PCBN Tool Wear for Hard Materials Based on Thermodynamics Principals

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Abstract: The temperature rise exceeds over 1000°C in cutting process while working with PCBN tools high speed machining. This intense temperature results in wearing of tools and thus diffusion and oxidation are mainly responsible for wearing. This paper proposes the oxidation and diffusion wearing for PCBN cutting tools and analysis has been carried out considering thermodynamics principles. The next step is to find out dissoluation concentration of PCBN tool materials. The temperature range is different for these materials. The Gibbs free energy criterion is utilized for analysis purposes and validates the formed diffusion reaction rules in extreme temperature scenario. The PCBN tools were used for carrying out machining tests at different speeds 50, 95,100 and 180 m/min, feed of 0.1, 0.2 and depth of cut was 0.1, 0.8, 1, and 1.5 mm respectively on controlled lathe machine PUMA300LM. It was revealed that experimentals results matches with theoratical data. These findings will be utilized for future reference for tools designing and material selection.

Keywords: Diffusion wear, Gibbs free energy criterion, machining tests, oxidation wear, PCBN tool wear.

1. INTRODUCTION

The cutting process has major challenges like tools diffusion which results in degradation of performance and surface smoothness. It also results in chattering, damaging of machine parts, tools, workpiece and so on [1].

PCBN has proven to be an effective engineering material for high speed machining because of iron and its alloys properties *i.e.* heat resistance, strength, thermal conductivity and inertial chemical characteristics [2]. The tool waering process results in more complications and challenges with rise in temperature and speed [3-7]. The damage and wear resulting from this high speed machining is very different from the common speed machining process [8]. The different failure mechanism can happen during poor working conditions in high speed machining environments as compared to classical cutting mechanisms and thus the consequences for tools wearing and damages are increased by manifold.

Non-linear and coupling effects are also responsible for wearing of tools. Thermodynamics theory can be applied for these non linear processes and it has proven to be very effective and feasible for analysis as well. The research based on thermodynamical principles is very limited.

This paper considers PCBN tools wear for high speed advanced cutting mechanism based on thermodynamical principles and also analysis of parameters considering oxidation and diffusion wear rules are carrid out. This research will also provide reference for design and optimization for different tool materials.

2. PCBN DIFFUSION WEARING FOR CERAMIC TOOLS

The absolute enthalpies H⊙= H⊙ T -H⊙ 298+ H⊙ 298 are computed considering at different temperature conditions comparing to the relative enthalpies H⊙ T -H⊙ 298 for BN, diamond C, Al_2O_3 and Si_3N_4 are produced by using thermodynamics data table [10] as shown in Table **1** and Fig. (**1**).

2.1. Al_2O_3 Ceramic Tool Material Solubility in Workpiece

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

3. EXPERIMENTAL SETUP

3.1. Devices Used for Experiment

PUMA300LM lathe machine controlled numerically.

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	
	$H_T^e - H_{598}^e$	H_T^e	$H_T^e - H_{298}^e$	H_T^e	$H_T^e - H_{298}^e$	H_T^e	$H_T^e - H_{298}^e$	H_T^e
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

