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Research Article

Cryogenic Hard Turning of Alloy Steel with Multilayer Hard Surface Coatings ($TiN/TiCN/Al_2O_3/TiN$) insert using RSM.

Suha K. Shihab[Á] *, Zahid A. Khan[Á], Aas Mohammad[Á] and Arshad Noor Siddiquee[Á]

[Á]Department of Mechanical Engineering, Jamia Millia Islamia University, New Delhi, India

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Abstract

This paper investigates the effect of different cutting parameters (cutting speed, feed rate, and depth of cut) on cutting forces in cryogenic hard turning processes. The workpiece material, hardened alloy steel AISI 52100, was machined on a CNC lathe with multilayer hard surface coatings ($TiN/TiCN/Al_2O_3/TiN$) insert 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 forces. 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. The results indicated that cutting forces are influenced principally by the cutting speed, feed rate and depth of cut. The ranges for best cutting parameters and model equations to predict the cutting forces were proposed. Confirmation experiments were performed to verify the pertinence of the developed empirical models. Finally, the optimum machining conditions to produce the minimum cutting forces under these experimental conditions were searched using desirability function approach for response factors optimization

Keywords: *Cryogenic, Cutting forces, Hard turning, Alloy steel, RSM.*

1. Introduction

Hardened steel such as AISI 52100 finds application in the manufacturing of components in automotive, gear, bearing, tool and die making industry. Automated and flexible manufacturing systems along with computerized numerical control (CNC) machines are employed by industries to manufacture high quality products with low cost and reduced time. In recent times, hard turning of steel is a topic of immense interest for industrial production and scientific research since it offers a number of potential advantages, including lower equipment costs, shorter setup time, high accuracy, fewer process steps, greater part geometry flexibility, and usually there is no need to use cutting fluid during turning of hard steel. It is expected that if hard turning is used to fabricate complex parts, manufacturing costs could be reduced by up to 30 times (Huang et al, 2007), (Aouici et al, 2012).

Currently, a cutting fluid is used to cool and lubricate the cutting process, which could reduce the cutting temperature and improve tool life to some extent. But the conventional cutting fluid is an environmental contaminant and the government has strict regulations limiting the dumping of the cutting fluid waste. Cryogenic cooling is an environment-friendly clean technology for the desirable control of cutting temperature and enhancement of the tool life. During the cryogenic machining of stainless steel, it was observed that there was less cutting force in cryogenic machining over dry cutting (Kalyan Kumar and Choudhury, 2008). Cryogenic cooling showed a substantial improvement in the cutting force, surface roughness and tool wear through the control of the cutting zone temperature (Dhananchezian and Kumar, 2011). It has been also found that the surface roughness gets reduced when machining with cryogenic cooling (Abdulkareem et al, 2009). Recently, studies have been conducted to investigate the effect of cryogenic machining on surface integrity (Umbrello et al, 2011), (Grzesik et al, 2012). It has been also found that the cryogenic machining performed with a large edge radius tool led to enhanced surface integrity (Pu et al, 2011), (Pu et al, 2012).

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 (Bouacha et al, 2010), (Aouici et al, 2011), (Saini et al, 2012), (Renzo et al, 2012), (Srinivasan et al, 2012), (Joardar et al, 2013), (Fnides et al, 2013).

It appears from the literature presented above that not much work has been done to investigate the effect cryogenic machining on cutting forces. Keeping this in view, an attempt has been made in this paper to investigate

*Corresponding author: **Suha K. Shihab**

the effect of three cutting parameters (cutting speed, feed rate and depth of cut) on cutting forces during CNC hard turning of AISI 52100 alloy steel under cryogenic cooling condition.

2. Experimental Procedure

In this study, the experiments were carried out under cryogenic cooling condition using liquid nitrogen (LN2) on a rigid CNC lathe machine (LEADWELL T-6) with a 7.5 kW spindle motor at 4500 rpm. 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. In addition, a Nozzle was used to direct the supply of LN2 to the workpiece. The experimental set up is illustrated in Figure 1. CNMG 120408-TN7105 hard multicoated carbide insert (TiN-TiCN-AL_2O_3-TiN) having nose radius of 0.8 mm was used as cutting tool. The turning length and diameter of the workpiece were fixed to 150 mm and 45 mm respectively. AISI 52100 hardened alloy steel, widely used in the automotive, gear, bearing and die industry, etc. was used as workpiece material. The chemical composition of AISI 52100 is shown in Table 1. The three controlled factors of the cutting speed (i.e., *A* (m/min)), the feed rate (i.e., *B* (mm/rev)), and the depth of cut (i.e., *C* (mm)) with three levels for each factor are presented in Table 2. The effects of the parameters on these forces are tested through a set of experiments based on standard RSM design called a central composite design (CCD) as showed in table 3.

