Effect of Cutting Parameters on Cutting Forces and MRR During Turning Hard Alloy Steel With and Without Coolant

Suha K. Shihab, Zahid A. Khan, Aas Mohammad, Arshad Noor Siddiquee

Abstract- This paper investigates the effect of different cutting parameters (cutting speed, feed rate, and depth of cut) on cutting force components and material removal rate (MRR) in dry and wet hard turning processes. The workpiece material, hardened alloy steel AISI 52100, was machined on a CNC lathe with coated carbide tool under different settings of cutting parameters. Three cutting parameters each at three levels were considered in the study. Central composite design (CCD) of experiment was used to collect experimental data for cutting force components and MRR. The results were analyzed using an effective procedure of response surface methodology (RSM) to determine optimal values of cutting parameters. Statistical analysis of variance (ANOVA) was performed to determine significance of the cutting parameters. Several diagnostic tests were also performed to check the validity of assumptions. The results indicate that cutting force components are influenced principally by the depth of cut, while the effect of both cutting speed and feed rate is small. On the other hand, the depth of cut has the most significant effect on the MRR; the cutting speed has less significant effect whereas feed rate has the lowest effect. Finally, the ranges for best cutting parameters and model equations to predict the cutting force components and MRR are proposed.

Keywords: Cutting forces, Material removal rate, Dry turning, Castrol coolant, Hard alloy steel

I. INTRODUCTION

Hard turning is generally used as a substitute to grinding for performing finishing operations for hardened steel (HRC 45 and above). The use of hard turning is not merely a widespread method but now it has become an accepted one for achieving an increased product quality in finishing operations. Turning of hard steel using advanced tool materials, such as coated carbide, ceramic and CBN inserts has more advantages e.g. short cycle time, process flexibility, compatible surface roughness, and higher material removal rate as compared to grinding or polishing [1-7]. Some researchers have studied the effect of cutting parameters under dry and wet cutting conditions on many response parameters such as cutting force components, tool wear, etc. to assess the preferable cutting parameters and conditions [8-10].

Cutting force is the important technological response parameter to control in machining process. It is the background for evaluation of the necessary power for machining, dimensioning of machine tool components and tool body. It influences machining system stability.

Manuscript received October, 2013.

Suha K. Shihab, Department of Mechanical Engineering, Jamia Millia Islamia University, New Delhi, India.

Zahid A. Khan, Department of Mechanical Engineering, Jamia Millia Islamia University, New Delhi, India.

Aas Mohammad, Department of Mechanical Engineering, Jamia Millia Islamia University, New Delhi, India.

Arshad Noor Siddiquee, Department of Mechanical Engineering, Jamia Millia Islamia University, New Delhi, India.

There have been considerable amount of research on cutting forces during turning steels. Lee [11] developed a theoretical model to predict cutting forces for machining hard materials and the predicted results from the model were found to be in good agreement with those measured from an experiment of hard machining of an AISI 4140 steel heat-treated bar using ceramic inserts. Panzera et al. [12] studied the effect of the cutting parameters (cutting speed, feed rate and depth of cut) on the cutting force components during turning AISI 1045 steel using coated carbide inserts under dry condition. The results of their study indicated that the three components of the turning force decreased slightly as cutting speed was elevated and increased linearly with feed rate and depth of cut. Furthermore, the analysis of variance indicated that the three components of the force were not significantly affected by cutting speed; however, they were significantly affected by feed rate and depth of cut. Alabi et al. [13] investigated the effect of cutting parameters on cutting forces during dry and wet turning for heat treated medium carbon steel. The results revealed that the machining forces for the dry turning were higher than that of the wet turning. They also suggested that for precision machining, dry turning is by far a better cost saver and cleaner option than wet turning. Sieben et al. [14] presented experimental study to investigate the turning of hardened AISI 6150 heat treatable steel using polycrystalline boron nitride (PCBN) tools to explore the effects of the cutting parameters (cutting speed, feed and depth of cut) on the cutting forces. They found no effect of the depth of cut on the force components for the selected ranges of depth of cut. Fernándezet-Abia et al. [15] studied the behaviour of austenitic stainless steel when machining at very high cutting speeds in dry turning. The results of their study indicated that the material used in the study undergoes a significant change in its behaviour when machined at cutting speeds above 450 m/min that favoured the machining operation. Further, the results also revealed that the main component of cutting forces reached a minimum value at this cutting speed. Krishna et al. [16] presented a specific study of the application of solid lubricants in turning of AISI1040 steel with carbide tool. It was observed from their experimental results that the cutting forces slightly increased or remained same with increase in cutting speed in dry and coolant conditions, but slightly increased while using solid lubricants. However, cutting forces were significantly less in all the solid lubricant conditions compared to dry and coolant machining. Stakhniv et al. [17] investigated the influence of machining process variables on the cutting force components in finish turning of KhVG hardened steel (60–62 HRC) using CBN tool. They found that the minimum magnitude of the cutting force fluctuations could be achieved under the following cutting parameters setting: cutting speed = 2 m/s, depth of cut = 0.1 mm, and feed rate

= 0.166 – 0.208 mm/rev. Sharma et al. [18] used the experimental data to construct model using neural networks in hard turning of adamite steel using coated carbide insert and reported the following results: (i) approaching angle influences cutting force and feed force positively but thrust force negatively, (ii) speed influences thrust force and feed force positively but tangential force negatively, (iii) feed rate influences tangential force, feed force, and thrust force positively and (iv) depth of cut influences tangential force, thrust force, and feed force positively. Xinfeng et al. [19] developed a model for predicting cutting forces in hard turning of 51CrV4 using CBN tool with a wiper cutting edge and for validation of the results, they compared the cutting forces predicted by the model with experimental measurements and found that most of the results agreed quite well.

The main purpose of hard machining is to increase the material removal rate (MRR) while keeping the quality of machined parts as per the design specifications. The material removal rate for a turning operation is given by the product of cutting speed, feed rate, and depth of cut. Therefore, if an increase in productivity is desired then an increase in these three cutting parameters is required [15, 20].

Keeping in view the significance of the cutting parameters in relation to the cutting forces and MRR, an attempt has been made in this paper to study the effect of three cutting parameters i.e. cutting speed, feed rate and depth of cut on thrust force (Fx), tangential force (Fy), feed force (Fz) and MRR in hard turning of AISI 52100 alloy steel with coated carbide insert under dry and wet conditions. Prediction models for Fx, Fy, Fz and MRR and also the optimization of the cutting parameters have been presented in the paper.

II. EXPERIMENTAL PROCEDURE

Hard turning of AISI 52100 hardened alloy steel under dry and wet conditions was carried out on CNC lathe machine. The chemical composition of AISI 52100 is shown in Table 1. The cutting parameters and their levels used in hard turning are shown in Table 2. A CNMG 120408-TN7105 coated carbide insert (TiN-TiCN-AL2O3-TiN) having nose radius of 0.8 mm was used as cutting tool. A tool holder (PCLNR 2020 K12) was used and it was held in a Kistler three-component piezoelectric dynamometer which gave measurements for cutting force components as illustrated in Figure 1.

III. EXPERIMENTAL DESIGN

Response surface methodology (RSM) based experimental design was used since it offers more advantages than other design methods. RSM provides a systematic procedure to determine a relationship between independent input process parameters and output (process response). Many researchers have used RSM in their research pertaining to hard turning [21-29]. The effect of various design parameters and the analysis with consideration of correlation between factors were studied through this design. In this work a sequential set of experimental runs was established using a Central Composite Design (CCD) built according to the design as shown in Table 3, and Table 4 to study the influence of three factors (cutting speed, feed rate, and depth of cut) on the responses (cutting forces and MRR) during dry and wet hard turning respectively. Table 3 and Table 4 also show the measured values of Fx, Fy, Fz and MRR for dry and wet hard turning respectively.

IV. RESULTS AND DISCUSSION

A. Effect of cutting parameters on the cutting forces based on analysis of variance

1. Thrust forces.

The experimental data were analysed through Design-Expert software. The results of analysis of variance (ANOVA) of thrust force (Fx) during dry hard turning are shown in Table 5 which shows the degrees of freedom (DF), sum of squares (SS), mean squares (MS), F-values (F-VAL.) and probability (P-VAL.). It can be seen from Table 5 that cutting speed (A), feed rate (B), depth of cut (C), the quadratic value of depth of cut (C2), and the interaction between feed rate and depth of cut (BC) all have the most significant effect on the (Fx) during dry hard turning; while the quadratic value of cutting speed (A2) and the interaction between cutting speed and feed rate (AB) has less significant effect, but the quadratic value of feed rate (B2) and the interaction between cutting speed and depth of cut (AC) have no significant effect. It is clear from Table 5 that the "Pred R-Squared" of 0.9905 is in reasonable agreement with the "Adj R-Squared" of 0.9968. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable and the resulted ratio is 91.363 which indicates an adequate signal. This model can be used to navigate the design space.

Final equation in terms of actual factors for the thrust force model (Fx) in dry turning is given by equation (1):

$$Fx = -58.39099 + 0.71823\,A + 391.92279\,B + 317.19055C - 1.33681E\text{-}003A^2 - 33.20707B^2 - 191.05966C^2 - 0.93694AB - 0.028875AC + 458.69792BC \quad (1)$$

The results of analysis of variance (ANOVA) of thrust force (Fx) during wet hard turning are shown in Table 6. It is clear from Table 6 that cutting speed (A), feed rate (B), depth of cut (C), the quadratic value of depth of cut (C2), and the interaction between feed rate and depth of cut (BC) have the most significant effect on the thrust force (Fx); while the quadratic value of feed rate (B2) and the interaction between cutting speed and depth of cut (AC) have less significant effect, but The quadratic value of cutting speed (A2) and the interaction between cutting speed and feed rate (AB) have no significant effect. It is clear from Table 6 that the "Pred R-Squared" of 0.9958 is in reasonable agreement with the "Adj R-Squared" of 0.9990. "Adeq Precision" measures the signal to noise ratio. The ratio of 164.779 indicates an adequate signal. This model can be used to navigate the design space.

Final equation in terms of actual factors for the thrust force model (Fx) in wet turning is given by equation (2):

$$Fx = -37.95874 + 0.22444A + 451.43851B + 314.97686C - 1.57091E\text{-}004A^2 - 703.78788B^2 - 172.08523C^2 - 0.15389AB - 0.076417AC + 389.89583BC \quad (2)$$

Figure 2 and Figure 3 present the normal probability plot of the residuuals for (Fx) during dry and wet hard turning respectively. These plots revealed that the residuals either fall on a straight line or are very close to the line implying that the errors are distributed normally. Figure 4 and Figure 5 show the standardized residuals with respect to the predicted values of thrust force (Fx) in dry and wet hard turning respectively. The residuals do not show any obvious pattren 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 the independence or constant variance assumption. Figure 6 and Figure 7 show that all values of thrust force are within reasonable limit for dry and wet hard turning. Figure 8 and Figure 9 illustrate the main effects of varying the two factors cutting speed (A) and feed rate (B) on thrust force (Fx) keeping the depth of cut (C) at constant level i.e. 0.6 mm during dry and wet hard turning respectively. It can be seen from these figures that the lower cutting speed and lower feed rate results in lower thrust force. Figure10 and Figure11 illustrate the main effects of varying the two factors cutting speed (A) and depth of cut (C) on thrust force with constant level of feed rate at 0.16 mm/rev for dry and wet hard turning respectively. It can be seen from these figures that lower cutting speed and lower depth of cut results in lower thrust force (Fx). The influence of varying the two factors feed rate (B) and depth of cut (C) on thrust force and keeping cutting speed at constant level i.e. 175 m/min is depicted in Figure 12 and Figure 13 for dry and wet hard turning respectively. From these figures it is observed that lower feed rate and lower depth of cut results in lower thrust force.

