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Cutting and wear behaviors of TiC based cermets cutter with nano-TiN modification ①

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Abstract: Cutting and wear properties of the TiC based cermets cutter with nano-TiN addition were discussed in order to provide a theoretical basis for the practical application of such cermets cutter. Wear surface and quantitative analysis of chemical composition were conducted using SEM and EDX. The results reveal that this kind of cermets cutter shows higher endurance than the conventional cermets cutter and cemented carbides cutter (YT15). Normal wear occurs under the condition of lower cutting parameters, and tipping will be the predominant failure mode when the parameters are higher. SEM analysis shows that the grain wear, oxidation wear and diffusion wear all exist. In addition, oxidation and diffusion become very obvious when the cutting parameters are large.

Key words: cutting properties; wear resistance; endurance; failure mode
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1 INTRODUCTION

Cermet has been widely used as a tool material owing to its good comprehensive properties such as high hardness, high transverse rupture strength, good chemical stability and excellent wear resistance[1]. In addition, TiC based cermets appeared in 1930s and developed very quickly after 1980s[2]. Early TiC based cermets cutter find limited application because of its lower mechanical properties. Subsequent investigation finds that addition of TiN aids to the improvement of mechanical properties because of the refining effect of the TiC matrix[3]. Furthermore, the introduction of Mo or Mo_2C can greatly improve the wettability between TiC and binder Ni[4]. Additionally, with the quick development of the nano-technology, researchers find that proper addition of nanoparticles into conventional materials can improve the mechanical properties such as bending strength, fracture toughness and room hardness [5-7]. In China, the cutters used in the processing of normalized carbon steels include high carbon tool steel cutter (such as T10, containing 1% carbon), high speed steel cutter (W18Cr4V), ceramic cutters (such as Al_2O_3 based ceramic cutter, Si_3N_4 based ceramic cutter) and especially cemented carbides cutter. Now, as a tool material, Ti(C, N) based cermets have attracted more and more attention in China. Though there are many reports about the microstructures, mechanical and physical properties of the Ti(C, N) based cermets and some researches on the cutting behaviors of the conventional cermets cutter[8-10], unfortunately, only a few studies on the TiC based cermets with nano-TiN addition and their application were found[11-13], the application of TiC based cermets cutter with nano-TiN addition and lower Co and Ni addition has not been reported so far. Consequently, the cutting and wear behaviors of such cermets cutter (tool A) were investigated in this paper when used in cutting normalized 45# carbon steel(containing 0.45% C). For comparison, the behaviors of the conventional cermets cutter (tool B) and cemented carbide cutter (YT15, tool C) were also investigated. Additionally, the wear and failure modes were discussed using SEM and EDX results.

2 EXPERIMENTAL

The new-kind of cermet cutter is TiC-TiN(nm)-Mo_2C-WC-Co-Ni system. The technical parameters of nanometer TiN powder (bought from Institute of Chengdu Organic Chemistry, Chinese Academy of Sciences) and other raw powders are listed in Table 1. The chemical composition and mechanical properties of the cutters used in the cutting experiment are given in Table 2.

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Table 1 Technological parameters of raw powders

Powder	w / %						Size/ μm
	C	S	N	O	Fe	Bal.	
TiC	18.8	0.027		0.001 72		Ti	3.87
Ni	0.178	0.003 3		0.001 06	0.003	Ni	2.95
Mo	0.009 4	0.003 2		0.001 22		Mo	2.34
TiN	0.089	0.001 2	19.9	0.000 14		Ti	2.45
TiN(nm)	1		19.3	2		Ti	0.03－0.05
WC	5.95				0.01		2.52
C			0.000 15	0.30		C	3.25

Table 2 Chemical composition and mechanical properties of tested cutters

Cutter	w / %						σ_{bb}/ MPa	HRA
	TiC	WC	TiN	Mo_2C	Ni	Co		
Tool A	49	15	10(nm)	16	5	5	1 260	92.3
Tool B	49	15	10(μm)	16	10		1 140	91.8
Tool C	15	79	–	–	–	6	1 300	91

