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INVESTIGATIONS OF MICRO-ALLOYED CAST STEELS

RAZISKAVE MIKROLEGIRANIH JEKLENIH LITIN

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This paper presents a review of the effect of micro-alloying with vanadium, niobium, titanium and zirconium in carbon and low-alloy cast steels of different compositions. The elements were added in different percentages and combinations to the base cast steels. Also, the effect of heat treatment on the experimental steels is presented. The micro-alloying improved the mechanical properties of the as-cast and heat-treated base steels significantly.

Key words: cast steel, chemical composition, micro-alloying, mechanical properties, heat treatment

Predstavljeni so rezultati raziskav o vplivu mikrolegiranja z vanadijem, niobijem, titanom in cirkonijem na mehanske lastnosti in trdoto ogljikove in malolegirane jeklene litine z različno sestavo. Mikrolegirni elementi so bili dodani osnovnemu jeklu individualno in v različnih kombinacijah. Mikrolegiranje je močno vplivalo na lastnosti tega jekla v litem stanju in po toplotni obdelavi.

Ključne besede: jeklene litine, kemična sestava, mikrolegiranje, toplotna obdelava, mehanske lastnosti

1 INTRODUCTION

Micro-alloyed steels are low, medium carbon steels or low-alloy steels with the addition of elements such as niobium, titanium, vanadium and zirconium. These additions increase the strength of the steel, individually, and also in different combinations. Initially, micro-alloyed wrought steels were produced with micro-alloying and with thermo-mechanical processing (heat treatment) for higher strength as well as toughness and good weldability. Similar improvements are required for steels in the as-cast condition, especially carbon and low-alloy steels that are used for many applications. Moreover, these castings are frequently used in extreme conditions of tensile and fatigue stressing, impact loading, creep, abrasion and corrosion. Generally, cast steels have the major advantage of wider ranges of composition, higher casting temperatures and fewer impurities over wrought steels. To meet the present critical applications of components, cast steels with higher strengths and toughnesses are used. In this paper, the effect of the micro-alloying elements on the properties of the cast steels is investigated.

2 TYPES OF ALLOY STEELS

Steels containing one or more alloying elements, other than carbon, are designed to enhance one or more of the steels' properties. Specifically, alloy steels are superior to plain carbon steels due to the effect of the alloying elements. All alloy steels can be classed into three groups with respect to the total content of alloying elements: low-alloy steels[1,2] with up to 5 %, medium-alloy steels[1] with 5 % to 10 % and high-alloy steels with more than 10 %.

In micro-alloy steel, minor amounts of vanadium, niobium and/or titanium, etc., are added[2,3]. The addition of these individual elements is generally less than 0.10 % and the total micro-alloying is less than 0.20 %.

3 BASE STEEL AND MICRO-ALLOYING

The chemical compositions of the base steels used for the micro-alloying experiments are presented in **Table 1**. The micro-alloying was achieved with the addition of vanadium, niobium, titanium and zirconium to the base steels. The contents of the micro-alloying elements are given in **Table 2**.

4 MECHANICAL PROPERTIES

The maximum yield and the ultimate tensile strengths[3–7] of the experimental steels, the base (UMA) and the micro-alloyed (MA), are shown in **Figure 1** and **Figure 2**. After micro-alloying (MA), the yield and tensile strengths[3] were increased by 110 % and 100 %, respectively, when compared to the un-micro-alloyed steels. The experimental steels[3] were quenched and tempered at various temperatures. A low carbon content was maintained in all the experimental steels to achieve sufficient ductility. The minimum yield strength and the ultimate tensile strength were obtained for 0.003 V and 0.001 Ti after tempering at 700 °C. In this steel the highest yield strength and the ultimate tensile strength were obtained with combined tempering at temperatures of 700 °C and 400 °C.

