Modeling of critical cutting speed of white layer formation in the hard-cutting process

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Abstract
The white layer formed during the hard-cutting process impacts the surface quality and mechanical properties of a workpiece significantly. Obtaining the accurate critical cutting speed for white layer formation is beneficial to the quality control and parameter selection of cutting. Accordingly, combining with the finite element (FE) method, a critical cutting speed model of white layer formation was developed based on the solid phase transformation free energy theory, in which the thermal–mechanical effects were considered. To calculate the free energy change during the hard-cutting process, an austenite transformation driving force model was established. This model indicated that the cutting temperature, stress, and strain can provide the required driving force for austenite transformation in the white layer formation process. An FE model of the hard-cutting process was created to obtain the thermal and mechanical parameters. The critical cutting speed of white layer formation of AISI 52100 hardened steel was predicted in this study. The predicted result was in accordance with the experimental result. Moreover, the relationship between the critical cutting speed and cutting parameters were analyzed explicitly. We found that the critical cutting speed of white layer formation increased with the tool rake angle and decreased with the increase in cutting thickness and flank wear.

Keywords Hard-cutting · White layer · Critical cutting speed · Austenite transformation driving force model

1 Introduction
Hardened steel, such as AISI 52100 steel, is commonly used for manufacturing parts, including bearings, tools, and molds owing to their high hardness and good mechanical strength. Hard-cutting, which has the advantages of high quality, high efficiency, and eco-friendliness, is used extensively in the finishing process of hardened steel. However, a workpiece is subjected to extremely high temperatures and severe plastic deformation because of high hardness. This leads to dramatic changes in the machined surface. Scholars have observed that a white layer, which differs from the bulk material in microstructure [1], surface quality [2], and mechanical properties [3], is formed on the machined surface during the hard-cutting process [4]. This white layer has complex effects on the performance of the workpiece [5]. Zhang et al. studied the influence of the white layer on wear resistance during sliding friction. They suggested that the resistance to abrasive wear improved because of the high hardness characteristic of the white layer [6]. Guo and Warren [7] measured the wear rate of a machined surface with and without the white layer under the condition of sliding contact. The results indicated that the wear rate of a surface with the white layer is lower than that without the white layer. However, Choi revealed that the white layer reduced the contact fatigue life of hard machined surfaces under low contact stress [8]. Guo et al. [9] also found that the white layer decreased the wear resistance under rolling contact conditions. They considered the residual tensile stress caused by the white layer promotes the initiation and propagation of fatigue cracks. Therefore, modeling the critical cutting speed of white layer formation in the hard-cutting process is vital for controlling the formation of the white layer and for selecting reasonable cutting parameters.
Recently, the properties and formation mechanism of the white layer were explored in detail. The crystalline grain of the white layer is significantly refined. The hardness and the retained austenite content of the white layer are higher than those of the bulk material [10]. Chou and Evans [11] observed the white layer morphology in the hard turning process of AISI 52100 steel. They considered that the formation of the white layer is dominated by a rapid heating–cooling process. Moreover, the cutting heat causes austenite and martensite transformations. Du et al. [12] analyzed the white layer of Ni based powder superalloy formed by the cutting process. They found that the phase transformation white layer can be obtained when the cutting temperature is lower than the phase transformation temperature. They suggested that plastic deformation promotes the formation of the white layer. Zhang et al. [2, 13] studied the formation mechanism of the white layer of AISI 52100. The experimental results demonstrated that the white layer is formed because of phase transformation, and the plastic deformation provides the phase transformation driving force, thereby accelerating the formation of the white layer.

