Journal of Iron and Steel Research, International 24 (2017) 823—829

ScienceDirect

Contents lists available at ScienceDirect

Journal of Iron and Steel Research, International

journal homepage: www.chinamet.cn

Tribological performance of uncoated and TiCN-coated D2, M2 and M4 steels under lubricated condition

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ARTICLE INFO

Key words:
D2 tool steel
M2 high speed steel
M4 high speed steel
TiCN coating
Friction
Wear

ABSTRACT

Hard coatings are used to improve the wear resistance of metals which largely depends on adhesion between substrate and coating. The wear and friction behavior of uncoated and TiCN-coated D2, M2 and M4 steels were evaluated by a pin-on-disk test under lubricated conditions. In order to evaluate the influence of lubricant on wear performance, dry friction tests were also performed. The results showed that friction coefficients were very similar for both uncoated and TiCN-coated steels. Under lubricated conditions, the uncoated D2 tool steel exhibited the lowest friction coefficient, but the TiCN-coated D2 steel presented the smallest wear rate. Abrasion was the main wear mechanism in all the tribocouples. Additionally, microhardness measurements were carried out, finding an influence of the steel substrate on the hardness of the coatings. Besides, adhesion test was conducted, suggesting a good adhesion of class 1 between substrates and TiCN coatings.

1. Introduction

The tool life is an important factor in manufacturing processes such as extrusion, forging and cutting. In this point, fine blanking process is an advanced and precise cutting method by which smooth surfaces with exact geometry can be obtained. Thipprakmas[1] described it as a process where the strength, hardness and wear deformation of tool components must be improved due to the severe plastic deformation. Recently, Cheon and Kim[2] mentioned that predicting the die and tool replacement time in the fine blanking process was very important in terms of product and cost efficiency; thus, in order to predict the tool life, tool wear must be constantly observed; in fact, they also described that most studies in this area were accomplished to understand the tool wear[2]. High speed steels have been used as tool materials due to their excellent mechanical properties combined with high wear resistance[3]. These properties are affected by their chemical composition, e. g., the hardness of medium carbon forging steels was increased by varying the vanadium content[4]. Nowadays, ceramic coatings are used to control friction and wear to enhance the service life of working tools and machine parts[5]; for example, titanium carbonitride (TiCN) coatings exhibit excellent mechanical properties such as low friction, high hardness, high toughness, and enhanced wear resistance[6]. Wei et al.[7] investigated the wear performance of D2 tool steel under dry friction and high-temperature conditions, observing that a suitable combination of hardness and toughness was necessary for a good wear resistance in high-temperature conditions. Some studies have been done in the field of wear behavior of TiCN coatings on different tool steels, such as the wear behavior of metal composites based on M3/2 high speed steel which was reinforced with two different percentages of TiCN (2.5 and 5.0 wt.%) and was manufactured following a conventional powder metallurgy which was investigated by Velasco et al.[8]. On the other hand, Bressan et al.[9] studied the M2 high speed steel (HSS) and tungsten carbide (WC) hard metal coated with TiAlN and TiCN by using the pin-on-disk standard test with different loads in order to compare the wear behavior of these Ti-based coatings, and found a better tribological performance on TiAlN coatings. M4 tool steel has been successfully used in tooling for the fine blanking process and in high-volume production of parts, due to its excellent mechanical properties and wear resistance, but

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Received 18 October 2016; Received in revised form 19 January 2017; Accepted 22 January 2017
Available online 15 August 2017
1006-706X/

its low availability and high cost are inconvenient to be taken into account when manufacturing a tooling; however, there are other steels with similar properties, such as M2 and D2 tool steels, which could be used as substitutes for the manufacture of fine blanking tooling, although the M2 and M4 steels have better wear resistance owing to their increased matrix and carbide phase hardness[3]. From the literatures, investigations related to friction and wear behavior of uncoated and TiCN-coated D2, M2 and M4 tool steels under lubrication conditions are very scarce. At this point, it is necessary to determine the tribological performance of these steels.