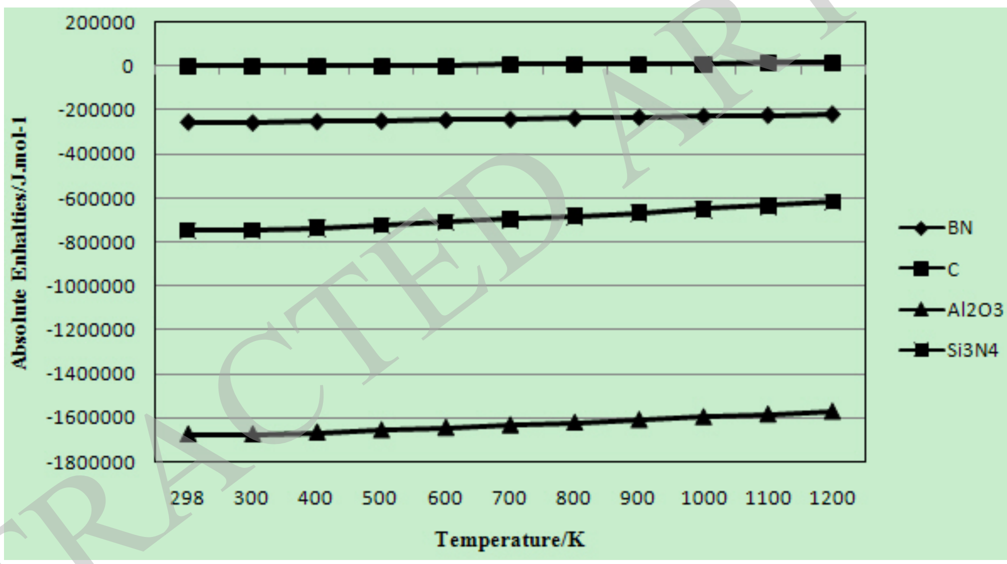


Fig. (1). Absolute enhaltpies at different temperatures.

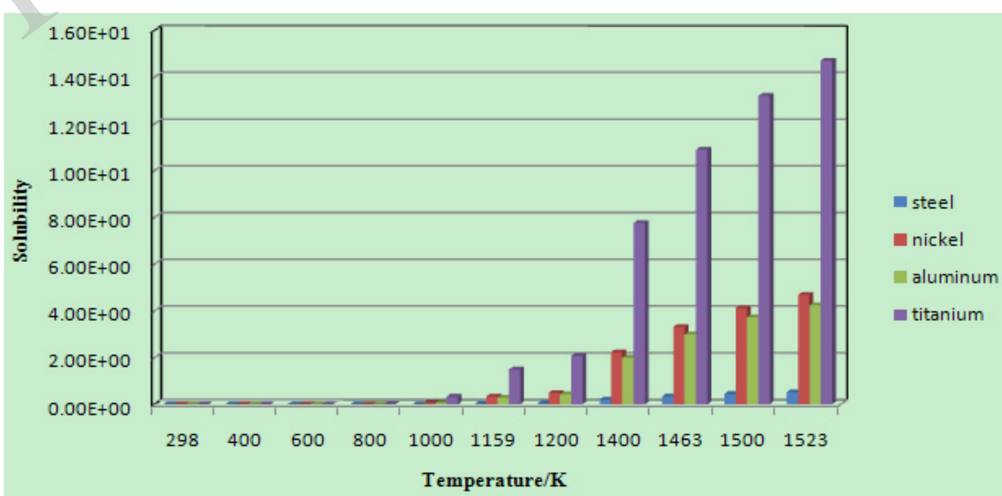


Fig. (2). PCBN tools solubility in typical workpiece materials.

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

3.2. Workpiece Materials

Aluminum alloy of these specifications: hardness value is 115HBW, diameter value is Ø54.5mm; stainless steel having hardness 184HBW, diameter is Ø47mm; abrasion resistant of cast iron MT-4 cast iron (cast iron for short hereinafter), hardness is 184HBW, diameter is Ø42mm; No. 35 steel, rigidity value is 169HBW, diameter is Ø48mm; pure nickel, rigidity is 51.9HBW, diameter is Ø28mm; titanium alloy, rigidity is 41.9HBW, diameter is Ø21mm. The details of workpiece components are shown as in Tables **3-6** [11].

3.3. Tools: GE Tools Produced in America

3.3.1. Cutting Mechanism

The Tables **3-6** descibes the different values of parameters utilized for cutting process on workpiece materials. The PCBN tools having different cutting speeds 10, 150 and 250 m/min were utilized and cut depth of 1, 2, 2.5 and 5 mm were considered for numerically controlled PUMA300LM lathe machine. These all experiments were carried out in the dry conditions and no fluid was used for 15 min. The handheld Infrared is used for the measurement of the cutting temperature and results are presented in Table **7**.

The diffusion and oxidation surface are analyzed using line scanning by element wear character, points from the bottom of wear region of material were selected to make energy spectrum analysis for aluminum, oxygen and titanium. For decreasing pollution effects from the surface, line scanning is applied on the surfaces of blades. The line scanning results from these experiments for aluminum, oxygen and titanium tools material employing machining nickel, aluminum alloy, 35 steel and cast iron is depicted in Figs. (**3-19**).

