Finite element investigation of cutting performance of Cr/W-DLC/DLC composite coated cutting tool

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Abstract

DLC has been applied as coating material in the machining of difficult-to-cut materials, and shows a good cutting performance. In this study, Cr/W-DLC/DLC-coated tools were compared with other three kinds of coated tools (TiC-, TiAlN-, Al2O3-) to investigate the cutting performance in the machining of Al–Si alloy. The influence of Cr/W-DLC/DLC-coated tools on the cutting performance under different cutting speeds was studied. Cutting force, cutting temperature, heat partition coefficient, cutting deformation rate, plastic deformation of machined surface, the interface temperature, and stress were investigated numerically with the aid of finite element method (FEM). Actual cutting experiments were carried out to verify the FEM models by means of the cutting force and cutting temperature measurement. The investigation results show that Cr/W-DLC/DLC-coated tool had the best cutting performance among these four kinds of coated tools. With the increasing of cutting speeds, cutting force and cutting temperature showed an increase trend, while the plastic deformation depth of machined surface and heat partition into cutting tool all showed a decrease trend during the machining with Cr/W-DLC/DLC-coated tool. This investigation can provide the theory basis or technical guidance for the cutting practice with Cr/W-DLC/DLC-coated tools.

Keywords

Cr/W-DLC/DLC coating · Heat partition · Cutting performance · Finite element method

1 Introduction

Under the current environment protection situation, the application of conventional metal cutting with cutting fluid exhibits great limitations. Because of the low friction coefficient between coating and workpiece material, dry cutting with coated tool has become an environmentally friendly and economical processing method [1]. In metal cutting applications, in order to prolong tool life and improve machining quality, advanced coating technology has been applied to cemented carbide or high-speed steel tools [2–4]. The actual cutting experiments can obtain part of cutting performances such as cutting force, cutting temperature, machined surface roughness, and tool wear. However, some indexes during the cutting process such as the shear angle at the first deformation zone, equivalent stress, heat transfer coefficient, temperature, and stress at the tool-chip interface cannot be obtained. Finite element method (FEM) is a highly efficient and commonly used numerical calculation method, which can solve the limitation of the actual cutting experiment, and can provide data that cannot be obtained through the actual cutting experiment [5].

DLC coating began to enter the metal cutting application in the 1990s. DLC is a kind of amorphous carbon or hydrogenated amorphous carbon thin-film material, which is composed of graphite-like carbon in diamond-like matrix. DLC is a metastable amorphous material, which is formed by the covalent bond of carbon atom coordination sp1, sp2, and sp3 [6–8]. The higher the sp3 bond content in DLC, the closer the properties of diamond, and the higher the sp2 bond content, the closer the properties of graphite. Chemical vapor deposition (CVD), physical vapor deposition (PVD), and liquid phase electrodeposition can be used to prepare DLC film coatings. DLC coating is similar to diamond coating in performance, and has excellent characteristics such as high hardness, high elastic modulus, good chemical inertia, self-lubricating, high-temperature strength, appropriate thermal conductivity,
and good corrosion resistance. It is suitable for coating metal cutting tools [9–12]. DLC coating helps to improve the durability and adaptability of cutting tools, which is considered to be the strategic material in the twenty-first century. However, low adhesion strength between DLC film and cutting tool substrate is the main obstacle for the wide application of DLC coated cutting tool, especially to single-layer DLC-coated tools [13–15]. In addition, brittle fracture is often caused by insufficient tightness of the DLC coating when the high-speed cyclic repeated contact occurs during cutting. At present, the above problems are usually solved by adding a transition interlayer between DLC coating and tool substrate. The transition interlayer can balance the thermal expansion and lattice difference between DLC coating and tool substrate, thus not only improving the bonding strength of DLC coating, but also reducing internal residual stress and improving toughness [16].