This work aims to determine the viability of D2 steel as tool material applied in the fine blanking process, providing a preliminary study to decrease the cost of tooling. Among D2, M2 and M4 tool steels, the D2 steel has better availability than the other metal substrates considered in this work. Besides, the present work allows a comparative study of the tribological performance of D2, M2 and M4 tool steels with and without TiCN coating in order to propose different configurations of substrate-coating that can be used in tooling design according to the volume production of tool parts in the fine blanking process. For that purpose, the tribological performance was experimentally investigated using the pin-on-disk method under lubricated conditions, considering that this method allows to simulate true in-service conditions[10]. The friction coefficient was obtained, and volume loss and wear rates were calculated. The wear mechanisms were determined after observation of worn surfaces. Additionally, dry friction tests were performed in order to propose D2, M2 and M4 uncoated tool steels in the fine blanking process. The influence of oil lubricant in friction tests was also discussed.

2. Materials and Methods

Specimens of D2, M2 and M4 commercial tool steels with 25 mm in diameter and 5 mm in thickness were coated with TiCN by physical vapor deposition (PVD) technique. The chemical composition and hardness of the tool steels are listed in Table 1.

Table 1
Chemical composition (wt. %) and hardness (HRC) of D2, M2 and M4 tool steels

Steel	C	Cr	V	W	Mo	Fe	Hardness
D2	1.5	12.0	1.0	—	1.0	Balance	60
M2	0.85—1.00	4.0	2.0	6.0	5.0	Balance	65
M4	1.3	4.0	4.0	5.5	4.5	Balance	61

Cross sections of D2, M2 and M4 steels were prepared and etched with nital (5 mL HNO_3 and 100 mL ethanol), and the microstructure before the deposition was analyzed by optical microscopy (OM), using a Carl Zeiss microscope Axion Image. Fig. 1 reveals the microstructure for each metal substrate; a microstructure with elongated primary carbides and a good distribution of secondary carbides can be observed in D2 steel while the microstructure of M2 steel exhibits a segregation of carbides. It is important to mention that these two metal substrates were obtained by melting process while M4 steel was prepared by powder metallurgy, which gives a different metal microstructure, as shown in Fig. 1 (c), where a major concentration of carbides with uniform distribution can be seen. The thickness and microhardness of the TiCN coatings provided by the supplier were 5 μm and 30 GPa ($HV_{0.05}$), respectively; however, the thickness of film and element concentration of TiCN coating were verified by using a scanning electron microscope (SEM, JEOL JSM-6510LV) equipped with energy dispersive spectrometer (EDS, X-Max^N Oxford Instruments) for each TiCN-coated steel substrate. The image analysis confirmed a coating thickness of 5 μm; whereas the EDS analysis for each system showed the same element concentration independent of the steel substrate. Fig. 2 exhibits SEM observation of TiCN coating on D2 and M2 steels; as representative for this study, the superior images show the microstructures features for TiCN, which looks similar between the two metal substrates. Flatted surfaces with some pores can be observed, while the EDS results prove that there is no variation in Ti content in each system; besides, the C and N exhibit similar concentrations suggesting a homogeneous TiCN phase for each steel substrate. Vickers indentations were measured by

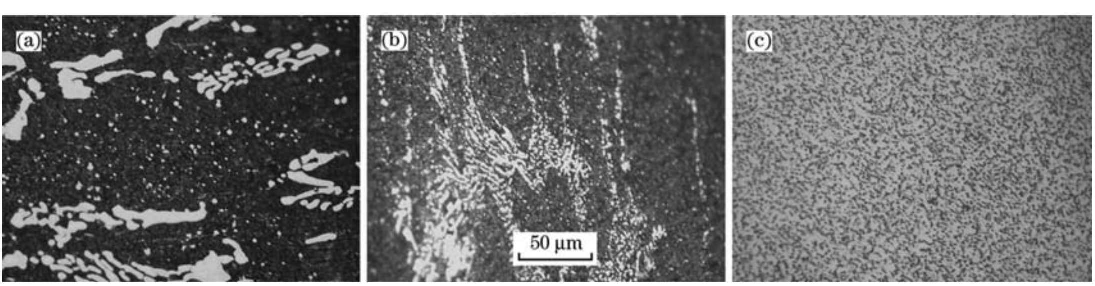

Fig. 1. OM micrographs of D2 (a), M2 (b) and M4 (c) steels.

