of surface roughness, is utilized to evaluate the performance of the turning operation. The surface roughness is known to be significantly affected by different cutting parameters, i.e., the depth of cut, spindle speed and feed rate [10].

Therefore, the surface roughness will be minimized if the appropriate cutting conditions are selected. Experimental design methods, such as the two-levels (2^k) factorial design, are frequently utilized to model the surface roughness, so the desired levels of machining parameters are achieved. There are numerous works reporting the success of implementing factorial design to study the relationship between machining factors and surface roughness. Among these works, Choudhury and El-Baradie [4] utilized a factorial design technique to study the effect of cutting speed, feed rate and depth of cut on surface roughness. The experimental study was conducted on a turning machine equipped with uncoated carbide inserts. The workpiece material used was EN24T steel. Wang and Feng [12] utilized a factorial design to develop an empirical model for suface quality in turning processes. The predicting model are based on workpiece hardness; feed rate; cutting tool point angle; depth of cut; spindle speed and cutting time. Arbizu and Luis Perez [1] deployed a 2^3 factorial design to construct a first order model to predict the surface roughness in a turning process of testpieces which followed ISO 4287 norm. Benga and Abrao [2] investigated the machining properties of hardened 100Cr6 bearing steel under continuous dry turning using mixed alumina, whisker reinforced alumina and polycrystalline cubic boron nitride (PCBN) inserts. A full factorial experimental design was used to determine the effects of feed rate and cutting speed on surface finish. Ozel, Hsu and Zeren [8] studied the effects of workpiece hardness, feed rate, cutting speed and cutting edge geometry on multi-responses, surface roughness and resultant forces, in the finish hard turning of AISI H13 steel. The experiments were conducted using two-level fractional factorial experiments while the statistical analysis was concluded in the form of analysis of variance (ANOVA).

Other experimental design approaches commonly utilized for modeling responses are the Taguchi technique and response surface methodology (RSM). Davim [5] studied the influence of velocity, feed rate and depth of cut on the surface roughness using Taguchi design. The material used in this turning process was free machining steel, 9SMnPb28k (DIN). The model for predicting the surface roughness was developed in order to optimize the cutting conditions. Sahin and Motorcu [9] utilized RSM to construct a surface roughness model for the turning process of AISI 1040 mild steel coated with TiN. Three machining parameters, depth of cut, cutting speed and feed rate, were included in the predicted model. For related publications, see Mihaiela and Costoiu [6], Kung, Hsu, Chen and Lin [7], Sun, Liang and Du [11].

According to the literature, the factorial design has proven to be practical and effective for use, so it was utilized in this study to quantify the effect of the machining factors on the surface roughness of the FDB sleeve. The next section provides detailed information regarding the methodology used and the background of turning process.

3 Methodology

Factorial designs are the experiment in which all possible combinations of the levels of the factors are investigated. This design is one of the mostly used types of experiment involving the study of the effects of two or more factors. As experimental results, the effect of primary factor or main effect is defined to be the change in response caused by a change in the level of the factor. In some experiments, when the difference in response between the levels of one factor is not the same at all levels of the other factor, there is an interaction between the factors. The most important case of factorial design is the design for k factors, when the experiment is conducted at two levels for each factor, the high and low levels of a factor. In this case, a complete replicate of such a design requires 2^k observations or 2^k factorial design. As shown in Fig.1, all treatment combinations can display geometrically as a cube.

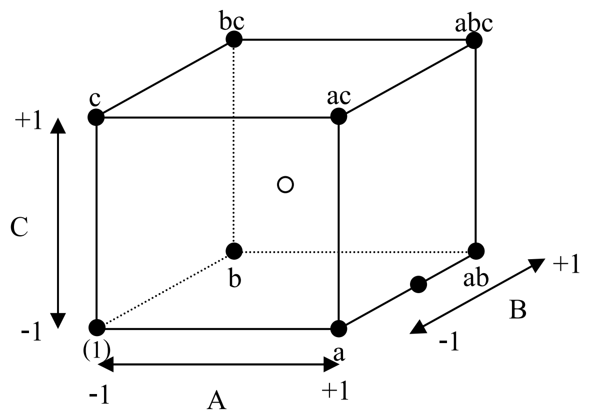

Fig.1 Geometric view of 2^3 factorial design.

For k = 3, the average main effects and interaction effects are

$$A = \frac{1}{4n}[a - (1) + ab - b + ac - c + abc - bc]$$

$$B = \frac{1}{4n}[b + ab + bc + abc - (1) - a - c - ac]$$

$$C = \frac{1}{4n}[c + ac + bc + abc - (1) - a - b - ab]$$

$$AB = \frac{1}{4n}[abc - bc + ab - b - ac + c - a + (1)]$$

$$AC = \frac{1}{4n}[(1) - a + b - ab - c + ac - bc + abc]$$

$$BC = \frac{1}{4n}[(1) + a - b - ab - c + ac - bc + abc]$$

$$ABC = \frac{1}{4n}[abc - bc - ac + c - ab + b + a - (1)]$$

4 Process Description

The sleeves of fluid dynamic bearing (FDB) spindle motors which have a dimension of 65 mm in diameter and 58 mm in length are the specimens in this experiment. The workpieces material used were free cutting stainless steel, grade AISI 12L14, and their chemical composition is 20% Cr and 2% Mo.