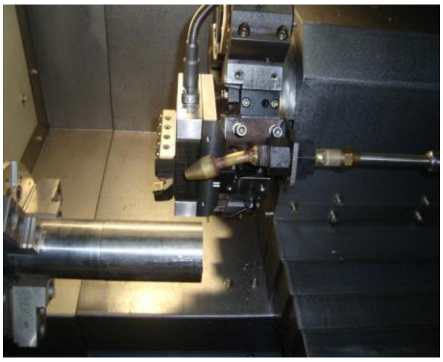

Figure1 Experimental set up

3. Results and Discussion

Analysis of variance (ANOVA) was employed to find the effects of cutting parameters (cutting speed (*A*), feed rate (*B*), and depth of cut (*C*)) on cutting forces (Fx, Fy, and Fz). After getting the results of ANOVA, the insignificant model terms were removed by selecting backward elimination procedure and then another ANOVA was performed to improve the model. The values of "Prob>F" greater than 0.1000 indicate model terms are not significant.

3.1 Analysis of Thrust force (Fx)

The results of analysis of variance (ANOVA) for reduced quadratic model for thrust force (Fx) are shown in Table 4. It can be seen from Table 4 that the model is significant and factors *B*, *C*, the quadratic value of cutting speed (A^2), the quadratic value of feed rate (B^2), and the quadratic value of depth of cut (C^2) have significant effect on the Fx while factor *A* has not significant effect. The "lack of fit'' of 0.206 implies the lack of fit not significant relative to the pure error. After calculating, the final equation of thrust force can be written in terms of code factors as :

$$Fx=+180.94-0.41A+25.11B+21.99C-69.38A^2+39.38B^2-20.32C^2 \quad (1)$$

While the following equation is the final empirical model in terms of actual factors:

$$Fx=-61.48683+4.31141A-081.65455B+207.39727C-0.012334A^2+10937.87879B^2-127.02273C^2 \quad (2)$$

The predicted values of Fx are compared with the corresponding experimental values. This is depicted in Figure 2. The normal probability plot of the residuals for Fx is shown in Figure 3. This plot 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 reveals the effect most influential machining factors i.e. cutting speed and feed rate on Fx. It can be seen from Figure 4 that low value of Fx is obtained at either the highest or the lowest values of cutting speed and feed rate combinations while keeping the depth of cut at constant value of = 0.6mm..

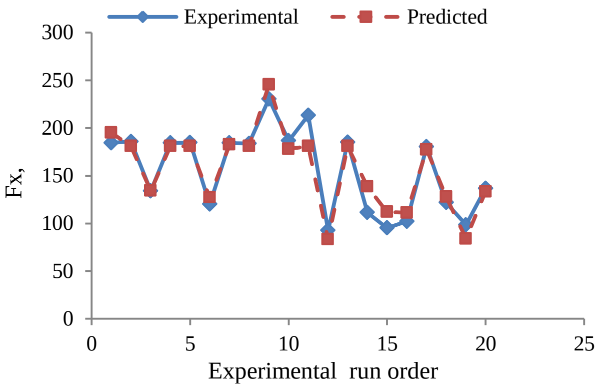

Figure2 comparison between measured and predicted values of Fx

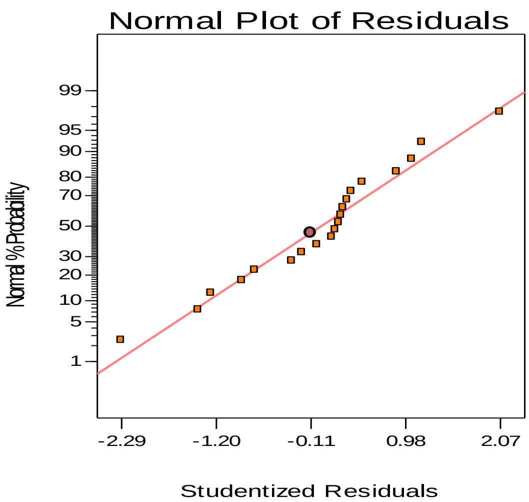

Figure3 Normal probability plot of Fx

Table1: Chemical composition of AISI 52100 alloy steel

C	Si	Mn	S	P	Ni	Cr	Mo	Cu	Fe
0.98	0.28	0.39	0.024	0.023	0.141	1.302	0.081	0.042	Rest

