Wear of PCBN tool when cutting materials difficult-to-cut based on thermodynamics entropy

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Abstract
Cutting temperature always highly reaches over to 1000℃ when high speed machining with PCBN tools. Diffusion of tool material element may have important influence on tool wear at such high temperature., the diffusion wear and oxidation wear have become the major wear mechanism. In this paper, the rules of diffusion wear and oxidation wear for PCBN cutting tools are proposed and analyzed based on thermodynamics theory. Dissolution concentrations in typical normal workpice materials of PCBN tool material at different temperature are then calculated. Diffusion reaction rules in high temperature are developed and analyzed using Gibbs free energy criterion. The machining tests were conducted using the PCBN tools at different cutting speeds of 50, 95,100 and 180 m/min, feed of 0.1, 0.2 and depth of cut of 0.1, 0.8, 1, and 1.5 mm respectively on PUMA300LM numerically-controlled lathe. It was found that the theoretical results were uniform with the experimental data; the results will provide useful references for tool material design and selection.

Key words: THERMODYNAMICS, SOLUBILITY, PCBN TOOL, DIFFUSION WEAR, OXIDATION WEAR.

1. Introduction

Tool wear is always a main problem in cutting zone because the diffusion wear of tool not only influences the machining precision and surface quality, but also possibly leads to cutting chatter as well as the damage of machine, tool and workpiece and so on [1].

Therefore, the measures such as the research on the mechanism of tool wear, the prediction and supervision to tool wear and the exchange of new tool in suitable time before the sharp wear for tools are more important, which can not only guarantee the cutting reliability for the machining system, improving the product quality, but also can fully develop the potential ability of the cutting tools, increasing production efficiency and economic benefit. In this way, this research on the wear rules has the important practical significance.

As with the excellent synthetical performance such as high strength, heat resistance（1670-1770K）, good thermol conductivity and chemical inertia on iron and its alloy, PCBN has become a much more appropriate engineering material[2],which is suitable for high speed machining especially .The mechanism of tool wear has become more complicated with the increasing speed and temperature[3-7]. Wan Yi et al. [8] considered that the mechanism of tool wear and damage during high speed machining were essentially different from that of the common traditional cutting speed machining. The tool would have different failure mechanism under such adverse working condition in high speed machining than that for the common cutting process, and the influence of cutting temperature and thermal stress to the wear and damage of tool would become more significant.

The tool wear is affected by many nonlinear and high coupling factors. Thermodynamics supplies a systemic analysis method to nonlinear mutual effect among many factors. Therefore it is very reasonable and feasible to reach the wear process by using of thermodynamics theory and method [9]. However, the research on the mechanism of tool wear from thermodynamics view is also still few.

In this paper, the research on diffusion wear and oxidation wear for PCBN tools during high speed cutting by using thermodynamics theory is advanced, which is to analyze the diffusion and oxidation wear rules for PCBN tools by the calculation of thermodynamics parameters in the cutting process, and moreover to direct the application of PCBN tools and supply reference for the design and optimization for tool materials according to the research conclusion.

2. Diffusion wear for PCBN ceramic tools

2.1. Analysis of standard heat of formation $\Delta_f H^{\odot}$ of compound and enthalpy value at different temperature

The absolute enthalpies $H_{\odot} = H_T^{\odot} - H_{298}^{\odot} + H_{298}^{\odot}$ are calculated at different temperature according to the relative enthalpies $H_T^{\odot} - H_{298}^{\odot}$ for BN, diamond C, Al_2O_3 and Si_3N_4 obtained by thermodynamics data table [10], which can be seen in Table 1.

Table 1. The absolute enthalpies of BN, Diamond C, Al_2O_3 and Si_3N_4

Temperature / K	BN		C		Al_2O_3		Si_3N_4	
	$H_T^{\odot} - H_{298}^{\odot}$	$H_T^{\odot}$	$H_T^{\odot} - H_{298}^{\odot}$	$H_T^{\odot}$	$H_T^{\odot} - H_{298}^{\odot}$	$H_T^{\odot}$	$H_T^{\odot} - H_{298}^{\odot}$	$H_T^{\odot}$
298	0	-252295	0	1883	0	-1675274	0	-744752
300	25	-255570	12	1895	158	-1675116	198	-744554
400	2008	-250287	871	2754	9039	-1666235	10768	-733984
500	4907	-247388	2069	3952	19151	-1656123	22430	-722322
600	8338	-243957	3501	5384	30011	-1645263	35020	-709732
700	12135	-240160	5125	7009	41411	-1633863	48437	-696315
800	16217	-236078	6919	8802	53247	-1622027	62605	-682147

