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Synergetic effect of niobium and molybdenum on abrasion resistance of high chromium cast irons

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ABSTRACT

This research presents the systematic study of the effects of niobium and molybdenum in high chromium cast irons (HCCI). Four 18%Cr/2.7%C alloys were melted: a base alloy, an alloy containing 1% Mo (free-Nb), an alloy containing 1% Nb (free-Mo) and a fourth alloy containing 1% Nb and 1% Mo. In general, Nb and Mo additions slightly increased (~3% to 10%) the Vickers hardness and the microhardness of the matrix. Regarding niobium carbides (NbC), nanohardness was measured. The fourth alloy presented harder (~13%) NbC than the Mo-free alloy. Abrasion tests using a Dry Rubber Wheel Abrasion Tester (DRWAT) were carried out using different severity levels of wear by varying the normal load and the size of the abrasive grains. For more severe conditions all alloys presented a similar abrasive wear response while micro-cutting as the wear micromechanism dominated. On the other hand, for a less severe test condition, the fourth alloy (containing Nb and Mo) presented a higher abrasion resistance (16%) than the base alloy and the wear predominantly occurred in the matrix. Concluding that, for low severity conditions (mild wear), even rather small amounts of Nb and Mo (in combination), can lead to significant gains in abrasion resistance of HCCI; representing a significant improvement to the cost-benefit ratio for industrial applications.

1. Introduction

High chromium cast irons (HCCI) are well known for their superior abrasion resistance, which results from the combination of a hard phase (mostly chromium carbides) embedded in a ductile metallic matrix. The abrasion resistance of HCCI was intensively studied and improved by controlling the hardness of the matrix (via heat-treatment) and by adjusting the volume fraction and the distribution of chromium carbides in accordance with the specific application [1,2]. Some studies demonstrated that the addition of carbide-forming elements (e.g. V, Ti, Mo, W, B and Nb) further enhanced the abrasion resistance of HCCI [3–9]. Many factors may influence the effect of niobium on the abrasion resistance of HCCI, i.e. microstructure, heat treatment and chemical composition. In the literature the following hypotheses can be found which explain in more detail the effect of niobium on the abrasion resistance of HCCI:

- Niobium forms very hard (NbC) carbides [7–14] with hardness values between 2400 HV and 2850 HV [15];
- NbC has a block-hook like morphology that can keep the carbide particles firmly embedded in the metallic matrix [7,9,11,12];
- Niobium increases the microhardness of the metallic matrix by solid solution [7,8,11];
- Niobium is in solid solution in the M_7C_3 carbides, increasing its hardness [7];
- Niobium addition refines the M_7C_3 precipitation, changing its morphology to a more isotropic shape (specially for hypereutectic HCCI) [8–10,13,14].

In general, the literature shows that the beneficial effect of Nb on the wear resistance of HCCI takes place for high concentrations of Nb (up to 12%). However, several authors [7,12,16–18] showed that smaller concentrations (less than 1%) of Nb can also have a beneficial effect on the wear resistance of HCCI (see Table 1) representing an advantageous cost-benefit ratio.

It is important to highlight that the results shown in Table 1 need to be interpreted with care. The mentioned studies [7,12,16–18] did not take into account the effect of other factors on the wear abrasive wear, such as the presence of other alloying elements (e.g. Mo), the refinement of the microstructure [19] and the presence of

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Table 1
Effect of small additions of Nb on the abrasive wear resistance of HCCI.

Author(s)	Material	Abrasion test configuration(s)	Main result(s)
Guesser et al. [16]	15-18Cr/2–4 C/1-2Mo Nb additions: 0–3%	Hammer-mill type, Paddle wear test, Ball mill test	Significant gains in wear resistance (up to 30%) were obtained with addition of Nb (~ 0.7%) for the hammer-mill and the paddle wear test configurations.
Mascia. [17]	15Cr/2.6 C/2Mo Nb additions: 0–1.5%	Two-body abrasion	The mass loss decreases by 50% with the addition of 0.5% Nb (austenite destabilization temperature of 950 °C).
Bouhamla et al. [18]	15Cr/2.3 C/0.02Mo Nb additions: 0–3%	Three-body abrasion Dry condition	The mass loss decreases by 60% with the addition of 0.5% Nb. The further increase of Nb (above 0.5%) does not show any significant effect on the wear resistance.
Chen et al. [7]	15 Cr/3.5C/3Mo Nb additions: 0–3.5%	Three-body abrasion. Wet condition	The effect of Nb content on wear resistance depends on the heat treatment. For an austenite destabilization temperature of 970 °C, the addition of 0.6% Nb increases the wear resistance by about 30%.
Filipovic et al. [12]	17Cr/2.9 C/1Mo Nb additions: 0–3.2%	Three-body abrasion Dry condition	The alloy with 3% Nb shows a ~30% higher abrasive wear resistance and a ~30% higher dynamic fracture toughness than the alloy without Nb addition.

pearlite. The investigations on the effect of small additions of Nb additions (Table 1) used alloys containing Mo (at different concentrations), which may hinder the interpretation of the role of Nb on the abrasive wear resistance. The present systematic study aims to close this gap.

