
AI translation · View original & related papers at
chinaxiv.org/items/chinaxiv-202303.00285

Effect of Heat Treatment Process on Mechanical Properties of Medium Carbon Low Alloy Steel Postprint

Authors: Pan Wei, Li Zulai, mountain spring, Jiang Yehua, Feng Zhiyang, Zhou Rong

Date: 2023-03-18T00:00:00+00:00

Abstract

Medium-carbon low-alloy steel was subjected to heat treatment via water cooling + salt bath isothermal quenching, air cooling + salt bath isothermal quenching, and direct salt bath isothermal quenching. The influence of heat treatment methods on the microstructure and mechanical properties of the alloy steel was investigated using color metallographic technique and XRD analysis, and the correlation between properties and microstructure was explored. The results demonstrate that heat treatment of medium-carbon low-alloy steel by air cooling + salt bath isothermal quenching and water cooling + salt bath isothermal quenching yields bainite/martensite duplex microstructures with varying lower bainite contents. The material properties are substantially enhanced compared to the as-cast state, with impact toughness increasing by 92%-183% and hardness increasing by 31%-55%. For material subjected to air cooling + salt bath isothermal quenching, as air cooling time increases, the lower bainite content in the duplex microstructure gradually decreases while the martensite content increases, with hardness and impact toughness exhibiting increasing and decreasing trends, respectively. The properties of medium-carbon low-alloy steel are closely correlated with the content of each constituent phase. When the lower bainite content is 30%-40% and the martensite content is 50%-60%, the bainite/martensite duplex microstructure achieves a favorable strength-toughness balance, endowing the material with high comprehensive properties.

Full Text

Effect of Heat Treatment Process on Mechanical Properties of a Medium Carbon Low Alloy Steel

PAN Wei, LI Zulai, SHAN Quan, JIANG Yehua, FENG Zhiyang, ZHOU Rong

School of Materials Science and Engineering, Kunming University of Science and Technology, Kunming 650093, China

Supported by Yunnan Provincial Science and Technology Department No. 619320130010.

Manuscript received December 17, 2014; in revised form March 5, 2015.

To whom correspondence should be addressed, Tel: 13888516050, E-mail: lizulai@126.com

Abstract

This study investigated the effects of various heat treatment processes on the microstructure and mechanical properties of a medium carbon low alloy steel using color metallography, X-ray diffraction (XRD), and mechanical testing. The heat treatment processes included water cooling followed by salt bath austempering, air cooling followed by salt bath austempering, and direct salt bath austempering. The results demonstrate that these treatments produce bainite/martensite duplex microstructures with varying bainite content, significantly improving mechanical properties compared to the as-cast condition. Specifically, impact toughness increased by 92%-183% and hardness increased by 31%-55%. For air cooling followed by salt bath austempering, the bainite content gradually decreased while martensite content increased with longer air cooling times, leading to corresponding increases in hardness and decreases in impact toughness. The mechanical performance of the medium carbon low alloy steel is closely related to the phase fractions in the microstructure. An optimal combination of mechanical properties was achieved with a duplex microstructure containing 30%-40% lower bainite and 50%-60% martensite.

Keywords: metallic materials, bainite/martensite duplex microstructure, austempering, color metallography, ductile fracture

Introduction

Bainite/martensite duplex steel exhibits high hardness, good toughness, and excellent comprehensive mechanical properties, making it highly valuable for applications in mining, construction materials, and other industries. Previous research by Tomita et al. demonstrated that in medium carbon low alloy steels, the presence of small amounts of upper bainite in a martensite matrix does not adversely affect strength and toughness, while bainite/martensite duplex

microstructures and carbide-free bainite/martensite duplex microstructures can improve both strength and toughness. Studies by Huang Weigang et al. and Song Yujiu et al. showed that in medium-low carbon and medium-high carbon low alloy steels, duplex microstructures containing appropriate amounts of lower bainite exhibit slightly reduced strength but significantly improved toughness compared to single martensitic structures. Liu Dongyu et al. found that bainite/martensite duplex steels possess not only excellent strength and toughness but also high fatigue limits and threshold stress values. Jiang Yehua's research indicated that medium carbon low alloy bainite/martensite duplex steel exhibits good strength-toughness combination and excellent abrasive wear resistance. Cai Minghui et al. demonstrated that replacing some martensite with appropriate amounts of bainite reduces the hardness ratio between hard and soft phases, which helps improve the toughness of the hard phase and thereby enhances the overall performance of duplex steels. However, these studies provided limited investigation into the quantitative relationship between bainite fraction and mechanical properties.

