

Development of Microalloyed High-Carbon Steels for Plough Disks

O.R. Crnkovic and F.L. Bastian

Plough disks are often made of high-carbon steels with small additions of chromium (0.40 to 0.60%), in the as-quenched and tempered condition. As a consequence, they combine wear resistance with the tensile, fatigue, and impact strength necessary to withstand extremely adverse work conditions. In an effort to produce steels for this use with improved mechanical properties, four different steel compositions, all microalloyed with niobium, were produced for the present work. Two steels kept the basic chromium content of the commercial alloy (0.40 to 0.60%), while this element was replaced with manganese in the other two steels. The chromium and manganese steels were produced with two levels of niobium. The Jominy hardenability, tensile properties, and impact and wear resistance of these materials were evaluated. A microstructural characterization was also performed. The results show that the developed steels can have the required hardness and strength levels. The high-niobium steels showed the best wear resistance but the poorest impact toughness. The wear resistance of the low-niobium steels was slightly higher and the impact toughness slightly lower than in the commercial alloy. The low-niobium steels show potential for commercial use.

Keywords
high-carbon steels, microalloyed steels, plough disks, plough steels, wear

1. Introduction

PLOUGH disks are normally made of high-carbon steels (Ref 1, 2), often with small additions of chromium. These steels are used in the as-quenched and tempered condition, with high tempering temperatures, around 500 °C, and hardness values about 41 to 42 HRC. As a consequence, these materials show a reasonable combination of mechanical strength, wear resistance, fracture toughness, and fatigue resistance.

It is felt that it is possible to improve the properties of plough steels by proper alloying and heat treatments. With this objective, two families of steels were produced for the present study. One mantained the basic chemical composition of the commercial chromium steel, with the addition of one of two different levels of niobium. The other had no chromium and instead had manganese as the main alloying element, also with one of two levels of niobium.

In order to assess the properties of the developed steels, their Jominy hardenabilities, tensile properties, and impact and wear resistance were evaluated. Their temper embrittlement susceptibilities were also evaluated through the chemical analysis of fracture surfaces using Auger electron spectroscopy. Microstructural characterization and fractographic analysis were also performed.

2. Materials Design

A material traditionally used for making plough disks in Brazil is a high-carbon chrominum steel whose chemical composition is shown in Table 1 with the designation L1. This steel is supplied as hot-rolled sheet, 12.5 mm thick. For making the disks the material is uncoiled and blanks are cold cut and drilled. The blanks are then heated to 970 °C, hot stamped to the final shape, oil quenched, and tempered above 500 °C to hardnesses in the range of 41 to 42 HRC.

Although adequate disks are produced following this route, the high hot-working temperature (970 °C) can cause substantial austenite grain growth which can be deleterious to the material fracture toughness and potentially to the wear resistance. One way of avoiding excessive grain growth could be through the pinning effect of niobium carbides resulting from the addition of niobium to the steel (Ref 3). Additionally, these carbides can increase the mechanical strength and may also have a beneficial influence on the abrasion resistance of the steel.

In order to study the influence of niobium on the mechanical properties of the material, steels with two levels of this element were produced: one low, nominal range of 0.02 to 0.04% (steel L2, Table 1); and the other higher, nominal range of 0.20 to 0.30% (steel L3, Table 1).

A substitution of manganese for chromium in the steel was also tried. The amount of manganese to be added to mantain the hardenability of the steel was estimated, using data published by Jatczak (Ref 4), to be in the range of 1.4 to 1.6%. Steels with this manganese content and two levels of niobium, nominal ranges of 0.02 to 0.04% (steel L4, Table 1) or 0.20 to 0.30% (steel L5, Table 1), were also produced.

In order to compare the properties of the experimental steels with those of the commercial composition produced at the same scale, steel L1 was also prepared in the laboratory. The nominal compositions of the steels produced are shown in Table 1.

