TriboBR
First International Brazilian Conference on Tribology – TriboBr-2010 and
ITS - IFToMM 2010 - 2nd International Tribology Symposium of IFToMM
24th to 26th november, 2010
Copacabana, Rio de Janeiro/RJ, Brazil
ISSN 2179-3956

ABRASIVE WEAR OF Nb-ALLOYED HIGH SPEED STEELS[1]

Paula Fernanda da Silva Farina[2]
Mário Boccalini Junior[3]

Abstract

The effects of volume fraction and morphology of niobium carbides in Nb-alloyed high speed steels were studied in front of abrasion. After heat treatment of quench and temper, to obtain the maximum hardness, the alloys were submitted to abrasive tests in a dry rubber wheel machine with hematite as abrasive. It was used the load of 130N, 200 rpm and total test time of 30min. The alloys were characterized in optical microscopy and SEM to determine the wear mechanisms and damages to the surface. The alloys with polygonal divorced eutectic carbides showed better abrasion wear resistance than the alloys containing chinese script-like eutectic carbides. The presence of NbC carbides is decisive for improving the abrasive wear resistance of the Nb-HSS alloys, and there is a carbide size and morphology for which the Nb-HSS alloys have a higher wear resistance.

Keywords: Abrasive wear; High speed steel; NbC carbide.

DESGASTE ABRASIVO DE AÇOS RÁPIDOS LIGADOS COM NIÓBIO

Resumo

Foram estudados o efeito da fração volumétrica e da morfologia dos carbonetos NbC em um aço rápido contendo nióbio (Nb-HSS) frente à abrasão. Após tratamento térmico de têmpera e revenimento para obtenção da máxima dureza, as ligas foram submetidas a ensaio de abrasão em abrasômetro do tipo roda de borracha utilizando hematita como abrasivo. Utilizou-se carga de 130N, 200 rpm e tempo total de ensaio de 30min. As ligas foram caracterizadas por meio de microscopia ótica e eletrônica de varredura para determinação dos mecanismos de desgaste e danos à superfície. As ligas com carbonetos eutéticos divorciados com morfologia poligonal apresentaram maior resistência ao desgaste abrasivo que os aços contendo carbonetos eutéticos cooperativos. A presença de carbonetos NbC é decisiva para o aumento na resistência ao desgastes dos Nb-HSS, e há um tamanho e morfologia para os quais estas ligas apresentam resistência ao desgaste mais alta.

Palavras-chave: Desgaste abrasivo; Aço rápido; NbC.

---

[1] *Technical contribution to the First International Brazilian Conference on Tribology – TriboBr-2010, November, 24th-26th, 2010, Rio de Janeiro, RJ, Brazil.*

[2] *MSc. Metallurgical Engineer. PhD Student in Metallurgical Engineer at Escola Politécnica da Universidade de São Paulo – Brazil.*

[3] *Dr. Metallurgical Engineer. Senior Researcher at Laboratory of Metallurgy and Ceramic Materials - Institute for Technological Research - São Paulo – Brazil.*

1 INTRODUCTION

High speed steels compose a family of alloys mainly used for cutting tools. The name *high speed steel* is a synthesis of two features: i) the alloys belong to the Fe-C-X multi-component system, where X represents a group of alloying elements in which Cr, W or Mo, V and Co are the principal ones; ii) the alloys are characterized by their capacity to retain a high level of hardness even when submitted to elevated temperatures resulting from cutting metals at high speed.(1,2)

In the seventies of the 20th century, a wave of cost savings based on the use of niobium as an alloying element was attempted.(3-5) The main research line was based in the idea of partially substituting niobium, a cheap and strong primary carbide forming element, for vanadium in the grades of the W-Mo and Mo high speed steel series, thus allowing the vanadium to be utilized at a lower level, predominantly for secondary precipitation hardening.

Cast alloys of the Fe-C-X system have been used in the outer shell of the work rolls for the finishing stands of hot rolling mills.(6,7) The idea of using these alloys for the manufacture of these work rolls resulted from an insight into the requirements involved in this type of application: fundamentally, the capacity to retain a high level of hardness even when submitted to high temperatures and wear resistance, both fulfilled by the classical high speed steels. The alloy design of these alloys is based on the composition of the classical M2 high speed steel, the main changes commonly being the higher carbon and vanadium contents.(8)

Investigations concerning the effect niobium additions on these cast alloys have been currently performed.(9,10) The objective of the present work is to investigate the abrasive resistance of Nb-alloyed high speed steel with lean composition, considering different Nb contents and different morphologies of the NbC carbides.