Table 1: Summary of chemical compositions of the base cast steels
Tabela 1: Pregled kemične sestave osnovnih in mikrolegiranih jekel

Ref No.	Experimental Steel	Elements in wt %								
		C	Si	Mn	P	S	Cr	Mo	Ni	Al
3	Steel 1 (UMA)	0.23	0.36	0.88	0.04	0.04	0.39	0.10	–	0.004
	Steel 1 (MA)	0.23	0.36	0.88	0.04	0.04	0.39	0.10	–	0.004
	Steel 2 (MA)	0.18	0.30	0.85	0.03	0.03	0.40	0.10	–	0.012
	Steel 3 (MA)	0.16	0.32	0.83	0.02	0.03	0.40	0.10	–	0.015
	Steel 4 (MA)	0.15	0.34	0.82	0.04	0.03	0.40	0.10	–	0.056
4	Steel 5 (UMA)	0.21	0.39	1.13	–	–	0.11	0.18	0.91	0.035
	Steel 5 (MA)	0.21	0.39	1.13	–	–	0.11	0.18	0.91	0.035
	Steel 6(MA)	0.20	0.52	1.24	–	–	0.41	0.29	0.76	0.007
5,6	Steel 7(UMA)	0.14	0.35	1.56	0.010	0.015	–	–	–	0.03
	Steel 8(MA)	0.15	0.31	1.41	0.010	0.015	–	–	–	0.02
	Steel 9(UMA)	0.14	0.30	1.54	0.009	0.02	–	–	–	0.03
	Steel 9(MA)	0.14	0.30	1.54	0.009	0.02	–	–	–	0.03
	Steel 10(MA)	0.14	0.32	1.55	0.009	0.016	–	–	–	0.02
7	Steel 11(UMA)	0.06	0.14	1.60	0.03	0.07	–	–	–	0.05
	Steel 12(MA)	0.06	0.14	1.80	0.03	0.08	–	–	–	0.05
	Steel 13(UMA)	0.06	0.09	1.85	0.01	0.10	–	–	–	0.01
	Steel 13(MA)	0.06	0.09	1.85	0.01	0.10	–	–	–	0.01
	Steel 14(MA)	0.07	0.09	1.85	0.03	0.07	–	–	–	0.04
	Steel 15(MA)	0.07	0.09	1.90	0.01	0.09	–	–	–	0.03

Table 2: Summary of the micro-alloying elements
Tabela 2: Pregled vsebnosti mikrolegiranih elementov

Reference	Experimental Steel	Elements in wt %			
		Vanadium	Niobium	Titanium	Zirconium
Ref. 3	Steel 1(UMA)	–	–	–	–
	Steel 1 (MA)	0.003	–	0.001	–
	Steel 2(MA)	0.11	–	0.01	–
	Steel 3(MA)	0.11	0.036	0.01	–
	Steel 4(MA)	0.11	0.036	0.04	–
Ref. 4	Steel 5 (UMA)	–	–	–	–
	Steel 5(MA)	0.09	–	–	–
	Steel 6(MA)	0.09	0.035	–	–
Ref. 5, 6	Steel 7(UMA)	–	–	–	–
	Steel 8(MA)	0.096	–	–	–
	Steel 9(UMA)	–	–	–	–
	Steel 9(MA)	0.092	0.047	–	–
	Steel 10(MA)	0.10	0.043	0.023	–
Ref. 7	Steel 11(UMA)	–	–	–	–
	Steel 12(MA)	–	–	–	0.005
	Steel 13(UMA)	–	–	–	–
	Steel 13(MA)	–	–	–	0.01
	Steel 14(MA)	–	–	–	0.02
	Steel 15(MA)	–	–	–	0.10

The mechanical properties for the micro-alloyed steel 5 and the corresponding base steel were tested after normalizing (920 °C), quenching (920 °C) and tempering (580 °C) as well as homogenization (1100 °C) treatments[4]. Due to the micro-alloying, the yield strength was increased by 118 % and the tensile strength by 65 %, respectively, when compared to the un-micro-alloyed steels. The minimum and maximum yield and tensile strengths[5] were obtained in steel 5 with the addition of 0.09 vanadium after the normalizing and homogenizing treatments.

The mechanical properties[5,6] were tested in the as-cast condition without any heat treatment. After the micro-alloying the yield and tensile strengths were increased by 55 % and 26 % with respect to the un-micro-alloyed steels. The minimum yield and the tensile strengths were obtained in the un-micro-alloyed steel 9 without any heat treatment. The addition of

