Modeling and Optimization of Cutting Temperature in Hard Turning of AISI 52100 Hardened Alloy Steel Using Response Surface Methodology

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Abstract This paper analyses the effect of cutting parameters, such as cutting speed, feed and depth of cut on the cutting temperature in dry turning of AISI hardened 52100 alloy steel of 58 HRC using multilayer coated carbide tool insert. The heat generation and temperature at the cutting zone have a significant impact on tool wear, tool life and surface integrity. The cutting temperature is strongly influenced by cutting parameters and increases with their levels. Therefore, it was imperative to optimize the cutting parameters and develop a model for the accurate prediction of cutting temperature. Response surface methodology based on central composite design (CCD) was used to investigate and optimize the cutting parameters on cutting temperature response. The diagnostic tests were carried out to check its validity. The analysis of variance (ANOVA) was performed to analyse the effect of process parameters and their interactions on cutting temperature response. The quadratic regression model in terms of cutting speed, feed and depth of cut for cutting temperature was developed. The predicted values of cutting temperature response are in good agreement with the experimental results.

Keywords Hard turning · Surface integrity · Response surface methodology · Central composite design

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1 Introduction

The heat generation and temperature at the cutting zone in hard machining affect the tool wear, tool life and machined surface integrity and can be improved by reducing the heat generation and temperature at tool–chip and tool–workpiece interface. Aouici et al. [1] developed the parametric relationship between the cutting speed, feed, depth of cut and the response cutting temperature using response surface methodology in dry hard turning of AISI H11 steel using CBN insert. The cutting speed, feed rate and depth of cut are found to be the most significant and influencing parameter on cutting temperature as it increases with an increase in their values. Tönshoff et al. [2] reported that the hard turning has been gaining the importance over conventional grinding process due to its benefits such as lesser set-up time, fewer process steps, process flexibility, greater part geometry and higher material removal rate. Huang et al. [3] stated that the hard turning is used to machine the complex parts, and the cost can be reduced up to 30% of the total manufacturing costs. Suresh et al. [4] and Saboo et al. [5] stated that the cubic boron nitride (CBN) and ceramic tool inserts are widely acceptable as it performs well in the machining of hardened alloy steels, but these tool inserts are very costlier. The development of new coating materials and coating deposition techniques leads the researchers to work in the area of machining of hardened alloy steel using coated carbide tools. Sutter et al. [6] studied the effects of the cutting speed and depth of cut on the temperature profile at the chip during orthogonal machining of 42CrMo4 steel using standard carbide TiCN coated tools. They performed the machining with a gas gun. It was found from their results that the temperature at the chip increases with the increase in both cutting speed and the depth of cut. Ren et al. [7] determined the cutting temperatures during hard turning of high chromium hard facing materials using PCBN tools. They found that the average cutting temperatures ranged from 600 to 700 °C, which increased with higher cutting speed and feed rate. Fnides et al. [8] found that the cutting speed has more significant impact on cutting temperature than the feed and depth of cut in turning of AISI H11 hardened alloy steel of hardness 50 HRC using ceramic tool insert at the dry condition. Lin et al. [9] reported that the cutting speed is the most dominant factor, which raises the cutting temperature significantly in hard turning of hardened AISI 4340 alloy steel by cubic boron nitride (CBN) tool inserts. Bouchelaghem et al. [10] showed that the cutting speed, feed and depth of cut are most influential factors on cutting temperature, and the increase in the levels of cutting parameters raises the cutting temperature in hard turning of AISI D3 steel at elevated hardness of 60 HRC using CBN tool inserts. However, very few publications can be found in the literature that discusses the effect of cutting parameters on cutting temperature in turning of alloy steel at elevated hardness of 58–60 HRC. The modeling and optimization of the cutting temperature in hard turning of alloy steels using multilayer coated carbide tools at elevated hardness are rarely reported in the literature. In view of this, an attempt has been made to investigate the effect of cutting parameters on cutting temperature in turning of AISI 52100 hardened

Table 1 Chemical composition of AISI 52100 hardened alloy steel (weight percentage)

C %	Si %	Mn %	P %	S %	Cr %	Ni %	Cu %	Fe %
1.04	0.18	0.35	0.007	0.004	1.35	0.076	0.058	Balance

steel at elevated hardness of hardness 58 HRC, which has wide applications in the automotive and allied industries.