2 MATERIALS AND PROCEDURES

Five alloys were studied: four Nb-alloyed high speed steels (HSS-Nb) and one “matrix steel” alloy, which plays the role of the “alloy with no eutectic carbides”. The nominal composition of the Nb0 alloy- 0.5%C; 4%Cr; 3%Mo; 2%W; 1%V- was used as base composition and 2.5%Nb and 5%Nb, along with stoichiometric carbon for NbC formation, were added to obtain the final composition of the HSS-Nb alloys. In addition, titanium was used as NbC modifier in two of them. Specimens were conventionally cast into prismatic moulds and the chemical compositions of the cast specimens are shown in Table 1.

Table 1 – Chemical composition of the HSS-Nb alloys

Alloy	Chemical composition (wt.%)						
	C	Cr	Mo	W	V	Nb	Ti
Nb0	0.51	4.18	3.27	1.91	0.97	-	-
Nb2.5	0.81	3.94	3.32	2.33	0.92	2.52	-
Nb2.5Ti	0.81	3.94	3.09	2.23	0.91	2.81	0.11
Nb5	1.05	3.81	3.33	2.83	0.92	5.73	-
Nb5Ti	1.07	3.80	3.07	2.56	0.92	5.73	0.09

The cast specimens were annealed (700ºC- 5h- furnace cooling) and test pieces for metallography and abrasive wear test were prepared. All the test pieces were heat treated through quenching (austenitization at 1100ºC- 2h- still air cooling) and double tempering (500ºC- 2h- still air cooling). For all the alloys, resultant bulk hardness ranged from 680 to 740 HV_2, while matrix micro-hardness ranged from 630 to 700 $HV_{0.1}$.

Conventional metallographic techniques, detailed described elsewhere,(10) were used to prepare the samples for microstructure characterization through optical microscopy, quantitative image analyses (volume fraction and perimeter of the eutectic carbides; 30 fields in each sample) and SEM.

Dry rubber wheel abrasion wear testing was carried out with the following parameters: 130N normal load, 200 rpm rotation, 30 minutes testing time and angular hematite as abrasive. Hematite particles were screened to obtain 90% between 105µm and 210µm and the same distribution was observed after the tests, i.e. the abrasive was not cracked during the test. Micro-hardness of the hematite particles was measured: 863 ± 67 $HV_{0.1}$.

The specimen was weighed before the test and after each 10 minutes testing in order to calculate the mass loss. Three samples of each alloy were tested. Mean mass loss thus obtained was used to calculate the wear coefficient (k) through equation 1, where F is the normal load, d is the total sliding distance and ρ is the alloy density (7.68 g/cm^3).

$$k = m.F^{-1}.d^{-1}.\ \rho^{-1} \qquad \text{Equation 1}$$

The worn surface of the test pieces were analyzed through SEM.

3 RESULTS AND DISCUSSION

3.1 Microstructure Characterization

Figure 1 shows the distribution and morphological details of the eutectic carbides in the microstructure of the HSS-Nb alloys.

All the alloys presented small amount of M_2C and V-rich MC eutectic carbides in the interdendritic areas, due to the segregation during solidification (1.6 vol.% in the case of Nb0 alloy). Nb2.5 alloy presented chinese script-like eutectic NbC carbides in the form of eutectic cells, while Nb2.5Ti alloy presented polygonal divorced NbC carbides (Ti addition promoted the precipitation of Ti(C,N) that plays the role of substrate for intense NbC nucleation, thus hindering its coupled growth with austenite). Coarse dendritic primary NbC and chinese script-like eutectic NbC were observed in the Nb5 alloy, since it is a hypereutectic one. In this case, Ti addition modified both primary and eutectic NbC and Nb5Ti alloy presented only divorced NbC with polygonal morphology. The matrix of the alloys consisted of tempered martensite with secondary carbides around 1µm diameter precipitated throughout.

