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ORIGINAL ARTICLE

Thermodynamical matching of alumina-based composite ceramic tools with typical workpiece materials

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Abstract Cutting temperature always highly reaches to over 1,000°C during high speed. Diffusion of tool material element may have important influence on tool wear at such high temperature. The advanced ceramic cutting tools have very good wear resistance, high refractoriness, good mechanical strength, and hot hardness. In this paper, the rules of diffusion wear for alumina-based ceramic cutting tools are proposed and analyzed based on thermodynamics theory. Dissolution concentrations in typical normal workpiece materials of ceramic tool materials at different temperatures 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 alumina-based composite ceramic tools at different cutting speeds of 10, 150, and 250 m/min, feed of 0.2 and 0.3, and depth of cut of 1, 2, 2.5, and 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.

Keywords Thermodynamics · Alumina-based ceramic tool · Diffusion wear · Matching

1 Introduction

As with the excellent synthetical performance such as high strength, high rigidity, anti-corrosion, anti-thermal shock, anti-creep and stable structure, and so on, ceramic has become a much more appropriate engineering material [1]. Ceramic cutting tools have unique chemical and mechanical properties, and these tools can offer increased metal removal rates, extended tool life, and have the ability to machine hard workpiece materials like stainless steel and hardened steel [2]. The wear behavior of ceramic cutting tools has to be properly understood for their effective utilization in machining hard materials. Silva and Abrao [3] observed that recent cutting tool materials such as ceramic and polycrystalline cubic boron nitride (PCBN) have stimulated investigations concerning the possible substitution of grinding operations by machining in the finishing of hardened steels. It was also indicated that in general, mixed alumina ceramic tool exhibited better performance than some of the PCBN tools. When successfully applied, ceramic cutting tools can increase the metal removal rate by several times over that obtained with conventional tool materials [4].

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 [5].

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 cannot 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

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research on the wear rules has the important practical significance.

Tool failure results from a combination of mechanical and chemical processes, but in high-speed machining of continuous chip forming workpiece materials like the steels, the dominant wear mode is chemical [6, 7]. Even when turning nickel-based alloys, Si_3N_4 has only good performance at low speeds, showing a quasi-exponential growth of the wear rates with increasing cutting speeds due to diffusion wear [8]. Yi et al. [9] considered that the mechanism of tool wear and damage during high-speed machining was essentially different from that of the common traditional cutting speed machining. The tool would have different failure mechanism under such adverse working conditions 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. Interdiffusion between elements of the workpiece and tool, solution of tool material, and formation of new phases by chemical reactions at the metal/ceramic interface leading to severe crater wear have been reported [6, 10–14]. Interdiffusion weakens the material structure, allowing fast disruption of the tool surface [15]. Tonshoff and Bartsch [10] detected components of the ceramic tool material in the secondary flow zone of the metal chip. Depletion of tool elements such as Si and Y at the flank face of the tool confirms that the ceramic dissolves into the hot metal [16]. Thermodynamic calculations addressing the chemical stability of Si_3N_4 and other cutting tool ceramics in machining of iron alloys were performed by Kramer and von Turkovich [17]. Other authors [6, 13, 18] have explored Kramer's model, but some chemical parameters used for the thermodynamic calculations were taken constant over a broad range of temperatures and concentration of alloying elements, which is a rather crude approximation. However, the research on the diffusion mechanism of Al_2O_3 ceramic tool wear is still few.

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 thermodynamics theory and method [19]. 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 ceramic tools during high-speed cutting using thermodynamics theory is advanced, which is to analyze the diffusion and oxidation wear rules for ceramic tools by the calculation of thermodynamic parameters in the cutting process and moreover to direct the application of ceramic tools and supply reference for the design and optimization of tool materials according to the research conclusion.

2 Diffusion wear for Al_2O_3 ceramic tools

In 1855, Fick [19] concluded a diffusion relation quantitatively in isotropy medium by means of heat conduction method based on the corresponding experiments, i.e., diffusion first law:

$$J = -D\frac{\partial C}{\partial \varphi}$$

Table 1 Absolute enthalpies and relative enthalpies at different temperatures of Al_2O_3 and Si_3N_4

Temperature (K)	Al_2O_3		Si_3N_4	
	$H_T^\odot - H_{298}^\odot$	$H_T^\odot$	$H_T^\odot - H_{298}^\odot$	$H_T^\odot$
298	0	−1,675,274	0	−744,752
300	158	−1,675,116	198	−744,554
400	9039	−1,666,235	10,768	−733,984
500	19,151	−1,656,123	22,430	−722,322
600	30,011	−1,645,263	35,020	−709,732
700	41,411	−1,633,863	48,437	−696,315
800	53,247	−1,622,027	62,605	−682,147
900	65,408	−1,609,866	77,456	−667,296
1,000	77,795	−1,597,479	92,928	−651,824
1100	90,372	−1,584,902	108,962	−635,790
1,200	103,115	−1,572,159	125,501	−619,251
1,300	116,005	−1,559,269	142,488	−602,264
1,400	129,032	−1,546,242	159,868	−584,884
1,500	142,186	−1,533,088	177,585	−567,167

