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HEAT TREATMENT EFFECT ON MICROALLOYED LOW CARBON STEEL WITH DIFFERENT BORON CONTENT

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ABSTRACT

The effect of different boron contents (between 3 and 70 ppm) on the metallurgical and mechanical properties of thermo mechanically carbon steel had been investigated. Three alloys were cast with different boron content. The alloys were subjected to thermo mechanical processing at temperature of 1200˚C and then quenched by air, oil or water as various quenching medium. Mechanical characteristics of those alloys were investigated through hardness and tensile tests at room temperature. Metallographic investigation was carried out using optical and scanning electron microscopes. Results revealed an improvement of the hot ductility of steels at increasing boron content. Ductility at 700, 900 and 1000 ^{o}C was higher than that at 800 ^{o}C, where boron microalloyed steels exhibit a region of ductility loss (hard region). Likewise, dynamic recrystallization only occurred at 900 and 1000 ^{o}C. The fracture surfaces of the tested steels showed ductile failure mode for all specimens except those with hard region the failure mode was ductile-brittle. Results are discussed in terms of dynamic recrystallization and boron segregation towards austenite grain boundaries, which may retard the formation of pro-eutectoid ferrite and increase grain boundary cohesion.

KEYWORDS: Boron Steel, Heat Treatment, Micro-Alloyed, Low Carbon Steel, Boron Effect, Metallurgical Properties, Mechanical Properties

INTRODUCTION

Adding boron to low alloy steel promotes bainite or martensite formation due to the suppression of austenite transformation which improves the strength and hardenability of the steel [1-8]. Increasing hardenability of steels by adding boron occurs by retarding the heterogeneous nucleation of ferrite at the austenite grain surface [9-10]. If the boron concentration is excessive, a boron carbide constituent, identified as $Fe_{23}(B,C)_6$ forms at the austenite grain boundaries of wrought steels [6].

Boron effect is entirely different in low and high carbon steel, plain and alloyed steel, with low and high soaking temperature, and more significantly with low and high cooling condition. In recent thermo-mechanical simulation study [11-15], the effectiveness of boron on hardenability has been found to be strongly dependent on soaking temperature and cooling condition, rather below a critical cooling rate boron has soften the low carbon aluminum killed steel.

The presence of the intergranular $Fe_{23}(B,C)_6$ constituent was found to not only decrease boron's hardenability effect but also seriously affect the notched toughness of steel. For example, when boron contents exceeded a value of 0.0025% in low carbon steel, both hardenability and toughness deteriorated due to the formation of this brittle boron carbide precipitate [6].Boron-containing steels is used in gas and oil pipelines, construction and automobile industries, machine components, tools, …etc. It also replaces the high-carbon and low-alloy steels used in a form of sheets and strips with low-cost.

Increasing carbon content decreases the effectiveness of boron [4], while adding certain alloying elements such as molybdenum, niobium and copper enhances the effect of boron on strengthening by lowering the austenite to ferrite transformation temperature [9-10].Therefore, boron is most effective in low carbon steels (up to 0.25% C) but is also widely used in medium carbon steels (up to 0.4%C).Addition of boron plays an important role in increasing remarkably the hardenability of steel [4, 11, 17]. Effect of boron content and heat treatment on mechanical and metallurgical properties in general has been investigated by various researchers [18-33].The low carbon boron-containing steels have better cold-forming characteristics and can be heat treated to equivalent hardness and greater toughness for a wide variety of applications, such as tools, machine components, and fasteners. The full effect of boron on steel hardenability can be obtained in fully deoxidized (aluminum-killed) steels.

In order to keep boron effectiveness for the hardenability, it has to remain in solid solution, hence some strong nitride and carbide formers are also added, such as Ti and Nb. The addition of Ti and Nb ties up nitrogen and carbon in steels therefore protecting boron from forming BN or $Fe_{23}(B,C)_6$. The boron remaining in solution will be able to segregate at austenite grain boundaries and occupy ferrite nucleation sites, hence delaying ferrite formation and promoting bainite formation.

Cooling of material from a higher temperature causes what is known as non-equilibrium segregation which is a kinetically dependent process. It increases with increasing cooling start temperature for the same cooling rate and decreases with increasing cooling rate at the same cooling starting temperature [34-35]. Westbrook [36] clarified the non-equilibrium segregation of boron to grain boundaries and detected a hardness increment at grain boundaries in a few quenched and dilute non-ferrous alloys.

