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TRIBOLOGICAL PROPERTIES OF TiCN-Ni CERMETS: INFLUENCE OF NbC ADDITION

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ABSTRACT

The development of Ti (CN) - based cermets have received a wider attention in the field of cutting tool materials in recent years. Ti (CN)-cermets posses excellent creep and wear resistance along with good surface finish and high temperature stability, which collectively make them preferable over conventional WC-Co materials. Also, the fracture toughness and high temperature mechanical properties can be controlled by varying the compositional parameters, such as the amount of different secondary and ternary carbides and binder. In order to understand the performance of cutting tool inserts, a systematic study of cermets at fretting wear contacts is of major significance. The present investigation aims at evaluating the fretting wear behavior of TiCN-20 wt. % Ni cermets with varying amounts of NbC secondary carbide (0-25 wt.%) against steel tested with different applied load (2-10 N) for 100,000 cycles at a frequency of 4 Hz. The friction coefficient does not vary much (0.35 to 0.4) with load, when smaller addition of NbC (up to 10 wt. %) is added to TiCN-20 wt % Ni cermet. However, higher COF (~ 0.52) is measured with TiCN-25NbC-20Ni cermet at 2N load and decreased to 0.43 as load is increased up to 10N. Though the wear rate was observed to increase with NbC addition at any given load, it decreases with load for all investigated cermets exhibiting a minimum of 1.93 X 10^{-6} mm^3/N-m for TiCN-5wt.% NbC-20 wt. % Ni cermet at 10N load.

1. INTRODUCTION

In an attempt to achieve more productivity and better tool life of cutting inserts, Cermets, in recent times, have received greater attention due to their higher cutting speeds and extended tool life with superior surface finish, compared to conventional WC-Co materials. TiCN cermets are widely accepted cutting tool inserts due to their high hardness and enhanced wear resistance along with their chemical stability at elevated temperatures [1, 2]. The toughness as well as other properties of the cermets can be controlled by adding Ni, Co or Fe and their alloy binders and various carbides such as WC, TaC, HfC, NbC [3-8]. The various purposes for which these carbides are added to TiCN- cermets are schematically shown in Fig.1. Adding WC is indispensable in many cases to achieve densification and fracture toughness, whereas NbC improves the interrupted cutting performance by increasing hot hardness and thermo-shock resistance at elevated temperatures. Typical core-rim structure, that forms during dissolution and reprecipitation process greatly influences the material properties of cermets [2,9].

Fretting, one of the important wear phenomena refers to any situation in which the contacts between materials are subjected to a low amplitude oscillatory sliding motion [10,11]. The displacement amplitudes (5-300 μm) encountered in fretting are smaller than those of reciprocating sliding [11]. This means that contact is maintained over most of the tribosurface during fretting. As a result, much of the wear debris produced by fretting remains trapped at the interface, which can cause seizure in components.

Most of the published tribological research of cermets is concerned about the sliding [12-18] and erosive [19-24] aspects involving severe wear contacts and very limited work [25,26] has been investigated on mild wear at fretting contacts. In evaluating the tribological behavior of TiC-based spark plasma sprayed cermet coating in fretting contacts, better wear resistance was reported at $500^{o}C$ when compared with that of conventional WC-Co coatings [25]. According to Sarkar et al.[26], the fretting wear resistance of the TiCN-WC-Ni cermets against steel increased with the amount of WC beyond 5 wt.%. The oxidation of the tungsten in rim phase was reported to be the major reason for the low fretting wear resistance for cermets with higher WC content.

A deeper understanding of the performance at fretting contacts definitely demands a systematic investigation of these cermets with varying fretting parameters. This work aims at evaluating the fretting wear behavior of Ti(CN)-NbC-Ni cermets by varying amount of NbC (5-25 wt. %) and applied load (2-10N). The dominant wear mechanisms are reported and correlated with the frictional characteristics at each stage.

2. EXPERIMENTAL DETAILS

2.1. MATERIALS

The cermets used in this study were fabricated from 30 gm batch of $Ti(C_{0.7}N_{0.3})$ (particle size 1.5µm, Kennametal) with different (0-25 wt. %) NbC as secondary carbide (particle size 1-2 µm, H.C. Stark) using Ni (particle size 1-2 µm, Novamet) as the binder. These cermets were cold compacted under a pressure of 100 MPa to give discs with 15 mm diameter and subsequently sintered at a temperature of 1510 ^{o}C for 1 hr under vacuum. One side of the sintered disks were polished to roughness of around 1 µm with diamond slurry. The composition and mechanical properties of investigated cermets are listed in Table 1. The addition of NbC appears to decrease both hardness and fracture toughness, while the hardness of base TiCn-20Ni cermet is 14 GPa, the hardness decreased to around 11-12 GPa with NbC addition, upto 25 wt. % . Similarly, a decrease in fracture toughness from 9.5 MPa-$m^{1/2}$ (TiCN-20 NI) cermet) to 7-8 MPa- $m^{1/2}$ is observed with NbC addition.