Table 2: Experimental factors and their levels

Factor	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 plan and results of cutting force components

Cutting parameters				Response parameters		
Run	*A* (m/min)	*B* (mm/rev)	*C* (mm)	Fx(N)	Fy(N)	Fz(N)
1	175.00	0.10	0.60	184.5	235.08	112.04
2	175.00	0.16	0.60	185.8	233.4	112.1
3	100.00	0.22	0.20	134.1	162.9	43.81
4	175.00	0.16	0.60	184.3	235.5	112.2
5	175.00	0.16	0.60	184.7	240.5	102.9
6	250.00	0.10	1.00	120.1	178.9	65.16
7	175.00	0.16	1.00	184.2	231.5	110.8
8	175.00	0.16	0.60	183.68	234.1	111.02
9	175.00	0.22	0.60	230.5	295.8	150.18
10	100.00	0.22	1.00	186.6	297	109.6
11	175.00	0.16	0.60	213.3	289.2	150.9
12	250.00	0.10	0.20	92.55	85.56	39.86
13	175.00	0.16	0.60	185.1	230.6	110.2
14	175.00	0.16	0.20	111.4	127.3	43.27
15	100.00	0.16	0.60	95.29	120.8	31.52
16	250.00	0.16	0.60	102.2	102.3	32.62
17	250.00	0.22	1.00	180.4	284.6	96.63
18	100.00	0.10	1.00	121.7	177.1	74.24
19	100.00	0.10	0.20	98.37	94.1	39.54
20	250.00	0.22	0.20	136.7	173.4	46.1

Table 4 ANOVA results for thrust force Fx

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	32292.51	6	5382.08	23.03	< 0.0001
A	1.69	1	1.69	7.227E-003	0.9335
B	6304.12	1	6304.12	26.97	0.0002
C	4834.72	1	4834.72	20.68	0.0005
A^2	13236.84	1	13236.84	56.63	< 0.0001
B^2	4263.87	1	4263.87	18.24	0.0009
C^2	1135.89	1	1135.89	4.86	0.0461
Residual	3038.66	13	233.74		
Lack of Fit	2355.22	8	294.40	2.15	0.2068
Pure Error	683.44	5	136.69		
Cor Total	35331.17	19			
	Std. Dev. = 15.29			R-Squared = 0.9140	
	Mean = 155.77			Adj R-Square =0.8743	
	C.V. = 9.81			Pred R-Squared =0.7620	
	PRESS =8407.73			Adeq Precision = 17.946	

Table 5 ANOVA results for tangential force Fy

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	79516.78	5	15903.36	20.34	< 0.0001
A	73.66	1	73.66	0.094	0.7634
B	19621.36	1	19621.36	25.10	0.0002
C	27650.77	1	27650.77	35.37	< 0.0001
A^2	31986.40	1	31986.40	40.91	< 0.0001
B^2	9300.55	1	9300.55	11.90	0.0039
Residual	10945.96	14	781.85		
Lack of Fit	8428.57	9	936.51	1.86	0.2560
Pure Error	2517.39	5	503.48		
Cor Total	90462.73	19			
Std. Dev. = 27.96			R-Squared = 0.8790		
Mean = 201.48			Adj R-Square =0.8358		
C.V. = 13.88			Pred R-Squared =0.7946		
PRESS =18584.60			Adeq Precision = 15.923		