Powders of TiC, WC, Ni, Mo_2C and nano-TiN, which had been dispersed by ultrasonic wave for 30 min, were mixed thoroughly in proper mass proportions. The mixing was done in a planetary ball mill (QM-1SP) for 24 h. A ball to powder mass ratio is 7∶1 and an alcohol to powder mass ratio is 2∶1. The mixture was then dried and 7% PVA with a concentration of 10% was added to the mixture as a binder before making the green compacts of the cutters. The compacts were pressed in a cold steel die at a uniaxial specific pressure of 160 MPa. Then the compacts were derosinated at 800 ℃ for 60 min in vacuum. Sintering was then performed in vacuum at 1 400 ℃ for 60 min, after which the compacts were milled on a tool grinder by a 80 mesh diamond grinding wheel until they met the needs of cutters whose dimension is shown in Fig. 1.

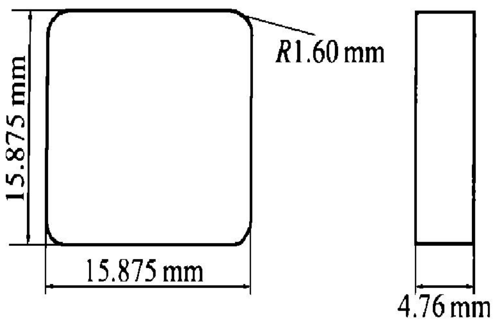

Fig. 1 Outline dimension of cermets cutters (SNUN150406)

The cutting tests were conducted on a CA6140 lathe. Tool angle and cutting conditions are listed in Table 3. The flank wear (VB) was measured at intervals until it was larger than 0.3 mm or the cutters chipped. Then, flank wear pattern and chipping zone were examined on the HITACHI X-650 scanning electron microscope (SEM) and JSM-6300 SEM at an accelerating voltage of 20 kV. Simultaneously, quantitative analysis of chemical composition of wear and chipping surface was conducted by using EDX attached to JSM-6300 SEM.

Table 3 Tool angle and cutting conditions

Tool angle	$\alpha_0 = 9°$, $\gamma_0 = -8°$, $\kappa_r = 90°$, $\kappa_r' = 30°$
Cutting speed, v_c	200, 300, 400 m/min
Feeding rate, f	0.1, 0.3, 0.5 mm/r
Depth of cut, a_p	0.5, 1, 2 mm
Cutting condition	Dry, no fluids

3 RESULTS

3.1 Wear resistant properties of different tools

Wear resistant behaviors under the cutting conditions of f being 0.1 mm/r, v_c being 200 m/min and a_p being 0.5 mm are shown in Fig. 2. Apparently, tool A shows the best wear resistance among three tools. The VB of tool A is below 0.25 mm in 430 min. It is estimated that the tool life of such tool can reach 500 min or longer. The experimental results reveal that the wear curve of tool A is very typical. That is, according to the curve the wear behavior can be divided into three stages: preliminary wear stage, stable wear stage and quick wear stage. Obviously, the second stage, which determines the tool life, is much longer in comparison with that of tool B and tool C.