900	20538	-231757	8868	10751	65408	-1609866	77456	-667296
1000	25070	-227225	10968	12851	77795	-1597479	92928	-651824
1100	29796	-222499	13212	15095	90372	-1584902	108962	-635790
1200	34704	-217591	15597	17480	103115	-1572159	125501	-619251

2.2. Solubility of Al2O3 ceramic tool material in workpiece material respectively

Solubility of PCBN tools when respectively machining steel material, titanium alloy, and pure nickel are presented in Table 2 .

Table 2. Solubility of PCBN tool when machining typical materials –carbon steel 、titanium alloy and aluminum alloy at different temperature(mol/m^3)

Temperature /K	298	400	600	800	1000	1159	1200	1400	1463	1500	1523
Gibbs free energy of BN	-226726	-217401	-199117	-180833	-162549	-148013	-144265	-125981	-120222	-116839	-114736
steel	5.61E-20	5.79E-14	4.16E-08	3.52E-05	2.01E-03	1.85E-02	2.99E-02	0.205	0.337	0.443	0.522
nickel	4.15E-15	2.46E-10	1.09E-05	2.30E-03	5.69E-02	0.331	0.484	2.23	3.31	4.11	4.68
aluminum	2.52E-15	1.69E-10	8.50E-06	1.91E-03	4.90E-02	0.291	0.427	2.00	2.99	3.72	4.24
titanium	1.45E-12	1.93E-08	2.00E-04	2.04E-02	0.326	1.49	2.07	7.76	10.9	13.2	14.7

3. Experiments setup

PUMA300LM numerically-controlled machine tool

Aluminum alloy material, hardness 115HBW, diameter Ø54.5mm; stainless steel material, hardness 184HBW, diameter Ø47mm; abrasion resistant cast iron MT-4 cast iron material (cast iron for short hereinafter), hardness 184HBW, diameter Ø42mm; No. 35 steel material, rigidity 169HBW, diameter Ø48mm; pure nickel material, rigidity 51.9HBW, diameter Ø28mm; titanium alloy material, rigidity 41.9HBW, diameter Ø21mm. The components of workpiece material are depicted as Table 3 to Table 6[11].

Table3. Chemical components of cast iron（%）

Element	C	Si	S	P	Cr Ni Cu Al Mo V	Fe
Content	3.38	2.1	0.121	0.072	Little	Other

Table 4. Chemical components of stainless steel （%）

Element	Cr	Ni	C	Si	Mn	P	S	Fe
Content	16.63	4.7	0.072	0.488	7.692	0.027	0.004	Other

Table 5. Chemical components of 35 steel（%）

Element	C	Si	Mn	S	P	Cr	Ni	Fe
Content	0.384	0.213	0.564	0.035	0.036	0.25	0.25	Other

Table 6. Chemical components of aluminum alloy（%）

Element	Si	Cu	Mg	Ni	Mn	Ti	Fe	Zn	Al
Content	11.5-13.0	0.8-1.3	0.8-1.3	0.8-1.3	≤0.15	≤0.2	≤0.7	≤0.2	Other

Nickel is pure nickel; component of titanium alloy is 73.68% of titanium and 26.32% of aluminum.

GE tools produced in American.

The machining tests were performed on workpiece materials in Table 3-6. The machining tests were conducted using the PCBN tools at different cutting speeds of 10, 150 and 250 m/min, feed of 0.2, 0.3 and depth of cut of 1, 2, 2.5 and 5 mm respectively on PUMA300LM numerically-controlled lathe. The machining studies were conducted in dry environment without any cutting fluid, for 15 min. The cutting temperature were measured with Handheld Infrared Thermometer produced in the United States whose accuracy was not high. Cutting condition and measurement results can be seen in Table 7.