2 Experimentation

2.1 Selection of Workpiece Material

In this study, AISI 52100 hardened alloy steel having a hardness of 58 HRC was selected as workpiece material. AISI 52100 hardened alloy steel has wide applications and is being used in automotive and allied industries such as bearings, forming rolls, spindles, tools and precision instrument parts. Table 1 shows the chemical composition of the workpiece material.

2.2 Selection of Tool

The cutting tool inserts and the tool holder were selected based on the literature review and the tool manufacturer's recommendation. The MTCVD multilayer coated carbide (TiN/TiCN/Al_2O_3)–[HK150, K-type] cutting tool insert having specification CNMG120408 and the tool holder with PCLNR 2020 K12 specification were selected for experimentation. The experiments were carried out on a rigid high precision HMT NH-18 lathe machine.

2.3 Selection of Cutting Parameters

Based on the previous research carried out and the tool manufacturer's recommendations, the cutting parameters were selected. Table 2 presents the cutting parameters and their coded and actual levels based on the central composite design of response surface methodology.

Table 2 Cutting parameters and their coded and actual levels using central composite design

Process parameters	Units	Limits				
		−1.682	−1	0	1	1.682
Cutting speed	m/min	90	100	115	130	140
Feed rate	mm/rev	0.05	0.075	0.10	0.125	0.150
Depth of cut	mm	0.1	0.2	0.3	0.4	0.5

2.4 *Design of Experiment*

The response surface methodology uses the statistical experimental design technique and least square fitting method for model generation. The central composite design (CCD) was used for experimental design. The prediction of the cutting temperature was carried out in terms of cutting parameters under dry environment. Cutting temperature values were measured using infrared thermometer and embedded thermocouple technique. Table 3 shows the experimental design and result for cutting temperature.

Table 3 Experimental design and result for cutting temperature

S. No.	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Cutting temperature (°C)
1	115	0.1	0.3	640
2	130	0.08	0.4	702
3	115	0.1	0.3	635
4	90	0.1	0.3	651
5	140	0.1	0.3	748
6	115	0.1	0.1	597
7	115	0.05	0.3	631
8	115	0.1	0.3	635
9	115	0.1	0.3	642
10	100	0.08	0.2	610
11	130	0.12	0.4	728
12	115	0.1	0.5	667
13	130	0.12	0.2	658
14	115	0.1	0.3	643
15	130	0.08	0.2	643
16	100	0.08	0.4	638
17	100	0.12	0.4	657
18	100	0.12	0.2	621
19	115	0.1	0.3	644
20	115	0.15	0.3	662

2.5 Measurement of Cutting Temperature

The cutting temperature at the cutting edge of the insert was measured with the help of embedded K-type thermocouple of range 50–1370 °C and −58–2498 °F and infrared thermometer (HTC IRX-68) of range 50–1850 °C and −58–3362 °F. Table 3 shows the experimental design and result for cutting temperature.

3 Result and Discussion

The MINITAB software was used for the analysis. Table 4 shows the ANOVA table for the quadratic model of cutting temperature, and it is clear from the ANOVA table that the *P*-values less than 0.0500 indicate the model terms are significant and the values greater than 0.1000 indicate the model terms are not significant. The cutting speed (V), depth of cut (D) and quadratic value of cutting velocity (V^2) have the most significant effect; while the feed (F) and the interaction between cutting speed and depth of cut (VD) have a less significant effect on cutting temperature. But the quadratic value of feed rate (F^2), the quadratic value of depth of cut (D^2), the interaction between cutting speed and feed rate (VF) and the interaction between feed rate and depth of cut (FD) all have no significant effect on cutting temperature. The below equation is in terms of coded factors can be used to make predictions of cutting temperature for given levels of each factor.

Table 4 ANOVA for quadratic model of cutting temperature

Source	DF	Seq SS	Contribution (%)	Adj SS	Adj MS	*F*-value	*P*-value
Model	9	24,932.0	98.52	24,932.0	2770.22	73.91	0.000
V	1	9918.0	39.19	9918.0	9918.03	264.62	0.000
F	1	1075.7	4.25	1075.7	1075.72	28.70	0.000
D	1	6930.6	27.39	6930.6	6930.56	184.91	0.000
$V * V$	1	6182.3	24.43	5709.5	5709.52	152.33	0.000
$F * F$	1	109.3	0.43	56.4	56.43	1.51	0.248
$D * D$	1	127.7	0.50	127.7	127.72	3.41	0.095
$V * F$	1	15.1	0.06	15.1	15.12	0.40	0.540
$V * D$	1	528.1	2.09	528.1	528.13	14.09	0.004
$F * D$	1	45.1	0.18	45.1	45.12	1.20	0.298
Error	10	374.8	1.48	374.8	37.48		
Lack of fit	5	296.0	1.17	296.0	59.19	3.75	0.086
Pure error	5	78.8	0.31	78.8	15.77		0.000
Total	19	25,306.8	100.00				