3. Steels Studied

Following the chemical compositions specified in Table 1, five experimental steels were produced in the laboratory. The steels were melted under vacuum and poured in air to produce

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Table 1 **Nominal chemical composition of the steels of the study**

Steel	Element, wt%						
	C	Si	Mn	Cr	Nb	P	S
L1	0.70-0.80	0.15-0.30	0.60-0.90	0.40-0.60	...	0.025 max	0.015 max
L2	0.70-0.80	0.15-0.30	0.60-0.90	0.40-0.60	0.02-0.04	0.025 max	0.015 max
L3	0.70-0.80	0.15-0.30	0.60-0.90	0.40-0.60	0.20-0.30	0.025 max	0.015 max
L4	0.70-0.80	0.15-0.30	1.40-1.60	...	0.02-0.04	0.025 max	0.015 max
L5	0.70-0.80	0.15-0.30	1.40-1.60	...	0.20-0.30	0.025 max	0.015 max

Table 2 **Chemical composition of the steels studied**

Steel	Element, wt%						
	C	Si	Mn	Cr	Nb	P	S
L1	0.72	0.21	0.88	0.53	...	0.021	0.024
L2	0.75	0.26	0.91	0.64	0.03	0.019	0.020
L3	0.75	0.31	0.93	0.61	0.28	0.011	0.017
L4	0.77	0.20	1.60	...	0.02	0.017	0.021
L5	0.77	0.31	1.47	...	0.41	0.018	0.017

100 kg ingots. The ingots were hot forged to bars with diameter of 38 mm and length of 800 mm. They were then hot rolled to plates of thickness of 12.5 mm and length of 1500 mm.

Table 2 shows that the chemical compositions of the steels are within the specified ranges with the exception of sulfur, which is slightly higher than the specified. Chromium is higher in steels L2 and L3. As the sulfur content is slightly higher in all steels, it should not impair the comparison of properties, and the differences in chromium content are not so large as to affect the properties substantially.

4. Experimental Methods

4.1 *Jominy Hardenability Tests*

The tests were performed following ASTM A 255 (Ref 5).

4.2 *Heat Treatments*

The steels were austenitized at 830 °C and quenched in oil at 60 °C. They were then tempered at temperatures between 460 and 500 °C, depending on the steel composition, in order to produce hardnesses between 40 and 42 HRC. The austenitization temperature of 830 °C was chosen in order to compare the properties of the steels for the same austenite grain sizes irrespective of the niobium content. The beneficial influence of niobium on the austenite grain size becomes more important when the steels are heat treated at high temperatures, such as 970 °C, the current industrial austenitization temperature.

4.3 *Optical Microscopy*

The nonmetallic inclusions were observed using unetched polished samples. The microstructure of the steels was analyzed using samples etched in a solution of 50% nital (5%) and 50% sodium metabisulfite (1%).

4.4 *Hardness Testing*

The Rockwell C hardness was measured following ASTM E 18 (Ref 6). At least five indentations were made for each microstructural condition. The results are presented as mean hardness values.

4.5 *Tensile Testing*

The tests were performed at room temperature following ASTM A 370 (Ref 7), using round tensile testpieces with a diameter of 6.25 mm and gauge length of 56 mm. Samples were taken from the longitudinal and transverse directions in relation to the rolling direction.

4.6 *Charpy Testing*

Charpy tests were undertaken following ASTM E 23 (Ref 8) with V-notch testpieces. The testing temperatures were from –50 to 200 °C at intervals of 25 °C. Specimens of orientations L-T and T-L, following ASTM E 616 (Ref 9), were tested. At least three testpieces were tested at each temperature. The results are presented as mean values.

4.7 *Auger Electron Spectroscopy*

This analysis was performed in order to assess the temper embrittlement susceptibility of the different steels. Small notched cylindrical testpieces were subjected to heat treatments which promote temper embrittlement (Ref 10) and then were fractured at a temperature of –100 °C in a chamber with ultrahigh vacuum (10^{-10} torr) coupled to the Auger equipment. The Auger spectroscopy analyses were made a few seconds after the testpieces were broken, giving the chemical composition of the fracture surfaces. The geometry, dimensions, and orientation of the testpieces used are shown in Fig. 1.

