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INVESTIGATION INTO THE MECHANICAL PROPERTIES OF MICRO-ALLOYED AS-CAST STEEL

RAZISKAVE MEHANSKIH LASTNOSTI MIKROLEGIRANIH JEKEL

Bommannan Chokkalingam[1], S. S. Mohamed Nazirudeen[2], Sukaswami S. Ramakrishnan[3]

[1, 2]Department of Metallurgical Engineering, PSG College of Technology, Coimbatore- 641 004. Tamil Nadu, India
[3]Mechanical Engineering, Karunya University, Coimbatore- 641 114. Tamil Nadu, India
bchokkalingam@gmail.com

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The effects of micro-alloying on the hardness, tensile strength, room-temperature impact energy and elongation of low-carbon as-cast steel have been investigated and compared with non-micro-alloyed as-cast steel. Elements such as vanadium, niobium, titanium and zirconium were added in combination as micro-alloys. The results show that the addition of these elements in the cast steel increases the hardness and tensile strength by 31 % and 10.3 %, respectively, while the elongation and impact energy decrease to 47.5 % and 43.7 %, respectively. This method of alloying refines the microstructure of the cast steel in the as-cast form.

Key words: cast steel, micro-alloying, tensile strength, hardness, toughness

Raziskan je vpliv mikrolegiranja na trdoto, raztržno trdnost, žilavost pri sobni temperaturi in razteznost ogljikove jeklene litine in primerjan z vplivom na litino brez mikrolegiranja. Kombinacije elementov: vanadija, niobija, titana in cirkonija, so bile dodane v litino. Rezultati kažejo, da dodatek teh elementov poveča trdoto in trdnost do 31 % oz. do 10,6 % in zmanjša raztezek za 47,5 %, žilavost pa za 43,7 %. Mikrolegiranje napravi mikrostrukturo jeklene zlitine bolj drobnozrnato.

Ključne besede: jeklena litina, mikrolegiranje, raztržna trdnost, trdota, žilavost

1 INTRODUCTION

In general, based on the method of production, steels can be classified as either wrought or cast steels. Wrought steel products are shaped by plastic deformation, whereas cast steel products are produced by casting methods. Normally, both these processes are used to produce steel products. In particular, the production of intricate internal shapes and complicated designs is easier in cast steel. Moreover, economic production of fewer quantities is an added advantage of the casting process over wrought steel processes. However, the mechanical properties of cast steels are lower when compared with wrought steels. Hence, the improvement in mechanical properties is further required for cast steel due to its wide use in applications like railways, chemical plants, automobiles and petroleum refineries, etc.

Generally, the mechanical properties are improved by alloying. The different types of alloying methods are low-level, medium-level, high-level and micro-level alloying. Among these alloying techniques, micro-alloying[1,2] is one of the methods in which the alloying elements such as vanadium, niobium, titanium and zirconium are added individually up to 0.10 %. The total micro-alloying additions of all these alloying elements combined to be within 0.20 %. This method is widely practiced in wrought steel processing, whereas it is less used in cast steel. A study of the combined addition of vanadium, niobium, titanium and zirconium in cast steel was not found in the existing literature. Hence in this work, the effect of a combined addition of all these alloying elements together in the cast steel was investigated. The microstructure, hardness, tensile strength, impact energy and elongation of micro-alloyed cast steel were investigated and compared with those of non-micro-alloyed cast steel.

2 EXPERIMENTAL PROCEDURE

The melting was performed using a medium-frequency coreless induction furnace with a holding capacity of 50 kg and a basic lining. The non-micro-alloyed and micro-alloyed cast steels' chemical compositions are given in **Table 1**. The mild steel scrap was melted initially and the alloys ferro-manganese, ferro-silicon were added into the melt. The micro-alloyed cast steel composition was achieved by the addition of the necessary alloys after testing the melt using a vacuum spectrometer. The vanadium level was maintained at 0.10 %, while the niobium, titanium and zirconium additions were maintained at 0.05 %, 0.025 % and 0.025 %, respectively. The micro-alloying elements vanadium, niobium and titanium were added into the molten metal in forms of ferro-vanadium, ferro-niobium and ferro-titanium, while ferro-zirconium was added in the ladle during the tapping of the molten metal from the furnace at 1610 °C. The de-oxidisers aluminium and

Table 1: Chemical composition of experimental cast steels in mass fractions, (*w*/%)
Tabela 1: Kemična sestava preizkusnih jeklenih litin v masnih deležih, (*w*/%)

Experimental Steels	Elements in mass fractions, *w*/%								
	C	Si	Mn	P	S	V	Nb	Ti	Zr
Non-micro-alloyed steel (NMA)	0.23	0.42	1.20	0.02	0.03	0.0	0.0	0.0	0.0
Micro-alloyed steel (MA)	0.23	0.42	1.20	0.02	0.03	0.10	0.05	0.025	0.025

calcium silicide were added in the ladle during tapping the molten metal from the furnace. Both molten steels were poured into standard Y-block sand moulds.

