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Effect of boron alloying element and annealing solution heat treatment on microstructure and mechanical properties of manganese steels

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ABSTRACT

In this paper, the effect of boron content in chemical composition of steel on improvement of microstructure and mechanical properties of manganese steels was investigated. The microstructure, by optical, SEM and FESEM microscopy, was investigated. In addition, mechanical tests such as tensile test, hardness and impact tests were performed on the samples. Microscopic test results show that the presence of 0.007% of boron consistently prevents formation of carbides in grain boundaries and also reduces the carbide sizes and improve uniform distribution. In presence of boron, annealing solution heat treatment, improve the morphology of carbides and modified it to spherical shape. The manganese steels by addition of boron alloy element and solution heat treatment, have higher hardness, impact energy and tensile strength.

Keywords: Hadfield steel, boron content, manganese steels, microstructure, carbide distribution, mechanical properties.

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INTRODUCTION

Cast Austenitic-Manganese steel which are known as Hadfield steel, was discovered in 1882 by Robert Hadfield. Because of their special properties, Manganese steels developed very fast as a useful engineering material (Akeel and Abdulrazaq, 2007; Ashok and Das, 2008). Today, these steels are widely used with slight change in the chemical composition and heat treatment in various industries. These industries include drilling, loader tooth, mines extraction, crushers, wear and abrasion resistant and cement industries and so (Bouaziz et al., 2011; Fredrik, 2009). Manganese steels (Hadfield) are very useful materials in industries that require the impact resistance, wear resistance high strength and ductility and also cost effective production (Hull, 1964). Concerning the shape and size and various thickness of components, the properties are not uniform in all the sections. Those properties can be improved by using suitable alloying elements or the heat treatment. In as cast condition, manganese steels include manganese carbides and cementites and have a brittle structure (Agunsoye et al., 2000). Heat treatments at 1000 to 1100°C for suitable times according to thickness of components, and consequently water quenching, dissolve the brittle phases and prevent the reformation of carbides during the cooling period and produce austenitic microstructure. Care should be observed to prevent local melting due to carbon segregation (Abbasi et al., 2009; Bhero et al., 2013). However, the solution treatment at high temperatures may lead to grain growth. Casting temperature and cooling rate of these steels in cast molds also affect the final size of austenite grains (Fredrik, 2009). There are many researches in various field, such as mechanical or microstructure improvements and role of alloying elements such as molybdenum and chromium (Balogun, et al., 2008). These studies lead to higher mechanical properties and wear and abrasion resistance (Bouaziz et al., 2011; Balogun et al., 2008; Wanhu et al., 2010).

Alloying elements also have other roles in the final properties of steels such as reduction of dissolved gases and reducing sustaining to impurities. Controlling each of these stages mainly affect the final properties of steel

(Xie et al., 1992; Ranjan et al., 1999; Perry and Green, 2008). Increasing the Al to composition caused increase in solubility of carbon in austenite and improved the hardness but impact toughness decreased (Bhero, et al., 2013). Moreover, the effect of elements such as vanadium, niobium, molybdenum, nickel, chromium, hydrogen, sodium and cobalt have been studied by many researchers (Bhero et al., 2013; Perry and Green, 2008; Jing and Zhang, 1997; Smith et al., 2004; Li et al., 2002; Bayraktar et al., 2004; Efstathion and Sehitoglu, 2008), but the effects of boron are less investigated. The main purpose of this paper is evaluating the effect of boron content and solution heat treatment on mechanical properties and microstructure of manganese steels.

METHODOLOGY

In this study, the effect of adding boron as alloying elements with 0.0, 0.003, 0.005 and 0.007% of weight percent to chemical composition of manganese steel and its effects on microstructure and mechanical properties of manganese steels have been studied. Table 1 illustrates the chemical composition of basic manganese steel according to ASTM A 128M Grade B-3 (WT%).

Table 1. ASTM A128 M: Chemical composition of austenitic manganese steels.

Grade	%C	%Mn	%Si (Max)	%P (Max)
B-3	1.12 - 1.28	11.5 - 14.	1	0.07

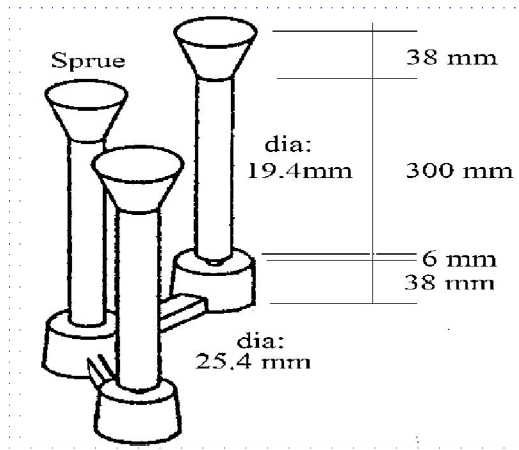

Figure 1. The pattern system for molding.

