# Study of Effects of Cutting Parameters on Cutting Forces Generated during Turning of Titanium Alloy and their Optimization

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**Abstract – Turning of titanium alloy (Ti-6Al-4V) as round specimen were done to study the effects of various process parameters of cutting speed, feed rate and depth of cut on cutting forces generated. Box-Behnken experimental design was used to initially select effective cutting parameters to be used further for performance of turning operations. ANOVA was applied to determine the significance of the cutting parameters. The model equations are formulated to predict cutting forces. Optimal values of cutting parameters were determined through response surface methodology. The validity of the model equations were checked by comparing the results obtained from equations and experiments. The model was optimized. A 100% desirability level in the turning process for economy was indicated by the optimized model. Optimum values of the cutting parameters were suggested which can be further used for machining of titanium alloy that will generate minimum cutting forces.**

**Index Terms – Turning, Titanium alloy, Cutting forces, Cutting parameters.**

## 1. INTRODUCTION

Rapid progress in the science and technology of materials has resulted in the development of a wide range of advanced engineering materials to be utilized in production of various components as desired by the customers. These materials are customized to attain special characteristics of the required applications such as high strength-to-weight ratio, high strength at elevated temperatures and excellent wear resistance etc [7, 8]. One of the materials of this group is titanium based alloy possessing superior properties of low density, high strength to weight ratio, good temperature resistance and corrosion resistance. Although these materials are being extensively used in many engineering applications such as aircraft turbine engine components, aircraft structural components, aerospace fasteners, high performance automotive parts, marine applications, medical devices, sports equipment, artificial parts of human body like pins for setting bones and biological implants, but wide use in such applications are prohibited by difficulty in making a product through welding and/or machining and their properties impose a lot of constraints in manufacturing [9,17-20]. These constraints can be lack of appropriate machining technology to take advantage of advanced materials and there is a great need for reliable and cost effective machining processes [1,16].

The components made out of titanium alloy can be manufactured by traditional machining methods like turning, grinding and milling. They can be further processed through fusion welding of different types [21-24]. The turning process has quiet significant contribution in machining of titanium alloys. During turning of titanium alloys, high cutting forces are produced which may further results into pre-mature failure of cutting tool resulting in increased tool wear, reduced tool life, deterioration of surface quality and dimensional accuracy of the finished product [10,15]. Short tool life is one of the main challenges while machining titanium alloys. This has limited the cutting tools to be made out of coated carbides and cemented carbide, and prevents the use of high cutting speeds [11]. The poor machinability of titanium alloys is due to their low thermal conductivity which increases the temperature at the cutting tool and the workpiece creating a very high temperature at the cutting zone. Additionally, the interface between titanium chips and cutting tools is usually quite small which results in high cutting zone stresses. There is also a strong tendency of the chips to get welded to the cutting tools [12]. It can be considered in any application where a combination of high strength at low to moderate temperatures, light weight and extra corrosion resistance are required. The machining of titanium alloy also serrates the work piece and cyclic chips, which are considered to be caused by adiabatic shearing [12]. At the same time the cost effectiveness in machining of titanium alloy can be achieved by elongating tool life through reduction of replacements of tool insert and resources used in machining [2].

The cutting forces are governed by various cutting parameters of cutting speed, feed rate and depth of cut [13, 14]. Therefore, the knowledge of cutting forces generated during machining processes under given conditions of cutting parameters can be an important criterion of material machinability, to both the designer and manufacturer of machine tools as well as user. Their prediction also helps in the analysis of optimization problems in machining economics, adaptive control applications, formulation of simulation models used in cutting databases.

The cutting force increases with enhancement of speed from 10-15m/min to 57-75m/min. It decreases with increase in cutting speed outside these speed ranges. Also, cutting force increases with increase in feed and depth of cut due to large volume of material being removed [3]. Laser assisted machining (LAM) technique can be used to minimize cutting force using the assistance of 1600W laser beam for titanium alloy. Chip segmentation by shear localization is an important process, which is observed in certain range of cutting speeds. This phenomenon might be desirable in reducing the level of cutting forces by improving chip evacuation [4]. During dry turning using a non-coated micro-grooved tool of titanium alloy, the use of 25 µm depth, micro grooved tool decreases cutting force and temperature in larger material removal rate turning [5]. The cutting forces have been observed to be lowered by application of cryogenic cooling during machining [6]. However, the thrust force has been found to be decreased by application of cryogenic cooling. The decrease in the main cutting force was due to lubricating effect of liquid nitrogen on the flank face.