using a microhardness tester (SMVK-1000ZS Model) with a load range from 0.49 to 9.80 N during 15 s; five measurements were taken at each load obtaining two diagonals for each test, and the lengths of these diagonals were determined by optical microscopy by using a Carl Zeiss microscope. Then, the microhardness value HV was calculated from the average diagonal length D and the load P of the indentations, according to:

$$HV=(1.8544)P/D^2 \quad (1)$$

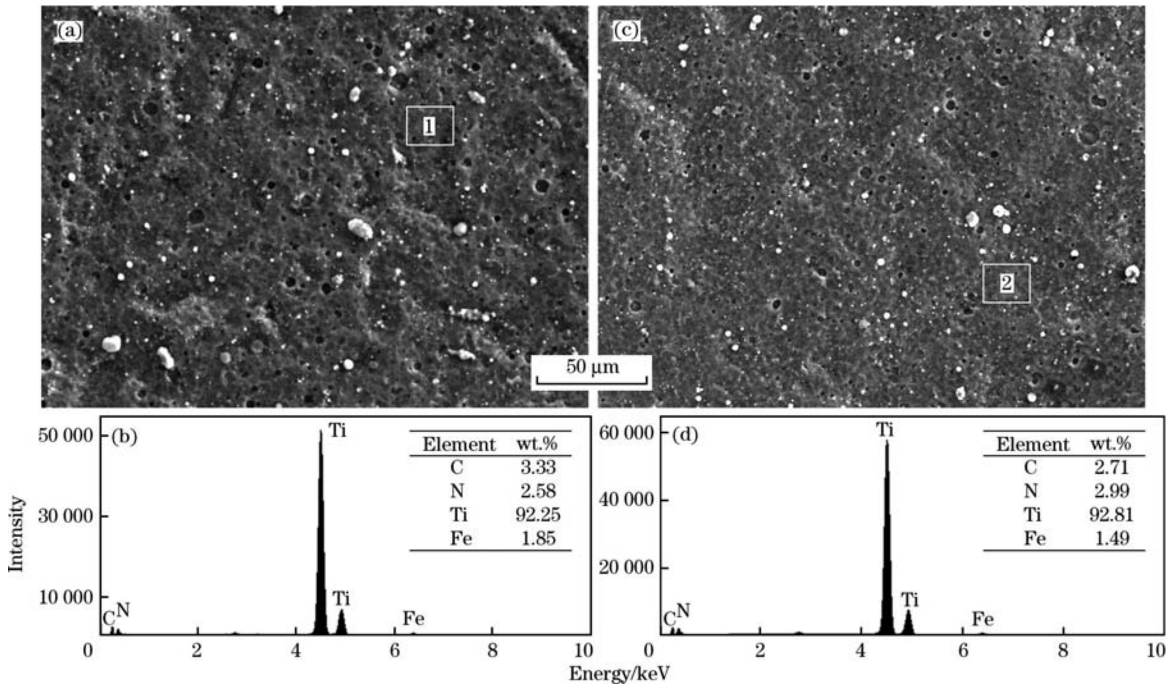

Fig. 2. SEM micrographs of TiCN on D2 (a) and M2 (c) steels, and their EDS analysis (b, d) respectively corresponding to the square area.