2.2. WEAR TESTS AND CHARACTERIZATION

The fretting experiments were performed using a computer-controlled fretting machine, (DUCOM TR281-M), which produces a linear relative oscillating motion with ball-on-flat configuration. By a stepper motor, the flat sample is made to oscillate with a relative linear displacement of constant stroke and frequency. The displacement of the flat sample is monitored by an inductive displacement transducer and a piezoelectric transducer is used to measure the friction force. Variation in tangential force is recorded and the corresponding coefficient of friction is calculated on-line with the help of a computer-based data acquisition system.

Polished cermets were used as flat (moving) materials. 8 mm diameter bearing grade (commercial SAE 52100 grade, hardness 63-65 HRc, data from supplier) steel balls were used as counter bodies (stationary). Prior to the fretting tests, both flat and ball were ultrasonically cleaned in acetone. The fretting experiments were performed on cermets against steel balls with varying load (P) of 2, 6 and 10N at 4Hz oscillating frequency and 100µm linear stroke for 100,000 (100K) cycles duration. Also, the combination of testing parameters results in the gross slip fretting contacts. All experiments were conducted in air at room temperature ($30\pm2^{0}C$) with relative humidity (RH) of 45±5%. The schematic of the fretting test configuration is shown in Fig. 2.

After each test, the worn surfaces of both the flat and the ball were ultrasonically cleaned with acetone and the wear scar profiles on each sample were obtained using a computer–controlled Laser surface profilometer (Mahr-Perthometer PGK 120). IR light (780nm) is focused onto the scar and the reflected light from the surface is directed to a detector. With the help of a transducer, the moving position of the light is converted to an electrical signal, which was further processed to generate the 3-D profile of the worn surface. The wear volume is calculated by integrating the surface area of each 2-D profile (extracted from different locations on 3-D profile) over distance. From the estimated wear volume, the specific wear rates [Wear volume/(load × total fretted distance)] are calculated. Further detailed characterization of the worn surfaces was performed using a scanning electron microscope (FEI QUANTA 2000 HV SEM) equipped with energy dispersive X-ray analysis (EDX).

3. RESULTS

3.1. FRICTIONAL BEHAVIOR

The frictional behavior of TiCN- Ni-NbC cermets were investigated under varying load (2 to 10N) with different amounts of NbC (0 to 25 wt. %) content. Fretting experiments were done for 100,000 cycles for a linear stroke of 100 μm with a 4Hz frequency. The COF against number of cycles plots for different amounts of NbC at varying loads are shown in Fig 3.

Broadly similar frictional behavior for all the investigated cermets at all loads is observed. In all cases, COF increases to a high value within running-in-period (10,000 cycles) and subsequently attains steady state behavior. However, a difference in steady state COF value exhibits and depends on NbC content as well as applied load. At 2N load, no significant difference in steady state COF is measured for cermets containing upto 10 %NbC and the steady state COF varies between 0.3 and 0.5. However, a high steady state COF of 0.5 is observed with cermet containing 25 % NbC. At 6N load, no considerable difference in steady state COF for the investigated cermets is observed and steady state COF varies between 0.34 and 0.40. At 10N load, a slightly different frictional behavior is noted. For 5% and 10 % NbC containing cermets, COF rises sharply to 0.42 and 0.5 respectively within first 10, 000 cycles and thereafter reaches a steady state COF of 0.5.

3.2. WEAR DATA

The wear volumes of TiCN- based cermets are estimated by laser surface profilometry analysis on worn cermet surfaces and specific wear rates are plotted in Fig.4. Overall observation is that as the load increases, wear rate decreases for all investigated cermets. The lowest wear rate of 1.93×10^{-6} mm^3/N-m is noted for TiCN-20Ni-5NbC cermet at 10N load while TiCN-20Ni cermet exhibits a wear rate of 2.27×10^{-6} mm^3/N-m. Under a particular load, as NbC content is increased, wear rate of TiCN-20Ni cermet increases and reaches a maximum of 6.107×10^{-6} mm^3/N-m with 25 wt.% NbC at 2N load. At 10N load, the difference in wear rate measured with different cermet composition is minimum. The influence of different amounts of reinforcements on the wear behavior of cermets was also reported in earlier investigations [13-15, 25]. It can be also noted here that the fretting wear rate of ceramics and ceramic composites typically vary over 10^{-6} to 10^{-7} mm^3/N-m [27]. Also, it is noted that the difference in wear rates of TiCN-20Ni-5NbC and TiCN-20Ni-10NbC is minimal at all loads, however the former experienced lowest wear. Hence based on wear data, it can be concluded that the amount of NbC and also applied load greatly influence the fretting wear of TiCN-based cermets.