4.8 *Wear Testing*

Two types of wear tests were performed: a dry sand, rubber wheel wear test, following ASTM G 65 (Ref 11), and a pin-on-

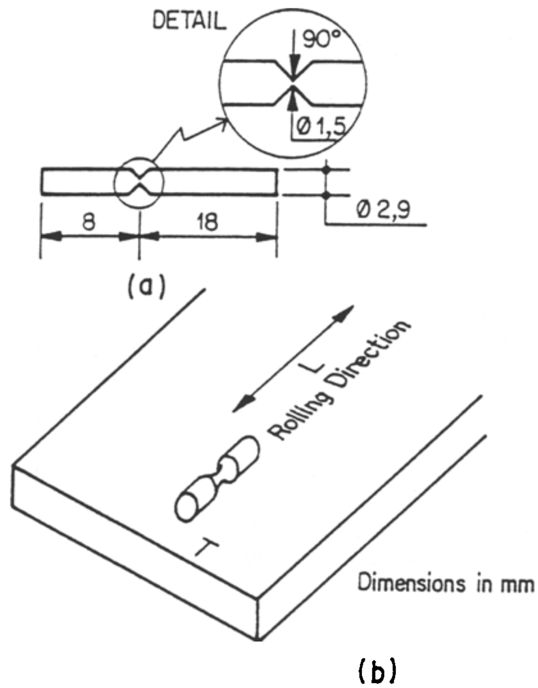


Fig. 1 Geometry (a) and orientation (b) of the Auger spectroscopy testpieces

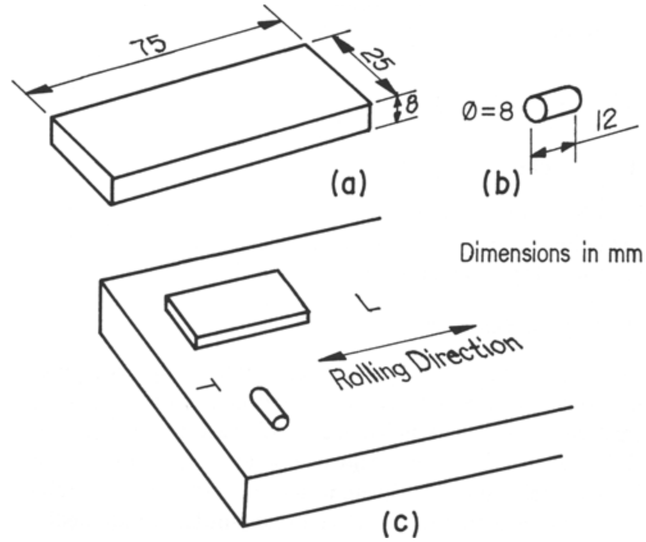


Fig. 2 Geometries, dimensions, and orientations of the wear testpieces. (a) Dry sand, rubber wheel wear testpiece. (b) Pin-on-disk wear testpiece. (c) Orientations of the testpieces

