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Predictive modeling of surface roughness in high speed machining of AISI 4340 steel using yttria stabilized zirconia toughened alumina turning insert

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ABSTRACT

An attempt has been made to investigate the surface finish of AISI 4340 steel for high speed machining using indigenously prepared yttria stabilized zirconia toughened alumina (ZTA) cutting inserts. These inserts are prepared through wet chemical co-precipitation route followed by powder metallurgy process. Response surface methodology (RSM) has been used to study the effect of different machining parameters i.e. cutting speed, feed rate and depth of cut on surface roughness of the job. The machining experiments are performed based on standard RSM design called central composite design (CCD). The mathematical model of surface roughness has been developed using second order regression analysis. The adequacy of the developed models and influence of each operating factors have been carried out based on analysis of variance (ANOVA) techniques. It can be concluded from the present study that for high speed machining this tool gives good surface finish. Key parameters and their interactive effect on each response have also been presented in graphical contours which may help for choosing the operating parameter preciously. Optimization of cutting parameters has also been carried out and 92.3% desirability level has been achieved using this optimal condition.

1. Introduction

Quality is one of the significant factors in today's manufacturing industry. It is the only component which can influence customer to a level of satisfaction. In industrial sector starting from a small company to a big aerospace sector, surface quality is detected by surface roughness of the product [1]. Measuring and characterizing the surface finish are two of the indicators of machining performance [2]. In general selected cutting operation has very less capability for getting good surface finish and in day to day the newer materials are coming rapidly into the manufacturing industry, so it is very difficult for an operator to select optimum cutting parameters to achieve best surface finish. In machining application, for any non conventional tool–work combination, it is necessary to know surface quality and dimensional precession in advance. For the same reason, development of a theoretical model is required to predict surface roughness as a function of operating conditions. The response surface methodology (RSM) is practical, economical and relatively easy to use. Thangavel and Selladurai [3] developed a mathematical model to study the effect of cutting parameters on the surface roughness using the response surface methodology (RSM). After the regression analysis and the variance analysis, it was found that the model was adequate and all the main cutting parameters had a significant impact on the surface roughness. The same methodology was used not only to develop the surface roughness model in dry turning of high-strength steel [4] but also turning of bearing steel with mixed ceramic inserts [5]. Davim [6] and Davim et al. [7] investigated the cutting parameters effect on the surface finish in steel turning using the design of the experiment and the artificial neural network. In the first paper, Taguchi method was used to model the surface finish with respect to cutting velocity, feed rate and depth of cut. And in the later paper, they tried to model the surface roughness using back propagation artificial neural network algorithm. Cakir et al. [8] investigated how the cutting parameters influence the surface roughness at the time of machining cold-work tool steel AISI P20 using coated inserts. A mathematical model has been developed and adequacy of the model has also been checked. Mittal and Mehta [9] proved that the surface finish was strongly influenced by the type of metal, speed, feed rate and tool nose radius. The surface finish model had been developed for aluminum alloy 390, ductile cast iron, medium carbon leaded steel, medium carbon alloy steel 4130 and inconel 718 for a wide range of machining conditions. The predictive modeling of surface roughness and tool wear in hard turning had been developed using regression and neural network [10,11]. In these studies, the effects of cutting edge geometry, work piece hardness, feed rate and cutting speed on surface roughness and tool wear had been investigated using CBN inserts. The same methodology was used to develop a mathematical model for