4. RESULTS AND DISCUSSION

4.1. Temperature Cutting Analysis

The elements present in tool materials were diffused at uneven rates at the surface edges. If scan map is closely observed, the locations of low end of the curve and the high nitrogen content of the curve were amongst the top of the curve.

From Figs. (**9-15**), it can be concluded that rank and flank faces pervaded when PCBN tools are employed for

Table 3. 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

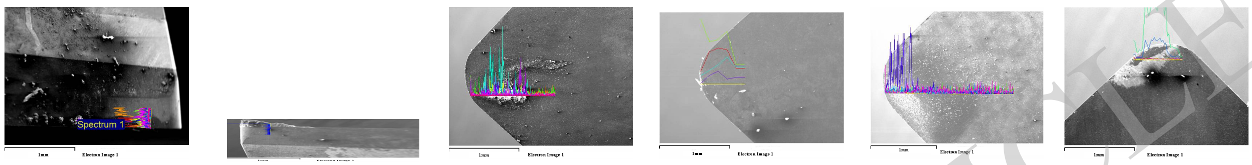
Table 6. Chemical components of aluminum alloy (%).

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

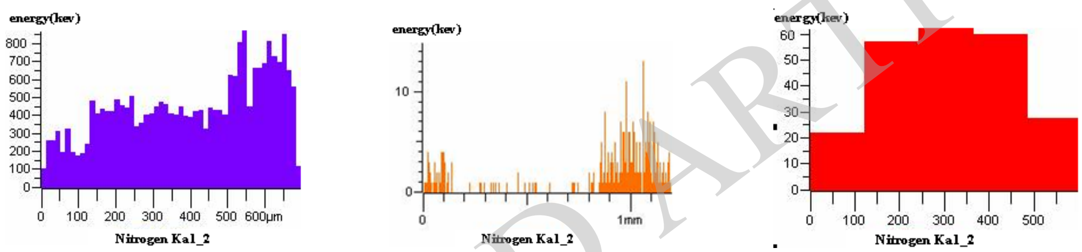
Nickel is pure nickel; titanium alloy consists of 73.68% titanium and 26.32% aluminum.

Table 7. Cutting condition and measurement results.

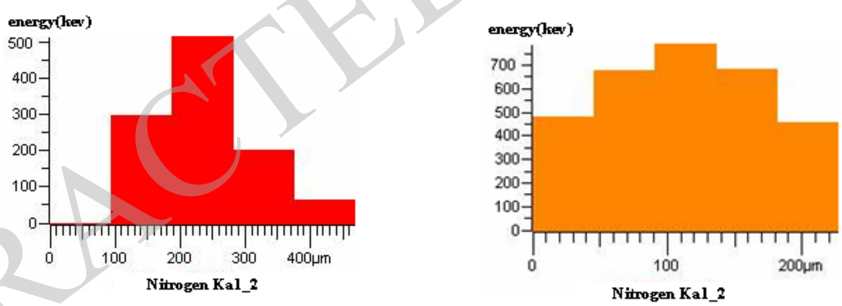
Workpiece Material	a_p(mm)	f(mm/r)	V(m/min)	Surface Roughness (μm)	Chip Temperature (°C)
Cast iron13	1.5	0.2	50	12.5→1.6	114
nickel14	1	0.2	95.4	12.5→1.6	87
Aluminum alloy16	1	0.2	180	1.6→2.0	42
Stainless steel17	0.1	0.1	100	0.8→0.4	32
35steel 18	0.1	0.1	100	2.5→2.0	61
Titanium 15	0.8	0.2	66	10→2.0	53



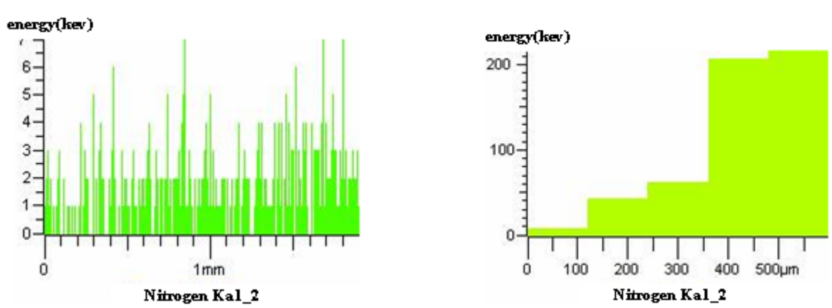
Figs. (3-8). Line scanning for machining nickel, aluminum alloy, stainless steel, 35 steel, cast iron, titanium alloy.