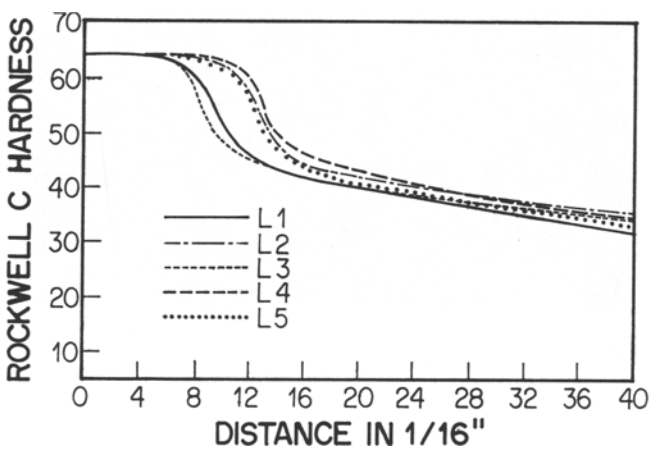


Fig. 3 Jominy hardenability curves of the steels

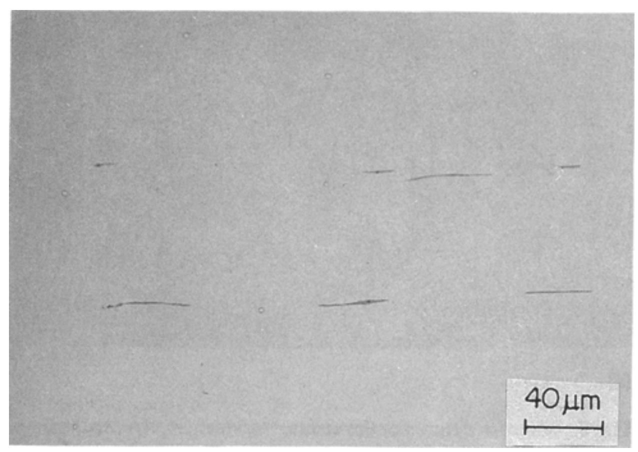


Fig. 4 Typical nonmetallic inclusions in the steels (photograph taken from steel L1)

disk test (Ref 10). The testpiece geometries, dimensions, and orientations are shown in Fig. 2. In the first method, the wear is caused by dry sand flowing between a rotating rubber wheel and the testpiece. In the second, a pin-shaped testpiece rotates with a spiral trajectory in contact with a rotating abrasive disk. A constant pressure is applied to the testpiece by a weight of 300 g.

In the dry sand, rubber wheel test, each result corresponds to the average of ten tests. Each test corresponds to 4000 revolutions of the rubber wheel, or 20 min, with an applied load of 13 kgf. The dispersion coefficient (v) is obtained using the expression $v = s\sqrt{x} \times 100\%$, where s is the standard deviation and $\bar{x}$ is the mean weight loss obtained in the tests. Following ASTM G 65, the dispersion coefficient must be smaller than 5% in order for the results to be considered reliable. The results are presented as mean weight losses during the tests.

In the pin-on-disk tests each result corresponds to the mean of three tests. Each test corresponds to six measurements of weight loss, at intervals of 216 seconds. The dispersion coefficient v was also calculated for these tests. The results are presented as an abrasion rate, corresponding to the weight loss per second.

5. Results

5.1 *Jominy Hardenability*

The results of the Jominy tests are shown in Fig. 3. The full line curve corresponds to the commercial alloy. The figure shows that the hardenabilities of the experimental steels, with the exception of steel L3, are higher than that of the commercial composition.

5.2 *Optical Microscopy*

5.2.1 Unetched Samples

The observation of the unetched material showed the occurrence of elongated manganese sulfide inclusions in all steels, as illustrated in Fig. 4, corresponding to the alloy L1.

5.2.2 Etched Samples

The quenching and tempering treatments produced typical tempered martensite with coalesced carbide microstructures, as illustrated in Fig. 5, which correspond to alloys L4 (Fig. 5a), and L5 (Fig. 5b). Even though the chemical compositions of the steels were substantially different, the microstructures resulting from the heat treatments were quite similar for all steels. Obviously the amount of niobium carbides was higher in the case of the high-niobium steels.

5.3 *Hardness Testing*

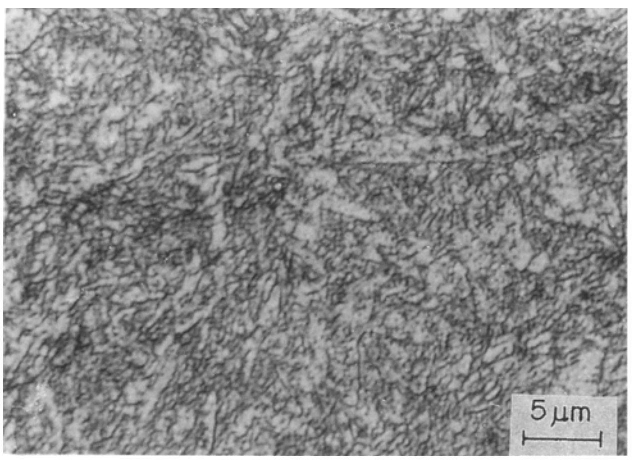
Hardness values between 62 and 64 HRC resulted from quenching. The tempering temperatures and resulting Rockwell C mean hardness values are shown in Table 3.