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surface roughness prediction of machined GFRP work piece. In this work analysis of variance (ANOVA) was used to check the validity of the model [12]. Study for the development of a surface roughness model was pursued by Sahin and Motorcu [13,14] by turning mild steel with coated carbide tool and hardened steel with CBN tool. Response surface methodology coupled with design of experiment was used to assess the contribution of machining parameters on roughness of the job. Mathematical equations were developed from which it can be concluded that feed rate is the most important factor for surface roughness of the work piece. The same methodology was also used by Noordin et al. [15] for modeling the cutting force and surface roughness when turning AISI 1045 steel with coated carbide tool. In this work, contribution of feed rate parameter was found to be maximum for force as well as for roughness modeling. An attempt was made to analyze the effects of depth of cut and machining time on machinability aspects such as machining force, power, specific cutting force, surface roughness and tool wear during turning of high chromium AISI D2 cold work tool steel using conventional and wiper ceramic inserts [16,17]. Rapid development in ceramics introduced ceramic composite for many engineering applications. Zirconia toughened alumina (ZTA) is a new addition in this category of ceramics which possesses good mechanical strength as well as toughness. ZTA is now extensively used for machining steel and cast iron at high speed. Three types of alumina based ceramic tool (zirconia toughened, titanium carbide reinforced and silicon carbide whisker reinforced) were used [18] for evaluating the cutting performance at the time of machining high tensile steel. The machinability of these tools has been characterized by cutting force produced, roughness of the job and wear rate of the tool. Senthil Kumar et al. developed a new alumina ceramic cutting tool by adding ceria to the aluminum matrix. The performance of this insert was compared with pure alumina and commercial ZTA insert [19]. In another work, the machinability of hardened steel was evaluated by measuring the performance of these tools in terms of cutting force produced, surface roughness of the work piece and wear rate of those cutting inserts [20]. In that work different wear mechanisms like adhesive, abrasive, diffusion were also validated at different operating conditions. In another work, Yttria stabilized zirconia toughened alumina inserts were prepared and the flank wear modeling of developed ZTA inserts was carried out using RSM [21] and Taguchi Method [22] when machining AISI 4340 steel. The purpose of this research work was to generate roughness data after turning AISI 4340 steel using a transformed toughening ZTA cutting insert developed by powder metallurgy routes. Surface roughness model has been developed in terms of cutting speed, feed rate and depth of cut using multi-regression RSM technique and factorial design of experiments. The aforesaid model was then used to generate contours of roughness for different cutting conditions with the same work tool combination. Analysis of variance (ANOVA) was used to assess the contribution of every machining parameter on the roughness of the job.

2. Experimental details

2.1. Synthesis of Y-ZTA powder

Yttria stabilized zirconia toughened alumina ceramic powder was synthesized by wet chemical synthesis route. The requisite amount of ingredients of 10–12 vol.% yttria stabilized zirconia (2 mol% Y_2O_3) in α-alumina matrix was prepared by wet mixing of aqueous solution of $Al(NO_3)_3.6H_2O$ (Loba Chemie, India), $ZrO(NO_3)_2.5H_2O$ (>BDH, India) and $Y(NO_3)_3.5H_2O$ (Aldrich, USA) followed by precipitation at pH ~ 9. The hydrated gelatinous precipitate was washed thoroughly with hot water for removal of nitrate ions. The nitrate free dried mass of gelatinous precipitate was calcined at the temperature range of 700–900 °C for 1–2 h. The calcined powders were wet-ball milled in organic media for 40–48 h using high purity (99.5%) alumina balls in 500 ml jar contained in planetary mill (Fritsch, Germany). The powder was characterized through particle size analyzer and FESEM studies (Fig. 1).

2.2. Preparation of cutting inserts

The requisite amount of dried milled powders for the preparation of tool inserts was uniaxially compacted at a pressure of 2.5 $t\,cm^{-2}$ into square shaped (16 mm × 16 mm × 6 mm) pellets in a die. The compacts were sintered at 1550–1650 °C for 1–3 h in an air atmosphere. The sintered specimen was cut to size by a diamond wheel in tailor made designed Jig-Fixture and polished slowly. The final shape and size of the specimen were almost identical to the international standard SNUN 120408 (ISO). Finally, the inserts were lapped/polished with fine diamond paste (0.5–1.0 μm) in a polishing machine. A flat land of angle 20° and width 0.2 mm was provided on each cutting edge to impart edge strength. After bevelling, the sharp edges were further rounded off, although slowly, as uniformly as possible by light honing. The final shape of the ZTA insert is depicted in Fig. 2 and the mechanical property of the same is presented in Table 1. AISI 4340 Steel was used in this experiment and the detail specifications are portrayed in Table 2.