Al–Si alloy is one of the cast aluminum alloys which have good casting performance, wear resistance, and the most varieties, and are widely used in the manufacture of engine pistons and other parts. The traditional processing method of Al–Si alloy is to use coated tools such as TiN-coated tools, TiAlN tools, and Al₂O₃ tools. However, these coated tools have strong adhesion and chemical reaction with Al–Si alloy during processing, which leads to rapid wear and short tool life. DLC-coated cutting tools have excellent characteristics such as high strength at high temperature, good corrosion resistance, and good self-lubricating performance, and are suitable for processing Al–Si alloy. Bhomnick et al. [17] used hydrogenated diamond-like carbon (α:C-H) coatings and diamond coatings for the drilling of subeutectic (Al-6.18.5% Si) Al alloy. The results show that aluminum adhesion is a limiting factor for cutting performance when drilling aluminum–silicon alloys, and α:C-H-coated tools can replace CVD diamond–coated tools. D’Orazio et al. [18] and Maksym et al. [19] used DLC-coated tool and TiAlN-coated tool to cut the AA7075 alloy and Ti-6Al-4 V alloy respectively. The results show that the wear of DLC-coated tool is lower than that of TiAlN-coated tool.

Considering the potential application of DLC composite-coated tools in Al–Si alloy cutting, a complete DLC-coated cemented carbide tool was prepared by DC plasma-enhanced chemical vapor deposition (PACVD). The coating deposited by PACVD technology has compact structure and small roughness and can be deposited at low temperature [20]. In this study, YG8 cemented carbide tool was chosen to be the substrate, and Cr/W-DLC/DLC composite coatings were prepared as the tool coating. The magnetron sputtering process prepares the Cr and W-DLC interlayer, and the preparation of the outermost layer of DLC films by plasma-enhanced chemical vapor deposition. Cr as the first transition interlayer can be attributed to three reasons. First, Cr, as a transition element, has higher hardness, higher density, good ductility, electrical conductivity, and thermal conductivity. Second, it can block the adverse effect of Co element in the carbide matrix on the nucleation of carbon atoms. Finally, Cr, as a carbide-forming element, can enter part of the solid solution in an atomic state, another forms a displacement alloy cementite, and some form a bonding phase with the cemented carbide substrate to form an alloy-phase bonding interface that can be well combined with the cemented carbide matrix [21]. The second transition interlayer is DLC coating doped with W element. The doped W element will exist as an amorphous structure in the carbon network structure, thereby alleviating internal residual stress (reducing pressure concentration) and enhancing comprehensive performance. W-DLC, as a support layer, can increase the crack suppression rate and increase the elastic recovery rate.

The thicknesses of Cr/W-DLC/DLC composite coatings was 3.3 μm. Figure 1 shows the cross-sectional morphology and element distribution of Cr/W-DLC/DLC-coated tools. It can be seen from Fig. 1 that the tool coating consists of three layers: Cr layer, W-DLC layer, and DLC layer.

In this study, advanced numerical simulation software is used to investigate the cutting performance of Cr/W-DLC/ DLC composite coating tool in Al–Si alloy (AC9B) machining. The influence of coating materials (TiC-, TiAlN-, Al₂O₃-, Cr/W-DLC/DLC-) and cutting speeds on cutting performance was discussed. The cutting performances of

![Cross-sectional morphology and element distribution of Cr/W-DLC/DLC-coated tools.](image-url)
Cr/W-DLC/DLC-coated tools in cutting force, cutting temperature, cutting deformation, and heat conductivity were investigated. In addition, the influence of cutting speed on the cutting performance was also studied. The results can contribute to the further study of Cr/W-DLC/DLC-coated tool failure mechanism and tool life. The description of the flow chart of the experimental method is shown in Fig. 2. First, the finite element simulation model was validated by the actual cutting experiments. The influence of coating material and cutting speed on cutting process and cutting performance of tool is analyzed by FEM. This study provides a basis for the development of DLC composite coatings and provides a basis for the application of DLC composite coatings in the field of metal cutting.