Rockwell indentation standard test CEN/TS 1071-8 was performed to assess the adhesion quality of TiCN coating on D2, M2 and M4 tool steels substrates using a load of 1470 N. Whereas, wear tests were carried out by a pin-on-disk method under lubricated conditions on a CSM instruments tribometer by employing 20 mL of Holifa cutting and forming oil at 50 ℃ which corresponds to the temperature of the fine blanking process measured in situ. WC ball, with diameter of 6 mm, microhardness of 1370 HV and elastic modulus of 670 GPa, was slid on the uncoated and TiCN-coated D2, M2 and M4 tool steels. The sliding distance, sliding speed and wear track radius were settled at 1000 m, 0.05 m · s^{-1} and 2 mm, respectively. The normal load used was 10 N corresponding to a maximum contact pressure between D2 tool steel specimen and tungsten carbide ball before yielding of D2 substrate. Kinetic friction coefficients values (μ_k) were obtained directly of Tribox 4.1 software. Volume loss (V) was calculated by a standard test method as indicated in ASTM G99-05, assuming that there is no significant pin wear:

$$V=2\pi R[r^2\sin^{-1}(d/2r)-(d/4)(4r^2-d^2)^{1/2}] \quad (2)$$

where, R represents the wear track radius; r is the pin end radius; and d is the wear track width, which was measured by image analysis using a Zeiss Axio Imager A1 microscope which was also used to investigate the wear mechanisms. The wear rate (k) was calculated from the relationship[11] in which the volume loss of the material is proportional to the applied normal load (F) and total sliding distance (S):

$$k=V/FS \quad (3)$$

3. Results and Discussion

3.1. Microhardness indentation

The applied loads selected on the indentation testing were less than 10 N because some researchers have reported that micro-cracking on TiCN coatings can be present for higher loads than this one[12]. Fig. 3 represents the hardness as a function of the applied load. This figure exhibits similar values of TiCN hardness provided by the supplier at 0.49 N; besides, a considerable decrease in the hardness from 0.49 to 1.96 N can be observed, while in the range from 1.96 to 9.81 N, the hardness presents a gradual decrease as the applied load increases. This behavior is due to the hardness values obtained and represents a composite hardness, i. e., the hardness of the coating is influenced by the hardness of the substrate. According to Lesage et al.[13], one way of

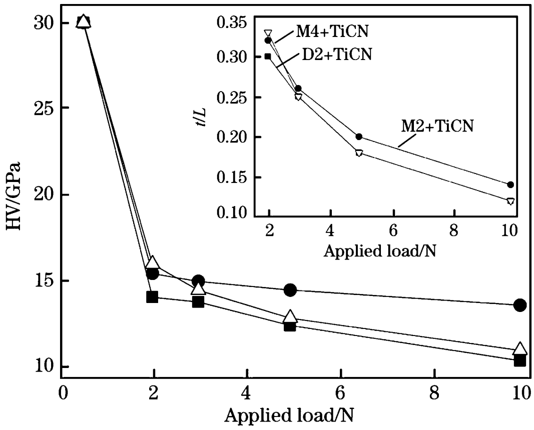

Fig. 3. Microhardness as a function of applied load for three TiCN-coated steel substrates.

observing the contribution of the substrate hardness in a composite hardness is through the ratio t/L, where t is the thickness of the coating and L is the length of the diagonal of the imprint, and then this ratio can range from 0 to 1. In that sense, the inset in Fig. 3 plots the ratio t/L *vs*. the applied load for the three TiCN-coated steel substrates.

It can notice a decreasing of this ratio for higher loads, tending to zero, which means that the hardness obtained should tend to the hardness of the substrate.

3.2. Adhesion

Fig. 4 illustrates the characteristic imprints of Rockwell indentation test on TiCN-coated tool steels. There is no visible delamination around the imprint, even where substrate piles up. The results show an adhesion class 1 according to standard test CEN/TS 1071-8. Vidakis et al.[14] considered that the type and volume of the coating failure zone by indentation test exhibit firstly in the film adhesion and secondly in the coating brittleness. Besides, they established that well adherent coatings can withstand shear stresses at the substrate-coating interface when the load is applied because of strong interfacial forces. Thus, the adhesion of the coating to the substrate is exhibited by the type of the coating failure zone. Although the imprint in TiCN-coated D2 steel is slightly larger than that in the other ones due to its lower hardness, no visible difference of adhesion behavior was found among the three TiCN-coated tool steels. According to Ref. [14], adhesion class for the coatings of this study represents strong interfacial bonds between the coating and the substrates. Sergejev et al.[15] investigated TiCN coating by physical vapor deposition on the punches produced from the Böhler S390 Microclean steel. In that study, two different surface preparation techniques, i. e. wet polishing (high surface roughness) and dry polishing (low surface roughness), were used. Rockwell adhesion test CEN/TS 1071-8 was used to study the adhesion between punch substrate and coating, and showed an adhesion class 2. This difference in class adhesion of TiCN coatings could be related to the substrates used and coating thicknesses.

