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Research Article

Effect of Heat Treatment on the Matrix Structure and Properties of ВЧ60 Ductile Cast Iron

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Abstract

Ductile iron represents a family of alloys with a wide range of properties achievable through controlled manipulation of the matrix microstructure. Furthermore, its lower cost compared to steel and superior properties to gray iron make ductile iron a favorable choice in many engineering applications. The higher carbon and silicon content in ductile iron significantly alters its mechanical properties. The elevated carbon content increases its susceptibility to quench cracking, while the higher silicon content decreases carbon solubility in austenite, leading to graphite precipitation and a ferritic matrix during slow cooling. Consequently, heat treatment is a critical process for optimizing ductile iron properties. Different grades of ductile iron castings are produced by obtaining different matrix microstructures, which are primarily achieved through heat treatment and cannot be readily obtained in the as-cast condition. This study investigates the effects of different heat treatment processes on the microstructure and mechanical properties of ВЧ60 (VCh60) ductile iron, conforming to the Russian standard ГОСТ 7293-85. To optimize the heat treatment parameters, this research utilized Thermo-Calc and JmatPro software to construct phase diagrams and generate Continuous Cooling Transformation (CCT) and Time-Temperature-Transformation (TTT) diagrams. These diagrams were instrumental in predicting optimal heat treatment parameters for achieving desired microstructures and mechanical properties. Consequently, this computational approach enabled the selection of appropriate heat treatment strategies for the investigated ductile iron.

Keywords

ВЧ60 Ductile Iron, ADI, Dual Phase Matrix, Heat Treatment, CCT, TTT, Mechanical Properties

1. Introduction

Ductile irons and austempered ductile irons (ADI) are ferrous cast irons that have undergone different austempering heat treatment conditions. Many scientists have examined the phase transformation and mechanical characteristics of graphite cast iron materials, and articles have been published that outline their performances in engineering service environments. The unusual structural integrity of ausferrite, or carbon saturation in the austenitic phase, and the acicular ferritic characteristics of the material might all play a role in the outstanding mechanical properties established [1]. The optimal microstructure consists of graphite nodules embedded in an ausferritic matrix, which comprises acicular ferrite and high-carbon austenite [2-4]. In the last fifteen years, researchers have focused on phase-change and mechanical features of graphite cast irons utilizing various chemical contents and heat treatment methods, as well as developing

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mathematical algorithms [5-9]. ADI is highly valued for its excellent combination of strength and ductility, making it a good alternative to steel castings and forgings, and even aluminum components in various applications, particularly in automotive manufacturing [10-12]. However, the production of ADI requires critical control, as the final ausferritic morphology is influenced by many factors, including chemical composition, heat treatment temperature, holding time, and cooling rate [13, 14]. Standard ADI grades have been established based on material properties [15].

The heat treatment process of ADI involves these key stages: heating to the austenitization temperature; holding time at the austenitization temperature; quick cooling to the temperature of isothermal transformation of austenite; holding time at this temperature until austenite is changed into bainaite; and dropping the temperature to ambient conditions, which is normally performed gradually to avoid stress accumulation [16]. Depending on holding time at isothermal transformation temperature, which be called austempering temperature, this stage is further divided into two continuous phase transformation steps. In the first step, austenite decomposes into acicular ferrite while enriching the remaining austenite with carbon, forming the unique ausferritic matrix. In the next step, the high-carbon austenite decomposes further into ferrite and carbon will be precipitated in form of carbides. Hence, some mechanical properties can be decreased because of bainite formation in the matrix [3, 14]. For large castings applied to complex loading conditions, conventional quenching and tempering treatments are generally preferred to achieve high overall mechanical performance [15].

In industry applications, ductile iron components require moderate strength but high elongation. One approach to achieving this balance is to increase the content of pro-eutectoid ferrite in ADI, leading to the development of ADI with dual matrix. The ductile iron with ferrite-ausferrite matrix has gained attention as a promising alternative for drive shaft and chassis components in the defense and automotive industries due to its superior properties, including a yield strength of approximately 380-550 MPa, tensile strength of 500-900 MPa, elongation of 14-20%, impact toughness of 45-55 J/cm², excellent corrosion resistance, and outstanding castability and machinability [17-19, 22]. A ferrite-ausferrite matrix can be achieved through partial austenitization followed by isothermal austempering. Results has shown that this structure offers comparable strength to pearlitic ductile iron while maintaining elongation similar to ferritic ductile iron [19-21].

