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Effect of Vanadium Microaddition on the Strength of Low-Carbon Cast Steel at Elevated Temperatures

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Abstract

The effect of vanadium microaddition on the strength of low-carbon cast steel containing 0.19% C used, among others, for castings of slag ladles was discussed. The tested cast steel was melted under laboratory conditions in a 30 kg capacity induction furnace. Mechanical tests were carried out at 700, 800 and 900°C using an Instron 5566 machine equipped with a heating oven of ± 2°C stability. Non-standard 8-fold samples with a measuring length of 26 mm and a diameter of 3 mm were used for the tests. It has been shown that, compared to cast steel without vanadium microaddition, the introduction of vanadium in an amount of 0.12% to unalloyed, low carbon cast steel had a beneficial effect on the microstructure and properties of this steel not only at ambient temperature but also at elevated temperatures when it promoted an increase in UTS and YS. The highest strength values were obtained in the tested cast steel at 700°C with UTS and YS reaching the values of 193 MPa and 187.7 MPa, respectively, against 125 MPa and 82.8 MPa, respectively, obtained without the addition of vanadium. It was also found that with increasing test temperature, the values of UTS and YS were decreasing. The lowest values of UTS and YS obtained at 900°C were 72 MPa and 59.5 MPa, respectively, against 69 MPa and 32.5 MPa, respectively, obtained without the addition of vanadium.

Keywords: Low-carbon cast steel, Microaddition elements, Mechanical properties at elevated temperatures

1. Introduction

Low-carbon cast steel is characterized by very good plastic properties with slightly worse strength properties. A ferritic - pearlitic microstructure with the predominant content of plastic ferrite is responsible for this combination of mechanical properties [1,2]. At the same time, these properties can be changed by increasing the Mn content to about 1.8% (solution strengthening) or by introducing micro-additives, such as V, Nb or Ti (structure refinement and strengthening with fine-dispersed particles of carbides and carbonitrides) [2-9].

Owing to its properties, mainly the plastic ones, this material is widely used for various types of castings, including castings whose surface is subjected to carburizing. Additionally, simple melting technology, good weldability and relatively low cost of castings manufactured from this type of steel make it also applicable for slag ladles [10,11]. The operating conditions of such castings are difficult due to the periodically repeated cycles of filling and emptying the ladles with liquid slag from metallurgical process. Hence, the purpose of this article was to show how the strength properties changed at selected temperatures of 700, 800 and 900°C along with the microstructure of low-carbon cast steel containing microadditions of vanadium compared to the cast steel without these additions.

2. Experimental

The tested cast steel was melted under laboratory conditions in a 30kg electric induction furnace. The furnace charge consisted of ARMCO iron, low-carbon steel scrap and ferroalloys of FeMn and FeSi. In the final stage of the melting process, Al and CaSi were used for deoxidation. After deoxidizing the metal bath, FeV was introduced into one of the melts. The chemical composition of molten cast steel is given in Table 1.

Table 1.
Chemical composition of the examined low - carbon cast steels

Material	Elements, wt. %							
	C	Si	Mn	Cr	P	S	Al	other
W	0.16	0.30	1.50	0.03	0.010	0.002	0.02	- 0.009% N
D	0.19	0.50	1.30	0.26	0.014	0.008	0.04	0.12 V 0.01% N

Cast test ingots were subjected to heat treatment including normalizing at 920°C. As a next step, samples for mechanical tests at ambient temperature and non-standard 26xϕ3 mm samples for tests at 700, 800 and 900°C were prepared. The static tensile test was carried out on an Instron 5566 machine equipped with a special Instron heating oven characterized by a ± 2°C stability. Before rupture, the samples were annealed for 10 minutes at the test temperature. Materials testing can be carried out in a wide range of strain rates. Based on the standard for a static tensile test, where the strain rate is kept in the range of 10^{-4} 1/s < ε < 10^{-2} 1/s, the strain rate $\varepsilon = 10^{-3}$ 1/s was selected for the current tests. After rupture, all samples were cooled in water to ambient temperature.
Metallographic examinations including the assessment of microstructure and fractography of the obtained fractures were carried out using a LeicaQWin light microscope equipped with a Leica DFC290 camera and a HITACHI 3200N scanning electron microscope.