The purpose of this work is to study the effect of heattreatment on microalloyed low carbon steel with different boron content. Metallurgical and mechanical properties were investigated through various measurements. Metallurgical measurements included dilatation behavior which exhibits the changes of austenite-ferrite, bainite and martensite transformation temperatures, grain size, ferrite-pearlite features such as layer thickness and distribution and bainite and martensite morphology. Mechanical measurements included hardness, tensile and impact values.

EXPERIMENTAL WORK

Casting

It has been previously shown [8] them anufacturing process of the low carbon microalloyed boron steel using open air induction furnace. In that research by the authors [8] the microstructure and mechanical properties were discussed for this boron steel at “as-cast” condition. The current research will investigate the effect of heat treatment on those properties; namely metallurgical and mechanical of this microalloyed steel having 0.0003, 0.005, 0.007and 0.02 wt% boron. The chemical composition of the manufactured steel alloys is shown in **Table 1**.

Table 1: Chemical Composition in Weight Percent (Wt %)

Alloy	C	Si	Mn	P	S	Cr	Al	B
0.0003B	0.230	0.362	1.13	0.0215	0.0131	0.133	0.117	**0.0003**
0.0050B	0.263	0.339	1.18	0.0242	0.0146	0.137	0.118	**0.0050**
0.0070B	0.275	0.306	1.43	0.0295	0.0142	0.052	0.0 14	**0.0070**
0.0200B	0.228	0.356	1.10	0.0215	0.0116	0.132	0.166	**0.0200**

Different plates of each alloywere heated up to 1200 °C and then were subjected to severe upset hot forging with reduction ratio of 80-90% incross-sectional area producing bars of 15.0 mm diameter, as shown in **Figure 1**. Alloy 0.02B steel couldn't be forged as it failed during forging as shown in **Figure 2**. After hot forging (HF) process, the steel bars were subjected to different cooling rates; air cooling; oil quenching or water quenching as depicted in **Figure 3**.

Figure 1: Hot Forging Process

Figure 2: Alloy 0.02B Steel Couldn't Be Forged

Tensile test specimens were extracted from each alloy to examine their mechanical properties according to ASTM E8-01 [37]. Tensile test was carried out at room temperature, and was conducted in house using universal testing machine UH-F1000KNI, SHIMADZU at across head speed of 5 mm/min. Charpy impact tests were performed at room temperature according to ASTME23-01[38]using a 300J Charpy impact machine.

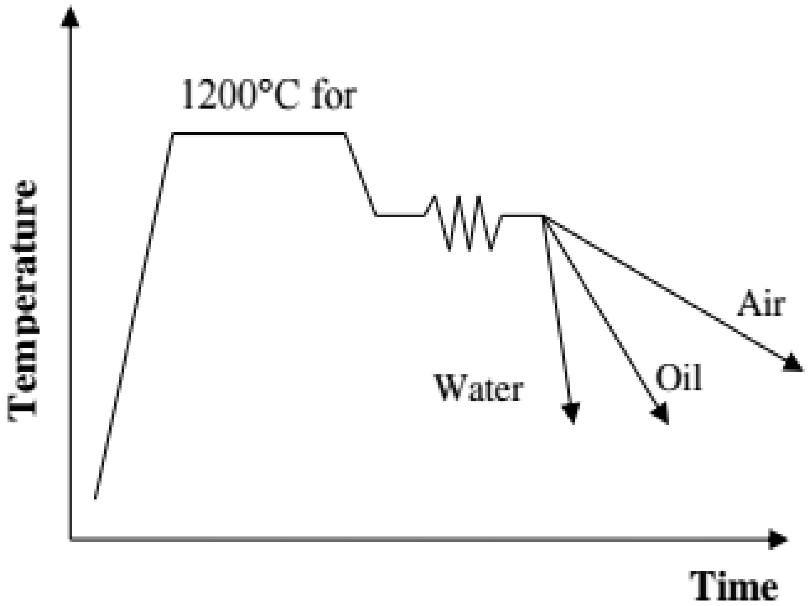


Figure 3: Thermo-Mechanical Process

Hardness test was conducted using Vickers hardness testing machine with 5kg load and holding time of 17 sec. Optical micrographs were taken on a Nikon optical microscope (EPIPHOT 200) for specimens from each alloy after mounting, grinding, polishing and etching with 2% nital for about 6 to 8 seconds. It was aimed to examine microstructure characteristics such as grain size, ferrite-pearlite features including layer thickness and distribution and bainite and martensite morphology. Scanning electron microscope JEOL 840A was used to clarify the grain size and the distribution of the different phases and their morphology. Energy Dispersive X-Ray Spectroscopy (EDX) was used for elements' analysis.