2. Tangential force.

Table 7 presents the results of analysis of variance (ANOVA) of tangential force (Fy) in dry turning. It is clear from Table 7 that factors A, B, C, and interaction BC have the most significant effect on the tangential force (Fy); while B2, C2, and interaction AC have less significant effect on Fy, whereas A2 and interaction AB have no significant effect. It is clear from Table 7 that the noise ratio "Adeq Precision" of 238.777greater than 4 this indicates an dequate signal. This model can be used to navigate the design space. The "Pred R-Squared" of 0.9977 is in reasonable agreement with the "Adj R-Squared" of 0.9995.

Final equation in terms of actual factors for the tangential force model (Fy) in dry turning is given by equation (3):

$$Fy = -26.36365 + 0.12823A + 553.85631B + 198.03754C - 3.20485E\text{-}004A^2 - 1445.20202B^2 - 30.64205C^2 - 0.45500AB - 0.12658AC + 2045.00000BC \quad (3)$$

Table 8 presents the results of analysis of variance (ANOVA) of tangential force (Fy) in wet turning. It is clear from Table 8 that factors A, B, C, B2, AC, and interaction BC have significant effect on the tangential force (Fy), but A2, C2, and interaction AB have no significant effect. It is clear from Table 8 that the noise ratio "Adeq Precision" of 467.506 greater than 4 this indicates an dequate signal. This model can be used to navigate the design space. The "Pred R-Squared" of 0.9996 is in reasonable agreement with the "Adj R-Squared" of 0.9999.

Final equation in terms of actual factors for the tangential force model (Fy) in wet turning is given by equation (4):

$$Fy = -9.79284 - 0.10175A + 473.80120B + 184.50384C + 1.64121E\text{-}004A^2 - 1382.44949B^2 - 5.79261C^2 + 0.15472AB - 0.12846AC + 2026.09375BC \quad (4)$$

Figure 14 and Figure 15 are the normal probability plot of the residuals of dry and wet hard turning respectively. These plots either fall on a straight line or are very close to the line implying that the errors are distributed normally. Figure 16 and Figure 17 show the standardized residuals with respect to the predicted values of tangential force in dry and wet hard turning respectively. It can be seen from these figures that the residuals do not show any obvious patren 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 the independence or constant variance assumption. Figure 18 and Figure 19 show that all values of tangential force are within reasonable limit in dry and wet hard turning respectively. In Figure 20 and Figure 21, it can be seen that the lower cutting speed and lower feed rate resulted in lower tangential force (Fy) during both dry and wet hard turning respectively. Similarly, Figure 22 and Figure 23 reveal that lower cutting speed and lower depth of cut resulted in lower tangential force (Fy) during both dry and wet hard turning respectively. The influence of feed rate and depth of cut on resultant force during dry and wet hard turning is depicted in Figure 24 and Figure 25 respectively. It can be seen from these figures that the lower feed rate and the lower depth of cut resulted in lower tangential cutting force (Fy).

3. Feed forces

The results of analysis of variance (ANOVA) of feed force (Fz) during dry turning are shown in Table 9. It can be seen from Table 9 that factors B, C, and interaction BC have the most significant effect on the feed force (Fz); While A2, C2, AB, and AC have less significant effect, but A,and B2 have no significant effect. It is clear from Table 9 that the noise ratio "Adeq Precision" of 138.795 greater than 4 this indicates an adequate signal. This model can be used to navigate the design space. The "Pred R-Squared" of 0.9952 is in reasonable agreement with the "Adj R-Squared" of 0.9990.

Final equation in terms of actual factors for the feed force model (Fz) in dry turning is given by equation (5):

$$Fz = -59.37030 + 0.43240A + 142.80051B + 198.00739C - 8.50101E\text{-}004A^2 - 314.39394B^2 + 28.20739C^2 - 0.54944AB - 0.096250AC + 471.87500BC \quad (5)$$

The results of analysis of variance (ANOVA) of feed force (Fz) in wet hard turning are shown in Table 10. It can be seen from Table 10 that factors B, C, C2, and interaction BC have the most significant effect on feed force (Fz); while B2 has less significant effect, whereas A, A2, AB, and AC have no significant effect. It is clear from Table 10 that the noise ratio "Adeq Precision" of 201.318 greater than 4 this indicates an adequate signal. This model can be used to navigate the design space. The "Pred R-Squared" of 0.9974 is in reasonable agreement with the "Adj R-Squared" of 0.9995.

Final equation in terms of actual factors for the feed force model (Fz) in wet hard turning is given by equation (6):

$$Fz = -54.51943 + 0.19265A + 365.79192B + 161.67098C - 3.30828E\text{-}004A^2 - 1169.69697B^2 + 56.80682C^2 - 0.21556AB - 0.044167AC + 407.50000BC \quad (6)$$

Figure 26 and Figure 27 present the normal probability plots of the residuuals in dry and wet hard turning respectively. This plots appear satisfactory where it revealed that the residuals either fall on a straight line or are very close to the line implying that the errors are distributed normally. Figure 28 and Figure 29 show that there are normaly and independantly distribution for values of feed forces in dry and wet hard turning respectively. Figure 30 and Figure 31 show that all values of feed force are within reasonable limits in dry and wet hard turning respectively. Figure 32 and Figure 33 are constructed to illustrate the main effects of varying the two factors cutting speed (A) and feed rate (B) parameters on feed force (Fz) and keeping the depth of cut (C) at constant level i.e. 0.6 mm for dry and wet hard turning respectively. It can be seen from these figures that lower cutting speed and lower feed rate resulted in lower thrust force. Similarly, in Figure34 and Figure35, it has been noticed that the same effect of interaction cutting speed (A) and depth of cut (C) on feed force (Fz) and keeping the feed rate (B) at constant level i.e. 0.16 mm/rev for dry and wet hard turning respectively, where lower cutting speed and lower depth of cut resulted in lower feed force. Figure 36 and Figure 37 show the effect of feed rate (B) and depth of cut (C) on feed force and keeping the cutting speed at constant level i.e. 175 m/min for dry and wet hard turning respectively. It can be seen fron these figures that lower feed rate and lower depth of cut resulted in lower thrust force.

B. Effect of cutting parameters on MRR based on analysis of variance

Table 11 presents the results of (ANOVA) for material removal rate (MRR) in hard turning. It is clear from Table 11 that all the factors, quadratic values of factors, and the interactions between them have significant effect on MRR. It is clear from Table 11 that the noise ratio "Adeq Precision" of 60.572 greater than 4 this indicates an dequate signal. This model can be used to navigate the design space. The "Pred R-Squared" of 0.8671 is in reasonable agreement with the "Adj R-Squared" of 0.9853.

Final equation in terms of actual factors for MRR model is given by equation (7):

MRR = +16800 - 96A -1.05E + 005B -28000C +600AB +160AC +1.75E + 005B C (7)

as in the previous analyses, Figure 38 presents the normal probability plot of the residuuals and it shows that the normality assumption is satisfactory. Figure 39 shows the standardized residuals with respect to the predicted values of MRR. The residuals do not show any obvious pattren 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 the independence or constant variance assumption. Figure 40 shows that all values of MRR are within reasonable limit. In Figure 41, Figure42, and Figure43, we can notice that the highest values of cutting speed,feed rate and depth of cut resulted in highest volume of material remval rate (MRR).

C. Optimization of cutting parameters

The optimization approach is quite advantageous in order to have the range of the cutting forces and MRR values and their corresponding optimum cutting parameters for certain ranges of input machining parameters. It would be helpful for a manufacturing engineer to select the cutting parameters for the desired machining performance of the product. The objective of this optimization is to find cutting parameters, within the selected range which minimize the cutting forces and maximize MRR.

Table 12 shows the RSM optimization results of cutting force components (Fx, Fy and Fz) and material removal rate (MRR) for dry hard turning in order of decreasing desirability level. It can be seen from Table 12 that the optimized value of Fx, Fy, Fz and MRR is within the range (144.849 N – 154.82 N), (134.218 N – 151.884 N), (38.319 N – 46.686 N) and (12668.9 mm3/min – 14083.9 mm3/min) respectively. Table 13 shows the RSM optimization results of cutting force components (Fx, Fy and Fz) and material removal rate (MRR) for wet hard turning. It can be seen from Table 13 that the optimized value of Fx, Fy, Fz and MRR is within the range (134.215 N – 137.961 N), (140.302 N – 146.756 N), (35.364 N – 38.175 N), and (12552.5 mm3/min – 13350.6 mm3/min) resepectively.

V. CONCLUSION

In this paper the effect of the cutting parameters on cutting force components and material removal rate during dry and wet (Castrol coolant) hard turning of AISI alloy steel with coated carbide insert was investigated. Optimum values of machining parameters have been computed using RSM design. Based on the results of the present investigations, following conclusions can be drawn:

The depth of cut has statistically the most significant effect on cutting force components during both dry and wet hard turning. The feed rate has relatively less effect on the cutting force components during both dry and wet hard turning. The cutting speed has a very small effect on the cutting forces during both dry and wet hard turning.

The three cutting force components (Fx, Fy, Fz) show decreasing trend with the decrease in cutting speed, feed rate, and depth of cut during both dry and wet hard turning.

The highest material removal rates are obtained at the highest values of cutting speed, feed rate, and depth of cut. The results showed that the depth of cut has the most significant effect on MRR. While the cutting speed has less significant effect and feed rate has the lowest significant effect on MRR.

The results indicated that RSM is very useful technique to model and to create equations for forecasting and optimizing with reasonably minimum possible experiments. It defined the degree of influence of each cutting parameters on the cutting force components and material removal rate. The approach can be recommended for optimizing hard turning and for that matter any other manufacturing process.

The optimization results suggest that within the investigated range of machining parameters, a combination of parameters with the highest level of cutting speed i.e. 250 m/min, the highest level of feed rate i.e. 0.22 mm/rev, and the lowest level of depth of cut i.e. 0.2 mm provides a good machining system stability during both dry and wet hard turning.

ACKNOWLEDGMENTS

The authors acknowledge Jamia Millia Islamia, New Delhi, India, IIT Delhi, New Delhi, India for providing facilities for conducting experiments and measurements which are reported in this paper and also Diyala University, Diyala, Iraq for providing financial assistance.

REFERENCES

[1] M. Remadna, and J- F. Rigal "Evolution during time of tool wear and cutting forces in the case of hard turning with CBN inserts" Journal of Materials Processing Technology, 2006, Vol.178, pp.67–75.

[2] E. Aslan, N. Camuscu , and B. Birgoren "Design ptimization of cutting parameters when turning hardened AISI 4140 steel (63 HRC) with Al2O3 + TiCN mixed ceramic tool. Mater" Des., 2007, Vol.28, pp.1618–1622.

[3] B.Fnides, M. A. Yallese, and H. Aouici " Hard turning of hot work steel AISI H11: Evaluation of cutting pressures, resulting force and temperature" MECHANIKA, 2008, Vol. 4, No72, pp.59-63.

[4] A. Ebrahimi, and M.M. Moshksar " Evaluation of machinability in turning of microalloyed and quenched-tempered steels: Tool wear, statistical analysis, chip morphology" Journal of materials processing technology, 2009, Vol.209, pp. 910–921.

[5] R.R. Malagi, and B.C. Rajesh " Factors Influencing Cutting Forces in Turning and Development of Software to Estimate Cutting Forces in Turning" IJEIT, 2012, Vol. 2, No.1, pp. 37-43.

[6] R. Suresh, S. Basavarajappa, V.N. Gaitonde, and G.L. Samuel "Machinability investigations on hardened AISI 4340 steel using coated carbide insert" Int. Journal of Refractory Metals and Hard Materials, 2012, Vol.33, pp. 75-86.