Experimental research has indicated that the white layer is induced by phase transformation in some cutting conditions [13, 14]. It is of great significance to predict the white layer based on the properties and formation mechanism of the white layer. Recently, scholars performed an in-depth exploration on the prediction of the white layer, in which the prediction model of the white layer thickness was the most studied. Chou and Evans [11] developed an empirical model based on the moving heat source. The model used the heat generated because of plastic deformation and friction as a moving heat source to calculate the temperature of the machined surface. If the machined surface temperature exceeded the phase transformation temperature, the white layer was considered to be formed. Umbrello et al. [15] established a finite element (FE) prediction model of the white layer thickness in a dry hard-cutting process based on the hardness condition. When the hardness of the machined surface exceeds the matrix hardness, the white layer is produced.

Stress and strain also influences the phase transformation temperature of the white layer [16]. Thus, some scholars believed that the calculation model of the white layer thickness should be built by considering the effects of stress and strain. The influence of stress on austenite transformation temperature was considered by Ramesh and Melkote, and the white layer thickness was predicted by using the FE method [17]. Duan et al. [18] considered the effects of alloy elements, stress, and strain on the phase transformation temperature of the white layer and established a critical austenite transformation temperature model of the white layer based on the phase transformation free energy theory. Then, the model was combined with a hard-cutting FE model to predict the thickness of the phase transformation white layer at different cutting parameters. Zeng et al. [19] also established a prediction model for white layer thickness based on the phase transformation mechanism. They considered the effects of stress, elastic strain, and plastic strain on the phase transformation temperature.

Although some investigations regarding the modeling of the white layer in the hard-cutting process were reported, certain problems are still unanswered:

1. The research on the theoretical modeling of the white layer primarily focuses on the prediction of the white layer thickness. Nevertheless, the prediction of the critical cutting speed of the white layer formation has not been studied in detail; however, establishing a model of critical cutting speed of the white layer formation has a guiding role in selecting reasonable cutting parameters.

2. In previous studies, critical austenite transformation temperature was selected as the critical condition of white layer formation [11, 17, 18]. However, the actual austenite transformation temperature is above the equilibrium phase transformation temperature without the influence of external force [13]. The key factor for austenite transformation is whether the phase transformation driving force can surpass phase transformation resistance [20]. Therefore, it is more accurate to use the phase transformation driving force as the critical condition.

3. The driving force of austenite phase transformation plays a significant role in the white layer formation in the hard-cutting process. The kinetics of austenite formation analyzed in previous studies primarily focused on the heat treatment processes [21–23]. However, plastic deformation, which has significant influence on the formation of the white layer, was not considered in these kinetics models. Therefore, stress and strain should be considered when calculating the austenite phase transformation driving force.

4. Stress and strain cannot be measured during the cutting process. However, hard-cutting FE models can simulate the stress and strain accurately. Therefore, combining the austenite phase transformation driving force model with the hard-cutting FE model to predict the critical cutting speed is worth studying.

Accordingly, a hard-cutting AISI 52100 steel FE model was developed to simulate the cutting temperature and stress and strain distributions of the hard-cutting workpieces. Then, a driving force model of the white layer austenite transformation was established based on the free energy change principle. The influences of cutting temperature, stress, and strain on the driving force were considered in this model. Next, a critical cutting speed model of the white layer formation was established by combining the driving force model with the hard-cutting FE model. The
critical cutting speed of white layer formation calculated using the theoretical model was compared with the cutting experimental results. Finally, the influences of cutting parameters, rake angle, and different levels of flank wear on the critical cutting speed of white layer formation were predicted and discussed.

2 Scheme of modeling the critical cutting speed of white layer formation

Hardened AISI 52100 steel (60 HRC) was selected for hard-cutting because of hardenability and wide application. Research by Zhang et al. [2] indicated that the retained austenite volume of the white layer was higher than that of the bulk material, demonstrating that austenite transformation occurred during the hard-cutting process. In the hard-cutting process, the phase transformation white layer is induced by solid phase transformation. During the austenite solid transformation process, the system has a spontaneous tendency to move to a state with lower free energy. The microstructure of hardened AISI 52100 steel is martensite. Thus, the austenite transformation cannot be performed unless the free energy of austenite is less than that of martensite. Free-energy change $\Delta G$ between the old and new phases is the phase transformation driving force. Phase transformation resistance was observed in the phase transformation process. Hence, the transformation cannot be induced unless the phase transformation driving force is greater than the phase transformation resistance. Therefore, a calculation model of the austenite transformation driving force needs to be developed.

