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# Machining Parameters Optimization of Developed Yttria Stabilized Zirconia Toughened Alumina Ceramic Inserts While Machining AISI 4340 Steel

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***Abstract*—**An attempt has been made to investigate the machinability of zirconia toughened alumina (ZTA) inserts while turning AISI 4340 steel. The insert was prepared by powder metallurgy process route and the machining experiments were performed based on Response Surface Methodology (RSM) design called Central Composite Design (CCD). The mathematical model of flank wear, cutting force and surface roughness have been developed using second order regression analysis. The adequacy of model has been carried out based on Analysis of variance (ANOVA) techniques. It can be concluded that cutting speed and feed rate are the two most influential factor for flank wear and cutting force prediction. For surface roughness determination, the cutting speed & depth of cut both have significant contribution. Key parameters effect on each response has also been presented in graphical contours for choosing the operating parameter preciously. 83% desirability level has been achieved using this optimized condition.

***Keywords*—**Analysis of variance (ANOVA), Central Composite Design (CCD), Response Surface Methodology (RSM), Zirconia Toughened Alumina (ZTA).

## I. INTRODUCTION

THE last two decades, manufacturing professionals and researchers have uncovered the significance and importance of the quantitative prediction of efficient machining parameters of non-conventional cutting tools. The economical performance of metal cutting operation, a predictive model has to be ascertained for any work tool combination between the input independent parameters and output variables. As the newer materials are gradually replacing the conventional cutting tool materials making machining operation smoother, it is essentially required to optimize the input parameters, such as feed rate, cutting speed, depth of cut, tool angle for improvement of output variables, such as tool life, cutting forces, surface roughness etc. Cutting force is one of these output variables that may have either direct or indirect effect on the performance of other variables such as tool wear rate, surface finish and machining cost. Before cutting operation, the operating conditions like power requirement, working materials, feed and depth of cut are to be selected. The cutting parameter influence on cutting forces and surface roughness in finish hard turning of MDN 250 steel using coated ceramic tool was studied [1]. Effect of three different forces i.e. feed force; thrust force and cutting force were investigated using RSM. The same approach was also used for investigating the effect of process parameters on force ratio and the relationship between force ratio and flank wear was also established while turning EN 24 using HSS tool [2]. RSM was also used by Noordin et al. [3] for modeling the cutting force and surface roughness when turning AISI 1045 steel with coated carbide tool. The contribution of feed parameter was found to be maximum for surface roughness and cutting force modeling. Some researchers also attempted [4] –[5] to analyze the effects of depth of cut and machining time on machinability aspects like machining force, power, surface roughness, cutting force and tool wear during machining of high chromium steel with ceramic inserts. Davim and Figueira [6] had evaluated the performance of conventional & wiper ceramic tools in terms of cutting forces, surface roughness and tool wear for hard turning AISI D2 steel. It was reported that, while machining, the wiper ceramic performed better in respect to surface roughness and tool wear whereas the conventional ceramic exhibited less machining force and power. An assay was made to establish a relation between tangential cutting force and flank wear while turning tool steel with different types of inserts like HSS, uncoated WC, coated TiAlN etc [7]. The same relationship between tool flank wear area and component of forces in single point turning had also been established by Sikdar and Chen [8]. Machining force evaluation was also done [9] when turning hardened AISI 4340 steel using coated carbide inserts. Investigators also reported that cutting force decreased slightly with the increase in work hardness. An experimental investigation about the effect of cutting forces on grey cast iron was carried out using silicon nitride based ceramic tool [10]. This tool also exhibited good performance at high cutting speed machining in respect to tool wear, temperature, surface finish of the work-piece. Cutting force prediction model was

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also attempted by Aykut et al. [11] for face milling of satellite 6 using artificial neural network (ANN).

An alternative approach for optimization is to adopt Taguchi's parameter design method based on orthogonal arrays (OA), which is widely used in research and industrial application. This method is economic one as fewer experiments are required to obtain the optimum levels of the process parameters. This technique was used by several researchers [12]-[15] for optimization of surface finish in turning operation with different work tool combinations. Comparison of tool life between ceramic and cubic boron nitride (CBN) cutting tools when machining hardened steels was evaluated by Sahin [16]. Mondal et al. [17] have tried to develop ZTA inserts by powder metallurgy route. The performance study was also carried out to benchmark the product. In another work [18], $Y_2O_3$ based partially stabilized zirconia insert was developed and its machinability study was carried out to see the stress induced transformation toughening phenomena in ZTA ceramics. Machinability study in respect of cutting forces, tool wear and surface finish was also conducted by Senthil et al. [19]-[20] with developed alumina based ceramic tools by adding ceria to alumina matrix while turning of hardened steel. In this work, different wear mechanisms like adhesive, abrasive, diffusion were also validated at different cutting conditions. Prediction of flank wear of ZTA cutting tool using response surface methodology and Taguchi method were also carried out by Mandal et al. [21]-[22]. A mathematical model was developed for flank wear and the adequacy checking of the model along with the significance and percentage contribution of each operating parameters was evaluated. The purpose of this research work was to generate machinability data for a transformation toughened ZTA cutting tool developed by powder metallurgy routes. The mathematical model for flank wear, cutting force and surface roughness have been developed using second order regression analysis. 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. The optimization of parameters has also been done for economy of machining using this non conventional cutting inserts.