2.3. Experimental conditions

The turning experiments were conducted in a lathe machine (HMT Ltd, India) powered by an 11 kW motor and speed range is 47–1600 RPM. The initial diameter of the bar was 140 mm and the length was 450 mm. The tool holder used was CSBNR2525N43 (NTK) and the tool angles were −6°, −6°, 6°, 6°, 15°, 15° and 0.8.

2.4. Measurement of surface roughness

The surface roughness of the AISI 4340 steel was measured after machining the job for 10 min (each run) by the help of a stylus instrument. The equipment used for measuring the surface roughness was a portable surface roughness tester SURTRONIC 25. The direction of the roughness measurement was perpendicular to the cutting velocity vector. A total of five measurements of surface roughness were taken at random on each machined surface and the average value was used in the analysis.

3. Statistical modeling

3.1. Response surface methodology

Response surface methodology or RSM comprises mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response. For applying RSM, selection of parameters, their range and proper experimental design is required. In our study, cutting speed, feed rate and depth of cut has been chosen as process parameters. The surface roughness of the job has been chosen as response factor. Central composite design (CCD) has been used as an experimental plan with all combinations of the factors at two levels, the star points are at the face of the cube portion on the design which corresponds to an α-value of 1 and this is commonly referred to as a face centered CCD and the centre points, as implied by the name, are points with all levels set to coded level 0—the midpoint of each factor range and this is repeated twice. The response variable investigated is the roughness of the job. The performance tests involved 16 trials. The experimental plan and result of the trials is reported in Table 3.

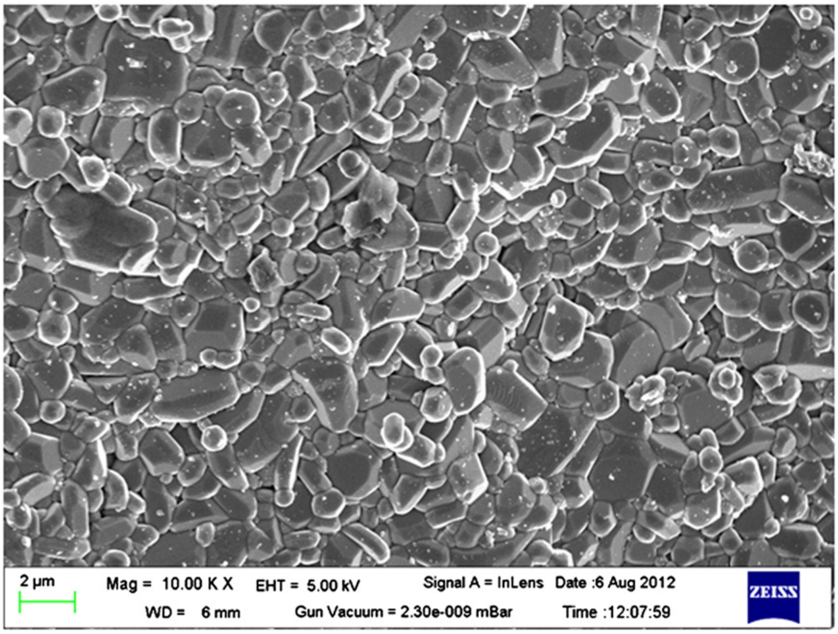

Fig. 1. FESEM photo of the Y-ZTA insert.

The response function representing the performance can be expressed as

$$Y = f(V, F, T) \tag{1}$$

where, $Y =$ response values.

The second order regression equation used to represent the response surface for m factors is given by

$$Y = A_0 + \sum_{i=1}^{m} A_i X_i + \sum_{i,j=1}^{m} A_{ij} X_i X_j + \sum_{i=1}^{m} A_{ii} X_i^2 \tag{2}$$

where, A_0 is the free term of the equation, the coefficients A_1, A_2............... A_m are linear terms; A_{11}, A_{22} .... A_{mm} are quadratic terms; and A_{12}, A_{13}............$A_{m-1,\ m}$ are the interaction terms.