Table 7. Cutting condition and measurement results

Workpiece material	a_p(mm)	f(mm/r)	V(m/min)	Surface roughness(μm)	Chip temperature（℃）
Cast iron13	1.5	0.2	50	12.5→1.6	114
nickel14	1	0.2	95.4	12.5→1.6	87
Aluminum alloy16	1	0.2	180	1.6→2.0	42
Stainless steel17	0.1	0.1	100	0.8→0.4	32
35steel 18	0.1	0.1	100	2.5→2.0	61
Titanium 15	0.8	0.2	66	10→2.0	53

In order to analyze diffusion and oxidation wear character, select points to make energy spectrum analysis in the bottom of wear region or non-cutting region. In addition, in order to decrease the influence of pollution factors in tool surface, make line scanning on blade surface, the line scanning results for element aluminum, oxygen and titanium of tools material when machining nickel, aluminum alloy, 35# steel and cast iron can be seen in Fig.1 to Fig.17.

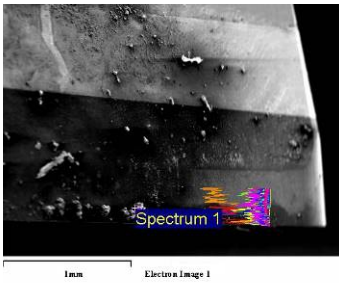

Figure 1. Line scanning when machining nickel

Figure 2. Line scanning when machining aluminum alloy

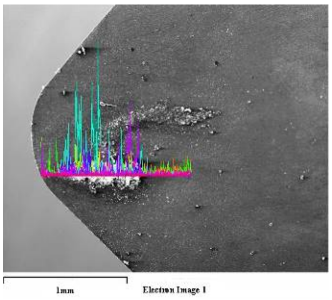

Figure 3. Line scanning when machining stainless steel

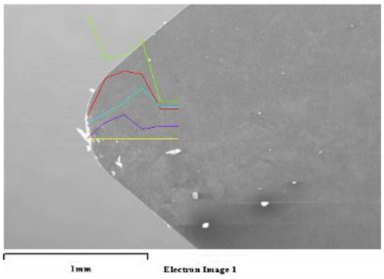

Figure 4. Line scanning when machining 35 steel

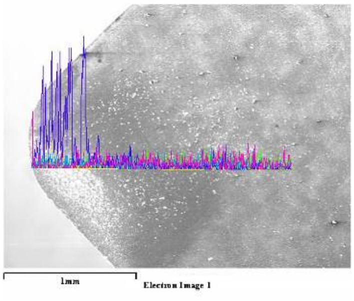

Figure 5. Line scanning when machining cast iron

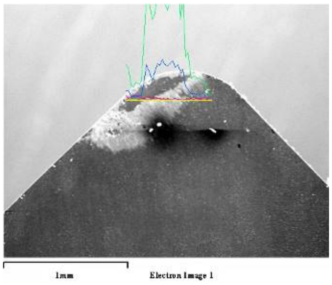

Figure 6. Line scanning when machining titanium alloy

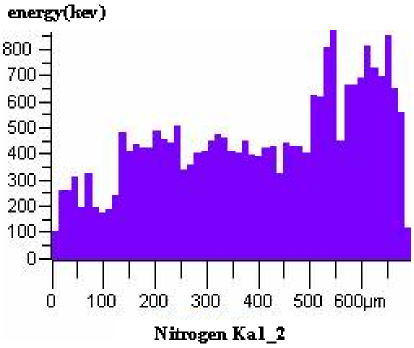

Figure 7. Elements components of nitrogen in line scanning when machining nickel

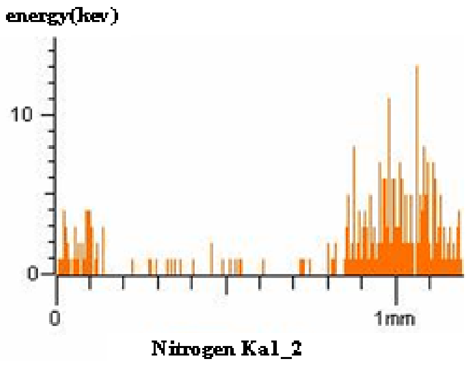

Figure 8. Elements components of nitrogen in line scanning when machining stainless

