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Effects of niobium addition on microstructure and tensile behavior of as-cast ductile iron

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A R T I C L E I N F O

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A B S T R A C T

The effects of niobium addition up to 0.11 wt% on the microstructure and tensile properties of as-cast ductile iron (ACDI) were investigated. Metallographic analyses by both optical microscopy (OM) and scanning electron microscopy (SEM) indicated that niobium (Nb) promoted the formation of pearlite, reduced pearlite lamellar spacing and decreased the extent of graphitization taking place in the Nb-alloyed ACDI. The nodularity and nodule counts of graphite changed insignificantly when the Nb content was less than 0.08 wt% in the ACDI. The analysis of precipitates by transmission electron microscopy (TEM) revealed that nano and micro sized (Nb, Ti) C carbides acted as nucleation site for graphites, and promoted the formation of large graphite nodules with low roundnesses as Nb content rose above 0.08 wt%. The results of tensile testing showed that the yield strength, ultimate tensile strength and elongation of the ACDI with 0.08 wt% Nb increased by 12.1%, 11.2% and 14.3% over those of the Nb-free ACDI, respectively. The optimum values of the yield strength, tensile strength and elongation of the Nb-alloyed ACDI were found to be 418 MPa, 746.0 MPa and 8.0%, respectively, at the Nb content of 0.08 wt%. The high strain hardening rates of the Nb-containing ACDIs implied that they were capable of spontaneously strengthening itself increasingly to a large extent, in response to a slight plastic deformation after yielding.

1. Introduction

More than 90% by weight of metallic materials used by human beings are ferrous alloys, which are classified into two groups based on the carbon (C) content in the alloys. Steel generally contains between 0.04 and 1.7 wt% C, while cast irons have between 1.8 and 4.0 wt% C [1]. Compared to steel, cast irons have relatively low melting temperatures, very good fluidity and castability, and moderate shrinkage during solidification and cooling [2,3]. But, engineering applications of cast irons were limited until ductile irons were successfully developed by adding a small amount of magnesium and/or cerium to the gray iron in 1948 [4,5]. Nowadays, ductile irons are widely used for manufacturing wheels, bearings and gears due to its excellent castability, good mechanical properties and low cost [3–8]. Due to the spherical graphite morphology, the strength of ductile iron is equivalent to that of carbon steel. Iacoviello et al. [9] found that graphite nodules present in the matrix of ductile iron behaved almost like voids with regard to mechanical properties. Ductile iron comprising graphite nodules with high counts and low average diameters exhibited better mechanical properties. In the past decades, the implementation of heat treatment processes and the introduction of alloying elements have been proven to be critical for the mechanical property improvement of ductile iron. Resulting from the application of heat treatment, austempered ductile iron (ADI) is one of the most studied variants for its excellent tensile strength, ductility and wear resistance [10–12]. However, increased manufacturing cost and extended production cycle limit a widespread application of austempered ductile iron. Research interests [13–18] have also been in developing alloying methods, in which the effects of alloying elements, such as copper, nickel or molybdenum on the improvement of the tensile strength, hardness, wear resistance and

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ductility of ductile iron are investigated. The introduction of different alloying elements into ductile iron enables the control and manipulation of phase constitution, microstructural refinement and solution strengthening. Consequently, the mechanical properties of ductile iron are improved and even optimized to achieve both high strengths and ductilities. Among various alloying elements, niobium is widely used for microstructural control in nickel-base alloys [19–21], steel [22–24] and cast irons [25–33]. Smith and Patel [21] pointed out that niobium, as a refractory element, was capable of improving mechanical properties of nickel-base alloys through carbide formation and precipitation hardening despite its limited benefit as a solid solution strengthener due to its relatively low melting point and modulus compared to other refractory elements (Mo. Ta and W). The review given by Morrison [22] recognized the advantages of adding a small amount (< 0.12 wt%) of niobium to C–Mn steels for property improvement. The Nb addition not only refined grain structure but also precipitated nano-sized NbC or NbCN particles during normalizing treatment. Mohrbacher [23] observed similar phenomena in multiphase steels microalloyed by Nb (< 0.2 wt%).