$$\begin{aligned}\text{Cutting temperature} = {} & 639.31 + 27.05 * V + 7.24 * F + 20.81 * D \\ & + 1.38 * V * F + 8.13 * V * D + 2.38 * F * D \\ & + 20.79 * V * V + 0.9761 * F * F - 2.25 * D * D.\end{aligned}$$

The model F-value of 73.91 implies the model is significant and could be used to predict the cutting temperature accurately. There is only a 0.01% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. The lack of fit F-value of 3.75 implies that the lack of fit is not significant relative to the pure error and can fit the model well (Table 5).

The predicted R^2 of 0.8966 is in reasonable agreement with the Adjusted R^2 of 0.9719; i.e. the difference is less than 0.2. Adeq precision measures the signal-to-noise ratio. A ratio greater than 4 is desirable, and ratio of 35.4493 indicates an adequate signal. This model can be used to navigate the design space.

Figure 1a shows the normal probability plot of the residuals of cutting temperature. The normal probability plot indicates whether the residuals follow a normal distribution or not. The points on the normal probability plots of the residuals fall on a straight line implying that the errors are distributed normally. It can be seen from Fig. 1b that all the actual values are following the predicted values. Figure 1c represents residuals versus the predicted response plot for cutting temperature. The plot shows the random scatter and contains no obvious pattern. This implies that the model proposed is adequate, and there is no reason to suspect any violation of the independence or constant variance assumptions.

Figure 2 shows contour plots of cutting temperature. Figure 2a shows the cutting temperature versus cutting speed and feed rate. From this graph, lower cutting temperature value of 586 °C has arrived between a feed rate of 0.05–0.12 mm/rev

Table 5 Model summary of cutting temperature

Std. dev.	R^2	R^2 (adj)	Press	R^2 (pred)	Adeq precision
6.12213	98.52%	97.19%	2617.60	89.66%	35.4493

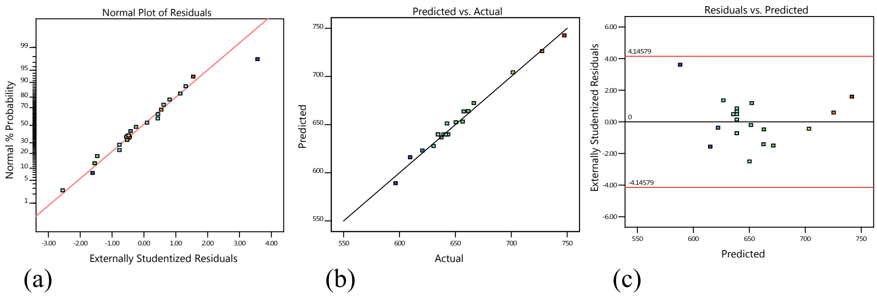

Fig. 1 **a** Plot of residuals versus normal probability, **b** plot of predicted versus actual values, **c** plot of residuals versus predicted values for cutting temperature

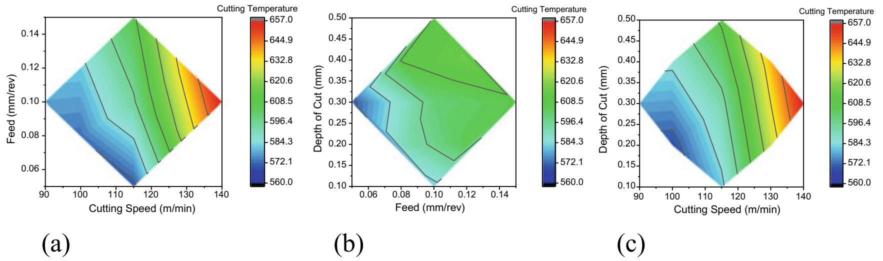

Fig. 2 Three-dimensional contour plots for cutting temperature **a** cutting speed versus feed rate, **b** cutting speed versus depth of cut and **c** feed rate versus depth of cut

and a cutting speed of 100–115 m/min. Figure 2b shows cutting temperature against the depth of cut and feed rate. The cutting temperature value of 586 °C has arrived between a feed rate of 0.05–0.12 mm/rev and depth of cut of 0.1–0.3 mm. Figure 2c shows cutting temperature against the depth of cut and cutting speed. The cutting temperature value of 586 °C has arrived between a depth of cut of 0.1–0.3 mm and cutting speed of 100–120 m/min. Figure 3 shows the surface plot for better visualization of the functional relationship between the dependant and two independent variables.