## II. MATERIAL, TEST CONDITION AND MEASUREMENT

### A. 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 $Y(NO_3)_3.5H_2O$ (Adrich, 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 700-900°C for 1-2 hours. The calcined powders was wet-ball milled in organic media for 40-48 hrs using high purity (99.5%) alumina balls in 500 ml jar contained in planetary mill (Fritsch,Germany). The morphology of the powders is shown in Fig.1 and characterized through FESEM study is shown in Fig.2.

Fig.1 Yttria stabilized ZTA powder

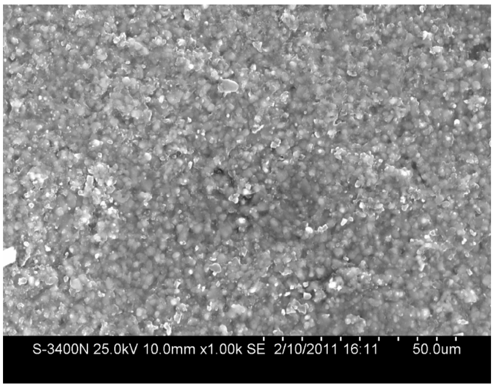

Fig. 2 FESEM photo of the powder

TABLE I
COMPOSITION & PROPERTIES OF CUTTING TOOL

| Details of inserts | Units | Zirconia Toughened Alumina (ZTA) |
|---|---|---|
| Composition | Wt (%) | $\infty$ $Al_2O_3$ + 14 wt % Y-PSZ + 2 wt % Ca-PSZ + 1wt % MgO |
| Theoretical Density | (%) | 98.4 |
| Hardness | HV | 1544 |
| Fracture Toughness | MPa $m^{1/2}$ | 4.5 |
| Compressive Strength | MPa | 4950 |
| Thermal Conductivity | W/mK | 16.5 |
| Type & Size | | SNUN 120408 |
| Geometry | | -6º,6º,6º,6º,15º,75º,0.8 mm, Edge bevel width,0.2 mm, 20º |

TABLE II
Alloying composition (wt %) of work piece 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 |

### *B. Preparation of Cutting Inserts*

The requisite amount of dried milled powders for the preparation of tool inserts were uniaxially compacted at a pressure of 2.5 ton cm-2 into square shaped (16 mm x 16mm x 6mm) pellets in a die. The compacts were sintered at 1550-1650°C for 1-3 hrs 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 made very close to the international standard SNUN 120408 (ISO). Finally, the inserts were lapped /polished with fine diamond paste (0.5-1.0 µm) in polishing machine. A flat land of angle 20 deg and width 0.2 mm was provided on each cutting edge to impart edge strength. After beveling, the sharp edges were further rounded off, although slowly, as uniformly as possible by light honing. The photo of insert is shown in Fig. 3 and mechanical properties of those insert was presented in Table I. AISI 4340 Steel was used in this experiment and the details specifications were depicted in Table II.

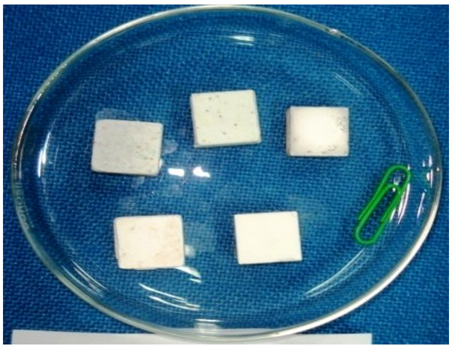

Fig. 3 ZTA inserts

### *C. Experimental Conditions*

The turning experiments were conducted in a lathe machine (HMT Ltd, India) shown in Fig. 4 is 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. The experimental condition is depicted in Table III.

TABLE III
Operating parameters with their levels

| Operating parameters | Unit | |
|---|---|---|
| Cutting speed | m/min | 150, 250, 350 |
| Feed rate | mm/rev | 0.18, 0.23, 0.28 |
| Depth of cut | mm | 0.5, 1.0, 1.5 |
| Environment | | Dry |

Fig. 4 Photo of lathe fitted with inserts

### *D. Measurement of Force*

The cutting forces were measured using Kistler piezoelectric dynamometer (model 9272) fitted in a developed fixture. This dynamometer can measure forces in 3 directions i.e. Fx, Fy & Fz and calibrated in the range of 0 to 5000 Newton. Kistler charge amplifier (model 5015A) was used to display the amplified value of force from charge. The Dynoware software installed in the PC was used to produce the force data in all three directions.