The reason why tool A possesses so many advan-

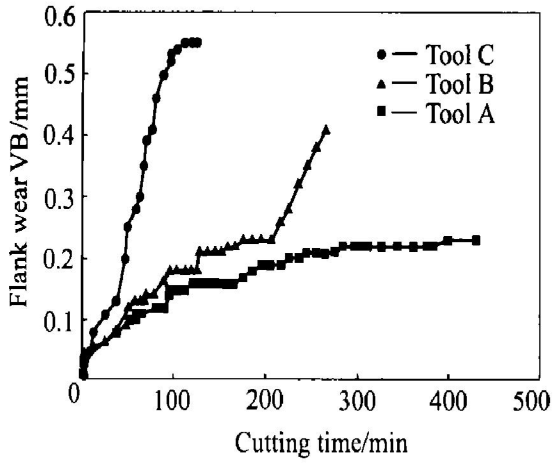

Fig. 2 Wear resistant properties of different cutters

tages in comparison with cemented carbides cutter can be described below. First, cermets have higher room and high temperature hardness. The hardness of the cermets is higher than that of the cemented carbides with similar binder phase mass percent because the hardness of TiC, the main ceramic phase of the cermets, is higher than that of WC, the main ceramic phase of the carbides. Furthermore, it has also been proved that the addition of nanometer TiN particles instead of conventional TiN is beneficial to obtaining higher strength, hardness and toughness of the cermets because the nanometer TiN particles can remain at/among the boundaries of TiC grains or in the binder phase and they will restrain the movement of the grain boundary and dislocations[13]. The strength and toughness of such cermets are lower than those of the YT15 cemented carbides but still acceptable. Second, cermets have better friction resistance and heat conductivity. The friction coefficient between cermets and steel is lower than that between cemented carbides and steel and cermets have higher heat-conductivity than cemented carbides. All these are in favor of causing a lower cutting temperature(θ), which is the key factor to the diffusion between tool and steel. It is known that the diffusion, especially the diffusion of C and Ni/Co from tools to steel at high cutting temperatures will decrease the mechanical properties of the cutting blade and increase the diffusion wear of the tools. Third, cermets have better oxidation and cohesion resistance. This is due to the formation of tight TiO_2 film over the surface of cermets tools, which happens between TiN/TiC and O_2 at a high temperature, could restrain oxidation, cohesive and diffusive wear. In contrast, the formation of porous WO_3 film on the surface of cemented carbides tool is not beneficial to the wear resistance of such tool. Moreover, the fine grain of cermets also helps hold the cohesive wear. In summary, tool A will become a very promising cutting tool because TiC based cermets with nanometer TiN addition have excellent mechanical and physical properties.

3.2 Effect of v_c, f and a_p on wear resistant behaviors of tool A

Fig. 3 shows the effect of v_c on the wear resistance of tool A under f = 0.1 mm/r and a_p = 0.5 mm. The effect of f on the wear resistance under v_c = 300 m/min and a_p = 0.5 mm is given in Fig. 4. Similarly, the influence of a_p on the wear resistance under v_c = 300 m/min and f = 0.1 mm/r is shown in Fig. 5. The results reveal that the flank wear VB increases quickly with increasing cutting parameters (i.e., f, v_c and a_p). The reason is that the increment of v_c, a_p and f will lead to the rise of cutting force (F_c), cutting temperature(θ), diffusion, oxidation and cohesion between tool and workpiece. The experiments also show that the wear is the most common failure mode and tipping will be predominant when the cutting parameters are higher. According to the famous Tailor formula, researchers found that among f, v_c and a_p the influence of v_c on tool life is the greatest, while the effect of a_p is the least.

