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Heat treatment featuring the key-parameters of high chromium white cast iron microstructure

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ABSTRACT

The high chromium white cast iron (HCWCI) has been on the scene for decades, with expectations to remain there due to its exceptional wear resistance. HCWCI is mostly applied as-cast, but it can also be used as a coating material. The carbides in HCWCI microstructure, whose composition depends on alloying and heat treatment regime, give this special feature to white cast irons. The investigation presented in this paper was carried out by examining two HCWCI alloys, denoted HCWCI_1 and HCWCI_2, both alloyed with molybdenum in addition to high chromium content. The HCWCI_1 alloy contains 24.48% Cr with 1.32% Mo, and HCWCI_2 contains 14.11% Cr with 2.47% Mo. Comprehensive qualitative microstructural characterization was performed on all types of samples: as-cast samples, those obtained after quenching (at -196 °C) and/or quenching followed by tempering (at 250 °C). Besides standard etching procedures, the selective color etching was also applied here. The microstructure parameters, such as width of secondary dendritic arms and carbides size, are measured and correlated with applied alloy obtaining procedure and heat treatment regime, so they can be discussed in relation to the microconstituent's ratio (such as ratio of different carbides) and morphology.

Keywords: correlation structure-characteristics, wearing, carbides, molybdenum, eutectic, austenite.

1. Introduction

White cast iron with high chromium content, also known as high chromium white iron (HCWCI), is a type of white cast iron that contains a significant amount of chromium in addition to carbon. The chromium content can range from 11% to 35%, ensuring a high level of wear resistance, corrosion resistance, and toughness (Sudhakar et al. 2022, Bedolla-Jacuinde et al. 2019, Bedolla-Jacuinde et al. 2021, Chabak et al. 2023). HCWCI is often used in applications that require exceptional wear resistance, such as mining equipment, oil drilling bits, rail track components, and the power generation industries. It is used in a variety of components, such as grinding balls, mill liners, crusher parts, and pumps.

The high chromium content in HCWCI creates an as-cast hard and wear-resistant microstructure that is composed of carbides, and other microconstituents (austenite, pearlite, martensite, and bainite) depending on the exact chemical composition, the ratio of main alloying elements, and temper state (Li et al. 2023, Filipović et al. 2014). The carbides, which are primarily made up of chromium, are dispersed throughout the matrix of the material, giving it high resistance to abrasive wear (Filipović et al. 2011, Wang et al. 2022, Çöl et al. 2016, Guerra et al. 2019). The martensite, which forms during the cooling process, provides the material with high tensile strength and toughness (Agunsoye et al. 2013). One of the most important characteristics of HCWCI is its corrosion resistance. The chromium in the material protects it from corrosion in aggressive environments. However, like other types of white cast iron, HCWCI is also brittle and can be challenging to work with. It can be prone to cracking during manufacturing or when subjected to impact or shock loading. To improve the mechanical properties of white cast iron, it must undergo heat-treatment to produce a specifically designed microstructure.

White cast iron with molybdenum and high chromium content is also known as high chromium-molybdenum white iron (HCMWCI). The high chromium content provides it with exceptional wear resistance, while the molybdenum content enhances its toughness and corrosion resistance. However, the addition of molybdenum to the material leads to the formation of a bainite, thereby imparting better toughness and impact resistance (Chen et al. 2020).

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2. Materials and methods

This investigation was conducted by metallographic examination of two HCWCI alloys. Both alloys were induction melted and cast into silicate sand molds bonded with CO2. Their chemical composition is presented in Tables 1 and 2. Heat treatment was conducted in an electrical furnace prior to sample preparation for testing. Samples were examined as-cast, after quenching (heated up to 1000 °C for 2 hours and cooled down to -196 °C), and quenching (from 1000 °C for 2 hours) followed by tempering at 250 °C for 3 hours.

Table 1 Composition of the high chromium white cast iron alloy 1: HCWCI_1

Alloy	C [%]	Cr [%]	Mo [%]	Ni [%]	Si [%]	Mn [%]	P [%]	S [%]
HCWCI_1	2.66	24.48	1.32	1.6	0.99	0.96	0.027	0.009

Table 2 Composition of the high chromium white cast iron alloy 2: HCWCI_2

Alloy	C [%]	Cr [%]	Mo [%]	Cu [%]	Si [%]	Mn [%]	P [%]	S [%]
HCWCI_2	3.29	14.11	2.47	0.94	0.87	0.93	0.028	0.003

The microstructure was assessed based on measuring the grain size and distribution by the linear-intercept technique, as defined in EN ISO 4499-2:2020 standard. An optical microscope equipped with the Image analysis device Leica Q5000MC was used.