RESULTS AND DISCUSSIONS

MICROSTRUCTURE

Hot Forged Air-Cooled Microstructure

Figure 4 shows the optical and SEM microstructure of hot forged air-cooled steels. It is clear from the optical microstructure that, hot forging decreases grain size because boron increases the non-recrystallization temperature thus hot forging is carried out at high temperature producing fine grains and preventing grain growth. From SEM micrographs, it seems clear that, increasing boron content (in existence of hot forging followed by air cooling) decreases pearlite grain size and thickness due to critical transformation temperatures (AC_1 and AC_3) as shown in **Figure 5(a) & (b)**. It is found at higher AC_1 and AC_3 temperatures, the pearlite precipitates early therefore it coarsens while at lowercritical transformation temperatures the pearlite refines. It is found that inter lamellar increases with increasing boron content as shown in **Figure 5(c)**. It is found that ferrite grain size is transformation critical temperatures dependent (AC_1 and AC_3) as shown in **Figure 6**.

Hot Forged Oil-Quenched Microstructure

Figure 7 shows the optical and SEM microstructure of hot forged oil quenched steels. It is clear from the optical microstructure that, hot forging decreases grain size. This is attributed to the role of fine $Fe_{23}(C, B)_6$ precipitate where it precipitates at the grain boundaries during the austenite-ferrite transformation impeding the ferrite nucleation.

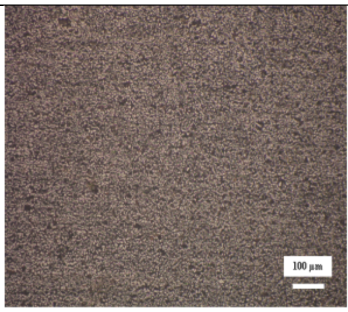
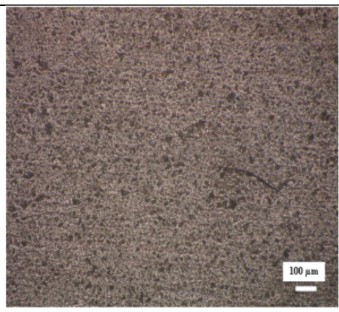
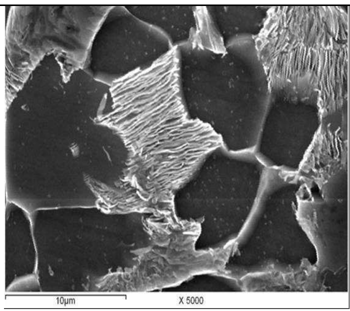
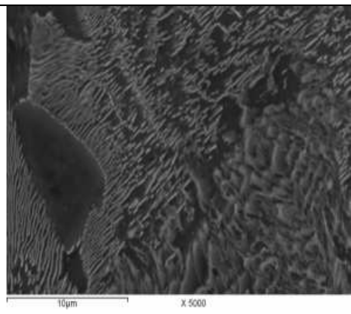
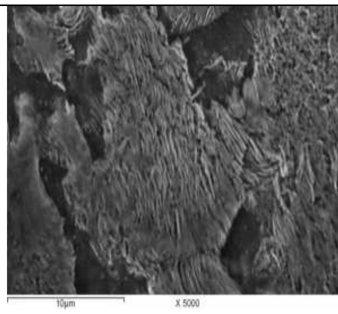
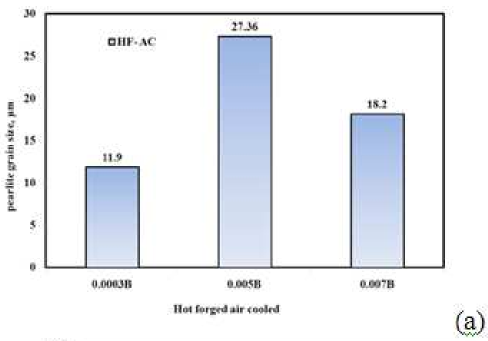
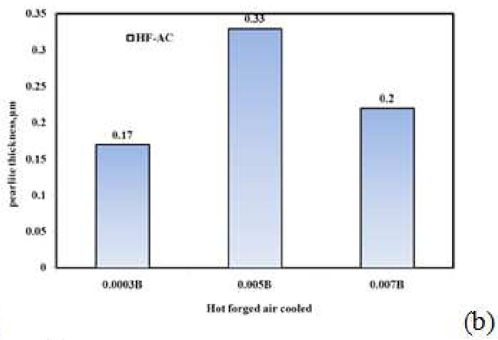
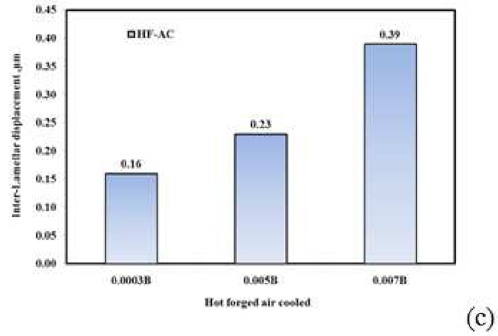
Hot Forged Air Cooled	0.0003B Steel	0.005B Steel	0.007B Steel
Optical Micrographs			
SEM Images			

