Effects of process parameters on the microstructure and mechanical properties of medium-carbon steels for improving high-strain rate properties

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Abstract. The effects of accelerated continuous cooling and isothermal heat treatment process on the microstructure and mechanical properties of medium carbon bainitic steels was investigated to find an alternative process of the conventional austempering treatment process. Two kinds of medium carbon steel billets melted by Vacuum Induction Melting (VIM) were hot rolled to the thickness of 6–12mm plates and accelerated-cooled to predetermined temperatures and then isothermal heat treatment was conducted immediately. For quantitative analysis of microstructures, the fraction of constituent phases such as retained austenite, martensite, and bainite was measured by XRD and dilatometry. A series of hardness, tensile, and impact tests was conducted to evaluate the mechanical properties of the plates. As the finish cooling temperature increased, the fraction of retained austenite increased and the fraction of martensite and bainite decreased due to the differences in carbon diffusion and transformation kinetics during isothermal heat treatment process. Microstructural observation results showed that the lath/block thickness and fraction of bainite and martensite were mainly dependent on austempering temperature and time. The thickness of bainite and the fraction of martensite were found to be the major factors influencing mechanical properties of the present medium-carbon nanostructured bainitic steels.

1. Introduction
The use of high hardness steel is increasing for armour protection. Recently there has been a growing interest in a new concept of bainitic steel having high hardness and strength due to high carbon content and fine microstructure. These bainitic steels are designed to have high strength of ~ 2.3 GPa and high hardness in the range of 600–670 Hv [1-3]. The microstructure of the steel consists of nano-sized bainitic ferrite lath and carbon enriched austenite film by isothermal heat treatment just above martensite start temperature – so often called ‘nanostructured bainitic steel’ [4-10]. In spite of high hardness and strength, the steel may be inapplicable to the commercial products due to their inherently low impact toughness and very long isothermal holding time for bainite transformation.

This study aims at replacing conventional prolonged austempering process by isothermal treatment after continuous accelerated cooling. For this purpose, the static and dynamic mechanical properties and microstructures of two medium carbon bainitic steels were examined under various conditions of the continuous accelerated cooling and subsequent isothermal treatment.

2. Experimental
To evaluate the effects of carbon content on the mechanical properties and microstructures, two kinds of medium-carbon steels were prepared with vacuum-induction-melting and hot rolling in thickness of
6~12 mm. Chemical compositions of the alloys are listed in Table 1.

Figure 1 represents continuous accelerated cooling and isothermal treatment process. The initial slab size for hot rolling was 120x220x290 mm and the finish rolling temperature was about 900°C. After hot rolling, acceleration cooling was performed by laminar cooling or spray cooling with water. The final cooling temperature of plates was controlled between 300°C to 600°C and the cooling rate was about 25°C/s. Then the cooled plates were isothermal-treated at 250°C for 1 hour for bainite transformation. In addition, for the purpose of comparison of high strain rate properties, the alloy B was austempered at various temperatures for 30 min in a salt bath for bainite transformation after austenitizing at 900°C.

The ferrite-austenite transition temperature (Ac₃) and martensite start temperature (Ms) were measured by dilatometric analysis. For quantitative analysis, the fraction of retained austenite and martensite was measured by XRD and dilatometry. A series of hardness, tensile, and impact tests was conducted and the high strain rate properties were also evaluated by performing the Split-Hokinson Pressure Bar (SHPB) test.

### Table 1. Chemical composition of the present medium carbon steels. (wt%)

| Specimen | C  | Si  | Mn  | Ni  | Cr+Mo+V | Fe   |
|----------|----|-----|-----|-----|---------|------|
| alloy A  | 0.27 | 0.23 | 0.97 | 3.03 | 0.82   | Bal. |
| alloy B  | 0.50 | 1.45 | 0.68 |     | 0.86   | Bal. |

![Figure 1](image_url)

**Figure 1.** Schematic diagram of accelerated cooling and isothermal treatment process.

### 3. Results & discussions

**3.1. Dilatometry study for analysis temperature of phase transformation**

Figure 2 shows the dilatation curves of the alloy A and alloy B. The Ac₃ and Ms temperature were measured as 780°C and 296°C for alloy A and 857°C and 270°C for alloy B, respectively. With these temperatures, the austenitizing and isothermal temperatures were determined.