5.4 *Tensile Properties*

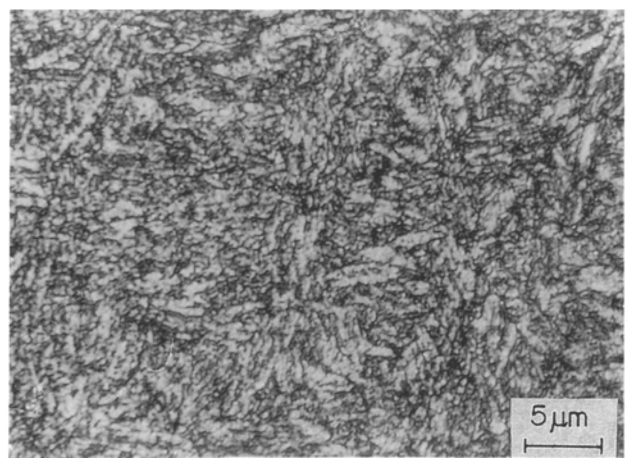
As a result of the tempering treatments at the chosen temperatures the steels presented the tensile properties shown in Table 4.

5.5 *Charpy Tests*

The results of the Charpy tests for the orientations T-L and L-T are shown in Fig. 6 and 7, respectively. The figures show



(a)



(b)

Fig. 5 Microstructures of the steels. (a) Steel L4. (b) Steel L5

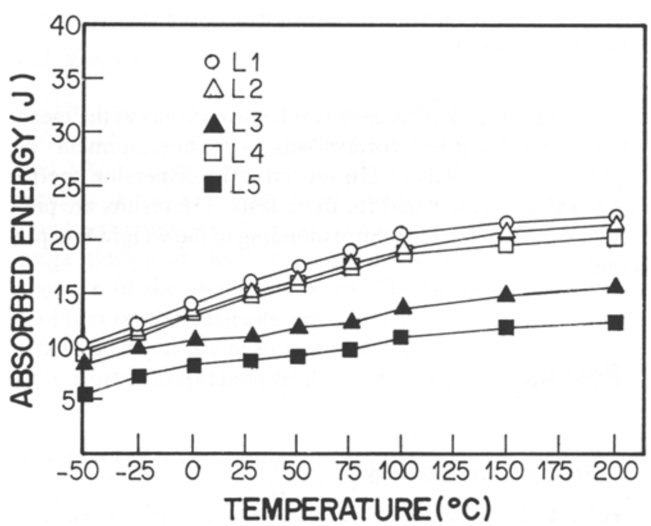


Fig. 6 Charpy V-notch absorbed energies as a function of temperature. Testpieces with the T-L orientation

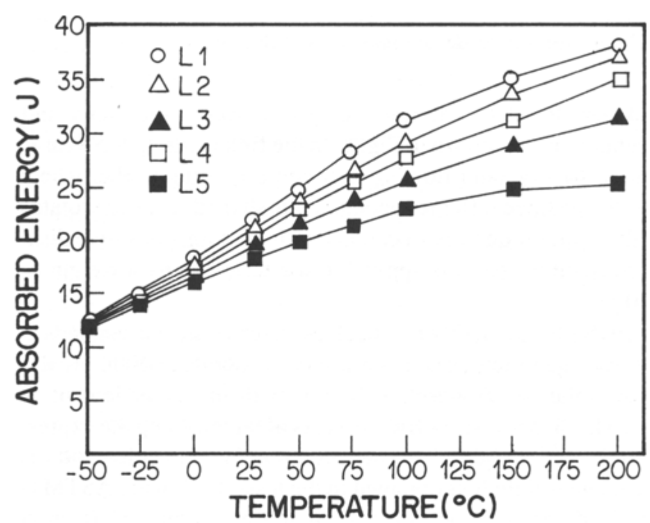


Fig. 7 Charpy V-notch absorbed energies as a function of temperature. Testpieces with the L-T orientation

that the steels with higher niobium content present lower absorbed energies for fracture and that the chromium alloys have higher impact toughness than the manganese alloys. The impact resistance is higher in the L-T orientation.