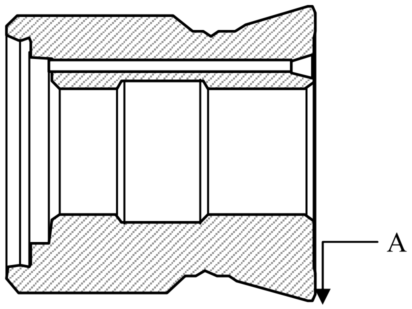

Fig.2 FDB sleeve and the focused toolpath.

Turning processes were carried out on a two axis CNC lathe with a maximum spindle speed of 15000 rpm. This machine was equipped with five inserts and operated under wet cutting conditions. The focused cutting area was the top cut operation of the FDB sleeves performed by insert A (Fig.2) due to the cost concern of manufacturer. The tool material for the inserts was uncoated carbide, KYOCERA PW30, and the surface texture measuring instrument used was ACCRETECH-TOKYO SEIMITSU model SURFCOM 1400D.

5 Design of Experiment

The experiment was conducted to analyze the effect of depth of cut, spindle speed and feed rate on the surface roughness (R_a). As a result (Table 1), each factor was set to the low (-1) and high (+1) levels.

Table 1 Factor levels.

Factor	Low	High
Coded levels	-1	+1
Depth of cut (mm)	0.01	0.02
Spindle speed (rpm)	5000	8000
Feed rate (mm/rev)	0.002	0.008

The selected experimental design is 2^3 full factorial design with five replicates and the design matrix is shown in Table 2.

According to the half-normal plot in Fig.3, feed rate (C) contribute the highest effect on the surface roughness, followed by spindle speed (B), depth of cut (A) in that order. This result is confirmed by the basis of the analysis of variance (ANOVA) in Table 3 which points out that all three main effects (A, B, C) are highly significant, since their p-values are much smaller than 0.05.

Table 2 Design matrix.

Standard order	Depth of cut	Spindle speed	Feed rate	R_a (μm)
1	0.01	5000	0.002	0.07699
2	0.01	5000	0.002	0.07592
3	0.01	5000	0.002	0.07682
4	0.01	5000	0.002	0.07535
5	0.01	5000	0.002	0.07504
6	0.02	5000	0.002	0.08521
7	0.02	5000	0.002	0.08405
8	0.02	5000	0.002	0.08596
9	0.02	5000	0.002	0.08488
10	0.02	5000	0.002	0.08424
11	0.01	8000	0.002	0.07431
12	0.01	8000	0.002	0.07584
13	0.01	8000	0.002	0.07674
14	0.01	8000	0.002	0.07661
15	0.01	8000	0.002	0.07407
16	0.02	8000	0.002	0.07792
17	0.02	8000	0.002	0.07843
18	0.02	8000	0.002	0.07893
19	0.02	8000	0.002	0.07724
20	0.02	8000	0.002	0.07824
21	0.01	5000	0.008	0.0728
22	0.01	5000	0.008	0.07323
23	0.01	5000	0.008	0.07328
24	0.01	5000	0.008	0.07463
25	0.01	5000	0.008	0.07561
26	0.02	5000	0.008	0.07424
27	0.02	5000	0.008	0.07376
28	0.02	5000	0.008	0.07377
29	0.02	5000	0.008	0.07413
30	0.02	5000	0.008	0.07333
31	0.01	8000	0.008	0.06444
32	0.01	8000	0.008	0.06525
33	0.01	8000	0.008	0.06502
34	0.01	8000	0.008	0.06695
35	0.01	8000	0.008	0.06595
36	0.02	8000	0.008	0.07095
37	0.02	8000	0.008	0.07092
38	0.02	8000	0.008	0.06902
39	0.02	8000	0.008	0.06931
40	0.02	8000	0.008	0.06952

Table 3 Analysis of variance (ANOVA) for surface roughness.