3. Experimental results and discussion

The tested low-carbon cast steel containing 0.19% C enriched with the microaddition of vanadium in an amount of 0.12% was characterized by a fine-grained pearlitic-ferritic structure, ensuring in a 15 mm thick cast wall after normalizing treatment at ambient temperature the following mechanical properties: UTS = 748 MPa, YS = 507 MPa, El = 25.3% and RA = 37%. Given that the tested material was intended for high temperature applications, the mechanical tests of cast steel with/without the microaddition of vanadium were carried out at 700, 800 and 900°C. The results of the tests are presented in Figures 1-2.
As expected, the generally known principle, according to which the strength properties of steel decrease with increasing temperature, was confirmed in the case of the tested materials [12]. It was shown that as the test temperature increased, the UTS as well as YS values decreased for both cast steels. However, in the examined range of temperatures, significant differences were observed between the tested materials, which might be due to the differences in microstructure caused by grain fragmentation with fine-dispersed vanadium carbides [13] and partial dissolution of complex carbide precipitates with increasing temperature. According to [12,13], the larger is the size of carbides, the slower they dissolve in the matrix.
It is worth noting that at the test temperatures, the values of UTS and YS were higher for the cast steel with vanadium microaddition. Quite interesting were also large differences between UTS and YS observed in the tested materials at 700°C compared to the results obtained at 800 or 900°C (Figs. 1-2). At 700°C, the values of UTS for the cast steel with and without the microaddition of vanadium were 193 MPa and 125 MPa, respectively, while at 900°C they amounted to 72 MPa and 69 MPa, respectively. The values of YS at 700°C were 187 MPa and 87 MPa, respectively, while at 900°C they reached 60 MPa and 33 MPa, respectively. Based on the results of dilatometric tests carried out for the low-carbon cast steel with 0.2% C (with 0.12% V), it has been established that temperature A_{e1} = 730°C and A_{e3} = 840°C. Therefore, at 700°C (below A_{e1} and A_{e3}), the microstructure of the tested cast steel should consist of ferrite and pearlite, and in the case of cast steel containing the addition of 0.12% V, apart from the phases already mentioned, the cast steel composition should also include fine-dispersed, vanadium-containing precipitates (carbides or carbotrides of the MC type) or complex precipitates enriched with strongly carbide-forming elements, like Cr, Mn and V, e.g. $(Fe, Mn)_3C$ carbides stable only at temperatures above 950°C [12]. However, at a temperature of 800°C (between A_{e1} and A_{e3}), after recrystallization of pearlite, in the microstructure of the tested materials, areas of austenite may additionally appear. In turn, at 900°C (above A_{e3}), only austenite and carbides will be present in the structure. According to [14,15], the total dissolution of vanadium-containing carbides and nitrides in microalloyed steel occurs at a temperature of about 1000°C. Therefore, it can be assumed that in the tested cast steel with the

addition of vanadium, at 800 and 900°C, partial dissolution of vanadium-containing precipitates takes place, which may also reduce the strength properties of the cast steel tested at this temperature. The differences obtained in YS results (Fig. 2) are more difficult to interpret due to the additional impact of trace contents of other elements present in the tested materials.

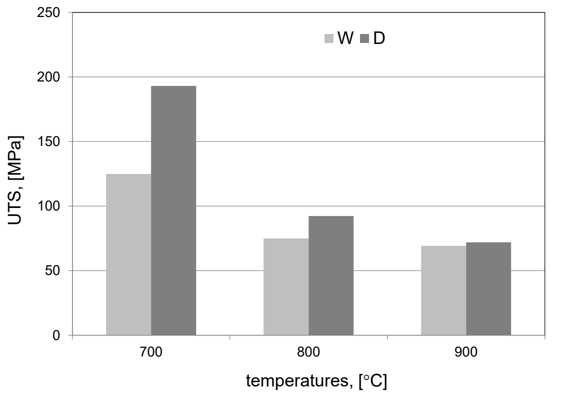


Fig. 1. Dependence of UTS on test temperatures (average of three measurements)