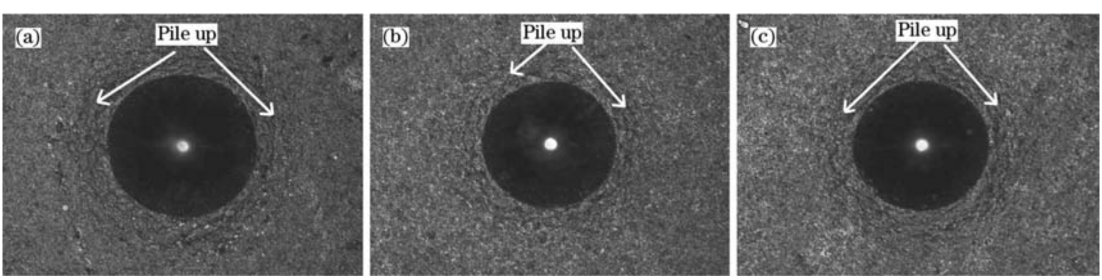

Fig. 4. Imprints of Rockwell indentation test for evaluation of adhesion between TiCN coating and D2 (a), M2 (b) and M4 (c) tool steel substrates.

3.3. Tribological behavior

The evolution of μ_k as a function of the sliding distance under oil lubricated conditions at 50 ℃ is shown in Fig. 5 for uncoated and TiCN-coated D2, M2 and M4 tool steels. Friction coefficients of M2 and M4 steels decrease during the entire test reaching mean values of 0.15 and 0.14, respectively. Moreover, the friction coefficient of D2 steel decreased during the first 150 m and then fluctuated at the next 100 m to reach a stable friction coefficient of about 0.1. Although D2 tool steel presents the lo-

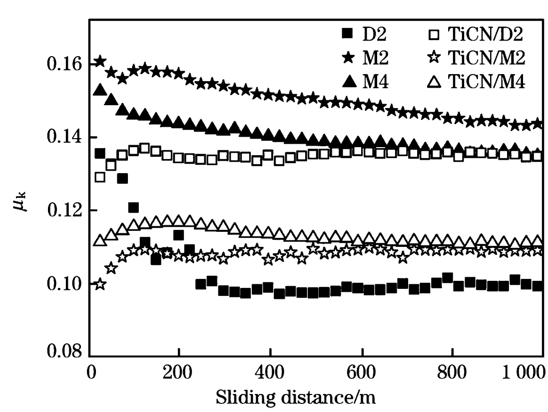

Fig. 5 Friction coefficients of uncoated and TiCN-coated D2, M2 and M4 steels under lubricated condition at 50 ℃.

west friction coefficient among the three steels, it can be seen from Table 2 that M4 steel exhibits the smallest wear rate.