3.1 *Optimization of Cutting Condition*

The optimum values of the cutting factors selected for the minimization of cutting temperature were obtained by numerical optimization applying desirability function. Table 6 shows the constraint for minimizing the cutting temperature. Table 7 shows the optimized values of cutting parameters as cutting speed: 102.318 m/min, feed

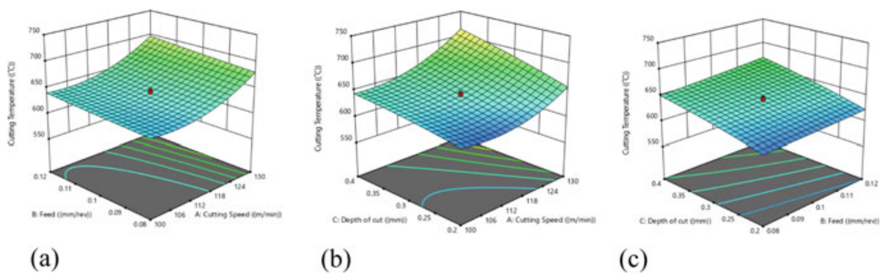

Fig. 3 Three-dimensional surface plots for cutting temperature **a** cutting speed versus feed rate, **b** cutting speed versus depth of cut and **c** feed rate versus depth of cut

Table 6 Constraints for the optimization process

Constraints	Unit	Target	Lower limit	Upper limit
Cutting speed	(m/min)	Is in range	100	140
Feed rate	(mm/rev)	Is in range	0.05	0.15
Depth of cut	(mm)	Is in range	0.10	0.50
Cutting Temp.	(°C)	Minimize	597	748

Table 7 Optimization results

Number	Cutting speed	Feed rate	Depth of cut	Cutting temperature	Desirability	
1	**102.318**	**0.051**	**0.100**	**596.987**	**1.000**	**Selected**
2	101.650	0.069	0.101	596.047	1.000	
3	105.185	0.054	0.117	595.152	1.000	
4	104.257	0.061	0.106	593.570	1.000	
5	102.484	0.056	0.102	596.172	1.000	
6	103.081	0.063	0.110	595.901	1.000	
7	103.332	0.053	0.101	595.045	1.000	
8	103.632	0.053	0.114	596.911	1.000	
10	107.574	0.055	0.101	589.442	1.000	

rate: 0.051 mm/rev and depth of cut: 0.10 mm and the corresponding value of cutting temperature response is 596 °C.

3.2 Validation of the Model

The model *F*-value of 73.91 is significant and the lack of fit *F*-value of 3.75 is not significant and it indicates that the model is adequate. The predicted values of cutting temperature were validated and verified through experimental runs and confirmatory test. The percentage of error between predicted and experimental values was found within ±5–8% which proved that the model is valid.

4 Conclusions

In this investigation, a central composite design (CCD)-based response surface methodology (RSM) was used to design the experiment and model the cutting temperature in terms of cutting parameters within the constraint in dry hard turning of AISI 52100 hardened alloy steel at elevated hardness of 58 HRC using multilayer coated carbide tool. The multilayer coated carbide ($TiN/TiCN/Al_2O_3$) insert performed well in hard turning and found to be more economical compared to costlier CBN insert. It was found that the cutting speed is the most significant parameter on cutting temperature followed by the depth of cut. The quadratic terms of *F, D* and interactions *VF* and *FD* had no influence on cutting temperature. The percentage contribution of cutting parameters, such as cutting speed, feed rate, depth of cut and quadratic term of cutting speed for cutting temperature is 39.19%, 4.25%, 27.39% and 24.43% respectively. The developed predictive model could be successfully used for the prediction of cutting temperature for different combination of cutting parameters within the constraint defined.

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