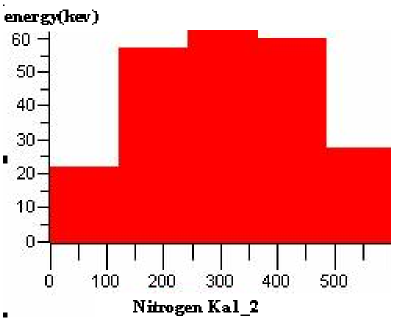

Figure 9. Elements components of nitrogen in line scanning when machining 35 steel

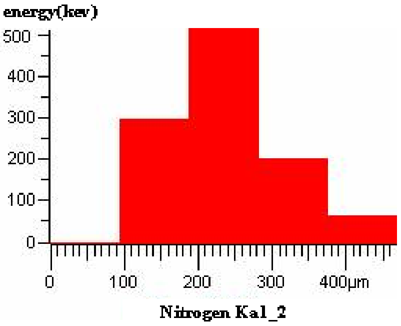

Figure 10. Elements components of nitrogen in line scanning when machining titanium alloy

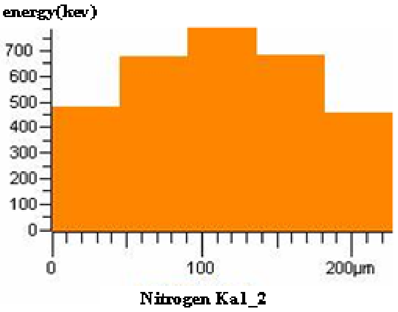

Figure 11. Elements components of nitrogen in line scanning when machining aluminum alloy

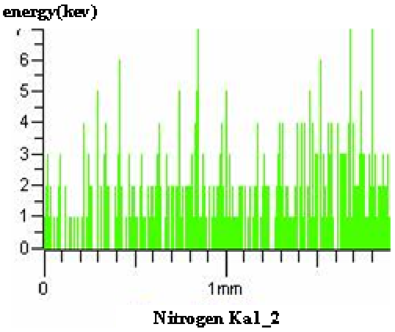

Figure 12. Elements components of nitrogen of rake face in line scanning when machining cast iron

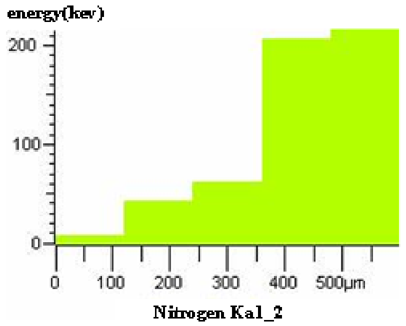

Figure 13. Elements components of nitrogen of r flank face in line scanning when machining cast iron

4 Results and Discussion

4.1 Analysis of cutting temperature

It was unevenly that cutting tool material elements diffused in different locations of edge. In the scan map, the location of any curve of the low nitrogen content were the low-end of the curve, the location of any curve of the high nitrogen content were the top of the curve.

It can be found from Figure 7-13 that there are the pervasion of elements on rake and flank face when cutting six kinds materials using PCBN tools. By comparing Figure 12 and 13, it can be found that flank face was bigger than rake face in both energy intensity and peak amplitude. It showed that the nitrogen element diffusion level was more serious in flank face when cutting cast iron. The reason was that there was higher temperature in tools' flank face.

Usually, in cutting the highest temperature existed in tool nose in addition to cutting stainless steel which being in the distant from the tip. As shown in Figure 8, energy intensity was reduced significantly in the distant from the tip. And then there was a steady trend. It showed that the cutting temperature was much higher than tool tip.

4.2 Explanation from the line scanning energy wave and chip elements distribution

When machining stainless and 35 steel, the diffusion unevenness of PCBN tool material element is greater than cast iron, results showed that the diffusion account is small and uniform when machining cast iron whose reason is that the most generation heat were taken away by chip, and a little was delivery by the tool. From Table 6, the temperature of cast iron chip was highly reached to 114℃(the measurement has large error which provide contrast reference), and others were only 87℃、42℃、32℃、61℃、53℃ respectively which were much lower than cast iron.

From Fig7 and Fig9, although the energy peak shape of nitrogen element is similar when machining nickel and 35 steel, the change amplitude of wave peak is also similar, the former peak intensity level is much higher than the latter which indicated that the diffusion of PCBN tool material element when machining nickel is much higher than 35 steel.