It is important to remember, in agreement with Eq. (3), that the wear rate depends on the applied load, the sliding distance and the volume loss; among these three parameters, only one of them is changed each time, which was determined in accordance with the ASTM G99 standard for measuring the wear track width; therefore, an increase in the wear rate is given by an increased wear track width; for the case of D2 steel, the wear rate increased could be related to a higher plastic deformation during the sliding contact due to the lower hardness of D2 steel compared with the hardness of M4 steel; nevertheless, the highest values of friction coefficient and wear rate can be observed in the M2 steel, and this behavior could be related to the fact that the M2 steel exhibits the highest hardness, then the tribosystem is carried out under severe abrasion condition at the first stage, leading to a higher debris producing high friction and wear rate values. Moreover, the TiCN-coated samples show a similar behavior during the test, reaching the steady-state stage after about 250 m, with mean friction coefficient values of 0.13, 0.10 and 0.11 for D2, M2 and M4 steels, respectively. Zhu et al.[16] evaluated the tribological properties of uncoated and TiCN-coated M2 tool steel by using an AISI 1019 steel as a counterpart, where the friction tests under lubricated conditions were performed by using a cross-cylinder wear test obtaining friction coefficients of 0.18 and 0.10 for M2/1019 and TiCN/1019 tribocouples, respectively. Both values are very similar to those obtained in this study. Besides, friction behavior of TiCN coatings deposited on WC cemented carbides was investigated by Wang et al.[17] on ball-on-disk tribometer using deionized water as a lubricant at room temperature. The normal load varied in the range of 3 to 12 N and the sliding speed varied in the range of 0.1 to 0.4 m/s. The total sliding distance was 1000 m where SiC balls were used as a counterpart. Specifically, when the TiCN coatings slid against SiC balls in water with a normal load of 9 N and sliding speed of 0.1 m/s, values of friction coefficient obtained ranged from 0.25 to 0.26. The differences between values obtained by Ref. [17] and the present study may be due to the counterpart and the type of lubricant used in friction tests. Additionally, dry friction tests were performed on uncoated D2, M2 and M4 steels, and friction coefficient values of 0.52, 0.49 and 0.48 for D2, M2 and M4 were obtained, respectively, making clear the influence of lubricating film on the friction behavior, as shown in Table 2. Meanwhile, Wang et al.[17] also found better tribological properties of TiCN coatings under lubricated condition. From Table 2 it can be seen that under lubricated conditions for TiCN-coated steels, M2 steel exhibits the lowest friction coefficient but D2 steel presents the smallest wear rate. Fig. 6 shows the optical micrographs of worn surfaces for both uncoated and TiCN-coated tool steels under lubricated condition. Compared to uncoated steels, widths of wear tracks are less wide, and then wear rates are lower on TiCN-coated tool steels indicating an improvement of wear resistance, which is related to higher hardness of TiCN coating; for this study, the intensity and duration of normal force, sliding speed, relative humidity and lubricity were constant; therefore, the wear mechanisms were observed to depend on the nature of materials (substrates) and their mechanical characteristics of surfaces. Fig. 6 also exhibits abrasive wear that can be observed as grooves or plowing marks parallel to the direction of sliding which are more visible on the uncoated steels where the surface of the wear track is similar for the three steels. In order to deepen on the wear mechanism, SEM investigation was carried out for each substrate. For M2 and M4 metal substrates, it cannot observe different wear mechanism from that observed in the optical images, and only slight marks of smashed material can be identified; however, this mechanism was more evident for D2 metal substrate, which could be related to the fact that the D2 steel has the lowest

Table 2

Average values of friction coefficient, volume loss and wear rate for uncoated and TiCN-coated D2, M2 and M4 tool steels

Sample	Condition	μ_k	Volume loss/m^3	Wear rate/(10^{-6} $mm^3 \cdot N^{-1} \cdot m^{-1}$)
D2	Dry	0.52±0.122	0.0913±0.0103	9.127±1.028
M2	Dry	0.49±0.170	0.0740±0.0226	7.403±2.264
M4	Dry	0.48±0.222	0.0659±0.0254	6.593±2.536
D2	Oil at 50 ℃	0.103±0.010	0.0114±0.0015	1.136±0.151
M2	Oil at 50 ℃	0.150±0.007	0.0138±0.0006	1.378±0.058
M4	Oil at 50 ℃	0.140±0.007	0.0085±0.0006	0.853±0.062
D2+TiCN	Oil at 50 ℃	0.134±0.004	0.0018±0.0004	0.177±0.038
M2+TiCN	Oil at 50 ℃	0.108±0.004	0.0028±0.0004	0.281±0.041
M4+TiCN	Oil at 50 ℃	0.112±0.003	0.0034±0.0005	0.343±0.054