**3.2. XRD analysis**

The role of martensite is very important on mechanical properties of steel. Especially, the mechanical properties (hardness, strength, etc.) of the medium-carbon bainitic steel are influenced by the martensite containing highly concentrated carbon. The X-ray analysis was conducted to identify the alloy phases and to evaluate their fraction. As shown in Figure 3, the hot-rolled plated was nearly martensitic and the peaks of retained austenite were not clearly detected, indicating very low retained austenite content if it exists.
3.3. Effect of austempering process on the high strain rate properties of the alloy B

In this study, static/quasi-static tensile test and high strain rate compression test with SHPB were conducted to evaluate the mechanical properties of quench-tempered (Q/T) and austempered samples of the alloy B. The strain rate of each test was $1 \times 10^{-3}$, 1, and $10^{3}$ /s, respectively.

In Table 2, the hardness of the alloy B austempered at different temperatures was compared with that of Q/T alloy. The hardness of the Q/T sample is the highest because of the high volume fraction of martensite. As the austempering temperature decreased, the hardness increased because the fraction of tempered martensite increased.

Figure 4 shows the quasi-static and high strain rate properties of the Q/T and austempered samples. Comparing with the Q/T treated sample, the austempered samples which have lower strength at quasi-static test condition tend to have high strength and also good ductility at high strain rate condition indicating austempering treatment could improve the impact properties of the steels at high strain rate test condition such as ballistic condition.

3.4. Effect of continuous accelerated cooling and isothermal treatment of the alloy B

Two finish cooling temperature of 610°C and 410°C were applied to alloy B for accelerated cooling. Figure 5 and Table 3 represent the cooling curves on the CCT diagram of the alloy B and the phase fraction calculated with JmatPro software. In the alloy B, high temperature phases such as pearlite and ferrite can form in the slow cooling rate because the CCT diagrams of the alloy B is shift to left than that of the alloy A. Microstructure in Figure 6 shows that, while the low cooled plate (air cooling) has pearlite, ferrite and bainite, the major phases of accelerated cooled plates were bainite and martensite. The accelerated-cooled plates cooled to finish cooling temperature were isothermal-treated at 250°C for 1 hr for bainite transformation.

The summary of hardness and tensile properties of the accelerated-cooled and isothermal heat-treated plates is represented in Figure 7. The air-cooled plate had low hardness and strength and high ductility
because the main phase was pearlite as shown in Figures 6(a) and (b). The accelerated cooled plates had higher hardness and strength because of high volume fraction of martensite (Figures 6(c) and (d)) but the ductility sharply decreased as the finish cooling temperature decreased because of formation of fresh martensite. The accelerated-cooled and isothermal treated plates had high strength and reasonable ductility because of the presence of bainite formed during isothermal treatment.

**Table 2.** Hardness of three-austempered conditions of B alloy plates investigated in this study.

| Conditions | Austempered | Q/T |
|------------|-------------|-----|
|            | 245°C 30min | 255°C 30min | 265°C 30min | 200°C 4hr |
| Hardness (HRC) | 56.0±0.09 | 55.7±0.08 | 53.5±0.09 | 59.0±0.15 |

**Figure 4.** (a) Quasi-static and (b) high strain rate properties of austempered and Q/T samples of the alloy B.

**Figure 5.** Accelerated cooling curves plotted in the continuous cooling transformation diagram of the alloy B.

**Table 3.** Calculated phase fractions of the alloy B samples with controlled cooling conditions.

| Conditions | Fraction of phases (%) |
|------------|------------------------|
|            | $f_M^a$ | $f_B^b$ | $f_F^c$ | $f_P^d$ | $f_A^e$ |
| Air cooling | 14.15 | 4.04 | 81.8 | |
| ACC610 | 13.81 | 74.55 | 4.38 | 7.15 | 0.15 |
| ACC410 | 79.3 | 20.05 | 0.06 | 0.02 | 0.58 |

$^a$ Martensite $^b$ Bainite $^c$ Ferrite $^d$ Pearlite $^e$ Austenite
Figure 6. Microstructure of the air cooled and accelerated cooled samples of the alloy B.

Figure 7. (a) hardness and (b) tensile properties of the alloy B with accelerated cooling only and accelerated cooling + isothermal treatment.