Figure 4: Comparison of Microstructure versus Boron Content for Hot Forged Air Cooled Steels







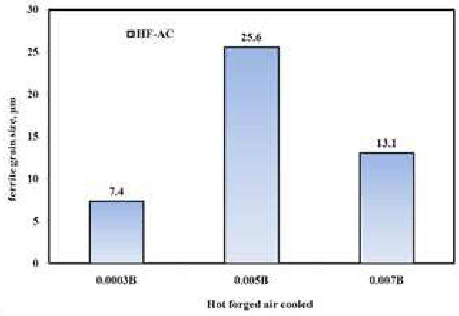


Figure 5: Pearlite Aspects of Hot Forged Air Cooled Steels, (A), (B) & (C).

Figure 6: Ferrite Grain Size Versus boron Content of Hot Forged Air-Cooled Steels

From SEM micrographs, it seems clear that, increasing boron content (in existence of hot forging followed by oil quenching) decreases bainite grain size and thickness due to critical transformation temperature dependence (bainite start, Bs). It is found that generally increasing boron content increasing bainite thickness.

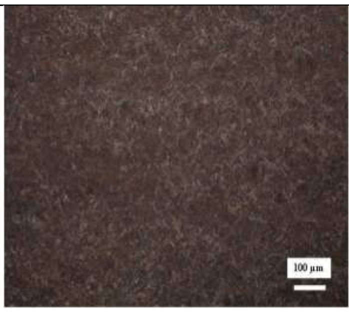
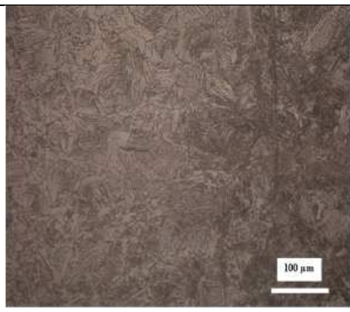
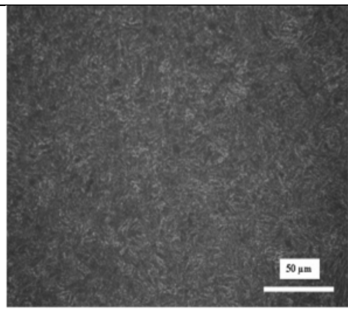
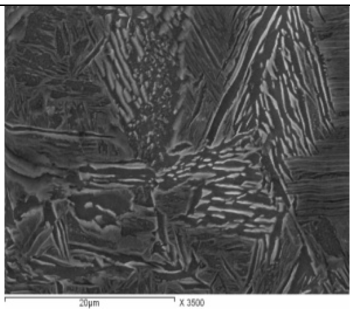
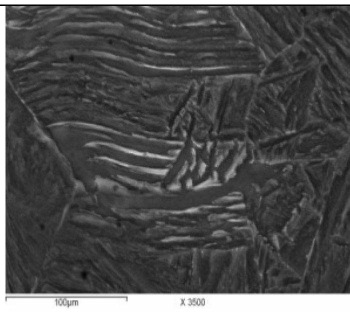
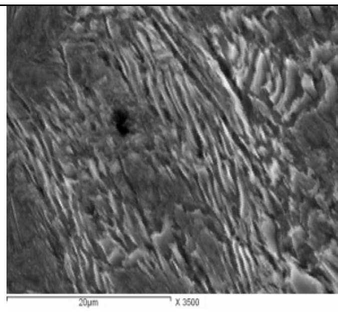
Hot Forged Oil-Quenched	0.0003B steel	0.005B steel	0.007B steel
Optical Micrographs			
SEM Images			

Figure 7: Comparison of Microstructure versus Boron Content for Hot Forged Oil Quenched Steels