2. Materials and methods

2.1. Materials

Four HCCI alloys were melted using an induction furnace (INDUCTO 50). As shown in Table 2, the main differences in the chemical composition of the alloys are the contents of Nb and Mo.

The sand mold, shown in Fig. 1a, allowed the casting of three blocks for each alloy (see Fig. 1b). Three test pieces for DRWAT were extracted from each block using wire electron-discharge machining (Fig. 1c). Smaller samples for microstructural characterization were taken from the surface of the test pieces. All samples were subjected to the same grinding process, employing a white aluminum oxide grinding wheel (60 Grit) in order to ensure the parallelism and the homogeneity of the surface finishing of each test piece.

The heat-treatment, shown in Fig. 2, consisted of a subcritical annealing at 700 °C for 2 hours to promote the complete transformation of austenite to ferrite plus carbides, followed by the re-austenitization at 1000 °C for 5 h and forced air quenching. Finally tempering was performed at 200 °C for 2 h. This procedure produced a tempered martensitic microstructure, free of pearlite, and with a very low percentage of retained austenite (undetectable under the optical microscope).

2.2. Microstructural characterization

Samples for microstructure characterization were prepared using an automatic polishing system (MD-System - Struers) and diamond paste (6 μm to 1 μm grain size). Vilella's reagent was used for the etching of the metallographic samples (immersion for 10 seconds). The microstructures were observed using optical (OM) and scanning electron microscopy (SEM). The volume fraction of M_7C_3 carbides (Vv) was measured using OM at a magnification of 200X and the software Leica QWin™ standard. The mean free path between the eutectic areas containing M_7C_3 carbides (λ) was calculated using the intercept method (see Eq. 1).

$$\lambda = (1 - Vv)/N_L \tag{1}$$

Where:

N_L represents the number of interceptions of the test line with M_7C_3 carbides per unit length [20].

Table 2
Chemical composition of alloys.

Designation	Cr	C	Si	Mn	S	P	Nb	Mo
0Nb/0Mo (base material)	20.2	2.85	0.62	0.79	0.019	0.02	0.04	0.03
0Nb/**1Mo**	19.5	2.78	0.59	0.77	0.020	0.03	0.04	**0.60**
1Nb/0Mo	20.7	2.82	0.51	0.74	0.019	0.02	**0.92**	0.04
1Nb/**1Mo**	19.1	2.84	0.62	0.73	0.019	0.03	**0.94**	**0.89**

Conventional macrohardness (bulk material, with a load of 30 kgf) and microhardness (on the metallic matrix of the microstructure, with a load of 0.1 kgf) were measured using a Vickers indenter. Nanohardness measurements on the M_7C_3 and NbC carbides were realized using nanoindentation (TI 950 TriboIndenter® - Hysitron) with a Berkovich tip and 5 mN of normal load.

2.3. Abrasive wear tests

Abrasion tests were carried out using a Dry Rubber Wheel Abrasion Tester (DRWAT) with three wear severity levels, defined by the variation in the normal load and the abrasive grain size, as presented in Table 3. The revolution of the wheel was kept constant (200 rpm) during test and test time was longer for the less severe conditions. The abrasive particles (silica sand) presented similar morphology (sphericity and aspect ratio) for the two sizes of abrasive employed, thereby eliminating the abrasive shape variable, which might change the wear mechanism of the tested alloys [21–23].

The dimensional wear coefficient (k) was calculated according to Rabinowicz' equation [25], Eq. (2), where the parameter Δm stands for the mass loss, while ρ is the material density, L is the sliding abrasion distance and F is the normal load.

$$k = \Delta m/(\rho \bullet L \bullet F)[mm^3/Nm] \tag{2}$$

3. Results and discussions

3.1. Microstructural characterization

Fig. 3 shows the SEM micrographs for each alloy, indicating that all microstructures are hypoeutectic. It is important to mention that the same cutting process was used for the extraction of the samples for metallography. The characterization indicated that:

- The base alloy 0Nb/0Mo (Fig. 3a) is composed of primary chromium carbides embedded in a matrix of martensite and secondary carbides;