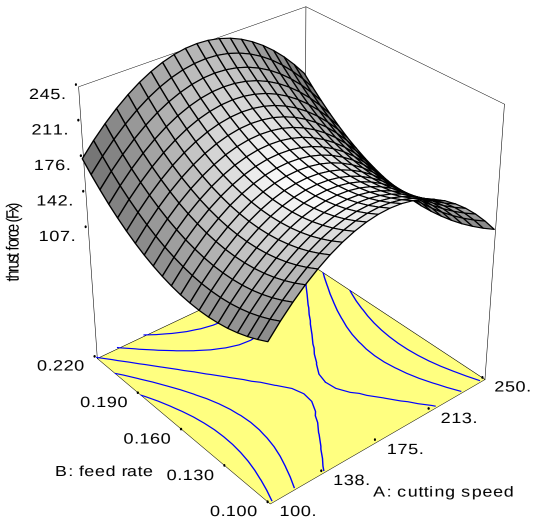

Figure 4 Effect of cutting speed and feed rate on Fx (depth of cut =0.6mm)

3.2 Analysis of Tangential Force (Fy)

Table 5 presents the results of analysis of variance (ANOVA) for reduced quadratic model for tangential force (Fy). It is clear from Table 5 that the model is significant and factors *B*, *C*, the quadratic value of cutting speed (A^2) and the quadratic value of feed rate (B^2) have significant effect on the tangential force (Fy) while factor *A* has not significant effect. The “lack of fit’’ of 0.256 implies the lack of fit not significant relative to the pure error. After calculating, the final equation of tangential force can be written in terms of code factors as:

$$Fy = +224.52-2.71A +44.30B +52.58C-99.98A^2 + 53.91B^2 \quad (3)$$

While the following equation is the final empirical model in terms of actual factors:

$$Fy= -127.11011+6.18471A-4053.84444B+131.46000C-0.017774A^2+14975.34722B^2 \quad (4)$$

The predicted values of Fy are compared with the corresponding experimental values. This is depicted in Figure 5. The normal probability plot of the residuals for

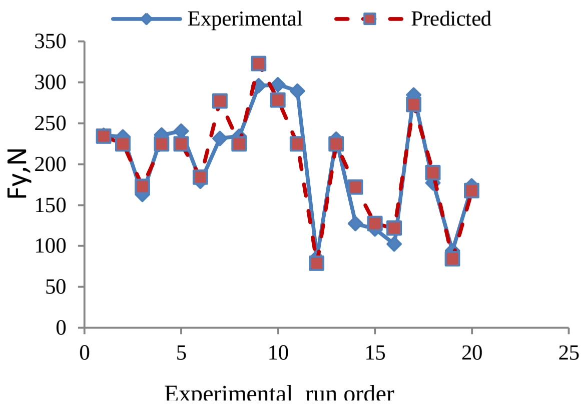

Figure5 comparison between measured and predicted values of Fy

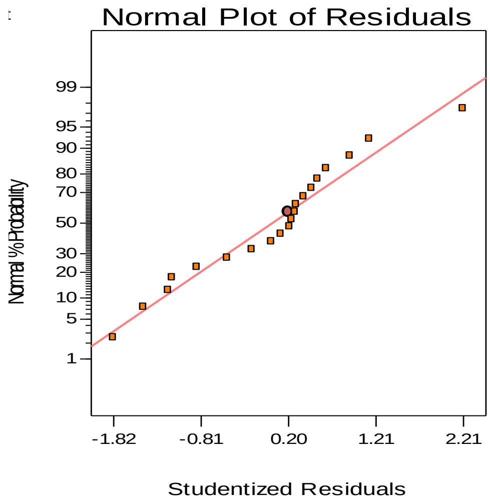

Figure 6 Normal probability plot of Fy

Fy is shown in Figure 6. This plot 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 7 reveals the effect most influential machining factors i.e. cutting speed and depth of cut on Fy. It can be seen from Figure7 that low value of Fy is obtained at either the highest or the lowest values of cutting speed and depth of cut combinations while keeping the feed rate at constant value of = 0.16mm/rev.