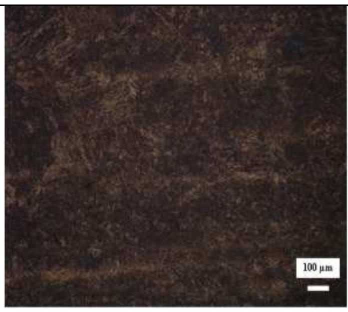
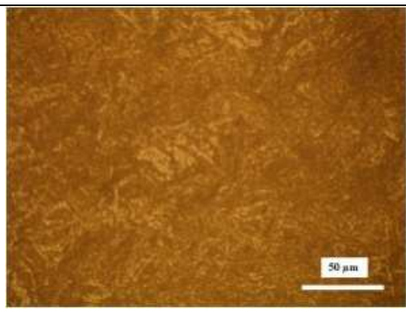
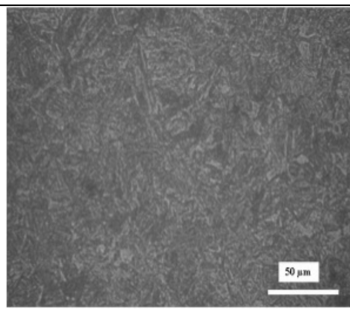
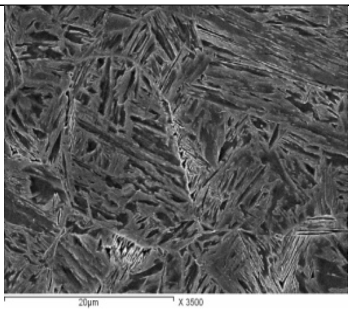
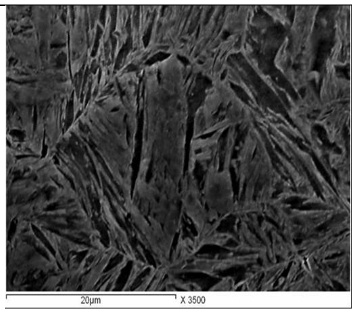
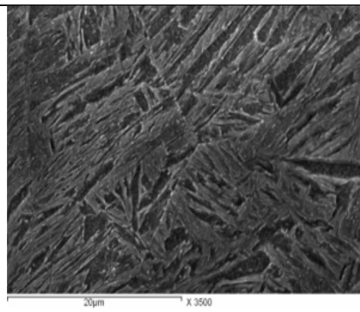
Hot Forged Water-Quenched	0.0003B Steel	0.005B Steel	0.007B Steel
Optical			
SEM			

Figure 8: Comparison of Microstructure versus Boron Content for Hot Forged Water Quenched Steels

Hot Forged Water-Quenched Microstructure

Figure 8 shows the optical and SEM microstructure of hot forged water-quenched steels. It is clear from the optical microstructure that, hot forging decreases grain size (approx. 18μm). This is attributed to the role of fine $Fe_{23}(C, B)_6$ precipitate where it precipitates at the grain boundaries during the austenite-ferrite transformation impeding the ferrite nucleation.

MECHANICAL PROPERTIES

HARDNESS

Effect of Cooling Rate and Boron Content

Figure 9 shows effect of thermo mechanical regimes on hardness for different steels. It is clear that hardness slightly increases due to hot forging. On the other hand, hardness highly increases due to oil or water quenched. This is attributed to the role of fine $Fe_{23}(C, B)_6$ precipitate where it precipitates at the grain boundaries during the austenite-ferrite transformation impeding the ferrite nucleation. Thus hardenability increases.

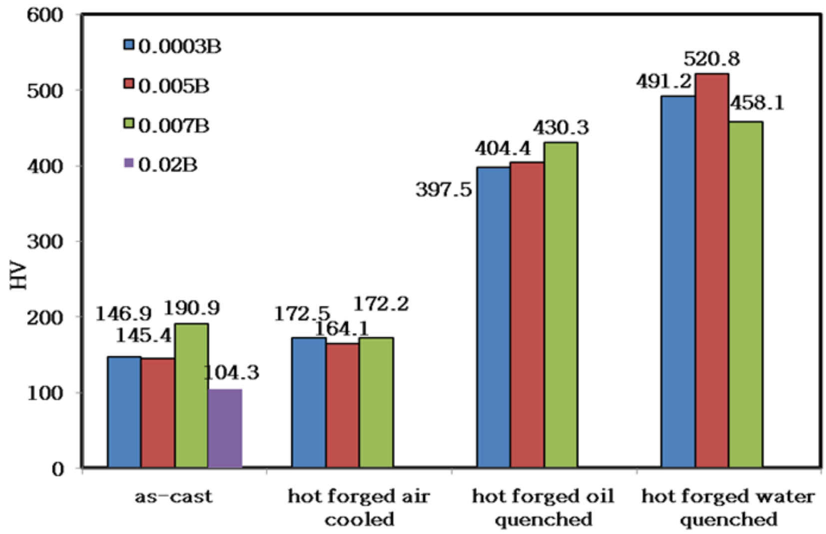


Figure 9: Effect of Cooling Rate and Boron Content on Hardness, HV

TENSILEPROPERTIES

Effect of Cooling Rate and Boron Content

Figure 10 shows the effect of heat treatment and boron content on ultimate tensile strength (UTS) for steel alloys. Tensile strength values for various boron contents are nearly equal in case of the as-cast condition and the effect of boron is very small. Same behavior is also noticed for hot forging air cooling condition. The effect of boron on tensile strength recorded better results in case of oil and water quenching of the hot forging specimens. It is worth mentioning that 0.005 and 0.007 boron steel exhibited the highest tensile strength values especially with oil and water quenching. The 0.0003 boron steel showed nearly same results with water quenching.