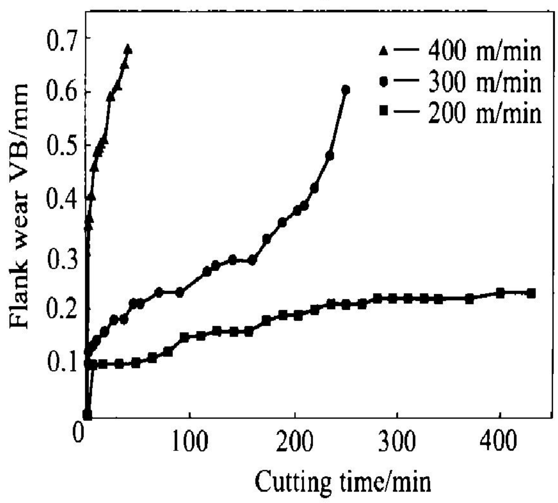

Fig. 3 Effect of v_c on wear resistant properties of tool A

3.3 Wear patterns of tool A

Figs. 6 (a), (b) and (c) show the macroscopic wear patterns of the flank wear of tool A under different cutting parameters. From Fig. 6 it can be seen that the flank wear zone consists of corner wear zone, normal wear zone and groove wear zone. Among these severest wear occurs in the grooves. In fact, the regularity of normal wear zone makes it convenient to measure VB. The smoothness of the flank wear shown in Fig. 6(a) explains that tool A is still in the stage of normal wear. Though Figs. 6 (b) and (c) show the obvious irregularity of the flank wear surface, the main failure mode of tool A is still wear. However, the increase in the cutting parameters results in severe wear that occurs in the flank. Macroscopic wear patterns of tool A under different conditions are

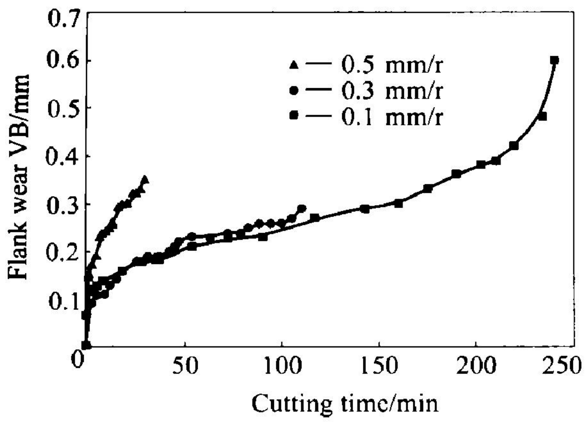

Fig. 4 Effect of f on wear resistant properties of tool A

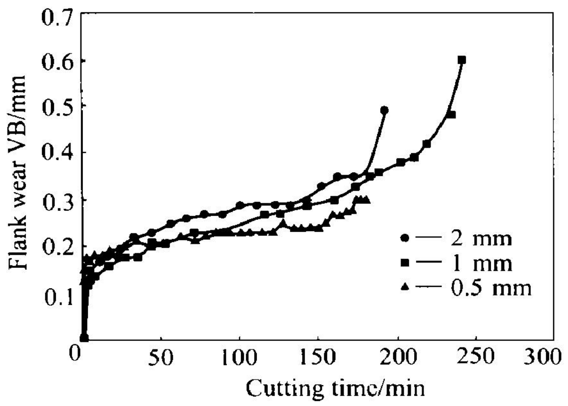

Fig. 5 Effect of a_p on wear resistant properties of tool A

given in Fig. 7. It can be seen from Fig. 7 that crater exists in the rake face. Similarly, crater width (KT) increases with the increase of cutting parameters. Additionally, the phenomena such as spalling can be found in the rank face, which is due to the greater thermal stress and mechanical shock in cutting under higher cutting parameters. Microscopic wear patterns of tool A under different conditions can be seen in Fig. 8. When the cutting depth rises, the grinding crack is not very clear (Figs. 8 (c) and (d)). This phenomenon means that higher depth of cut does not necessarily result in the acceleration of wear of tool A. However, it should be emphasized that tool A will fail easily in the form of breakage as formation, propagation and aggregation of micro crack become easier under higher cutting depth. Similarly, the main failure mode under higher cutting speed and feeding rate is the breakage of tool. Grinding cracks and macroscopic cracks can be easily seen in tool flank (Figs. 8 (a) and (b)). Subsequent investigations found that formation location of micro-cracks may be TiC/TiC boundaries, TiC/Ni boundaries or defects such as micro-voids, micro-pores and impurities. Micro-cracks propagate along the interfaces of TiC/TiC, TiC/Ni or other modes. Finally, the aggregation of micro-cracks and the formation of bigger crack make tool A readily fail in the form of breakage under higher cutting parameters.

