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As-cast mechanical properties of vanadium/niobium microalloyed steels

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Abstract

Tensile and room temperature Charpy V-notch impact tests along with microstructural studies were used to evaluate the variations in the as-cast mechanical properties of low-carbon steels with and without vanadium and niobium. Tensile test results indicate that good combinations of strength and ductility can be achieved by microalloying additions. While the yield strength and UTS increase up to respectively 370–380 and 540–580 MPa in the microalloyed heats, their total elongation range from 20 to 25%. TEM studies revealed that random and interphase fine-scale microalloy precipitates play a major role in the strengthening of the microalloyed heats. On the other hand, microalloying additions significantly decreased the impact energy and led to the dominance of cleavage facets on the fracture surfaces. It seems that heterogeneous nucleation of microalloy carbonitrides on dislocations along with coarse ferrite grains and pearlite colonies trigger the brittle fracture in the microalloyed heats.
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Keywords: Cast steel; Microalloyed steel; Niobium; Vanadium

1. Introduction

Although wrought grades of microalloyed steels have been available for years, demands for producing low-cost, higher strength steel castings with good toughness and weldability have encouraged some researchers to focus on cast grades of these steels. Microalloyed cast steels are basically low to medium carbon steels with manganese levels in the 1.2–2 wt% range, and additions of conventional microalloying elements such as titanium, niobium, and vanadium [1,2]. Some grades of microalloyed cast steels, especially French grades, are alloyed with nickel [3]. These steels exhibit a combination of high strength with good toughness and weldability. Nowadays, microalloyed cast steels have found many applications in the manufacturing of industrial parts such as offshore platform nodes, centrifugal cast pipes, machinery supports, nuclear reactor support frames, natural gas compressor housing, ingot moulds and buckets which were all produced by expensive manufacturing processes before [2,4].

Since most of these parts have to be heat treated before use, the effects of different heat treatment variables have been the subject of many investigations [3–7]. The heat treatment of these steels has been generally performed in three stages: homogenization, austenitization followed by quenching or air cooling, and tempering at subcritical temperatures. It has also been reported that special intercritical heat treatments can be used to improve the toughness of these materials. Basically, the ultimate goal of these heat treatments is to benefit from fine ferrite grains by controlling austenite grain growth and precipitation hardening. Hence, the microalloying elements niobium and vanadium are added to microalloyed cast steels primarily to provide grain refinement and response to aging. Niobium, often at levels of less than 0.05%, effectively prevents undesirable grain growth and can also contribute to precipitation strengthening. Vanadium, in particular, at levels of less than 0.1% forms strengthening carbonitride precipitates [8–12].

In contrast to the heat-treated grades, mechanical and microstructural properties of as-cast microalloyed steels have not been investigated yet. Therefore, it seems valuable to study the mechanical properties of the cast microalloyed steels in the as-cast condition in order to examine the possibility of achieving good combinations of properties and producing some industrial parts with these inexpensive steels.

The objective of this study was to assess the influence of vanadium and niobium as microalloying additions on the strength and impact toughness of a low-carbon steel in the as-cast condition.

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Table 1
Chemical compositions of the alloys studied (wt%)

Designation	C	Mn	Si	P	S	Al	V	Nb
B	0.15	1.56	0.35	0.01	0.015	0.03	–	–
V	0.15	1.41	0.31	0.01	0.015	0.02	0.09	–
Nb	0.14	1.50	0.33	0.008	0.010	0.03	–	0.04

2. Experimental procedure

2.1. Materials

A 100 kg capacity, 125 kW, 3 kHz basic lined induction furnace was used for melting. After complete melting of base material, graphite and ferromanganese were added to the melts to adjust carbon and manganese contents. The heats were appropriately deoxidized with ferrosilicon and Al shot. Microalloying elements were added to the melts in the form of ferrovanadium and ferroniobium. The base composition for all heats was selected to be about 0.15 wt% carbon and 1.5 wt% manganese. Vanadium and niobium levels in microalloyed heats were selected to be respectively about 0.1 and 0.04. Furthermore, sulfur plus phosphorous levels ranged from 0.02 to 0.035% for all heats. Table 1 shows the chemical compositions of the heats (B stands for the base composition). All heats were poured directly from the furnace into the moulds at 1590 °C. The test materials were produced in the form of 3-in. Y-blocks using sand moulds.

2.2. Microstructural characterization

Metallographic samples were prepared using standard polishing techniques and were then etched with 2% Nital. An Omnimet image analyzer was used to measure the area fraction of pearlite. Since ferrite grains were not equiaxed in the as-cast microstructures, the ferrite mean free path was used to characterize the fineness of ferrite phase by using following equation [13]:

$$\lambda = \frac{V_{V\alpha}}{N_L}$$

where $V_{V\alpha}$ is the volume fraction of ferrite and N_L is the number of ferrite intercepted per unit length. Twenty measurements were recorded for every microstructure and the average was taken as the area fraction of pearlite and ferrite mean free path.

Etched samples were studied in a CamScan SEM equipped with an Oxford instruments EDS analyzer in order to observe the microstructures more closely. In addition, fractographic examinations of the impact specimens were carried out to allow a better understanding of the micromechanisms of fracture in different alloys.

For TEM studies, slices of about 400 μm in thickness were cut using an electro-discharge machine (EDM). These samples were subsequently ground to a thickness of 100 μm. Discs of about 3 mm in diameter were punched from the thinned wafers and TEM foils were prepared by electropolishing these discs in a Fishione twin jet unit. A solution of 10% perchloric acid in acetic acid electrolyte was used for electropolishing. The foils were examined by a Philips 400T scanning transmission electron microscope operating at 120 kV.

2.3. Mechanical properties

To evaluate mechanical properties, tensile, microhardness, and standard room temperature Charpy V-notch (CVN) tests were conducted. Three tensile specimens prepared according to ASTM-E8 from different parts of each block were tested in an MTS tensile testing machine of 150 kN capacity at a crosshead speed of 1 mm min^{-1}. Three Charpy impact specimens were also prepared from different parts of each block according to ASTM-E23 and tested at room temperature. Vickers microhardness measurements were taken from individual ferrite grains using a load of 5 g. Measurements from 100 grains on each sample were used to calculate the mean value of hardness.

3. Results and discussion

3.1. Microstructural characterization

Optical microscopy studies revealed that the addition of microalloying elements did not considerably change the main microstructural features due to the fact that all microstructures consisted of coarse ferrite grains and pearlite. Representative optical micrographs of the base and microalloyed heats are presented in Fig. 1.

Image analysis and linear intercept method were used to measure pearlite content and ferrite mean free path in order to study the microstructural changes due to the microalloying additions. The results summarized in Table 2 show that the pearlite content in the Nb-bearing heat has increased from 26 to 29%. In other words, the presence of niobium increases pearlite content while vanadium addition does not change it. The observed increase in pearlite content of the Nb-bearing alloy can be related to the behavior of free Nb atoms in austenite which has been recognized as “non-equilibrium segregation” or “quenched-induced segregation” [14,15]. Previous investigations have suggested that Nb atoms segregate to certain microstructural regions such

Table 2
Pearlite content and ferrite mean free path in different alloys

Designation	Ferrite mean free path (μm) ±95% CL[a]	Pearlite content (%) ±95% CL
B	59 ± 2	26 ± 1
V	61 ± 4	26 ± 1
Nb	46 ± 4	29 ± 2

[a] 95% confidence limit.

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