Figure 10 shows that tensile parameters showed lesser values for steel with zero boron content. From this figure it is clear that tensile parameters followed the same tendency regarding heat treatment conditions, namely the tensile strength increased gradually with air cooling, oil quenching and water quenching, respectively.

The increase of tensile strength of hot forged air cooled structure is due to hot forging which plays two roles. The first role is homogenized fine precipitation $Fe_{23}(C, B)_6$ which is responsible for grain refinement. The second role appears when the steel is hot forged followed by either oil or water quenched where fine precipitation $Fe_{23}(C, B)_6$ impedes ferrite nucleation during austenite-ferrite transformation [39] as shown in **Figures.7, 8 &10**.

In case of water quenching, the boron effect is minimal and can be ignored except with alloy with zero boron where adding only 0.0003 wt% boron could raise the ultimate tensile strength of the steel by about 25%.

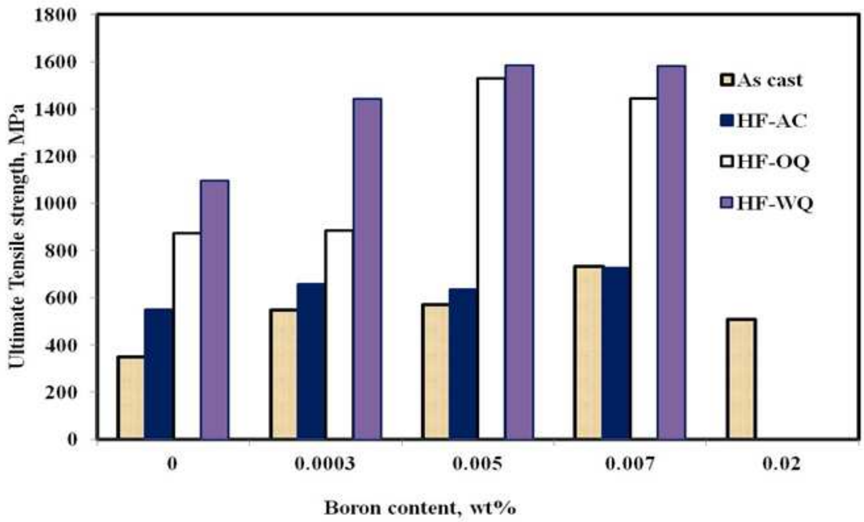


Figure 10: Effect of Heat Treatment and Boron Content on Ultimate Tensile Strength

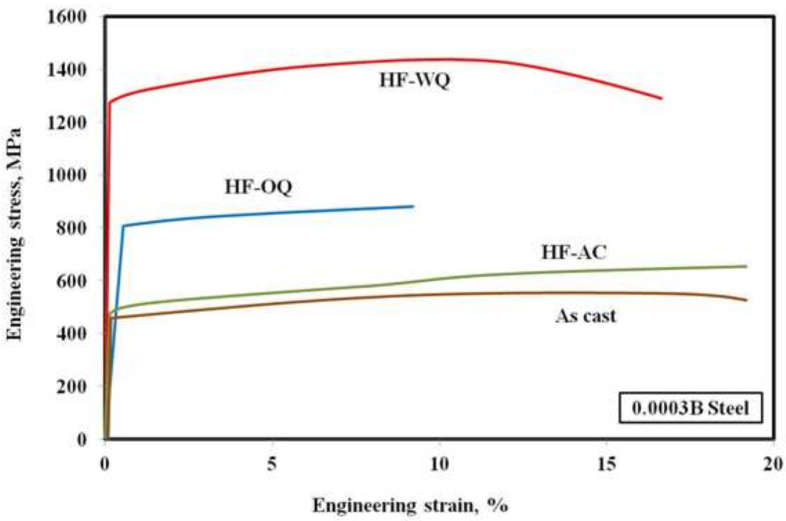


Figure 11: Stress-Strain Curves of 0.0003B Steel at Various Treatment Conditions

From **Figure 11** it is found that hot forged air cooled slightly enhances elongation compared to the as cast condition. Abrupt deterioration in elongation values was observed with hot forged condition either with oil or water quenching due to existence of hard phases (bainite or martensite). Specimens of hot forged water quenched steel recorded the highest tensile values (σ_y=810 and σ_T=1443MPa). This is attributed to the existence of martensite phase. Bainite phase in hot forged oil quenching condition enhances the σ_T and σ_y tensile values, 61% and 53% respectively compared to as cast condition. On the other hand, the elongation percentage decreases from 20% to 8% (60% decreases). It is worth mentioning that hot forging shares with only 20% in the total increase of the tensile strength.