3.3. SEM OBSERVATION OF WORN CERMET SURFACES

In order to understand the wear mechanisms, detailed microstructural investigation was carried out using SEM equipped with EDX. Fig 5 shows the SEM images of cermet without NbC after fretting at different loads, revealing severe abrasion throughout the worn surface. One can clearly note occurrence of spalling of tribolayer at 2N and 6N. Though the observed difference in severity of abrasion is small (see Figs. 5a, c and e) with increasing load for different cermets, the entrapment of debris in the deeper grooves can be observed at 6N load (see Figs. 5d and f). Overall, abrasive wear is the dominant wear mechanism for TiCN-20Ni under investigated fretting conditions.

The worn surfaces of TiCN-20Ni-xNbC cermet exhibit similar type of wear mechanism as compared with TiCN-20Ni cermet under similar fretting conditions, but certain differences are observed in Figs.6-8. The formation of tribolayer/transfer layer and debris are observed when 5 wt. % NbC is added in TiCN- 20Ni, as shown in Figs. 6a to c. Fig. 6c also reveals considerable adhesion of compacted debris on the worn surface. Similar topographical features of abrasion with increased adhesion of tribolayer are also noted in worn surfaces of TiCN-20Ni-10NbC cermets (see Fig.7a-d). However, SEM images of worn surfaces of TiCN-20Ni-25NbC cermet reveal a severe abrasion at 2N load (Fig.8a) and dispersed debris / spalled tribolayer at higher magnifications (Fig.8b and c). The defragmented layer confirms severe wear under fretting contacts. EDS analysis on the worn surface (Fig.8f) of TiCN-20Ni-25NbC is placed on Fig, 8e as insert. EDS analysis indicates that the tribolayer is rich with NbO and little amount of Fe (see Fig. 8e), which suggests the tribooixidation occurring at fretting contacts.

4. DISCUSSION

In general, the wear of materials is influenced by mechanical as well as material parameters. From table 1 it is clear that addition of NbC influences the hardness and toughness, but no definite inference can be made out. Investigating influence of load by keeping other operating parameters constant results in clear understanding of the wear and friction behavior of cermets. Fretting of metallic materials is often characterized by oxidative wear, whereas that of ceramic and their composites is influenced by abrasive, adhesive and tribooxidation.

Based on the friction, wear data and topographical analysis of different tribosurfaces using (Laser surface profilometer and SEM-EDX), the wear behavior of TiCN-20Ni-xNbC cermets can be summarized. In general, abrasion, adhesion and spalling of tribochemical layer can be noted in the fretting wear of investigated TiCN-based cermets.

The friction curves reveal that the steady state COF value of TiCN-20Ni cermet/steel couple doesn't change much with increase in load. Similar behavior is observed for cermets upto 10 wt. % NbC addition. It is apparent from the friction results that abrasion is the major mechanism in fretting and the difference in severity in abrasion with increase in load is negligible. During fretting, hard carbonitride particles are probably being debonded and embedded in soft steel causing severe abrasion on cermet surface. An increase in COF is observed with 25 wt. % NbC in TiCN-20Ni cermet at all loads when compared with other cermets and the COF value decreases from 0.49 to 0.43 as load increased from 2 to 10N. It is thought that that tribosurface of TiCN-20Ni-25NbC cermet oxidizes along with abrasion by carbonitride-embedded counterbody material, finally increasing friction and wear [26]. EDX analysis on the worn surface of TiCN-20Ni-25NbC also confirms the tribooixidation occurring at fretting contacts. With higher load, the COF decreases with 5wt. % NbC addition but an increase in COF is observed with 10 to 25 wt. % NbC additions to TiCN-20Ni cermet. Increase in NbC results in increased amount of debris and their continuous ejection during fretting process apparently causing increased abrasion and friction.

In the investigate fretting conditions, abrasion is found to be the predominant wear mechanism irrespective of NbC content and applied load. It is already accepted that the abrasive wear in brittle solids is similar to the damage mechanism formed by sharp indenter.

As sharp asperity/indenter slides over the surface, the lateral cracks grow upwards from the subsurface removing the material as platelets. The volume of wear per unit sliding distance of the interface is given by [28]

$$V = \frac{\alpha N(E/H)W^{9/8}}{K_c^{1/2} H^{5/8}}$$

where W = normal contact force;

K_c = fracture toughness

E = elastic modulus H = hardness

N = total number of contacting asperities and

α = material-independent constant.