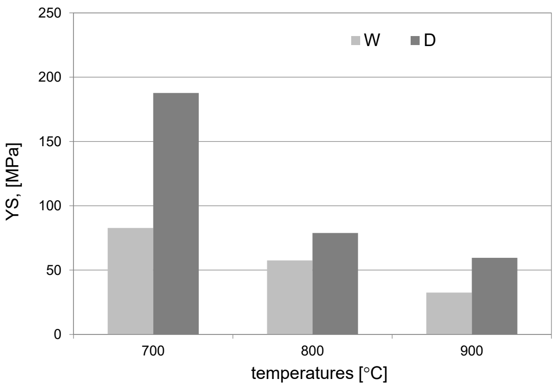
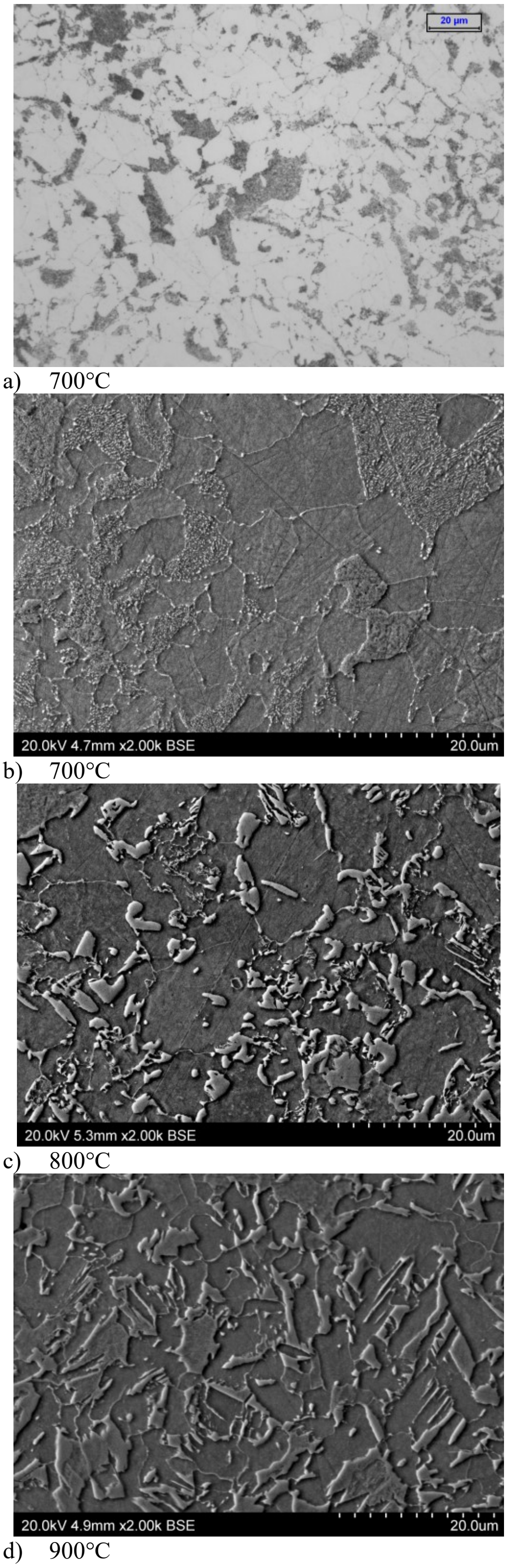


Fig. 2. Dependence of YS on test temperatures (average of three measurements)

After mechanical tests, samples were cut out and prepared for metallographic examinations. Figures 3-4 show the microstructures of low-carbon cast steel after testing at 700, 800 and 900°C. Differences in the cast steel microstructure after heating and holding at selected test temperatures are clearly visible. Therefore, it should be expected that in large castings of slag ladles made of low-carbon steel, under the conditions of their operation, local changes in strength and microstructure may occur with a great impact on the service life.