[7] R. Suresh , S. Basavarajappa, and G.L. Samuel "Some studies on hard turning of AISI 4340 steel using multilayer coated carbide tool" Measurement ,2012, Vol.45, pp.1872–1884.

[8] M. Thomas and Y.Beauchamp " Statistical investigation of modal parameters of cutting tools in dry turning" International Journal of Machine Tools and Manufacture, 2003, Vol.43, pp.1093–1106.

[9] A. K Kirillov, A. S. Vereshchaka, A. A. Kozlov, and Z. Yu. Robakidze "Dry Cutting of Hard-To-Machine Materials, with Compensation of the Physical Functions of the Lubricant and Coolant Fluid" Russ. Eng. Res.,2009, Vol.29, No.4, pp.433–437.

[10] D. Jianxin, Z. Jiantou, Z. Hui, and Y. Pei "Wear mechanisms of cemented carbide tools in dry cutting of precipitation hardening semi-austenitic stainless steels" Wear ,2011, Vol.270, pp.520–527.

[11] T. H. Lee " Development of a Theoretical Model to Predict Cutting Forces for Hard Machining" International Journal of Precision Engineering and Manufacturing,, 2011, Vol.12, No.5, pp.775-782.

[12] T.H. Panzera, Pa. R. Souza, J. C. C. Rubio, A. M. Abrão, and T. R. Mansur "Development of a three-component dynamometer to measure turning force" Int J Adv Manuf Technol 2011, DOI 10.1007/s00170-011-3866-5.

[13] A.G.F. Alabi, T.K. Ajiboye, and H.D. Olusegun "Investigating the cutting forces in heat treated medium carbon steel when turning on a lathe machine" Design and Technology, 2009, Vol.8, No.1, pp.80 - 93.

[14] B. Sieben, T. Wagner, and D. Biermann " Empirical modeling of hard turning of AISI 6150 steel using design and analysis of computer experiments" Prod. Eng. Res. Devel, 2010, Vol.4, pp.115–125.

[15] A.I. Fernández-Abia, J. Barreiro, L. N. López de Lacalle, and S. Martínez " Effect of very high cutting speeds on shearing, cutting forces and roughness in dry turning of austenitic stainless steels" Int J Adv Manuf Technol, 2011, Vol.57, pp.61–71.

[16] P.V. Krishna, R. R Srikant, and D.N. Rao "Experimental investigation to study the performance of solid lubricants in turning of AISI1040 steel" JET, 2010, Vol.224, pp.1273-1281.

[17] N. E. Stakhniv, L. N. Devin, I. A. Petrusha, and A. S. Osipov " Dynamic Phenomena in Finish Turning of Hardened Steels with cBN_Based Tools" Journal of Superhard Materials, 2009, Vol.31, No3, pp.196–202.

[18] V. S. Sharma , S. Dhiman , R. Sehgal , and S. K. Sharma " Estimation of cutting forces and surface roughness for hard turning using neural networks" J Intell Manuf, 2008, Vol.19, pp.473–483.

[19] HE.Xinfeng , WU Su, and H. Kratz "Forces in Hard Turning of 51CrV4 with Wiper Cutting Tool" Tsinghua Science and Technology, 2006, Vol.11, No.5, pp.501-506.

[20] K. Hassan, A. Kumar, and M.P. Garg " Experimental investigation of Material removal rate in CNC turning using Taguchi method" IJ Engineering Research and Applications, 2012, Vol.2, No.2, pp.1581-1590

[21] C. Courbon, D. Kramar, P. Krajnik, F .Pusavec b, J. Rech, and J. Kopac " Investigation of machining performance in high-pressure jet assisted turning of Inconel 718: An experimental study" International Journal of Machine Tools & Manufacture, 2009, Vol.49, pp.1114–1125.

[22] K. Bouacha, M. A. Yallese , T. Mabrouki, and J-F. Rigal " Statistical analysis of surface roughness and cutting forces using response surface methodology in hard turning of AISI 52100 bearing steel with CBN tool"Int. Journal of Refractory Metals and Hard Materials, 2010, Vol.28, pp.349–361.

[23] H. Aouici, M,A. Yallese, K. Chaoui, T. Mabrouki, and J-F. Rigal "Analysis of surface roughness and cutting force components in hard turning with CBN tool: Prediction model and cutting conditions optimization" Measurement , 2012, Vol.45, pp.344–353.

[24] S.Saini, I. S. Ahuja , and V.S. Sharma "Modelling the effects of cutting parameters on residual stresses in hard turning of AISI H11 tool steel. Int J Adv Manuf Technol, 2012, DOI 10.1007/s00170-012-4206-0.

[25] H. Joardar, N.S.Das, and G. Sutradhar " An experimental study of effect of process parameters in turning of LM6/SiCP metal matrix composite and its prediction using response surface methodology" International Journal of Engineering Science and Technology, 20113, Vol.8, pp.132-141.

[26] B. Fnides, M. A. Yallese, T. Mabrouki, and J-F Rigal " Application of response surface methodology for determining cutting force model in turning hardened AISI H11 hot work tool steel" Sadhana, 20113, Vol.6, No.1, pp.109–123.

[27] H. Aouici, M. A. Yallese, B. Fnides, K. Chaoui, and T. Mabrouki " Modeling and optimization of hard turning of X38CrMoV5-1 steel with CBN tool Machining parameters effects on flank wear and surface roughness" Journal of Mechanical Science and Technology, 2011, Vol.25, pp.2843-2851.

[28] S. D. Renzo, P. A. Marques, G. Ambrogio, D. Umbrello, P. M. Saraiva, and J. G. Requeijo " White and Dark Layer Analysis Using Response Surface Methodology" International Journal Total Quality Management and Excellence, 2012, Vol.39, No.4, pp.1335-1340.

[29] A. Srinivasan, R.M. Arunachalam, S. Ramesh and J.S. Senthilkumaar " Machining Performance Study on Metal Matrix Composites-A Response Surface Methodology Approach" American Journal of Applied Sciences, 2012, Vol.9, No.4, pp.478-483.

Table1. Chemical composition of work material AISI 52100 Alloy steel

C	Si	Mn	S	P	Ni	Cr	Mo	Cu	Fe
0.98	0.28	0.57	0.026	0.023	0.141	1.12	0.081	0.042	Balance

Table2. Cutting parameters are used in turning tests

Cutting parameters	**symbol**	**unit**	**Level-1**	**Level-2**	**Level-3**
Cutting speed	*A*	(m/min)	100	175	250
Feed rate	*B*	(mm/rev)	0.1	0.16	0.22
Depth of cut	*C*	(mm)	0.2	0.6	1

Table3. Experimental results of cutting force components and material removal rate in dry hard turning

Cutting parameters				**Response parameters**			
Run	***A* (m/min)**	***B* (mm/rev)**	***C* (mm)**	**Fx(N)**	**Fy(N)**	**Fz(N)**	**MRR (mm^3/min)**
1	175.00	0.16	0.20	130.7	123.1	39.29	5600
2	100.00	0.10	0.20	96.37	97.03	32.17	2000
3	175.00	0.10	0.60	191.5	231.6	137.7	10500
4	100.00	0.22	1.00	289.6	628.2	301.7	22000
5	175.00	0.16	0.60	224.5	316.2	153.7	16800
6	175.00	0.16	0.60	224.3	318.3	154.2	16800
7	175.00	0.16	0.60	222.2	314.5	152.3	16800
8	175.00	0.16	1.00	255.2	497.2	275.5	28000
9	175.00	0.16	0.60	223.2	315.8	153.3	16800
10	250.00	0.16	0.60	225.4	306.6	150.7	24000
11	250.00	0.22	1.00	288.6	598	285.1	55000
12	250.00	0.10	0.20	115.7	90.21	37.01	5000
13	175.00	0.16	0.60	229.7	316.5	156.9	16800
14	175.00	0.16	0.60	227.2	318.1	156.4	16800
15	100.00	0.10	1.00	199.5	382.3	244.2	10000
16	250.00	0.10	1.00	218.8	354.2	242.6	25000
17	175.00	0.22	0.60	255.3	388.1	165.8	23100
18	250.00	0.22	0.20	144.9	131.6	39.32	11000
19	100.00	0.22	0.20	139	152.7	39.26	4400
20	100.00	0.16	0.60	206.6	319.9	145.5	9600

Table4. Experimental results of cutting force components and material removal rate in wet hard turning

Cutting parameters				**Response parameters**			
Run	***A* (m/min)**	***B* (mm/rev)**	***C* (mm)**	**Fx(N)**	**Fy(N)**	**Fz(N)**	**MRR (mm^3/min)**
1	175.00	0.16	0.20	113.8	118.2	35.3	5600
2	100.00	0.10	0.20	81.16	90.59	27.76	2000
3	175.00	0.10	0.60	172.2	230.4	127.8	10500
4	100.00	0.22	1.00	265	632.7	284.7	22000
5	175.00	0.16	0.60	202	311.5	142.9	16800
6	175.00	0.16	0.60	203	311.5	143.4	16800
7	175.00	0.16	0.60	203.1	312.1	143.4	16800
8	175.00	0.16	1.00	236.4	503.6	270.5	28000
9	175.00	0.16	0.60	204.2	313.4	144.1	16800
10	250.00	0.16	0.60	208.4	304.6	143.6	24000
11	250.00	0.22	1.00	275.5	614	280.2	55000
12	250.00	0.10	0.20	103.6	84.52	32.44	5000
13	175.00	0.16	0.60	201.5	308.5	141.7	16800
14	175.00	0.16	0.60	204.2	313.8	144.7	16800
15	100.00	0.10	1.00	195.1	385.6	237.3	10000
16	250.00	0.10	1.00	205.9	360.8	240.8	25000
17	175.00	0.22	0.60	228	383.3	151.4	23100
18	250.00	0.22	0.20	133.3	139.9	36.84	11000
19	100.00	0.22	0.20	116.1	146.5	31.92	4400
20	100.00	0.16	0.60	195.1	320.9	140.3	9600

Table5. ANOVA results of thrust force Fx in dry turning

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	55668.12	9	6185.35	668.05	< 0.0001
A	388.50	1	388.50	41.96	< 0.0001
B	8733.80	1	8733.80	943.29	< 0.0001
C	39066.25	1	39066.25	4219.33	< 0.0001
A^2	155.49	1	155.49	16.79	0.0022
B^2	0.039	1	0.039	4.245E-003	0.9493
C^2	2569.87	1	2569.87	277.56	< 0.0001
AB	142.21	1	142.21	15.36	0.0029
AC	6.00	1	6.00	0.65	0.4394
BC	969.54	1	969.54	104.71	< 0.0001
Residual	92.59	10	9.26		
Lack of Fit	54.04	5	10.81	1.40	
Pure Error	38.55	5	7.71		
Cor Total	55760.71	19			
Std. Dev. = 3.04		R-Squared = 0.9983			
Mean = 205.41		Adj R-Square = 0.9968			
C.V. = 1.48		Pred R-Squared = 0.9905			
PRESS = 528.42		Adeq Precision = 91.363			

Table 6. ANOVA results of thrust force Fx in wet turning

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	52141.34	9	5793.48	2115.39	< 0.0001
A	551.16	1	551.16	201.25	< 0.0001
B	6756.88	1	6756.88	2467.16	< 0.0001
C	39682.44	1	39682.44	14489.38	< 0.0001
A^2	2.15	1	2.15	0.78	0.3967
B^2	17.65	1	17.65	6.45	0.0294
C^2	2084.78	1	2084.78	761.22	< 0.0001
AB	3.84	1	3.84	1.40	0.2640
AC	42.04	1	42.04	15.35	0.0029
BC	700.50	1	700.50	255.78	< 0.0001
Residual	27.39	10	2.74		
Lack of Fit	21.25	5	4.25	3.46	0.0996
Pure Error	6.14	5	1.23		
Cor Total	52168.73	19			
Std. Dev. = 1.65		R-Squared = 0.9995			
Mean = 187.38		Adj R-Square = 0.9990			
C.V. = 0.88		Pred R-Squared = 0.9958			
PRESS = 218.88		Adeq Precision = 164.779			