Figs. (9-11). Components of nitrogen in line scanning machining nickel, stainless and 35 steel.



Figs. (12, 13). Nitrogen elements components in line scanning for machining titanium and aluminum alloy.



Figs. (14, 15). Nitrogen elements components Of rake and flank face in line scanning when machining cast iron.

cutting six kinds of materials. The flank face appeared to be bigger than rake face for both peak and energy amplitude. In cutting cast iron case, the diffusion level for nitrogen proved to be more serious in flank face. It was due to the extreme value of temperature observed in flank face of tools.

The high value of temperature in the cutting process was observed in tool's nose as well as for stainless steel cutting process which existed away from tip. It can be revealed from the Fig. (**10**), the intensity observed in energy was reduced considerably from the tip in case of distant object. A steady trend was observed and also cutting temperature was more as compared to the tool tip.

4.2. Energy Related to Line Scanning and Chip Components Distribution

In case of cutting process of stainless steel and 35 steel, the more uneven surfaces edges were observed in PCBN tool material as compared to cast iron. It is due to the fact that cast iron diffusion is uniformly distributed having small values and chip takes the most of the produced heat and minimum amount of heat is delivered to the tool itself. The cast iron chip temperature exceeds up to 114°C (measured temperature may have errors due to contrast reference values) as shown in Table **6**. The other temperature values observed were much smaller as compared to the cast iron case *i.e.* 87°C, 42°C, 32°C, 61°C, 53°C.

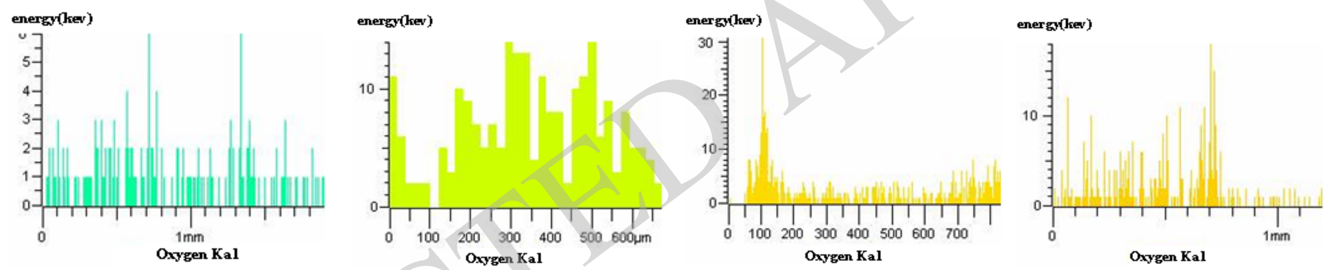
It can be revealed from Figs. (**9**, **11**) that the nitrogen energy element is identical to the machining nickel and 35 steel. The wave peak amplitude is also same for both cases and the intensity level for 35 steel is having more value as compared to the nickel which is related to the PCBN tool material diffusion.

From Fig. (**12**) analysis, it can be concluded that aluminum alloy energy peaks have shown considerable variations and in case of titanium alloy a significant diffusion has occurred.