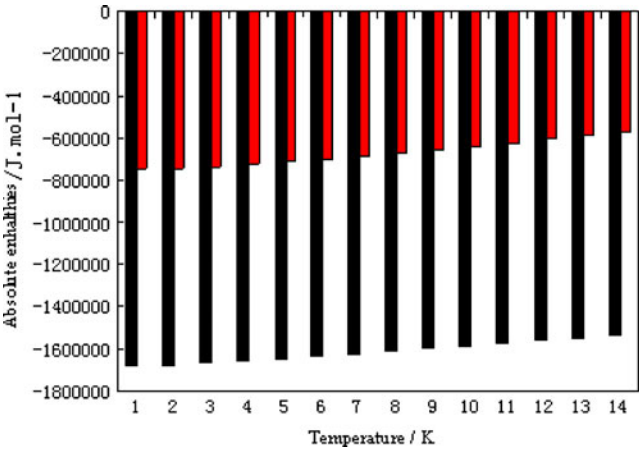

Fig. 1 Absolute enthalpies at different temperatures of Al_2O_3 (*black*) and Si_3N_4 (*red*). Note: the numbers in abscissa represent temperatures 298 K, 300 K, 400 K, 500 K, 600 K, 700 K, 800 K, 900 K, 1,000 K, 1,100 K, 1,200 K, 1,300 K, 1,400 K, and 1,500 K, respectively

where J is the diffusion flux, i.e., diffusion gross amount passing unit section vertical to diffusion direction in unit time; C is the volume concentration, i.e., atom amount of diffusion material in unit volume; $\frac{\partial C}{\partial \varphi}$ is the concentration gradient; and D is the diffusion coefficient, $D = D_0 \exp\left(-\frac{Q}{RT}\right)$, where D_0 is diffusion constant (m^2/s), Q is diffused activation energy (J/mol), R is gas constant, which equals to 8.314, [J/(mol K)], T is thermodynamic temperature (K).In the cutting process, because of high temperature in cutting zone as well as the compact contact between rake face and flank face of tools and the new cutting surface, there is much greater chemical activity among cutting scraps, workpiece, and tool faces. In this way, the chemical elements in the contact surface between tool materials and workpiece materials may be diffused to each other so as to change their chemical components and influence cutting behavior. During high-speed machining, workpiece materials continuously flow in cutting distortion zone, and moreover, diffusion flux J is also kept in high degree among diffusion zones. Strong plastic deformation of workpiece materials will also increase dislocation density and interstice. All of these factors lead to strengthen the mutual diffusion greatly.

According to the second law of thermodynamics, the change of Gibbs free energy is a criterion to judge whether one reaction or change can take place spontaneously or not in constant temperature and pressure. This criterion cannot only judge the direction for chemical reaction but also can be used for judging diffusion rules when workpiece is processed by tools [20]. Suppose A is tool material, B is workpiece material, judging whether elements in A diffused in elements in B can be concluded by calculating Gibbs free energy after diffusion:

$$\Delta G_m = \Delta H_m - T \Delta S_m \tag{1}$$

$$\Delta H_m = H_{AB} - H_A - H_B \tag{2}$$

$$T \Delta S_m = RT(x_A \ln x_A + x_B \ln x_B) \tag{3}$$

where ΔG_m is the Gibbs free energy for diffusion reaction; ΔH_m is the enthalpy after diffusion mixing; ΔS_m is the mixing enthalpy after diffusion; H_i is the enthalpy for each component; and x_i is the concentration for each component $(x_A + x_B = 1)$.If $\Delta G_m > 0$, diffusion reaction does not happen; if $\Delta G_m = 0$, diffusion reaction reaches to balance. Only if $\Delta G_m < 0$ can diffusion reaction happen; therefore, the optimal combination for tool–workpiece materials is as follows according to Eqs. 1–3.

ΔH_m is a positive with much greater absolute value, $H_{AB}=0$, and H_A and H_B are all negative with much greater absolute value. Only in this way will ΔG_m be greater than zero, which means that the diffusion does not happen or hardly happen between these two materials. Next, the diffusion wear rules for Al_2O_3 ceramic tools will be analyzed from two aspects including enthalpy value and diffusion concentration.

2.1 Analysis of standard heat of formation $\Delta_f H^\odot$ of compound and enthalpy value at different temperatures

At temperature, T, and standard pressure, $P^\odot$, reaction heat for 1 mol compound formatted by elementary substance in the most stable state is called standard mole enthalpy of formation or standard formation heat for this compound

Table 2 Solubility of Al_2O_3 ceramic tool when machining typical materials at different temperatures

Solubility	933	1,000	1,200	1,400	1,500	1,600	1,613	1,700	1,743	1,800
Fe	2.28618E−17	4.71E−16	5.28E−13	7.96E−11	5.92E−10	3.42E−09	4.23E−09	1.61E−08	2.97E−08	6.39E−08
Ni	3.68982E−05	0.000116	0.001638	0.010879	0.023202	0.045012	0.048767	0.080776	0.101746	0.135836
Ti	9.11146E−05	0.000269	0.003308	0.019871	0.04071	0.076253	0.082263	0.13266	0.165067	0.217021

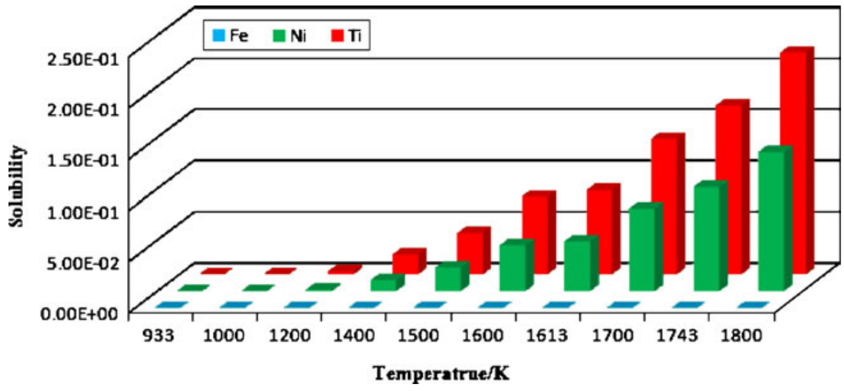

Fig. 2 Solubility of Al_2O_3 ceramic in typical workpiece materials

[21]. The traditional ceramic tools include alumina ceramic tools and silicon nitride ceramic tools; the standard formation heats for alumina ceramic and silicon nitride, respectively, are as follows:

Standard formation heat $\Delta_f H^{\odot}$ for Al_2O_3:

$\Delta_f H^{\odot} = -1,675,274\ \mathrm{Jmol}^{-1}$

Standard formation heat $\Delta_f H^{\odot}$ for Si_3N_4:

$\Delta_f H^{\odot} = -744,752\ \mathrm{Jmol}^{-1}$.