Fig. 9 shows the microscopic and macroscopic patterns in groove wear zone under f = 0.1 mm/r, a_p= 0.5 mm and v_c= 400 m/min. It can be seen from Fig. 9 that most small round balls are distributed in the groove wear zone. According to the crystallization theory, the regularity and roundness of the balls indicate that the transformation from liquid phase to solid phase exists in the cutting process. Notably, though the working temperature in the groove zone is lower than the corner wear zone and rake face, oxidation and diffusion also exist and friction between chips and groove zone is greater. The result is that high temperature makes chips melt and solidify in the groove zone(Fig. 9(b)). That is, the round balls in the groove zone are from chips. This can be confirmed by the subsequent EDX analysis (i. e., this can seen from zone H in Table 4). According to iron carbon equi-

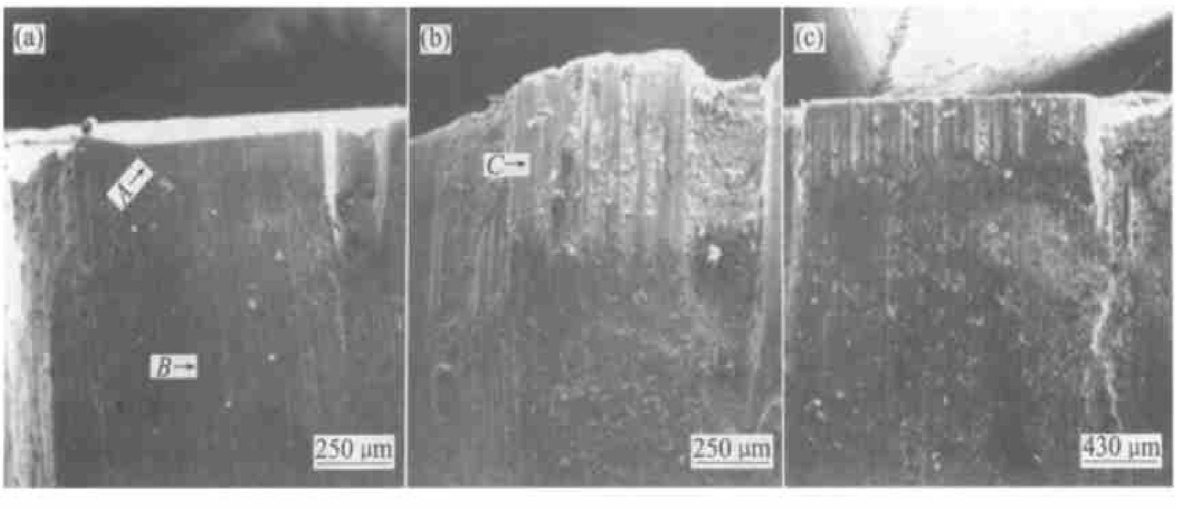

Fig. 6 Macroscopic wear patterns in tool flank under different conditions
(a) —200 m/min, 0.5 mm, 0.1 mm/r, 430 min; (b) —400 m/min, 0.5 mm, 0.1 mm/r, 5 min;
(c) —300 m/min, 1 mm, 0.1 mm/r, 143 min