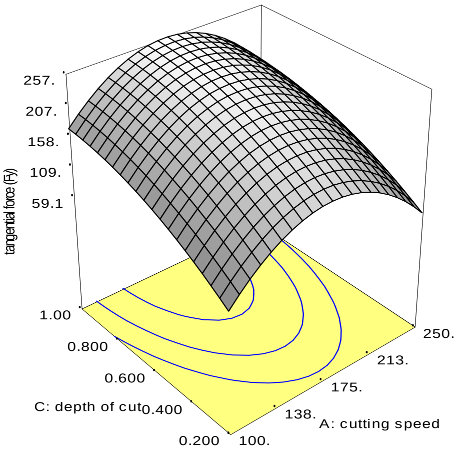

Figure7 Effect of cutting speed and depth of cut on Fy (feed rate = 0.16mm)

3.3 Analysis of Feed Force (Fz)

The results of analysis of variance (ANOVA) for reduced quadratic model for feed force (Fz) are shown in Table 6. It can be seen from Table 6 that factors *B*, *C*, A^2, B^2, and C^2 have significant effect on Fz while factor *A* has not significant effect. The "lack of fit'' of 0.541 implies the lack of fit not significant relative to the pure error. After calculating, the final equation of feed force can be written in terms of code factors as :

$$Fz=+108.22-1.83A+11.55B+24.39C-63.66A^2+35.38B^2-18.70C^2 \quad (5)$$

While the following equation is the final empirical model in terms of actual factors:

$$Fz=-91.96100+3.93673A-2952.26061B+201.18864C-0.011318A^2+9827.27273B^2-116.85511C^2 \quad (6)$$

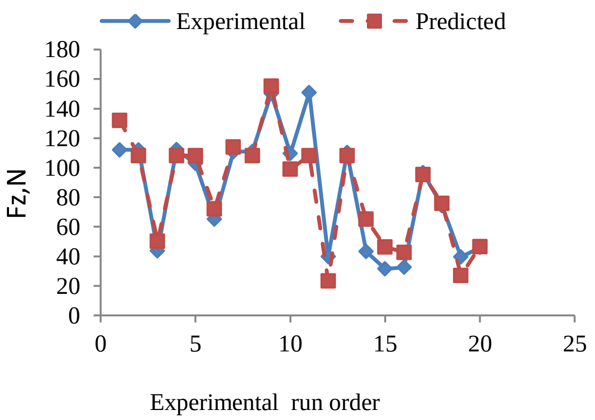

Figure 8 comparison between measured and predicted values of Fz

The predicted values of Fz are compared with the corresponding experimental values. This is depicted in Figure 8. The normal probability plot of the residuals for Fz is shown in Figure 9. This plot revealed that the residuals either fall on a straight line or are very close to the line implying that the errors are distributed normally. Figure10 reveals the effect most influential machining factors i.e. cutting speed and depth of cut on Fz. It can be seen from Figure10 that low value of Fz is obtained at either the highest or the lowest values of cutting speed and depth of cut combinations while keeping the feed rate at constant value of = 0.16mm/rev.

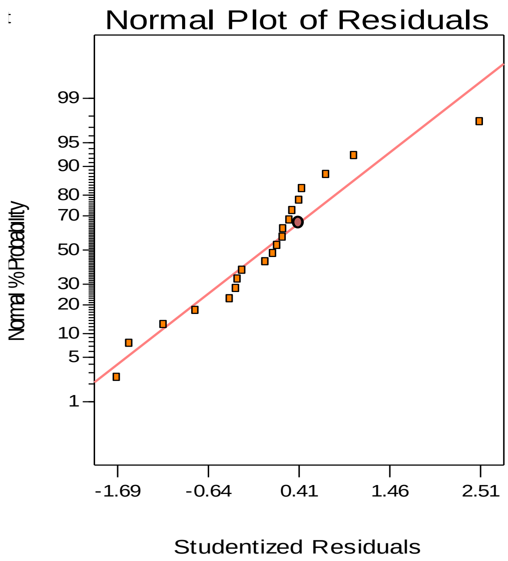

Figure 9 Normal probability plot of Fz

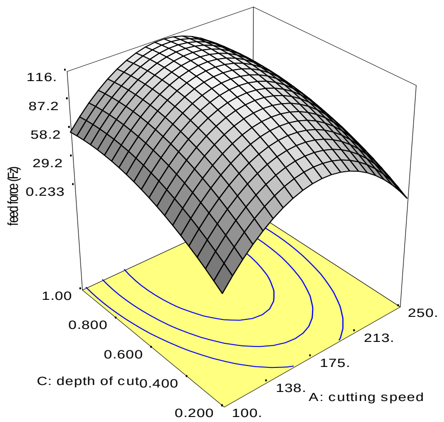

Figure10 Effect of cutting speed and depth of cut on Fz (feed rate = 0.16mm)

3.4 Optimizations for Cutting Force Components

The optimization approach is quite advantageous in order to have the range of the cutting forces 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. Table 7 shows the RSM optimization results of cutting force components (Fx, Fy and Fz). It can be seen from Table 7 that the optimized value of Fx, Fy, and Fz is within the range (78.0837 N – 86.8699 N), (73.2287 N – 85.3179 N), (6.15001 N – 27.3328N) respectively.