It has been reported that there are several ways to improve and ensure efficient and economic machining of titanium alloy but hardly any literature is readily available which discusses the optimization of cutting parameters which will minimize the cutting forces generated during turning of titanium alloy especially with the use of response surface methodology. Therefore, it is planned to study the effects and optimization of the cutting parameters during turning of titanium alloy (Ti-6Al-4V) so that it will be able to minimize the cutting forces. The results may be useful to the engineer and the manufacturers involved in production of products out of titanium alloy.

## 2. EXPERIMENTATION

Titanium alloy, Ti-6Al-4V (Grade5) of length 350 mm and diameter 40 mm was used as base material for performing turning operation using various combination of cutting parameters. The chemical composition of titanium alloy has been shown in Table-1. Coated cemented carbide tool inserts (PVD) were used to turn each workpieces. The cutting tool inserts were coated with AlSiTiN at the top and a second layer of AlTiN having nose radius of 0.8 mm. The tool holder used was designated as WIDIA ID 2L PCLNR 1616 H12. The turning of the titanium alloy were conducted with different combination of possible three level of cutting parameters as presented in Table-2. Before performing turning operation 2mm material from the workpiece was machined in order to remove any undulations. The experiments were carried out under wet conditions using cutting fluid as water soluble oil with 75% water and designated as Servo cut S lubricant oil. It has superior cooling and lubricating properties which impart excellent surface finish and minimizes tool wear. The lathe machine was having provision of giving maximum spindle speed of 2000 rpm as shown in Fig.1(a). The chuck used to mount the job is three jaw chucks. The lathe tool dynamometer which is used measure three forces i.e axial force, radial force and tangential force acting in three mutually perpendicular directions has been shown in Fig. 1(b).

Response surface methodology based on Box-Behnken design was used for optimization of results and analysis, as it provides more advantages over other methods of design. A systematic procedure is provided by Response Surface Methodology for determining relationship between independent cutting parameters and output. Design expert software was used to a obtain set of experimental runs of Box-Behnken design to study the effect of process parameters of cutting speed, feed rate, depth of cut on cutting forces.

Table 1 Chemical composition of titanium alloy

| Components | Aluminium | Iron | Oxygen | Vanadium | Titanium |
|---|---|---|---|---|---|
| Weight% | 6 | 0.25 | 0.2 | 4 | 90 |

Table 2 Cutting parameters and their levels

| Factors | Symbols | Level-1 | Level-2 | Level-3 |
|---|---|---|---|---|
| Cutting speed (m/min) | A | 90 | 150 | 239 |
| Feed rate (mm/rev) | B | 0.10 | 0.15 | 0.20 |
| Depth of cut (mm) | C | 0.2 | 0.5 | 0.8 |

Figure 1(a) Lathe machine tool used in experiments.

Figure 1(b) Dynamometer used in experiment.

## 3. RESULTS AND DISCUSSIONS

The cutting forces of axial, radial and tangential force generated under varying combination of cutting parameters of cutting speed, feed rate and depth of cut have been shown in Table-3. The results of ANOVA for reduced quadratic model for all the three cutting forces of axial, radial and tangential force have been depicted in Table-4, 5 and 6 respectively. It is observed that the model F-Value for all the three forces are 521.85, 529.94 and 17.82 respectively, which implies that the models are significant. There is only 0.01%, chance that the model F-value may be large which could occur due to noise.

The final empirical relations for cutting forces as a function of coded factors have been given in equations 1, 2 and 3 respectively.

$$Fx=124.96-12.95A+1.49B-0.048C+1.24AC+5.37A^2-0.69B^2 \quad (1)$$

$$Fy=86.16-5.63A+1.49B+0.39C-0.75AB+2.72A^2 \quad (2)$$

$$Fz=464.5-24.47A+4.75C-8.97A^2-9.58C^2 \quad (3)$$

Similarly, the final empirical expressions for cutting forces in terms of actual factors have been presented by equations 4, 5 and 6 respectively

$$Fx=174.006-0.524A+112.670B-9.338C+0.056AC+9.800E\text{-}004A^2-276.316B^2 \quad (4)$$

$$Fy=101.923-0.209A+62.853B+1.296C-0.202AB+4.964E\text{-}004A^2 \quad (5)$$

$$Fz=440.195+0.207A+122.266C-1.638E\text{-}003A^2-106.433C^2 \quad (6)$$

Table 3 The cutting forces measured under varying cutting parameters of cutting speed, feed rate and depth of cut