Source	Sum of squares	Df	Mean square	F value	Prob > F
Model	0.00113	7	0.000161	195.3932	< 0.0001
A-Depth	0.000157	1	0.000157	189.8734	< 0.0001
B-Speed	0.000238	1	0.000238	288.2275	< 0.0001
C-Feed	0.000614	1	0.000614	743.0893	< 0.0001
AB	1.85E-06	1	1.85E-06	2.238777	0.1444
AC	3.17E-05	1	3.17E-05	38.40623	< 0.0001
BC	1.6E-05	1	1.6E-05	19.40623	0.0001
ABC	7.14E-05	1	7.14E-05	86.51109	< 0.0001
Pure Error	2.64E-05	32	8.26E-07		
Total	0.001156	39			

Moreover, the interaction effects (AB, BC, AC) exist and are based mostly on the above factors, with the highest term, ABC. It is interesting to note that the interaction AB is still included in the model even its p-value is as high as 0.1444 (>0.05). This scenario can be explained by the hierarchical principle which indicates that if there is a high-order term in the model, it will contain all the lower-order terms composing it. The regression model for surface roughness is shown as follows:

Surface Roughness = 0.045105+2.80967*Depth + 3.96200E-006*Speed + 6.29067*Feed – 3.25667 E-004*Depth*Speed - 445.46667*Depth*Feed - 1.03167E-003*Speed*Feed + 0.059400*Depth* Speed*Feed.

According to Table 4, the R^2 statistic, which is the measure of the proportion of total variability explained by the model, is equal to 0.9771 or close to 1, which is desirable. The adjusted R^2 is also utilized to consider the model significance since it is useful when comparing model with different number of terms. The results show that the adjust R^2 (0.9721) is not significantly different from the ordinary R^2 (0.9771). Another statistic, the prediction error sum of squared (PRESS), is used as a measure of how accurate the model will predict new data.

Table 4 Statistics regarding the developed model.

Statistics	Value
R-Squared	0.9771
Adj R-Squared	0.9721
Prediction Error Sum of Squared (PRESS)	4.129E-005

Since the empirical model has a small value of PRESS (only 4.129E-005), the model is likely to be a good predictor.

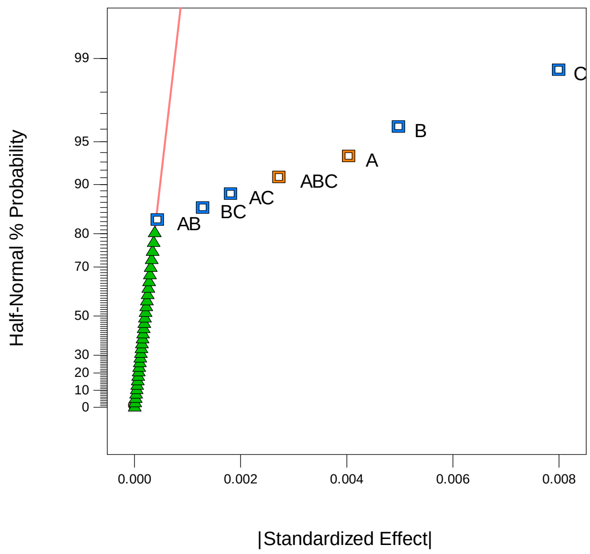

Fig.3 Half-normal plot of effects.

After the regression model of surface roughness was developed, the model adequacy checking was performed in order to verify that the underlying assumption of regression analysis is not violated. Fig.4 illustrates the normal probability plot of the residual which shows no sign of the violation since each point in the plot follows a straight line pattern.

Moreover, the residual versus predicted values in Fig.5 shows that each point scatters randomly and there is no unusual pattern and outlier detected in the plot. The residual plot of each factor (depth of cut, spindle speed and feed rate) in Fig.6, 7 and 8 indicate that the variance of residual is constant.

As a result, the normality, independence and constant variance assumptions still hold in this case.

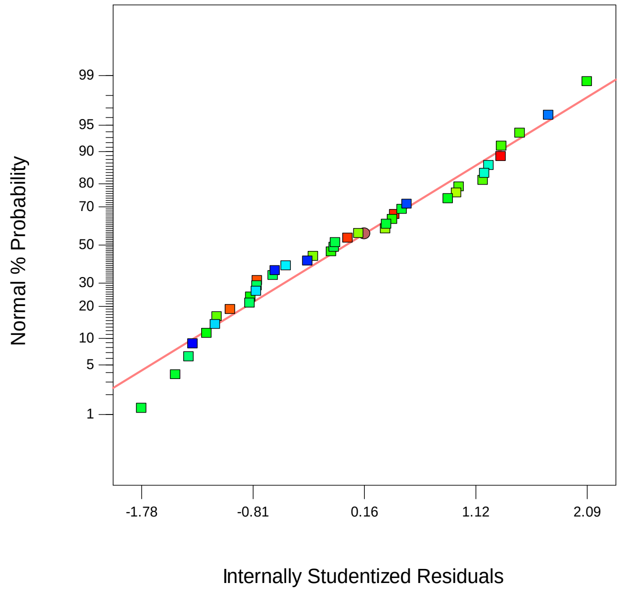

Fig.4 Normal probability plot of residuals.