### *E. Measurement of Surface Roughness*

The surface roughness of the AISI 4340 steel was measured by the help of a stylus instrument. The equipment used for measuring the surface roughness was a portable surface roughness tester SURTRONIC 25 which is shown in Fig. 6. The direction of the roughness measurement was perpendicular to the cutting velocity vector. A total of five measurement of surface roughness were taken at random on each machined surface and the average value was used in the analysis.

### *F. Measurement of Flank Wear*

Flank wear in the ceramic cutting insert is mechanically activated wear usually by the abrasive action of the hard work piece material with the ceramic tool. The flank wear is characterized by the abrasive groove and ridges on the flank face. The width of the flank wear land was measured using a Tool Makers Microscope (Mitutoyo Make, Model No TM 505 with magnification in the range of X30 to X150 and 1 micron resolution. The photo of this Microscope is shown in Fig.5. It was measured perpendicular to the major cutting edge and from the position of the original major cutting edge after 10 minutes of machining using same operating condition for each inserts. The photo of flank wear is also presented in Fig.7.

## III. Statistical Modeling

### *A. Response Surface Methodology*

RSM is a type of modeling to find out the relation between various factors with the response. It is useful for developing, through a set of experiments based on standard RSM design called a central composite design (CCD) whereby the factorial

Fig. 5 Tool Maker's Microscope

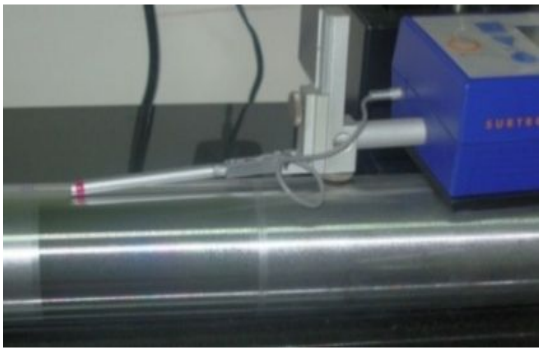

Fig. 6 Surface Roughness Measurement

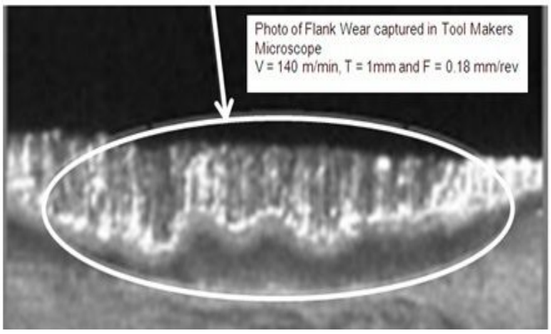

Fig. 7 Photo of Flank Wear

improving and optimizing the process which provides through understanding of the process within the region of interest. For using RSM, a proper design of experiments is essentially required where parameter along with their range selection is important. In the present investigation, cutting speed, feed rate and depth of cut are identified as process parameters. Flank wear ($V_B$), cutting force ($F_z$) & surface roughness ($R_a$) are the responses. The effects of the parameters on these are tested portion is a full factorial design 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 variables investigated are the forces. The number of performance tests involved 16 trials. The result of the trials was reported in the design layout Table IV.

The response function representing the performance can be expressed as

$$Y = f\left(V, F, T\right) \qquad (1)$$

Where, Y = response values

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

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

Where, $A_0$ is the free term of the equation, the coefficients $A_1$, $A_2$………….. $A_i$ are linear terms; $A_{11}$, $A_{22}$ ………… $A_{ii}$ are quadratic terms; and $A_{12}$, $A_{13}$……………$A_{ij}$ are the interaction terms.

For three factors, the selected polynomial could be expressed as

$$Y = A_0 + A_1V + A_2F + A_3T + A_{12}VF + A_{13}VT + A_{23}FT + A_{11}V^2 + A_{22}F^2 + A_{33}T^2 \qquad (3)$$

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

### *B. Modeling of Flank Wear*

After calculating the coefficient values in (3), the mathematical model has been determined as

$$\text{Flank Wear} = 0.22 + 0.051A + 0.017B + 0.028C + 0.0025AB + 0.005AC - 0.00603A^2 + 0.00396B^2 - 0.00103C^2 \qquad (4)$$

The adequacy and significance of the regression model was tested using ANOVA method. Test for significance on individual model coefficients and test for lack-of-fit was also estimated. An ANOVA table is commonly used to summarize the test performed in this work. From this ANOVA table it is shown the Model F – value of 53.59 which implies the model is significant. The insignificant model terms (not counting those required to support hierarchy) can be removed and may result in an improved model. By selecting the backward elimination procedure to automatically reduce the terms that are not significant, the resulting ANOVA table for the reduced quadratic model for Flank Wear is shown in Table V.

The Model F-value 159.97 implies the model is significant.