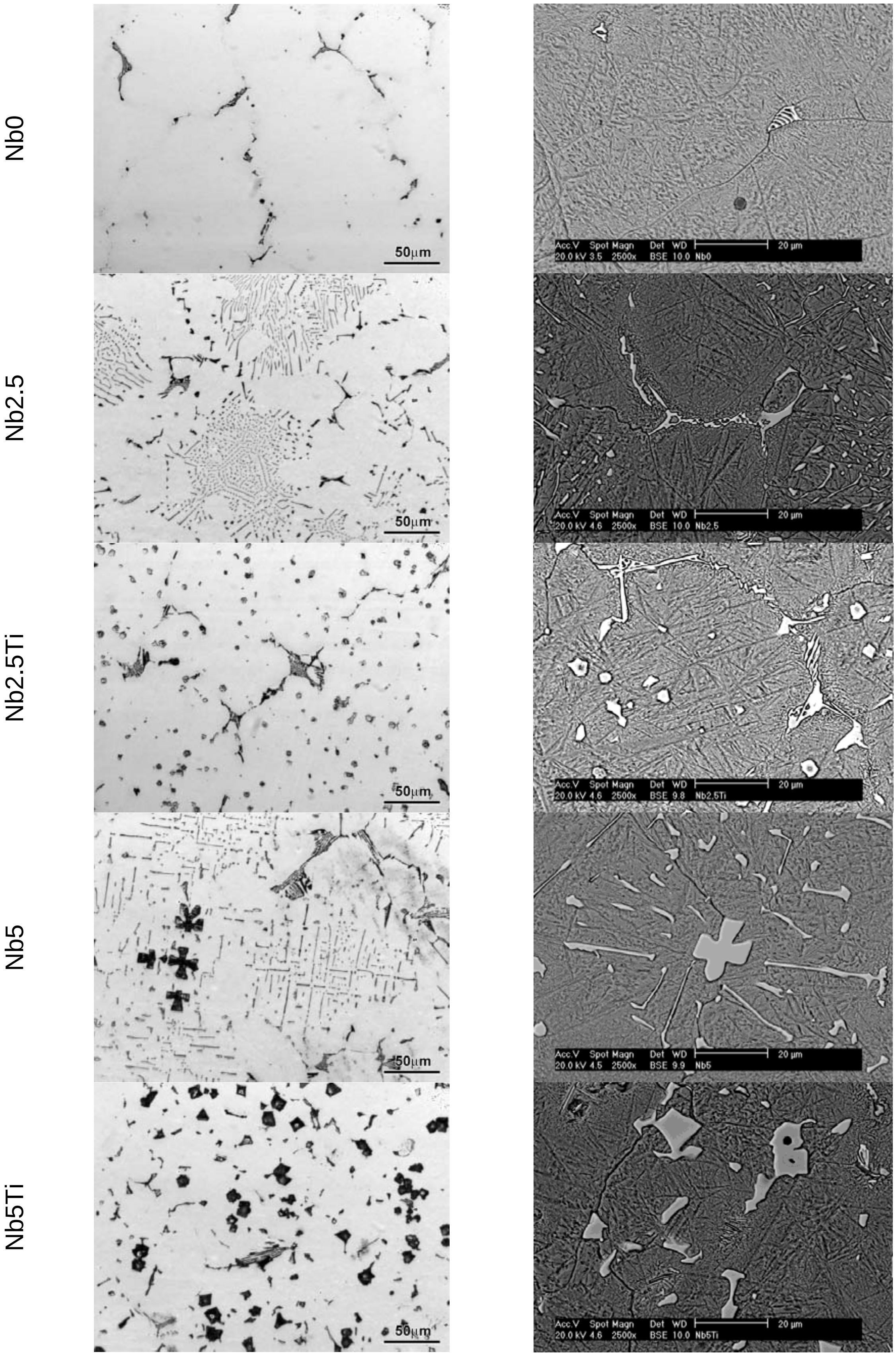


Figure 1 – Distribution and morphological details of the eutectic carbides in the microstructure of the HSS-Nb alloys. (a) Nb0; (b) Nb2.5; (c) Nb2.5Ti; (d) Nb5; (e) Nb5Ti.

Table 2 shows the values of mean volume fraction (Vv) and mean perimeter (P) of eutectic carbides in the microstructure of the HSS-Nb alloys (95% confidence level). Since chinese script-like morphology is quite different from a rounded one, it was argued that the size of the eutectic carbides is more properly evaluated through the perimeter instead of equivalent diameter. Thus, it can be seen that Ti addition strongly modifies the morphology of primary and eutectic NbC and increases the mean eutectic carbide size, mainly in the hypereutectic alloy.