| Runs | Cutting Speed, m/min | Feed Rate, mm/rev | Depth of Cut, mm | Axial Force, N | Radial Force, N | Tangential Force, N |
|---|---|---|---|---|---|---|
| 1 | 150 | 0.1 | 0.2 | 116 | 83 | 395 |
| 2 | 150 | 0.15 | 0.5 | 124.9 | 86 | 463 |
| 3 | 239 | 0.15 | 0.2 | 142 | 95 | 479 |
| 4 | 90 | 0.15 | 0.8 | 140 | 92 | 472 |
| 5 | 150 | 0.15 | 0.5 | 144.6 | 97 | 474 |
| 6 | 150 | 0.2 | 0.8 | 115 | 82 | 440 |
| 7 | 239 | 0.1 | 0.5 | 145 | 94 | 476 |
| 8 | 239 | 0.2 | 0.5 | 119 | 84 | 442 |
| 9 | 150 | 0.15 | 0.5 | 123 | 85 | 453 |
| 10 | 150 | 0.2 | 0.2 | 124.9 | 86 | 463 |
| 11 | 90 | 0.1 | 0.5 | 123.6 | 85.11 | 456 |
| 12 | 150 | 0.15 | 0.5 | 125 | 88 | 459 |
| 13 | 90 | 0.2 | 0.5 | 124.9 | 86 | 463 |
| 14 | 90 | 0.15 | 0.2 | 124.9 | 86 | 463 |
| 15 | 150 | 0.1 | 0.8 | 118 | 83.99 | 426 |
| 16 | 150 | 0.15 | 0.5 | 124.9 | 86 | 463 |
| 17 | 239 | 0.15 | 0.8 | 124.9 | 86.99 | 458 |

Table 4 Reduced ANOVA model for axial force

| Source | Sum of squares | df | Mean square | F-value | p-value |
|---|---|---|---|---|---|
| Model | 1490.82 | 6 | 248.47 | 521.85 | 0.0001 |
| A | 1357.74 | 1 | 1357.74 | 2851.57 | 0.0001 |
| B | 17.73 | 1 | 17.73 | 37.24 | 0.0001 |
| C | 0.018 | 1 | 0.018 | 0.039 | 0.8480 |
| AC | 6.25 | 1 | 6.25 | 13.13 | 0.0047 |
| $A^2$ | 124.57 | 1 | 124.57 | 261.63 | 0.0001 |
| $B^2$ | 2.01 | 1 | 2.01 | 4.23 | 0.0667 |
| Residual | 4.76 | 10 | 0.48 | | |

Table 5 Reduced ANOVA model for radial force

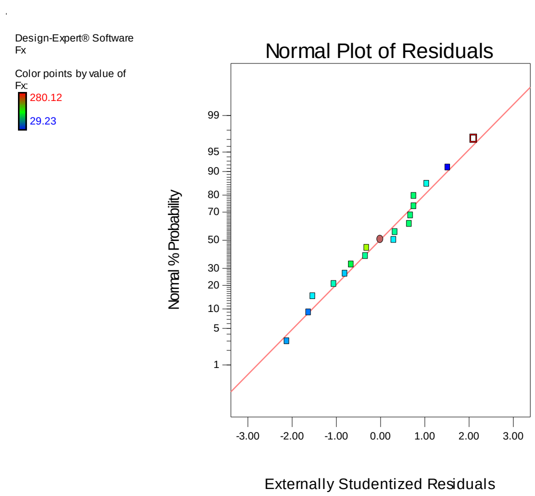
| Source | Sum of squares | df | Mean square | F-value | P-value |
|---|---|---|---|---|---|
| Model | 306.40 | 5 | 61.28 | 529.94 | 0.0001 |
| A | 256.80 | 1 | 256.80 | 2220.76 | 0.0001 |
| B | 17.77 | 1 | 17.77 | 153.68 | 0.0001 |
| C | 1.21 | 1 | 1.21 | 10.46 | 0.0080 |
| AB | 2.25 | 1 | 2.25 | 19.46 | 0.0010 |
| $A^2$ | 32.07 | 1 | 32.07 | 277.29 | 0.0001 |
| Residual | 1.27 | 11 | 0.12 | | |

Table 6 Reduced ANOVA model for tangential force

| Source | Sum of squares | df | Mean square | F-value | P-value |
|---|---|---|---|---|---|
| Model | 5859.64 | 4 | 1464.91 | 17.82 | 0.0001 |
| A | 4845.52 | 1 | 4845.52 | 58.94 | 0.0001 |
| C | 180.50 | 1 | 180.50 | 2.20 | 0.1642 |
| $A^2$ | 348.03 | 1 | 348.03 | 4.23 | 0.0620 |
| $C^2$ | 387.42 | 1 | 387.42 | 4.71 | 0.0507 |
| Residual | 986.47 | 12 | 82.21 | | |

3.1 Normal plot of probability

The normal plot of probability of axial, radial and tangential forces has been shown in Fig.2. It is understood that the residuals either fall on a straight line or lie very close to the line showing the errors are normally distributed.