TABLE IV
EXPERIMENTAL PLAN AND RESULTS

| Run | A: Cutting Speed | B: Feed | C: Depth of cut | Flank Wear | Cutting Force | Surface Roughness |
|---|---|---|---|---|---|---|
| | | | | mm | N | Micron |
| 1 | 140 | 0.12 | 1.5 | 0.18 | 393 | 4.02 |
| 2 | 420 | 0.24 | 0.5 | 0.25 | 568 | 2.05 |
| 3 | 420 | 0.12 | 1.5 | 0.28 | 397 | 3.36 |
| 4 | 420 | 0.12 | 0.5 | 0.22 | 403 | 2.03 |
| 5 | 280 | 0.24 | 1.0 | 0.25 | 567 | 3.86 |
| 6 | 280 | 0.18 | 0.5 | 0.19 | 469 | 3.65 |
| 7 | 140 | 0.24 | 0.5 | 0.16 | 425 | 3.30 |
| 8 | 280 | 0.18 | 1.0 | 0.23 | 454 | 3.92 |
| 9 | 140 | 0.18 | 1.0 | 0.16 | 463 | 3.65 |
| 10 | 420 | 0.24 | 1.5 | 0.32 | 603 | 3.34 |
| 11 | 420 | 0.18 | 1.0 | 0.27 | 468 | 3.22 |
| 12 | 280 | 0.18 | 1.5 | 0.25 | 494 | 4.02 |
| 13 | 280 | 0.18 | 1.0 | 0.21 | 462 | 3.95 |
| 14 | 140 | 0.24 | 1.5 | 0.20 | 582 | 4.12 |
| 15 | 280 | 0.12 | 1.0 | 0.20 | 380 | 3.95 |
| 16 | 140 | 0.12 | 0.5 | 0.13 | 415 | 3.22 |

TABLE V
RESULTING ANOVA TABLE (PARTIAL SUM OF SQUARES) FOR RESPONSE SURFACE QUADRATIC MODEL
(RESPONSE: FLANK WEAR)

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F | |
|---|---|---|---|---|---|---|
| Model | 0.03694 | 4 | 0.0092 | 159.97 | < 0.0001 | significant |
| A-Cutting Speed | 0.02601 | 1 | 0.0260 | 450.56 | < 0.0001 | |
| B-Feed | 0.00289 | 1 | 0.0028 | 50.06 | < 0.0001 | |
| C-Depth of cut | 0.00784 | 1 | 0.0078 | 135.81 | < 0.0001 | |
| AC | 0.0002 | 1 | 0.0002 | 3.46 | 0.0896 | |
| Residual | 0.00064 | 11 | 5.77273E-05 | | | |
| Lack of Fit | 0.00044 | 10 | 0.0000435 | 0.2175 | 0.9424 | Not significant |
| Pure Error | 0.0002 | 1 | 0.0002 | | | |
| Cor Total | 0.03758 | 15 | | | | |
| Std. Dev. | 0.0076 | | R-Squared | 0.9831005 | | |
| Mean | 0.21875 | | Adj R-Squa | 0.9769552 | | |
| C.V. % | 3.4733 | | Pred R-Squa | 0.9676703 | | |
| PRESS | 0.00121 | | Adeq Precn | 45.204919 | | |

TABLE VI
RESULTING ANOVA TABLE (PARTIAL SUM OF SQUARES) FOR RESPONSE SURFACE QUADRATIC MODEL
(RESPONSE: CUTTING FORCE)

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F | |
|---|---|---|---|---|---|---|
| Model | 73217.1 | 5 | 14643.42 | 25.062172 | < 0.0001 | significant |
| A-Cutting Speed | 2592.1 | 1 | 2592.1 | 4.4363719 | 0.0614 | |
| B-Feed | 57304.9 | 1 | 57304.9 | 98.077176 | < 0.0001 | |
| C-Depth of cut | 3572.1 | 1 | 3572.1 | 6.1136391 | 0.0330 | |
| AB | 3698 | 1 | 3698 | 6.3291166 | 0.0306 | |
| BC | 6050 | 1 | 6050 | 10.354558 | 0.0092 | |
| Residual | 5842.8375 | 10 | 584.28375 | | | |
| Lack of Fit | 5810.8375 | 9 | 645.6486111 | 20.176519 | 0.1712 | Not significant |
| Pure Error | 32 | 1 | 32 | | | |
| Cor Total | 79059.938 | 15 | | | | |
| Std. Dev. | 24.171962 | | R-Squared | 0.9260961 | | |
| Mean | 471.4375 | | Adj R-Squared | 0.8891442 | | |
| C.V. % | 5.1272888 | | Pred R-Squared | 0.6257811 | | |
| PRESS | 29585.721 | | Adeq Precision | 16.848798 | | |

