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Effects of tungsten on the microstructure and on the abrasive wear behavior of a high-chromium white iron

E. Cortés-Carrillo [a], A. Bedolla-Jacuinde [a,*], I. Mejía [a], C.M. Zepeda [a], J. Zuno-Silva [b], F.V. Guerra-Lopez [b]

[a] *Universidad Michoacana de San Nicolas de Hidalgo, Mexico*
[b] *Universidad Autónoma del Estado de Hidalgo, Mexico*

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ABSTRACT

In the present study, systematic additions of tungsten (up to 10.3 wt%) and their effects on the microstructure, hardness, microhardness, and abrasive wear of 17%-Cr white iron was analyzed. Six high-chromium iron alloys with different tungsten additions were melted in an open induction furnace and cast into sand molds to obtain 50-mm × 25-mm cross-sectional bars. The alloys were characterized by optical and electronic microscopy, energy dispersive spectroscopy, and X-ray diffraction. The bulk hardness and microhardness of the different phases of the microstructure (matrix and carbides) were measured in the as-cast conditions and after a destabilization heat treatment at 950 °C for 45 min. Abrasive wear resistance tests were undertaken for the different irons according to the ASTM G65 standard in both as-cast and heat-treated conditions. The results show that, when tungsten is added up to 4 wt%, it partitions either to the matrix or to the M_7C_3 carbide, causing a moderate strengthening in both phases and contributing to an increase in the overall hardness of the alloys. When tungsten additions are higher than 4%, the presence of harder M_2C and M_6C carbides is prevalent in the microstructure and the bulk hardness of the alloys increased. The wear behavior was found to be consistent with the hardness values; an increase in the wear resistance occurred as the tungsten additions were increased. However, such an increase in the wear resistance is not considerable (just 13% higher for 10.3% tungsten addition to the iron). Tungsten was found not to have an important effect on the secondary carbide precipitation during heat treatment, and the wear behavior had the same trend as that in the as-cast alloys. The results are discussed in terms of the partition of tungsten to the carbide and matrix and on its tendency to form harder M_6C-type carbides.

1. Introduction

The mining and mineral processing industry, which is one of the main consumers of high-chromium white irons, demands increasingly wear resistance to improve operations. Researchers all around the world are still working on this traditional alloy, trying to improve its wear resistance and fracture toughness, the main requirements in typical applications in the mineral processing industry (grinding, crushing, milling, pumping, etc.).

One strategy to improve wear resistance has been through the use of alloying elements; particularly, the addition of carbide-forming elements to obtain harder carbides or to increase the eutectic carbide's hardness. Alloying elements such as vanadium, tungsten, titanium, and niobium have been added to white iron alloys [1–15] with different levels of success. The aim of these additions, as stated before, is usually to achieve some modification of the eutectic carbide structure by obtaining harder carbides, although they may improve the hardenability of the matrix.

In the particular case of tungsten addition, some important works are highlighted. Kopycinski and Piasny [16] added combinations of tungsten and titanium at concentrations of 5% to a high-chromium cast iron and reported the formation of metal carbides (MCs) additional to the eutectic M_7C_3. They argued that the formation of these carbides caused a beneficial effect in the as-cast properties, particularly in the wear resistance. They also highlighted that the presence of titanium masked the possible effect of tungsten since the presence of primary MCs is notorious in the structure.

Since tungsten partitions to the carbide and to the matrix, it has been used in combination with molybdenum to increase hardenability. Yokomizo et al. [17] added combinations of tungsten and molybdenum to explore the continuous-cooling curves in high-chromium white irons and found that the presence of tungsten retards the pearlite formation; this means that it improved the hardenability when combined with molybdenum.

Tungsten contents up to 25% have been used for different amounts

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* Corresponding author.
E-mail address: abedolla68@gmail.com (A. Bedolla-Jacuinde).

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of chromium and molybdenum in particular applications of impellers for slurry pumping in the mining industry [18]. Microstructural results for these irons indicate the formation of M_6C carbides when the tungsten content is higher than 10%. For this particular operation, in an erosive and wet environment, corrosion resistance plays an important role, and the authors have reported that the incorporation of tungsten and chromium produces a good combination of erosion-corrosion resistance. Some other studies on erosion-corrosion in white irons with tungsten contents up to 2.5% and 28% Cr [19] report an improvement on this property due to the presence of tungsten that increases the hardness of both the matrix and the eutectic carbide.

In hypereutectic irons with 24% Cr and 2.8% W [20], the presence of tungsten produced an increase in the eutectic carbide volume fraction. This paper also reported a homogeneous distribution of tungsten in both the matrix and the carbides; no other carbide type was reported due to the low content of tungsten. The presence of this element was reported to produce more martensite in the as-cast structure, which increased the hardness as well as the wear resistance.

In irons with carbon contents between 2.3 and 3.2%, chromium between 21 and 23%, and tungsten between 10 and 12%, Heydari et al. [21] reported the formation of complex constituents that contain tungsten-rich austenite and W_6C carbides, suggested to be formed due to a eutectic reaction along with the M_7C_3 carbide during the solidification process. An improvement in wear resistance has been reported for higher concentrations of carbon and tungsten.

In hypereutectic irons [22], the presence of 12% W has been reported to produce larger primary carbides and to change the eutectic carbide morphology. It has also been reported that tungsten is distributed uniformly in both the matrix and eutectic carbides.