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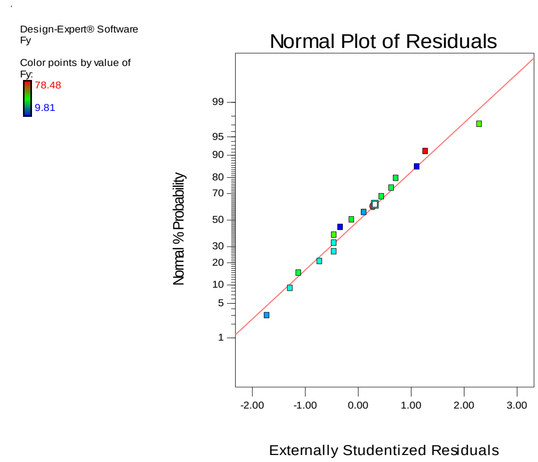


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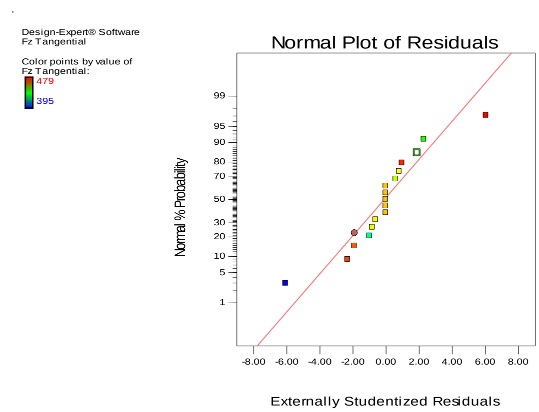


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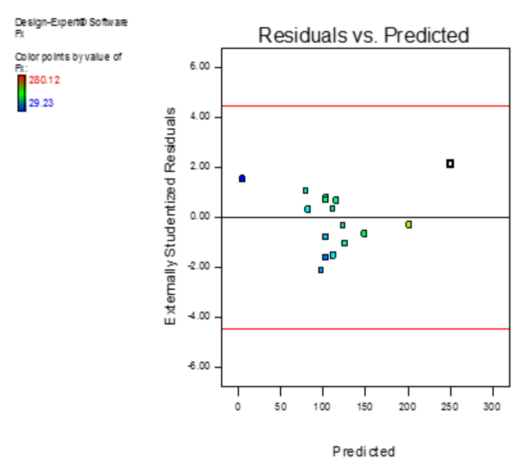
Figure 2 Normal probability plot for (a) axial force, (b) radial force and (c) tangential force.

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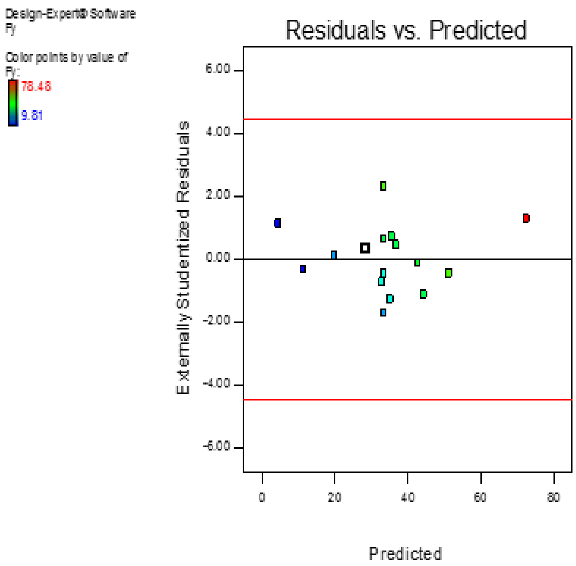


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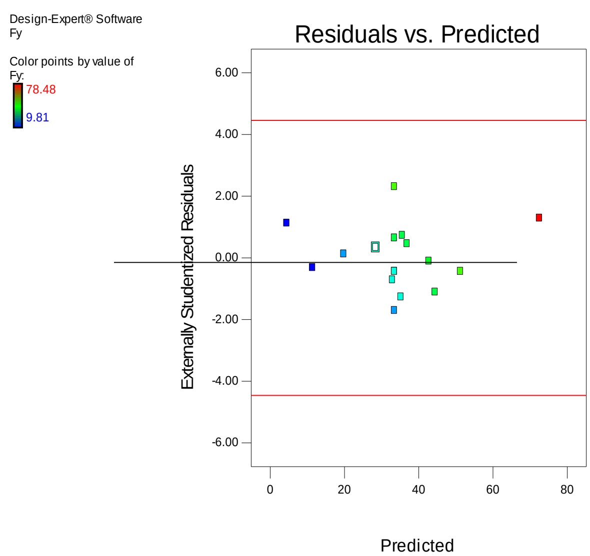