Table7. ANOVA results of tangential force Fy in dry turning

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	4.241E+005	9	47123.03	4579.50	< 0.0001
A	990.42	1	990.42	96.25	< 0.0001
B	55243.42	1	55243.42	5368.67	< 0.0001
C	3.479E+005	1	3.479E+005	33811.45	< 0.0001
A^2	8.94	1	8.94	0.87	0.3733
B^2	74.44	1	74.44	7.23	0.0227
C^2	66.10	1	66.10	6.42	0.0296
AB	33.54	1	33.54	3.26	0.1012
AC	115.37	1	115.37	11.21	0.0074
BC	19270.77	1	19270.77	1872.77	< 0.0001
Residual	102.90	10	10.29		
Lack of Fit	92.55	5	18.51	8.94	0.1387
Pure Error	10.35	5	2.07		
Cor Total	4.242E+005	19			
Std. Dev. = 3.21		R-Squared = 0.9998			
Mean = 301.01		Adj R-Square = 0.9995			
C.V.= 1.03		Pred R-Squared = 0.9977			
PRESS = 994.16		Adeq Precision = 238.777			

Table 8. ANOVA results of tangential force Fy in wet turning

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	4.456E+005	9	49513.43	17835.92	< 0.0001
A	525.19	1	525.19	189.19	< 0.0001
B	58444.50	1	58444.50	21053.10	< 0.0001
C	3.675E+005	1	3.675E+005	1.324E+005	< 0.0001
A^2	2.34	1	2.34	0.84	0.3798
B^2	68.11	1	68.11	24.54	0.0006
C^2	2.36	1	2.36	0.85	0.3780
AB	3.88	1	3.88	1.40	0.2646
AC	118.81	1	118.81	42.80	< 0.0001
BC	18916.10	1	18916.10	6814.03	< 0.0001
Residual	27.76	10	2.78		
Lack of Fit	10.04	5	2.01	0.57	0.7259
Pure Error	17.72	5	3.54		
Cor Total	4.456E+005	19			
Std. Dev. = 1.67		R-Squared = 0.9999			
Mean = 309.32		Adj R-Square = 0.9999			
C.V. = 0.54		Pred R-Squared = 0.9996			
PRESS = 186.52		Adeq Precision = 467.506			

Table 9. ANOVA results of feed force Fz in dry turning

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	1.382E+005	9	15352.20	2019.01	< 0.0001
A	6.56	1	6.56	0.86	0.3748
B	1890.63	1	1890.63	248.64	< 0.0001
C	1.350E+005	1	1.350E+005	17758.93	< 0.0001
A^2	62.88	1	62.88	8.27	0.0165
B^2	3.52	1	3.52	0.46	0.5115
C^2	56.01	1	56.01	7.37	0.0218
AB	48.91	1	48.91	6.43	0.0296
AC	66.70	1	66.70	8.77	0.0142
BC	1026.05	1	1026.05	134.94	< 0.0001
Residual	76.04	10	7.60		
Lack of Fit	59.67	5	11.93	3.64	0.0911
Pure Error	16.37	5	3.27		
Cor Total	1.382E+005	19			
Std. Dev. = 2.76		R-Squared = 0.9994			
Mean = 153.13		Adj R-Square = 0.9990			
C.V. = 1.80		Pred R-Squared = 0.9952			
PRESS = 658.36		Adeq Precision = 138.795			

Table 10. ANOVA results of feed force Fz in wet turning

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	1.345E+005	9	14947.36	4542.40	< 0.0001
A	14.16	1	14.16	4.30	0.0648
B	1415.15	1	1415.15	430.05	< 0.0001
C	1.321E+005	1	1.321E+005	40136.80	< 0.0001
A^2	9.52	1	9.52	2.89	0.1197
B^2	48.76	1	48.76	14.82	0.0032
C^2	227.18	1	227.18	69.04	< 0.0001
AB	7.53	1	7.53	2.29	0.1614
AC	14.05	1	14.05	4.27	0.0657
BC	765.19	1	765.19	232.54	< 0.0001
Residual	32.91	10	3.29		
Lack of Fit	27.59	5	5.52	5.19	0.0474
Pure Error	5.31	5	1.06		
Cor Total	1.346E+005	19			
Std. Dev. = 1.81		R-Squared = 0.9998			
Mean = 145.05		Adj R-Square = 0.9995			
C.V. = 1.25		Pred R-Squared = 0.9974			
PRESS = 351.23		Adeq Precision = 201.318			

Table 11. ANOVA results of Material Removal Rate MRR

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	2.553E+009	6	4.256E+008	213.45	< 0.0001
A	5.184E+008	1	5.184E+008	260.00	< 0.0001
B	3.969E+008	1	3.969E+008	199.06	< 0.0001
C	1.254E+009	1	1.254E+009	629.14	< 0.0001
AB	5.832E+007	1	5.832E+007	29.25	< 0.0001
AC	1.843E+008	1	1.843E+008	92.44	< 0.0001
BC	1.411E+008	1	1.411E+008	70.78	< 0.0001
Residual	2.592E+007	13	1.994E+006		
Lack of Fit	2.592E+007	8	3.240E+006		
Pure Error	0.000	5	0.000		
Cor Total	2.579E+009	19			
Std. Dev. = 1412.04		R-Squared = 0.9900			
Mean = 16800		Adj R-Square = 0.9853			
C.V. = 8.40		Pred R-Squared = 0.8671			
PRESS = 3.427E+008		Adeq Precision = 60.572			

Table12. Optimization of cutting parameters for cutting forces and MRR for dry turning

No.	Cutting speed (m/min)	feed rate (mm/rev)	depth of cut(mm)	Fx(N)	Fy(N)	Fz(N)	MRR (mm^3/min)	Desirability
1	250.00	0.22	0.20	145.633	135.293	38.602	12860.3	0.608
2	250.00	0.22	0.21	147.354	138.414	40.098	13121.3	0.608
3	250.00	0.22	0.21	149.615	142.539	42.077	13466.6	0.608
4	249.34	0.22	0.21	149.074	141.458	41.596	13321.4	0.607
5	250.00	0.22	0.22	153.406	149.523	45.438	14051.6	0.607
6	250.00	0.22	0.20	144.849	134.218	38.319	12668.9	0.606
7	248.07	0.22	0.23	154.82	151.884	46.686	14083.9	0.604
8	244.44	0.22	0.21	149.193	141.066	41.668	12883.5	0.601

Table13. Optimization of cutting parameters for cutting forces and MRR for wet turning:

No.	Cutting speed (m/min)	feed rate (mm/rev)	depth of cut (mm)	Fx (N)	Fy (N)	Fz (N)	MRR	Desirability
1	250.00	0.22	0.21	136.798	144.52	37.183	13161.3	0.599
2	250.00	0.22	0.21	137.961	146.756	38.175	13350.6	0.599
3	250.00	0.22	0.20	135.098	141.265	35.743	12885.3	0.599
4	248.62	0.22	0.20	134.467	140.333	35.364	12711.2	0.598
5	250.00	0.22	0.21	136.654	144.299	37.598	13037.3	0.598
6	247.66	0.22	0.21	136.552	144.51	37.232	12996.3	0.597
7	246.36	0.22	0.20	134.215	140.302	35.400	12552.5	0.596
8	250.00	0.22	0.21	135.894	142.923	37.710	12772.2	0.595

