Modelling and prediction of cutting temperature in the machining of H13 hard steel of multi-layer coated cutting tools

Jingjie Zhang (✉ zjj@qlu.edu.cn)

Qilu University of Technology

Zhanqiang Liu

Shandong University

Chonghai Xu

Qilu University of Technology (Shandong Academy of Sciences)

Jin Du

Qilu University of Technology (Shandong Academy of Sciences)

Guosheng Su

Qilu University of Technology (Shandong Academy of Sciences)

Peirong Zhang

Qilu University of Technology (Shandong Academy of Sciences)

Xiangfei Meng

Qilu University of Technology (Shandong Academy of Sciences)

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Title: Modelling and prediction of cutting temperature in the machining of H13 hard steel of multi-layer coated cutting tools

Jingjie Zhang ^{1,2,*}, Zhanqiang Liu ³, Chonghai Xu ^{1,2}, Jin Du ^{1,2}, Guosheng Su ^{1,2}, Peirong Zhang ^{1,2}, Xiangfei Meng ^{1,2}

¹ School of Mechanical and Automotive Engineering, Qilu University of Technology (Shandong Academy of Sciences), Jinan 250353, China

² Key Laboratory of Equipments Manufacturing and Intelligent Measurement and Control, China National Light Industry, Qilu University of Technology (Shandong Academy of Sciences), Jinan 2550353, China

³ School of Mechanical Engineering, Shandong University, Jinan 250000, China

* Correspondence: E-mail: zjj@qlu.edu.cn

Abstract: The coating effect on the cutting temperature has long been a hot topic in understanding heat transfer mechanism in machining coated tools, and especially the multi-layer coated tools. For multi-layer coated tools, the coating structure, coating thickness and coating material will affect the cutting temperature of the tools. This paper is devoted to the cutting temperature in dry turning of H13 hardened steel with multi-layer coatings. New analytical models for estimating coating temperature and coating-substrate interface temperature were proposed. The multi-layer coating can be equivalent to mono-layer composite coating, which applies equivalent coating layer approach, and was developed to estimate the cutting temperature in turning by heat transfer model of mono-layer coated tool. The analyzed results were compared to appropriate experimental process data using thermocouples and FEM simulated data. The models were verified can accurate temperature under the same cutting conditions for two multi-layer coated tools.

Keywords: machining; multi-layer coated tool; composite coating; equivalent coating layer; cutting temperature;

1 Introduction

Today, the majority of cutting tools are coated tools. The role of coating to prolong tools life, reduce cutting temperature and improve surface integrity of workpiece. The milestone in the development of cutting tools materials has been the application of advanced cemented carbides deposited with various structures of thin coating films. Almost all cutting tools are

coated with thin layers, such as titanium carbide(TiC), titanium carbonitride(TiCN), titanium nitride(TiN), and aluminum oxide(Al_2O_3) to improve machining performance [1]. Coating layer thickness of 1–5 μm for mono-layer and up to 20 μm for multi-layer coatings is commonly adopted. The application of coated tools results in prolonged tool life as well as an increase in the cutting speed at which the tools can be operated.

As temperature is a fundamental importance in machining, many attempts have been made to investigate the mechanism of cutting heat generation, cutting heat partition and heat transfer in the coated tools. Different coating materials and substrate materials of coated tools have a great influence on heat generation and temperature field [2, 3], especially the multi-layer coated tools with multiple coating layers. Compared with uncoated tools, coated tools with thin coating have different mechanisms in heat partition, heat transfer and temperature distribution during the cutting process. Each thin coating of multi-layer coated tools has different physical property, mechanical property, and thermo-physical. Therefore, coated tools have their own characteristics of heat transfer and temperature distribution.

The heat transfer and temperature field in coated tool body has been one of the major subjects in metal cutting research. Grzesik and Nieslony [2] used an analytical method to predict heat partition coefficient in the stationary tool and in the moving chip with uncoated and multi-layer coated tools. The results showed that the temperature depended on tool–chip contact length, Peclet number and the specific friction energy, respectively. It was also found that multi-layer coated tools (TiC/ Al_2O_3 /TiN, TiC/Ti(C,N)/ Al_2O_3 /TiN) increased about 30% more heat into chip due to friction. Grzesik et al. [4] used finite difference method to calculate the rake face temperature and flank face temperature of uncoated tool P20 and coated tool TiC/TiN. Coatings changed the distribution of the interface temperature along the tool–chip contact length. In particular, for TiC and TiC/TiN coatings with high thermal conductivity, a widely flat area with a constant temperature was revealed.