5.6 *Auger Electron Spectroscopy*

The fractured Auger testpieces presented areas of intergranular and transgranular fracture. Separate analyses were performed in those areas and the analyses showed that there was phosphorus segregation to the prior-austenite grain boundaries in all steels. This resulted in peaks of high intensity in the Auger spectrographs of the intergranular fracture regions of the specimens in opposition to the transgranular fracture regions (Ref 10, 12). The phosphorus concentration at the grain boundaries of the five steels studied is shown in Table 5. The concentration of carbon was also higher at the grain boundaries, whereas no chromium, manganese, or niobium segregation to the boundaries was detected (Ref 10, 12).

5.7 *Fractography*

The fractographic analysis of the tensile testpieces broken at room temperature showed that all steels fractured by a mixture of ductile, quasi-cleavage, and intergranular mechanisms. The Charpy testpieces broken at this temperature also showed a mixture of those modes of fracture, with some areas of cleavage as illustrated in Fig. 8(a). The areas of cleavage increased at the lower testing temperatures, as illustrated by Fig. 8(b), which corresponds to samples broken at −50 °C.

5.8 *Wear Tests*

The results of the dry sand, rubber wheel wear tests are presented in Fig. 9. The figure shows that the steel without nio-

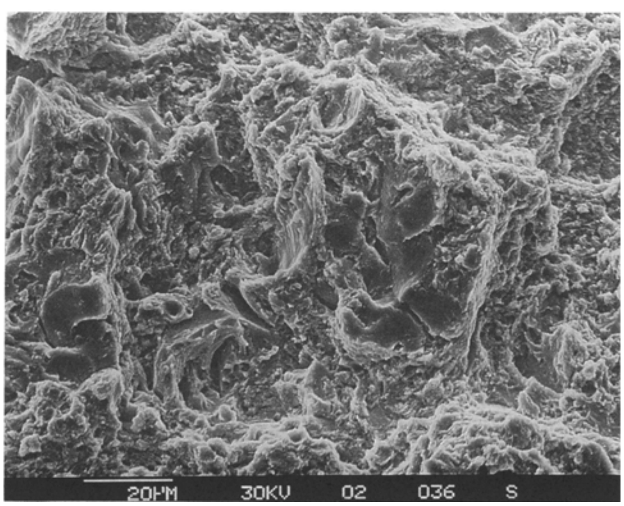
Table 3 Tempering temperatures and resulting hardness of the steels

Steel	Tempering temperature, °C	Hardness, HRC
L1	470	42
L2	480	41
L3	500	41
L4	460	41
L5	480	42

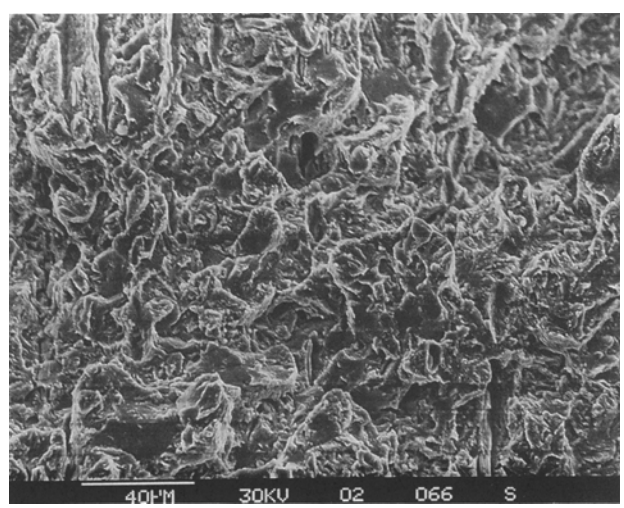
Table 4 Tensile properties of the steels

Steel	Orientation	Yield limit, MPa	Ultimate tensile stress, MPa	Elongation, %
L1	L	1135	1319	13.5
	T	1125	1308	13.5
L2	L	1129	1314	14.4
	T	1114	1297	14.1
L3	L	1200	1352	14.7
	T	1173	1338	13.4
L4	L	1174	1341	14.1
	T	1171	1340	14.0
L5	L	1184	1346	14.0
	T	1178	1335	11.6

L, longitudinal; T, transversal to the rolling direction.