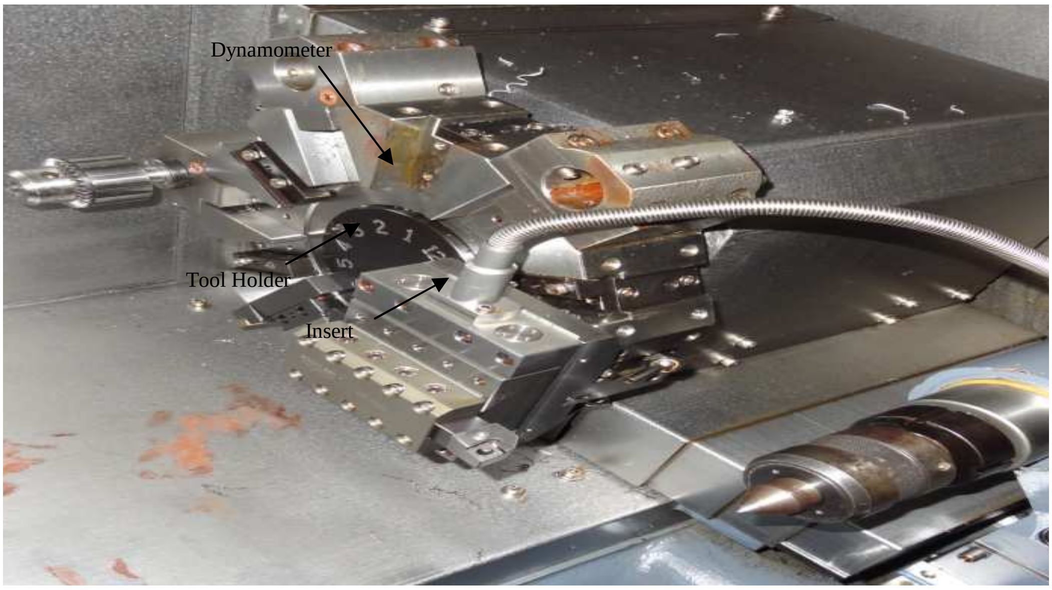

Figure1. Tool insert and piezoelectric dynamometer in CNC lathe machine

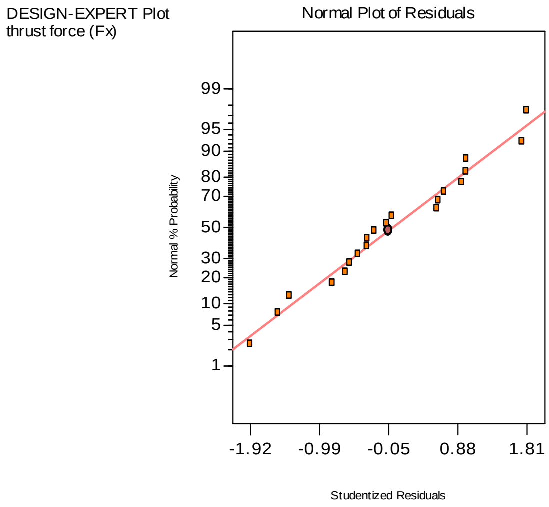

Figure2. Normal plot of residuals in dry turning

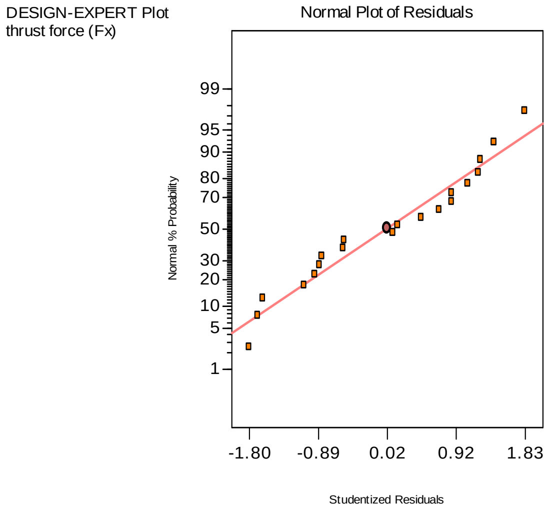

Figure3. Normal plot of residuals in wet turning

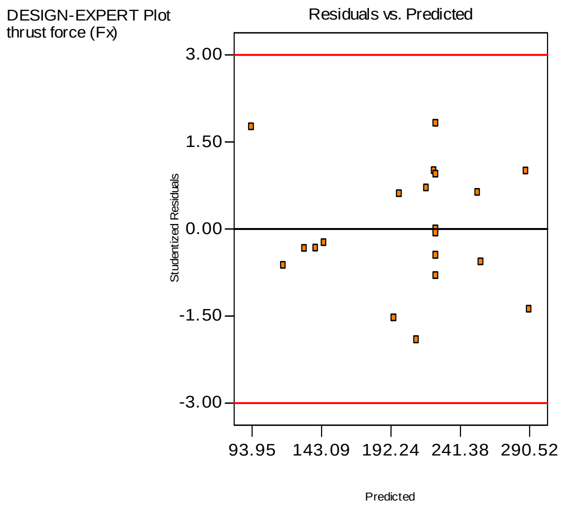

Figure4 Plot of residuals vs. predicted response in dry turning

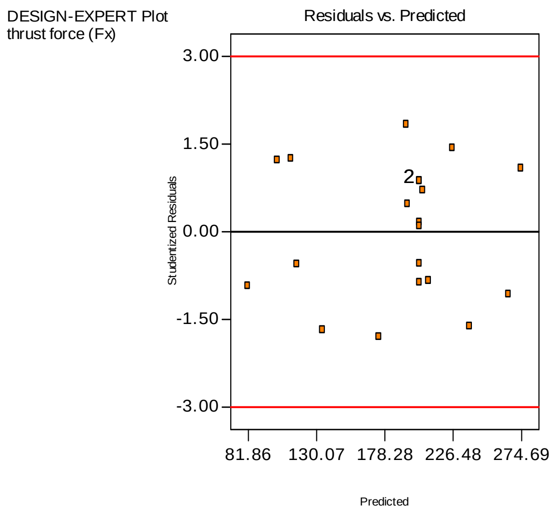

Figure5 Plot of residuals vs. predicted response in wet turning

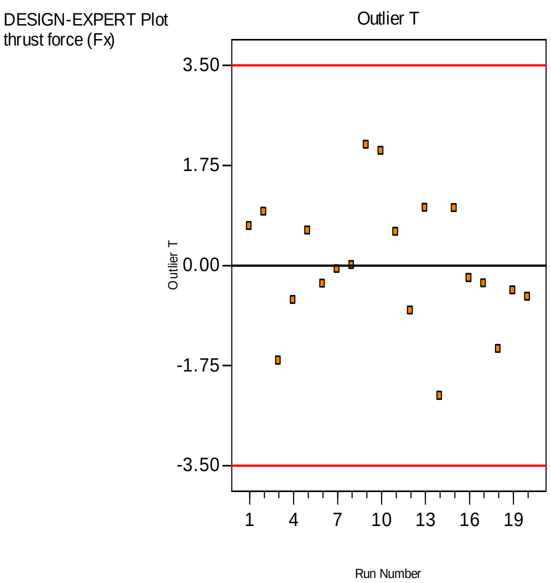

Figure6. Plot of outlier T in dry turning

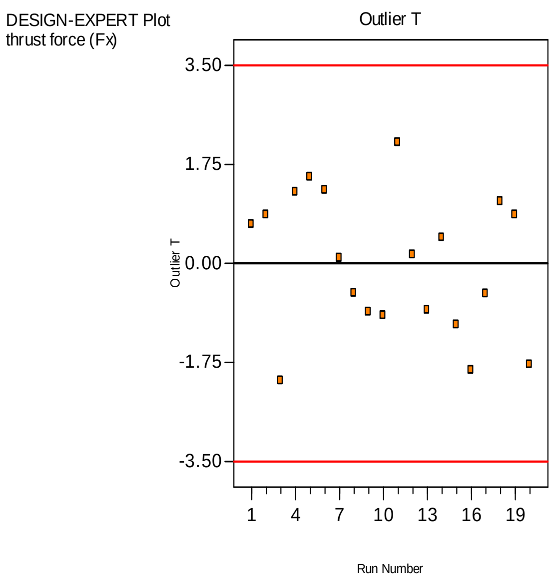

Figure7. Plot of outlier T in wet turning

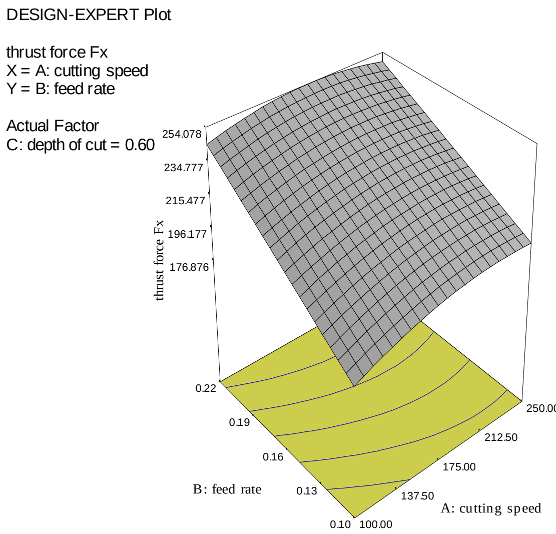

Figure8. Effect of cutting speed and feed on Fx in dry turning

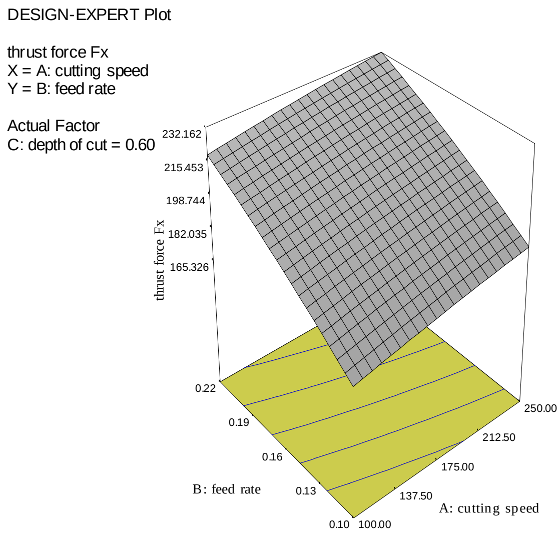

Figure9. Effect of cutting speed and feed on Fx in wet turning

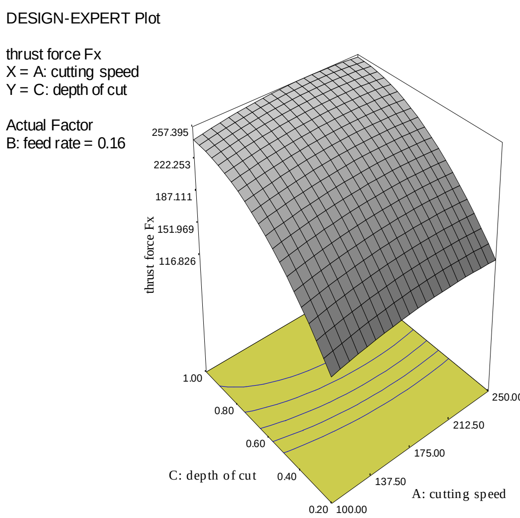

Figure10. Effect of cutting speed and depth of cut on Fx in dry cutting

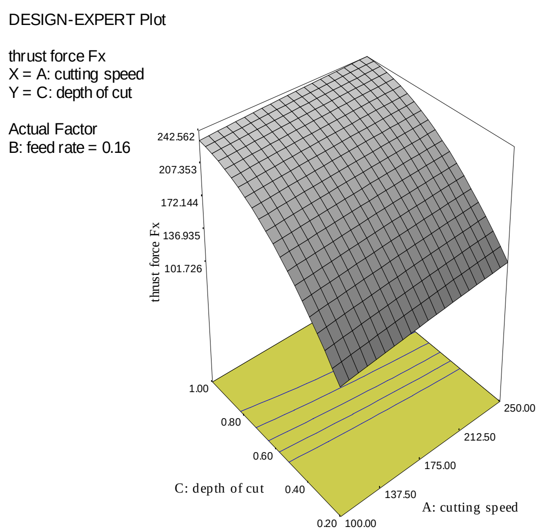

Figure11. Effect of cutting speed and depth of cut on Fx in wet turning