Since the ratio (E/H) does not vary greatly for different brittle solids[29, 30], the wear rate should be dependent on H, K and W. For the investigated cermets, the measured wear rate is found to have a linear correlation with $\left[\frac{W^{1/8}}{K_c^{1/2} H^{5/8}}\right]$.

Summarizing the tribological data and topographical analysis, it can be said that TiCNi-20Ni cermets experience predominantly abrasion with spalling of underneath layer, whereas TiCN-20Ni-25NbC shows severe wear by abrasion, adhesion and tribooxidation occurring at the tribocontacts under identical conditions. Implication of the work can be realized for cutting tool applications where reduced COF and wear are highly significant. From this study, it can be concluded that TiCN-20Ni-xNbC/steel tribocouple can be useful, where x is limited upto 10 wt. %.

5. CONCLUSIONS

TiCN -20Ni-xNbC (x: 0-25 wt.%) cermets are fretted against bearing steel for a duration of 100,000 cycles with a linear stroke of 100 μm with frequency of 4Hz. Based on the experimental observations, the following conclusions can be drawn:

1. Lowest steady state friction of 0.30 is observed for TiCN-20Ni-5NbC/steel tribocouple at 2N load where as highest COF of ~0.5 is observed for TiCN-20Ni-25NbC/steel tribocouple under 2N load for all investigated fretting conditions of cermets.
2. Wear rate is observed to be decreasing with increase in load for all investigated materials. Highest wear of 6.107×10^{-6} mm^3/N-m is observed for TiCN-20Ni-25NbC at 2N load and lowest wear rate of 1.93×10^{-6} mm^3/N-m is observed for TiCN-20Ni-5NbC at 10N load.
3. Abrasion and spalling of underneath material are predominant in TiCN-20Ni cermets whereas abrasion, tribooxidation are the dominant wear mechanisms in TiCN-20Ni-NbC cermets fretted against steel. Improved tribooxidation and further ejection of debris during fretting cause severe wear in cermet containing 25%NbC.

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TABLES

Table 1. Composition and mechanical properties of investigated cermets.

Sample code	Composition	Ti(CN) wt. %	NbC wt. %	Ni wt. %	Density gm/cc	HV GPa	Fracture toughness, Mpa√ m	Transverse Rupture strength, MPa
BS 2-2	Ti(CN)-20Ni	80	0	20	5.27	14.2	9.5	-
BS 5-1	Ti(CN)-5NbC-20Ni	75	5	20	5.82	11.21	8.75	106
BS 4-1	Ti(CN)-10NbC-20Ni	70	10	20	5.92	11.78	7.34	158
BS 5-2	Ti(CN)-25NbC-20Ni	55	25	20	6.25	13.02	8.04	153

Table 2. Peak and steady-state COF values at different loads.

Material	**2N**		**6N**		**10N**	
	Peak value*	Steady-state value	Peak value	Steady-state value	Peak value	Steady-state value
TiCN- 20Ni	**0.27**	0.39	**0.24**	0.38	**0.45**	0.37
TiCN- 20Ni-5NbC	**0.41**	0.30	**0.32**	0.33	**0.41**	0.35
TiCN- 20Ni-10NbC	**0.50**	0.34	**0.31**	0.35	**0.37**	0.37
TiCN- 20Ni-25 NbC	**0.52**	0.49	**0.42**	0.42	**0.40**	0.43

*Peak value in running-in-period

FIGURES

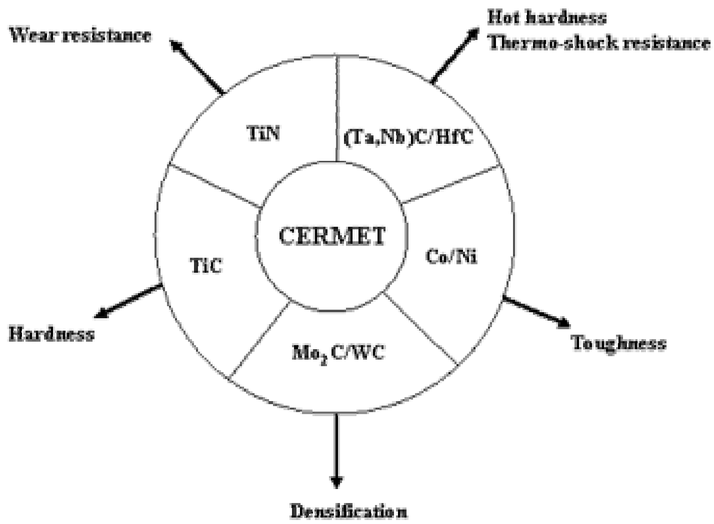

Fig.1. Schematic of cermet composition and properties.