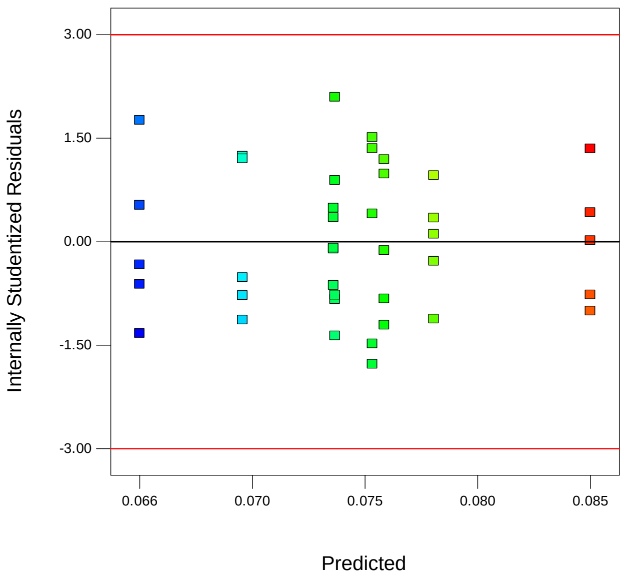

Fig.5 Residual VS predicted.

Fig 9, 10 and 11 show the interaction plots: depth of cut*spindle speed, depth of cut*feed rate and spindle speed*feed rate and their response surface (surface roughness: R_a). Fig.12, 13 and 14 illustrate the contour plots of the interaction AB, AC and BC. These plots indicate that the surface roughness will be minimized if depth of cut is set to the low level while the spindle speed and feed rate are high. Moreover, these results agree with the conclusions from the response plots in Fig.15, 16 and 17

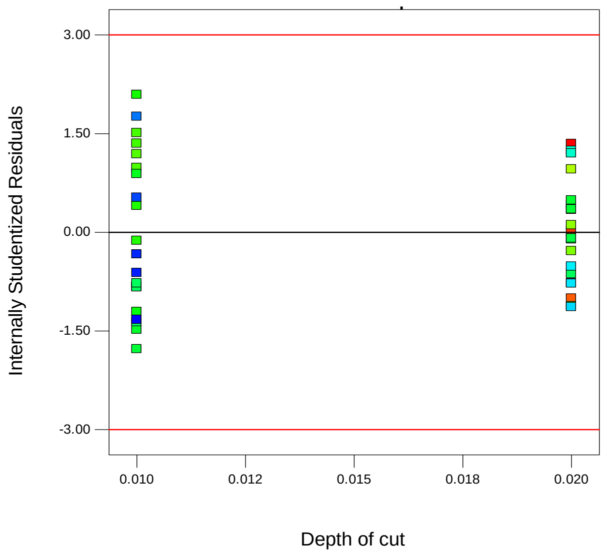

Fig.6 Residual VS predicted (Depth of cut).

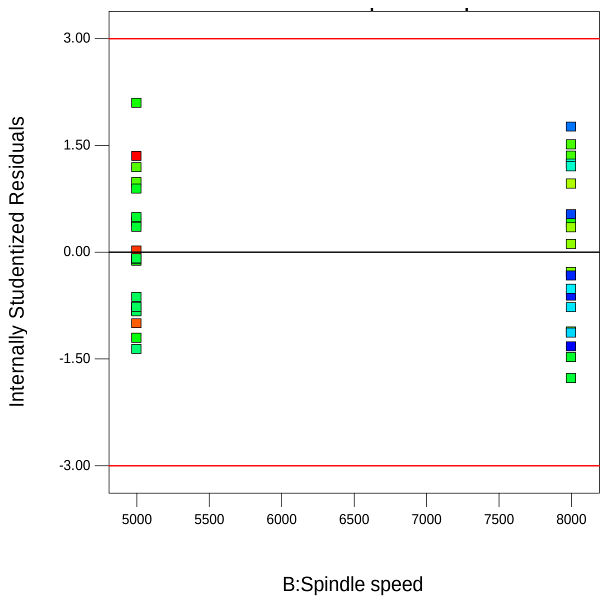

Fig.7 Residual VS predicted (Spindle speed).

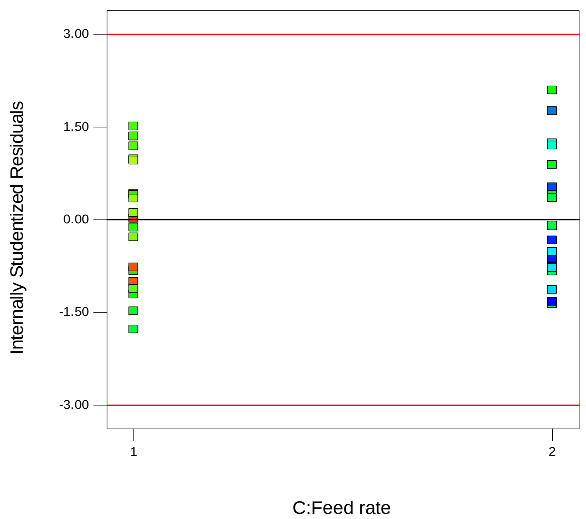

Fig.8 Residual VS predicted (Feed rate).