By combining the hard-cutting FE model with the austenite transformation driving force model, a critical cutting speed prediction model of the white layer formation was established. The flowchart is shown in Fig. 1. First, a FE hard-cutting model was developed to provide data

![Flowchart for predicting the critical cutting speed of white layer formation](image-url)
to the critical cutting speed. Second, an austenite transformation driving force model under the influence of cutting temperature, stress, and strain was established. The temperature, stress, and strain energy extracted from the FE model were imported to the austenite transformation driving force model to calculate the austenite transformation driving force at different cutting conditions. Then, the critical cutting speed of austenite transformation was determined by comparing the austenite transformation driving force provided by the hard-cutting process with the critical driving force of austenite transformation. Finally, the accuracy of the model was verified. If the white layer cannot be observed on the machined surface at a cutting speed lower than the critical cutting speed predicted by the model, but can be observed at a cutting speed higher than the critical cutting speed, it is considered that the model can accurately predict the critical cutting speed of the white layer formation.

The critical cutting speed model cannot consider the factors that affect austenite transformation in the white layer owing to the complicity of this process. Therefore, the prediction model was simplified and the following basic assumptions were made:

1. The workpiece is free of impurities after heat treatment and the influence of cementite on austenite transformation driving force is ignored.
2. When the austenite transformation driving force provided by the hard-cutting process reaches the critical driving force, it is considered that austenite transformation can occur on the machined surface.

4 Modeling of critical cutting speed of white layer formation

4.1 Calculation model of austenite phase transformation driving force in the hard-cutting process

4.1.1 Driving force of austenite transformation provided by the cutting temperature

Kooiker et al. [26] established a martensite to austenite reversion model and demonstrated that temperature is a main factor affecting the austenite transformation process. In the white layer austenitizing process, martensite \( M \) is the parent phase, whereas austenite \( \gamma \) is the new phase. Figure 3 shows the tendency of martensite and austenite free energy with temperature. Martensite cannot be transformed to austenite unless the molar free energy of austenite is lower than that of martensite:

\[
\Delta G^M_{\gamma} = G_\gamma - G_M < 0
\]

where \( \Delta G^M_{\gamma} \) is the austenite transformation driving force induced by the cutting temperature (J/mol), \( G_\gamma \) is the molar free energy of austenite (J/mol), and \( G_M \) is the molar free energy of martensite (J/mol). At the austenite equilibrium
transformation temperature $A_{cm}$, $\Delta G_{v}^{M\rightarrow V} = 0$. However, austenite transformation cannot be performed in this case. When the cutting temperature is higher than $A_{cm}$, $\Delta G_{v}^{M\rightarrow V} < 0$. Thus, the driving force can be provided by the cutting temperature to promote austenite transformation.

The free energy of a substance is given by [27]:

$$G = H - TS$$

where $H$ is the molar enthalpy (J/mol), $S$ is the molar entropy ($J/(mol \cdot K)$), and $T$ is the temperature (K).

The free energy, enthalpy, and entropy of a system change with the temperature. In the constant-pressure process, molar enthalpy change $\Delta H$ due to temperature is written as [28]:

$$\Delta H = \int_{T_1}^{T_2} C_p(T)dT$$

where $C_p(T)$ is the molar heat capacity at constant pressure (J/(mol \cdot K)).

Molar entropy change $\Delta S$ due to temperature is given as [28]:

$$\Delta S = \int_{T_1}^{T_2} \frac{C_p(T)}{T}dT$$

Through regression analysis of the experimental data, the relationship between the $C_p(T)$ and temperature is described using a polynomial relationship [28]:

$$C_p(T) = a + bT + cT^2$$

where $a$, $b$, and $c$ are constants, whose martensite and austenite values are shown in Table 4.