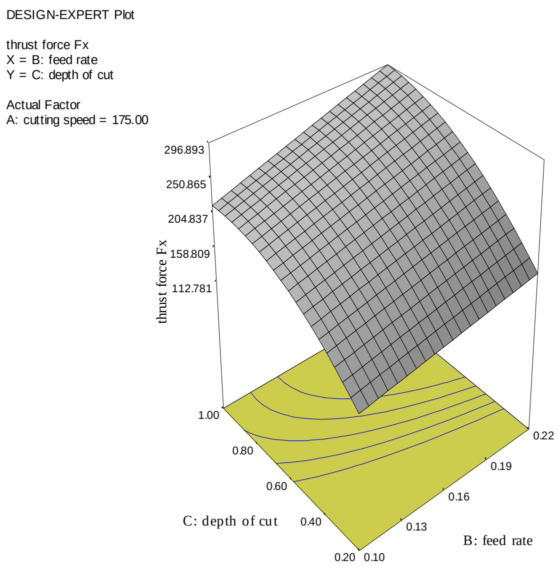

Figure12. Effect of feed and depth of cut on Fx in dry turning

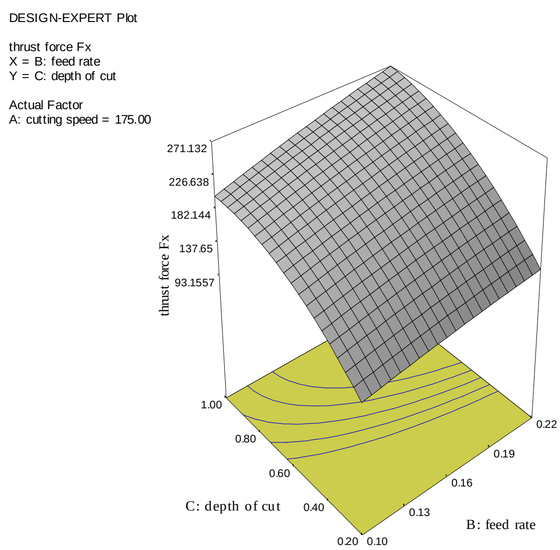

Figure13. Effect of feed and depth of cut on Fx in wet turning

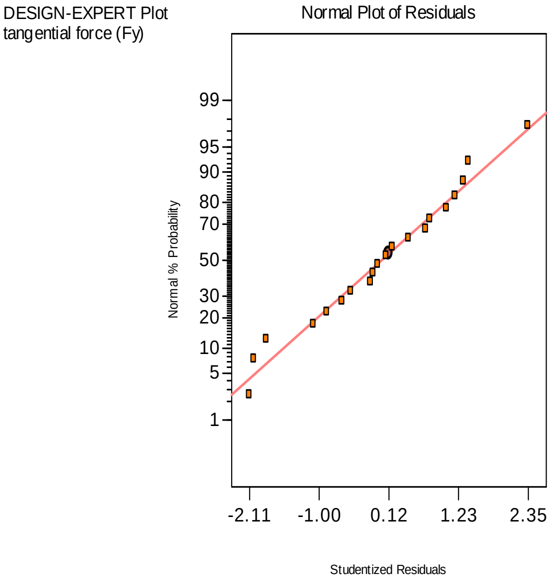

Figure14. Normal plot of residuals response in dry turning

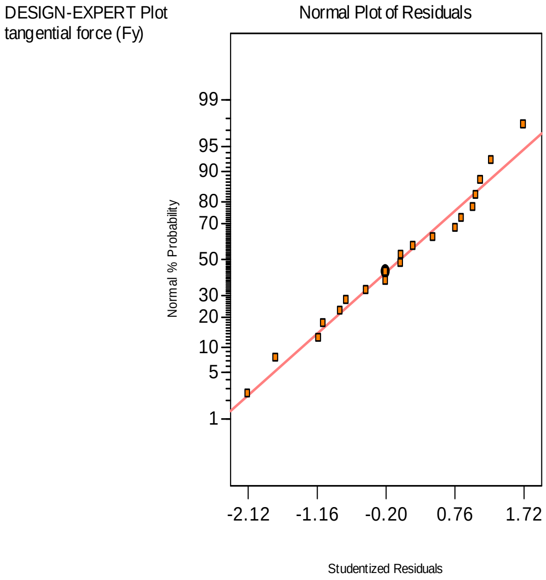

Figure15. Normal plot of residuals response in wet turning

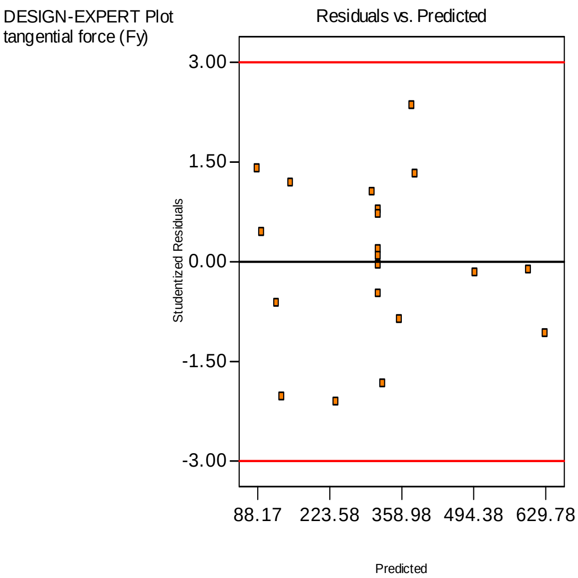

Figure16. Plot of residuals vs. predicted response in dry turning

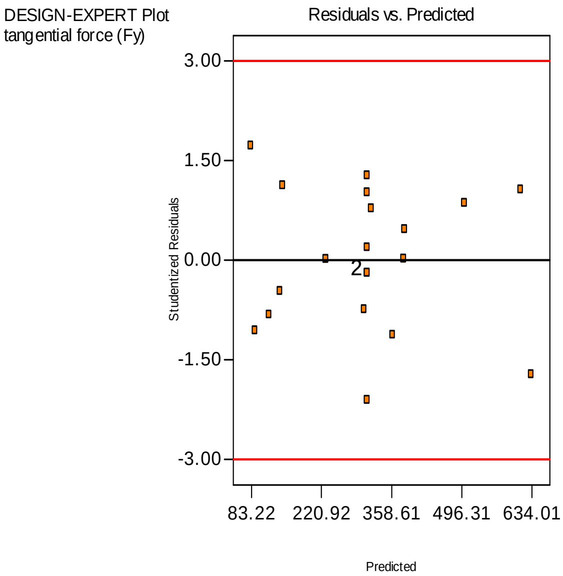

Figure17. Plot of residuals vs. predicted response in wet turning

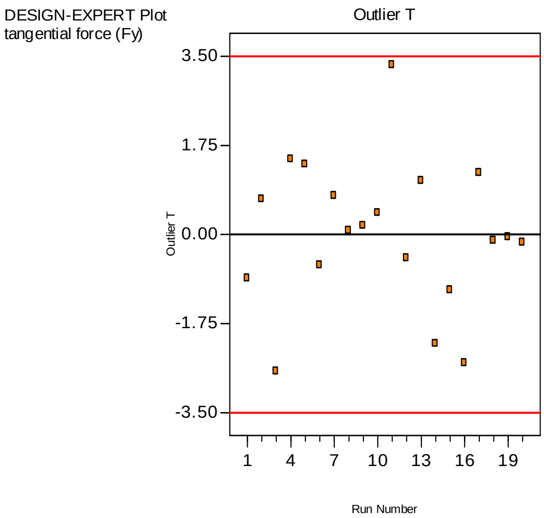

Figure18. Plot of outlier T in dry turning

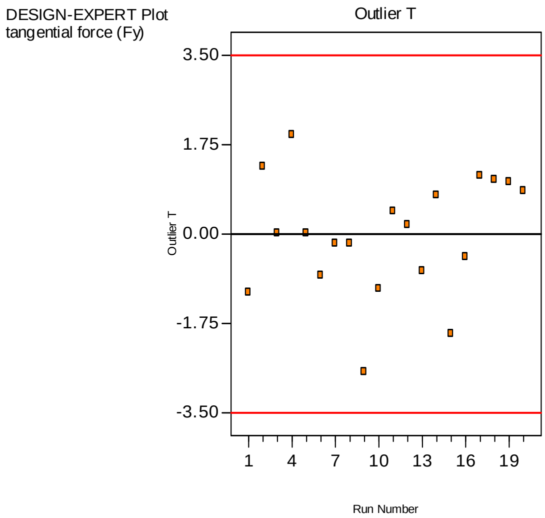

Figure19. Plot of outlier T in wet turning

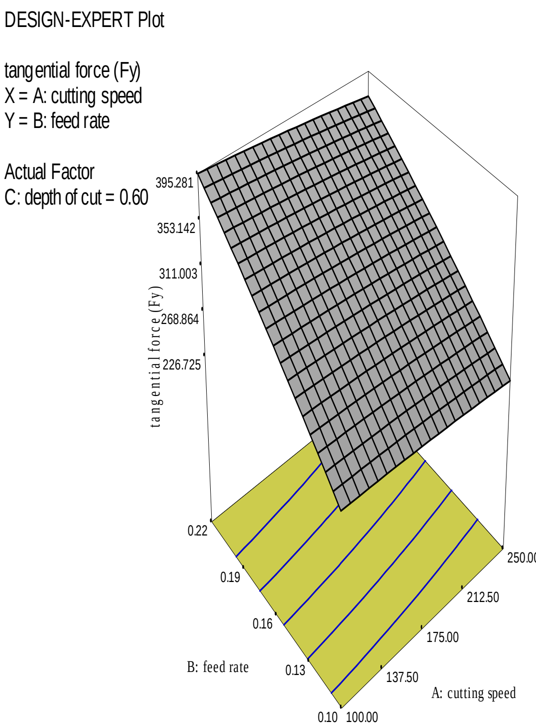

Figure20. Effect of cutting speed and feed on Fy in dry turning

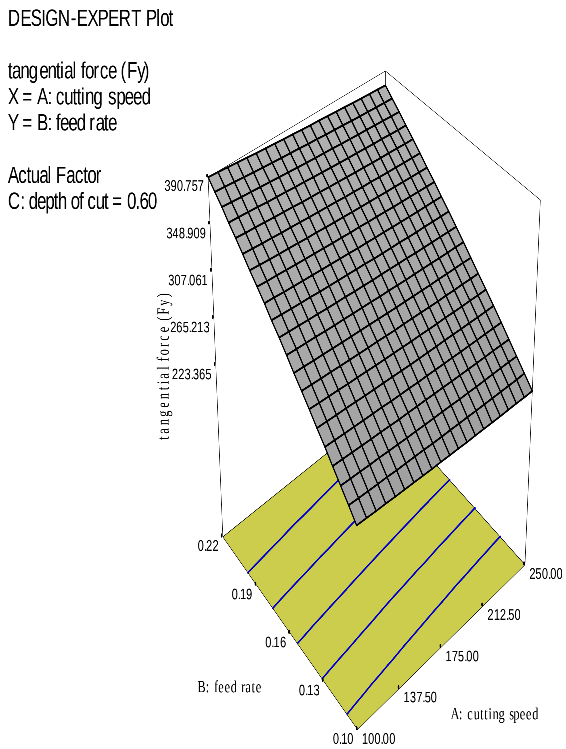

Figure21. Effect of cutting speed and feed on Fy in wet turning

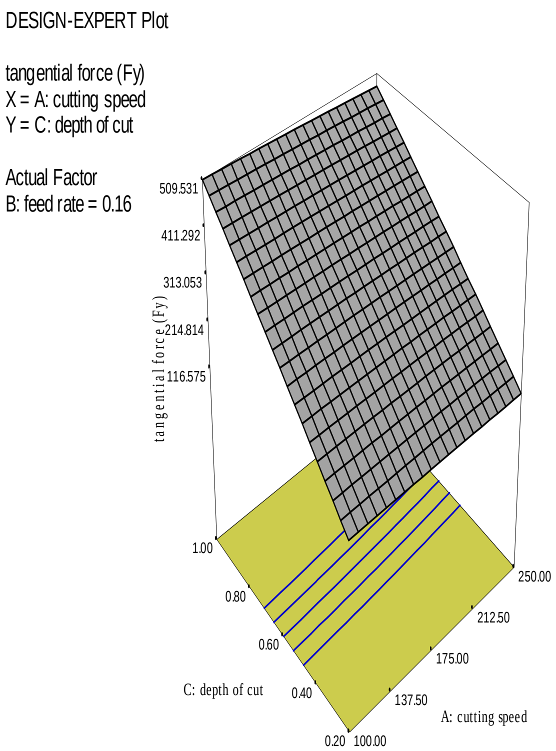