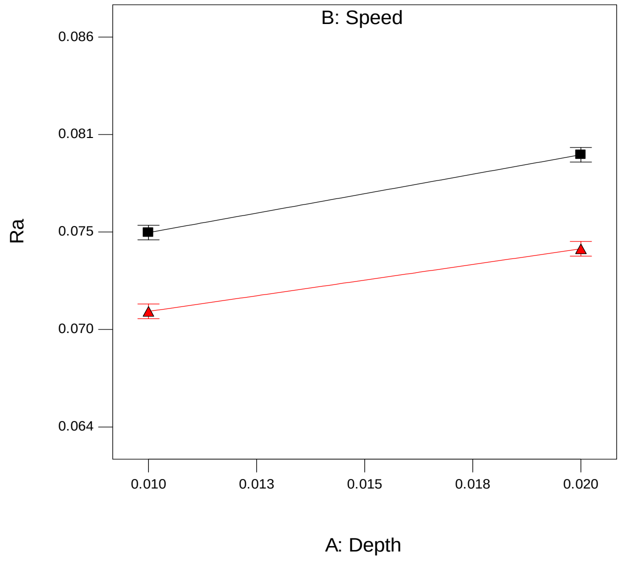

Fig.9 Interaction plot AB

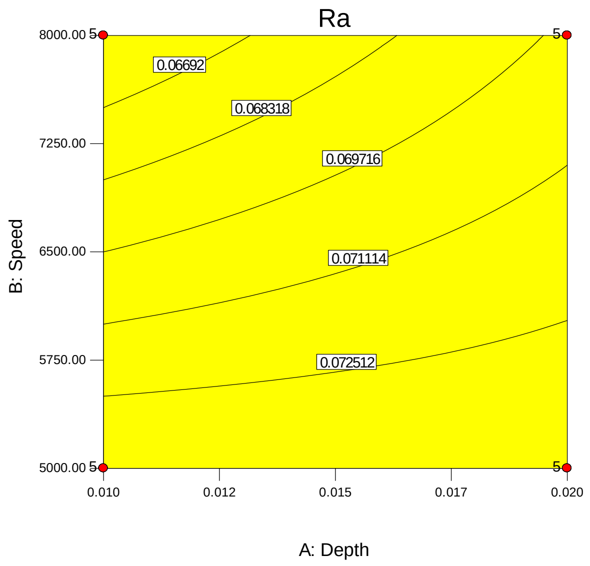

Fig.12 Contour plot of the interaction AB.

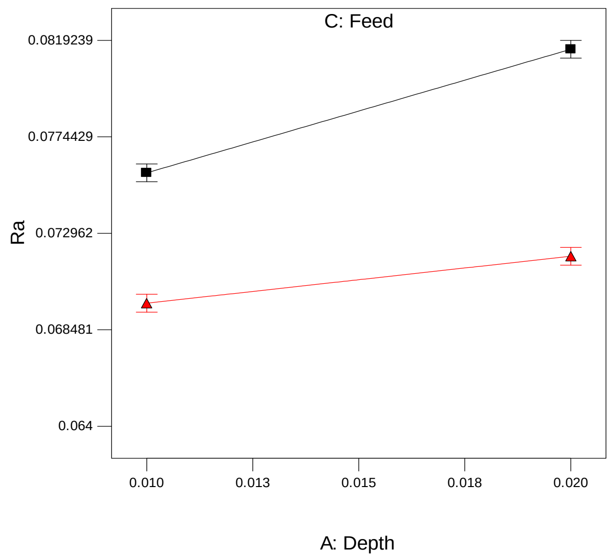

Fig.10 Interaction plot AC

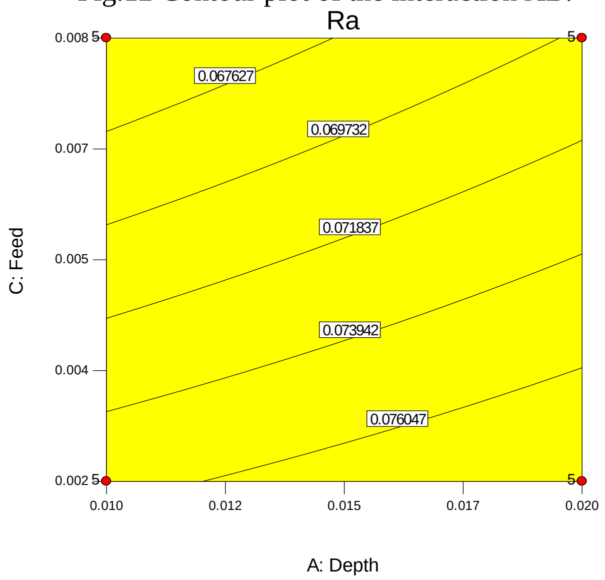

Fig.13 Contour plot of the interaction AC.