2 Finite element model and heat partition model

2.1 Establishment of finite element model

The ambient temperature of workpiece and cutting tool is set to 20 °C. The length of workpiece is 6 mm and the height is 2 mm. In the finite element (FE) model, the cutting tool is fixed in the \(X\) and \(Y\) directions, and the workpiece is set to move in the \(X\) positive direction with the cutting speed relative to the tool, while the \(Y\) direction is fixed. The cutting tool cuts into the workpiece from the initial position. The chips continue to form as the tool cuts into workpiece. The friction coefficient between DLC-coated cemented carbide tool and high Al–Si alloy is 0.1 [22]. The simulation calculation model selects the standard detailed calculation (standard) mode which is built into the AdvantEdge software. Metal cutting can be regarded as a process in which large deformation is concentrated in a small area [23]. The 3-D cutting simulation cutting model is converted into a 2-D cutting simulation model to reduce the simulation time without affecting the results, as shown in Fig. 3. In this study, the mesh of the tool tip and cutting deformation area are appropriately encrypted, and other parts are divided by a larger mesh.

Power-law material constitutive model is used for simulation. Material constitutive parameters are determined according to the software material library. Therefore, the tool-workpiece friction model, chip separation model, meshing and material model and failure criteria are quantified by software library. The thermophysical properties of workpiece materials used in simulation are shown in Table 1. In the simulation process, Carbide Grade K in the software library is selected as the tool matrix material. The tool coating material is designed as Cr/W-DLC/DLC, and its thermophysical properties are shown in Table 2 [9, 24, 25].

![Fig. 2 The description of the experiment methodology flow chart](image)
According to the principle of metal cutting, cutting heat is generated in three deformation zones. Shaw [26] proposed that all cutting energy is converted into heat in the cutting process. Heat is transferred to the workpiece, tool, and chip, as shown in Fig. 4. In the secondary deformation zone, the cutting heat ratio of chips flowing into the tool-chip interface
can be represented by symbol $R_2$. $R_2$ is called chip heat distribution coefficient. Shear angle ($\phi$) and chip thickness ($h_D$) are necessary parameters for calculating heat distribution coefficient $R_2$. Using the measuring tool of Advantedge software, the shear angle and chip thickness as shown in Fig. 5 can be obtained. The $l_f$ is the tool-chip contact length along the rake face of the tool. Referring to the slip line theory put forward by Lee and Schaefer [27], $l_f$ can be determined by the formula shown in Eq. (1).

$$l_f = h_D \frac{\sqrt{2}}{2 \sin \phi \sin \left( \frac{\pi}{4} + \phi - \gamma_0 \right)}$$  \hspace{1cm} (1)

where $h_D$ is the undeformed chip thickness, $\phi$ is the shear angle, and $\gamma_0$ is the tool rake angle. The effective heat partition coefficient ($R_2$) entering to the chip at the tool-chip interface is described as follows [28].

$$R_2 = \frac{q_2 \left( l_f / k_1 \right) - \bar{\theta}_s + \theta_0}{q_2 \left( l_f / k_1 \right) + q_2 \left( 0.377 l_f / k_2 \sqrt{\nu_{ch} l_f / 4 \alpha} \right)}$$  \hspace{1cm} (2)

where $q_2$ is the heat flux in the secondary deformation zone, $\bar{\theta}_s$ is the mean temperature nearby the first deformation zone, $\theta_0$ is the ambient temperature of workpiece, $k_2$ is the thermal conductivity of chip, $\nu_{ch}$ is the chip velocity, and $\alpha$ is the thermal diffusivity of the workpiece. Therefore, heat partition into the cutting tool ($R_{tool}$) is determined as Eq. (3):

$$R_{tool} = 1 - R_2 = 1 - \frac{q_2 \left( l_f / k_1 \right) - \bar{\theta}_s + \theta_0}{q_2 \left( l_f / k_1 \right) + q_2 \left( 0.377 l_f / k_2 \sqrt{\nu_{ch} l_f / 4 \alpha} \right)}$$  \hspace{1cm} (3)