The absolute enthalpies $H_{\odot} = H^{\odot}_{T} - H^{\odot}_{298} + H^{\odot}_{298}$ are calculated at different temperatures according to the relative enthalpies $H^{\odot}_{T} - H^{\odot}_{298}$ for Al_2O_3 and Si_3N_4 obtained by thermodynamics data table [21], which can be seen in Table 1 and Fig. 1.

Analysis and discussion:

1. From Fig. 1, enthalpies of Al_2O_3 and Si_3N_4 all increase with the increase of temperature; therefore, diffusion between tool material and workpiece material will be strengthened with the increase of temperature.
2. From Eq. 1 $\Delta H_{\mathrm{m}} = H_{\mathrm{AB}} - H_{\mathrm{A}} - H_{\mathrm{B}}$, suppose that solid solution is an ideal solution formed by the dissolution in workpiece material after the decomposition of Al_2O_3 and Si_3N_4, i.e., and the formed solid solution accords with Raoult's law [22]; therefore, mixing enthalpies H_{AB} between Al_2O_3 and workpiece as well as Si_3N_4 and workpiece, respectively, equal to zero, and since the absolute enthalpies of Al_2O_3 have the maximum value, then the mixing enthalpies, ΔH_{m}, of Al_2O_3 also have the maximum value. So at the same temperature, diffusion reaction will hardly happen; besides, the free energy of formation of Al_2O_3 is larger than that of Si_3N_4, which also indicates that Al_2O_3 is much more suitable to be used as tool materials than Si_3N_4. Next, Al_2O_3 ceramic tools will be taken as an example to analyze the diffusion wear rules.

2.2 Solubility of Al_2O_3 ceramic tool material in workpiece material, respectively

Gibbs free energy is also called free energy whose calculation equation is as follows:

$$G = U + pV - TS$$

where U, p, V, T, and S are internal energy, pressure, volume, temperature, and entropy, respectively. The change of Gibbs free energy is a criterion to judge whether one reaction or change can take place spontaneously or not in constant temperature and pressure, and if $\Delta G<0$, diffusion happens spontaneously, $\Delta G_{\mathrm{m}}=0$ reaction reaches to balance, and $\Delta G>0$, diffusion does not happen [22]. Next, the diffusion rules for Al_2O_3 ceramic tool will be analyzed according to the change of Gibbs free energy. In high-speed machining, tool wear mechanism is diffusion wear. Suppose that tool material is AxByCz; the formed free energy for tool material can be calculated as the following equation [23]:

$$\Delta G^{0}_{\mathrm{f},AxByCz} = x\Delta\overline{G}_{\mathrm{A}} + y\Delta\overline{G}_{B} + z\Delta\overline{G}_{C} \qquad (4)$$

where $\Delta G^{0}_{\mathrm{f},AxByCz}$ is the formed free energy when tool material AxByCz dissolves and is diffused in tool–workpiece solution:

$\Delta\overline{G}_{i}(i = \mathrm{A},\ B \text{ or } C)$ relative mole free energy of element i for tool material in solid solution.

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

According to thermodynamics theory, the following equation can be obtained:

$$\Delta\overline{G}_i = \Delta\overline{G}_i^{xs} + RT\ln c_i \tag{5}$$

where $\Delta\overline{G}_i^{\mathrm{xs}}$ is the excess free energy of solid solution formed by each element A, B, C in tool material; R is the mole gas constant; and c_i is the solubility expressed by mole fraction for element i of tool material in workpiece material. Combining 4 and 5, then:

$$\begin{aligned}\Delta G^0_{\mathrm{f},AxByCz} &= x\Delta\overline{G}_A + y\Delta\overline{G}_B + z\Delta\overline{G}_C \\ &= \Delta\overline{G}^{\mathrm{xs}} + RT(x\ln c_A + y\ln c_{\mathrm{B}} + z\ln c_C)\end{aligned}$$

, where $\Delta\overline{G}^{xs} = x\Delta\overline{G}_A^{xs} + y\Delta\overline{G}_B^{xs} + z\Delta\overline{G}_C^{xs}$, and then solubility of tool material in workpiece material is as follows:

$$C_{AxByCz} = \exp\left(\frac{\Delta G_{AxByCz} - \Delta G^{\mathrm{xs}} - RTM}{NRT}\right) \tag{6}$$

where C_{AxByCz} is the solubility of tool material in workpiece material; $M = x\ln x + y\ln y + z\ln z$; and $N = x + y + z$. Therefore, if we know the formed free energy $\Delta G^0_{\mathrm{f,AxByCz}}$ of tool material at different temperatures and excess free energy ΔG_i^{xs} of solid solution formed by each element in tool material, then limit solubility of tool material in workpiece material can be calculated according to Eq. 6, which can also make the prediction to tool wear state.