The present work addresses this gap by subjecting a medium carbon low alloy steel to various heat treatments including water quenching followed by salt bath austempering and air cooling followed by salt bath austempering. Using XRD analysis, color metallography, and quantitative metallographic analysis, we characterized the volume fractions of bainite, martensite, and austenite in the duplex microstructures. The study systematically investigates how different heat treatment processes affect the microstructure and mechanical properties of the steel and explores the correlations between performance and the relative contents of bainite, martensite, and austenite.

1. Experimental Methods

The experimental steel was designed utilizing carbon for solid solution strengthening, carbon and manganese for austenite stabilization, manganese for hardenability improvement, silicon for strongly inhibiting carbide precipitation, and chromium and boron for strength enhancement. The chemical composition is listed in Table 1.

The steel was cast in sand molds using a 50 kg medium-frequency induction furnace. The steel liquid was tapped at 1520°C and poured at 1450°C into keel blocks. Standard Charpy V-notch impact test specimens measuring 10 mm × 10 mm × 55 mm were cut by wire electrical discharge machining for impact toughness testing.

Multiple groups of impact specimens were subjected to different heat treatment processes: (1) heating at 900°C for 12 minutes, water cooling for 2-4 seconds, then austempering in a 300°C salt bath for 40 minutes; (2) heating at 900°C for 12 minutes, then direct austempering in a 300°C salt bath for 40 minutes; (3) heating at 900°C for 12 minutes, air cooling for 2-4 seconds, then austempering in a 300°C salt bath for 40 minutes; (4) heating at 900°C for 12 minutes,

air cooling for 6-8 seconds, then austempering in a 300°C salt bath for 40 minutes; (5) heating at 900°C for 12 minutes, air cooling for 10-12 seconds, then austempering in a 300°C salt bath for 40 minutes. The austempering treatment was performed in a mixed salt bath containing 75% KNO₃ and 25% NaNO₃. Three specimens were prepared for each heat treatment condition, with as-cast specimens serving as the control group.

Phase analysis was conducted using a Rigaku MiniFlex 600 X-ray diffractometer with a cobalt target. The retained austenite content was calculated using the formula:

$$W_a = \frac{I_a}{I_a + K_{b/a}I_b}$$

where W_a is the mass fraction of retained austenite, I_a is the integrated intensity of the retained austenite diffraction peak, I_b is the integrated intensity of the matrix diffraction peak, and $K_{b/a}$ is the ratio of integrated intensities of the strongest diffraction peaks for retained austenite and the matrix. The bainite content was determined using color metallography with Image-Pro Plus software. The volume fraction of green needle-like structures (lower bainite) in the metallographic images was measured as the relative bainite content. The martensite content was then calculated based on the measured bainite and retained austenite contents.

Color metallographic samples were prepared using LePera's reagent, which consists of a 1:1 mixture of 10 g/L sodium metabisulfite aqueous solution and 40 g/L picric acid ethanol solution, with an etching time of 3 minutes. To avoid experimental error from field selection, 20 different fields were examined for each specimen and the average values were reported.

Impact toughness was measured using a JBN-300B impact testing machine. Hardness was measured using a Model 150 Rockwell hardness tester. Fracture surface morphology was examined using scanning electron microscopy.

2.1 Effect of Heat Treatment Process on Microstructure

Figure 1 [Figure 1: see original paper] shows the X-ray diffraction patterns for specimens subjected to different heat treatment processes. Analysis reveals that all heat-treated specimens consist of austenite and α -ferrite phases. Since the (110) γ peak of austenite overlaps with the (110) α peak of martensite, the (220) γ austenite peak and (110) α martensite peak were selected for comparison to calculate retained austenite content. The results indicate retained austenite contents of 25%, 14.1%, 12.7%, 8.1%, and 7.6% for water cooling 2-4 seconds + salt bath austempering, direct salt bath austempering, air cooling 2-4 seconds + salt bath austempering, air cooling 6-8 seconds + salt bath austempering, and air cooling 10-12 seconds + salt bath austempering, respectively.