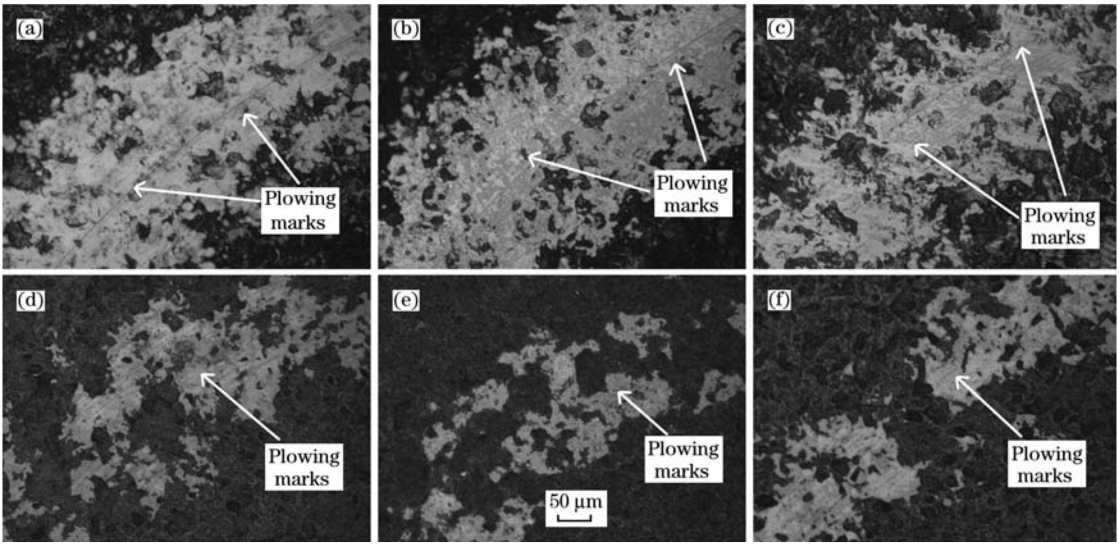

Fig. 6. Optical micrographs of worn surfaces for uncoated D2 (a), M2 (b), M4 (c) and TiCN-coated D2 (d), M2 (e), M4 (f) tool steels.

hardness, allowing more wear; SEM images of D2 system are presented as representatives of SEM investigation in Fig. 7, which shows the SEM micrographs of wear tracks for both uncoated and TiCN-coated D2 tool steels together with the EDS analysis inside and outside the worn track. It is observed that according to the morphology of the surface, in both uncoated and coated cases, most of the surfaces was first crushed by the continuous contact of the pin and then some wear debris particles that were trapped between the pairs in contact with the characteristic marks of the abrasion mechanism (plowing