Table 2- Mean volume fraction (Vv) and mean perimeter (P) of eutectic carbides

Alloy	Vv (%)	P (μm)
Nb0	1.6 ± 0.3	n.d.
Nb2.5	6.6 ± 0.6	10.3 ± 0.3
Nb2.5Ti	6.4 ± 0.6	13.1 ± 0.4
Nb5	10.4 ± 1.4	13.8 ± 0.5
Nb5Ti	10.1 ± 1.3	21.2 ± 0.9

3.2 Abrasive Wear

Figure 2 shows the values of the wear coefficient for the HSS-Nb alloys (95% confidence level).

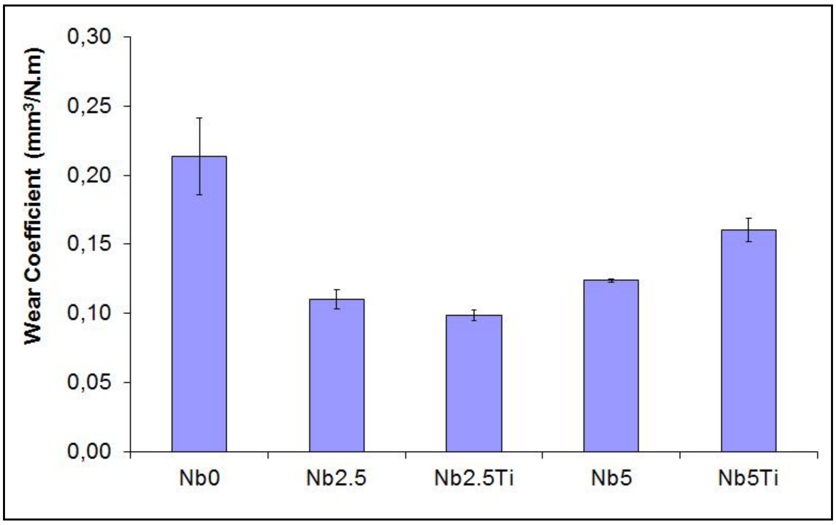
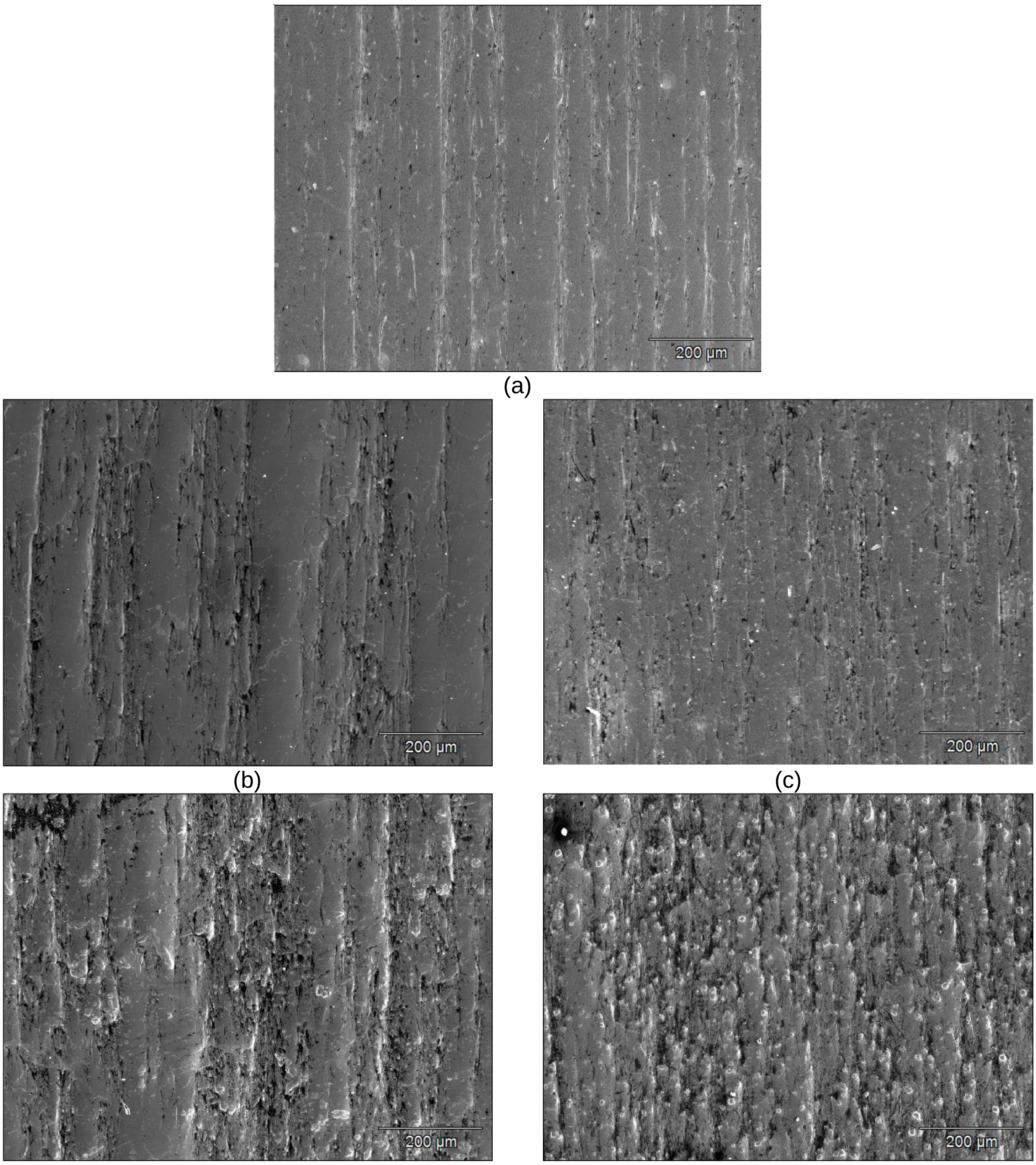