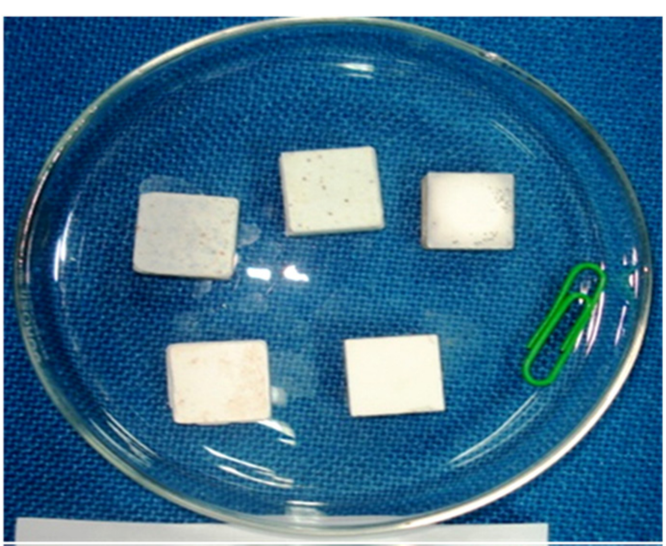

Fig. 2. Y-ZTA inserts.

For three factors, the selected polynomial could be expressed as

$$Y = A_0 + A_1 V + A_2 F + A_3 T + A_{12} VF + A_{13} VT + A_{23} FT + A_{11} V^2 + A_{22} F^2 + A_{33} T^2. \tag{3}$$

The values of the coefficients of the polynomial of Eq. (3) were calculated by the multiple regression method. The Design Expert software (Version 8.0.1) was used to calculate the coefficient values.

3.2. Modeling of surface roughness

After calculating the coefficient values in Eq. (3), the mathematical model for surface roughness has been determined as

$$\text{Surface Roughness} = +3.97 - 0.43 * A + 0.009000 * B + 0.46 * C - 0.023 * A * B + 0.012 * A * C - 0.0025 * B * C - 0.55 * A^2 - 0.082 * B^2 - 0.15 * C^2. \tag{4}$$

Significance test for the model as well as each term and Lack of fit estimation were carried out using the analysis of variance (ANOVA) method. From this method, the backward elimination procedure was applied for removing insignificant model terms. The resulting ANOVA of surface roughness for reduced quadratic model is shown in Table 4. The Model F-value of 40.16 implies that it is significant. There is only a 0.01% chance that a “Model F-Value” comes large

Table 1
Details of composition and properties of the cutting tool material.

Details of inserts	Units	Zirconia toughened alumina (ZTA)
Composition	wt. (%)	86 wt.% α-Al_2O_3 + 14 wt.% Y-PSZ
Theoretical density	(%)	98.4
Hardness	HV	1544
Fracture toughness	MPa $m^{1/2}$	4.5
Compressive strength	MPa	4950
Thermal conductivity	W/m K	16.5
Type & size		SNUN 120408
Geometry		−6°, −6°, 6°, 6°, 15°, 75°, 0.8 mm, Edge bevel width, 0.2 mm, 20°

Table 2
Alloying composition (wt.%) of workpiece material (AISI 4340 steel).

C	Mn	P	S	Si	Ni	Cr	Mo
0.45	0.70	0.04	0.03	0.25	1.65	0.85	0.25

because of noise factor. From this table, it can be concluded that the main effect of Cutting Speed (A), Depth of Cut (C) & Cutting Speed $(A)^2$ is the noteworthy model term. The R^2 value is high close to 1, which is desirable. The "Pred. R-Squared" of 0.83 is in reasonable agreement with the "Adj R-Squared" of 0.89. The adjusted R^2 value is particularly useful when comparing models with different number of terms. "Adequate Precision" which measures the signal to noise ratio should be greater than 4 and in this study, this same ratio is 18.65 which indicates that this model can be used to navigate the design space.