TABLE VII
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 | 5.6196217 | 3 | 1.8732 | 40.15784 | < 0.0001 | significant |
| A-Cutting Speed | 1.85761 | 1 | 1.8576 | 39.82347 | < 0.0001 | |
| C-Depth of cut | 2.12521 | 1 | 2.1252 | 45.56028 | < 0.0001 | |
| A2 | 1.6368017 | 1 | 1.6368 | 35.08978 | < 0.0001 | |
| Residual | 0.5597533 | 12 | 0.0466 | | | |
| Lack of Fit | 0.5593033 | 11 | 0.0508 | 112.9906 | 0.0733 | not significant |
| Pure Error | 0.00045 | 1 | 0.0004 | | | |
| Cor Total | 6.179375 | 15 | | | | |
| Std. Dev. | 0.2159771 | | R-Squared | 0.909416 | | |
| Mean | 3.47875 | | Adj R-Squared | 0.88677 | | |
| C.V. % | 6.2084688 | | Pred R- Squared | 0.834296 | | |
| PRESS | 1.0239485 | | Adeq Precision | 18.64704 | | |

There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Results from Table 5 indicate that the model is still significant. However the main effect of Cutting Speed (A), Feed Rate (B) and Depth of Cut (C) and the two level interactions of Cutting Speed and Depth of Cut (AC) are the significant model terms. The lack of fit can still be said to be insignificant. The $R^2$ value is high close to 1, which is desirable. The "Pred. R-Squared" of 0.9676 is in reasonable agreement with the "Adj R-Squared" of 0.9769. The adjusted $R^2$ value is particularly useful when comparing models with different number of terms. "Adequate Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Our ratio of 45.205 indicates an adequate signal. So, this model can be used to navigate the design space.

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

$$\text{Flank Wear}, V_b = 0.22 + 0.051A + 0.017B + 0.028C \\ + 0.005AC \qquad (5)$$

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

$$\text{Flank Wear}, V_b = 0.02975 + 0.000292\,\text{Cutting Speed} + 0.2833 \\ \text{Feed Rate} + 0.036\,\text{Depth of Cut} + 0.0000714 \\ \text{Cutting Speed} * \text{Depth of Cut} \qquad (6)$$

### C. Modeling of Cutting Force

After calculating the coefficient values in (3), the mathematical model for cutting force has been determined as

$$\text{Cutting Force} = 466.62 + 16.10A + 75.70B + 18.90C + 21.50AB \\ - 13.25AC + 27.50BC - 5.43A^2 + 2.57B^2 \\ + 10.57C^2 \qquad (7)$$

The adequacy and significance of the regression model was tested using ANOVA method. Test for significance on individual model coefficients and test for lack-of-fit was also estimated. An ANOVA table is commonly used to summarize the test performed. From this ANOVA table it is shown the Model F – value of 12.38 which implies the model is significant. The insignificant model terms (not counting those required to support hierarchy) can be removed and may result in an improved model. By selecting the backward elimination procedure to automatically reduce the terms that are not significant, the resulting ANOVA table for the reduced quadratic model for cutting force is shown in Table VI. The Model F-value of 25.06 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Results from Table VI indicate that the model is still significant. However the main effect of Cutting Speed (A), Feed Rate (B) and Depth of Cut (C) and the two level interactions of Cutting Speed and Feed Rate (AB), Feed Rate and Depth of Cut (BC) are the significant model terms. The lack of fit can still be said to be insignificant. The $R^2$ value is high close to 1, which is desirable. The "Pred. R-Squared" of 0.6257 is in reasonable agreement with the "Adj R-Squared" of 0.8891.The adjusted $R^2$ value is particularly useful when comparing models with different number of terms. "Adequate Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Our ratio of 16.8487 indicates an adequate signal. So, this model can be used to navigate the design space.

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

$$\text{Cutting Force}, F_z = 471.44 + 16.10A + 75.70B + 18.90C + 21.50AB \\ + 27.50BC \qquad (8)$$

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

$$\text{Cutting Force}, F_z = 468.33 - 0.3457\,\text{Cutting Speed} - 371.66\,\text{Feed Rate} \\ - 127.20\,\text{Depth of Cut} + 2.5595\,\text{Cutting Speed} * \\ \text{Feed Rate} + 916.66\,\text{Feed Rate} * \text{Depth of Cut} \qquad (9)$$

### D. Modeling of Surface Roughness

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

$$\text{Surface Roughness} = 3.97 - 0.43A + 0.009B + 0.46C - 0.023AB \\ + 0.012AC - 0.0025BC - 0.55A^2 - 0.082B^2 \\ - 0.15C^2 \qquad (10)$$

The adequacy and significance of the regression model was tested using ANOVA method. From this ANOVA table it is shown the Model F – value of 12.22 which implies the model is significant. The insignificant model terms (not counting those required to support hierarchy) can be removed and may result in an improved model. By selecting the backward elimination procedure to automatically reduce the terms that are not significant, the resulting ANOVA table for the reduced quadratic model for surface roughness is shown in Table VII. The Model F-value of 40.16 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Results from Table VII indicate that the model is still significant. However the main effect of Cutting Speed (A), Depth of Cut (C) & Cutting Speed $(A)^2$ are the significant model terms. The lack of fit can still be said to be insignificant. The R2 value is high close to 1, which is desirable. The "Pred. R-Squared" of 0.8342 is in reasonable agreement with the "Adj R-Squared" of 0.8867.