The metallographic examinations were made with a light microscope using broken specimens from Charpy impact tests that were also used in the SEM and EDS analyses. These analyses were performed using a scanning electron microscope, JEOL JSM 6360, with an energy-dispersive spectroscopy (EDS) analyzer (LN2 type detector). The accelerating voltage at the time of the EDS was 25 kV, the working distance was 17mm and the probe current was 1.0 nA. The hardness was measured by using a Zwick hardness tester with an indentation load of 10 kg. The impact energy was measured with the Charpy method using standard test pieces (55 mm length, 10 mm square with V notch (45°, 2 mm deep with 0.25 mm radius at the base notch). The tensile test was performed in a Microtek tensile testing machine.

3 RESULTS AND DISCUSSION

3.1 Effects of micro-alloying elements

The purposes of adding micro-alloying elements to the cast steel are either to get fine grains or to form precipitates. The various factors contributing to the increase in hardness of the micro-alloyed cast steel are variations in the pearlite content, the ferrite grain size and the formation of fine carbonitride precipitates. Among these factors, the increase in hardness and strength is mainly due to carbonitride precipitates. Based on earlier studies[3–6], carbonitride precipitates form in the matrix, precipitate at the gamma/alpha interphase and with random precipitation.

The micro-alloying elements titanium and niobium precipitate at elevated temperatures[6–12] and generally, both elements form a precipitate in the matrix. The second and third type of carbonitrides formed when there are sufficient amounts of titanium and niobium present in the form of a solid solution in austenite during the transformation stage at the upper critical temperature.

The micro-alloying element vanadium precipitates as vanadium carbide at lower temperatures on the advancing gamma/alpha interface. It forms either as an interphase precipitate or random precipitate in the super-saturate ferritic matrix. Fine carbonitride precipitates distributed mainly in ferrite grains are very effective at strengthening. Earlier microhardness studies on ferrite grains[5–8] revealed that the increase in the strength/ hardness of micro-alloyed cast steels is mainly due to precipitation hardening, and the effect of solid-solution strengthening is lower. The solid solution of micro-alloying atoms is negligible due to the lower concentration of micro-alloying atoms after the formation of carbonitrides. The increase in the strength and hardness of vanadium micro-alloyed cast steel is due to the formation of vanadium carbonitrides V (CN)[5,6,10,12]. The increase in the amount of micro-alloying elements increases the volume fraction of the precipitates.

Zirconium is a nitride and also a strong oxide forming element. In the solid-state zirconium nitride[11,12] has a high melting point and a high hardness. The zirconium carbide forms at a higher temperature, whereas the zirconium nitride forms at a lower temperature. It was found that the zirconium addition improves the hardness and does not decrease the impact toughness. The zirconium addition causes sulfide inclusions to shape as globular rather than elongated, which improves the toughness and ductility of the micro-alloyed cast steel.

3.2 Microstructures

The microstructure of non-micro-alloyed and micro-alloyed as-cast steels is shown in **Figure 1** (a) and (b)

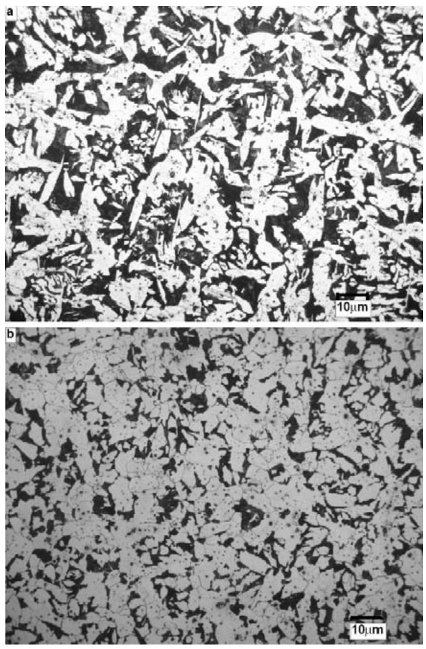

Figure 1: Microstructures of cast steel a) Non-micro-alloyed (NMA), b) Micro-alloyed (MA)
Slika 1: Mikrostruktura jeklene litine a) brez mikrolegiranja (NMA), z mikrolegiranjem (MA)

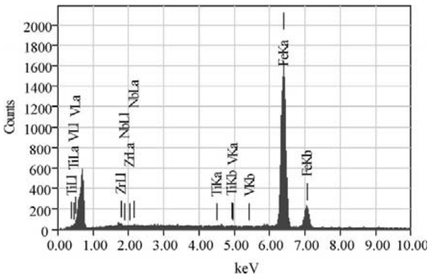

Figure 2: EDS analysis of micro-alloyed cast steel
Slika 2: EDS-analiza mikrolegirane jeklene litine

respectively. The microstructure in **Figure 1b** clearly shows a finer grain size in the micro-alloyed than in the non-micro-alloyed cast steel.