The coating material plays an important role in the cutting heat transfer process. One of the coating materials(Al_2O_3) has better thermal barrier performance. Many typical coating structures take Al_2O_3 with thermal barrier as the intermediate coating [5]. It is uses Al_2O_3 low thermal conductivity and the thermal conductivity decreases with the increase of temperature [6, 7]. In order to reveal the influence of coating material and coating thickness on the cutting

heat transfer, the heat transfer in the cutting of coated tools was studied. Zhang [8] studied the influence of coating material on the temperature distribution in the coating through numerical model, and research showed that the temperature decline trend of Al_2O_3 coated tool was faster than that of TiC and TiN coated tools. Ferreira et al. [9] compared and analyzed the effect of Al_2O_3 coating thickness on the temperature in the tool-chip interface and the temperature in the tool body. It was found that with the increase of coating thickness, the temperature in the tool-chip interface increased with the coating thickness, the temperature in the coated tool body decreased significantly. Oliveira [10] coated the substrate of K10 carbide tool with three different coatings (Co, TiN, Al_2O_3) and loaded a constant heat flow $q(t)=25\times 10^5\text{W/m}^2$ on the tool surface (simulating the heat flow density at the tool-chip interface under orthogonal cutting conditions). The experimental temperature on the tool surface of the coated tool is much higher than that of the uncoated tool due to the heating resistance of the coating. However, the coated tool's body temperature decreases greatly. The coating of $2\mu\text{m}$ thickness can drop 14% in temperature. When coating thickness exceeds $5\mu\text{m}$, the effect of coating on heat transfer is dependent on the coating-substrate interface. For TiN coating, the temperatures decreased to 26, 34 and 41% at $5\mu\text{m}$, $10\mu\text{m}$ and $20\mu\text{m}$ thickness.

Coating element content is affecting the cutting heat transfer. Zhao et al. [11] studied the heat transfer performance of TiAlN coated tools through orthogonal cutting experiment and finite element simulation, analyzed the tool coating ($\text{Ti}_{0.41}\text{Al}_{0.59}\text{N}$, $\text{Ti}_{0.55}\text{Al}_{0.45}\text{N}$) and fed on the influence of temperature. Compared with $\text{Ti}_{0.55}\text{Al}_{0.45}\text{N}$ coated tools, $\text{Ti}_{0.41}\text{Al}_{0.59}\text{N}$ coated tools can reduce the generation of cutting heat and tool temperature. The results show that with the increase of Al element content, more Al_2O_3 has an obvious blocking effect on the cutting heat flow during continuous cutting, and it can play heat barrier effect on the cutting heat transfer in the cutting process. In order to verify the heat transfer performance of TiAlN coating, Marta et al. [12] used the simulation experiment to research the thermal conductivity of coated tools. The study found that the temperature increased by about 0.18°C/s in the first 100s, while the temperature increased by about 0.07°C/s after 100s to 260s. Through the comparison experiment, it can be concluded that TiAlN coating can significantly limit the heat flux (about 200W/m^2), which verifies the thermal barrier function of TiAlN coating in the cutting process. Samani [13, 14] tested the heat transfer performance of TiN and

TiAlN coatings by pulsed photothermal reflection technology. And it was found that the thermal conductivity of coatings decreased with the increase of coating layers. The thermal conductivity of the pure TiN coating was about 11.9W/mK. With the increase of (Al+Si) /Ti atomic ratio, the thermal conductivity of the coating decreased sharply. The decrease of thermal conductivity can be attributed to the increase of phonon scattering due to the destruction of the coating column structure, the decrease of the preferred orientation, the decrease of the coating grain size, and the appearance of misalignment at the interface.

For the discussion of cutting temperature, the influences of coating properties on heat generation, heat partition, tool-chip interface temperature, tool-workpiece interface temperature and heat transfer or heat flux in the coated tools, especially the multi-layer coated tools, have been a primary issue faced by the researchers.

The multi-layer coated tools with multiple coatings of different materials and different thickness, the interface between coating and coating, and the interface between coating and surface, so the heat transfer of multi-layer coated tool is more complex. The cutting temperature changes can be caused by only a few nanometers variation in thickness of coating layer in a multi-layer coating. Compared with the heat transfer of multi-coated tool, the heat transfer of mono-layer coated tool is clear and definite.