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

$$\text{Surface Roughness}, R_a = 3.89 - 0.43A + 0.46C - 0.66A^2 \qquad (11)$$

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

$$\text{Surface Roughness}, R_a = 1.189 + 0.0157\,\text{Cutting Speed} + 0.9222 \\ \text{Depth of Cut} - 0.000033\,\text{Cutting Speed}^2 \qquad (12)$$

### E. Confirmation Run

In order to verify the adequacy of the model developed, five confirmation run experiments were performed as depicted in Table VIII. The test condition for first three confirmation run experiments were among the cutting conditions that were performed previously and the remaining two experiments were done taking the operating conditions outside the design space. Using the point prediction capability of Design Expert software, the results were predicted with 95% confidence level. The predicted values of flank wear, cutting force & surface roughness were calculated from (6), (9) and (12) respectively. The percentage error also calculated and the range varies between -14.14 to 11.06 %.

## IV. RESULT AND DISCUSSION

The mathematical model furnished for Flank Wear, Cutting Force and Surface Roughness in section 3.2, 3.3 and 3.4 respectively can be employed to predict the parameters at the time of turning AISI 4340 steel with ZTA inserts in conventional lathe. The main and interaction effect of parameters on force were computed and plotted in Fig. 8(a) to Fig. 9(c).

### *A. Direct Effect of Variables*

It can be derived from Fig. 8(a) that the cutting speed plays a predominant role for the determination of flank wear, cutting force & surface roughness. For the constant feed rate and depth of cut, when the cutting speed increases the flank wear decreases first & then increases but the cutting force increases throughout the range. The surface roughness plays a different role and decreases at higher cutting speed. From Fig. 8(b) it can be concluded that at constant cutting speed & feed rate when depth of cut increases the flank wear & cutting force decreases and then significantly increases but increment of surface roughness value is less at higher cutting speed. From Fig. 8(c), it can be derived that the feed rate also plays a significant role. For the constant cutting speed & depth of cut when feed rate increases the flank wear & cutting force increases but surface roughness significantly decreases.

### *B. Interaction Effect of Variables*

From the Fig. 9(a), it can be concluded that among the two parameters depth of cut & cutting speed the influence of second one is much more and the increment rate of flank wear is also very high with the increment of cutting speed. In Fig. 9(b), it is seen that the feed parameter is most important for cutting force determination and when it increases the cutting force also increases very much. From Fig. 9(c), it can be concluded that for the determination of surface roughness the influence of cutting speed is much more. When cutting speed increases the surface roughness increases up to middle level but after that the surface roughness decreases rapidly with the increase of cutting speed.

### *C. Optimization of Parameters*

In the present study, desirability function optimization of the RSM has been employed for multiple response optimizations. The optimization module simultaneously satisfies the requirements placed on each of the responses and factors in an attempt to establish the appropriate model. During the optimization process the aim was to find the optimal values of the cutting parameters in order to minimize the values of flank wear, cutting force, surface roughness etc. during the hard

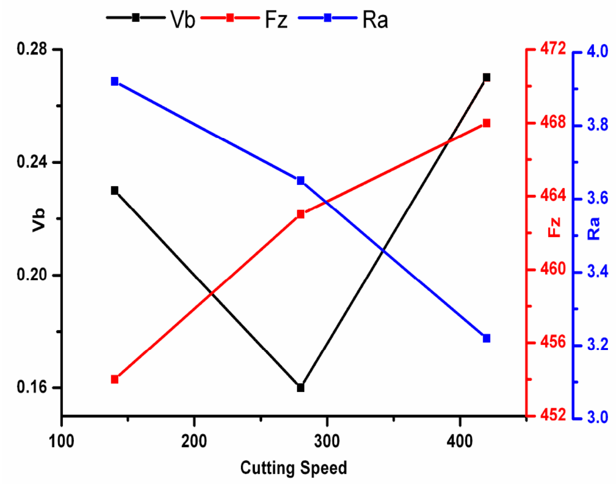

Fig. 8(a) Vb, Fz & Ra values with respect to Cutting Speed when Feed = 0.18 mm/rev, DOC = 1.00

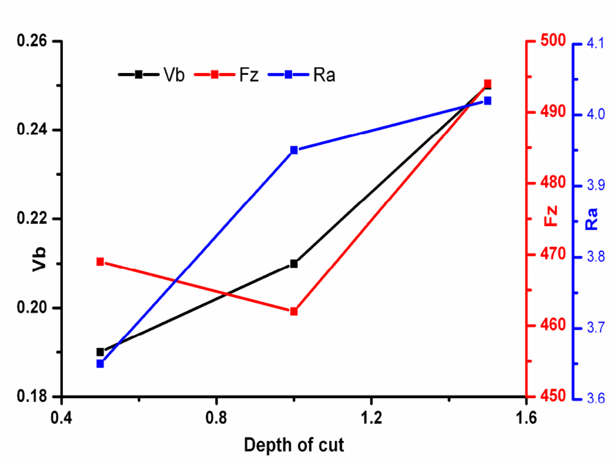

Fig. 8(b) Vb, Fz & Ra values with respect to Depth of Cut when Cutting Speed = 280 m/min, Feed = 0.18 mm/rev