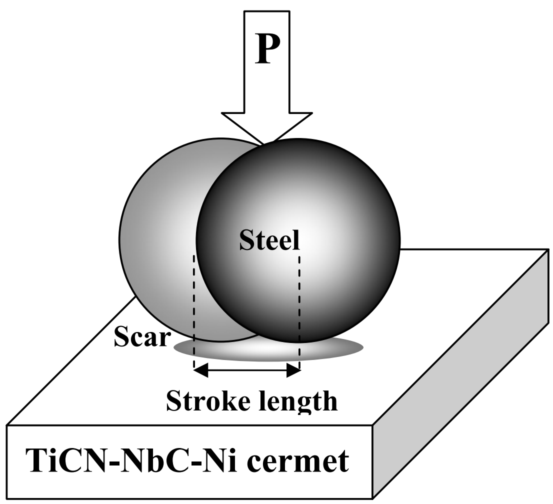

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Fig. 2. Schematic of the fretting test set-up. The testing conditions: Constants-Stroke length 100 µm, Oscillation frequency 8Hz and Cycles 100K. Variables- Normal load (2-10N) and NbC amount (5-25 wt. %).

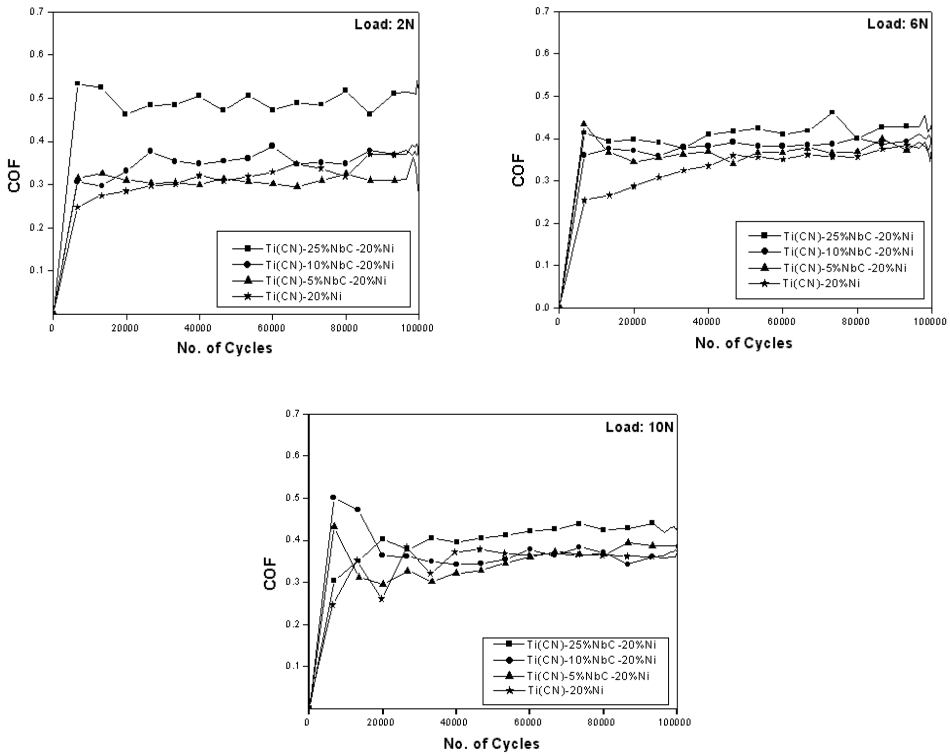

Fig. 3. The frictional behavior of TiCN-20Ni-xNbC cermets (x:0-25wt.%) at different loads during fretting against bearing steel. Fretting conditions: 100, 000 cycles, 4Hz frequency and 100 µm stroke length.