The following equations are the final empirical models in terms of coded factors for:

$$\text{Surface Roughness}, R_a = 3.89 - 0.43 * A + 0.46 * C - 0.66 * A^2. \tag{5}$$

While, the following equations are the final empirical model in terms of actual factor for:

$$\text{Surface Roughness}, R_a = 1.18900 + 0.015798 * \text{Cutting Speed} + 0.92200 * \text{Depth of Cut} - 0.0000337075\ \text{Cutting Speed}^2. \tag{6}$$

3.3. Confirmation run

In order to verify the adequacy of the developed model, five confirmation run experiments were performed as depicted in Table 5. The test conditions for the first three confirmation run experiments were selected from the previously run experiments and the next three runs were performed outside the range of operating condition previously used in the experiments. Using Design Expert software, the result was predicted within the 95% confidence level. The predicted value of surface roughness was calculated from Eq. (6). The percentage error was also calculated and the range varies between −12.39 and 3.92%.

Table 3
Experimental plan & result.

Run no.	Machining parameters			Response parameter
	Cutting speed (A) (m/min)	Feed rate (B) (mm/rev)	Depth of cut (C) (mm)	Surface roughness (Ra) (μm)
1	140	0.12	1.5	4.02
2	420	0.24	0.5	2.05
3	420	0.12	1.5	3.36
4	420	0.12	0.5	2.03
5	280	0.24	1.0	3.86
6	280	0.18	0.5	3.65
7	140	0.24	0.5	3.30
8	280	0.18	1.0	3.92
9	140	0.18	1.0	3.65
10	420	0.24	1.5	3.34
11	420	0.18	1.0	3.22
12	280	0.18	1.5	4.02
13	280	0.18	1.0	3.95
14	140	0.24	1.5	4.12
15	280	0.12	1.0	3.95
16	140	0.12	0.5	3.22

Table 4
Resulting ANOVA table (partial sum of squares) for response surface quadratic model (response: surface roughness).

Source	Sum of squares	df	Mean square	F value	P-value Prob > F	
Model	5.62	3	1.87	40.16	<0.0001	Significant
A-Cutting speed	1.86	1	1.86	39.82	<0.0001	
C-Depth of cut	2.12	1	2.12	45.56	<0.0001	
A^2	1.64	1	1.64	35.09	<0.0001	
Residual	0.56	12	0.05			
Lack of fit	0.56	11	0.05	112.99	0.0733	Not significant
Pure error	0.00	1	0.00			
Cor total	6.18	15				
Std. dev.	0.21		R-Squared	0.91		
Mean	3.48		Adj R-Squared	0.89		
C.V. %	6.21		Pred R-Squared	0.83		
PRESS	1.02		Adeq Precision	18.65		

4. Result and discussion

The mathematical model furnished in Section 3.2 can be employed to predict the surface roughness at the time of turning AISI 4340 steel with Y-ZTA inserts in conventional lathe. The main effect and interaction effect of parameters on roughness were computed and plotted in Fig. 3(A) to 3(C).

4.1. Direct effect of variables

It can be derived from Fig. 3(A), that the cutting speed plays a predominate role for the determination of surface roughness of the job. For the constant feed rate and depth of cut, when the cutting speed is low the roughness increases and alternatively at higher cutting speed, the roughness of the job reduces significantly. This phenomenon occurs due to cutting force variation at the time of machining. In another work of the same author [23], it was shown that the cutting force was almost constant at higher speed of operation. From Fig. 3(B), it can be concluded, at constant cutting speed & feed rate, when the depth of cut increases the roughness increases significantly. The reason of the same is the increment of cutting force at higher depth of cut [23]. It is also evident from Fig. 3(C) that feed rate plays an important role for determination of roughness of the job. At constant cutting speed & depth of cut, the roughness decreases significantly with the increase of feed rate. This is mainly due to the effect of feed force [23] which comes into play at higher feed rate and almost constant at higher feed rate so the job produced at this feed rate also has good surface finish.