Table 6 ANOVA results for feed force Fz

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	25243.00	6	4207.17	14.55	< 0.0001
A	33.64	1	33.64	0.12	0.7385
B	1333.56	1	1333.56	4.61	0.0512
C	5946.28	1	5946.28	20.56	0.0006
A^2	11145.27	1	11145.27	38.54	< 0.0001
B^2	3441.94	1	3441.94	11.90	0.0043
C^2	961.32	1	961.32	3.32	0.0913
Residual	3759.42	13	289.19		
Lack of Fit	2283.55	8	285.44	0.97	0.5411
Pure Error	1475.87	5	295.17		
Cor Total	29002.42	19			
	Std. Dev. = 17.01		R-Squared = 0.8704		
	Mean = 84.73		Adj R-Square =0.8105		
	C.V. = 20.07		Pred R-Squared =0.6873		
	PRESS =9068.14		Adeq Precision = 13.088		

Table 7 Optimization Results

No.	Cutting speed (m/min)	feed rate (mm/rev)	depth of cut(mm)	Fx(N)	Fy(N)	Fz(N)	Desirability	Remarks
1	101.83	0.18	0.20	83.1361	84.3782	9.10948	1.000	selected
2	249.62	0.12	0.30	86.1299	83.0551	26.6414	1.000	
3	102.25	0.17	0.20	78.0837	75.4638	6.15001	1.000	
4	101.55	0.12	0.22	79.0084	73.2287	17.5943	1.000	
5	100.44	0.11	0.23	86.8699	85.3179	27.3328	1.000	
6	248.38	0.14	0.32	85.8579	83.4804	22.7491	1.000	
7	100.04	0.16	0.29	83.6276	85.3043	14.5665	1.000	
8	101.57	0.15	0.28	81.8389	80.4686	15.5462	1.000	
9	102.66	0.16	0.26	82.2401	81.0947	13.5419	1.000	
10	101.57	0.15	0.28	81.6964	80.403	14.8757	1.000	

4. Conclusions

Experiments on the hard turning of alloy steel AISI 52100 were carried out under cryogenic cutting conditions with multilayer hard surface coatings (TiN/TiCN/Al_2O_3/TiN) insert. The Central composite design (CCD) based on the response surface methodology (RSM) was used to analyze the effect of cutting parameters (cutting speed, feed rate, and depth of cut) on the cutting forces and to determine optimal values of cutting parameters. Based on the results of the present study, the following conclusions can be drawn:

- The central composite design used in this study proved to be an effective tool for modeling the cutting forces and the reduced quadratic model developed using RSM is reasonably accurate and can be used for prediction within the limits of the factors investigated.
- ANOVA results revealed the amount of cutting forces (Fx, Fy, Fz) that majorly influenced by cutting speed, feed rate and depth of cut in the cryogenic hard turning process
- It can be concluded from thrust force model that feed rate, depth of cut, cutting speed^2, feed rate^2, and depth of cut^2 have significant effect on thrust force
- It can be concluded from tangential force model that feed rate, depth of cut, cutting speed^2, and feed rate^2 have significant effect on tangential force
- It can be concluded from feed force model that feed rate, depth of cut, cutting speed^2, feed rate^2, and depth of cut^2 have significant effect on feed force.
- The results of ANOVA and the validation experiments confirm that the developed mathematical model revealed perfect fit and predicted values are very close to experimental values.
- The optimal setting of cutting parameters are found to be cutting speed of 101.83m/min, feed rate of 0.18mm/rev and depth of cut of 0.2 mm. with estimated cutting forces (Fx, Fy, and Fz) of 83.1361N, 84.3782N and 9.10948N, respectively

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