Figure 2 – Wear coefficient of the HSS-Nb alloys. Dry rubber wheel testing: 130N, 200rpm, 30 min, hematite (-210μm+105μm; 860 $HV_{0.1}$).

It can be seen that the presence of carbides was decisive for improving the abrasive wear resistance, since Nb0 alloy showed the highest wear coefficient. However, Figure 2 also shows that increasing volume fraction of eutectic carbides does not necessarily imply increasing abrasive wear resistance, since the alloy Nb5Ti presented the highest wear coefficient among those alloys with NbC carbide.

Figure 3 shows a broad view of the worn region of the abrasive wear test piece. Wear paths are not homogenous and do not show the same aspect for all the alloys, mirroring the variation of the volume fraction and morphology of the eutectic carbides in the Nb-HSS alloys. Also, the amount of pits in the worn surface has increased with increasing volume fraction of NbC carbides.



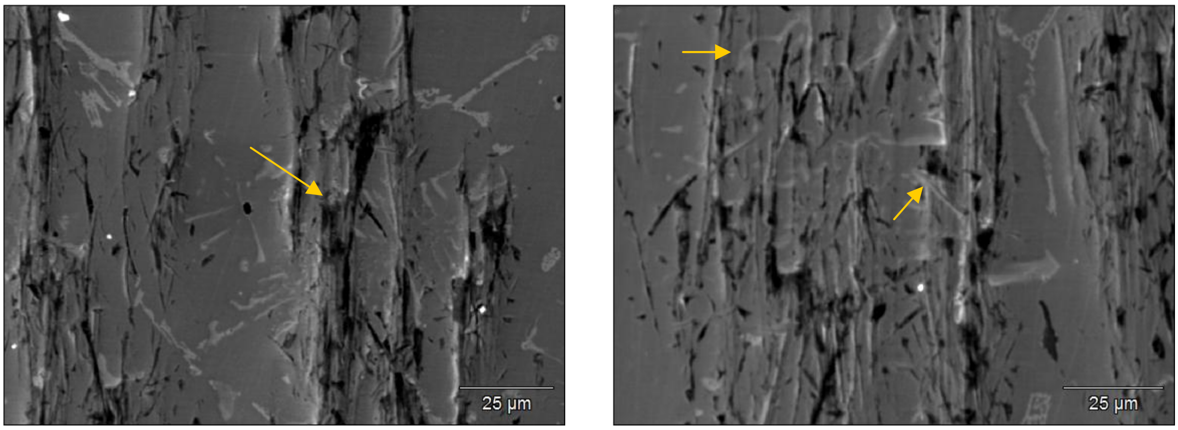
(a)

(b) (c)

(d) (e)