Figure 2 [Figure 2: see original paper] presents the microstructures of medium carbon low alloy steel specimens in different conditions after etching with 4% nitric acid alcohol solution. The as-cast microstructure consists primarily of typical lamellar pearlite. The microstructure after water cooling 2-4 seconds + salt bath austempering consists of retained austenite and needle-like structures that intersect at various angles with random distribution and varying thickness. Martensite is more resistant to etching than lower bainite; after light etching with 4% nitric acid alcohol solution, martensite appears lighter while bainite appears darker. Both needle-like martensite and needle-like lower bainite appear dark black, with intersecting needles at specific angles. Martensite needles are short and thick, intersecting at approximately 60° , while lower bainite needles are thin and long with more random distribution, intersecting at angles of $55-65^\circ$. Therefore, the needle-like structures observed in Figure 2b could be either martensite or lower bainite and cannot be distinguished unambiguously.

Figure 3 [Figure 3: see original paper] shows the color metallographic microstructures after different heat treatment processes. Bainite etches more readily than martensite and retained austenite. During etching, bainite is rapidly attacked while martensite and retained austenite etch more slowly. After 3 minutes of etching with LePera's reagent, a sulfide or nitrite film forms on the more heavily corroded bainite surface, appearing green under reflected light microscopy. Martensite, being less corroded, shows brown or tan coloration, while retained austenite, which is difficult to etch, appears light brown or bright white. This color contrast clearly distinguishes the microstructural constituents: lower bainite appears as fine, elongated needles; martensite as short, thick lath structures; and the coarse needles in Figure 2b are revealed to be clusters of overlapping bainite laths.

The microstructures in Figure 3 reveal that water cooling 2-4 seconds + salt bath austempering (Figure 3a) and direct salt bath austempering (Figure 3b) produce fine, numerous lower bainite needles with small inter-lath spacing. In contrast, various air cooling + salt bath austempering treatments produce coarser, less numerous bainite needles with larger spacing (Figures 3c, 3d, and 3e). This difference arises because slower cooling during air cooling allows sufficient carbon diffusion from the ferrite-austenite interface into austenite at higher temperatures, resulting in bainite composed of wider ferrite laths. Due to the higher transformation temperature and smaller undercooling, the free energy difference between the new and parent phases is smaller, producing fewer, wider ferrite laths with larger spacing. Conversely, water cooling + salt bath austempering or direct salt bath austempering provides greater undercooling, larger free energy differences, and consequently produces narrower, more numerous ferrite laths with smaller spacing.

Using XRD, color metallography, and quantitative metallographic analysis, the volume fractions of bainite, martensite, and austenite were determined. In the color metallographic images, green needle-like structures represent lower bainite, and their area percentage corresponds to the relative bainite content. The mea-

sured lower bainite contents for different heat treatment processes are 29.28%, 56.26%, 35.6%, 25.8%, and 14.9%, respectively. Martensite contents were calculated based on bainite and retained austenite measurements, with the phase fractions for each condition summarized in Table 2 .

Table 2 shows that higher bainite content corresponds to lower martensite content and relatively lower retained austenite content. This relationship is visually evident in Figure 3, where Figure 3b (direct salt bath austempering) shows high bainite content with low martensite, while Figure 3e (air cooling 10-12 seconds + salt bath austempering) shows low bainite content with high martensite, consistent with the quantitative results.

Figure 4 [Figure 4: see original paper] illustrates the effect of air cooling time on the microstructure constituents in air cooling + salt bath austempering treatments. The variation in phase contents is directly related to air cooling time before austempering (with direct salt bath austempering considered as zero air cooling time). As air cooling time increases, the bainite content gradually decreases while retained austenite content increases. Direct salt bath austempering, with large undercooling and high driving force, produces numerous ferrite laths and high bainite content. In contrast, air cooling for 10-12 seconds before austempering results in minimal undercooling and low bainite content. Additionally, reduced undercooling decreases the driving force for transformation, slowing the reaction and making transformation more difficult, which leads to increased retained austenite content with decreasing undercooling. Unlike direct austempering, water quenching + salt bath austempering rapidly forms a certain amount of coarse martensite with obvious surface relief (Figure 3a). During subsequent isothermal transformation, the lower sample temperature provides insufficient driving force, resulting in only partial transformation of undercooled austenite to bainite, with the remainder retained as austenite. Consequently, water cooling + salt bath austempering produces relatively high martensite and retained austenite contents.