1. Diffusion solubility of Al_2O_3 ceramic tools with Fe element when machining steel material

Excess free energy of aluminum in Fe [24] is $\Delta G_i^{\mathrm{xs}} = -44.8\left(\mathrm{kJmol}^{-1}\right)$ and that of oxygen in Fe [24] is $\Delta G_i^{\mathrm{xs}} = 52.7\left(\mathrm{kJmol}^{-1}\right)$; therefore, solubility of Al_2O_3 ceramic tool material when machining steel material can be calculated as the following equation:

$$C_{Al_2O_3} = \exp\left(\frac{\Delta G_{Al_2O_3} - 38.91T - 68,500}{41.57T}\right). \tag{7}$$

2. Diffusion solubility of Al_2O_3 ceramic tools with titanium element when machining titanium alloy

Solubility of aluminum in β titanium at 1,470°C is 33% [25], and then solubility of Al_2O_3 in β titanium is half of 33%, that is, 16.5%; therefore, excess free energy of oxygen in titanium can be obtained by adverse calculation method. From literature [22], the relationship between standard formation Gibbs free energy of Al_2O_3 and temperature can be expressed as follows: $\Delta G = -1,682,900 + 323.24\ T$. The temperature range is from 660°C to 2042°C; therefore, standard formed Gibbs free energy of Al_2O_3 at 1,470°C (equal to 1,743 K) equals to −1,119,492 J. According to Eq. 6, the following equation can be obtained:

$$\begin{gathered}0.165 = \exp\left(\frac{-1{,}119{,}492.68 - \left(\Delta G^{xs}_{O\ in\ titanium} + \Delta G^{xs}_{Al\ in\ titanium}\right) - 8.314\times 1{,}743(2\ln 2 + 3\ln 3)}{5\times 8.314\times 1{,}743}\right) \\ -130,552.85 = -1,119,492.68 - \left(\Delta G^{xs}_{O\ in\ titanium} + \Delta G^{xs}_{Al\ intitanium}\right) - 8.314\times 1,743(2\ \ln\ 2 + 3\ \ln\ 3) \\ -130,552.85 = -1,119,492.68 - \left(\Delta G^{xs}_{O\ in\ titanium} + \Delta G^{xs}_{Al\ in\ \mathrm{titanium}}\right) - 67,850 \\ 130,552.85 = 1,119,492.68 + \left(\Delta G^{xs}_{O\ in\ titanium} + \Delta G^{xs}_{Al\ in\ titanium}\right) + 67,850 \\ \Delta G^{xs}_{O\ in\ titanium} + \Delta G^{xs}_{Al\ in\ titanium} = -1,056,789.8.\end{gathered}$$

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

Therefore, solubility of Al_2O_3 ceramic tools in titanium alloy material can be obtained as follows:

$$C_{\mathrm{Al}_2O_3} = \exp\left(\frac{\Delta G_{Al_2O_3} - 38.91T + 1,056,789.8}{41.57T}\right). \quad (8)$$

3. Diffusion solubility of Al_2O_3 ceramic tools when machining aluminum alloy

Excess free energy of aluminum in aluminum is zero, and solubility of oxygen in aluminum is close to zero. Al_2O_3 is a compound with much stronger chemical stability which is hard to be composed and decomposed; therefore, the possibility for diffusion wear is very small. However, tools and workpiece materials are all with aluminum element, which leads to much better compatibility for each other; therefore, workpiece material is easy to adhesive on tool surface.

4. Diffusion solubility of Al_2O_3 ceramic tools when machining nickel

Solubility of oxygen in nickel at 1,440°C is 0.6% [25] because solubility of aluminum in nickel at 1,360°C (equal to 1,633 K) is 11% and then solubility of Al_2O_3 in nickel is half of 11%, that is, 5.5%; therefore, according to the equation $\Delta G = -1,682,900\ T + 323.24$, standard formed Gibbs free energy of Al_2O_3 at 1,360°C (equal to 1,633 K) equals to −1,155,049.08. According to Eq. 6, the following equation can be obtained:

$$\begin{aligned}
0.055 &= \exp\left(\frac{-1,155,049.08-\left(\Delta G^{xs}_{O\ in\ nickel}+\Delta G^{xs}_{Al\ in\ nickel}\right)-8.314\times 1,633(2\ln 2+3\ln 3)}{5\times 8.314\times 1,633}\right)\\
-196,891.7 &= -1,155,049.08 - \left(\Delta G^{xs}_{O\ in\ nickel} + \Delta G^{xs}_{Al\ in\ nickel}\right) - 63,572.69\\
196,891.7 &= 1,155,049.08+\left(\Delta G^{xs}_{O\ in\ nickel} + \Delta G^{xs}_{Al\ in\ nickel}\right) + 63,572.69\\
\Delta G^{xs}_{O\ in\ nickel} + \Delta G^{xs}_{Al\ in\ nickel} &= -1,021,730.07.
\end{aligned}$$

Therefore, solubility of Al_2O_3 ceramic tools in nickel material can be obtained as follows:

$$C_{Al_2O_3} = \exp\left(\frac{\Delta G_{Al_2O_3} - 38.91T + 1,021,730.07}{41.57T}\right) \quad (9)$$

Solubility of Al_2O_3 ceramic tools when, respectively, machining steel material, titanium alloy, and pure nickel is presented in Table 2 and Fig. 2.

3 Experiment setup

3.1 Experiment device

PUMA300LM numerically controlled machine tool was used.

3.2 Workpiece materials

Aluminum alloy material, hardness 115HBW, diameter ϕ54.5 mm; stainless steel material, hardness 184HBW,

Table 7 Cutting condition and measurement results

Workpiece material	a_p (mm)	f (mm/r)	V (m/min)	Cutting temperature (°C) (with low precision, only for comparison and reference)
Cast iron	5	0.3	150	92
Nickel	1	0.2	100	82
Stainless steel	2.5	0.2	150	36
Titanium alloy	2	0.2	150	75
Aluminum alloy	1	0.2	250	34
45# steel	1	0.2	150	38

diameter ϕ47 mm; abrasion-resistant cast iron MT-4 cast iron material (cast iron for short hereinafter), hardness 184HBW, diameter ϕ42 mm; no. 35 steel material, rigidity 169HBW, diameter ϕ48 mm; pure nickel material, rigidity 51.9HBW, diameter ϕ28 mm; titanium alloy material, rigidity 41.9HBW, diameter ϕ21 mm. The components of workpiece material are depicted as Tables 3, 4, 5, and 6 [26].

