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Self-organization wear characteristics of MTCVD-TiCN-Al_2O_3 coated tool against 300M steel

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ABSTRACT

The chemical thermodynamic of the cutting process was analyzed by Gibbs free energy function method. Tool life, wear characteristics, surface roughness and fractal characteristics of surface profile curves were investigated by high-speed turning of 300M with coated cutting tool. According to the chemical thermodynamic analysis, some products may be generated in this cutting system, which have a positive effect on high-speed cutting, such as TiO_2 and SiO_2. The reasons for the tool failure involved adhesive wear, abrasive wear, chipping, coating spalling and micro-crack. The self-organization wear characteristics (e.g. oxygen-containing surface layer and secondary structures) of the coated tool were found, which can play the role of protection, lubrication and heat insulation. The formation and disappearance of the self-organization structures affected the size of surface roughness. On the basis of the fractal analysis, a more stable and better machined surface quality was obtained at v_c = 300 m/min which can be selected for finish machining.

1. Introduction

In the modern manufacturing technology, ensuring machined quality, improving cutting efficiency, reducing production cost and saving energy are the development trend of manufacturing industry [1–3]. Therefore, the high-speed dry cutting technology emerges as the time require. However, the intense friction and high temperature in the cutting area can easily lead to dramatic tool wear during high-speed dry cutting process.

On the one hand, the prolonged tool life can be obtained by improving the friction contact conditions of tool-workpiece and tool-chip. For instance, the advanced cooling and lubricating technology (such as low temperature cooling, minimal quantity lubrication and compresses-are cooling) [4–6], can effectively reduce the cutting temperature and friction coefficient, thereby reducing tool wear. The optimal design of tool composition and structural can achieve self-lubricating cutting without external lubrication oil [7–9], such as the addition of solid lubricants, in-situ reaction, soft coating, micro-pool self-lubricating, etc., so as to improve the friction contact condition.

On the other hand, the self-organization phenomenon is found in high-speed dry cutting, which is characterized by the formation of thin tribo-films or secondary structures at the friction surface [10]. The interaction with the environment or structural modification of the surface material leads to the generation of the self-organization structures. For example, oxide thin films and secondary structures with complex amorphous structure are produced on the TiAlCrN/NbN nano-multilayered coatings surface [11,12], due to the coating grain refinement. These tribo-oxides (e.g. Al-O, Cr-O and Nb-O) play a role in protection, lubrication and heat insulation [11], which can improve the friction-reducing and wear-resistant performance of the tools. Owing to the high chemical stability, the generation of the alumina-like thin films on the insert surface can result in the reduction of adhesion of the workpiece material [12]. Then the chips take most of the cutting heat, thereby the cutting tool life is prolonged and the machined surface quality was improved. The Al_2O_3 tribo-film is detected on the worn surface when the PCBN tool with TiAlN-nanocoating machined high-strength steel AISI 4340 [13], which exhibit much more adequate for heat protection and friction reduction. So the better cutting performance is obtained from the TiAlN-nano-coating. Additionally, the similar cutting phenomenon is also found on the worn surface of PVD TiAlN+TiN coated cemented carbide tools [14].

High-strength alloy steel is a typical aviation material, which has high strength, high toughness and high hardness [15,16]. The cutting characteristics of serious tool wear and unstable machined quality are expressed during machining of high-strength steel. So the high-efficiency and high-quality machining of high-strength steel is facing enormous challenges. For high-strength steel, the most commonly used

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tool is carbide tool [17,18], coated tool [16,19,20], ceramic tool [21–23] and PCBN tool [13,23–25]. The primary causes of PVD coated tool wear is serious adhesive wear, coating spalling and micro-chipping [16]. The ceramic tool material is suitable for machining of high-strength steel at higher cutting speed because of high mechanical properties at high temperature [21]. Moreover, adhesion, abrasion and oxidation are the main wear mechanisms, while machining of high-strength steel 300M with Al_2O_3 ceramic tool at 300–600 m/min [21]. In addition, for CBN tools, the primary reasons of tool wear is abrasion and adhesion in the turning of high-strength steel AISI 4340 [23].

From the above research analysis, the reason for the tool failure is a combination of multiple mechanisms in the high-speed cutting process [12,16,21]. Moreover, the formation of the self-organization structures is constrained by the cutting temperature and cutting force [10,11,13]. Therefore, revealing the friction-reducing mechanism of the structures is particularly important to improve the tool life and surface integrity.

In this work, the chemical thermodynamic was analyzed by Gibbs free energy function method to obtain the possible products in the cutting process. Tool wear characteristics of self-organization and fractal characteristics of surface profile curves were investigated by high-speed turning of 300M with coated cutting tool to reveal the wear mechanisms.

2. Material and methods

A CNC lathe (Model CKD6136i) was used in the experiment, which was manufactured by the Dalian Machine Tool Group Corp. of China. Dry cutting was carried out in the experiment. The workpiece material was 300M high-strength steel (40CrNi2Si2MoVA), which was widely used in landing gear of aircraft. The tensile strength, yield strength, elongation in 50 mm and reduction of area are 1930 MPa, 1620 MPa, 9% and 32% [26], respectively. The hardness of 300M is 47 HRC. Table 1 exhibits the chemical composition of 300M [26].