2.3 Verification of the FE models

In order to verify the FE model, the actual cutting experiment was carried out, and the cutting force and cutting temperature were measured. Cutting tools had 20° rake angle and 0° clearance angle and 0.5-mm cutting edge radius. The cutting speeds employed in this experiment were 78, 152, 244, 304, and 378 m/min. Depth of cut and feed rate were maintained constants at 0.4 mm and 0.1 mm/r, respectively. All of the cutting tests were conducted at a lathe CA6140 (maximum speed 1400r/min, power 7.5KW). The experimental apparatus is shown in Fig. 6 a. The advanced infrared thermal imager Flir A315 is used to record the cutting temperature in the cutting process, and the emissivity is 0.1.
The infrared thermal imager has been calibrated according to JJF 1187–2008 thermal image calibration specification. Cutting forces in three directions ($F_x$, $F_y$, $F_z$) were measured by Kistler 9129A dynamometer. The experimental recorded data of the temperature and cutting force are shown in Fig. 6b and c.

The change of main cutting force and cutting temperature obtained by dynamometer and simulation is shown in Fig. 7 and Fig. 8, respectively. Figure 7 shows the resultant cutting force comparison measured from Cr/W-DLC/DLC-coated tools through cutting experiments and FE simulations. As can be seen from Fig. 7, the cutting force values obtained from FE simulation of Cr/W-DLC/DLC-coated tools at different speeds are basically the same as the measured values with the actual cutting experiments. The influence of cutting speed on cutting temperature obtained by cutting experiment and finite element simulation is shown in Fig. 8. From Fig. 8, cutting temperature of Cr/W-DLC/DLC-coated tools obtained by FE simulations is close to the experimental values, and the cutting temperature increases with the increasing of cutting speed.

The simulation process is established under certain assumptions and theoretical conditions. The constitutive model and material parameter settings used are different from the actual workpiece material. In addition, there is a gap between chip fracture and separation criteria with the actual cutting, which makes the gap between simulation results and the actual cutting situation reasonable. Therefore, the finite element model was verified by measuring the main cutting force and cutting temperature in actual cutting experiments. It can be seen from Fig. 7 and Fig. 8 that the finite element model can be used to study the cutting performance of coated tools.

3 Influences of coating materials on cutting performance

Elastoplastic deformation and friction occur in the cutting tools, chips, and the surface layer of the workpiece during metal cutting, which will generate cutting force and cutting heat. Cutting force and cutting heat directly affects tool wear and its durability, machining accuracy, and machined surface quality. TiC, TiAlN, and Al$_2$O$_3$ coating materials were selected as comparisons to study the performance of Cr/W-DLC/DLC-coated tools in cutting force, cutting temperature, cutting deformation, coating-substrate interfacial stress, and thermal conductivity of the rake face. TiC coating has higher hardness, strength, and stiffness, and has a lower coefficient of friction (about 0.2–0.3) [29]. At the same time, it has good thermal stability (melting point above 3000°C) and good electrical conductivity [30]. Al$_2$O$_3$ coating has excellent heat resistance and stability [31]. TiAlN coating has good high-temperature oxidation resistance and age hardening [32]. At present, these three kinds of coating materials have been widely used in high-temperature and wear-resistant coatings in cemented carbide tools. The thermal conductivity parameters of the four coating materials are shown in Table 3 [28, 33–35].

3.1 Influences of coating materials on cutting temperature and cutting force

Figure 9 shows a comparison of various cutting forces and cutting temperatures measured by FE simulations from TiC-, TiAlN-, Al$_2$O$_3$-, and Cr/W-DLC/DLC-coated tools. In Fig. 9 a, $F_x$ and $F_y$ are the cutting component forces in the $x$ and $y$
y directions, respectively, and $F$ is the total cutting force; $F_f$ is the tangential frictional force acting on the rake face of the chip. $F_n$ is the normal force of the chip acting on the rake face, and $\gamma_0$ is the rake angle of the cutting tool. Then there are:

$$F = \sqrt{F_x^2 + F_y^2}$$  \hfill (4)

$$F_f = F_x \sin \gamma_0 + F_y \cos \gamma_0$$  \hfill (5)