Sand molding

The molding of samples was done by CO_2/Silicate sand process. To prevent the chemical reaction between the sand and molten metal, the surface of molds was chromate sand and the silica sand was the support. In addition, the surface of molds was coated by special coating. These samples had cylindrical shape with 30 mm diameter and 300 mm height. Figure 1 show the pattern layout for molding.

Melting and casting

The 300 kg induction furnace was used for preparation of molten steel. The high manganese and low alloy steel scrap were added into the furnace and after melting, the required graphite and Fe-60% Mn were added to molten metal to adjust the carbon and manganese content. Ferro-alloy Fe-10% B was used for adding of 0.003, 0.005 and 0.007% boron to the melt and required calculations were done. For degassing of molten steel, pure aluminum in amount of 0.06% was added to the molten steel in ladle. In all the cases, the tapping temperature was 1520°C and the pouring temperature of molten steel to the molds was 1480°C (Bhero et al., 2013; Smith et al., 2004; Li et al., 2002; Bayraktar et al., 2004). The chemical composition of molten steel after the adding of boron is shown in Table 2.

Table 2. Chemical composition of molten manganese steel with boron content.

Heat	%C	%Si	%Mn	%Al	%Cr	%B	%Fe
1	1.12	0.5	11.82	0.04	0.83	0.00	Bal.
2	1.16	0.51	11.83	0.04	0.85	0.003	Bal.
3	1.14	0.52	11.78	0.03	0.82	0.005	Bal.
4	1.15	0.51	11.81	0.03	0.84	0.007	Bal

After the cooling of specimens to ambient temperature, the specimens were discharged from the sand mold and shot blasted. Then the solution heat treating was carried out in an electric furnace. The gradient of temperature was 200°C per hour to reach the 1050°C and stay at it for one and half hours and then rapidly quenched in hot water. After the cutting of runners and risers and shot blasting and machining, the specimens were prepared for optical and SEM metallography and hardness, impact and tensile mechanical tests (Efstathion and Sehitoglu, 2009; Dobrzanki et al., 2008; García et al., 2005; Yunhan et al., 2005).

RESULTS AND DISCUSSION

Metallography and microstructure

Figure 2 shows the microstructure of manganese steels with various amount of boron. The presence of boron in casting, prevent the carbides formation at grain boundaries and breaks and distribute the carbides inside the grains, and makes a uniform distribution of carbides