CONCLUSIONS

Three alloys were cast with different boron content. The alloys were subjected to thermo mechanical processing at temperature of 1200˚C and then quenched by air, oil or water as various quenching medium. Metallurgical and mechanical properties of these alloys were investigated through metallographic tests using optical and scanning electron microscopes and mechanical tests using hardness and tensile machines at room temperature. From this research the main concluding remarks are:

- Increasing boron contentimproves hot ductility of steels.
- Ductilityat 700, 900 and 1000 ^{o}Cis higher thanthat at 800 ^{o}C, where boron microalloyed steels exhibit a region of ductility loss (hard region). Likewise, dynamic recrystallization only occurred at 900 and 1000 ^{o}C.
- The fracture surfaces of the tested steels showed ductile failure mode for all specimens except those with hard region the failure mode was ductile-brittle.
- The existence of fine $Fe_{23}(C, B)_6$ precipitate increased hardness in case of oil or water quench than in case of hot forging. It is believed that this precipitation impedes ferrite nucleation during austenite-ferrite transformation which increases hardness with hot forging.
- Steel with 0.005 and 0.007 boron exhibited the highest tensile strength values especially with oil and water quenching. This is attributed to the existence of martensite or bainite phase. The 0.0003 boron steel showed nearly same results with water quenching.
- Effect of boron on tensile strength is minimized with water quenching.
- With oil or water quenching abrupt deterioration in elongation values was observedfrom 20% to 8% (60% decreases) with hot forged condition due to existence of hard phases (bainite or martensite).

REFERENCES

1. P.D. Deeley, KJ.A. Kundig, Review of Metallurgical Applications of Boron Steels, Shield alloy Corporation, Newfield, New Jersey. T.W. Lippert, Boron, the Iron Age, Nov. 19, 1942.
2. R. Walter, British Patent160, 792, 1921; U.S. Patent!, 519, 388, Aug. 13, 1921.
3. M.A. Grossman, Trans. AIME, 150, pp. 227, 1942.
4. B.M. Kapadia, R.M. Brown, W.J. Murphy, Trans. AIME, 242, pp. 1689, 1968.
5. G.F. Comstock, Trans. AIME, 150, pp. 408, 1942.
6. R.A. Grange, Boron in Iron and Steel, Boron, Calcium, Columbium and Zirconium in Iron and Steel Alloys of
7. Iron, Research Monograph Series, John Wiley and Sons, Inc. N.Y., N.Y. p. 3, 1957.
8. M. El-Shennawy, A. I. Farahat, M. I. Masoud & A. I. Abdel-Aziz, Effect of Boron Content on Metallurgical And Mechanical Characteristics of Low Carbon Steel, *Int. Jl. Mech. Engg. (IJME)*, Vol. 5 (2), 2016, pp. 1-14.