The expressions of $H$ and $S$ were obtained by integrating Eqs. (3) and (4):

$$H = H(298K) + \int_{298K}^{T_2} C_p(T)dT$$

$$S = S(298K) + \int_{298K}^{T_2} \frac{C_p(T)}{T}dT$$

where $H(298K)$ and $S(298K)$ are the molar enthalpy and molar entropy at 298 K. The $H(298K)$ and $S(298K)$ values of martensite and austenite are shown in Table 5.

By combining Eq. (5) with Eqs. (6) and (7) and substituting the data in Tables 1 and 2 in Eqs. (6) and (7), we obtain the change rule of $H$ and $S$ due to temperature:

$$H^M = 17.49T + 12.385 \times 10^{-3}T^2 - 6312$$

$$S^M = 17.49\ln T + 24.77 \times 10^{-3}T - 83$$

$$H^V = 26.61T + 3.14 \times 10^{-3}T^2 - 1428.62$$

Table 2 Physical properties of AISI 52100 steel [18]

| Temperature (°C) | Young’s modulus (GPa) | Poisson’s ratio | Expansion (×10⁻⁶/(°C)) | Conductivity (W/(m°C)) |
|------------------|------------------------|----------------|------------------------|------------------------|
| 22               | 201.0                  | 0.277          | 11.5                   | 52.5                   |
| 200              | 179.0                  | 0.269          | 12.6                   | 47.5                   |
| 400              | 163.0                  | 0.255          | 13.7                   | 41.5                   |
| 600              | 103.0                  | 0.342          | 14.9                   | 32.5                   |
| 800              | 86.9                   | 0.396          | 15.3                   | 26.0                   |
| 1000             | 67.0                   | 0.490          | 15.3                   | 29.0                   |
| 1500             |                        |                |                        |                        |

| Temperature (°C) | Specific heat (J/(kg(°C))) | Density (kg/m³) |
|------------------|-----------------------------|-----------------|
| 25               | 458                         |                 |
| 200              | 640                         | 7827            |
| 430              | 745                         |                 |
| 540              | 798                         |                 |

Table 3 Tool geometry and the cutting parameters

| Rake angle $\gamma_0$ (°) | Relief angle $\alpha_0$ (°) | Flank wear $VB$ (mm) | Cutting speed $v$ (m/min) | Chip thickness $a_c$ (mm) |
|--------------------------|-----------------------------|----------------------|--------------------------|--------------------------|
| $-10^\circ$, 0°, 10°    | 7°                          | 0, 0.1, 0.2          | 28 ~ 550                 | 0.05, 0.1, 0.15          |

Fig. 3 Tendency of martensite and austenite free energy with temperature
$S' = 26.61\ln T + 6.28 \times 10^{-3}T - 119.81$ \hspace{1cm} (11)

where $H^M$ and $H^T$ indicate the molar enthalpy of martensite and austenite, and $S^M$ and $S^T$ indicate the molar entropy of martensite and austenite, respectively.

Combination of Eqs. (1) and (2) to the following relationships:

$$\Delta G_{V}^{M\rightarrow T} = G^T - G^M = H^T - TS' - (H^M - TS^M)$$

$$= \Delta H^{M\rightarrow T} - T \Delta S^{M\rightarrow T}$$ \hspace{1cm} (12)

After substituting Eqs. (8), (9), (10), and (11) in Eq. (12), $\Delta G_{V}^{M\rightarrow T}$ can be given as

$$\Delta G_{V}^{M\rightarrow T} = 45.93T + 9.245 \times 10^{-3}T^2 - 9.127\ln T + 4883.38$$ \hspace{1cm} (13)

Thus far, the calculation model of austenite transformation driving force provided by the cutting temperature has been established. When $\Delta G_{V}^{M\rightarrow T} = 0$, the free energy of martensite is equal to that of austenite. If $\Delta G_{V}^{M\rightarrow T}$ is less than 0, the molar free energy difference between austenite and martensite provides the driving force for $M \rightarrow T$ transformations.