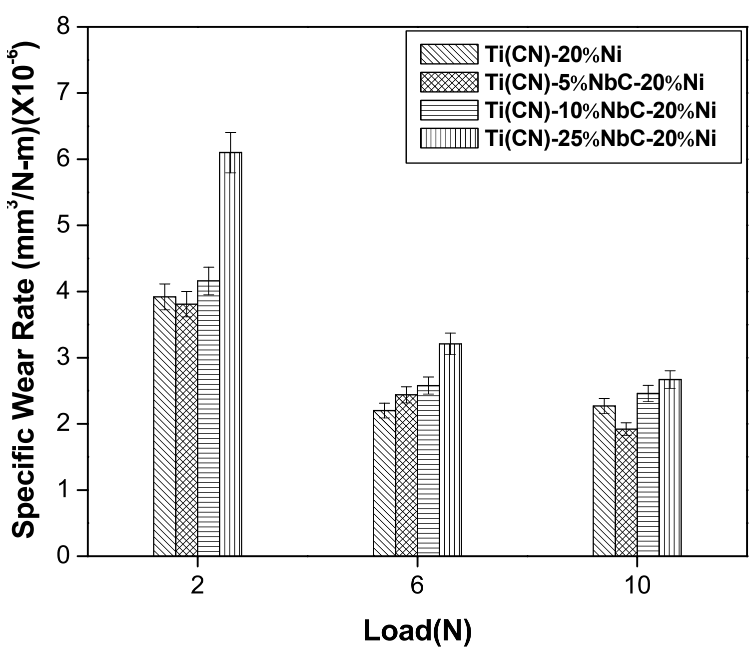

Fig. 4. Variation of specific wear rate for TiCN-20Ni-xNbC (x: 0-25 wt.%) against bearing steel under different loads. Fretting conditions: 100,000 cycles, 4Hz frequency and 100 µm stroke length

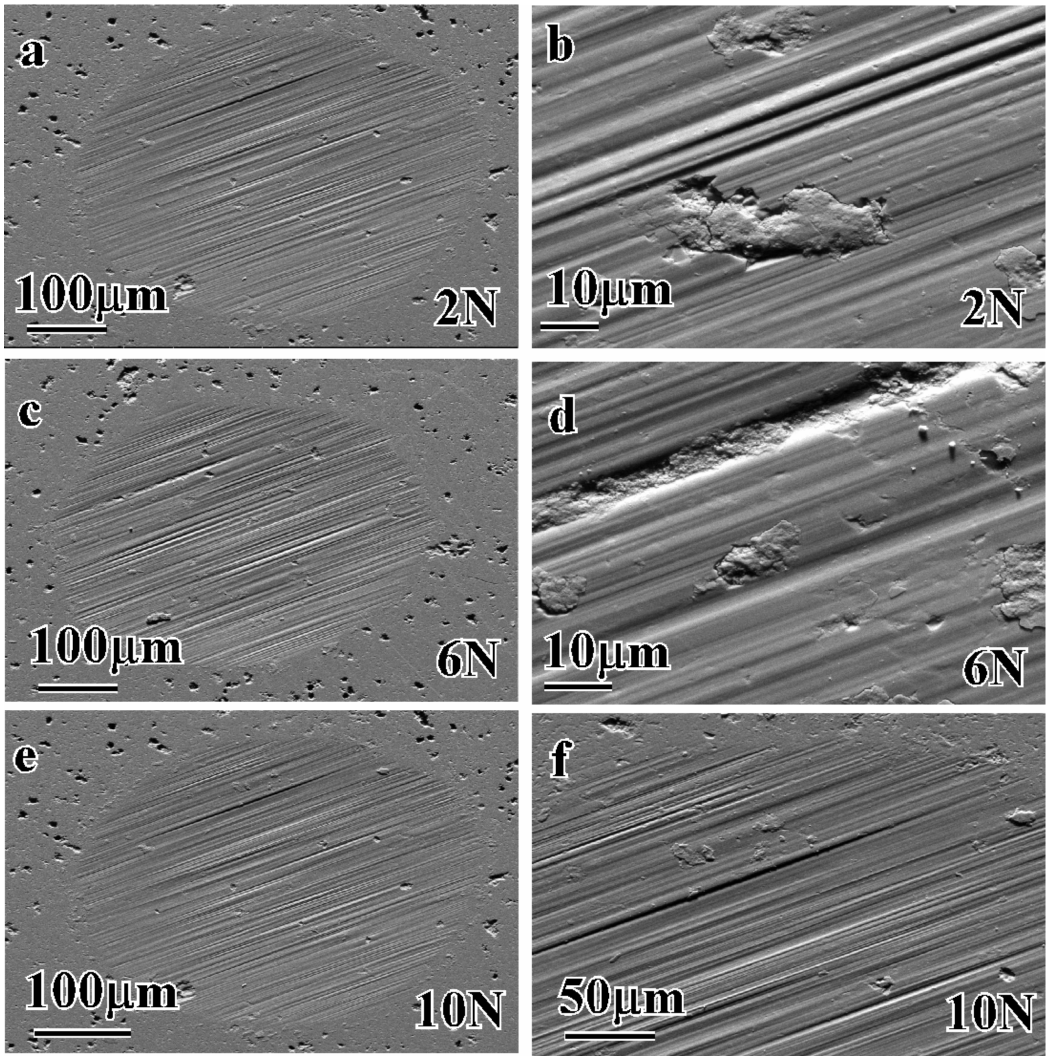

Fig. 5. Fretted surfaces of TiCN-20Ni cermet flats after 100,000 fretting cycles at various loads. Arrow marks indicate fretting direction. Fretting conditions: 4Hz frequency and 100µm stroke length. Counterbody: bearing steel.