9. M. Deighton, J. Iron Steel Inst., 205, p. 355, 1967.
10. J. E. Morral, T. B. Cameron, Boron Hardenability Mechanisms, Boron in Steel, S. K. Banerji, J. E. Morral, eds., TMS/AIME, p. 19, 1980.
11. P. Åkerström and M. Oldenburg, Studies of the thermo-mechanical material response of a Boron steel by inverse modelling, J. Phys. IV France 120 (2004) 625-633.
12. Anjana Deva, Vinod Kumar, Saikat K. De, B. K. Jha, and S. K. Chaudhuri, Microstructural Control in Aluminium-Killed Low C-Mn Boron Containing Steel for Improved Formability and Cold Reducing Properties, Materials and Manufacturing Processes, 25: 99–105, 2010.
13. T. Chandra, N. Wanderka, W. Reimers , M. Ionescu, Simulation of Thermo-Mechanical Controlled Rolling and Continuous Cooling of Wire Rods, Materials Science Forum (Volumes 638-642), pp. 3236-3241.
14. Kumar, V., Improving Steel Processing Through Thermo-Mechanical Simulation Studies, Materials Performance and Characterization, Vol. 4, No. 3, 2015, pp. 421-435.
15. Bingtao Tang , Qiaoling Wang, Zhaohui Wei, Xianju Meng, Zhengjun Yuan, FE Simulation Models for Hot Stamping an Automobile Component with Tailor-Welded High-Strength Steels, Journal of Materials Engineering and PerformanceMay 2016, Volume 25, Issue 5, pp 1709-1721.
16. K. Yamanaka, Y. Ohmori, Effect of Boron on Transformation of Low Carbon Low Alloy Steels, Trans, ISIJ, 17,p. 92, 1977.
17. D. McLean, "Grain boundaries in metals" (Clarendon Press, Oxford, 1957).
18. Ph. Maitrepierre, J. Rafes-Vernis and D. Thivellier: Boron in Steel, ed. by S., K. Banerji and J. E. Morral,AIME, Warrendale, PA, 1979.
19. R. A. Grange and J. B. Mickel: Trans. Am. Soc. Met., 53, p. 15, 1956.
20. Fábio Dian Murari, André Luiz Vasconcelos da Costa e Silva, Roberto Ribeiro de Avillez, Cold-rolled multiphaseboron steels: microstructure and mechanical properties, Journal of Materials Research and Technology Volume 4,Issue 2, April–June 2015, Pages 191–196.
21. Stefan Golling, Rickard Östlund, Mats Oldenburg, Characterization of ductile fracture properties of quenchhardenableboron steel: Influence of microstructure and processing conditions, Materials Science andEngineering: A, Available online 5 February 2016.
22. M. Naderi, M. Ketabchi, M. Abbasi, W. Bleckb, Analysis of microstructure and mechanical properties of differenthigh strength carbon steels after hot stamping, Journal of Materials Processing Technology, Volume 211, Issue 6,1 June 2011, Pages 1117–1125.
23. W. Stevens and A.G. Haynes, The Temperature of Formation of Marten site and Bainite in Low-alloy Steel, *JISI*,Vol 183, 1956, p 349–359.
24. K.W. Andrews, Empirical Formulae for the Calculation of Some Transformation Temperatures, *JISI*, Vol 203,1965, p 721–727.

25. George Krauss, Steels Processing, Structure, and Performance, 2005 ASM International.
26. Peter Ernst' Effect of boron on the mechanical properties of modified 12 % chromium steels', 1988.
27. Effect of boron content and heat treatment process onmicrostructure and mechanical properties of low bainitic steelplates, Heat Treatment of Metals, Volume 36, Issue 11, November 2011, Pages 7680,
28. Güler, H. , Ertan, R., Özcan, R., Effect of heat treatment on the microstructure and mechanicalproperties of 30MnB5 boron steel, Materiali in Tehnologije.
29. PallabMajumdar, Effects of heat treatment on evolution of microstructure of boron free and boron containing biomedical Ti–13Zr–13Nb alloys, Micron 43, (2012), 876–886.
30. P. Srithananan, P. Kaewtatip, V. Uthaisangsuk, Micromechanics-based modeling of stress–strain and fracture behavior of heat-treated boron steels for hot stamping process, to appear in: Materials Science & Engineering A, 2016.
31. HandeGüler, RukiyeErtan,ReşatÖzcan, Investigation of the hot ductility of a high-strength boron steel, Materials Science & Engineering A, 608 (2014), 90–94.
32. T.K. Eller, L. Grevea, M.T. Andresa, M. Medrickya, A. Hatschera, V.T. Meindersb and A.H. van den Boogaard, Plasticity and fracture modeling of quench-hardenable boron steel with tailored properties, Journal of Materials Processing Technology 214, (2014), 1211–1227.
33. HandeGüler, RukiyeErtan, ReşatÖzcan, Characteristics of 30MnB5 boron steel at elevated temperatures, Materials Science & Engineering A, 578, (2013), 417–421.
34. K. T. Aust, S. J. Armijo, E. F. Kock, J. A. Westbrook, Trans. Amer. Soc. Metals 60, p. 360, 1967.
35. T. R. Anthony, Acta Metall. 17, p. 603, 1969.
36. J. H. Westbrook, Int. Metall. Rev., 9, p. 415, 1964.
37. ASTM E8 / E8M-15a, Standard Test Methods for Tension Testing of Metallic Materials, ASTM International, West Conshohocken, PA, 2015.
38. ASTM E23-12c, Standard Test Methods for Notched Bar Impact Testing of Metallic Materials , ASTM International, West Conshohocken, PA, 2012.
39. Fabio Dian Murai, Andre Luiz Vasconcelos da Costa e Silva, RobertoRiberiro de Avillez, Effect of boron on the microstructure and mechanical properties of cold rolled multiphase steels, 2011.