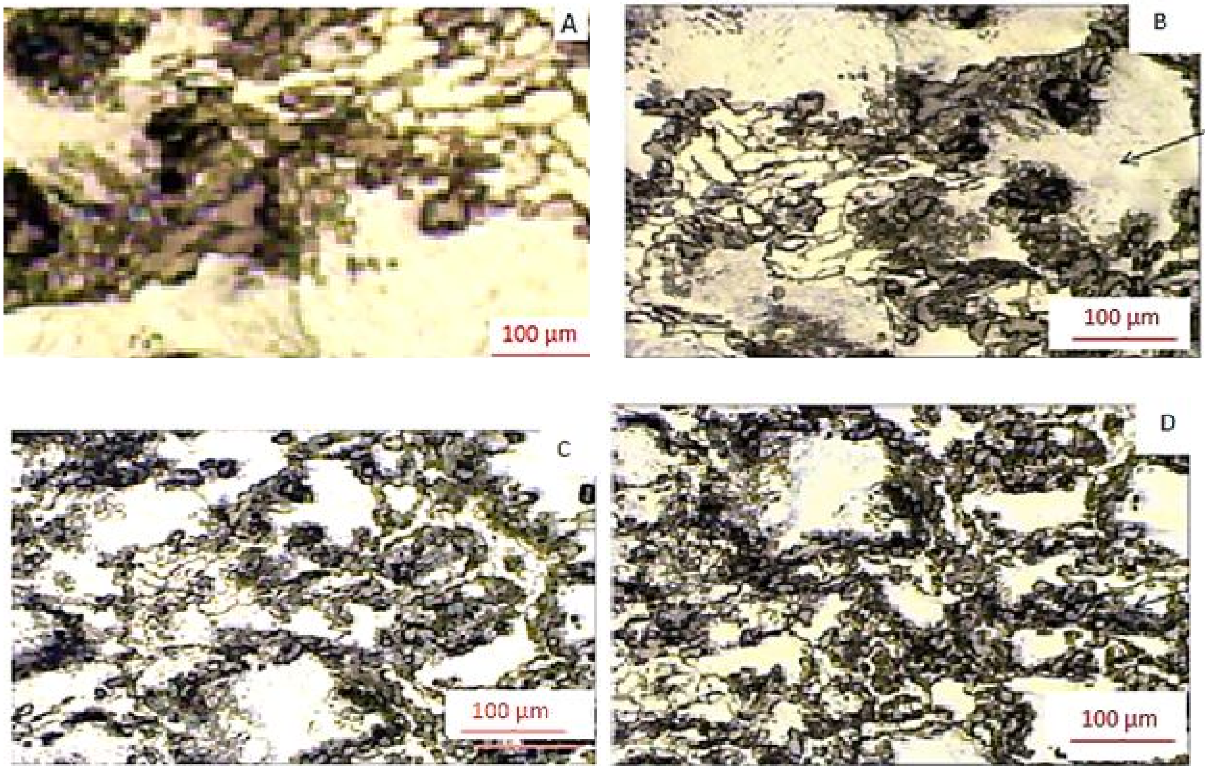

Figure 2. Microstructure of samples with various amounts of boron before the heat treatment: A) 0.0%; B) 0.003%; C) 0.005%; D) 0.007%.

in austenitic microstructure. In solution heat treated manganese steels, increasing the boron content, reduces the carbide precipitation in grain boundaries and reduces the brittle behavior of grain boundaries due to carbides segregation and improve the toughness. As seen from the figures, at 0.003% boron, segregation of carbides in grain boundaries is less than for 0.0% boron. In Figure 2a, the morphology of manganese carbides are of a layered type which segregated at grain boundaries, but most of the manganese carbides are dissolved in austenite in 0.007% boron and remaining parts have spherical morphology, Figure 2d. This means the presence of boron has minimum 2 effects: the first is improvement of dissolution of manganese carbides in microstructure and the second consist of modification of remaining carbide morphologies. The higher amounts of 0.007% boron content can create boron carbides which have opposite effect on toughness and impact resistance (Abbasi et al., 2010; Kuyucak and Zavadil, 2000).

Figure 3 shows the Scanning Electron Microscopy images of samples with 0.0 to 0.007% Boron content after the heat treatment. As can be seen, the morphology of carbides before the heat treatment is acicular which have more volume in grain boundaries. But after heat treatment, the volume percent of carbides reduced significantly and the morphology of rBayraktard carbides are spherical.

Mechanical properties

Hardness

Figure 4 shows the effect of boron content on Brinell hardness of samples before and after the solution heat treatment. In all the samples, addition of boron increases the hardness. The maximum hardness was achieved for 0.007% content of boron at solution heat treatment conditions. The boron content prevents segregation of carbides at grain boundaries and redistributes of the carbides in the whole of matrix and the heat treatment improve hardness of samples by almost 38 to 55% for all ranges.

Tensile test

Manganese steels have high resistance to elastic deformation, and have high yield strength. However, due to their brittle nature, manganese steels have low tensile strength and low plastic deformation behavior in as cast condition. The boron content in alloy steel prevents the segregation of manganese carbide in grain boundaries and redistributes of carbides in austenitic microstructure and the heat treatment, increase the plastic deformation capability and tensile strength. The details of those