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

3.3 Tools: ISCAR tools produced in Israel

Ti[C,N] mixed alumina ceramic cutting tool inserts from Israel were used to machine the materials.

3.4 Cutting process

The machining tests were performed on workpiece materials in Tables 3, 4, 5, and 6. The machining tests were conducted using the alumina-based composite ceramic tools at different cutting speeds of 10, 150, and 250 m/min, feed of 0.2 and 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 was measured with Handheld infrared thermometer produced in the USA whose accuracy was not high. Cutting condition and measurement results can be seen in Table 7.

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 tool material when machining nickel, aluminum alloy, 35# steel, and cast iron can be seen in Figs. 3, 4, 5, 6, and 7 and Tables 9, 10, and 11.

4 Results and discussion

4.1 Explanation from the standard Gibbs free energy

The experiment results showed that diffusion amount of element aluminum and oxygen in workpiece is very small for Al_2O_3 is a compound with much higher stability compared with other tool materials including tungsten carbide, titanium carbide, silicon nitride, and so on. The standard Gibbs free energy of Al_2O_3 is a negative one with

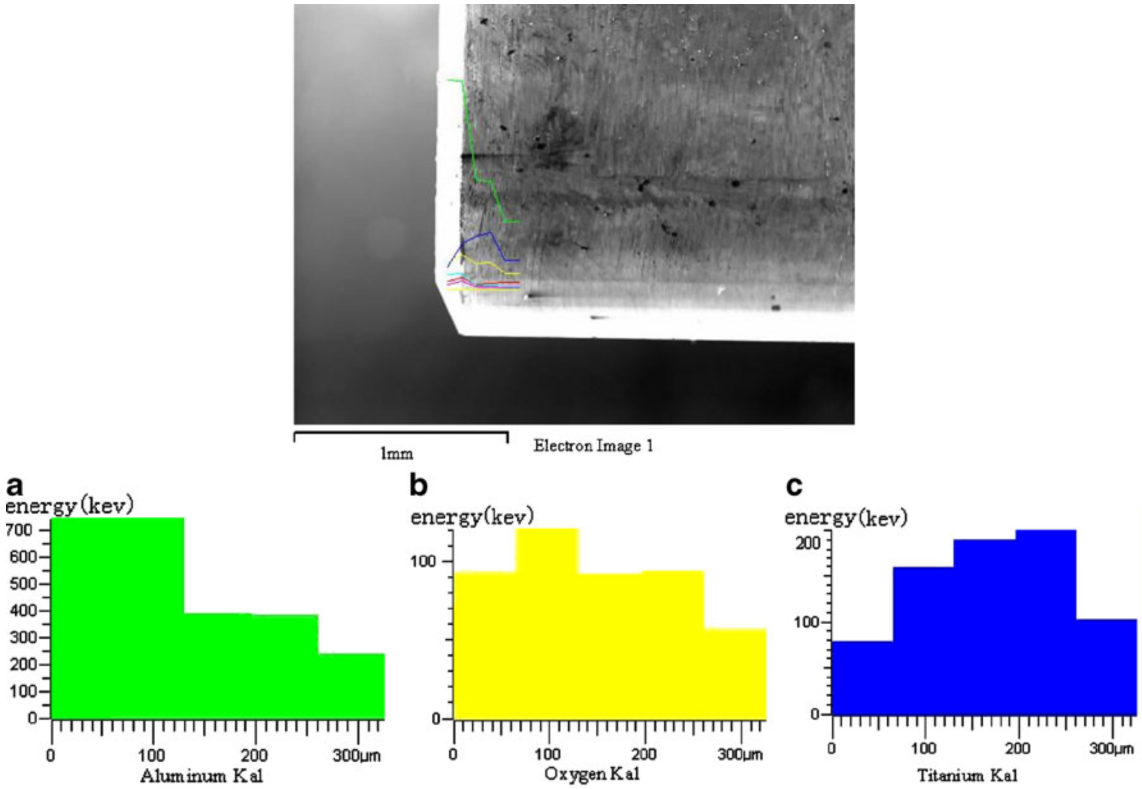

Fig. 3 Line scanning when machining nickel. *1–3* Element components of aluminum, oxygen, and titanium, respectively, in line scanning when machining nickel