From Fig 10, the energy peak when machining aluminum alloy have significant changes when machining titanium alloy which indicated that dramatic diffusion was taken place.

From Fig 11, the change amplitude of wave peak is flat, and the curve position near tool tip is low which indicated the strong diffusion here, from the contrast between Fig 7 and Fig 11, the change amplitude of wave peak when machining nickel is larger than aluminum alloy which indicated that the diffusion of PCBN tool material element when machining nickel is much higher than aluminum alloy. From Table 5 to 6 and Table 8, it can be seen that the element content in the aluminum alloy chips has been down from 81.85% to 64.47% decreased to 17.38%, and the steel content in 35 steel had a decrease of 14.04% ,this results showed that the activity of aluminum alloy is higher than 35 steel which implied that the solubility of tool material element in aluminum is higher than 35 steel; The above analysis showed that the solubility order of PCBN tool material in workpiece material was: titanium alloy＞ nickel ＞aluminum alloy ＞35 steel which is uniform with theory calculation.

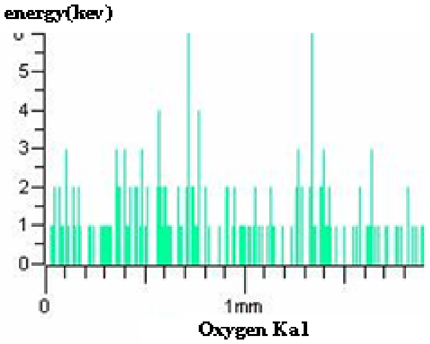

Figure 14. Elements components of oxygen in line scanning when machining cast iron

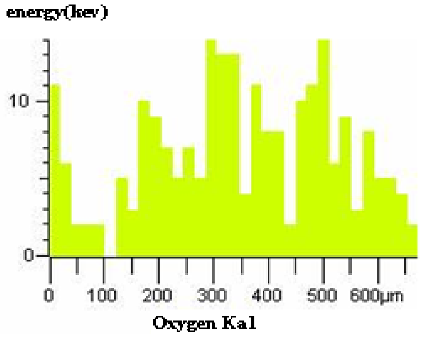

Figure 15. Elements components of oxygen in line scanning when machining nickel

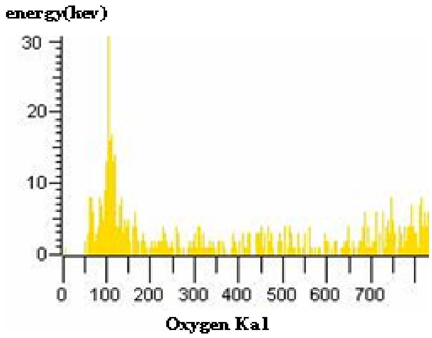

Figure 16. Elements components of oxygen in line scanning when machining aluminum alloys in rake face

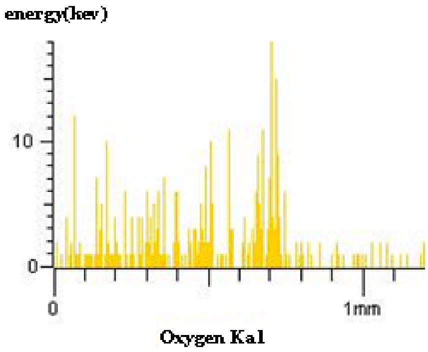

Figure 17. Elements components of oxygen in line scanning when machining stainless steel in rake face

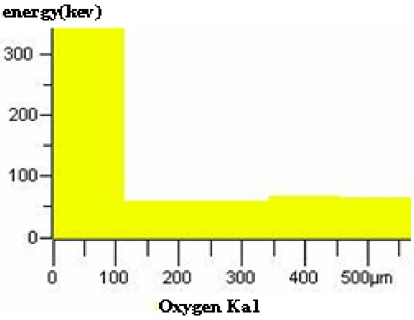

Figure 18. Elements components of oxygen of flank face in line scanning when machining stainless steel