In this paper, multi-layer coated tools are equivalent to mono-layer coated tools by equivalent coating layer approach. And the mono-layer coated tools heat transfer model is established. Finite element simulation results used to verify the effectiveness of equivalent coating layer approach on estimating coating temperature enhancing in the cutting heat transfer of multi-layer coated tools. Furthermore, the cutting temperature of multi-layer coated tools is established modelling through heat transfer model of mono-layer coated tools.

2. Heat transfer model of coated tools

There are three heat sources in the cutting process, i.e., shear deformation heat source, tool-chip heat source and tool-workpiece heat source. Heat generated of coated tools concentrate near the tool-chip interface. Thus, a constant equivalent temperature T_w is instead of three heat sources acting on the cutting tools rake face.

The coating thickness of the mono-layer is 1-8 μ m [15, 16]. The thickness of the substrate of coated tools to be much greater than the coating thickness. It can be regarded as

semi-infinite. Cutting heat transfer of coated tools can be regarded as solid heat transfer with boundary transfer problem. According to the geometric size of coated tools, initial conditions and boundary conditions, heat transfer model of mono-layer coated tools is established under the condition of the tool rake face temperature is given. The heat transfer model and boundary conditions in the cutting deformation zone are shown in Fig. 1.

Fig. 1 Schematic of coated tools heat transfer

The following assumptions are made in order to derive the model of the proposed heat transfer process [17]: (1) thermal properties such as thermal conductivity and diffusivity are independent of temperature and they are uniform for coating layer; (2) in addition to the rake face, the rest of the surface is adiabatic surfaces; (3) tool coating and substrate ($x=d$) has no additional heat resistance. Through the above assumptions, the established heat transfer model of mono-layer coated tools is simplified to one-dimensional heat transfer model.

The cutting heat transfer model of mono-layer coated tools is based on Fourier heat transfer theory without considering heat transfer time. Rake face temperature and the other side of the substrate temperature are given. It is supposed that the heat transfer in coating and substrate interface is well, the temperature of coating and substrate are equal at the coating-substrate interface. Assumes that rake face temperature is T_w , environment temperature is T_0 , initial temperature is $T_{initial}=T_0$, coating thickness is d , the thickness of the coated tools is L . And assumed that cutting heat transfers only along the thickness direction.

In the rectangular coordinate, the heat transfer differential is equation as follows:

$$\frac{\partial^2 T}{\partial x^2} = 0 \quad 0 < x < L \quad (1)$$

Initial condition:

$$\begin{aligned} T|_{x=0} &= T_w & 0 < x < d \\ T|_{x=L} &= T_0 & d < x < L \end{aligned} \quad (2)$$

At the interface between the coating and the substrate, the temperature and the heat flux are equal in both these films.

$$\begin{aligned} T_T|_{x=d} &= T_s|_{x=d} \\ -\lambda_c \frac{\partial T}{\partial x}|_{x=d} &= -\lambda_s \frac{\partial T}{\partial x}|_{x=d} \end{aligned} \quad (3)$$

In Eqs.(3), T_T is the temperature of tool coating, T_s is the temperature of tool substrate, λ_c is the thermal conductivity of coating, λ_s is the thermal conductivity of the tool substrate.

The general solution of Eqs.(1) is as follows:

$$T = c_1 x + c_2 \quad (4)$$

Solve the differential equations, obtained:

$$\begin{aligned} T(x) &= \frac{T_0 - T_w}{\frac{\lambda_s}{\lambda_c}(L-d) + d} x + T_w & 0 < x < d \\ T(x) &= \frac{(T_0 - T_w)}{(L-d) + \frac{\lambda_s}{\lambda_c} d} x + \frac{(T_w - T_0)L}{(L-d) + \frac{\lambda_s}{\lambda_c} d} + T_0 & d < x < L \end{aligned} \quad (5)$$

Eqs.(5) is a heat transfer model. It can be seen that the coated tools temperature is related to thermal conductivity of coating, substrate and coating thickness. The temperature can be calculated when the coated tool is quantified. It can be seen from Eqs.(5), in heat transfer model of mono-layer coated tools, the smaller thermal conductivity of the coating, the lower the cutting temperature.

3. Equivalent coating layer approach

The equivalent coating layer approach has been proposed for simulation interface temperature, cutting forces and some cutting process outputs of coated tools [18-20]. The multi-layer coated tools can be equivalent to mono-layer coated tools using the equivalent coating layer approach. The equivalent thermal conductivity of the multi-layer coating may be

calculated based on the thermodynamic principle of one-dimensional heat transfer.