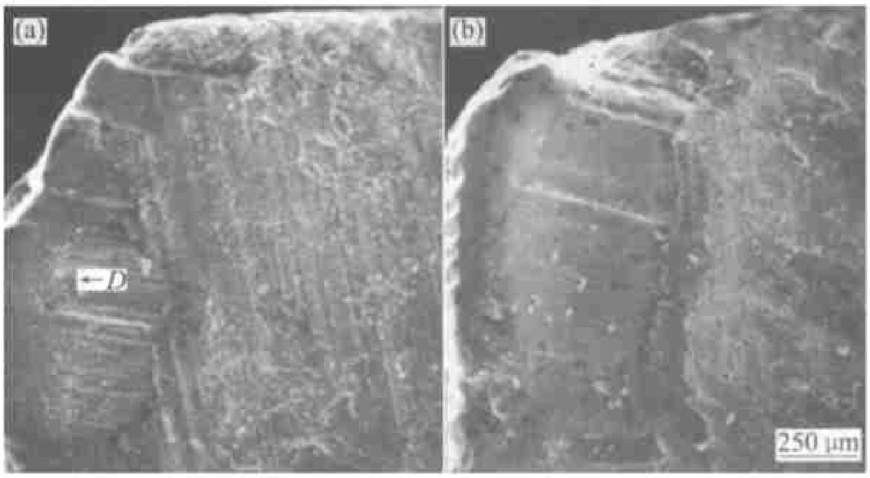

Fig. 7 Macroscopic wear patterns in rake face under different conditions
(a) —200 m/min, 0.5 mm, 0.1 mm/r; (b) —300 m/min, 0.5 mm, 0.5 mm/r

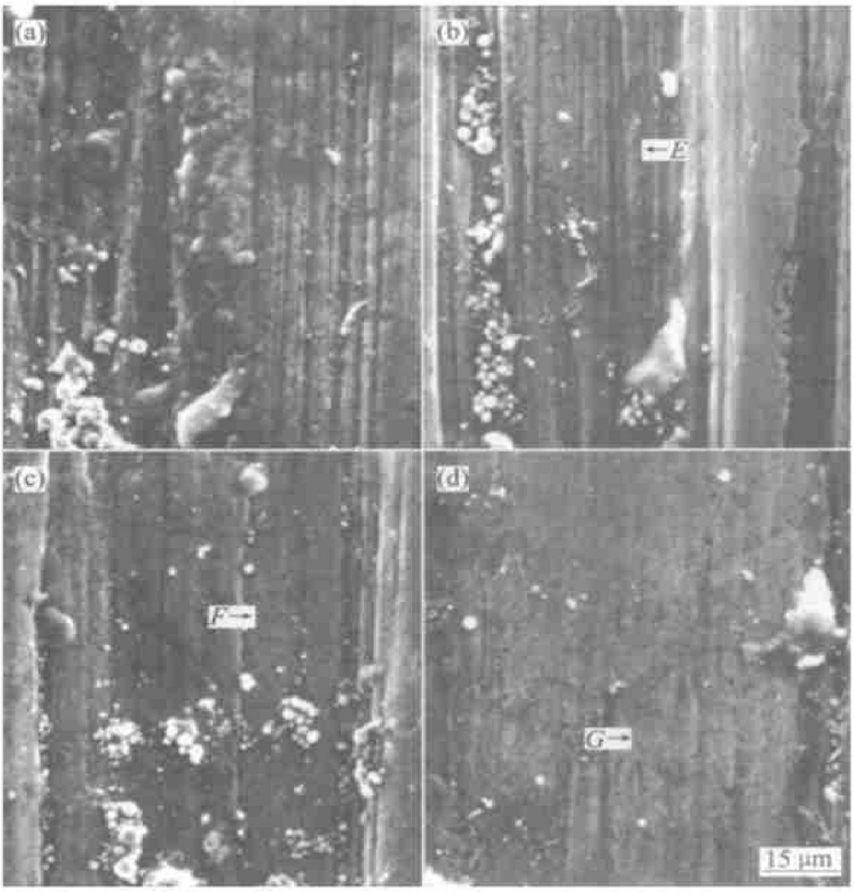

Fig. 8 Microscopic wear patterns observed in tool flank
(a) —300 m/min, 0.5 mm, 0.1 mm/r; (b) —300 m/min, 0.5 mm, 0.5 mm/r
(c) —300 m/min, 1 mm, 0.1 mm/r; (d) —300 m/min, 2 mm, 0.1 mm/r

librium diagram, the highest cutting temperature under such cutting conditions is not lower than 1 450 ℃. This also explains why tool easily fail in the form of breakage under higher cutting parameters.