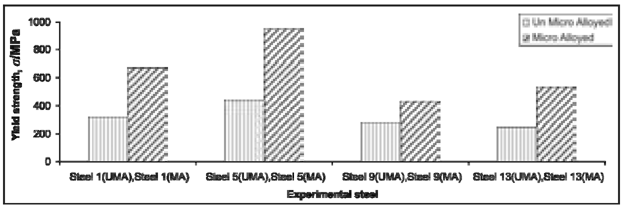

Figure 1: Yield strength
Slika 1: Meja plastičnosti

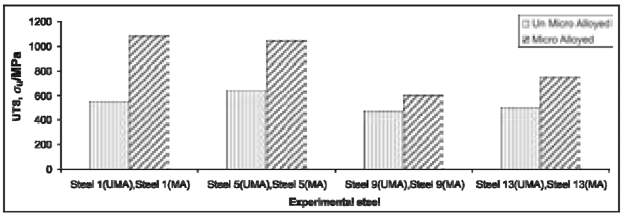

Figure 2: Ultimate tensile strength
Slika 2: Raztržna trdnost

vanadium individually increased both the yield strength and ultimate tensile strength up to 100 MPa. After micro-alloying, the steel 9, with 0.092 vanadium and 0.047 niobium, had its yield strength and ultimate tensile strength increased by 160 MPa and by 125 MPa.

Zirconium was also added as a micro-alloying element to the low-carbon base steel[7]. Four trials were made by varying the content of zirconium in the base steel and the mechanical properties were tested after quenching, tempering and homogenizing. After the addition of zirconium, the yield and tensile strengths were increased by 120 % and 50 % with respect to the un-micro-alloyed steel. The minimum values for the yield and tensile strengths were found for the micro-alloyed steel 13 after homogenization. The tempering treatment improved both the ultimate tensile strength and the yield strength in steel 13 with 0.01 zirconium more than the quenching and the homogenizing.

The elongation and reduction of area obtained for the experimental steels un-micro-alloyed and micro-alloyed are shown in **Figure 3** and **Figure 4**, respectively[3,4,7]. The elongation and the reduction of the area after micro-alloying[3] for the steel 11 are lower by 27 % and 28 %, respectively.

The minimum and maximum elongation and reduction of area[3] were found for the steel 1 after tempering at 400 °C and 700 °C, respectively.

For the steel 5, after micro-alloying the elongation and the reduction of area were decreased by 44 % and 45 %, respectively. The minimum elongation and reduction of area for the steel 5 were found after homogenization and normalization and the benefit of micro-alloying was achieved in steel 5 only after quenching and tempering at 580 °C.

After micro-alloying[5,6] in steel 9, the elongation was decreased by 36 %. The minimum elongation was found for the micro-alloyed steel 9 and maximum for the un-micro-alloyed steel 9.

The elongation and the reduction of area due to micro-alloying[7] in steel 13 were decreased by 40 % and 70 %, respectively, with respect to the un-micro-alloyed steel 11. The minimum elongation and reduction of area were found after quenching and the maximum after tempering at 450 °C.

The hardness[3,5,6,7] of the experimental steels is shown in **Figure 5**. After micro-alloying, the hardness was increased by 146 % in steel 1, 27 % in steel 9 and 130 % in steel 13, respectively.