$$F_n = \sqrt{F^2 - F_f^2}$$  \hfill (6)

where $F_x$ and $F_y$ are average values in the stable cutting process. In this way, the total cutting force, tool-chip friction force, and normal force of different coated tools are obtained. As shown in Fig. 9 a, the cutting force of Cr/W-DLC/DLC-coated tools is obviously smaller than that of other coated tools. The main reason is that the friction coefficient between coating material and workpiece material (Al–Si alloy) is different (Al–Si alloy). The Cr/W-DLC/DLC coating has the property of self-lubricating, so the friction between Cr/W-DLC/DLC coating and Al–Si alloy is significantly lower than that of other three coated tools.

The lower the friction between the tool and the workpiece, the lower the energy consumption and the lower the cutting heat. The change of cutting temperature with the cutting distance from the finite element analysis is shown in Fig. 9 b. As shown in Fig. 9 b, the order of peak temperature recorded from the four coated tools is $\mathrm{Al}_2\mathrm{O}_3 > \mathrm{TiAlN} > \mathrm{TiC} > \text{Cr/W-DLC/DLC}$.

### 3.2 Influences of coating material on shear angle and chip thickness

As mentioned above, shear angle and chip thickness are important parameters that can be used to evaluate cutting deformation [28]. As shown in Fig. 10, under the same cutting conditions, the four coated tools have different chip thicknesses and shear angles. Larger shear angle and smaller chip thickness mean lower cutting deformation rate, which indicates relatively small deformation during cutting. It can be seen from Fig. 10 that the Cr/W-DLC/DLC-coated tool has the smallest chip thickness and the largest shear angle, which means that the Cr/W-DLC/DLC-coated tool undergoes minimal deformation during the machining. According to metal cutting principle [26], cutting deformation ration ($\Delta h$) can be defined as the following equation:

![Fig. 9 Cutting force and cutting temperature distribution obtained by FE simulation. a Cutting force; b cutting temperature ($v_c = 400 \text{ m/min}, a_p = 2 \text{ mm}, f = 0.15 \text{ mm/r}$)](image-url)
where $\phi$ is the shear angle in the first deformation zone. The cutting deformation rate obtained from Eq. (7) is shown in Fig. 11. It further intuitively verified the cutting deformation ration of four kinds of coated tools in the cutting of Al–Si alloy. It can be seen that the cutting deformation with TiC-coated tool is the largest one while the Cr/W-DLC/DLC-coated tool is the smallest one.

### 3.3 Influences of coating materials on heat distribution

In the actual cutting test, the real-time temperature of the whole cutting area is measured by infrared thermal imager. However, the temperature distribution on the tool rake face cannot be distinguished, including the peak temperature and its position on the tool rake face. Therefore, the thermal conduction in the coating of cutting tool and the temperature field of cutting tool substrate which cannot be clearly identified by infrared thermal imager can be obtained by finite element simulation. In FE simulation, the average value of cutting deformation zone temperature is recorded as the simulation result of cutting temperature.

The temperature distribution in the tool can also be clearly determined from Fig. 12. Based on these temperature maps, not only the maximum temperature on the rake face of the tool can be determined, but also the temperature distribution perpendicular to the rake face can be obtained. It can be seen from Fig. 12 that the chip temperature gradient is large, and it can be seen that most of the cutting heat is taken away by the chip. The cutting temperature field shown in Fig. 12 can be used to study the influence of tool coating material on the maximum cutting temperature. In the same temperature range, the distribution area and temperature value of $\text{Al}_2\text{O}_3$-coated tools in the high-temperature area are significantly higher than those of TiAlN-coated tools and TiC coated tools. The temperature distribution of Cr/W-DLC/DLC-coated tools is shown in Fig. 12 d. It can be seen that the maximum temperature of the rake face is obviously lower than that of the other three coated tools, and the area size of the high temperature area is also significantly lower than those of the other three coated tools. It proves that the thermal diffusion of the Cr/W-DLC/DLC-coated tool is significantly better than those of the other three coating materials.