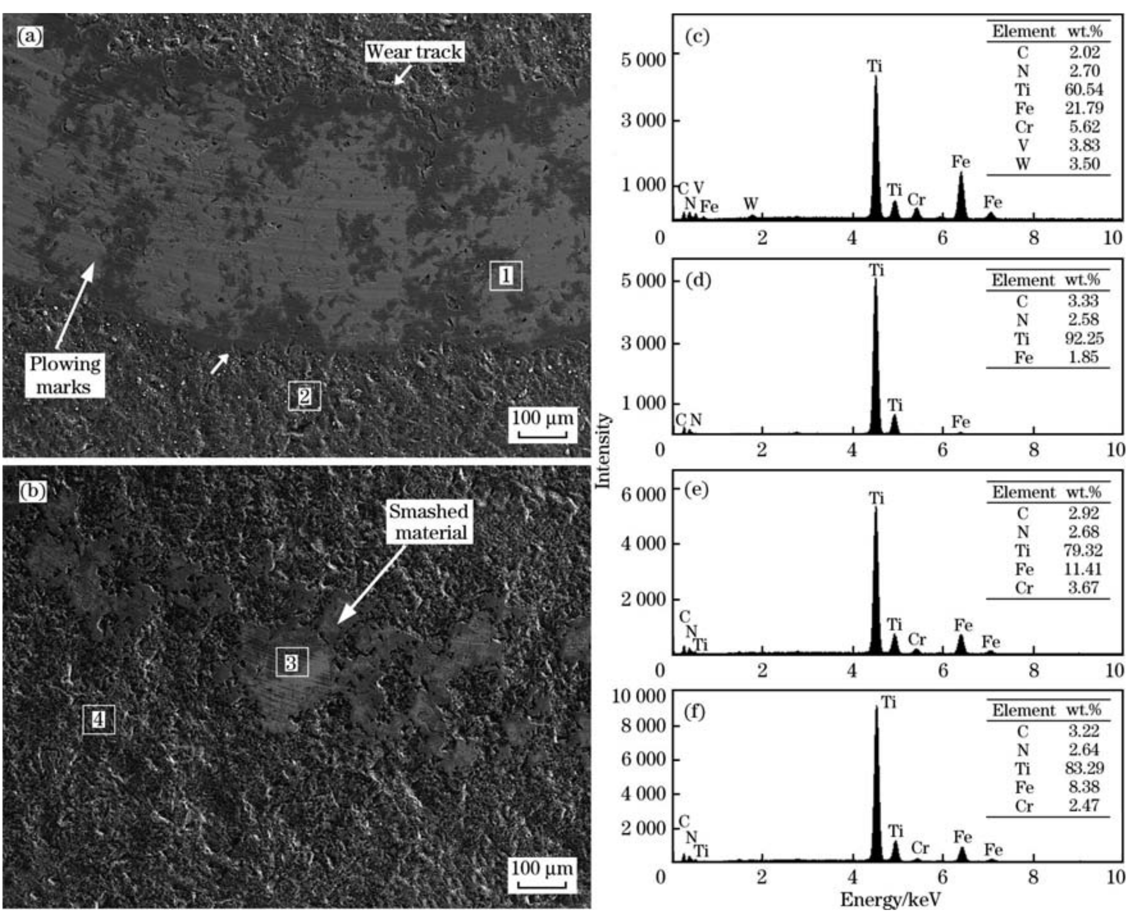

Fig. 7. SEM micrographs of worn surfaces for uncoated (a) and TiCN-coated (b) D2 tool steel and EDS analysis (c－f).

marks), which confirms the above mentioned in the optical micrographs. Whereas, the EDS analysis makes evident the minimal wear for the case of TiCN-coated D2 steel which exhibits lower Ti concentration compared to the initial Ti element concentration (Fig. 2), and it can also be observed the presence of Fe element, while the EDS for uncoated D2 substrate shows the elemental concentration characteristics of the D2 steel. Finally, no-homogeneous wear into the wear track observed on both uncoated and TiCN-coated steels may be due to surface irregularities of the samples which could be related to its surface roughness.

4. Conclusions

(1) A contribution of the metal substrate in coating hardness is observed in each of the three cases. This behavior is more evident in the range from 1.96 to 9.81 N where the hardness reported is a composite hardness.

(2) The influence of the lubricant on the friction behavior can be clearly seen since the friction coefficients of uncoated steels decrease considerably by about 3 to 4 times. Besides, under lubricated conditions, the uncoated and TiCN-coated steels have similar values; however, the TiCN-coated ones have lower wear rates, one order of magnitude approximately, due to their higher hardness. All the tribocouples presented abrasion as the main wear mechanism.

(3) After reviewing all the test data under lubricated conditions, it can be set as the main conclusion that the uncoated steels could be suitable for another engineering application where only the friction behavior is considered.

(4) Since the wear of the tooling has an influence on the volume production of parts, it is clear that uncoated and TiCN-coated tool steels, with different wear factors, cannot be used to manufacture the same number of parts. For low-volume production of parts, an uncoated steel could be used.

Acknowledgment

The authors would like to acknowledge the financial support of Tecnológico Nacional de México (TNM) (Grant No. 5724.16P).

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