Fig. 2 Multi-layer coated tools equivalent modeling

As shown in Fig. 2, the multi-layer coating is represented by a mono-layer composite coating with 3–4 elements across thickness. Equivalent thermal conductivity strongly depends on the numbers of coating layers, coating thickness and coating material. For multi-layer coated tools, it can be determined using thermodynamics expression [18-22], as follows:

$$\frac{\sum_{i=1}^t x_i}{\lambda_{eq}} = \frac{x_1}{\lambda_1} + \frac{x_2}{\lambda_2} + \dots + \frac{x_t}{\lambda_t} \quad (6)$$

where, x_i thickness values of individual coating layers ($i=1, 2, 3, \dots, n$), λ_i thermal conductivities of individual coating layers ($i=1, 2, 3, \dots, n$), $\sum x_i$ total thickness of the equivalent layer, λ_{eq} equivalent thermal conductivity of the equivalent layer.

Calculations of the rake face temperature require values of the thermal diffusivity is quantified. It can be determined as the ratio of the equivalent thermal conductivity to the equivalent volumetric heat capacity (C_{eq}). The proper formula can be derived by summing volumes of the individual layers V_i to obtain the total coating. For example, in the case of an i -layer coating it can be written as follows:

$$V_{eq} = V_1 + V_2 + \dots + V_i$$

where, V_{eq} is summing volumes of multi-layer coated tool, V_i is the volumes of i -layer ($i=1, 2, 3, \dots, t$).

ρ_i is density of i -layer for multi-layer coated tools. By considering adequate thicknesses (x_i) and densities (ρ_i) of each coating layers and replacing the density by $\rho_i = C_i/c_{pi}$ (where, C_i is heat capacity of i -layer, c_{pi} is the specific heat of i -layer), the final equation can be expressed in the form:

$$\frac{\sum_i (x_i \rho_i c_{\rho i})}{C_{eq}} = \frac{x_1 \rho_1 c_{\rho 1}}{C_1} + \frac{x_2 \rho_2 c_{\rho 2}}{C_2} + \dots + \frac{x_i \rho_i c_{\rho i}}{C_i} \quad (7)$$

According to the above proposed model, the multi-layer coated tools can be equivalent to mono-layer coated tools. Using Eqs. (6) and (7) can obtain the thermal conductivity and thermal diffusivity of equivalent mono-layer composite coating.

4. Finite element simulation of multi-layer coated tools

The finite element simulation used for orthogonal metal cutting simulation is based on the Lagrange techniques and explicit dynamic, thermos-mechanically coupled model software with adaptive refinement.

Table 1 Coated tools geometry and cutting parameters

	TiAlN/TiN	TiN/TiC/TiN
Corner radius (mm)	0.02	0.02
Rake angle	5.0	5.0
Flank angle	5.0	5.0
Cutting speed (m/min)	40,60,90,120,200,250	40,60,90,120,200,250
Feed speed (mm/r)	0.2	0.2
Cutting depth (mm)	0.25	0.25
Cutting length (mm)	3.0	3.0

According to the multi-layer coated tools geometry and cutting conditions, the finite element simulation model is established. The workpiece is set as a rectangle, its size is 3mm×0.7mm.

Fig. 3 Schematic of cutting temperature distribution (a) coated tool and (b) TiAlN/TiN coating

The grid number of multi-layer coated tools set for 100000, and adopted local grid refinement technology. The tool tip refined. The minimum grid side length 0.1 mm. The tool and workpiece contact part refinement. The minimum grid side length 0.2 mm.

The finite element simulation for multi-layer coated tools developed. One is a multi-layer coated tools model, and the other is an equivalent model of mono-layer composite coated tools. A simulation model of TiAlN/TiN multi-layer coated tools is shown in Fig. 3.

5. Experimental setup

In experiment, temperature measurements made using thermocouple sensor by turning a round bar with 300 mm length, and 70 mm external diameter. The cutting experiment performed with a turning lathe CA6140. The workpiece material used in the turning experiment is H13 hardened steel. Table 2 and Table 3 give the chemical composition, physical and mechanical properties of H13 hardened steel, respectively. The cutting tools are multi-layers coated tools namely TiAlN/TiN and TiN/TiC/TiN.