(a)



(b)

Fig. 8 Typical fracture surfaces of the Charpy testpieces tested at (a) room temperature and (b) −50 °C. Steel L2. Testpiece orientation: L-T

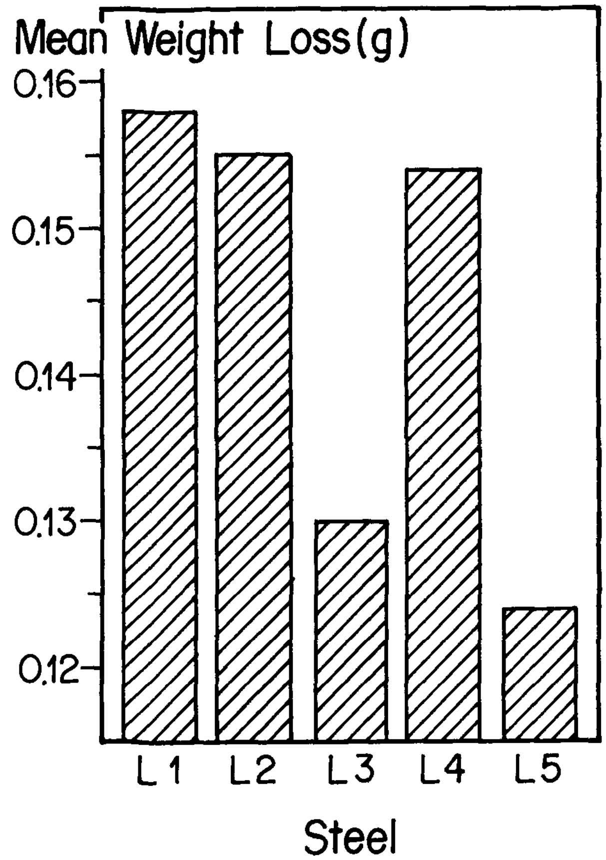


Fig. 9 Mean weight losses during the dry sand, rubber wheel wear tests

Table 5 Phosphorus concentration at the prior-austenite grain boundaries

Steel	L1	L2	L3	L4	L5
P, at.%	8.5	10.5	9.0	11.6	8.7

bium (L1) presented the highest weight loss, while the steels with high niobium presented the lowest losses. Steels L2 (Cr with 0.03% Nb) and L4 (Mn with 0.02% Nb) showed equivalent weight losses.

The results of the pin-on-disk tests are shown in Fig. 10. Here also the steel without niobium (L1) showed the highest weight loss per second, while the steels with high niobium presented the smallest losses. Steel L4 showed higher wear resistance than steel L2.

6. Discussion

The results show that the Jominy hardenabilities of the designed alloys are higher, as expected, than that of the commercial composition, without Nb. They also show that the subtitution of Mn for Cr in the alloys did not spoil their hardenabilities. On the other hand, it is possible to obtain the re-

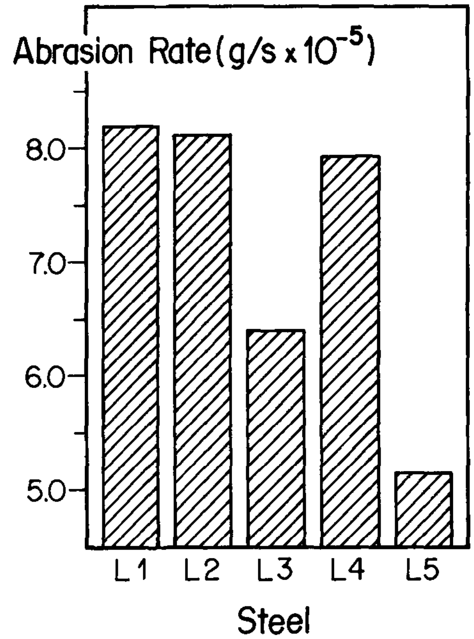


Fig. 10 Mean weight losses per second during the pin-on-disk wear tests

quired hardness values with the designed steels through proper quenching and tempering treatments.

The Nb additions did not show any substantial influence on P segregation, in agreement with the results of Antunes and Avillez (Ref 13) and in opposition to the prediction of Yu and McMahon (Ref 14). The substitution of Mn for Cr in the alloy did not markedly influence the P segregation. No Mn or Cr segregation to the grain boundaries was observed for either the Cr and Mn steels with Nb additions or the commercial steel. The segregation of C to the grain boundaries probably prevents segregation of those elements into that region.