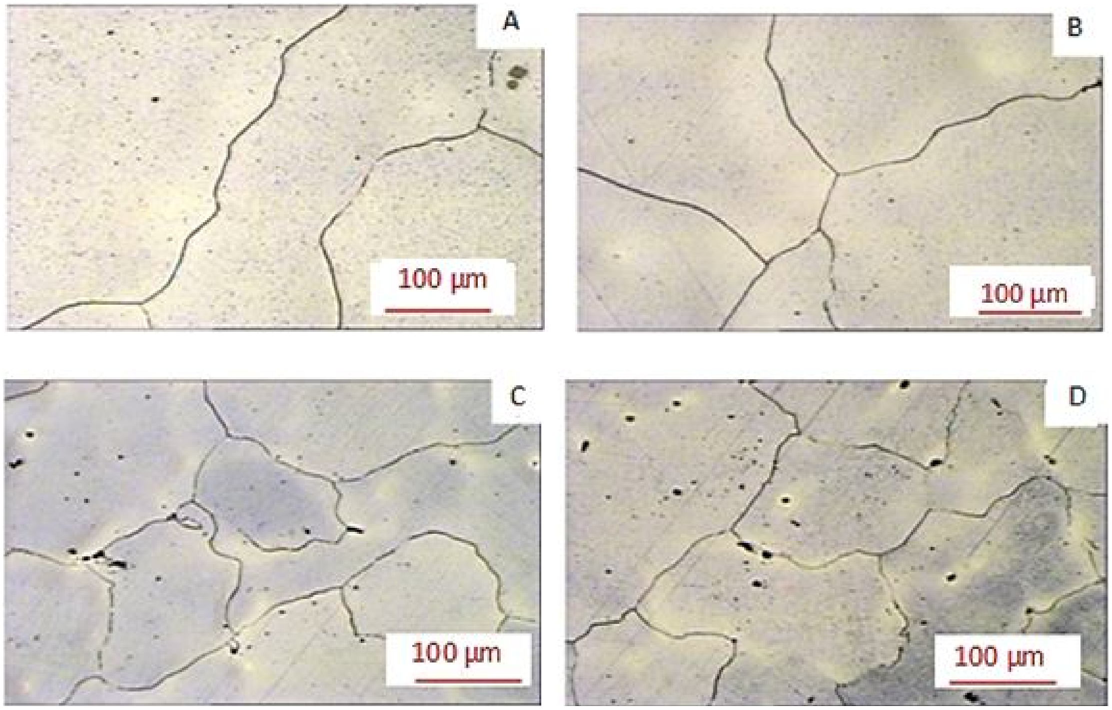

Figure 3. Microstructure of samples with various amounts of boron after the heat treatment: A) 0.0%; B) 0.003%; C) 0.005%; D) 0.007%.

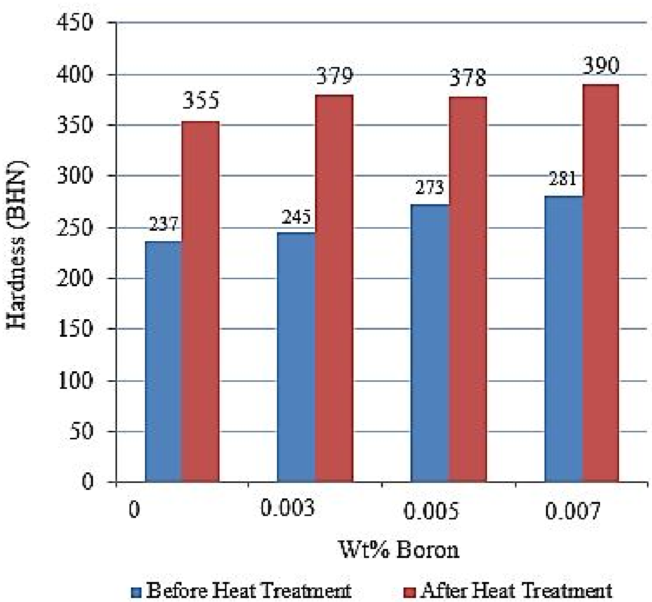

Figure 4. Effect of boron content on hardness of manganese steel before and after solution heat treatment.

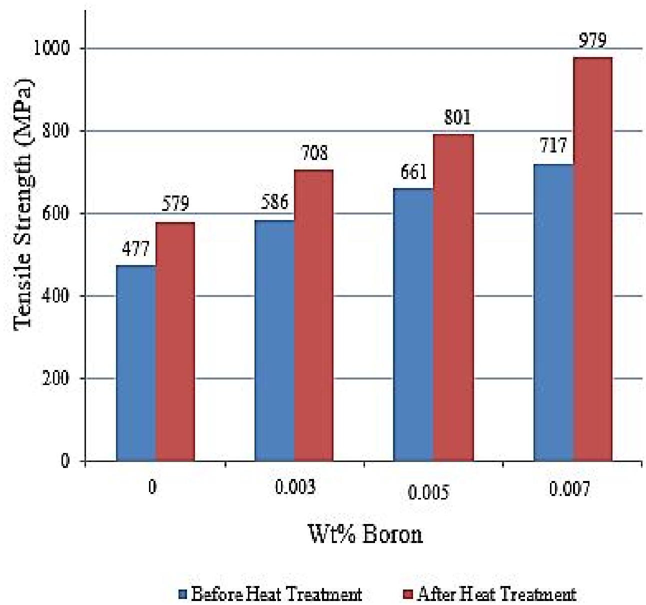

Figure 5. Effect of the boron content on tensile strength of manganese steel before and after the solution heat treatment.

effects are shown in Figure 5.