4.1.2 Driving force of austenite transformation provided by stress and strain

In the hard-cutting process, the white layer formation is affected by plastic deformation and cutting temperature. Ramesh and Melkote [17] investigated the influence of stress and strain on the austenite equilibrium transformation temperature $A_{cm}$ and found that high stress and strain causes a decrease in $A_{cm}$. This demonstrates that the austenite transformation driving force can be provided by the plastic deformation in the hard-cutting process.

According to the thermodynamic principles of phase transformation, the free energy change due to stress $P$ at constant temperature $T$ is [28]:

$$\Delta G_T = \int_{P_1}^{P_2} VdP$$ \hspace{1cm} (14)

where $\Delta G_T$ is the free energy change induced by stress (J/mol) and $V$ is the molar volume of a substance (m$^3$/mol).

Table 4 Parameters of molar heat capacity [28]

| Phase      | a   | b          | c  |
|------------|-----|------------|----|
| Martensite | 17.49 | 24.77$x10^{-3}$ | 0  |
| Austenite  | 26.61 | 6.28$x10^{-3}$  | 0  |

As the molar volume of martensite differs from that of austenite, $\Delta G_T$ cannot be calculated using Eq. (14) directly. However, the free energy is state variable, and $\Delta G_T$ is only related to the initial and final states of the system, not the process. Therefore, $\Delta G_T$ caused by pressure can be expressed by:

$$\Delta G_T^{M\rightarrow T} = (V_f - V_M)(P - P_0) = \Delta V^{M\rightarrow T}(P - P_0)$$ \hspace{1cm} (15)

$\Delta V^{M\rightarrow T}$ is the molar volume increment from martensite to austenite. $P$ is the compressive stress on the machined surface caused by the cutting process (Pa), and $P_0$ is the stress on the surface before the cutting process (i.e., atmospheric pressure). The stress produced by the hard-cutting process is much larger than the atmospheric pressure. Hence, it is assumed to be $P_0 = 0$ Pa.

The molar mass of iron is 55.85 g/mol, and the densities of austenite and martensite are 7.633 g/cm$^3$ and 7.571 g/cm$^3$, respectively. Therefore, the molar volume increment from martensite to austenite is given as follows:

$$\Delta V^{M\rightarrow T} = \frac{55.85\text{g/mol}}{7.633 \times 10^{-6}\text{g/cm}^3} - \frac{55.85\text{g/mol}}{7.571 \times 10^{-6}\text{g/cm}^3} = -0.06 \times 10^{-6}\text{m}^3/\text{mol}$$ \hspace{1cm} (16)

By combining Eqs. (15) and (16), the free energy change of austenite transformation affected by stress can be obtained:

$$\Delta G_T^{M\rightarrow T} = -0.06 \times 10^{-6}P$$ \hspace{1cm} (17)

When a workpiece is deformed, the work done by the external force is transformed into strain energy $W_S$ and stored in the workpiece. Then, the external force decreases gradually, the strain energy storage caused by elastic deformation is released. This provides the driving force for phase transformation. The strain energy in a micro-element is expressed as [18]:

$$dW_S = \frac{1}{2}(\sigma_1 \varepsilon_1 d\varepsilon_1) + \frac{1}{2}(\sigma_2 \varepsilon_2 d\varepsilon_2) + \frac{1}{2}(\sigma_3 \varepsilon_3 d\varepsilon_3)$$

$$= \frac{1}{2}(\sigma_1 \varepsilon_1 + \sigma_2 \varepsilon_2 + \sigma_3 \varepsilon_3) d\varepsilon_1 d\varepsilon_2 d\varepsilon_3$$ \hspace{1cm} (18)

The strain energy $W_S$ can be obtained using the hard-cutting FE model, and thus $W_S$ is directly extracted from the post-processing results of the FE model instead of establishing the calculation model of $W_S$.