3.4 EDX analysis result of wear surface of tool A

EDX analysis results of wear surface are listed in Table 4. Table 5 gives the chemical compositions of chips under different cutting conditions.

Comparison between zone *A* and zone *B* reveals that the Ni and Co contents in flank wear zone are much lower than those in the matrix. The reason is that Ni and Co, the softer and tougher phase in Ti(C, N) based cermets, can be easily ground off by hard particles. Notably, Ni and Co contents in rake wear zone (zone *D*) are close to those in the flank wear zone (zone *A*). Moreover, O content

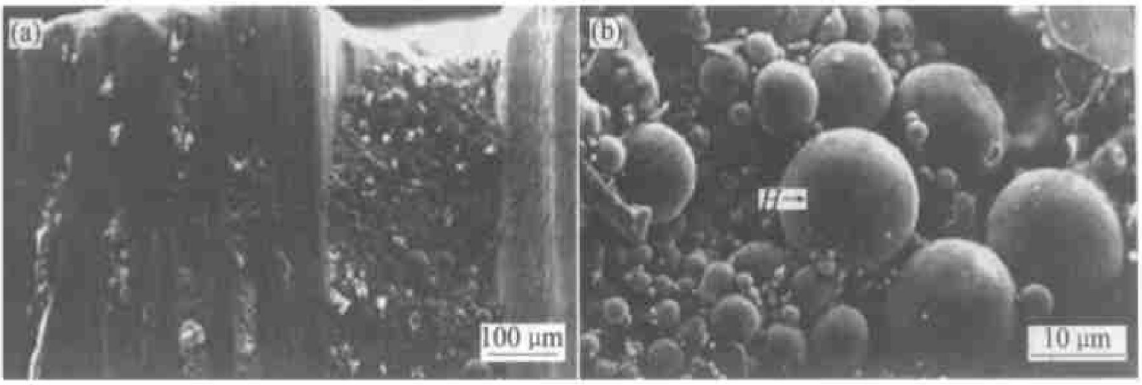

Fig. 9 Wear patterns observed in groove wear zone
(a) —Macroscopic; (b) —Microscopic

Table 4 Chemical compositions of wear surface (mass fraction, %)

Condition	Zone	Ti	Ni	Co	Mo	W	O	Fe
1	*A* (flank wear)	48.40	0.31	0.40	10.92	27.43	5.97	6.57
1	*B* (matrix)	46.17	3.58	4.27	11.44	28.60	5.34	0.61
1	*D* (rake wear)	52.81	0.44	0.36	11.85	30.60	2.76	1.55
3	*C* (flank wear)	42.59	0.00	0.00	9.04	11.89	19.34	17.14
4	*E* (flank wear)	40.81	0.36	0.57	11.12	25.43	13.35	8.37
5	*F* (flank wear)	47.11	0.56	0.42	12.30	28.01	6.32	5.27
6	*G* (flank wear)	41.31	0.99	1.73	13.84	24.71	11.26	6.16
7	*H* (groove wear)	0.82	0.00	2.36	0.26	0.00	1.20	95.32

Condition 1: 200 m/min, 0.5 mm, 0.1 mm/r; Condition 3: 400 m/min, 0.5 mm, 0.1 mm/r; Condition 4: 300 m/min, 0.5 mm, 0.3 mm/r; Condition 5: 300 m/min, 0.5 mm, 0.5 mm/r; Condition 6: 300 m/min, 1 mm, 0.1 mm/r; Condition 7: 300 m/min, 2 mm, 0.1 mm/r.