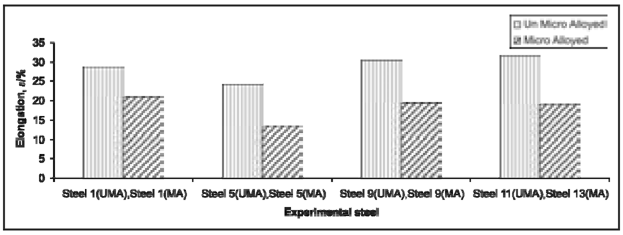

Figure 3: Percentage elongation
Slika 3: Raztezek v odstotkih

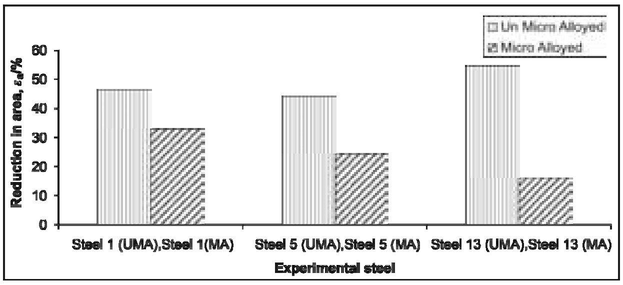

Figure 4: Percentage reduction in area
Slika 4: Skrček v odstotkih

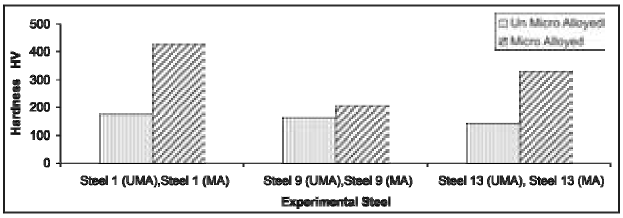

Figure 5: Hardness
Slika 5: Trdota

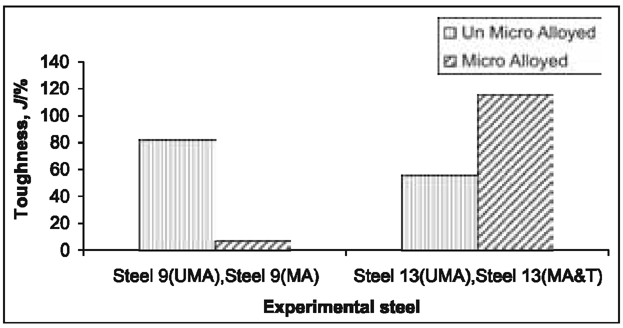

Figure 6: Impact toughness
Slika 6: Udarna žilavost

The minimum and maximum hardness[3] were obtained in steel 1 with 0.003 V and 0.001 Ti after hardening and tempering at 500 °C. The minimum hardness was found for the un-micro-alloyed steel 9 and the maximum for the micro-alloyed steel 9 without heat treatment[5,6]. The maximum hardness[7] was found for the micro-alloyed quenched steel 13 with 0.005 of zirconium and the minimum for the un-micro-alloyed steel 13.

Generally, the hardness was higher after quenching and tempering treatments than in the as-cast condition.

The toughness[5,6,7] obtained with the micro-alloyed and the un-micro-alloyed for the experimental steel 9 and steel 13 is shown in **Figure 6.** The toughness[5,6,7] due to micro alloying[7] was decreased by 90% in the micro-alloyed steel 9 without heat treatment and increased by 110% in the micro-alloyed tempered steel 13 with 0.01 zirconium.

5 MICRO-ALLOYING MECHANISMS

A fine grain size[3] was achieved in micro-alloyed steel 1 compared with that of the un-micro-alloyed steel 1. Generally, grain refinement was found in all the micro-alloyed steels. In micro-alloyed steels the titanium precipitates as TiN and the vanadium as VC/V(CN). Nb precipitates from the matrix as NbC/Nb (CN) independently, or on the existing TiN particles. The grain refinement and precipitation hardening induce the higher strength and hardness of the micro-alloyed steels.

In steel 5, micro-alloyed with vanadium,[4] the strengthening is achieved with a fine precipitation of VC in the ferrite matrix and also with the fine interlamellar spacing of pearlite. The vanadium addition in the as-cast condition affects the grain size of the ferrite also.

The increase in yield and ultimate tensile strengths and hardness[5,6] in the micro-alloyed steel 9 is due to the formation of a fine scale of carbonitride precipitates. The micro-alloy carbonitrides precipitate on the advancing alpha/gamma interface. The micro-alloying of the niobium precipitates in the matrix or at the austenite grain boundaries, whereas the vanadium precipitates as V(C,N) as an interphase or random precipitation.

Zirconium is a strong nitride-[7] and oxide-forming element. In the zirconium micro-alloyed steels the ZrC precipitates form at higher temperatures and the ZrN precipitates at lower temperatures. The precipitation of ZrN and the heat treatment improves the mechanical properties of the micro-alloyed steel 13 very much with respect to the addition of zirconium.

6 CONCLUSION

I In this article the effects of micro-alloying additions of vanadium, niobium, titanium and zirconium in low-carbon base steels of different compositions, as cast and after heat treatment are presented and discussed.
The chemical composition of the base steel used and the individual and combined additions of micro-alloying elements used for the experimental work are given.
The minimum and maximum values of the mechanical properties obtained in the micro-alloyed cast steels in the quoted references are summarized and discussed.

II Generally, the ultimate tensile strength, yield strength and hardness are greater with micro-alloyed cast steels, while the ductility, measured as elongation and the reduction of area, is smaller. Also, the notch toughness is lower after micro-alloying.

III In steels micro-alloyed with vanadium, niobium and titanium, the tensile strength was lower in the presence of titanium. The vanadium addition individually increased the yield strength and the tensile strength up to 100 MPa, whereas vanadium and niobium additions increased the yield strength and ultimate tensile strength by 128 MPa and 90 MPa, respectively.

IV The hardness was higher after micro-alloying the zirconium, especially after tempering. An increased hardness and toughness were obtained with 0.005–0.01 % of zirconium.

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