2.2 Effect of Heat Treatment Process on Mechanical Properties

Table 3 compares the hardness and impact toughness of specimens before and after heat treatment. Compared to the as-cast condition, heat-treated specimens show substantial improvements in both hardness and impact toughness, with increases of approximately 92%-183% in impact toughness and 31%-55% in hardness. The as-cast microstructure consists primarily of lamellar pearlite, while heat-treated microstructures transform to bainite/martensite duplex structures. Martensite provides high hardness while lower bainite contributes good toughness, and the duplex structure combines these benefits to achieve significantly enhanced comprehensive mechanical properties.

Direct salt bath austempering yields the highest impact toughness but the lowest hardness, while air cooling 10-12 seconds + salt bath austempering produces the lowest impact toughness but the highest hardness. Correlating with the mi-

microstructural data in Table 2 reveals that direct salt bath austempering produces the highest bainite content and lowest martensite content, whereas air cooling 10-12 seconds + salt bath austempering yields the lowest bainite content and highest martensite content. This demonstrates a close relationship between mechanical properties and phase fractions.

Comparing water cooling 2-4 seconds + salt bath austempering with air cooling 2-4 seconds + salt bath austempering shows that although the water-cooled treatment produces less bainite, it contains significantly more retained austenite, resulting in comparable impact toughness. This indicates that retained austenite contributes positively to impact toughness. Furthermore, comparing different air cooling times reveals that impact toughness tends to decrease with decreasing bainite content, while hardness tends to increase with increasing martensite content.

Figure 5 [Figure 5: see original paper] shows the effect of air cooling time on mechanical properties in air cooling + salt bath austempering treatments. Hardness increases while impact toughness decreases with longer air cooling times. Combined with Figure 4, which shows increasing martensite and decreasing bainite contents with longer air cooling times, this further confirms the strong correlation between mechanical properties and microstructure. Overall, water cooling 2-4 seconds + salt bath austempering, air cooling 2-4 seconds + salt bath austempering, and air cooling 6-8 seconds + salt bath austempering all produce good combinations of hardness and impact toughness.

Research indicates that multiphase structures with high retained austenite content exhibit better comprehensive ductility and toughness, but excessively high retained austenite content reduces fatigue limits and threshold stress values, decreasing wear life. Therefore, retained austenite content should be maintained at an optimal level of approximately 5%-15%. To achieve good comprehensive mechanical properties in medium carbon low alloy steel, the microstructure should contain 30%-40% bainite and 50%-60% martensite, which provides a well-balanced combination of hardness and impact toughness.

Figure 6 [Figure 6: see original paper] presents the fracture morphologies of impact specimens in the as-cast condition and after air cooling 2-4 seconds + salt bath austempering. The as-cast specimen shows a relatively smooth fracture surface with clear "river pattern" characteristics, indicating cleavage fracture. In contrast, the heat-treated specimen exhibits numerous shear dimples formed by plastic deformation, with fracture occurring along the edges of hard phases, characteristic of ductile fracture. These observations correlate well with the low impact toughness of as-cast specimens and high impact toughness of heat-treated specimens. During crack propagation, retained austenite impedes crack growth, absorbing significant impact energy through micro-scale plastic deformation. The heat-treated specimen shows numerous small, uniformly distributed dimples with tear ridges at the fracture surface, consistent with its high hardness and high toughness values. This demonstrates that isothermal quenching of medium carbon low alloy steel to form lower bainite/martensite

duplex microstructures provides both high toughness and good ductility.

Conclusions

1. Air cooling + salt bath austempering and water cooling + salt bath austempering of medium carbon low alloy steel produce bainite/martensite duplex microstructures with varying lower bainite contents, significantly improving material properties compared to the as-cast condition. Impact toughness increases by 92%-183% and hardness increases by 31%-55%.
2. In air cooling + salt bath austempering treatments, increasing air cooling time gradually decreases the lower bainite content while increasing martensite content in the duplex microstructure, resulting in increased hardness and decreased impact toughness.
3. The mechanical properties of medium carbon low alloy steel are closely related to phase fractions. As lower bainite content increases (and martensite content decreases), hardness decreases while impact toughness increases. An optimal combination of mechanical properties is achieved with a duplex microstructure containing 30%-40% lower bainite and 50%-60% martensite.