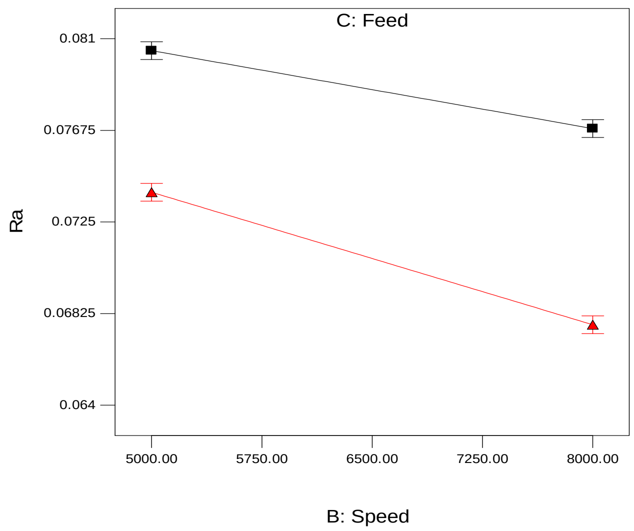

Fig.11 Interaction plot BC

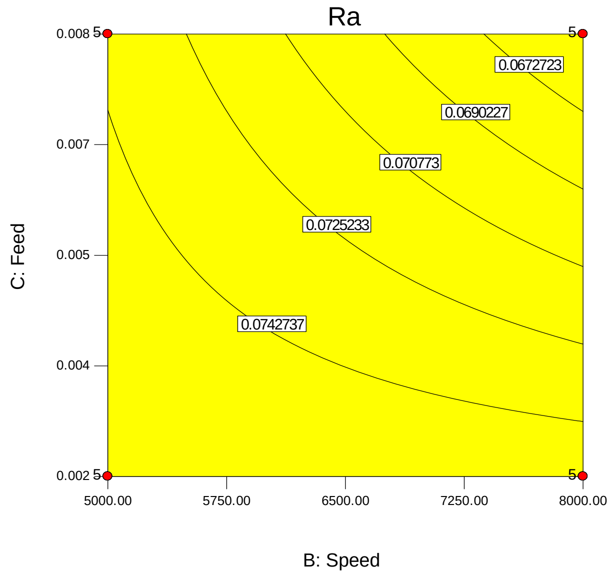

Fig.14 Contour plot of the interaction BC.