The peak temperature position on the rake face of the tool is mainly affected by the contact length between the tool and the chip, which can be defined as Eq. (2). According to Eq. (2), the tool-chip contact length is defined by the undeformed chip thickness, shear angle, and tool rake angle. When the undeformed chip thickness and the tool rake angle are constant, the shear angle is the decisive factor of the tool-chip contact length. Therefore, with the increase of shear angle, the tool-chip contact length decreases. It can be seen from Fig. 10 that the four kinds of coating materials have different shear angles when cutting Al–Si alloy. Compared with TiAlN-, TiC-, and $\text{Al}_2\text{O}_3$-coated tools, Cr/W-DLC/DLC-coated tools have the largest shear angle. Therefore, it can be inferred that compared with the other three coated tools, the chip contact length of the rake face of the Cr/W-DLC/DLC-coated tool is the shortest, and the peak temperature position is closest to the tool tip. Figure 13 shows the rake surface peak temperatures and their positions of four coated tools obtained under the same coating thickness (coating thickness is 3.3 μm) and the same cutting speed (cutting speed is 400 m/min). As shown in Fig. 13, the coordinates on the left represent the peak temperature of the tool rake face, and the
Fig. 12 Cutting temperature field of different coated tools
coordinates on the right represent the peak temperature position of the tool rake face, that is, the distance \( l \) from the tip to the peak temperature position on the tool rake face. The distance \( l \) from the tip to the peak temperature location is indicated in Fig. 5. It can be seen from Fig. 13 that among the four coated tools, the rake face temperature of \( Al_2O_3 \)-coated tools is the highest, but the peak temperature position on the rake face is the shortest. \( Cr/W-DLC/DLC \)-coated tools have a minimum rake face temperature of 189.3°C, and the highest temperature on the rake face is the shortest distance from the tool tip, about 24.22 μm. Figure 14 shows the change of the horizontal distance between the temperature values of different coated tools and the rake face peak temperature. It can be seen from Fig. 14 that the temperature of the highest point of the rake face of the four coated tools decreases approximately linearly with the increase of the horizontal distance of the rake face of the tools. The temperature of \( Cr/W-DLC/DLC \)-coated tools decreased slowly with a small slope. The results show that \( Cr/W-DLC/DLC \)-coated tool has a slow temperature change and a small thermal shock to the tool substrate.

The proportion of cutting heat flowing into the cutting tool mainly depends on the thermal conductivity of the coating material. For the steady-state heat conduction of the coated tool, the smaller the thermal conductivity of the coating material, the less the heat transferred to the cutting tool, so the lower the temperature of the tool matrix. It can be seen from Table 3 the order of thermal conductivity from largest to smallest is \( Cr/W-DLC/DLC > TiC > TiAlN > Al_2O_3 \). According to the FE simulation results, combined with the characteristics of the workpiece and the coating material, the heat partition into the tool can be calculated according to Eq. (3), as shown in Fig. 15. It shows the heat partition coefficients of TiC-, TiAlN-, Al2O3-, and Cr/W-DLC/DLC-coated tools under the same cutting conditions (400 m/min cutting speed). Among these four coatings, the heat partition of the Cr/W-DLC/DLC-coated tool on the rake face is the maximum \( (R_{tool} = 0.17) \), and the heat partition of the Al2O3 coated tool is the minimum \( (R_{tool} = 0.031) \). The thermal conductivity of the Cr/W-DLC/DLC coating is 500 W m\(^{-1}\) K\(^{-1}\) that much higher than those of the other three coatings. The high thermal conductivity of Cr/W-DLC/DLC coating means that it provides the highest heat distribution for cutting tools at the tool-chip interface. According to Fig. 9 b, Cr/W-DLC/DLC-coated tools generate much less cutting heat in the cutting process than the other three coated tools. It can be inferred that although the large thermal conductivity of the Cr/W-DLC/DLC coating results in a large heat
partition into the cutting tool, the cutting heat generated in the second deformation zone through the Cr/W-DLC/DLC coating flowing into tool substrate is far less than those of the other three coatings in the actual cutting process. Al₂O₃ coating has the characteristics of low thermal conductivity which can effectively prevent cutting heat from flowing into the tool and suppressing the increase of the tool temperature.