Figure 8. Accelerated cooling curves plotted in continuous cooling transformation (CCT) diagram of the alloy A.

Figure 9. Microstructure of air-cooled and accelerated-cooled alloy A.
3.5. Effects of continuous accelerated cooling for alloy A

Accelerated cooling of the hot-rolled plates of the alloy A was conducted from the finish rolling temperature of 900°C to the finish cooling temperatures of 620°C, 454°C, and 350°C followed by air cooling to room temperature. Figure 8 and Table 4 show the cooling curves on the CCT diagram of the alloy A and the phase fraction after cooling to RT calculated with JmatPro software. The accelerated plates of the alloy A consisted of martensite, bainite, and retained austenite. As the finish accelerated cooling temperature decreased from 620°C to 350°C, the martensite fraction increased and the bainite fraction decreased while the retained austenite fraction only slightly increased. The optical microstructure of the accelerated-cooled alloy A is shown in Figure 9.

Figure 10 shows the hardness and tensile properties of accelerated cooling samples of the alloy A. The direct quenched plate had the highest hardness and tensile strength due to the highest fraction of martensite. The air-cooled plate had lower hardness and strength because of higher fraction of bainite. For the accelerated plates, the yield strength decreased and elongation increased with decreasing the finish cooling temperature because the retained austenite fraction increased correspondingly.

Table 4. Calculated phase fractions of the alloy A samples with controlled cooling conditions.

| Conditions | Volume fraction of phases (%) | | | |
|------------|-------------------------------|---|---|---|
|            | f_M  | f_B   | f_F  | f_A  |
| Air cooling| 75.13 | 24.56 | 0.01 | 0.29 |
| ACC620     | 86.42 | 13.25 | 0.32 |
| ACC454     | 95.07 | 4.57  | 0.36 |
| ACC350     | 99.38 | 0.25  | 0.37 |
| Direct quench| 99.46 | 0.15  | 0.39 |

*a Martensite  b Bainite  c Ferrite  d Austenite

Figure 10. (a) hardness and (b) tensile properties of the accelerated-cooled plates of the alloy A.

4. Conclusions
- The austempered alloy B had better high strain rate properties than the Q/T sample due to high strength and good ductility.
- By adapting the accelerated cooling and isothermal process to substitute the austempering process, 0.5 wt% medium carbon bainitic steel (alloy B) showing the high hardness and over 2000 MPa tensile strength was achieved. These excellent mechanical properties are originated from a mixed microstructure of martensite and bainite.
• In the case of the accelerated cooling process for 0.23 wt% low carbon bainitic steel (alloy A), the hardness and tensile strength increased as the finish cooling temperature decreased because the volume fraction of martensite increased but that of bainite decreased.
• The present accelerated cooling and isothermal process can substitute the austempering process with salt bath in bainitic steel.

References
[1] Bhadeshia H and Edmonds D 1983 Met. Sci. 17 420–5
[2] Caballero F, Bhadeshia H, Mawella K, Jones D and Brown 2001 P Mater. Sci. Technol. 17 512–6
[3] Gong W, Tomota Y, Harjo S, Sua Y H, Aizawa K 2015 Acta Mater. 85 243-9
[4] Caballero F, Bhadeshia H, Mawella K, Jones D and Brown P 2002 Materials science and technology 18 279-84
[5] Sung H K, Shin S Y, Hwang B, Lee C G, Kim N J and S Lee 2010 Korean Journal of Metals and Materials 48 798-806
[6] Bhadeshia H and Edmonds D 1983 Metal Science 17 411-9
[7] Lee D J, Kim M S, Ku G E, Heo S H, Kim N Y and Lee J M 2018 Korean Journal of Metals and Materials 56 221-6
[8] Caballero F, Roelofs H, Hasler S, Capdevila C, Chao J, Cornide J and Garcia-Mateo C 2012 Materials Science and Technology 28 95-102
[9] Garcia-Mateo C, Jiménez J A, Yen H W, Miller M, Morales-Rivas L, Kuntz M, Ringer S, Yang J R and Caballero F 2015 Acta Materialia 91 162-73
[10] Kim G H, Jang J H, Kim S H, Kim B J, Sohn K Y and Nam D G 2017 Korean Journal of Metals and Materials 55 559-65