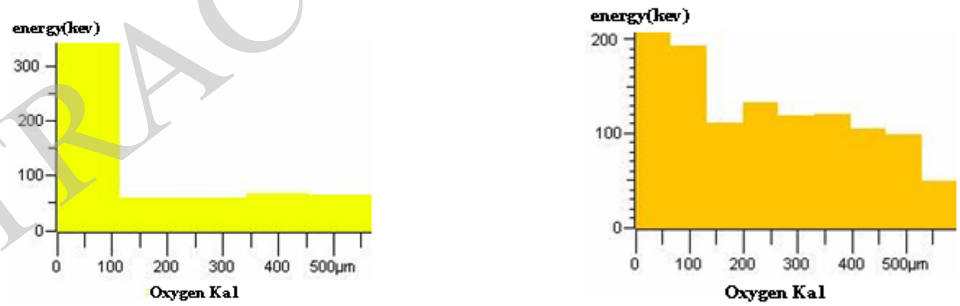
The change in amplitude value for wave peak is uniform and flat while the curve position adjacent to the tip is small which is due to the diffusion process is observable in Fig. (**13**). Comparing contrast in Figs. (**9**, **13**), it can be seen that the changing amplitude for wave peak is larger for nickel machining as compared to aluminum alloy due to the fact of PCBN tool material element diffusion. Analyzation from Fig. (**22**), Tables **5** and **6**, it is revealed that aluminum alloy element content has reduced from 81.85% to 64.47%. For the 35 steel alloy, the steel content has been reduce up to14%. The results obtained from this analysis show that aluminum alloy is more soluble as compared to 35 steel. It is concluded from the above observations that for PCBN tool workpiece materials, the solubility order is as follows: titanium alloy> nickel >aluminum alloy >35 steel which is identical with theoretical computations.

4.3. Oxidation Analysis

It is evident from flank and rake face PCBN analysis of six workpiece materials represented in Figs. (**16-21**) have been oxidized and significant oxygen content have appeared



Figs. (16-19). Line scanning for oxygen element components machining cast iron, nickel, aluminum alloys and stainless steel in rake face.



Figs. (20, 21). Line scanning for oxygen flank face element components when machining stainless steel and 35 steel.

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	100.00	

Element	Weight%	Atomic%
Al K	61.19	73.68
Ti K	38.81	26.32
Totals	100.00	

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	100.00	

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	100.00	

Element	Weight%	Atomic%
C K	10.36	33.13
O K	2.53	6.08
Al K	0.91	1.30
Si K	0.32	0.44
Mn K	0.65	0.46
Fe K	85.22	58.60
Totals	100.00	

Figs. (22-26). Chip's element when machining nickel, titanium, aluminum and 35 steel.

on tools chip. The intensity of oxygen for different locations at tool tip was having various values and a significant oxidation proved that large oxygen contents were present.

From Fig. (**20**), it is obvious that wave change graph was having abrupt changes for stainless steel machining which showed that oxidation process was severe in this case. It was due to the lower thermal conductivity of stainless steel and most of the heat was utilized for tool heating and tip was responsible for high temperature rise and oxidation process occurred abruptly without any issues. The contrast comparison between Figs. (**19**, **20**) revealed that the flank face change was more obvious than rake face change and so the rake face was easily oxidized because of having high temperature.

It is also visible from Figs. (**22-26**) that the oxygen element content was present in energy spectrum of five kinds of chips which showed oxidation occurred here as well. Different percentages of oxygen content in chip for 35 stainless steel with PCBN were as: 35 steel (6.08%)>stainless steel (5.63%) > cast iron (4.66%) > aluminum alloy (3.37%). From the result, it was obvious that oxidation machining for 35 steel aluminum was considerably high, It showed that the oxidation machining 35 steel was obviously high, but the aluminum alloy was more stable, while cast iron and stainless steel values lie between first two materials.

From the above analysis, it can be inferred that oxidation was more obvious and dramatic for 35 steel while the most stable value was observed for aluminum alloy. The cast iron and stainless steel values lie between these two values.

CONCLUSION

(1) All six normal material workpiece resulted in the diffusion and oxidation wear.

(2) With increase in temperature, the solubility of tool material also exceeded exponentially. For more temperature, high diffusion was visible and the solubility order for PCBN tool workpiece materials were as follows: titanium alloy > nickel > aluminum alloy >35 steel, which was also in accordance with with the theoratical computations.

(3) The oxidation degree for machining with different PCBN materials were categorized as follows: 35 steel > stainless steel > cast iron > aluminum alloy.

It is also evident that 35 steel oxidation was significant while aluminum alloy was more stable stainless steel and cast iron lie between the first two tool materials.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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