The EDS analysis of the micro-alloyed cast steel is shown in **Figure 2**. This analysis confirms the presence of the elements V Nb, Ti and Zr in the micro-alloyed cast steel.

3.3 Fracture surface

The fractured surfaces of all the broken impact specimens were examined using scanning electron microscopy with the aim to understand the mechanisms of the fracture of both. The fracture surfaces are shown in **Figure 3** (a) and (b). Changes were observed in the fracture with respect to the size, shape, and depth of the micro-voids, and the size and shape of the fracture facets.

The fracture appearance in **Figure 3a** is an intergranular brittle fracture characterized by coarse facets with numerous very small solidification defects, while **Figure 3b** shows a normal brittle fracture with fine cleavage facets without solidification defects.

The causes of the intergranular fracture in the cast steel are sulphur distribution, cooling rate, larger grain size, aluminium and nitrogen contents. The various methods to control these defects are controlling the aluminium and nitrogen contents in the liquid steel, the use of vacuum melting to remove nitrogen to a low level, the addition of cerium to form stable nitrides, and grain refinement by the addition of alloying elements such as titanium, zirconium, vanadium, niobium and boron. Grain refinement is an effective method among these to reduce the intergranular fracture and solidification defects. A finer grain size was obtained by the addition of micro-alloying elements and solidification defects were also not found in the fractured surface of the micro-alloyed cast steel specimen.

3.4 Mechanical properties

The mechanical properties hardness, tensile strength, room-temperature impact energy and percentage elongation given in **Table 2** show the average properties of various test specimens at different positions. The results indicate that the addition of micro-alloying increases

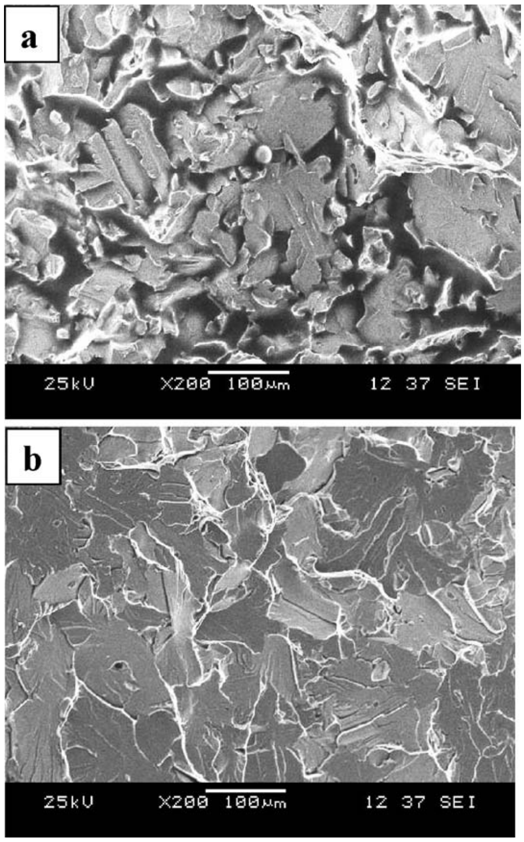

Figure 3: Fracture analysis of cast steel a) Non-micro-alloyed (NMA), b) Micro-alloyed (MA)
Slika 3: Površina preloma jeklene litine a) brez mikrolegiranja (NMA), b) z mikrolegiranjem (MA)

significantly the tensile strength and the hardness, whereas it decreases the percentage elongation and the room temperature impact toughness considerably. The increase of hardness and tensile strength to 31 % and 10.3 %, respectively, was observed in the V, Nb, Ti and Zr micro-alloyed as-cast steel compared to the non-micro-alloyed as-cast steel. The elongation and room-temperature impact toughness of the micro-alloyed as-cast steel decreases to 47.5 % and 43.7 %, respectively, compared to the non-micro-alloyed as-cast steel.

Table 2: Mechanical properties of experimental cast steels
Tabela 2: Mehanske lastnosti preizkusnih jeklenih litin

Experimental steels	Hardness, HV	UTS, MPa	Elongation, %	Impact toughness, J
Non-micro-alloyed steel (NMA)	168	580	17	16
Micro-alloyed steel (MA	220	640	9	9

4 CONCLUSIONS

The effect of steel micro-alloying with vanadium, niobium, titanium and zirconium as micro-alloying elements on the hardness, tensile strength, percentage elongation and room-temperature impact toughness were investigated in as-cast steel. The results obtained are: as follows

An increase in hardness to 31 % was obtained for micro-alloyed cast steel compared with non-micro-alloyed cast steel and the highest hardness of 220 HV was obtained for micro-alloyed cast steel.

The tensile strength was increased by 10.3 % in micro-alloyed cast steel when compared to non-micro-alloyed cast steel with the highest strength of 640 MPa obtained.

The elongation and the impact toughness of the micro-alloyed as-cast steel showed a decrease of 47.5 % and 43.7 %, respectively, when compared to those of the non-micro-alloyed as-cast steel.

A smaller grain size was obtained in the micro-alloyed as-cast steel.

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