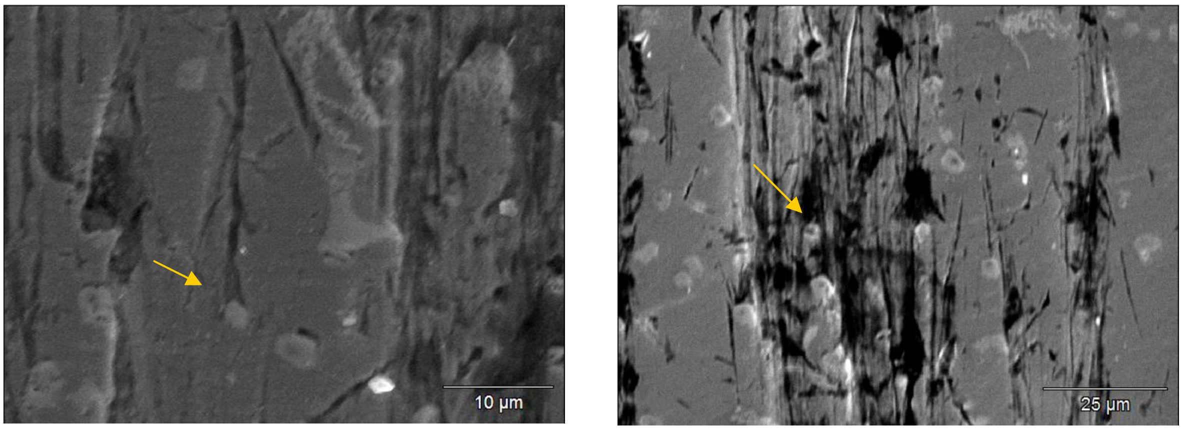
Figure 3 – Top view of the worn test pieces. (a) Nb0; (b) Nb2.5; (c) Nb2.5Ti; (d) Nb5; (e) Nb5Ti. SEM – backscattered electrons.

Figure 4 and Figure 5 show details of the worn surface of the Nb2.5 and Nb2.5Ti alloys, respectively. Chinese script-like eutectic NbC carbide was cut by the abrasive and just part of it was pulled out along with the matrix, the remaining being kept as matrix reinforcement (Figure 4). On the other hand, polygonal divorced NbC was not cut by the abrasive nor pulled out, even when the surrounding matrix was severely worn (Figure 5b), and eventually impeded the sliding action of abrasive particles (see arrow in Figure 5a). Also, no cracked polygonal NbC was observed in the worn surface (indeed, it must be noted that the size of the polygonal NbC in Figure 5 is comparable to its size in Figure 1).



(a) (b)

Figure 4 - Details of the worn test piece of the Nb2.5 alloy. SEM – backscattered electrons.



(a) (b)

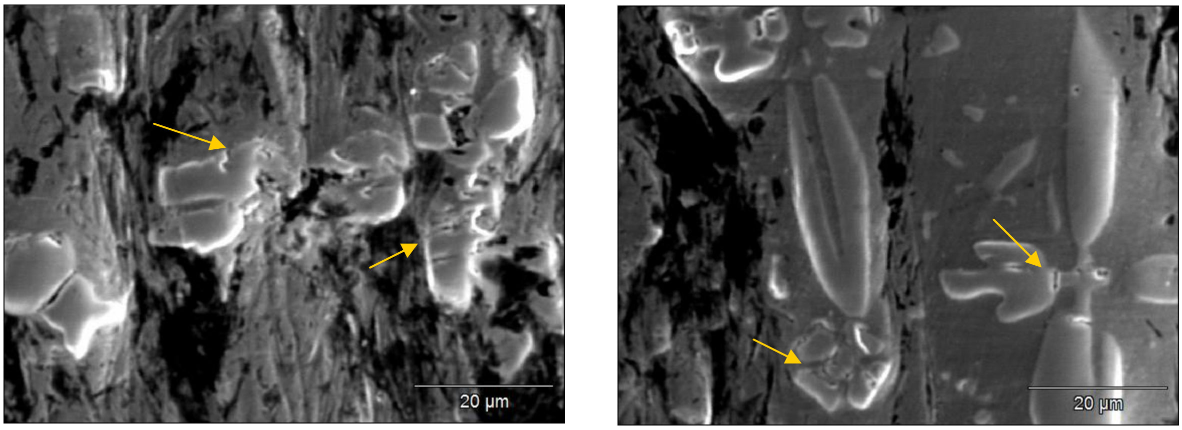
Figure 5 - Details of the worn test piece of the Nb2.5Ti alloy. SEM – backscattered electrons.