4.2. Interaction effect of variables

Fig. 4(A) concludes that, among the two parameters feed rate & cutting speed the influence of the second one is much more and the surface roughness of the job varies continuously with the increase of cutting speed but it is almost constant with the change of feed

Table 5
Confirmation experiments.

Run No	Operating condition			Surface roughness value		% Error
	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Predicted value (μm)	Experimental value (μm)	
1	420	0.24	0.5	2.34	2.05	−12.39
2	280	0.24	1	3.89	3.86	−0.77
3	140	0.24	1.5	4.12	4.12	0
4	120	0.16	0.5	3.06	3.08	+0.65
5	400	0.30	1.5	3.49	3.39	−2.86
6	500	0.30	1.5	2.04	2.12	+3.92

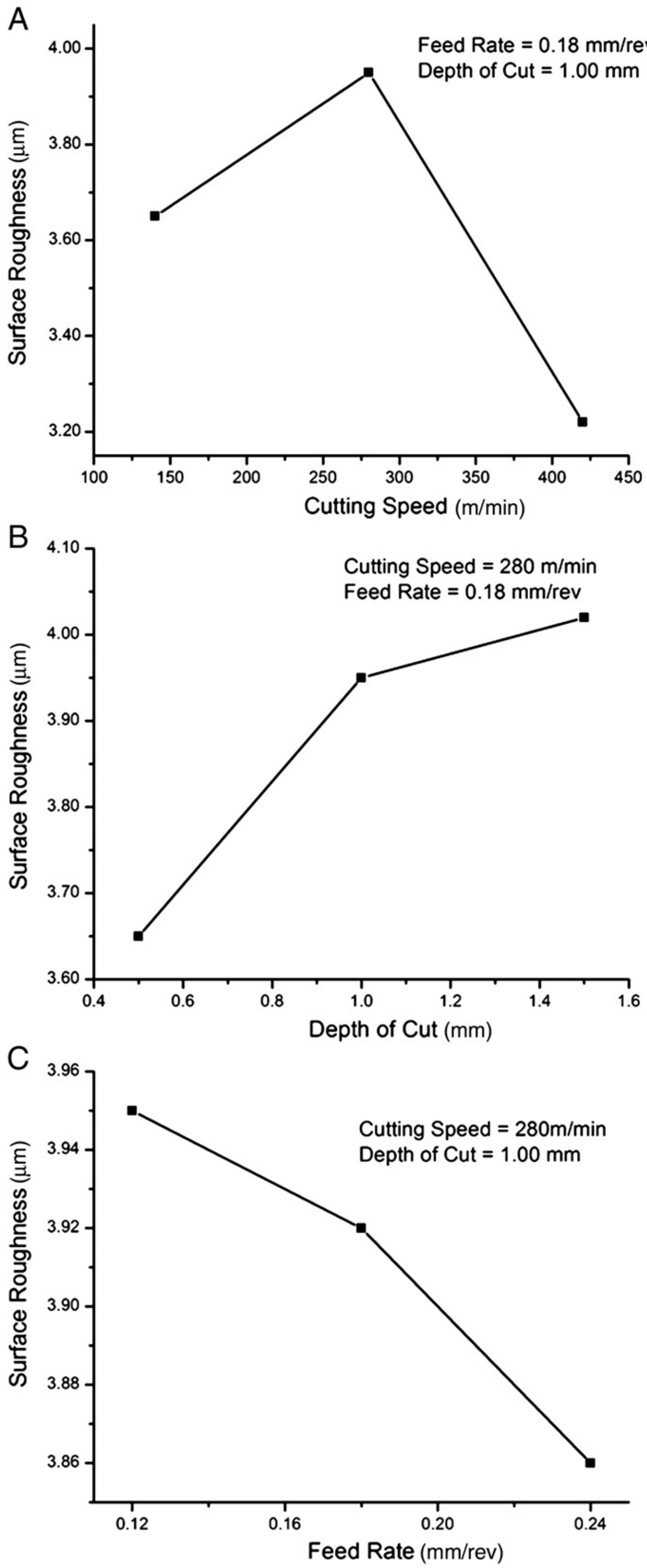

Fig. 3. (A). Direct effects of cutting speed on surface roughness. (B). Direct effects of depth of cut on surface roughness. (C). Direct effects of feed rate on surface roughness.