A cemented carbide tool with a MTCVD-TiCN-Al_2O_3 thick coating was selected in the tests, which was made from Kennametal. The insert type was SNMG120408FN, and the graded of the tool was KCP10B. The type of the tool holder was MSSNR2020K12. All the tests were carried out with the following geometry parameters: nose radius r_ε = 0.8 mm; side cutting edge angle κ_r = 45°; inclination angle λ_s = 0°; rake angle γ_0 = 6°; and clearance angle α_0 = −6°. The cutting conditions selected in the experiment are given in Table 2.

In the work, a USB200 tool microscope was selected to measure the width of flank wear (VB). In the cutting process, the wear criterion was the average flank wear VB_{ave} = 0.3 mm. Meanwhile, a portable surface roughness tester with a model of CS-3200 was used to measure the machined surface roughness of 300M. The arithmetic mean value of R_a which was measured five times was calculated and used in the work. A scanning electron microscopy (SEM, Model FEI Sirion200) was selected to analyze the microstructure pattern and element composition of the tool worn surface, which was equipped with an energy dispersive X-ray spectrometer (EDX).

3. Results and discussion

3.1. Chemical thermodynamic analysis between coating and workpiece

3.1.1. Calculation method

Gibbs free energy function method was adopted to analyze the chemical compatibility [27], which is one of the common simplified calculation methods. The chemical reaction equation:

$$\sum l_i A_i = \sum n_i B_i \tag{1}$$

where A_i is reactant, B_i is resultant, l_i and n_i are the equation coefficients (mol).

ΔG_T^Θ is the standard Gibbs free energy (J). According to the thermodynamics, if $\Delta G^\Theta{}_T < 0$, the chemical reaction Eq. (1) can be carried out spontaneously under an isothermal isobaric condition and in a closed system.

On the basis of Gibbs free energy function method [27], ΔG_T^Θ can be calculated as:

$$\Delta G^\Theta{}_T = \Delta H^\Theta{}_{298} - T\Delta\Phi_T \tag{2}$$

where T is absolute temperature (K), $\Delta H^\Theta{}_{298}$ is thermal effect of the standard reaction at room temperature (J), $\Delta\Phi_T$ is Gibbs free energy function (J K^{-1}).

ΔH_{298}^Θ and $\Delta\Phi_T$ are given as follows:

$$\Delta H^\Theta{}_{298} = \sum (n_i \Delta H_{Bi,f,298})_{\text{resultant}} - \sum (l_i \Delta H_{Ai,f,298})_{\text{reactant}} \tag{3}$$

$$\Delta\Phi_T = \sum (n_i \Phi_{Bi,T})_{\text{resultant}} - \sum (l_i \Phi_{Ai,T})_{\text{reactant}} \tag{4}$$

where $\Delta H_{Bi,f,298}$ and $\Delta H_{Ai,f,298}$ are the standard molar heat of formation of B_i and A_i at 298 K (J mol^{-1}), respectively. $\Phi_{Bi,T}$ and $\Phi_{Ai,T}$ are Gibbs free energy function of B_i and A_i (J mol^{-1} K^{-1}), respectively. There data can be obtained by consulting the thermodynamic data handbook [27].

3.1.2. Thermodynamic calculation of chemical reaction

In the present work, the tool coating material mainly included Al_2O_3, TiCN, TiN and TiC, while the chemical composition of 300M mainly included Si, Cr, Fe, C, Mo, Mn, V, S and P. In addition, O_2 and N_2 are possible to react with coating and workpiece at high cutting temperature. The possible chemical reaction of this cutting system and its Gibbs free energy are presented in Table 3. According to the previous research [28], a three-dimensional finite element model was established to analyze the cutting temperature. The choice of temperature in Table 3 was based on the analysis result.

All chemical reactions can occur in the temperatures (Table 3). Al and Ti of the coating material are prone to oxidation. Due to the higher stability of TiO_2, Ti is more likely to be oxidized to TiO_2. Moreover, this oxidation reaction is more intense with the increase of temperature. Under the same conditions, the stability of V_2O_5 is better than that of V_2O_3. The reaction products of V are mainly including VC and VN which have high wear resistance. Mo_2C and Cr_3C_2 are the reaction products of Mo and Cr, respectively, which have high-temperature stability and high wear resistance. SiO_2 and Si_3N_4 are the reaction products of Si.

In a word, the main possible products include: (1) Gain strengthening and refinement: VC, VN, Mo_2C; (2) Oxidation resistance and wear resistance: Cr_3C_2, Si_3N_4, Al_2O_3, TiN; (3) Self-lubrication and wear resistance: TiO_2, V_2O_5, SiO_2, TiC.

3.2. Tool life and wear characteristics of self-organization

3.2.1. Tool life

The average flank wear progression of KCP10B when turning of 300 M is presented in Fig. 1. There was a normal flank wear progression of KCP10B. For example, before the failure of the tool, it passed though initial wear, stable wear and rapid wear. At v_c = 300 m/min, the longer initial running-in with three stages (the first stage (I) was about 1 min, the second stage (II) was about 14 min, the third stage (III) was about 22 min) resulted from the lower cutting force and cutting temperature. In stable wear stage, the tool exhibited a lower wear rate. So the tool life was more than 140 min at v_c = 300 m/min.

Table 1
Chemical composition of 300 M (wt%).

Si	Ni	Mn	C	Cr	Mo	V
1.45–1.80	1.65–2.00	0.65–0.90	0.40–0.46	0.70–0.95	0.30–0.45	≥0.05