Figure 6 shows the stress-strain curve for heat treated manganeses with 0.003% Boron content. Presence of boron does not only increase the tensile strength, but also improve the strain hardening of steel.

Impact test

Figure 7 shows the impact test results for various amounts of boron as an alloying element in austenitic-manganese steel samples before and after the solution

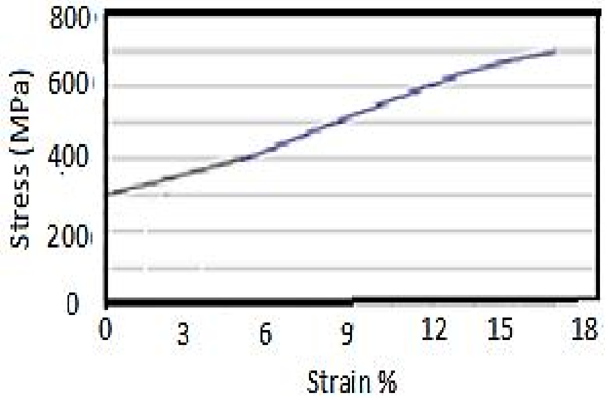

Figure 6. Stress-strain curve for the heat treated manganese steel with 0.003% boron content.

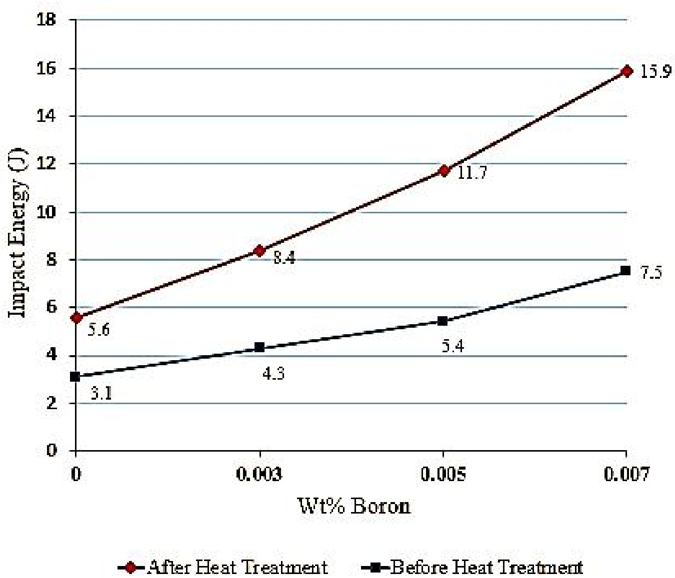

Figure 7. Effect of the boron content on impact energy of manganese steels before and after the solution heat treatment.

heat treatment. It is clear that the increase of boron content increase the impact energy toughness.

DISCUSSION AND CONCLUSION

The results showed that the presence of 0.3 boron in cast structure prevents creation of layers of carbides at grain boundaries and breaks carbides, and creates spherical and uniform distribution of carbides in austenitic structure. In addition by increasing the amount of boron, the hardness of samples increases before and after the heat treatment, but due to the formation of spherical carbides, the ductility is not reduced. The results of microscopic investigation and mechanical tests on manganese steels with boron content also show the following results:

1. By the annealing solution heat treatment, manganese carbides will dissolve in austenitic microstructure and their layer shape will convert to the spherical shape.
2. Presence of boron in chemical composition of manganese steel prevents formation and precipitation of manganese carbide in grain boundaries and cause uniform distribution of remaining carbide in austenitic microstructure. This phenomenon prevents the brittle behavior of steel and increase toughness of castings.
3. By increasing the amount of boron, the hardness will increase before and after the solution heat treatment, without reduction of energy impact and ductility.
4. At 0.007% boron, fine and spherical carbides will be formed in austenitic microstructure of manganese steel which increase hardness, toughness, tensile strength and modifies the carbide distribution and morphology in both heat treated and non-heat treated states.
5. Combination of the solution heat treatment and alloying by 0.007% of boron gives the optimum mechanical properties and microstructure modification in manganese steels.

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