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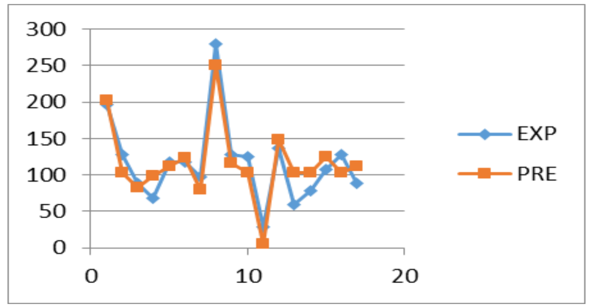
Figure 3 Plot of Residuals v/s Predicted plot for (a) axial force, (b) radial force and (c) tangential force.

3.2 Plot of residuals v/s predicted

The plot of residuals v/s predicted for cutting forces has been presented Fig.3. The figure depicts the standardized residuals with respect to the predicted values of cutting forces and it can be seen that the residuals do not show any obvious pattern and are distributed in both positive and negative directions. This implies that the model is adequate and there is no reason to suspect any violation of independent or constant violation.

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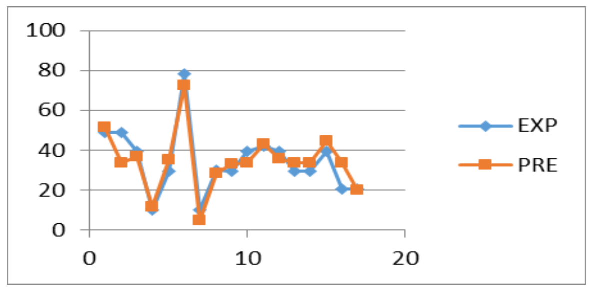


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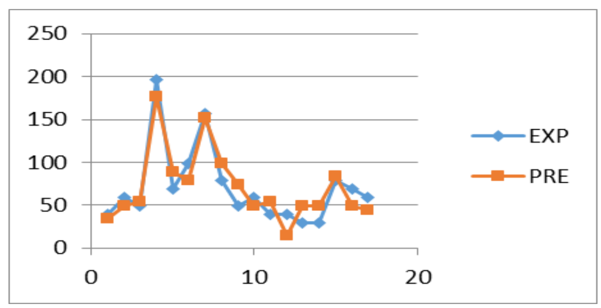


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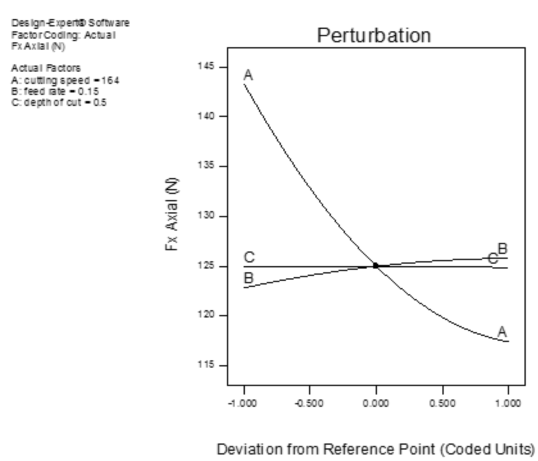
Figure 4 Plot of experimental v/s predicted values for (a) axial force, (b) radial force and (c) tangential force.

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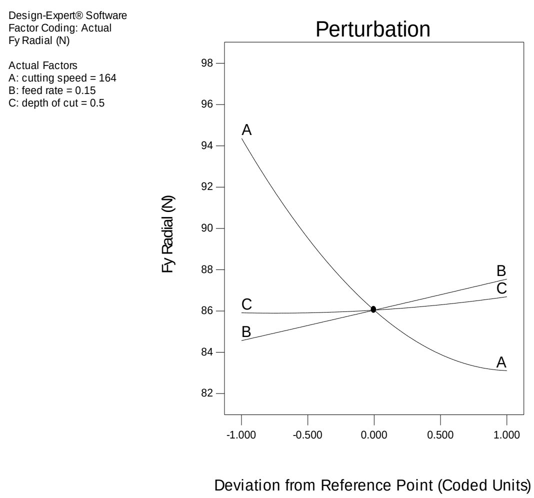