Table 2 Chemical composition of experimental materials H13 hardened steel [w/%]

Chemical component	C	Si	Mn	Cr	Mo	V	P	S
GB/T1299-2000	0.32~ 0.45	0.80~ 1.20	0.20~ 0.50	4.75~ 5.50	1.10~ 1.75	0.80~ 1.20	≤0.03	≤0.03

Table 3 Physical and mechanical properties of experimental materials H13 hardened steel

Properties	H13
Density ρ (kg/m ³)	7800
Thermal conductivity λ (W/m°C)	28.6
Young's modulus E (GPa)	211
Yield stress σ_s (MPa)	1075.6
Hardness (HRC)	48~52
Heat capacity C (J/kg°C)	460
Thermal diffusivity a (m ² /s)	7.92×10 ⁻⁶

The thermocouple embedded in the turning tool is shown in Fig. 4. The coated tool was drilled into two mounting holes to install the thermocouples sensor. The holes were covered with a thin HT-CPS to prevent potential damage from cutting chip. The signals can be

translated from the sensor to computer through the amplifier and A/D convertor.

Fig. 4 Tool sample with thermocouple mounting hole (a) schematic and (b) actual photograph

Fig. 5 Tool temperature measurement setup

An overview of the experimental setup is shown in Fig. 5. The feed rate was $f = 0.2$ mm/rev, while the depth of cut was $a_p = 0.2$ mm. The machining operation was then performed with a constant chip section and a constant cutting speed. The data acquired by thermocouples sensor and then was recorded by computer.

6. Results and Discusses

6.1 The equivalent parameters of multi-layer coated tools

The two multi-layer coated tools are TiAlN/TiN and TiN/TiC/TiN. Fig. 6 is the structure of TiAlN/TiN and TiN/TiC/TiN multi-layer coated tools. Table 4 summarizes mechanical and thermal properties of each coating layer of TiAlN/TiN and TiN/TiC/TiN multi-layer coated tools [23-29, 30]. Based on thermal conductivity and individual layers coating thickness of TiAlN/TiN and TiN/TiC/TiN multi-layer coated tools, the equivalent thermal conductivity is

obtained at temperature of 500°C as shown in Table 2. The equivalent volume heat capacity of TiAlN/TiN and TiN/TiC/TiN multi-layer coated tools are 3.34 and 2.91 J/m³ °C. Equivalent thermal diffusivity is calculated directly from calculated quantities of equivalent heat capacity, density, and thermal conductivity.

Fig. 6 Structure (SE image) of carbide substrate and components of TiAlN/TiN and TiN/TiC/TiN. Magnification: .5000x.

Table 4 Coating properties

Coating		TiC	TiN	TiAlN	TiAlN/TiN	TiN/TiC/TiN
Young's modulus	$E(\text{GPa})$	450-496	250	370		
Density	$\rho(\text{kg/m}^3)$	4650-4900	4650	1892		
Thermal conductivity(500°C)	$\lambda(\text{W/m } ^\circ\text{C})$	37	23	15.4	15.1	24.25
Heat capacity	$C_{eq} (\text{J/m}^3^\circ\text{C})$	2.55	3	3.6	3.34	2.91

The equivalent thickness of the mono-layer composite coating for TiAlN/TiN and TiN/TiC/TiN multi-layer coated tools is 3.5μm and 5μm, respectively.

6.2 Calculated results of heat transfer modeling

The cutting temperature for the equivalent mono-layer composite coating is then calculated by Eqs. (5). The analysis temperature is shown in Fig. 7. With the coating thickness increased, the cutting temperature is gradually reduced in the coating. Due to multi-layer coating equivalent to mono-layer composite coating, temperature gradient does not exist at the coating interface. Compared with TiN/TiC/TiN coated tool, the temperature at the first

coating layer of TiAlN/TiN coated tool here cutting temperature is lower than that of TiN/TiC/TiN. It explained that heat transfer performance of TiN/TiC/TiN coating is better than that of TiAlN/TiN coated tool. Compared with TiAlN/TiN multi-layer coated tool which coating thickness is $3.5\mu\text{m}$, TiN/TiC/TiN multi-layer coated tool which coating thickness is $5\mu\text{m}$ can play a better role in reducing cutting temperature.

Fig. 7 Cutting temperature of the equivalent mono-layer composite coating for TiAlN/TiN and TiN/TiC/TiN multi-layer coated tools

The cutting temperature of multi-layer coated tools is related to many factors, such as thermal physical properties of coating material and substrate material, the friction coefficient between coating and workpiece, the partition of cutting heat flowing into the cutting tool and coating structure, etc. It is considered from the influence of the coated tools for cutting heat transfer, multi-layer coated tools with the same coating structure (including the thickness and layers), and its heat transfer performance is related to thermal physical properties of the multi-layer coatings. Using equivalent coating layer approach, multi-layer coating is equivalent to mono-layer composite coating.