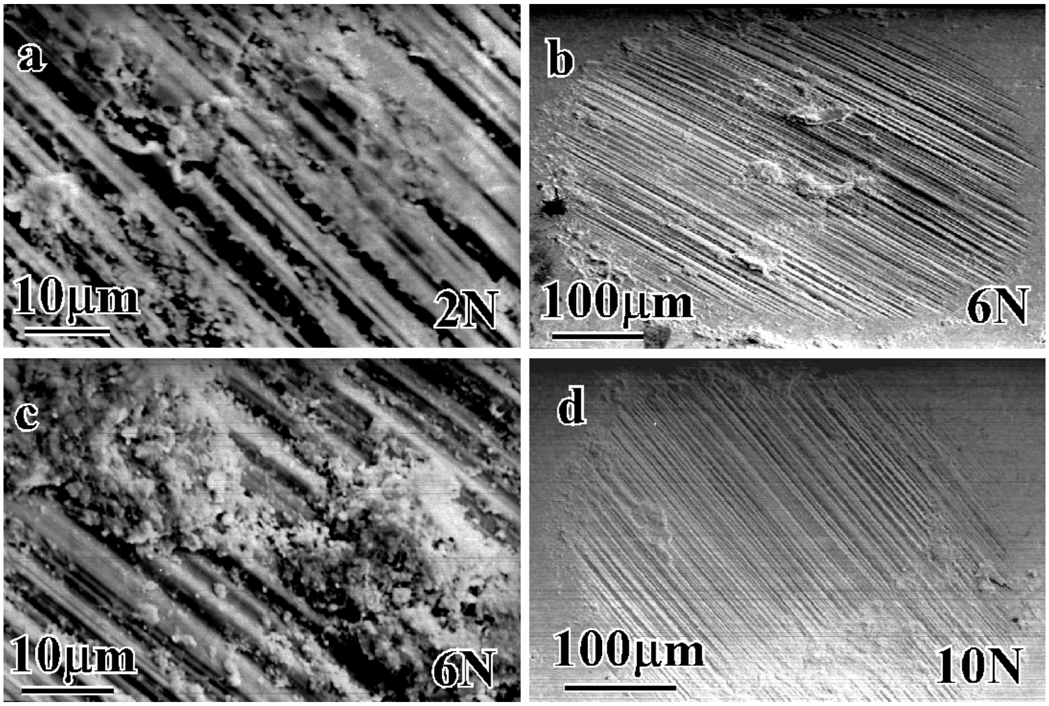

Fig. 6. Fretted surfaces of TiCN-20Ni-5NbC cermet flats after 100,000 fretting cycles at various loads. Fretting conditions: 4Hz frequency and 100μm stroke length. Counterbody: bearing steel.