3.4 Influences of coating materials on the temperature and stress of coating-substrate interface

The temperature and stress of coating-substrate interface have important influence on the failure of tool coating. Excessive coating-substrate interface temperature will reduce the strength of tool coating and substrate. High stress will produce microcracks in tool coating and then peels off and fails. The values of temperature and stress at the coating-substrate interface obtained from TiC-, TiAlN-, Al₂O₃-, and Cr/W-DLC/DLC-coated tools are shown in Fig. 16. It can be seen from Fig. 16 that the temperature and stress at the coating-substrate interface obtained from Al₂O₃-coated tool are the highest of the four coating tools, which are 293.8°C and 440.5 MPa, respectively. Cr/W-DLC/DLC-coated tools have the lowest temperature and stress values at the coating-substrate interface, which are 185.0°C and 346.5 MPa, respectively.

It is divided into two parts near the stagnation point at the tool tip in metal cutting. One part of the metal forms the chip, and the other part is pressed into the new surface of workpiece. Metals that are pressed into a new machined surface usually have residual stress after machining. The extension direction is shown in Fig. 17 a. Figure 17 b shows the distribution of the equivalent stress along the maximum value of the tip toward the inside of the tool in the rake face. It can be seen from Fig. 17 b that the stress and its gradient in the coated tool change greatly, and the stress drastic changes at the interface between the coating and the tool substrate. Excessive internal stress will lead to the cracking and peeling of the coating, thus cause coated tool failure. Figure 18 shows the equivalent stress distribution and enlargement of rake face and rake face during finite element simulation. It can be seen from Fig. 18 that the stress reaches the maximum at a certain distance from the side to the blade tip, which corresponds to the position where the flank wear of cutting tool occurs.
4 Influences of cutting speed on cutting performance

In order to study the effect of cutting speed on cutting performance of Cr/W-DLC/DLC-coated tools, cutting experiments based on FE simulation were carried out. The cutting speeds used in the simulation are 400 m/min, 800 m/min, 1200 m/min, 1600 m/min, and 2000 m/min. The cutting depth is kept at 2 mm, and the feed speed is kept at 0.15 mm/r. The cutting tool has a rake angle of 20 and a rake angle of 0 and a cutting edge radius of 0.5 mm.

4.1 Influence of cutting speed on cutting temperature and cutting force

The friction between tool rake face and chip bottom in secondary deformation zone increases with the increase of cutting speed, and the friction between tool rake face and workpiece surface in tertiary deformation zone increases with the increase of cutting speed. The increase of these two kinds of friction leads to the increase of cutting force. In addition, higher cutting speeds lead to rapid plastic deformation and shear slip in the first deformation zone, which leads to an
increase in cutting force. The increase of plastic deformation, shear slip, and friction will result in the increase of cutting temperature. Figure 19 and Fig. 20 show the cutting force and cutting temperature corresponding to different cutting speeds. It can be seen from Fig. 19 and Fig. 20 that both the cutting force and the cutting temperature increase with the increasing of the cutting speed.

### 4.2 Influence of cutting speed on shear angle and chip thickness

After simulation, the shear angle and chip thickness are measured with advanced software measuring tools, as shown in Fig. 21. The results show that with the increase of cutting speed, the shear angle increases, while the chip thickness decreases. In other words, higher cutting speed will cause smaller deformation in the cutting process. The results of Fig. 22 also prove the relationship between cutting speed and cutting deformation. It can be seen from Fig. 22 that the cutting deformation ratio and the cutter-chip contact length decrease with the increase of cutting speed.