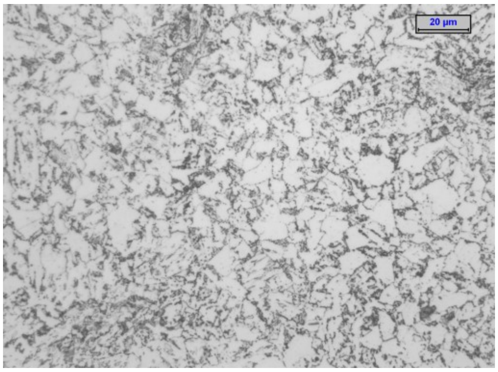
a) 700°C

b) 700°C

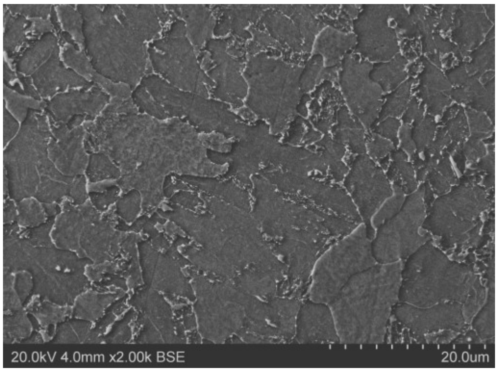
c) 800°C

d) 900°C

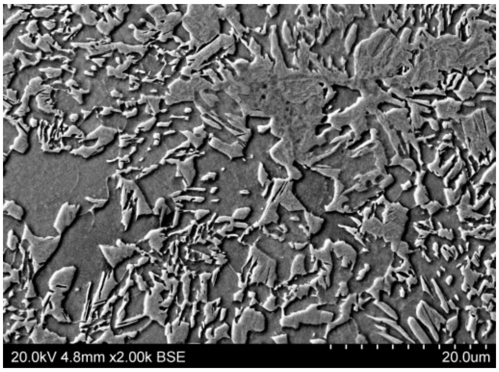
Fig. 3. Microstructures of the investigated cast steel after testing at 700, 800 and 900°C temperatures, **sample W**, nital etching, LM and SEM



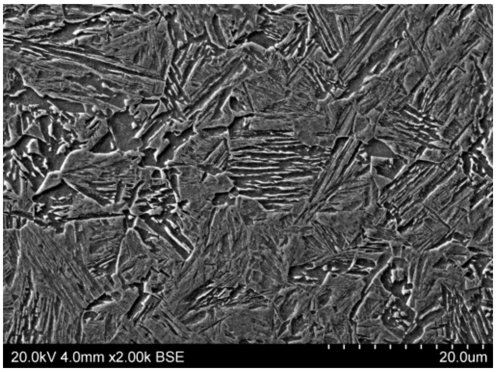
a) 700°C



b) 700°C



c) 800°C



d) 900°C

Fig. 4. Microstructures of the investigated cast steel after testing at 700, 800 and 900°C temperatures, **sample D**, nital etching, LM and SEM

A visual assessment of the scrap of samples after mechanical tests was also carried out. It shows that in all samples which have failed at 700, 800 and 900°C there is a characteristic neck in the zone of rupture (cracks), confirming high plastic properties of the tested cast steel.

The conducted tests have confirmed that it is justified to introduce the microaddition of vanadium into cast steel, as it not only improves the properties of low-carbon cast steel at ambient temperature, but also has a beneficial effect on properties at elevated temperatures (700, 800 and 900°C).

4. Conclusions

- Studies showed that the introduction of 0.12% vanadium microaddition to low-carbon cast steel had a favourable effect on the microstructure and selected mechanical properties of this cast steel~~,~~ at elevated temperatures.
- It was found that as the test temperature increased from 700 to 900°C, the values of both UTS and YS decreased in the investigated cast steel (with/without the addition of vanadium). The probable cause was partial dissolution of vanadium-enriched precipitates taking place with the increasing temperature, the largest difference being reported for the temperature range between 700 and 800°C. On average, for the vanadium-enriched cast steel, the values of UTS and YS have decreased by approx. 48% and 42%, respectively.

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