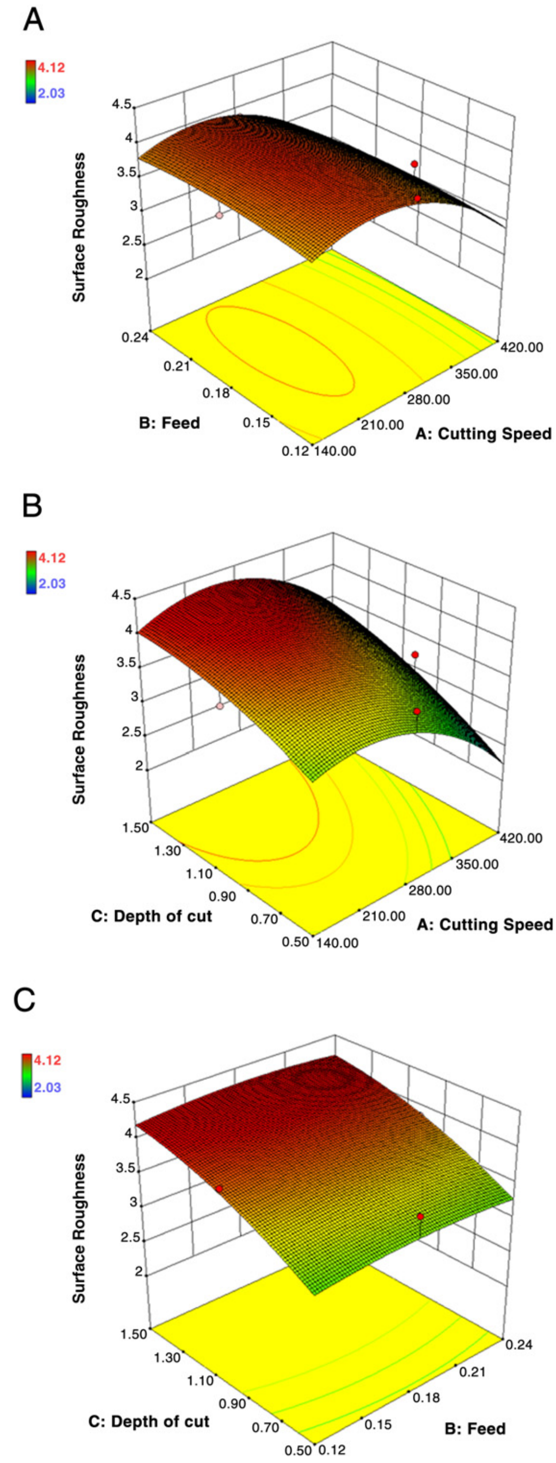

Fig. 4. (A). Interaction effects of surface roughness with feed & cutting speed. (B). Interaction effects of surface roughness with depth of cut & cutting speed. (C). Interaction effects of surface roughness with depth of cut & feed.

rate. In Fig. 4(B), it is seen that when the depth of cut increases, the roughness decreases but when the speed increases the roughness first increases and then decreases.

From Fig. 4(C), it can be concluded that for the determination of surface roughness the influence of depth of cut is much more than feed rate. When depth of cut increases the roughness decreases but roughness is constant for variation in feed rate.

4.3. Optimization of parameters

In the present study, desirability function optimization of the RSM has been employed for surface roughness optimizations. During the

Table 6
Optimisation result.