The Charpy tests showed that the fracture toughness of all Nb steels was lower than that of the commercial steel, for both tested orientations, with the highest Nb steels having the poorest impact resistance, whereas the Cr steels had a slightly better performance than their Mn counterparts. The Charpy results of the present work do not fully characterize the impact toughness potential of the Nb steels, because the chosen austenitizing temperature (830 °C) is much smalller than the temperature used commercially (970 °C). In the latter case, the steel without Nb should show substantial austenite grain growth, which can cause loss of toughness. This should not happen with the Nb steels, where the Nb carbides can easily prevent grain growth. Work done with 0.8% C steels with and without Nb additions (Ref 15) showed that at 950 °C the austenite grain size was 41.1 μm for the steel without Nb while it was 16.5 μm for the steel containing 0.045% Nb. On the other hand, it is known that loss of toughness results from excessive austenite grain growth.

Both wear tests produced equivalent results: the steel without Nb showed the poorest wear resistance and the highest-Nb steels showed the best. An unexpected result was that even a low Nb content (0.02 to 0.03%) could slightly improve the wear resistance of both the Cr and Mn steels. Another interesting result was that the Mn steels showed better wear resistance than their Cr counterparts.

The higher wear resistance of the steels with Nb is probably due to the presence of niobium carbides. The influence of these carbides is more evident in the case of the high-Nb steels where the amount of particles gets markedly higher. Carbides are known to improve the wear resistance of steels (Ref 16-18). The influence of the niobium carbides in the case of the low-Nb steels, where the amount of particles is not greatly increased by the Nb addition, is less evident. This effect could result from the dispersion of the particles precipitated in the ferrite matrix, reinforcing it and, consequently, increasing the wear resistance of the steel (Ref 19).

The higher wear resistance of the Mn steels could be attributed to the influence of Mn on the amount of retained austenite after quenching. It has already been shown that tempered martensite with residual austenite presents very high wear resistance (Ref 20-21). Residual austenite is thought to add toughness to the matrix, provide support for the carbides, and be capable of undergoing transformation during wear, all this having a favorable effect on wear resistance (Ref 20-21).

When analyzing the industrial possibilities of the alloys studied, the high-Nb alloys merit attention for their higher wear resistance. The impact toughness of these alloys is much lower than that of the commercial Cr alloy without Nb, but both Cr and Mn steels with low Nb content (0.02 to 0.03%) show a slightly better wear resistance than the commercial alloy. It is known that the main problem with plough disks is their durability, which depends mainly on their wear resistance, although their mechanical strength and impact resistance are also important. As a consequence, the Mn and also the Cr alloys with small Nb additions show potential commercial use. It should not be forgotten that the commercial austenitization temperature for these alloys is 970 °C, which should decrease the fracture resistance of the commercial steel (L1), although not the fracture resistance of the alloys with Nb.

Even though the present research was focused on plough steels, the developed materials may be used wherever a combination of mechanical strength and wear resistance is required, such as in components for the railway, mining, and minerals industries, earth moving equipment, and others.

7. Conclusions

Four experimental plough disk steels were produced at laboratory scale and their properties compared to those of the commercial composition, produced at the same scale. Two of the experimental steels had Cr as the main alloying element and one of two levels of Nb: 0.02 to 0.04% or 0.2 to 0.3%. The other two steels had Mn as the main alloying element and one of the same two levels of Nb. An analysis of the properties of the steels led to the following conclusions:

- The required levels of hardness and tensile properties were obtained with the experimental steels.
- All the alloys studied, irrespective of the chemical composition, Cr or Mn as the main alloying element, and Nb content, showed some P grain boundary segregation. No Cr, Mn, or Nb segregation was observed.
- The steels with high Nb content showed the best wear resistance but the lowest Charpy impact toughness, much smaller than that of the commercial alloy.
- The wear resistance of the Mn steels was higher than that of the Cr steels.
- The wear resistance of the low-Nb steels was slightly higher than that of the commercial alloy, while the Charpy impact toughness was slightly lower. Both the Cr and the Mn steels with small Nb additions show potential for commercial use.

Acknowledgments

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