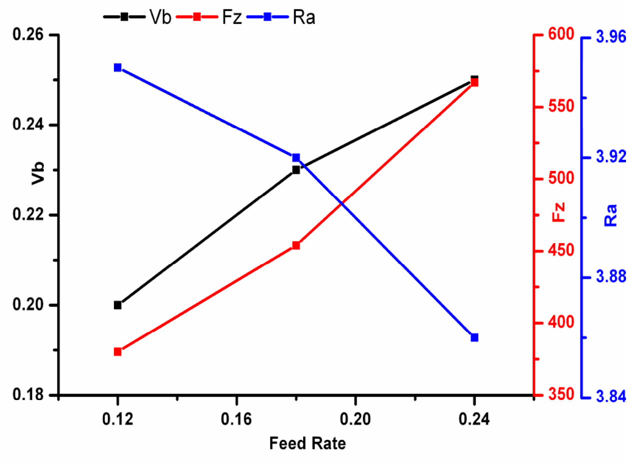

Fig. 8(c) Vb, Fz & Ra values with respect to Feed rate when Cutting Speed = 280 m/min, DOC = 1.00 mm

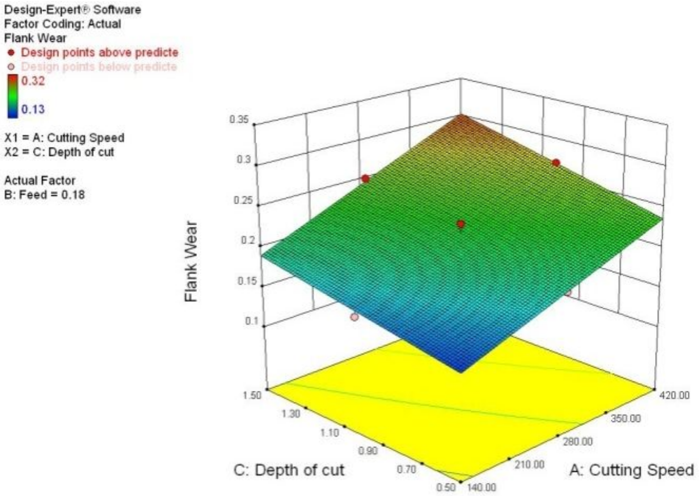

Fig. 9(a) Interaction effects of flank wear with depth of cut & cutting speed at constant feed

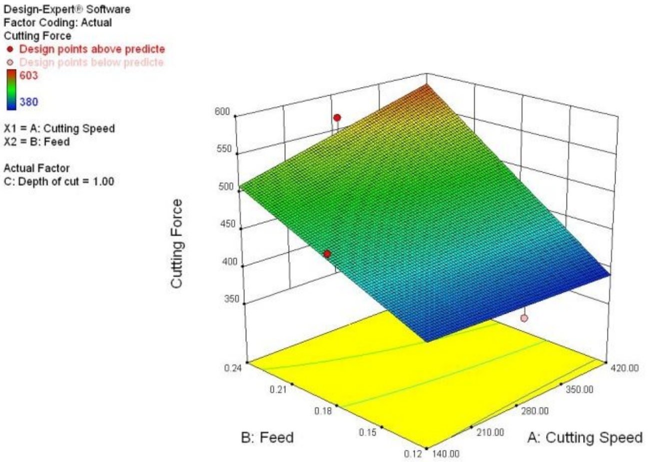

Fig. 9(b) Interaction effects of cutting force with feed & cutting speed at constant depth of cut

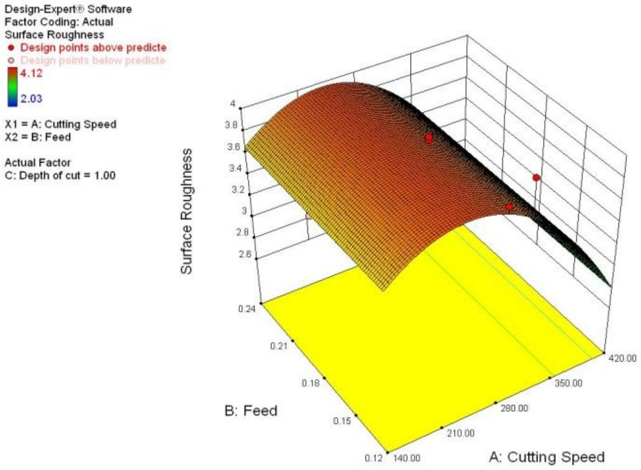

Fig. 9(c) Interaction effects of surface roughness with feed & cutting speed at constant depth of cut