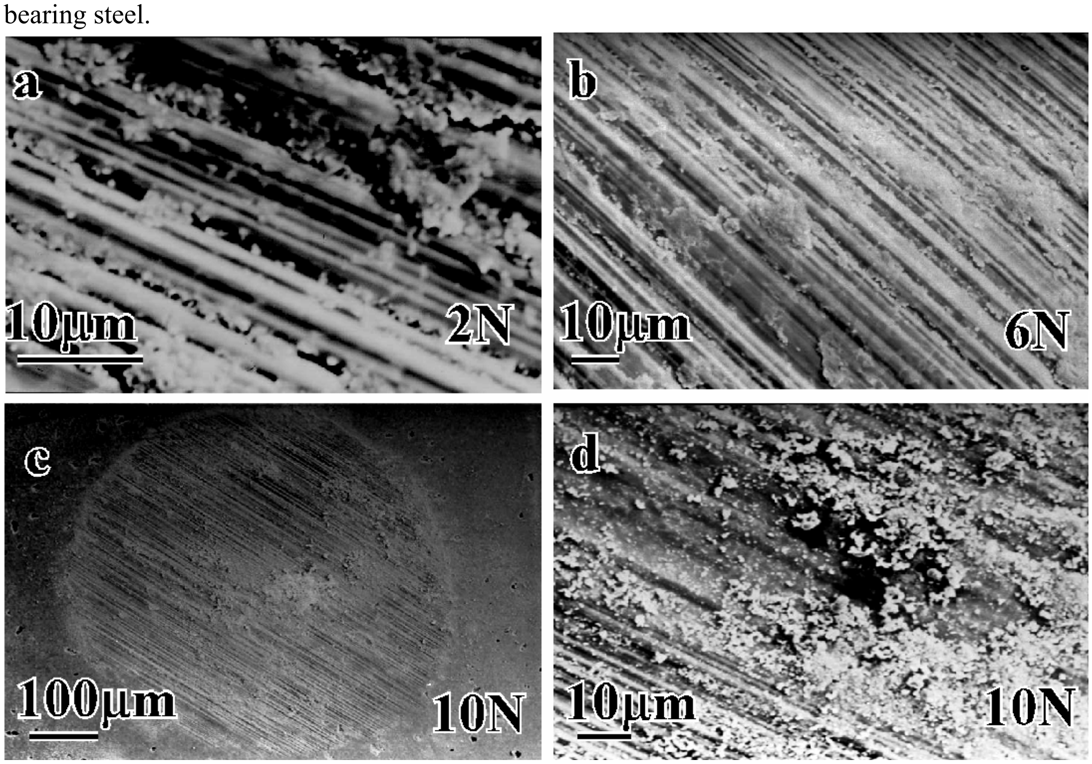

Fig. 7. Fretted surfaces of TiCN-20Ni-10NbC cermet flats after 100,000 fretting cycles at various loads. Fretting conditions: 4Hz frequency and 100μm stroke length. Counterbody: bearing steel.

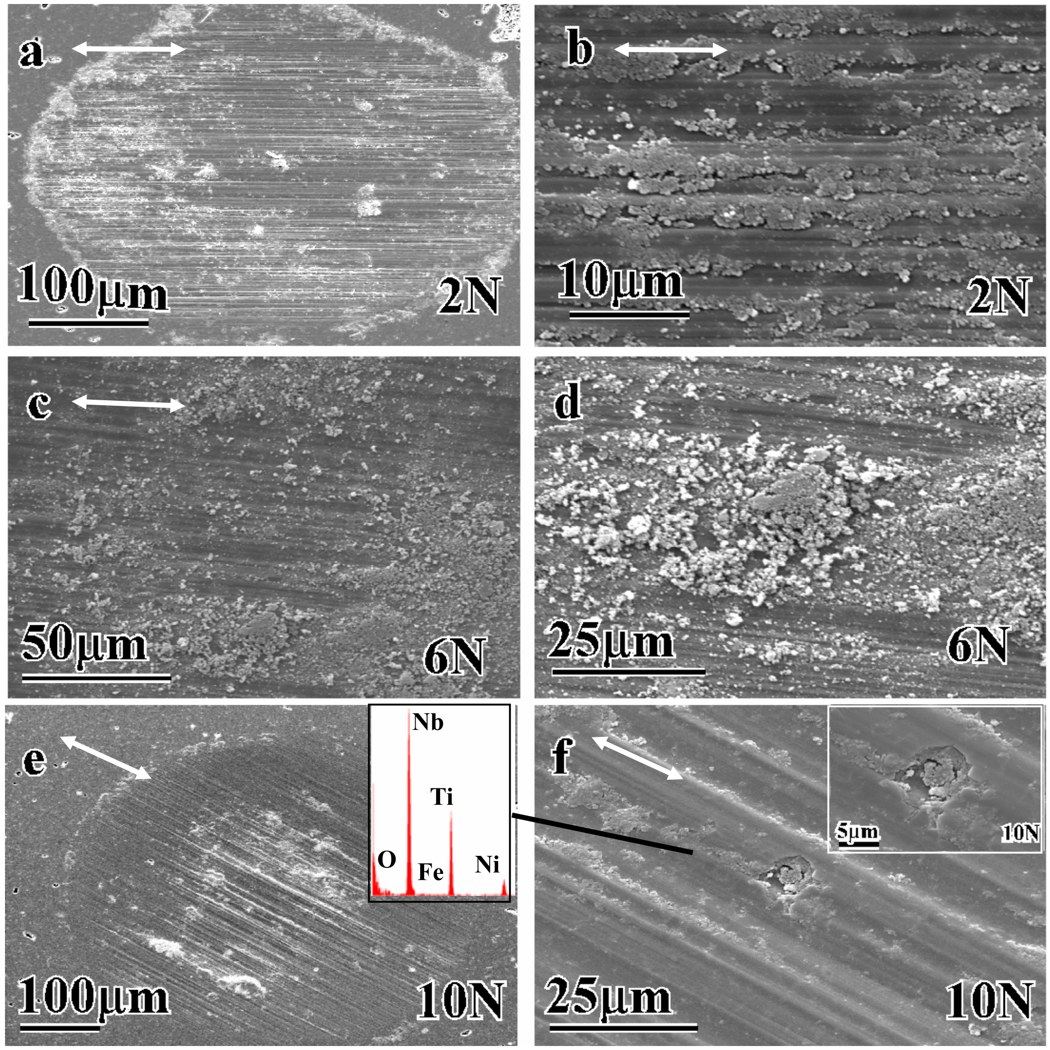

Fig. 8. Fretted surfaces of TiCN-20Ni-25NbC cermet flats after 100,000 fretting cycles at various loads. Arrow marks indicate fretting direction. Fretting conditions: 4Hz frequency and 100μm stroke length. Counterbody: bearing steel.