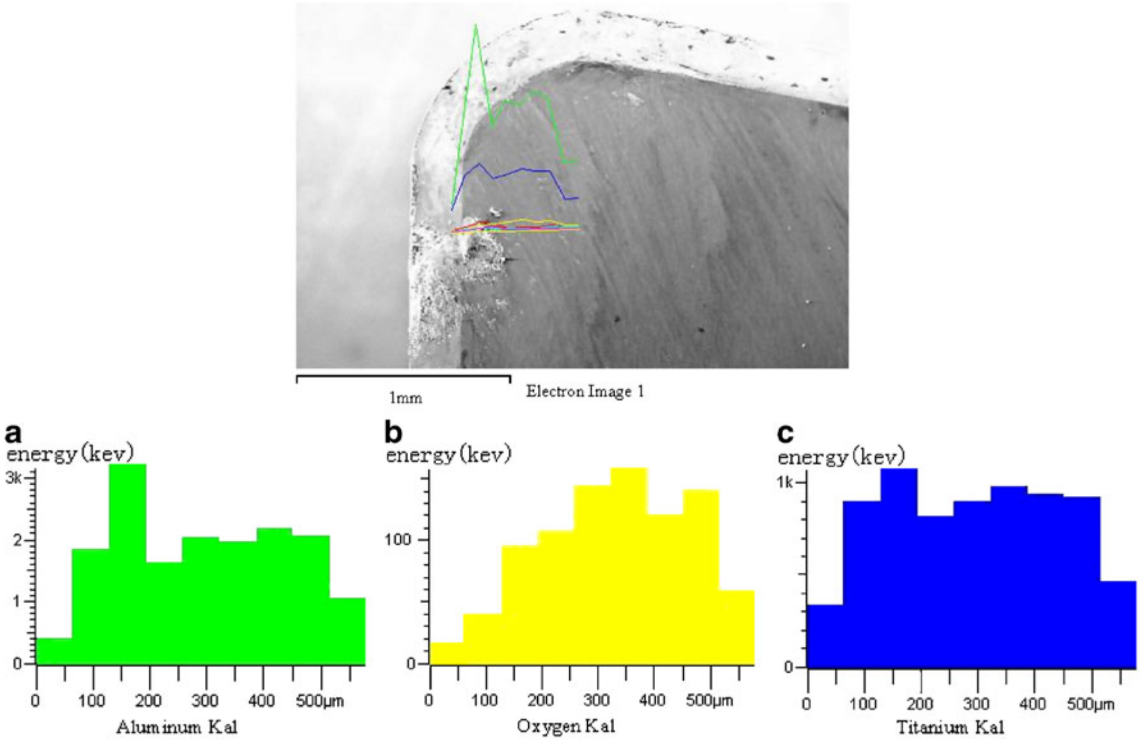

Fig. 4 Line scanning when machining titanium-based alloy. *1–3* Element components of aluminum, oxygen, and titanium, respectively, in line scanning when machining titanium-based alloy

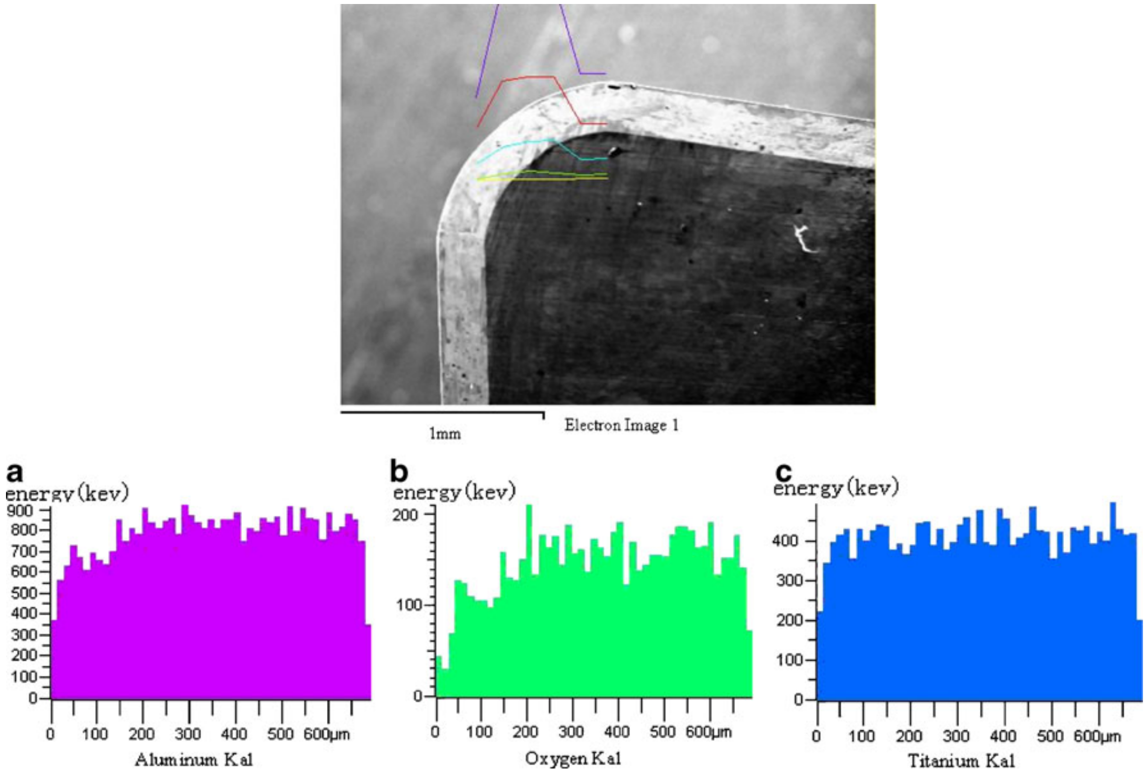

Fig. 5 Line scanning when machining 35 steel. *1–3* Element components of aluminum, oxygen, and titanium, respectively, in line scanning when machining 35 steel