References

1. Fang Hongsheng, Liu Dongyu, Bai Bingzhe, Chang Kaidi, Gu Jialin, Yang Zhigang. The latest advancement of carbide-free bainite/martensite duplex phase steel. *Heat Treatment of Metals*, 26(10), 4 (2001).
2. Richardson R.C.D. The Relationships between Wear Behavior and Basic Material Properties for Pearlitic Steels. *Wear of Materials*, 60(1), 75 (1980).
3. Ahmadabadi M N. Bainitic transformation in austempered ductile iron with reference to untransformed austenite volume phenomenon. *Metallurgical and Materials Transactions A*, 28(10), 2159 (1997).
4. Tomita Y, Morioka K. Effect of microstructure on transformation-induced plasticity of silicon-containing low-alloy steel. *Materials Characterization*, 38(4), 243 (1997).
5. Huang Weigang, Xu Rong, Fang Hongsheng, Zheng Yankang. Impact toughness of medium low carbon silicon modified bainitic steel. *Journal of Iron and Steel Research*, 9(2), 31 (1997).
6. Song Yujiu, Lu Jintang, Liu Jinghua, Shen Lian, Rao Qichang, Zhou Huijiu. The strength and toughness of the martensite bainite mixed microstructure. *Transactions of Materials and Heat Treatment*, 3(1), 11 (1982).

7. Liu Dongyu, Xu Hong, Yang Kun, Bai Bingzhe, Fang Hongsheng. Effect of bainite/martensite mixed microstructure on the strength and toughness of low carbon alloy steel. *Acta Metallurgica Sinica*, 40(8), 882 (2004).
8. Jiang Yehua. *Doctorate Dissertation: Controlled Cooling Bainite Phase Wear-Resisting Cast Iron Grinding Balls and Research of Cast Steel Plate*. Kunming University of Science and Technology, 2000.
9. Cai Minghui, Ding Hua, Zhang Sujian, Li Long, Tang Zhengyou. Deformation and fracture characteristics of ferrite/bainite dual-phase steels. *Chinese Journal of Materials Research*, 23(1), 83 (2009).
10. Girault E, Jacques P, Harlet Ph, Mols K, Van Humbeeck J, Aernoudt E, Delannay F. Metallographic methods for revealing the multi-phase microstructure of TRIP-assisted steels. *Materials Characterization*, 40(2), 111 (1998).
11. Cui Zhongqi, Tan Yaochun. *Metallography and Heat Treatment*, 2nd Edition. Beijing: Mechanical Industry Press, 2007, p. 253, p. 260, p. 308.
12. Zhang Peng, Han Bo, Zhang Fucheng, Lü Bo, Zheng Chunlei, E Lijun. Colored metallography of bainite steel. *Heat Treatment of Metals*, 34(10), 42 (2009).
13. Chen Yantang, Fang Hongsheng, Bai Bingzhe, Yang Zhigang, Li Qi, Hou Chuanji, Gao Fan. Effect of silicon on impact wear behavior of high strength and high toughness bainitic steels. *Heat Treatment of Metals*, 26(8), 5 (2001).
14. Li Shutang. *Metal X-ray Diffraction and Electron Microscopic Analysis Technology*. Beijing: Metallurgical Industry Press, 1980, p. 143.
15. Zhang Xun. The application of colored metallographic in power system. *Journal of Anhui Electric Power College for Staff*, 7(1), 96 (2002).
16. Xu Zuyao, Li Xuemin. The diffusion of carbon during the formation of low carbon martensite. *Acta Metallurgica Sinica*, 19(2), 83 (1983).
17. Zhao Hui, Shi Jie, Li Nan, Wang Cunyu, Hu Jin, Hui Weijun, Cao Wenquan. Effects of Si on the microstructure and mechanical property of medium Mn steel treated by quenching and partitioning process. *Chinese Journal of Materials Research*, 25(1), 45 (2011).
18. Ren Yongqiang, Shang Chengjia, Zhang Hongwei, Yuan Shengfu, Chen Erhu. Effect of retained austenite on toughness and plasticity of 0.23C-1.9Mn-1.6Si steel. *Chinese Journal of Materials Research*, 28(4), 274 (2014).
19. Yang Fubao, Bai Bingzhe, Liu Dongyu, Chang Kaidi, Wei Dongyuan, Fang Hongsheng. Microstructure and properties of a carbide-free bainite/martensite ultra-high strength steel. *Acta Metallurgica Sinica*, 40(3), 296 (2004).

20. Yan Yunhui, Ma Pengren, Cao Yuguang, Zhang Jian. Recognition and classification of metal fracture surface images based on syntax pattern recognition. *China Mechanical Engineering*, 15(3), 259 (2004).

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv –Machine translation. Verify with original.