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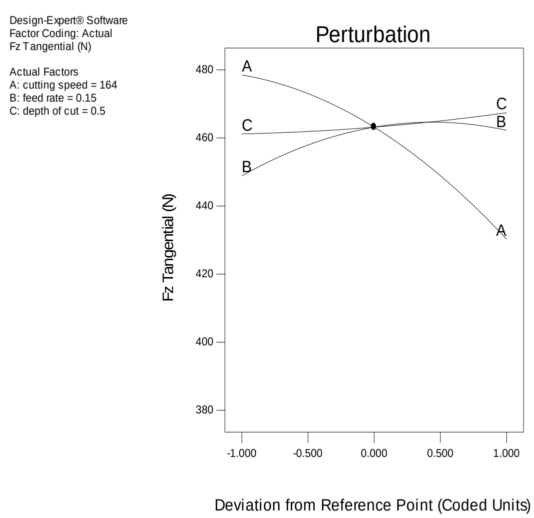



(c)

Figure 5 Perturbation plot for (a) axial force, (b) radial force and (c) tangential force.

3.3 Comparison of measured and predicted values of cutting forces

The predicted values of cutting forces from regression Eqn. (4), (5) and (6) corresponding to different machining parameters were obtained and subsequently compared with the corresponding experimental values. The comparison of predicted values and experimental values has been shown in Fig.4. It is observed that the predicted values lie very close to the experimental values. This confirms the validity of the equations used for prediction of cutting forces of axial, radial and tangential force.

3.4 Perturbation plot for cutting forces

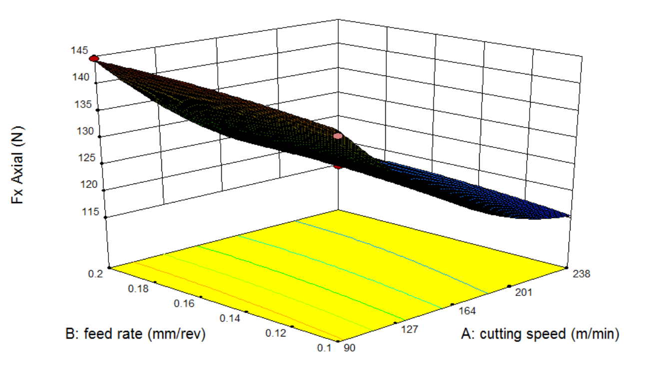
The perturbation plot for cutting forces has been presented in Fig.5. It is observed that the forces decreases with increase in cutting speed and these increases with increase of feed rate and depth of cut.

3.5 Surface plots of cutting forces

The surface plots of axial force v/s cutting speed and feed rate, axial force v/s cutting speed and depth of cut and axial force v/s feed rate and depth of cut have been presented in Fig.6. Similarly the surface plots of radial force v/s cutting speed and feed rate, radial force v/s cutting speed and depth of cut and radial force v/s feed rate and depth of cut have been shown in Fig.7.

In line with these, the surface plots of tangential force v/s cutting speed and feed rate, tangential force v/s cutting speed and depth of cut and tangential force v/s feed rate and depth of cut have been given in Fig.8. It is observed that the values of cutting forces in all the cases of axial force, radial force and tangential force decreases with increase in spindle speed. This is due to thermo mechanical instability behaviour of titanium. At higher cutting speeds thermo mechanical instability may be intense and hence less work was needed for the shear failure. Due to this instability less force was needed to cut the workpiece while cutting velocity increases. Therefore, value of average cutting force decreases with increase in cutting speed.

It is also observed that value of cutting force of axial force, radial force and tangential force increases gradually with an increase in feed rate. This is due to the fact that the volume of the work material coming in contact with the tool or the volume of the material being removed also increases with increase in feed rate. Similar to variation of cutting forces with respect to feed rate, it is further understood that values of cutting forces increases with an increase in depth of cut. This might have happened due to again enhancement of material coming in contact with tool with increase of depth of cut.

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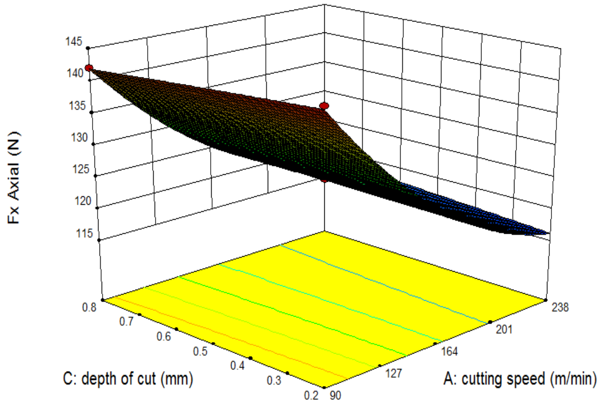