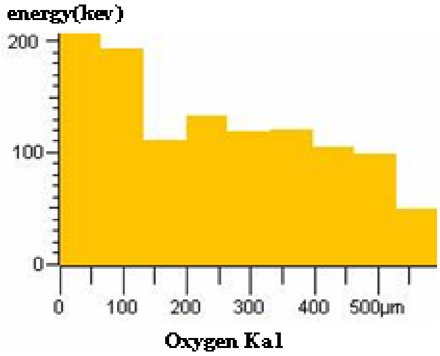

Figure 19. Elements components of oxygen of flank face in line scanning when machining 35 steel

Table 8. Elements of chip when machining nickel

Element	Weight%	Atomic%
C K	31.23	65.20
O K	2.97	4.66
Si K	1.32	1.18
Mn K	0.49	0.22
Fe K	63.99	28.74
Totals	100	100

Table 9. Elements of chip when machining titanium

Element	Weight%	Atomic%
Al K	61.19	73.68
Ti K	38.81	26.32
Totals	100	100

Table 10. Elements of chip when machining aluminum

Element	Weight%	Atomic%
C K	15.21	29.09
O K	2.35	3.37
Mg K	1.05	0.99
Al K	75.75	64.47
Mn K	0.71	0.30
Cu K	4.93	1.78
Totals	100	100

Table 11. Elements of chip when machining 35 steel

Element	Weight%	Atomic%
O K	1.70	5.63
Si K	0.53	1.01
Cr K	14.67	14.90
Mn K	7.66	7.37
Fe K	70.02	66.23
Ni K	5.41	4.87
Totals	100	100

4.3 Analysis of oxidation

From Fig 14 to 19, the flank face and rake face of PCBN when machining six workpiece material all had been oxidized since the oxygen element appeared in the line scanning in tool chip; Degree of oxidation at different locations around the tool tip is different, the location whose curve is higher must have large oxygen content which indicated dramatic oxidation here.

From Fig 18, the change amplitude of wave peak was the most dramatic when machining stainless steel which indicated that the most severe oxidation here. The reason was that the stainless steel had low thermal conductivity ,and the majority cutting heat were taken away by tool which caused high temperature in tool tip to be easily oxidized.

The contrast between Fig 17 to 18 showed that ,the change amplitude of wave peak of oxygen of flank face when machining stainless steel was significantly larger than the rake face which indicated that the oxidation was even more serious on rake face, since the rake face had the higher temperature to be easily oxidized.

From Table 8 to 11, oxygen elements were also found in the energy spectrum of the five kinds chips which proved the oxidation generation. It could also see from Table 8 to 11 that the order of the atomic percentage of oxygen content in chips when machining 35 steel stainless steel cast iron aluminum alloy with PCBN were as follows:

35 steel（6.08%）＞stainless steel（5.63%）＞cast iron（4.66%）＞aluminum alloy（3.37%）

The above order indicated that the oxidation when machining 35 steel was the most dramatic, and the most stable was aluminum alloy, stainless steel and cast iron were in the center.

5 Conclusions

(1)The diffusion wear and oxidation wear all take place when machining six normal workpiece materials.

(2)The solubility of tool material in workpiece material increased exponentially with the increasing of temperature which indicated that the higher temperature was ,the dramatic diffusion wear was , the solubility order of PCBN tool material in workpiece material was: titanium alloy＞ nickel ＞aluminum alloy ＞35 steel which is uniform with the theory calculation.

(3) the order of the oxidation degree when machining 35 steel stainless steel cast iron aluminum alloy with PCBN were as follows:

35 steel＞stainless steel＞cast iron＞aluminum alloy

The above order indicated that the oxidation when machining 35 steel was the most dramatic, and the most stable was aluminum alloy, stainless steel and cast iron were in the center.

6 Acknowledgments

The author gratefully acknowledges the National Natural Science Foundation(No.51465009、No.61461008);Natural Science Foundation of Guizhou Province(Guizhou Science and Technology AgencyJ[2014]2085,[2014]2086);Academician workstation of Guizhou Institute of Technology(Academician workstation(2014)4007); Department of Education of Guizhou Province 125 project; the doctoral starting up foundation of Guizhou Institute of Technology (XJGC20131201)；The Bidding Projects of Guizhou Province 2013 on teaching content and course system reform(Research on international personnel training mode in General University of Guizhou Province).

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