Figure22. Effect of cutting speed and depth of cut on Fy in dry cutting

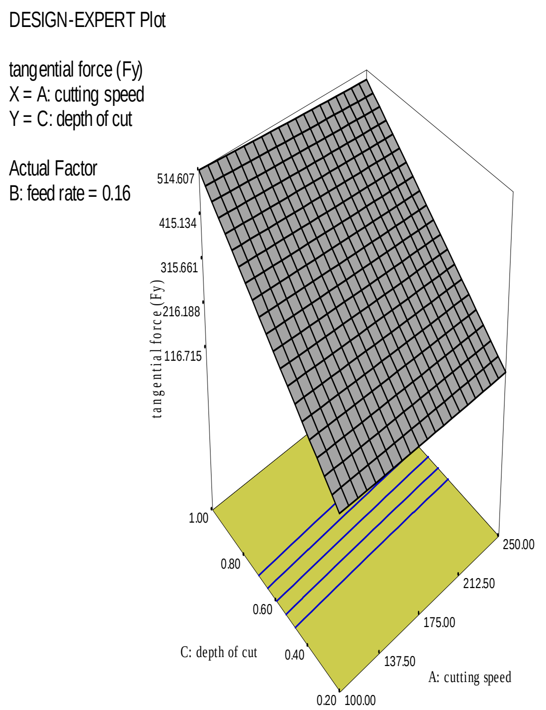

Figure23. Effect of cutting speed and depth of cut on Fy in wet turning

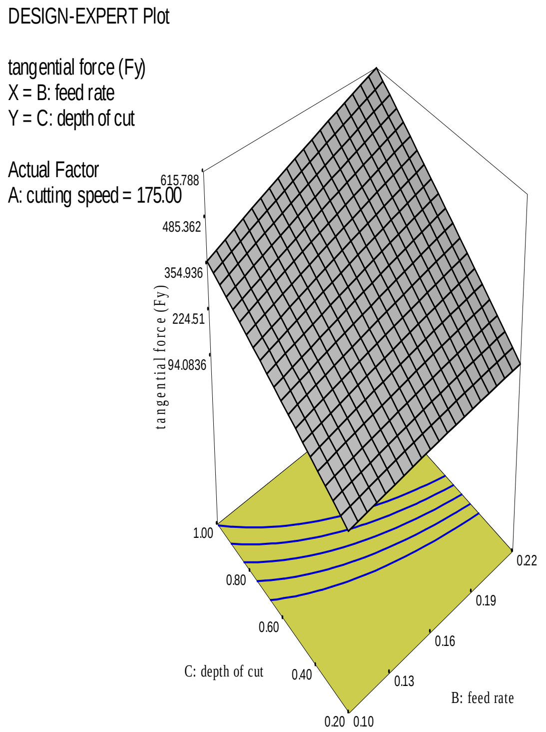

Figure24. Effect of feed and depth of cut on Fy in dry turning

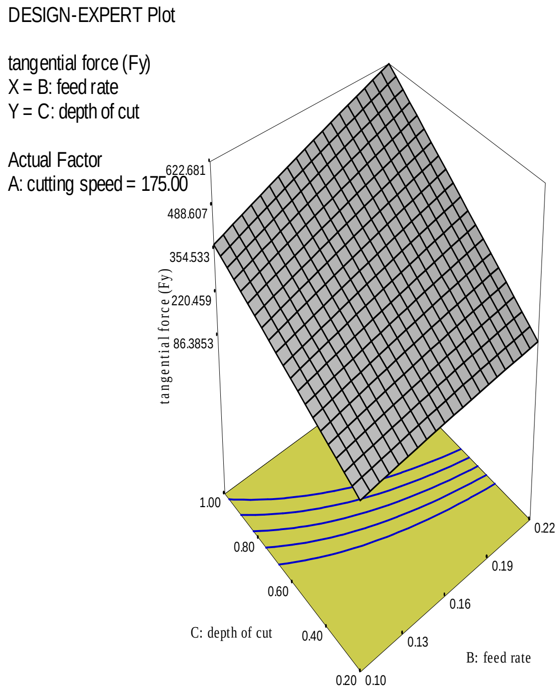

Figure25. Effect of feed and depth of cut on Fy in wet turning

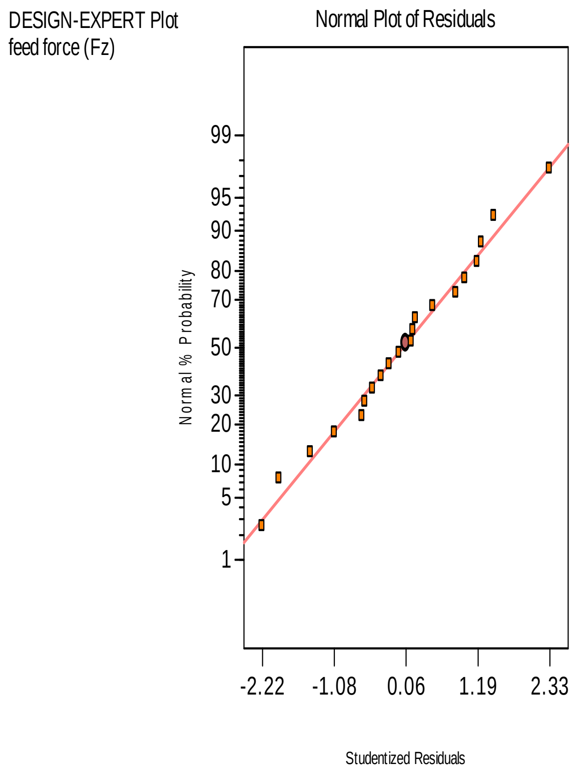

Figure26. Normal plot of residuals response in dry turning

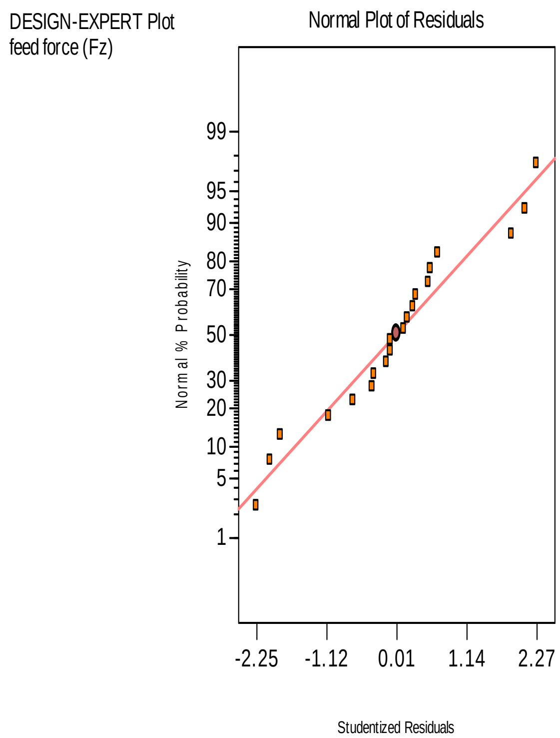

Figure27. Normal plot of residuals response in wet turning

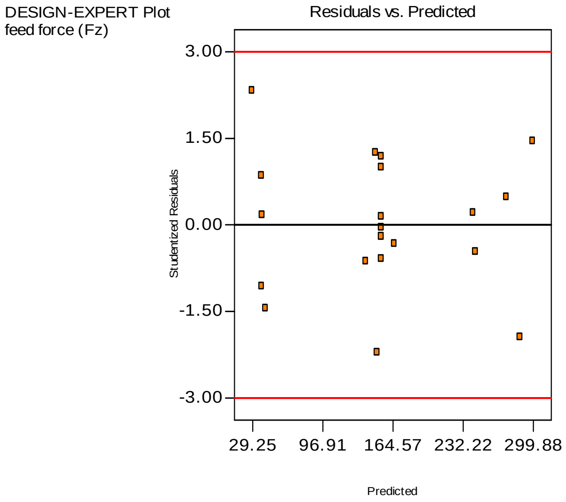

Figure28. Plot of residuals vs. predicted response in dry turning

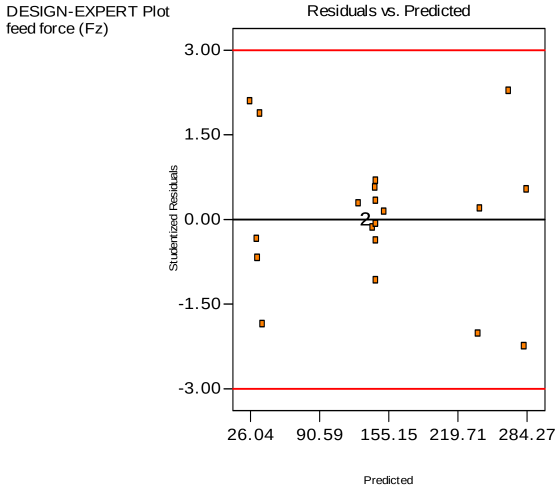

Figure29. Plot of residuals vs. predicted response in wet turning

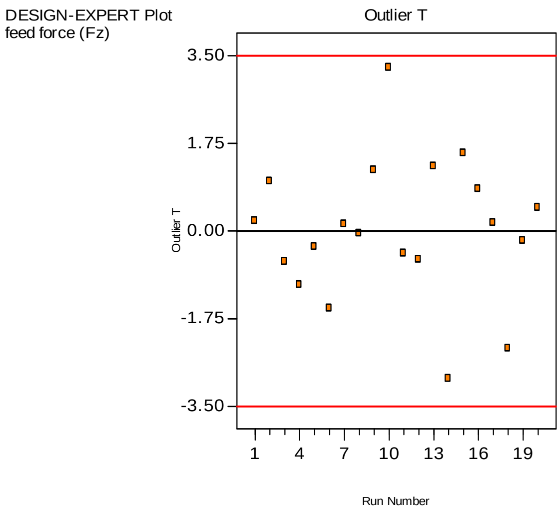

Figure30. Plot of outlier T during dry turning

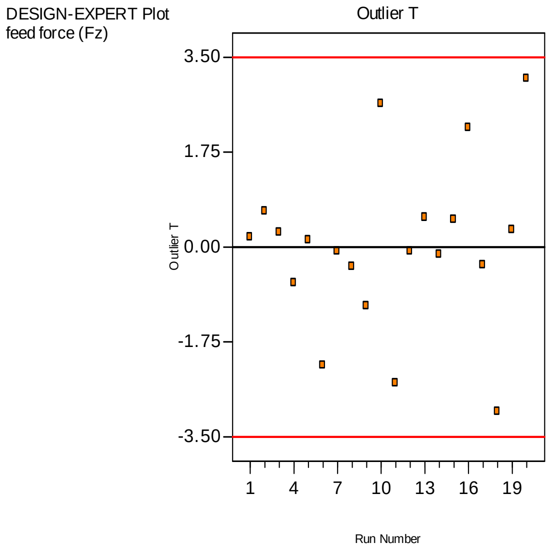

Figure31. Plot of outlier T during wet turning

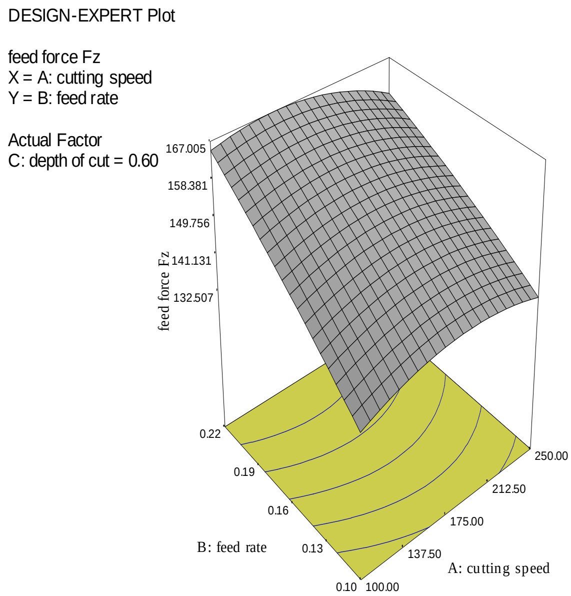

Figure32. Effect of cutting speed and feed on Fz in dry turning