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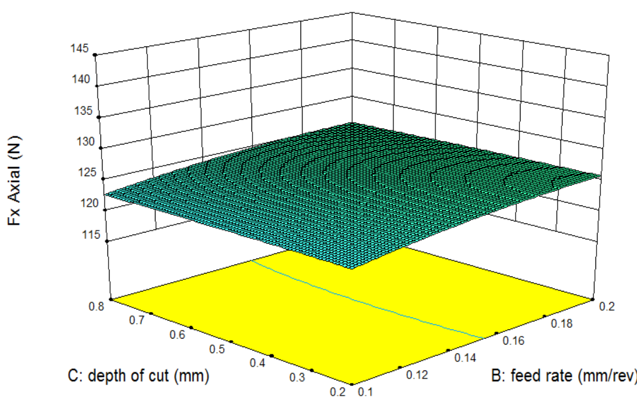
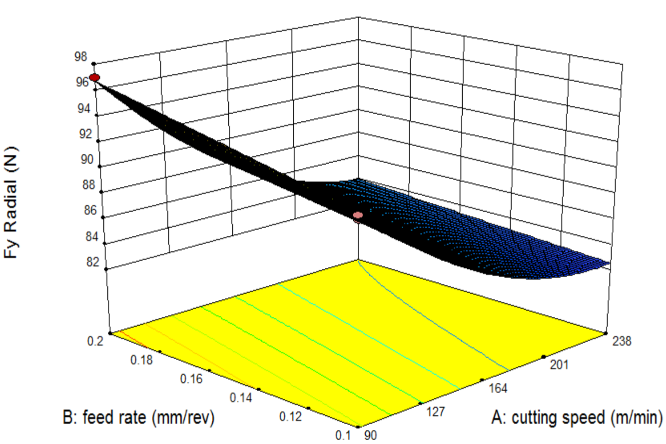



(c)

Figure 6 Surface plot of (a) axial force v/s cutting speed and feed rate, (b) axial force v/s cutting speed and depth of cut and (c) axial force v/s feed rate and depth of cut.

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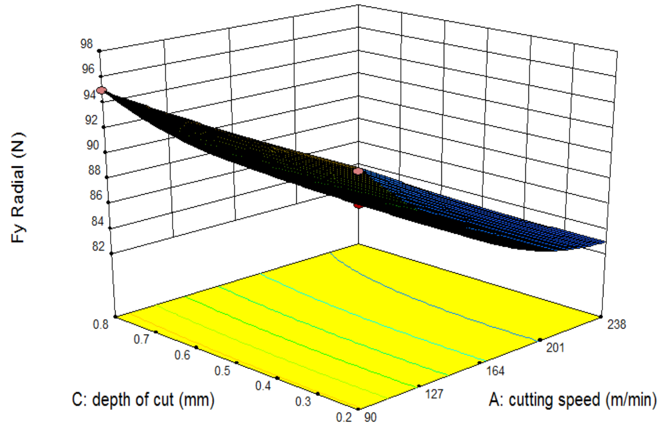


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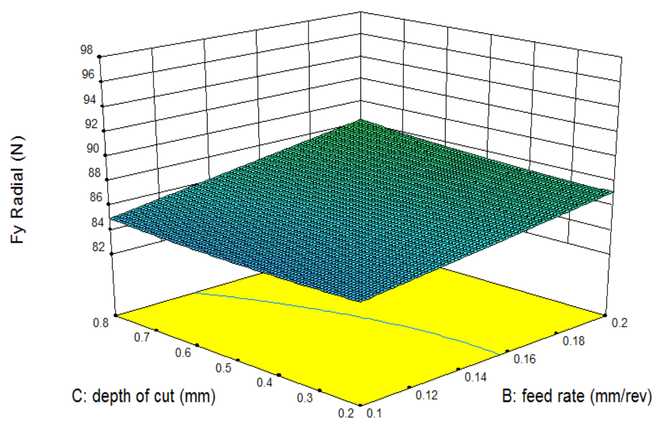
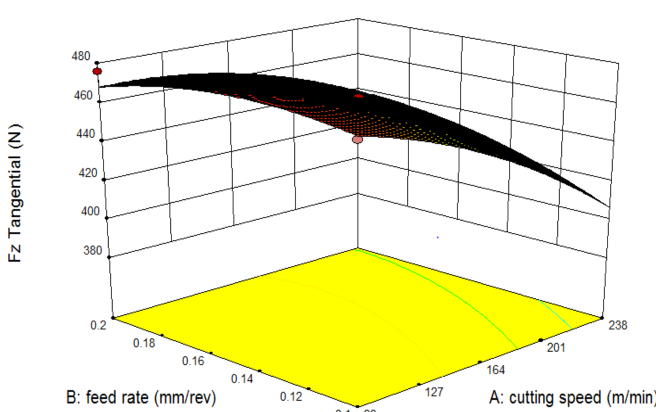



(c)

Figure 7 Surface plot of (a) radial force v/s cutting speed and feed rate, (b) radial force v/s cutting speed and depth of cut and (c) radial force v/s feed rate and depth of cut.