In a general way, the presence of tungsten has been conducive to improving the wear resistance in different ways: by increasing the hardness of the matrix due to the solid solution or by the formation of higher martensite amounts; by the increase in the hardness of the eutectic M_7C_3 carbide; or by contributing to form some other carbides such as MC, M_2C, or M_6C. Furthermore, special casting techniques have been successfully applied to incorporate WC particles into the liquid iron during casting to produce WC-reinforced composites [23]. Then, according to the literature, when the main goal is to increase wear resistance, the addition of tungsten to white irons could help.

2. Experimental procedure

The high-chromium irons used in the present study were made in a laboratory induction furnace by using high-purity raw materials. Six alloys with different tungsten contents were produced and cast in sand molds. The calculated chemical composition was selected as: 15% Cr, 3% C, 2% Mo, 0.5% Ni, 0.5% Si, 1% Mn, and different contents of W, ranging from 0 to 10%. 3 kg of each alloy was melted and poured at 1490 °C into sand molds for each composition. The cavity in the mold was rectangular bar-like, and bars of $50 \times 25\ \mathrm{mm}^2$ cross section were obtained in the as-cast conditions. Chemical analysis was undertaken by spectrometry from chill samples obtained during casting for each alloy, and the results are shown in the next section.

Half of the material was heat-treated at three different temperatures (850, 900, and 950 °C) for 45 min to destabilize the austenite, and then was air-cooled to room temperature. Samples for metallography and wear tests were obtained from the alloys in the as-cast and heat-treated conditions. The sample cutting was carried out on a Discotom by using an abrasive disc; the cutting was driven as slowly as possible in order to avoid excessive overheating that may cause cracking in the samples. Additionally, copious amounts of water as coolant were used.

Samples for metallography were prepared in the traditional way with abrasive paper and then polished on nylon cloths using diamond paste. Once polished, the specimens were etched with Vilella's reagent (5 mL of HCl and 1 g of picric acid in 100 mL of ethanol) for 30 s to reveal the microstructure. The carbide volume fraction was measured by image analysis on digital micrographs. The phase constitution was determined by X-ray diffractometry in a SIEMENS 5000 diffractometer by using Cu-Kα radiation in a 2θ range of 30–130°. Scanning electron microscopy (SEM; JEOL 6400) was also used for imaging. The wear behavior testing of the high-chromium irons in the as-cast and heat-treated conditions was undertaken under abrasive wear by using a rubber wheel testing machine and using silica sand as the abrasive.

The wear tests were performed by placing the rubbing surface of the wheel against a $(25 \times 25)\text{-mm}^2$ surface of the iron sample with a contact load of 30 N and pouring the abrasive particles between the surfaces. The rubbing surfaces were in contact for 15 min at a speed of 500 rpm. The iron samples were polished to a 0.25-μm finish before the test. The volume lost from each sample was determined by an optical profiler, a NANOVEA PS50 3D Non-Contact Profiler. Worn surfaces and worn surface cross-sections were characterized by SEM.

3. Results and discussion

3.1. Microstructure, as-cast and heat-treated

The chemical composition of the experimental white irons is given in Table 1. As can be seen, the composition is quite homogeneous and the different tungsten contents ranging from 0 to 10.3% are clearly highlighted. Small variations in carbon and chromium may contribute to small variations in the eutectic carbide volume. However, as shown below, the important variations in the carbide volume are clearly influenced by the tungsten content. Variations in Mo, Ni, and Mn could influence the hardenability and, therefore, the martensite content in the as-cast conditions. For these variations, we consider that there is no significant effect, as the presence of tungsten may mask this effect since it partially dissolves in austenite, thereby increasing the hardenability.

As reported elsewhere, the typical as-cast microstructure for these kinds of alloys is a network of eutectic M_7C_3 carbides in an austenitic matrix [24]. Small amounts of martensite are also present in the eutectic areas or at the periphery of the primary austenite. These areas are depleted in carbon since, during cooling, the solubility of carbon in austenite diminishes and the eutectic carbides absorb such carbon. Therefore, during cooling, these areas of austenite transform to martensite since the low carbon content raises the martensitic transformation start temperature (Ms) [25]. In addition, small amounts of molybdenum carbide (Mo_2C) could be present in these alloys since molybdenum is commonly added to increase hardenability, but it is well known that this element partitions not only to the matrix and the eutectic carbide, but also forms its own M_2C carbide at the end of the solidification process [26–28].

Table 1
Chemical composition for the six white irons under the study.

	C	Cr	Mo	Ni	Si	Mn	W	Fe
Cast 1	2.71	16.97	1.88	0.57	0.66	1.04	**0.00**	Balance
Cast 2	2.79	17.29	1.78	0.59	0.64	1.08	**0.65**	Balance
Cast 3	2.89	17.27	1.80	0.61	0.59	1.12	**1.48**	Balance
Cast 4	2.60	17.13	1.71	0.63	0.70	1.08	**2.01**	Balance
Cast 5	2.69	17.06	1.79	0.73	0.64	1.00	**4.21**	Balance
Cast 6	2.67	17.10	1.80	0.67	0.66	1.03	**10.3**	Balance

*Note: the amount of each element is in %wt.