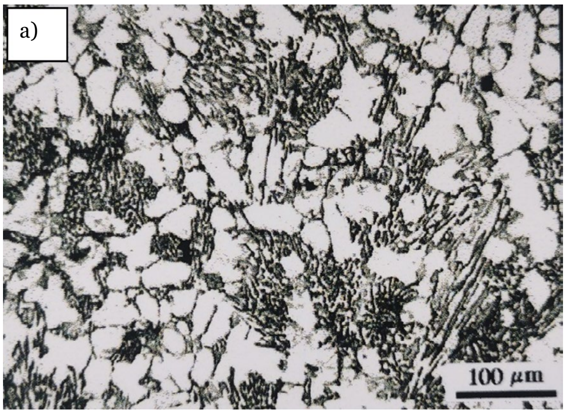
For preparation, specimens were fine grinded up to 1000 grit paper quality, polished with alumina slurry kit, and then cleaned ultrasonically in ethanol and water. For microstructure revealing, the etching agents such as: hydrochloric acid, picric acid, nital (nitric acid in ethanol) and Murakami's reagent (potassium ferricyanide and potassium hydroxide mixture) were used, tailored to the alloy temper and the specific features to be revealed in the microstructure.

3. Results and discussion

The as-cast microstructures of both alloys consist of primary dendrites of austenite (γ) and carbides. HCWCI alloys contain several types of carbides M_3C, M_7C_3 or $M_{23}C_6$, depending on the alloy composition and heat treatment employed (Agunsoye et al. 2013). Figure 1 presents as-cast microstructure of both alloys at the same magnification, a) HCWCI_1 and b) HCWCI_2. The microstructure was revealed by etching in nital+picric acid. A finer and more homogeneous dendritic structure is observed in the HCWCI_2 alloy, at the same magnification, in an alloy with lower Cr, but higher Mo content. There are primary γ dendrites and eutectic, which consists of carbides and γ. According to the alloys composition and literature (Chen et al. 2020), carbides are predominantly of M_7C_3 type, but Mo_2C carbides can also be present, typical for this alloy composition (Maratray and Usseglio-Nanot 1971). Selective color etching used in metallography enables microstructure revealing by color, and hence allows specific stereological features detection and measurements. The result of selective color etching in Murakami's reagent is depicted in Figure 2. Here, Mo_2C carbides containing Mo are present in the microstructure of the base metal. It has been reported (Maratray and Usseglio-Nanot 1971) that the presence of Mo_2C is confirmed in all studies concerning Mo-containing alloys, and has been proven by XRD examinations, appearing in small patches of eutectic, just like in Figure 2.

Figure 3 a) HCWCI_1 and b) HCWCI_2 alloys, at comparable but higher magnification than in Figure 1, show microstructures developed by nital+picric acid etching. This reveals that the microstructure of HCWC_1 alloy consists of primary phase islands surrounded by the eutectic. HCWCI_2 exhibits a microstructure with well-pronounced dendrites.

After austenitizing heat treatment at 1000 °C, followed by quenching and cooling down in liquid N2, fine precipitates of secondary carbides are observed in the dendritic regions, the amount of γ retained in the dendrite area increased, and martensitic transformation can be noted.