Therefore, the driving force of austenite transformation induced by the cutting temperature, stress, and strain is described as:

$$\Delta G^{M\rightarrow T} = \Delta G^{M\rightarrow T}_V + \Delta G^{M\rightarrow T}_T + W_S$$ \hspace{1cm} (19)

$$\Delta G^{M\rightarrow T} = 45.93T + 9.245 \times 10^{-3}T^2 - 9.127\ln T$$

$$+ 4883.38 - 0.06 \times 10^{-6}P + W_S$$ \hspace{1cm} (20)

where the unit of $W_S$ is J/mol.

Table 5 Molar enthalpy and molar entropy of austenite and martensite at 298 K [28]

| Phase      | $H$(298K)/(J/mol) | $S$(298K) | $H$(J/(mol · K)) |
|------------|-------------------|------------|-------------------|
| Martensite | 0                 | 27.28      | 0                 |
| Austenite  | 6.78              | 33.66      | 6.78              |
4.2 Calculation of critical cutting speed for white layer formation

Before calculating the critical cutting speed, the stress, strain, and strain energy should be calculated using the FE model. This model aims to predict the critical cutting speed for white layer formation. Therefore, only the data of the top surface of the workpiece were extracted to calculate the driving force, and the subsurface was not considered. The data extraction position is the contact point between the tool tip and the machined surface, as shown in Fig. 4.

After extracting the data of \( T \), \( P \), and \( W_5 \) from the FE simulation results, \( \Delta G^{M\rightarrow r} \) was calculated using Eq. (20). The temperature, stress, strain energy, and \( \Delta G^{M\rightarrow r} \) at different cutting speeds (\( \gamma_0 = -10^\circ \), \( a_c = 0.1 \) mm, \( VB = 0 \) mm) are shown in Table 6.

Khodabakhshi and Kazeminezhad [29] measured the change in free energy in the austenite transformation process of carbon steel. The result showed that the free energy required for austenite transformation of carbon steel is 1156 J/mol, i.e., the critical austenite transformation driving force is 1156 J/mol.

The austenite transformation driving force calculated at different cutting speeds (\( \gamma_0 = -10^\circ \), \( a_c = 0.1 \) mm, \( VB = 0 \) mm) was compared with the critical austenite transformation driving force, as shown in Fig. 5. At cutting speeds of 28 m/min and 44 m/min, the austenite transformation driving force provided by the hard-cutting process is lower and higher than the critical austenite transformation driving force, respectively. This indicates that the white layer cannot and can be formed on the machined surface at the aforementioned cutting speeds. At the critical cutting speed, the austenite transformation driving force is equal to the critical austenite transformation driving force. Moreover, the critical cutting speed of the white layer formation (i.e., 38 m/min) was determined using the linear fitting method.

4.3 Model validation

To verify the accuracy of the simulation model, the predicted critical cutting speeds were compared with the experimental results. The cutting experiments were performed using the MULTUS B400-W machining center. The set-up of the hard-cutting experiment is shown in Fig. 6. The hard-cutting experiments were performed at

Table 6 FE prediction data and \( \Delta G^{M\rightarrow r} \) at different cutting speeds (\( \gamma_0 = -10^\circ \), \( a_c = 0.1 \) mm, \( VB = 0 \) mm)