Nb microalloying to grey cast iron and its influence on mechanical properties are widely studied [25–29]. Zhou et al. [25] found that, adding about 1.48 wt% Nb to grey cast irons increased hardness and wear resistance considerably due to the massive presence of large-sized NbC phases with dimensions over 10 µm, an increase in the number of eutectic cells, and a reduction in the graphite size and the pearlite interlamellar spacing. The study by Devecili and Yakut [27] showed that the addition of 0.65 wt% Nb led to the formation of 10 µm chunky Nb and Ti containing phases in grey cast irons, and improved their abrasion resistance and tensile strength. It has been indicated [26] that, with niobium level above 0.1 wt% primary NbC carbides could be formed in the liquid iron, which acted as nuclei for the eutectic reaction, i.e., the transformation of the liquid phase into austenite and graphite or cementite. This explained the observation, that the eutectic cells became finer with niobium additions. When the niobium content exceeded the alloying limit of 0.2 wt%, such primary carbides were formed already at elevated temperature becoming coarser with time and could thus be found in the microstructure as NbC even by optical microscopy. Zhu et al. [29] introduced 0.11 wt% Nb into grey cast irons and observed their improved high-temperature tensile strength and oxidation resistance. It was noted that brittle breaking occurred with the specimen containing niobium of 0.037 wt%, and ductile breaking occurred with the specimen containing niobium of 0.11 wt%, and the fracture exhibited ductile dimples. Fraś et al. [30] studied the effect of small additions of niobium (up to 0.038 wt% Nb) on structure and mechanical properties of ductile iron. It was indicated that niobium increased graphite nodule count with small diameters and the fraction of carbides in ductile iron, although the effect of small additions of niobium on type of matrix is negligible. The Nb-alloyed ductile irons exhibited the improved tensile and yield strengths, but the reduced elongation. The work by Souza et al. [31] showed that the 0.47 wt% Nb addition to nodular cast irons (NCIs) led to a 20% increase in their yield and tensile strengths over the values for the Nb-free NCI because of the increase in pearlite content. A modest increment of tensile ductility and Charpy toughness appeared while only 0.23 wt% Nb was introduced. Alias et al. [32] alloyed the ductile iron with 0.5–2.0 wt%. Their results showed that the Nb addition in ductile iron provided significant enhancement in mechanical properties when compared to unalloyed ductile iron. Addition of higher amount of niobium had further increased the strength and impact toughness properties. Bedolla-Jacuinde et al. [33] investigated the effect of niobium in the range of 0–0.8 wt% in Ni-containing ductile cast irons. Niobium was observed to be directly related to the formation of polygonal niobium carbides of the type NbC, which had the size of as large as 8 µm in the irons with 0.8 wt% Nb. The amounts of pearlite and ferrite phases were not affected by the niobium content added in their study. Neither nodule count nor nodularity was affected by such niobium addition. The Nb effect on the microstructure of the Ni-containing ductile iron contributed to a small increase in yield and tensile strength as well as in hardness along with a decrease in ductility. So far, it appears that Nb addition to ductile iron has not been extensively studied, in particular at a microalloying level of up to 0.10 wt%, although, in principal, it could provide microstructural refinement and precipitation strengthening due to its strong carbide forming tendency. It is of interest whether similar positive effects of Nb microalloying on the mechanical properties of ductile cast iron could be obtained.

In the present work, the effects of Nb microalloying up to 0.11 wt% on the microstructure of the as-cast ductile iron (ACDI) were studied using metallographic analyses. The microstructural analyses by optical microscopy (OM), scanning electron microscopy (SEM) and transmission electron microscopy (TEM) revealed that phase constituents and constitution as well as phase morphology in the ACDI were influenced by Nb addition. The mechanical properties of the Nb-alloyed ACDI were evaluated by tensile testing. Based on the results of tensile testing, the optimum content of Nb with respect to both improved tensile strengths and elongations was identified.

2. Experimental procedure

2.1. Material preparation

The raw materials employed in this study were pig iron, steel scrap, 80MnFe, copper, nickel and ferro-niobium (Fe65Nb). All the materials were melted and homogenized at 1520–1540 ℃ in an induction furnace having a maximum capacity of 16 kg. Upon the completion of placing 1.2 wt% Fe-Si-Mg-Ba alloy (41.3 wt% Si, 6.9 wt% Mg and 1.52 wt% Ba) on the bottom of the preheated ladle (covered with an iron sheet), the melt was poured into the ladle at a temperature of 1440–1460 ℃ for spherodization. After skimming the slag off the surface of the spherodized melt, 0.8 wt% Fe-Si-Al alloy (74–79 wt% Si, 0.8–1.6 wt% Al and 0.5–1.0 wt% Ca) was added for inoculation. At last, all the melts were poured into a Y-block sand mold as illustrated in Fig. 1. It should be noted that a small amount of melt was poured into a metal mold for producing white iron specimens with a dimension of 0.004×Φ0.040 mm, which were used for the chemical composition verification. The results of chemical analyses are shown in Table 1.

2.2. Microstructural analysis

Metallographic specimens were sectioned, mounted, and polished from the bottom of Y-type specimens, and prepared following the standard metallographic procedure. After polishing and 4% Nital etching of metallographic specimens obtained from the bottom of Y-

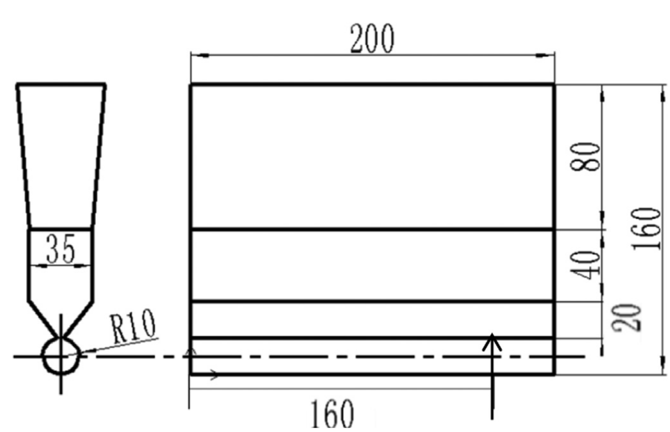

Fig. 1. Dimensions of the Y-block sand casting employed in the present study, and the arrow-pointed location in which specimens were sectioned for metallographic analyses and mechanical testing.