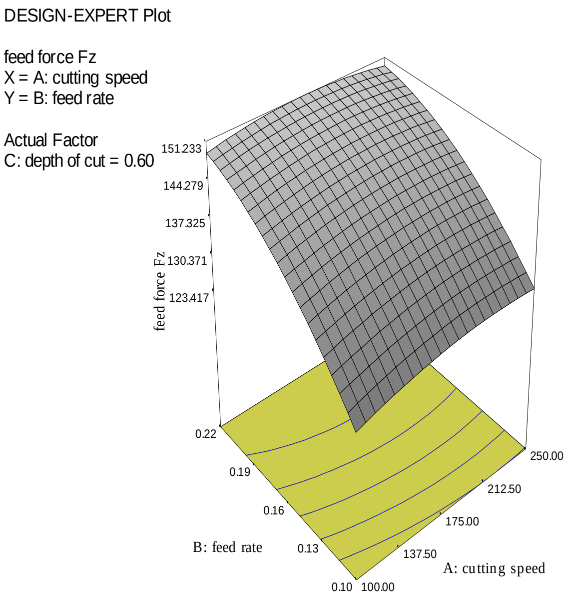

Figure33. Effect of cutting speed and feed on Fz in wet turning

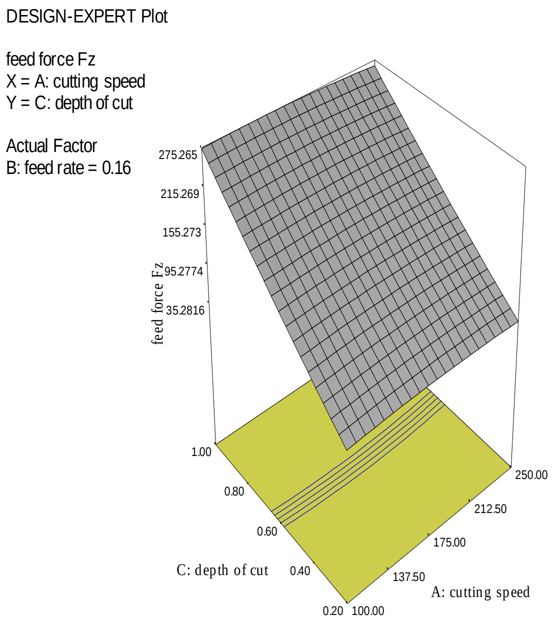

Figure34. Effect of cutting speed and depth of cut on Fz in dry cutting

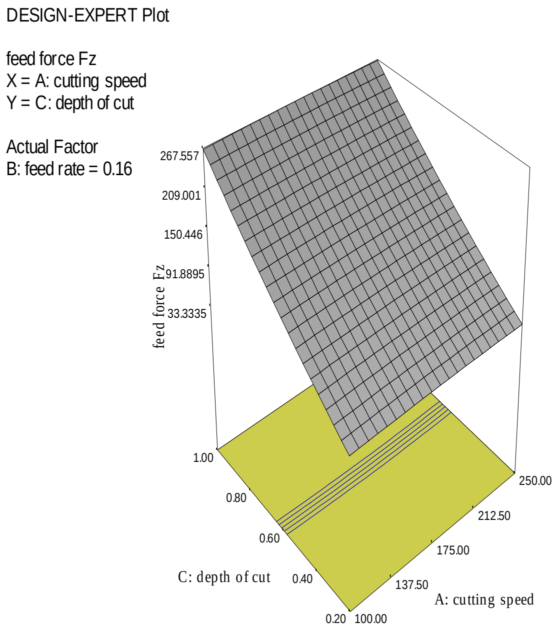

Figure35. Effect of cutting speed and depth of cut on Fz in wet turning

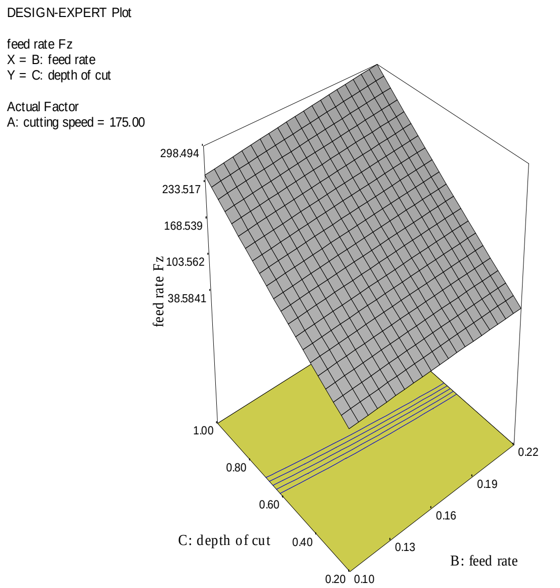

Figure36. Effect of feed and depth of cut on Fz in dry turning

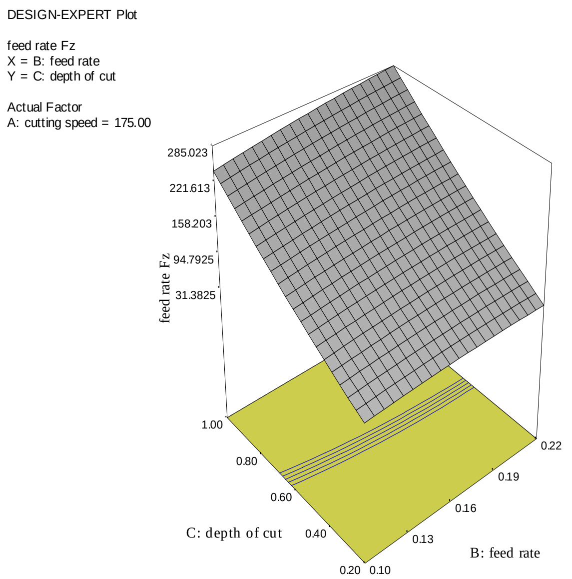

Figure37. Effect of feed and depth of cut on Fz in wet turning

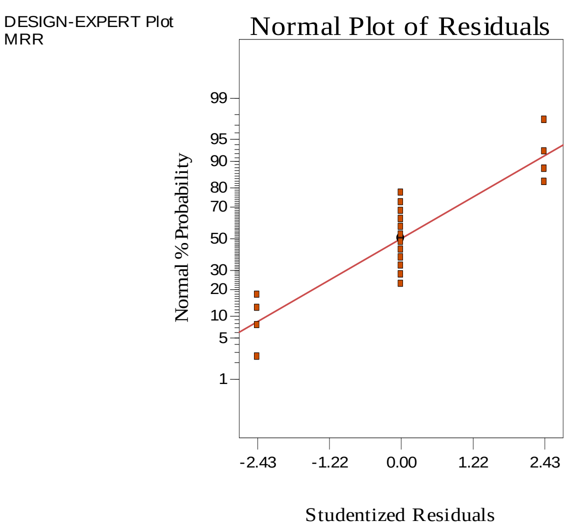

Figure38. Normal plot of residuals

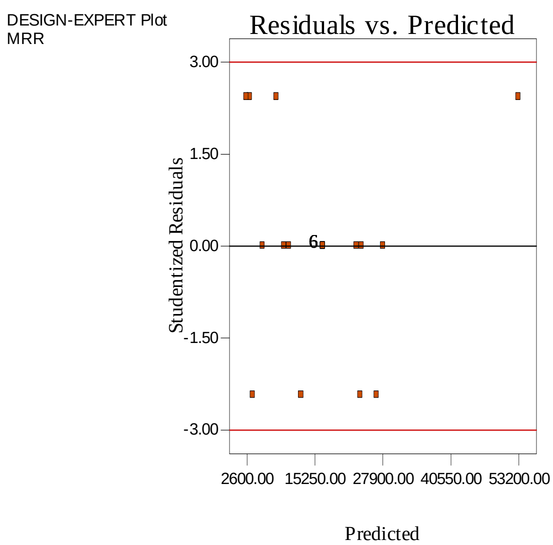

Figure39. Plot of residuals vs. predicted response

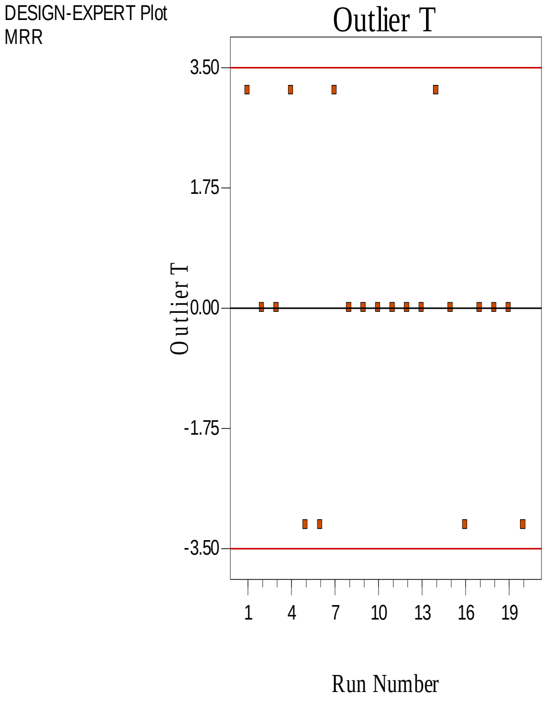

Figure40. Plot of outlier T

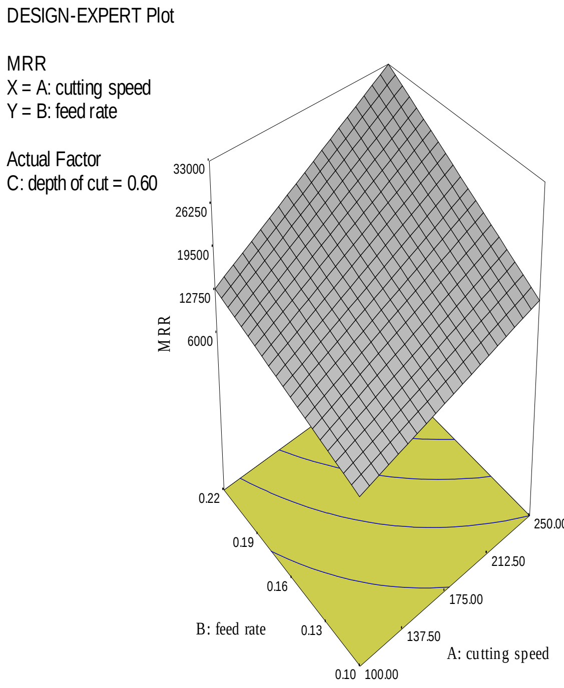

Figure 41. Effect of cutting speed and feed on MRR

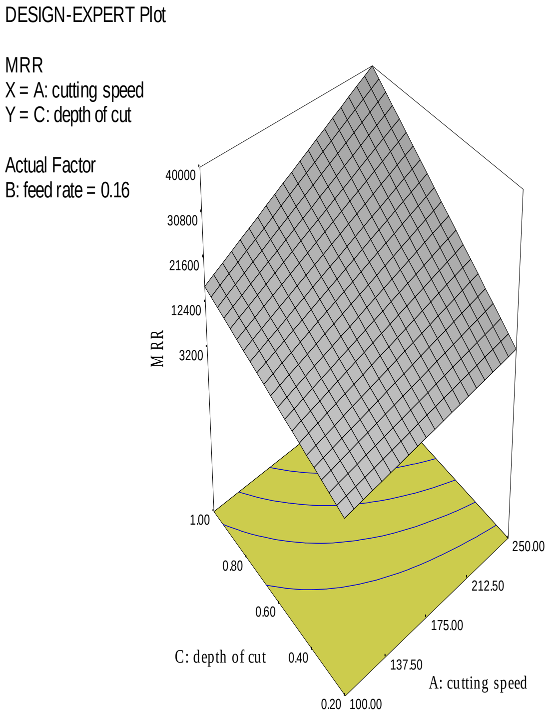

Figure42. Effect of cutting speed and depth of cut on MRR

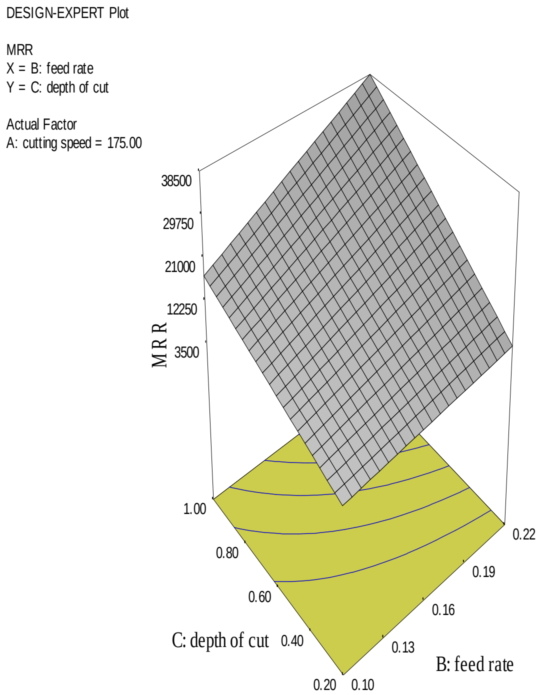

Figure43. effect of feed and depth of cut on MRR