6.3 Finite element simulation of multi-layer coated tools and mono-layer composite coated tools

The Finite Element simulation results are shown in Fig. 8. The temperature results are rake face temperature and coating and substrate interface temperature of TiAlN/TiN and TiN/TiC/TiN multi-layer coated tools temperature and equivalent mono-layer composite coated tools temperature. Rake face temperature and coating–substrate temperature is the average temperature.

Fig. 8 The finite element simulation results of multi-layer coatings and mono-layer composite coatings ($v=120\text{m/min}$)

Compared with two kinds of finite element simulation modeling of rake face temperature, the error of TiAlN/TiN coated tool is 3.3%, the error of TiN/TiC/TiN coated tool is 4.6%. Compared with two kinds of finite element simulation modeling of coating and substrate interface temperature, the error of TiAlN/TiN coated tool is 2.6%, the error of TiN/TiC/TiN coated tool is 2.5%. The errors of simulation temperatures are small.

6.4 Experimental results

Experimental tests of TiAlN/TiN and TiN/TiC/TiN multi-layer coating tools cutting temperature, as shown in Fig. 9. The experiment temperature of the measurement point gradually increased with increasing cutting speed.

Fig. 9 The experimental results with various cutting speed

Fig. 10 Experimental results and calculated results of TiAlN/TiN and TiN/TiC/TiN multi-layer coated tools ($v=120\text{m/min}$)

When the cutting speed of 120 m/min, TiAlN/TiN and TiN/TiC/TiN multi-layer coated tools internal measurement point temperature of 426°C and 494°C respectively. Fig. 10 was calculation temperature and experimental measurement temperature of TiAlN/TiN and TiN/TiC/TiN multi-layer coating tools. The rake face temperatures were estimated according to rake face temperature model[31], coating-substrate interface temperatures were estimated based on heat transfer modeling, and the measurement point(from the rake face of 2.5 mm) temperatures were obtained by experiment, respectively. Compared between the experimental temperature and the calculated temperature, including TiAlN/TiN multi-layer coating tool error was 9.8%, TiN/TiC/TiN multi-layer coating tool error was 5.4%.

7. Conclusions

In this paper, cutting temperature of multi-layer coated tools were studied. Based on the analytical models, the cutting temperatures of multi-layer coated tools can be obtained. The main conclusions are as follows:

- (1) The equivalent coating layer model for multi-layer coating is in good agreement with multi-layer coating model in FEM predictions within 5% difference.
- (2) The present investigation revealed that analytical models can also be favored for the modelling of cutting temperatures for the multi-layer coating. The cutting temperatures of multi-layer coated tools were calculated and compared with experimental results, and the error is within 10%.
- (3) It can also be essential for practice that the rake face temperatures and coating-substrate interface temperatures predicted can support the choice of coated tools for

defined machining parameters in order to avoid excessive thermal loading of the tools, and provide the reasonable selection of coated tools to improve the machining performances and prolonged tool life.

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Authors Contributions

Jingjie Zhang and Zhanqiang Liu conceived and designed the study. Jingjie Zhang performed the experiments. Jingjie Zhang and Jin Du analyzed data and wrote the paper. Chonghai Xu, Jin Du, Guosheng Su, Peirong Zhang, Zhanqiang Liu, Xiangfei Meng reviewed and modified the manuscript. All authors read and approved the manuscript.

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Competing Interests

The authors declare that they have no competing financial interests.

Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability

The codes used or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

Figure 1

Schematic of coated tools heat transfer

Figure 2

Multi-layer coated tools equivalent modeling

(a)

(b)

Figure 3

Schematic of cutting temperature distribution (a) coated tool and (b) TiAlN/TiN coating

(a)

(b)

Figure 4

Tool sample with thermocouple mounting hole (a) schematic and (b) actual photograph

Figure 5

Tool temperature measurement setup

Figure 6

Structure (SE image) of carbide substrate and components of TiAlN/TiN and TiN/TiC/TiN. Magnification: .5000x.

Figure 7

Cutting temperature of the equivalent mono-layer composite coating for TiAlN/TiN and TiN/TiC/TiN multi-layer coated tools

Figure 8

The finite element simulation results of multi-layer coatings and mono-layer composite coatings
 $v=120\text{m/min}$

Figure 9

The experimental results with various cutting speed

Figure 10

Experimental results and calculated results of TiAlN/TiN and TiN/TiC/TiN multi-layer coated tools
 $v=120\text{m/min}$