### 4.3 Influence of cutting speed on plastic deformation of machined surface

There are two reasons for the plastic deformation of the machined surface. On the one hand, in the cutting process, a negative shear zone will form under the cutting layer in front of the tool tip. In the negative shear zone, the workpiece material produces plastic shear slip and bending deformation, which results in the plastic deformation of the machined surface. On the other hand, friction occurs
between the tool side and the machined surface in the third deformation zone, which will lead to residual stress and work hardening of the machined surface. The surface plastic deformation has important influence on the mechanical properties of the machined workpiece. The serious plastic deformation of machined surface will produce high residual stress and change grain structure, thus affecting surface quality and fatigue life of workpiece. The plastic deformation of the machined surface decreases with the increase of the depth of the material from the machined surface in the vertical direction [36]. Figure 23 shows the depth of plastic deformation at different cutting speeds. The schematic diagram of plastic deformation depth is shown in Fig. 23 a. It can be seen that the cutting speed has a great influence on the depth of plastic deformation in the machined surface from Fig. 23 b. The increases of cutting speed will reduce the depth of plastic deformation in the machined surface when other cutting parameters remain unchanged. The maximum depth of plastic deformation in the machined surface is 0.16 mm when the cutting speed is 400 m/min. The depth of plastic deformation is reduced to 0.05 mm when the cutting speed is 2000 m/min. This is because the contact time between the tool and the workpiece material decreases with the increase of cutting speed, and the contact time is too short for severe plastic deformation to occur in the machined surface of the workpiece.

4.4 Influences of cutting speed on heat distribution

The temperature in the secondary deformation zone is mainly caused by the friction between the rake face and the chip in the cutting process. With the increasing of friction time, the friction heat is accumulated on the tool rake face. The chip separation point of temperature accumulation on the rake face of the tool reaches its peak. It can be seen from Fig. 24 that the peak temperature of the rake face increases with the increasing of cutting speed, and the distance between the peak temperature of the rake face and the tool tip decreases with the increasing of cutting speed. It can be inferred that with the increase of cutting speed, the contact length between cutter and chip decreases. Chip contact length directly affects chip friction in cutting process, and then affects chip deformation rate, machining surface integrity, and tool wear. It can be concluded that the higher the speed, the more conducive the cutting process.

The influence of cutting speed on heat distribution in secondary deformation was studied by finite element simulation. Figure 25 shows the heat distribution of cutting tools at different cutting speeds. It can be seen from Fig. 25 that with the increase of cutting speed, the heat distribution of the cutting (Rtool) tool decreases. One reason for this trend is that with the increase of cutting speed, the contact time between the rake face and the chip bottom is shortened, and
the time for cutting heat to enter the tool is reduced. Another reason is that in high-speed machining, a large amount of cutting heat is taken away by chips, so less cutting heat flows into the tool.

5 Conclusions

The influences of coating materials on cutting performances were studied in the machining of Al–Si alloy (AC9B). Especially, through FE simulation and practical cutting experiments, the cutting performance of Cr/W-DLC/DLC-coated tools is studied. The main results are summarized as follows:

(1) The results of Cr/W-DLC/DLC-coated tools are in good agreement with the cutting force and cutting temperature obtained from the FE simulations and cutting experiments. It proves that FE model built in this study can be employed to the analysis of coated tool cutting performance.

(2) The cutting force and cutting temperature during the machining with Cr/W-DLC/DLC-coated tools are significantly lower than those of the TiC-, TiAlN-, Al₂O₃-coated tools. Heat partition into cutting tools obtained from Cr/W-DLC/DLC coated tools is higher than that of TiC-, TiAlN-, and Al₂O₃-coated tools. Cr/W-DLC/DLC-coated tools also have good cutting deformation characteristics, lower film-based interface temperature, and stress, which is beneficial to actual cutting processing.

(3) Among the four kinds of coated tools, the peak temperature of the rake face of Cr/W-DLC/DLC-coated tools is the lowest, and the peak temperature is closest to the tool tip.

(4) In the machining with Cr/W-DLC/DLC-coated tools, the cutting force and temperature gradually increased, and the cutting deformation rate, the depth of plastic deformation of the machined surface, and the thermal conductivity of the rake surface gradually decreased as the increasing of cutting speed.

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Declarations

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