Figure 6 and Figure 7 show details of the worn surface of the Nb5 and Nb5Ti alloys, respectively. Cracked NbC carbides is the main feature observed in both alloys, regardless the morphology of the carbide. Also, it is interesting to note that carbide cracking did not result solely from the contact with the abrasive, since cracked NbC carbides located out of the abrasive path were also observed.

The features of the worn surfaces of the Nb-HSS alloys shown by Figures 4 to 7 allow to argue that carbide cracking is the wear micro-mechanism responsible for increasing wear coefficient with increasing volume fraction of NbC carbide in the Nb-HSS alloys. Since the hardness of the hematite abrasive is more than 1.2 times the hardness of the matrix and, on the other hand, it is less than one third the hardness of the NbC carbide (2500-3000HV), the preferential wear of the softer matrix has occurred, thus exposing the carbide particles and making them more prone to fracture. Then, NbC carbide size has controlled the wear loss:

i) Although primary NbC carbide in the Nb5 alloy is much larger than chinese script-like or polygonal NbC carbides in the Nb2.5 and Nb2.5Ti alloys, its population is very low and a small increase in the wear loss has resulted.

ii) Microstructure of the Nb5Ti alloy presents only large polygonal NbC carbides and, thus, a high value of the mean carbide perimeter was observed (Table 2). Then, wear loss of the Nb5Ti alloy significantly increased in comparison to the wear loss of the other NbC-containing alloys.



(a) (b)

Figure 6 - Details of the worn test piece of the Nb5 alloy. SEM – backscattered electrons.

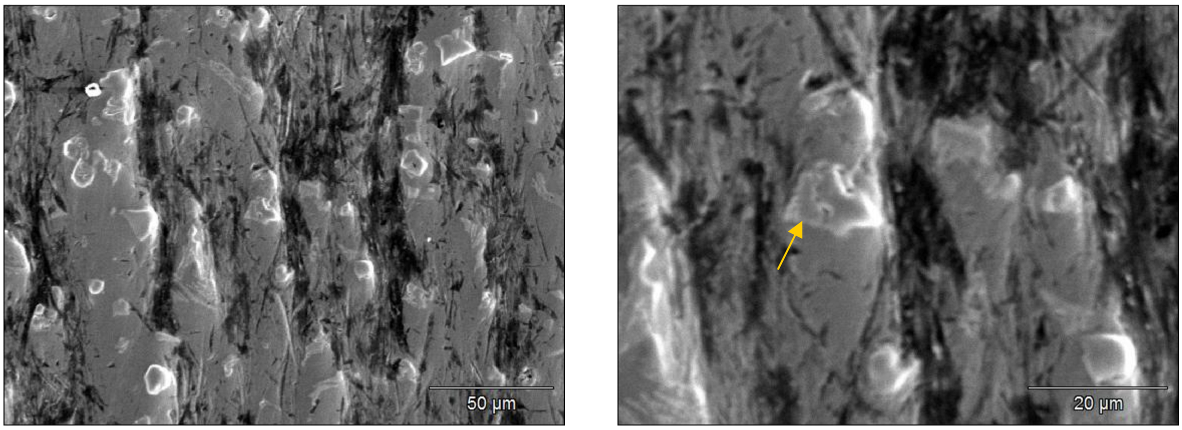


Figura 7 - Details of the worn test piece of the Nb5Ti alloy. SEM – backscattered electrons.

Figure 8 quantitatively represents the relationship between the wear coefficient and the size of the NbC carbide, by means of the carbide perimeter.

At a first glance, one could reason that it is a fairly linear correlation, but the point related to Nb2.5Ti alloy. However, it seems that reasoning on a correlation in which that point is a minimum describes more properly the observed relationship between wear micro-mechanisms and microstructure; i.e. small polygonal morphology is the best compromise between the two roles the NbC carbides play in the wear mechanism of the Nb-HSS alloys: in one hand, it is large enough to avoid cutting and to stop abrasive sliding; in the other, it is not so large as to become vulnerable to fracture.