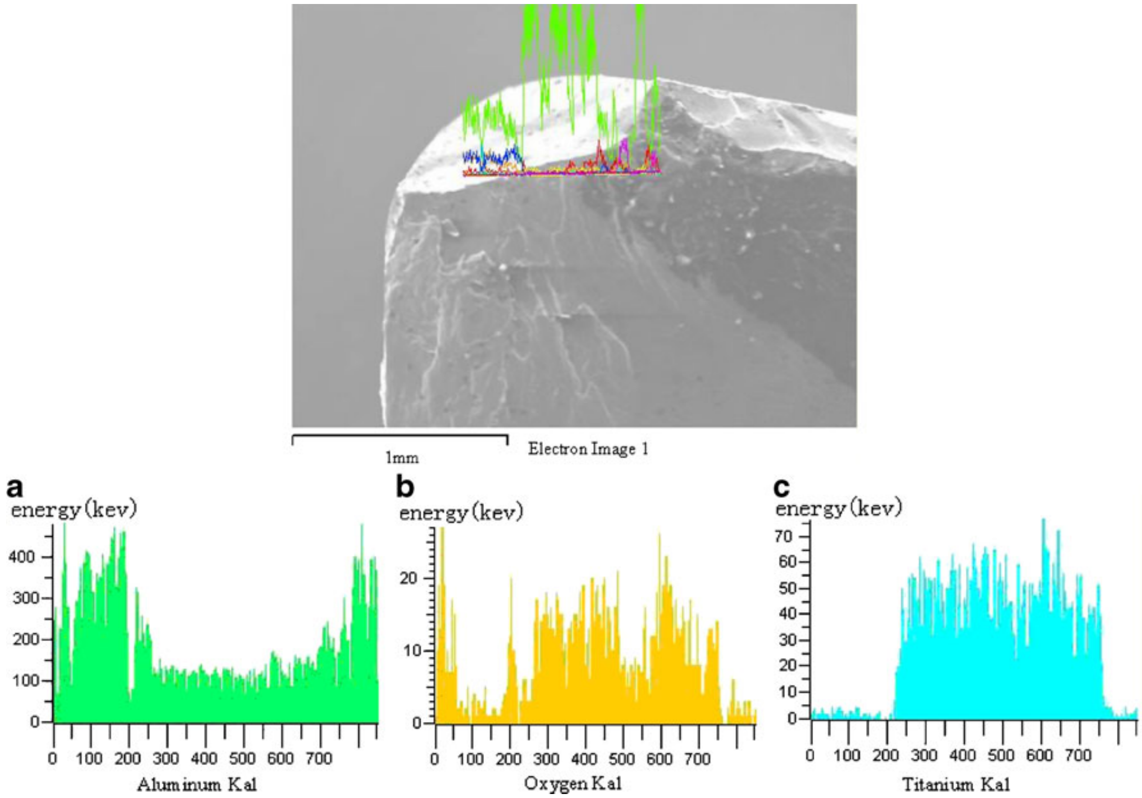

Fig. 6 Line scanning when machining aluminum alloy. *1–3* Element components of aluminum, oxygen, and titanium, respectively, in line scanning when machining aluminum alloy

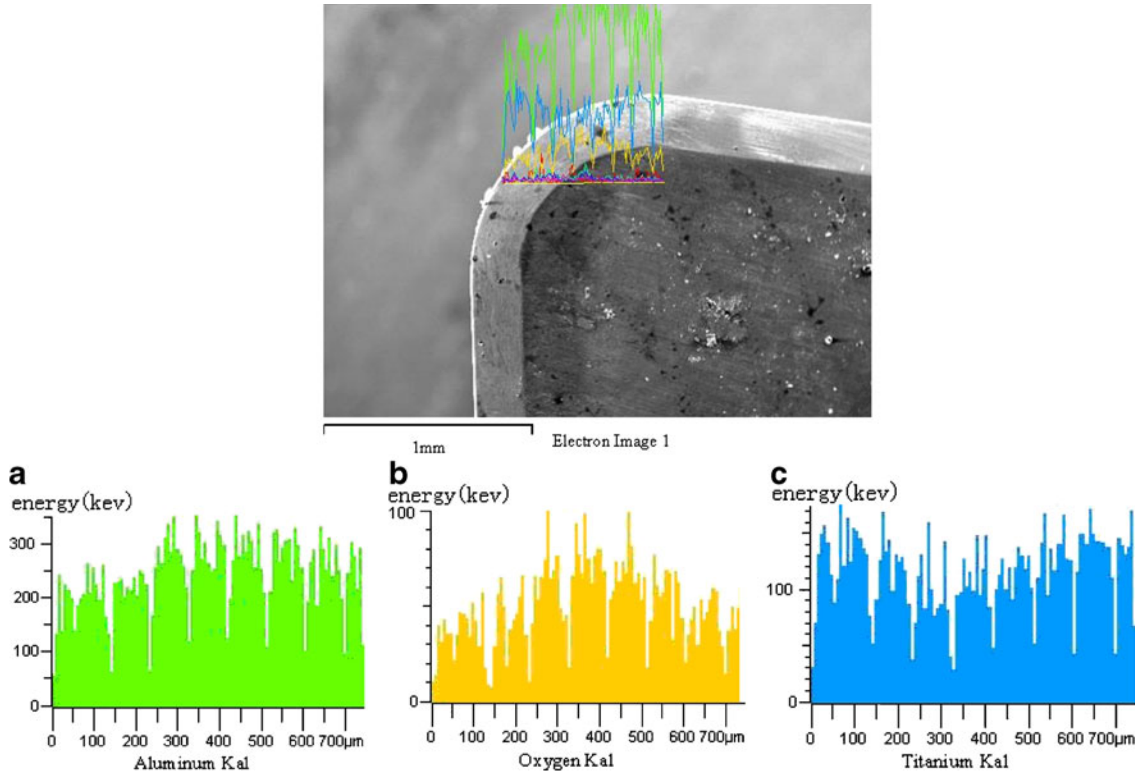

Fig. 7 Line scanning when machining cast iron. *1–3* Element components of aluminum, oxygen, and titanium, respectively, in line scanning when machining cast iron

Table 8 Standard free Gibbs energy of several compounds

Temperature (K)	933	1,000	1,200	1,400	1,500	1,600	1,700
Al_2O_3	−1,381,317.08	−1,359,660	−1,295,012	−1,230,364	−1,198,040	−1,165,716	−1,133,392
WC	−35,948	−35,777	−35,307	−34,852.6	−34,626	−34,399.4	−34,624.5
TiC	−173,712	−173,027	−170,723	−167,841	−166,398	−164,954	−163,507.7
Si_3N_4	−428,932	−407,826	−344,824	−281,822	−250,321	−218,820	−192,044 (1,687 K)

much greater absolute value; therefore, diffusion is hard to happen. From Table 8 and Fig. 8, the absolute value of standard Gibbs free energy for Al_2O_3 is far higher than that of other three tool materials, which shows that this compound is much more stable and is hard to be decomposed.