Solution number	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Surface roughness (μm)	Desirability	Remarks
1	420.00	0.24	0.50	2.33900	0.923	Selected
2	420.00	0.24	0.50	2.33900	0.923	
3	420.00	0.14	0.50	2.33900	0.923	
4	420.00	0.22	0.50	2.33900	0.923	
5	420.00	0.14	0.50	2.33900	0.923	
6	420.00	0.24	0.50	2.33900	0.923	
7	420.00	0.20	0.50	2.33900	0.923	
8	420.00	0.12	0.50	2.33900	0.923	
9	420.00	0.16	0.50	2.33900	0.923	
10	420.00	0.24	0.50	2.33900	0.923	
11	420.00	0.19	0.50	2.33900	0.923	
12	420.00	0.23	0.50	2.33900	0.923	
13	420.00	0.15	0.50	2.33900	0.923	
14	420.00	0.12	0.50	2.33900	0.923	
15	420.00	0.18	0.50	2.33900	0.923	
16	420.00	0.14	0.50	2.33901	0.923	
17	420.00	0.22	0.50	2.33901	0.923	
18	420.00	0.19	0.50	2.33901	0.923	
19	420.00	0.23	0.50	2.33901	0.923	
20	420.00	0.13	0.50	2.33901	0.923	
21	420.00	0.12	0.50	2.33901	0.923	
22	420.00	0.21	0.50	2.33901	0.923	
23	420.00	0.13	0.50	2.33902	0.923	
24	420.00	0.23	0.50	2.33903	0.923	
25	419.93	0.21	0.50	2.33984	0.923	
26	420.00	0.24	0.51	2.34619	0.921	
27	420.00	0.24	0.51	2.35146	0.920	
28	420.00	0.24	0.52	2.36064	0.917	
29	419.98	0.12	0.63	2.46173	0.891	
30	412.39	0.24	0.50	2.43227	0.886	
31	420.00	0.24	0.67	2.49523	0.882	
32	420.00	0.12	0.67	2.49523	0.882	
33	420.00	0.24	0.68	2.50910	0.878	
34	420.00	0.12	0.69	2.51047	0.878	
35	420.00	0.24	0.73	2.54874	0.867	
36	420.00	0.12	0.78	2.60076	0.853	
37	420.00	0.24	0.79	2.61081	0.850	
38	420.00	0.16	0.83	2.64738	0.839	
39	340.76	0.12	0.50	3.12005	0.586	

optimization process the aim was to find the optimal values of cutting parameters to minimize the values of surface roughness during the hard turning process. Nowadays, for minimizing the operation time, the need of higher cutting speed is increasing. So from our non conventional cutting inserts to produce better surface finish, one of the constraints used is maximum cutting speed. The other parameters are kept in range. The optimal solutions are reported in Table 6 in order of decreasing desirability level. The desirability level is constant up to solution no. 25 and after solution no. 25, the desirability level is decreasing when the operating parameter is changing. So, we can conclude that in the highest feed rate & highest cutting speed with lowest depth of cut the performance of the cutting tool is optimized and the desirability level is 92.3% in these optimized conditions.

5. Conclusion

In this paper, response surface methodology (RSM) is applied for the development of mathematical model of surface roughness. This roughness model is developed for turning of AISI 4340 steel using indigenously prepared yttria stabilized zirconia toughened alumina (ZTA) inserts. The central composite design is applied to see the influence of each parameter and their interaction effect on surface finish operation. The following conclusions can be drawn from this investigation.

- The central composite design employed in this study proved to be an effective tool for modeling the surface finish operation.
- The reduced quadratic model developed using RSM is reasonably accurate and can be used for prediction within as well as outside the limits of the factors investigated.
- The results of ANOVA and the validation experiments confirm that the developed mathematical model shows excellent fit and predicted values are very close to experimental values.
- Surface roughness model: Direct effect of cutting speed, depth of cut & cutting speed^2 has maximum influence on the surface roughness. It can also be understood that using this tool work piece combination higher cutting speed gives good surface finish operation which is very much desirable for high speed machining application.
- Using the point prediction method of optimization, the optimal setting of machining parameters are found to be cutting speed of 420 m/min, feed rate of 0.24 mm/rev and depth of cut of 0.5 mm. The desirability of this optimized condition also comes around 92.30%. This means that this developed insert is very much suitable for higher productivity operation.
- It should also be possible to apply the same mathematical procedure for this work tool combination in other standard processes such as milling, drilling etc.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ijrmhm.2012.12.007.

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