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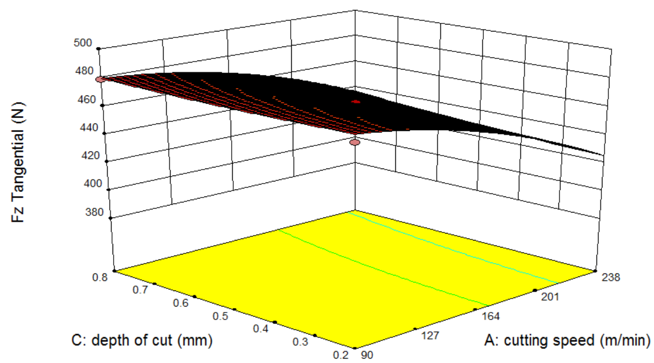


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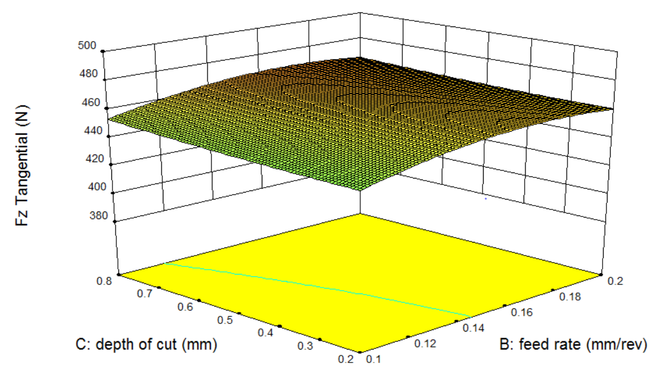


(c)

Figure 8 Surface plot of (a) tangential force v/s cutting speed and feed rate, (b) tangential force v/s cutting speed and depth of cut and (c) tangential force v/s feed rate and depth of cut.

## 1. OPTIMIZATION OF THE RESULTS

The results of the optimization of cutting forces with objective of minimization of it, with respect to cutting speed, feed rate and depth of cut have been presented in Table-7. It is observed that the optimum values of axial force, feed force and tangential force are of the order of 113.9N, 82.1N and 401.4N respectively at cutting parameters of cutting speed, feed rate and depth of cut of approximately 235m/min, 0.1mm/rev and 0.2mm.

Table 7 Optimization of cutting forces

| Sr. No. | Cutting speed, m/min | Feed rate, mm/rev | Depth of cut, mm | Fx | Fy | Fz |
|---|---|---|---|---|---|---|
| 1 | 238.00 | 0.100 | 0.200 | 113.98 | 82.12 | 401.36 |
| 2 | 238.00 | 0.100 | 0.203 | 114.00 | 82.12 | 401.40 |
| 3 | 238.00 | 0.100 | 0.214 | 114.05 | 82.13 | 401.55 |
| 4 | 237.97 | 0.101 | 0.200 | 114.01 | 82.12 | 401.73 |
| 5 | 237.14 | 0.100 | 0.200 | 114.02 | 82.11 | 401.98 |
| 6 | 238.00 | 0.100 | 0.232 | 114.14 | 82.16 | 401.80 |
| 7 | 238.00 | 0.101 | 0.200 | 114.05 | 82.14 | 402.17 |
| 8 | 238.00 | 0.100 | 0.200 | 114.20 | 82.17 | 401.99 |
| 9 | 235.81 | 0.100 | 0.245 | 114.08 | 82.10 | 402.94 |
| 10 | 235.16 | 0.100 | 0.200 | 114.12 | 82.10 | 403.41 |

## 6. CONCLUSIONS

The effects of cutting parameters on cutting forces generated during turning of titanium alloy (Ti6Al4V) have been investigated. The parameters are optimized with the objective of minimization of cutting forces. The present investigation can be concluded as follows

1. Box-behnken design based RSM can be effectively used to model the relationship between cutting parameters and performance characteristics.
2. The cutting forces are influenced principally by the cutting speed, feed rate, depth of cut, the quadratic value of feed rate, the interaction between cutting speed and feed rate, and the interaction between cutting speed and depth of cut as evident from ANOVA results.
3. The optimal cutting forces during turning of titanium alloy are observed as axial force of 113.9N, feed force of 82.1N and the tangential force 401.4N at cutting parameters of the order of cutting speed of 235.1mm/min, feed rate of 0.1mm/rev and depth of cut of 0.2 mm respectively. The desirability of this optimized condition is about 100%.

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