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

From the three groups of figures (*1–3* in Figs. 3, 4, and 5), the comparison results showed that the change amplitude of wave peak when cutting titanium alloy is greatest and that for pure nickel is greater, and it also can be seen that the wave peak is most stable when cutting 35# steel compared with titanium alloy and pure nickel.

From *1–3* in Fig. 5, wave peak of line scanning energy wave for aluminum, oxygen, and titanium are all much stable in measuring position when cutting 35# steel, and the change amplitude of wave peak is also much smaller, which indicates that content change of oxygen element and aluminum element is smaller in wear region of tools and non-cutting region. So the dissolution and diffusion concentration of oxygen and aluminum in workpiece materials in insert are very low, and tools are hard to be made diffusion wear.

From the two groups of figures (*1–3* in Figs. 3 and 4), it can be known that the change amplitude of wave peak is much greater than pure nickel when cutting titanium alloy; especially, there is a great decrease for wave value in inserts which showed that content change of oxygen element and aluminum element is smaller in wear region of tools and non-cutting region. The dissolution and diffusion concentration of oxygen and aluminum in workpiece material in insert are very low and tools are also hard to be made diffusion wear.

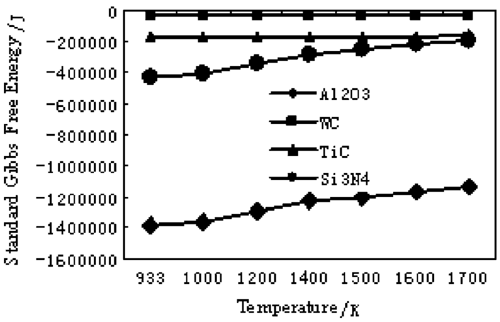

Fig. 8 Comparison on standard Gibbs free energy between several compounds

From the two groups of figures (*1–3* in Fig. 4 and Tables 9, 10, and 11), it also can be seen that the change amplitude of wave peak when cutting titanium alloy is much greater than pure nickel; especially, there is a great decrease for wave value in inserts which shows that content change of oxygen element and aluminum element is greater in wear region of tools and non-cutting region. The dissolution and diffusion concentration of oxygen and aluminum in workpiece material in inserts is much higher than pure nickel, and tools are easy to make diffusion wear.

The reasons include two aspects: one is that the absolute value of excess free energy for these two tool elements (aluminum and oxygen) in titanium is much greater than that in nickel so as to be easy to dissolve into titanium; the other one is that the cutting temperature when cutting titanium and aluminum alloy are lower than nickel, which indicates that a small amount of cutting heat is taken away by workpiece material and absorbed much by tool material when machining. Therefore, tool temperature will increase quickly and strengthen the diffusion of tool materials in workpiece. From Tables 9, 10, and 11, it can be observed that the aluminum element did not appear in workpiece material chip when cutting 35# steel, which showed that aluminum element is hard to be diffused and dissolved into workpiece material and so is hard to be measured; the content of aluminum and oxygen in tool material when cutting titanium alloy is higher than that for cutting nickel, which also proves that diffusion solubility of tool material

Table 9 Elements of chip when machining nickel

Element	Weight %	Atomic %
O K	0.81	2.86
Al K	1.77	3.70
Ni K	97.42	93.44
Totals	100.00	

Table 10 Elements of chip when machining titanium–aluminum alloy

Element	Weight %	Atomic %
C K	20.22	35.46
O K	20.42	26.89
Al K	33.62	26.25
Si K	0.39	0.30
Ti K	24.60	10.82
Fe K	0.74	0.28
Totals	100.00	

in titanium and aluminum alloy is larger than that in pure nickel (note that from Table 10, we know that content of aluminum when cutting can reach to over 33.62%, the reason being titanium and aluminum alloys are used as workpiece materials; the material contains aluminum in much higher proportion). The above test conclusions are accordant to that of the calculation results in this paper.

4.3 Other analysis

From Fig. 6 (and *1–3* of the same figure), it indicates that the content of aluminum element in blades increases greatly when Al_2O_3 ceramic tools cut aluminum alloy, which is due to much greater compatibility between Al_2O_3 ceramic tools and aluminum alloy; therefore, it is easy to be clung together when being machined; from the two sets of data in *1–3* of Fig. 5 and Table 10, we can know that there is much greater difference in wear mechanism of tools when machining cast iron and 35# steel under the same cutting condition; though cast iron and 35# steel both belong to steel material, the workability for 35# steel material is better than for cast iron in anti-diffusion wear. Because tool wear is a process affected by several nonlinear and strong coupling effects, each kind of effect influences together, which leads to more research on wear mechanism.

5 Conclusions

1. Solubility of tool material in workpiece material increases in exponential function with the increase of temperature; however, Al_2O_3 is a compound with much stronger stability and is hard to be decomposed, so the diffusion solubility of Al_2O_3 ceramic tools when machining the above workpiece materials are all much small.
2. Solubility order of Al_2O_3 ceramic tools in workpiece materials when machining several common workpiece materials is as follows: titanium > nickel > steel. At the same cutting temperature, solubility of Al_2O_3 ceramic tools in titanium alloy has the maximum value; therefore, it is not appropriate for machining titanium alloy, and in steel, it has the minimum value, so it is most suitable for machining steel.
3. At the same cutting condition, the wear performance of tools when machining cast iron and 35# steel are very different, and the wear mechanism should be researched more and extensively surveyed.

Table 11 Elements of chip when machining 35 steel

Element	Weight %	Atomic %
O K	7.83	22.87
Mn K	0.57	0.49
Fe K	91.60	76.64
Totals	100.00	

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