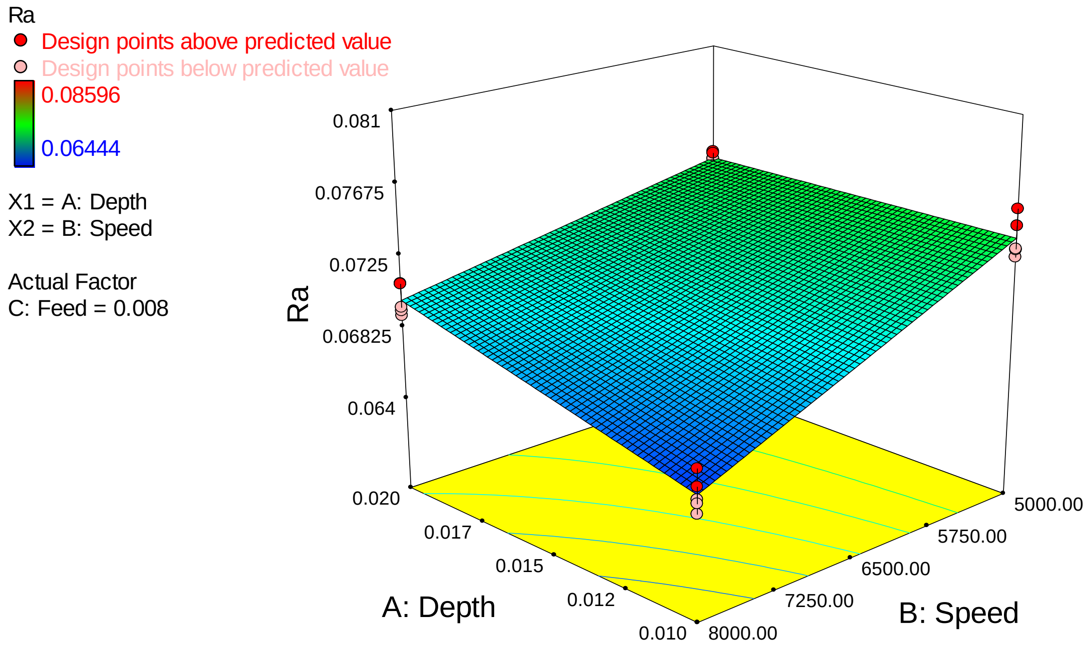

Fig.15 Response plot of the interaction AB

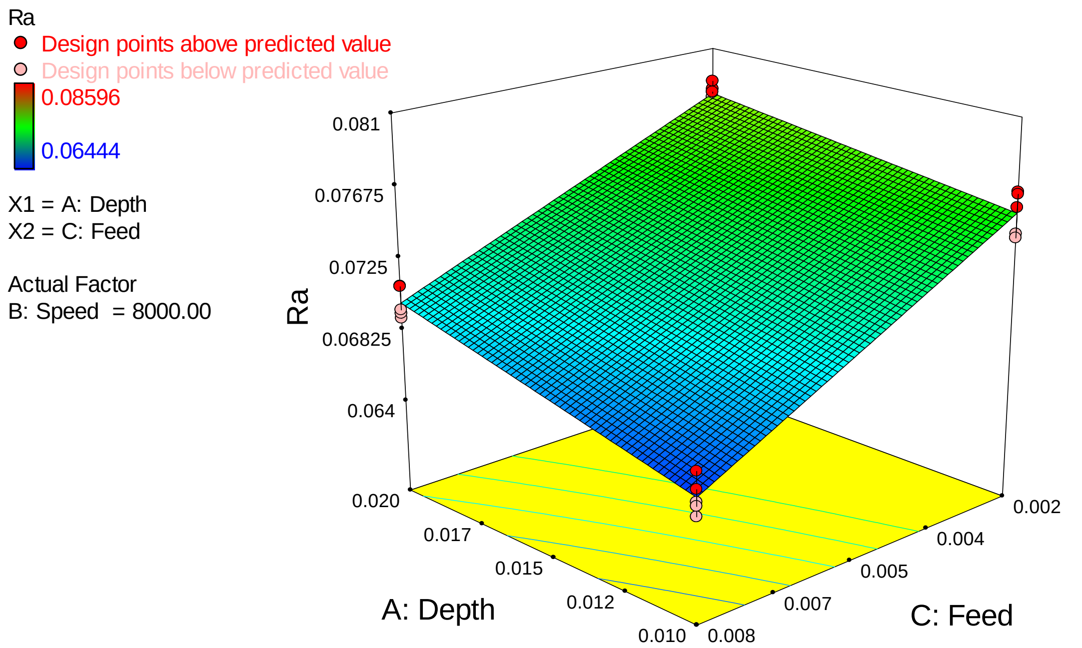

Fig.16 Response plot of the interaction AC

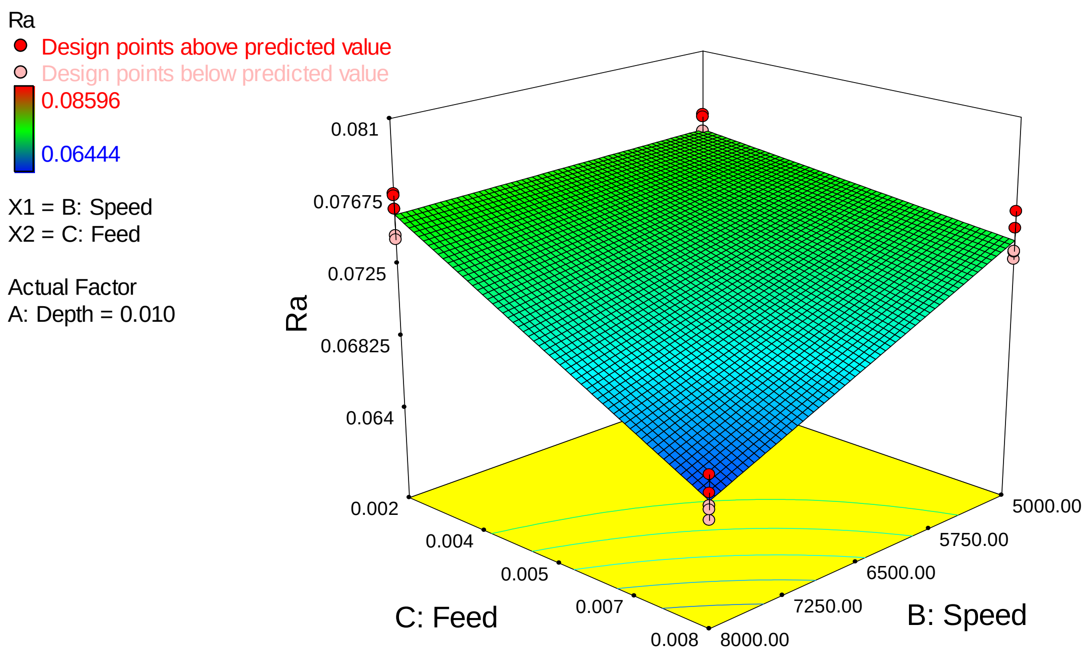

Fig.17 Response plot of the interaction BC

Fig.18 represents the cube plot which depicts the three-factor interaction among depth of cut (A), spindle speed (B) and feed rate (C). According to the plot, the surface roughness is significantly minimized (R_a = 0.065522 μm) when the depth of cut is set to the low level (0.01 mm) feed rate and spindle speed are high (0.008 mm/rev and 8000 rpm respectively).

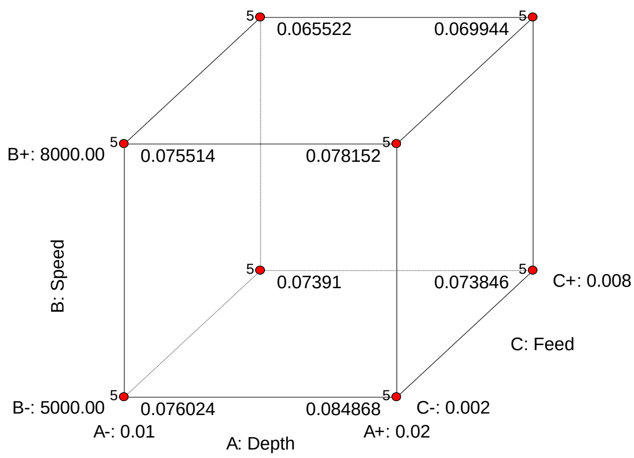

Fig.18 Cube plot of the interaction ABC.

6 Confirmation Experiment

After the regression model and the optimal levels of each machining factor were achieved, the confirmation test was performed in order to validate the minimum surface roughness obtained from the optimization process. For this reason, forty FDB motor sleeves were sampled and tested by following the optimal conditions: depth of cut = 0.01 mm, feed rate = 0.008 mm/rev and spindle speed = 8000 rpm. According to the experiment, since the 95% confidence interval of the predicted surface roughness (0.0641μm, 0.0655μm) includes the observed average (R_a = 0.06444 μm), there is no significant difference between these two values (Table 5).

Table 5 Results of the confirmation experiment

Response	Predicted average	C.I. of predicted Average		Observed average
		95% low	**95% high**	
R_a	0.06552	0.0641	0.0655	0.06444

7 Insights for Practitioners

The most crucial contribution of this research is the achievement of the best cutting condition which can significantly minimize the surface roughness of the FDB sleeve. Before the implementation, the cutting condition was set by the manufacturer as follows:

Table 6. Results of the implementation

Factors	Before optimization	After optimization
Depth of cut	0.015 mm	0.01 mm
Spindle speed	8000 rpm	8000 rpm
Feed rate	0.005 mm/rev	0.008 mm/rev
R_a	0.07416 μm	0.06444 μm

However, after the response surface method was implemented, the optimal cutting condition was utilized and the average surface roughness was minimized from 0.07416 μm to 0.06444 μm or about 8% compared to the initial cutting condition.