Table 5 Chemical compositions of chips under different conditions (mass fraction, %)

Test condition	O	Ti	Fe	Co	Ni	Mo	W
1	3.73	0.00	94.88	1.39	0.00	0.00	0.00
2	4.06	0.11	94.17	1.66	0.00	0.00	0.00
3	6.58	0.10	91.26	2.06	0.00	0.00	0.00

Condition 1: 300 m/min, 0.5 mm, 0.1 mm/r; Condition 2: 300 m/min, 1 mm, 0.1 mm/r; Condition 3: 300 m/min, 2 mm, 0.1 mm/r

in zone *D* is slightly lower than that in the flank and matrix wear zone (zones *A* and *B*). In addition, higher O content in the flank wear zone states that the oxidation wear is severe in this zone. Comparison between zones *A* and *C* reveals oxidation is more severe under higher cutting speed. Similarly, as much Co and Ni is ground off, no such elements are observed in zone *C*. Notably, Fe content in zone *C* is much higher than that in zones *A*, *B* and *D*. This shows that the diffusion wear plays a more important role in the whole wear process under higher cutting speed. It also can be seen from Table 4 that the main chemical composition of small round balls distributed in groove wear zone (zone *H*) is Fe and O (that is, the balls result from the melting and solidification of chips in processing), this correlates well with the results discussed above. Apparently, some Co and Ti in matrix are diffused into chips, but Ni element is not observed in zone *H*. The phenomenon shows the diffusion of Ni is more difficult than Co under the same cutting conditions. Data in zones *C*, *E*, *F* and *G* compared with those in zone *A* show that oxidation and diffusion abrasion are more obvious in tool flank under higher cutting parameters. Additionally, oxidation and diffusion wear in rake wear zone (zone *D*) are less than those in flank wear zone (zone *A*). This also reveals that the Ti(C, N) based cermet materials possess excellent crater wear resistance.

It can be seen from Table 5 that more Co and Ti in tool surface can be diffused into the chips, oxidation and diffusion will become more severe with the increase of depth of cut. In fact, with increasing cutting speed and feeding rate, the same results will be obtained.

4 DISCUSSION

In earlier studies, it has been found that the main wear mechanisms of cermets are cohesive wear and spalling of ceramic phases[14, 15]. According to the experimental results mentioned above, the wear mechanism of tool A can be summarized as follows.

a) Grain wear. As discussed above, hard phase particles (TiC or Ti(C, N)) in cermets are scaled and act as grains in processing normalized medium carbon steel. In fact, the grooves in tool flank result from grain wear. Ref. [14] found that grooves arise from the propagation of cracks and subsequent scaling of surface materials. Because TiC based cermets with nanometer TiN addition possess better comprehensive mechanical properties such as high hardness and finer microstructure in comparison with those of conventional cermets and cemented carbides, so tool A has better grain wear resistant properties.

b) Cohesion wear. Cohesion between chips and tool surface will occur under higher stress and cutting temperatures. Generally, breakage due to cohesion wear occurs on the workpiece side. In fact, the combined action of contact fatigue, thermal stress and surface deficiencies make cohesion wear also happen on the tool side. That is, the softer and tougher particles (Ni, Co or Ni-Co alloy) will be dragged out by chips. However, bigger spalling pits are not observed in the microscopic patterns (Fig. 6 and Fig. 8). This shows that tool A has good cohesion wear resistant properties. According to the results discussed above, cohesion wear plays a minor role in the whole wear process of tool A.

c) Oxidation wear. As mentioned above, higher cutting temperature (sometimes above 1 450 ℃) and cutting heat under higher cutting parameters make oxidation very active, though tool A has good heat resistance, excellent chemical stability and good oxidation resistance. Oxidation phenomenon mostly appears in groove wear zone and flank wear zone. In addition, Co in tool matrix can easily oxidize at high temperatures and form softer oxidations such as CoO and Co_3O_4. These oxidations can be ground off and thus oxidation wear also occurs.

d) Diffusion wear. Co and Ni in tool matrix can be diffused into workpiece and chips; as a result, tool becomes more brittle owing to the diminishing of the tough phase in tool matrix. On the other hand, Fe in workpiece and chips can be diffused into tool and forms a new brittle phase in tool matrix. All these result in the decrease of mechanical and physical properties plus more severe wear.

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