| \( v \) (m/min) | \( T \) (K) | \( P \) (MPa) | \( W_5 \) (J/mol) | \( \Delta G^{M\rightarrow r} \) (J/mol) |
|----------------|------------|--------------|------------------|-------------------------------|
| 28             | 720        | 1882         | -158             | -731                          |
| 44             | 784        | 2123         | -202             | -1409                         |
| 56             | 816        | 2262         | -291             | -1798                         |
| 100            | 932        | 2753         | -323             | -2884                         |
| 150            | 1003       | 3108         | -332             | -3479                         |
| 200            | 1067       | 3523         | -356             | -4001                         |
| 250            | 1187       | 3944         | -360             | -4803                         |
| 300            | 1202       | 4026         | -364             | -4898                         |
| 350            | 1237       | 4212         | -368             | -5104                         |
| 400            | 1242       | 3566         | -201             | -4924                         |
| 450            | 1248       | 3365         | -184             | -4926                         |
| 500            | 1255       | 3195         | -162             | -4930                         |
| 550            | 1259       | 3036         | -113             | -4892                         |
the cutting speeds of 28 m/min, 34 m/min, and 44 m/min ($v_0 = -10^\circ$, $a_c = 0.1$ mm, $VB = 0$ mm). The material and cutting tool used in the experiments were consistent with those used in the FE model. The machined surfaces were observed using a scanning electron microscope (SEM). Before observation, a part of the specimen was cut from the workpiece using the wire cutting method. To avoid damaging the white layer, the specimen was intercepted in the direction perpendicular to the machined surface, as shown in Fig. 7a. Therefore, the cross section is the part to be observed, as shown in Fig. 7b. Figure 8 shows the SEM images of the machined surface at the cutting speeds of 28 - 44 m/min. The images shown in Fig. 8a, b indicate that only the plastic deformation layer produced by the hard-cutting process was observed on the machined surface at the cutting speeds of 28 m/min and 34 m/min, and no white layer was produced. However, a white layer with the thickness of less than 1 μm was observed on the machined surface at the cutting speed of 44 m/min, as shown in Fig. 8c. These experiments indicated that the critical cutting speed of the white layer formation is between 34 and 44 m/min. The critical cutting speed predicted by the model was 38 m/min, which is within the range of the experimental result.

The prediction model was further validated by comparing the numerical predictions with the experimental results given in Ref [2]. Figure 9 shows the SEM images of the machined surface when the cutting speeds are 250 m/min, 350 m/min, and 450 m/min. Although the white layer can be observed on the machined surface at these three cutting speeds, the thickness of the white layer varies with the cutting speed. Figure 10 shows the variation of white layer thickness with the cutting speed. The white layer thickness increases with the cutting speed at cutting speeds lower than 350 m/min and tends to decrease at cutting speeds higher than 350 m/min. The austenite transformation driving force $\Delta G^{M\rightarrow\gamma}$ is the key factor for white layer formation. This indicates that the tendency of the white layer with the cutting speed must be consistent with that of the $\Delta G^{M\rightarrow\gamma}$ with cutting speed. Figure 5 shows the tendency of $\Delta G^{M\rightarrow\gamma}$ with cutting speed. The comparison shows that the tendency of white layer thickness is consistent with that of $\Delta G^{M\rightarrow\gamma}$. Accordingly, it can be demonstrated that the established model can predict the critical cutting speed of white layer formation accurately.

5 Results and discussion

The austenite transformation driving force model demonstrates that cutting temperature, stress, and strain affect the white layer formation, while cutting conditions, such as chip thickness, tool angle, and tool wear, have influence on the cutting temperature and plastic deformation of the machined surface, thus affecting the critical cutting speed of white layer formation. Therefore, the influence of cutting conditions on the critical cutting speed for white layer formation was predicted and discussed.

5.1 Influence of chip thickness on the critical cutting speed of white layer formation

The austenite phase transformation driving forces $\Delta G^{M\rightarrow\gamma}$ at different chip thicknesses ($VB = 0$ mm, $v_0 = -10^\circ$) were
calculated (Fig. 11a). We observed that $\Delta G_{M-\gamma}$ increased with the chip thickness at the same cutting speed. The cutting temperature, stress, and strain energy of the machined surface increased with the chip thickness. This results in the increase in $\Delta G_{M-\gamma}$. When the chip thickness is 0.15 mm, $\Delta G_{M-\gamma}$ exceeds the critical austenite phase transformation driving force at the cutting speed of 35 m/min. This indicates that the white layer is formed at this cutting speed. The critical cutting speeds of white layer formation at different chip thicknesses were predicted using the critical cutting speed prediction model, as shown in Fig. 11b. The critical cutting speeds are 40.2 m/min, 38 m/min, and 34.5 m/min at chip thicknesses of 0.05 mm, 0.1 mm, and 0.15 mm, respectively. However, the critical cutting speeds decreased slowly with the increase in chip thickness.