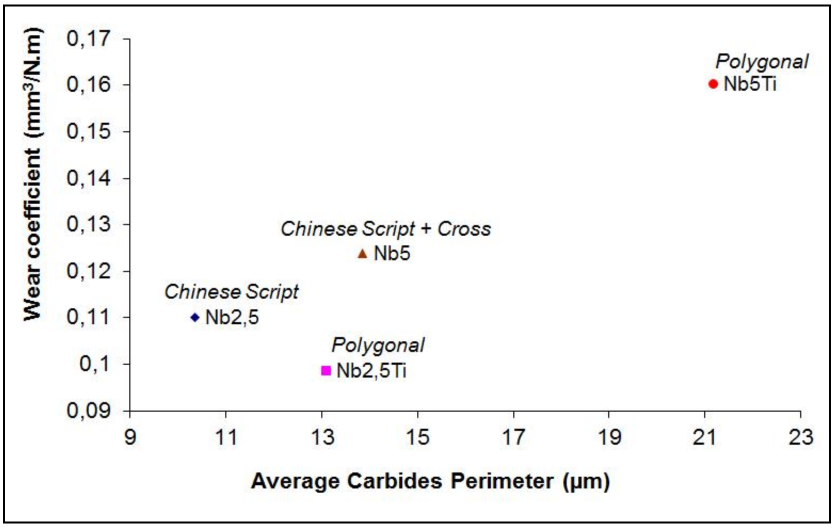


Figure 8 – Relationship between wear coefficient and average NbC carbide perimeter.

4 CONCLUSIONS

4.1 The presence of NbC carbides is decisive for improving the abrasive wear resistance of the Nb-HSS alloys, regardless their volume fraction and morphology.
4.2 Matrix grooving along with carbide cutting or along with carbide cracking are the prevalent sets of wear micro-mechanisms in the Nb-HSS alloys.
4.3 The mean size of the NbC carbide determines its wear mechanism: cutting prevails for the smaller sizes and cracking prevails for the bigger ones. There is a carbide size for which none of these mechanisms is observed and it is related to the higher wear resistance of the Nb-HSS alloys.

Acknowledgements

To Fundação de Amparo à Pesquisa do Estado de São Paulo – Fapesp for financial support through project 04/05690-3, to Villares Rolls for the MSc. grant and to Surface Phenomena Laboratory-Escola Politécnica da Universidade de São Paulo for using the rubber wheel tribometer.

REFERENCES

1 ROBERTS, G.; KRAUSS, G.; KENNEDY, R. **Tool Steels**. ASM International, 5th ed., 1998.
2 HOYLE, G. **High Speed Steels**. Cambridge:Butterworth, 1988.
3 RIEDL, R.; KARAGÖZ, S.; FISCHMEISTER, H.; JEGLITSCH, F. Developments in high speed tool steels. **Steel Research**, v. 58, n. 8, p. 339-52, 1987.
4 THOMPSON, J.; CESCON, T.; KEOWN, S.R. Alloy substitution in M2 high-speed steel. In: **Proceedings of International Conference on Towards Improved Performance of Tool Materials**, Teddington, 1981, Metals Society, 1982, p.37-42.
5 BROOK, G.B.; CROMPTON, J.M.G. Niobium in High Speed Tool Steels. In: **Fulmer Research Institute**, Report 319/4, 1971.
6 HASHIMOTO, M., ODA, T.; HOKIMOTO, K.; KAWAKAMI, T.; KURAHASHI, R. **Nippon Steel Technical Report**, v. **66**, p.82-90, 1995.
7 SANO, Y., HATTORI, T., HAGA, M. Characteristics of High-carbon High Speed Steel Rolls for Hot Strip Mill. **ISIJ International** v.32, n.11, p. 1194-1201, 1992.

8 BOCCALINI JR., M, GOLDENSTEIN, H. Solidification of high speed steels. **International Materials Review**, v. 46, n.2, p.92-115, 2001.

9 BOCCALINI, M. JR.; CORRÊA, A.V.O; SINATORA, A. Niobium in multi-component white cast iron. **Proceedings of the International Conference on Abrasion Wear Resistant Alloyed Cast Iron for Rolling and Pulverizing Mills**, Trento-Italy, v. 1, 2008, p. 49-64

10 SILVA, P.F., FARINA, A.B., BOCCALINI JR., M. Ligas “aço matriz + NbC” – Caracterização no estado bruto de fundição. **Tecnologia em Metalurgia e Materiais**, São Paulo, v.4, n.3, p. 43-49, jan.-mar. 2008.