8 Conclusions

The purpose of this research is to quantify the effect of depth of cut, spindle speed and feed rate on surface roughness of the FDB sleeve in HDD. The factorial design was utilized to obtain the best cutting condition which leads to the minimization of the surface roughness. The half normal plot and ANOVA indicate that the feed rate (C) is the most significant factor followed by spindle speed (B) and feed rate (A). Moreover, it is interesting to note that there are interactions among these three factors with the highest order term, ABC. Regarding the model validation, the regression model developed proves to be accuracy and has the capability to predict the value of response within the limits of factors investigated. After the optimal cutting condition is implemented, the surface roughness is significantly reduced about 8 percent.

9 Discussions

The research methodology can be extended to the application of the response surface methodology (RSM) in order to optimize the response. The RSM is a compilation of statistical and mathematical techniques to analyze, model and optimize processes. The purpose of this method is to establish the unknown relationship between the independent variables (input factors) and the process responses. Surface experiments are performed to fit either a first order model (linear function) or a second order model to the observations.

Another powerful method is the Taguchi design. The Taguchi method utilized the statistical design of experiment in the form of orthogonal array to determine the optimal settings of the process and achieve the operation on-target. The mean response for each run in the orthogonal array is analyzed and the signal-to-noise ratio (SNR) is deployed to analyze the variation. The three categories of them (nominal the best, larger the better, smaller the better) are adopted to obtain the optimal performance.

In addition to the factorial design experiment, the RSM and Taguchi design are proved to be potential methodologies to develop an empirical model and optimize the surface roughness of the metal workpieces.

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