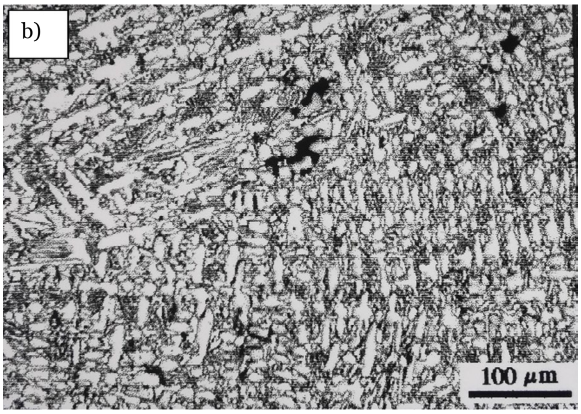


Fig. 1. As-cast microstructure of a) HCWCI_1 and b) HCWCI_2

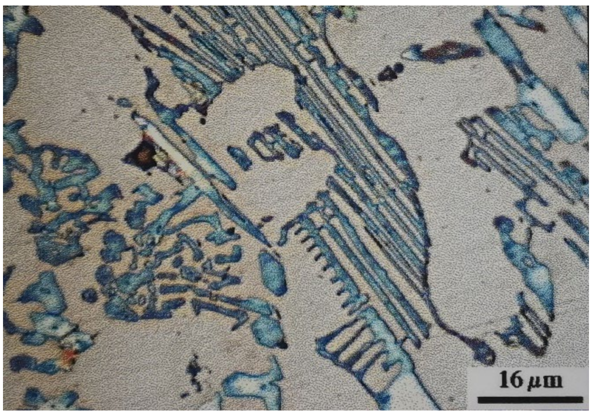


Fig. 2. As-cast microstructure of HCWCI_1, etched in Murakami's reagent

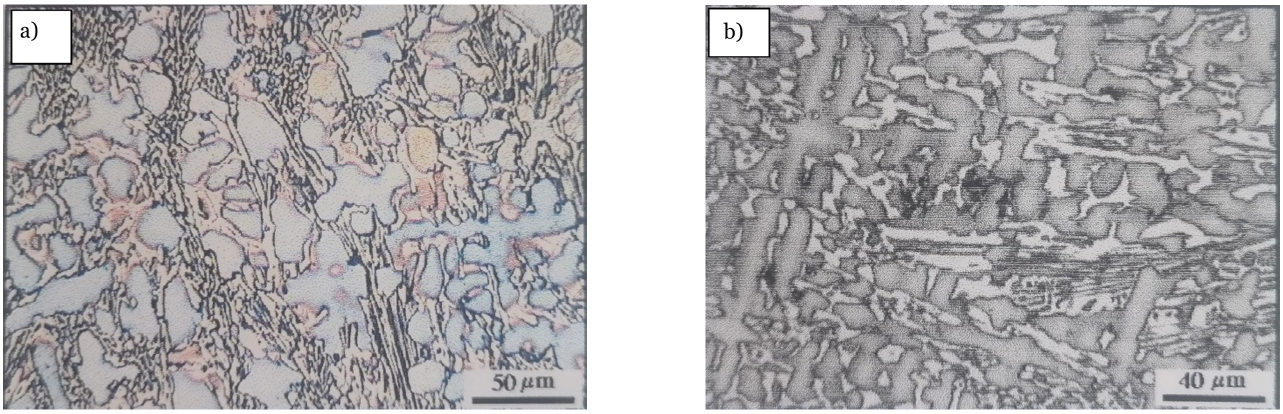


Fig. 3. As-cast microstructure of a) HCWCI_1 and b) HCWCI_2

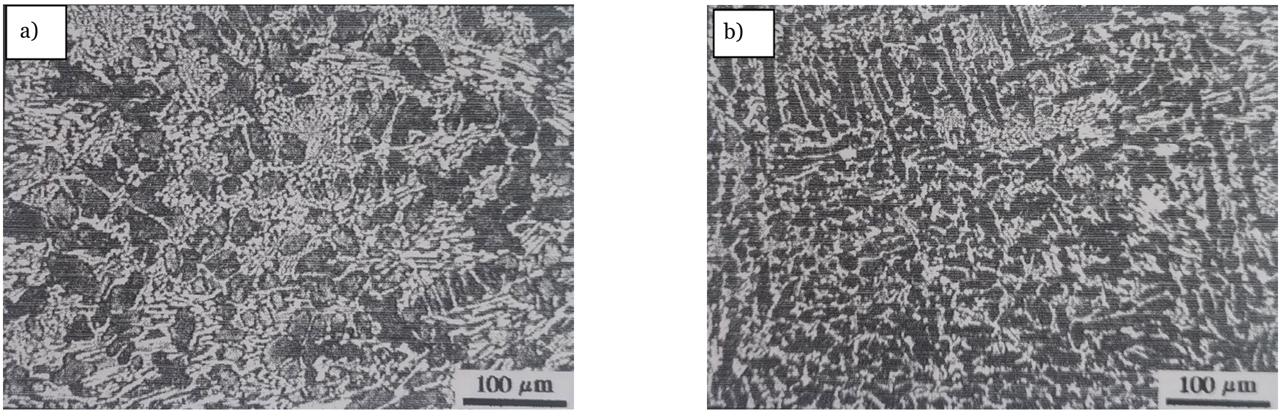


Fig. 4. Quenched and tempered Microstructure of a) HCWCI_1 and b) HCWCI_2

Similarly, after austenitizing heat treatment at 1000 °C and subsequent quenching followed by a slow (atmospheric) cooling down, instead of martensitic transformation, the bainitic phase is revealed, as shown in Figure 4. HCWCI_2 alloy, which has lower Cr, but higher Mo content, exhibits a finer microstructure. The distribution of the austenite transformation products and precipitated carbides is more uniform compared to the as-cast samples.

Conclusion

Microstructure developed during heat treatment of cast iron with molybdenum and high chromium content (HCMWI) revealed carbides as the primary microconstituent, which form due to the high levels of chromium and molybdenum in the material. Carbides present here are mostly of M_3C and M_7C_3 type, but also include the Mo_2C carbide, which is typical for this alloy. Martensite in HCMWI forms during the fast cooling process from the austenitic phase (quenching). Martensite is notably hard and contributes high tensile strength to the material. Bainite is a microconstituent in HCMWI that develops due to the addition of molybdenum in the alloy It forms at lower cooling rates and provides the material with improved toughness and ductility. Given its contribution to the alloy's performance, this technological parameter is critically important.

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