### 5.2 Influence of rake angle on the critical cutting speed of white layer formation

The tendency of $\Delta G_{M-\gamma}$ with the cutting speed at different rake angles is displayed in Fig. 12a ($VB = 0$ mm, $a_c = 0.1$ mm). When the tool angle changes from a negative rake angle to a positive rake angle, the driving force decreases significantly. The tool rake angle has obvious influence on the cutting temperature, stress, and strain. When $\gamma_0$ changes to a positive rake angle, the extrusion and friction between the tool rake face and chip are reduced, leading to the decrease in cutting temperature, stress, and strain, and thus the decrease in $\Delta G_{M-\gamma}$. Figure 12b shows the change rule of critical cutting speed of white layer formation with the rake angle. When $\gamma_0$ changes from $-10^\circ$ to $10^\circ$, the critical cutting speed increases from 38 to 59.9 m/min. The positive rake angle increases the critical cutting speed of white layer formation rapidly.

### 5.3 Influence of flank wear on the critical cutting speed of white layer formation

Figure 13a shows the change in $\Delta G_{M-\gamma}$ with the cutting speed at different levels of flank wear ($a_c = 0.1$ mm, $\gamma_0 = -10^\circ$). At the same cutting speed, $\Delta G_{M-\gamma}$ increases significantly with the flank wear. The cutting heat produced in the hard-cutting process increases significantly with the flank wear, providing higher driving force for austenite transformation. Moreover, the stress and strain energy increase with the flank wear. This further promotes austenite transformation. The influence of flank wear on the critical cutting speed of white layer formation is shown in Fig. 13b. When the flank wear were 0.1 mm and 0.2 mm, the critical cutting speeds were 30 m/min and 23.3 m/min, respectively. The flank wear reduces the critical cutting speed of white layer formation significantly.
Conclusion

The main aim of this study is to establish a prediction model of the critical cutting speed of white layer formation and investigate the influence of cutting conditions on the critical cutting speed of white layer formation. The following conclusions can be derived:

1. The critical austenite transformation driving force, instead of austenite transformation temperature, was selected as the critical condition of white layer formation. Additionally, the austenite transformation driving force of the white layer in the hard-cutting process was derived mathematically, in which the effects of cutting temperature, stress, and strain on the phase transformation driving force were considered. The calculation results indicate that cutting heat and plastic deformation can provide driving force for austenite transformation.

2. The prediction model of critical cutting speed of white layer formation was presented by combining the driving force model with the hard-cutting FE model. The effects of thermal and mechanical factors on the critical cutting speed were considered explicitly. The predicted critical cutting speed agreed well with the experimental result. This demonstrates that the established model is valid for predicting the critical cutting speed of phase transformation white layer formation.
3. On the account of the established model, the critical cutting speeds of white layer formation at different cutting conditions were simulated. The cutting temperature, stress, and strain energy increased with the chip thickness and flank wear. This results in the increase in $\Delta G^{M-W}$. Therefore, the critical cutting speed of white layer formation decreased with the increase in cutting thickness and flank wear. When the rake angle changes from a negative rake angle to a positive rake angle, the cutting temperature, stress, and strain reduced, resulting in the decrease in $\Delta G^{M-W}$ and increase in the critical cutting speed.

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**Availability of Data and Material** All data generated or analyzed during this study are included in this published article.

**Code Availability** The code used in the study are available from the corresponding author on reasonable request.

**Declarations**

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Conflict of interest** The authors declare no competing interests.

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