TABLE VIII
CONFIRMATION EXPERIMENT

| Run | Parameters | | | Predicted Value | | | Experimental Value | | | % Error | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed | Feed | Depth of cut | Flank Wear | Cutting Force | Surface Roughness | Flank Wear | Cutting Force | Surface Roughness | Flank Wear | Cutting Force | Surface Roughness |
| 1 | 420 | 0.24 | 0.5 | 0.2537 | 538 | 2.34 | 0.25 | 568 | 2.05 | -1.48 | 5.28 | -14.14 |
| 2 | 280 | 0.24 | 1 | 0.2357 | 547 | 3.89 | 0.25 | 567 | 3.86 | 5.72 | 3.52 | -0.77 |
| 3 | 140 | 0.24 | 1.5 | 0.2077 | 556 | 4.12 | 0.20 | 582 | 4.12 | -3.85 | 4.46 | 0 |
| 4 | 120 | 0.16 | 0.5 | 0.1325 | 426 | 3.06 | 0.15 | 416 | 3.08 | 11.6 | -2.40 | 0.64 |
| 5 | 400 | 0.3 | 1.5 | 0.3287 | 747 | 3.49 | 0.33 | 735 | 3.39 | 0.39 | -1.63 | -2.94 |

TABLE IX
CONSTRAINT FOR OPTIMIZATION OF CUTTING CONDITION

| Condition | Goal | Lower Limit | Upper Limit |
|---|---|---|---|
| Cutting Speed | Maximize | 140 | 420 |
| Feed | is in range | 0.12 | 0.24 |
| Depth of cut | is in range | 0.5 | 1.5 |
| Flank Wear | Minimize | 0.13 | 0.32 |
| Cutting Force | Minimize | 380 | 603 |
| Surface Roughness | Minimize | 2.03 | 4.12 |

TABLE X
OPTIMIZATION RESULT

| Number | Cutting Speed | Feed | Depth of cut | Flank Wear | Cutting Force | Surface Roughness | Desirability | |
|---|---|---|---|---|---|---|---|---|
| 1 | 420.00 | 0.12 | 0.50 | 0.21975 | 398.937 | 2.17831 | 0.81838124 | Selected |
| 2 | 418.61 | 0.12 | 0.50 | 0.219324 | 398.983 | 2.19529 | 0.81639154 | |
| 3 | 420.00 | 0.12 | 0.50 | 0.220044 | 400.144 | 2.18093 | 0.81629188 | |
| 4 | 420.00 | 0.12 | 0.50 | 0.220249 | 400.983 | 2.18272 | 0.81484185 | |
| 5 | 416.74 | 0.12 | 0.50 | 0.218678 | 399.063 | 2.21618 | 0.81401364 | |
| 6 | 420.00 | 0.12 | 0.50 | 0.220737 | 402.983 | 2.18689 | 0.81138402 | |
| 7 | 420.00 | 0.12 | 0.52 | 0.221368 | 398.516 | 2.22169 | 0.81088548 | |
| 8 | 420.00 | 0.12 | 0.50 | 0.220947 | 403.846 | 2.18865 | 0.80989436 | |
| 9 | 419.98 | 0.12 | 0.53 | 0.221681 | 398.433 | 2.23046 | 0.80936988 | |
| 10 | 420.00 | 0.12 | 0.56 | 0.223696 | 397.909 | 2.2828 | 0.80008346 | |

process. The constraints used during the optimization process are summarized in Table IX. The optimal solutions are reported in Table X in order of decreasing desirability level.

## V. CONCLUSION

In the present work, flank wear, cutting force & surface roughness modeling was done using central composite design of response surface methodology. The model for all these responses had been developed using indigenously prepared ZTA cutting inserts when turning AISI 4340 steel in lathe. The adequacy of the developed models and influence of each operating factors have been checked based on ANOVA techniques. The following conclusion can be drawn as under:

1. The central composite design which is used in this study proved to be an effective tool for modeling.
2. The reduced quadratic model developed using RSM is appropriate and can be used for prediction within the limits of factors as well as beyond the limits.
3. The result of ANOVA and the validation experiments confirm that the developed model shows excellent fit and predicted values are very close to experimental values.
4. Flank Wear Model: Direct effect of cutting speed, feed rate & depth of cut and the interaction effect of cutting speed and depth of cut are influencing factors for the determination of flank wear. Among these parameters cutting speed has the maximum contribution on the wear value.
5. Cutting Force Model: Direct effect of cutting speed, feed rate & depth of cut and the interaction effect of cutting speed*feed rate and feed rate*depth of cut are influencing factors for the determination of cutting force. Among these parameters the contribution of feed is highest.
6. Surface Roughness Model: Direct effect of cutting speed, depth of cut & cutting speed$^2$ has influence on the measurement of surface roughness. This roughness increases with the increase of speed up to middle level and then decreases.
7. Using this method, the optimized conditions are cutting speed of 420 m/min, feed rate of 0.12 mm/rev and depth of cut of 0.50 mm gives 81.83% desirability.

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