This study investigates the effects of various heat treatment processes on the microstructure and mechanical properties of high-strength ductile iron. The heat treatment methods examined include quenching and austempering; austempering and three-phase region heat treatment.

2. Materials and Methods

The initial charge materials consisted of pig iron, steel scrap, ductile iron scrap, and ferro alloys including FeCr, FeSi, and FeMn. The ductile iron was melted via induction furnace. Table 1 presents the chemical composition of ВЧ60 ductile iron as per ГОСТ 7293-85, alongside the actual composition of the experimental melt, determined by optical emission spectrometry. The analysis confirmed that the melt composition met the standard requirements.

Spheroidization was carried out using the intermediate alloy VE08-099, added at 2% of the molten iron weight. The Sandwich method was employed for the spheroidization process, followed by graphitization treatment using 0.5% Fe-Si75. The treated molten iron was poured into an Y-shaped block sand mould in accordance with ASTM A439-83 at a temperature of 1450 ℃. Test samples were cut in the lower part of the Y-shaped block. The dimension of the optical sample was 15 mm × 15 mm × 10 mm, and subsequently subjected to heat treatment for further analysis.

The Thermo-Calc and JmatPro software were used to construct the phase diagram of the material and generate CCT (Continuous Cooling Transformation) and TTT (Time-Temperature-Transformation) diagrams. The input parameters includes austenitization temperature at 900 ºC, molten iron composition in table 1. These diagrams were essential for identifying critical transformation points and optimizing the heat treatment process.

Table 1. *Chemical Composition of Ductile Cast Iron ВЧ60.*

	C	Si	Mn	P	S	Cr	Ni	Cu
Std	3.2 - 3.6	2.4 - 2.8	0.4 - 0.7	≤ 0.1	≤ 0.02	≤ 0.15	≤ 0.4	≤ 0.3
Sample	3.2	2.45	0.64	0.02	0.02	0.12	0.04	0.11

Standard sample preparation techniques, including grinding, polishing, and etching, were employed for microstructural evaluation. Samples were ground using a Struers grinder with SiC abrasive paper, progressing through grit sizes of 200, 400, 600, 800, 1000, 1200, and 1500. Following grinding, the samples were polished on a Struers

polishing machine using Cr_2O_3 powder with a particle size of less than 1 μm. The polishing process was limited to a maximum duration of 30 minutes. After polishing, the samples were cleaned with water and dried. Etching was performed using a solution consisting of 75% HNO_3, 24% HCl, and 1% HF. The etchant was lightly applied to the sample surface. The surface was carefully observed during etching; the initial mirror-like finish of the cast iron transitioned to a dark gray color, revealing microstructural features. Once the features became visible, the samples were cleaned with water, dried, and prepared for microscopic examination.

The Axio Observer D1M optical microscope was used to analyze the microstructure. Phase fractions were determined using the Matavis Hard software integrated with the optical microscope. Hardness measurements were performed using the AT200 DR-TM hardness tester, each measurement was taken three times per location, and the average value was recorded.

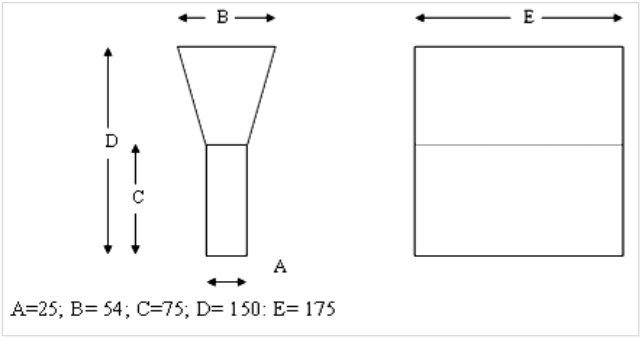

Figure 1. *Y-Block Castings for Strength Testing and Microstructural Analysis (mm).*

3. Results and Discussion

3.1. As-cast Ductile Iron Microstructures

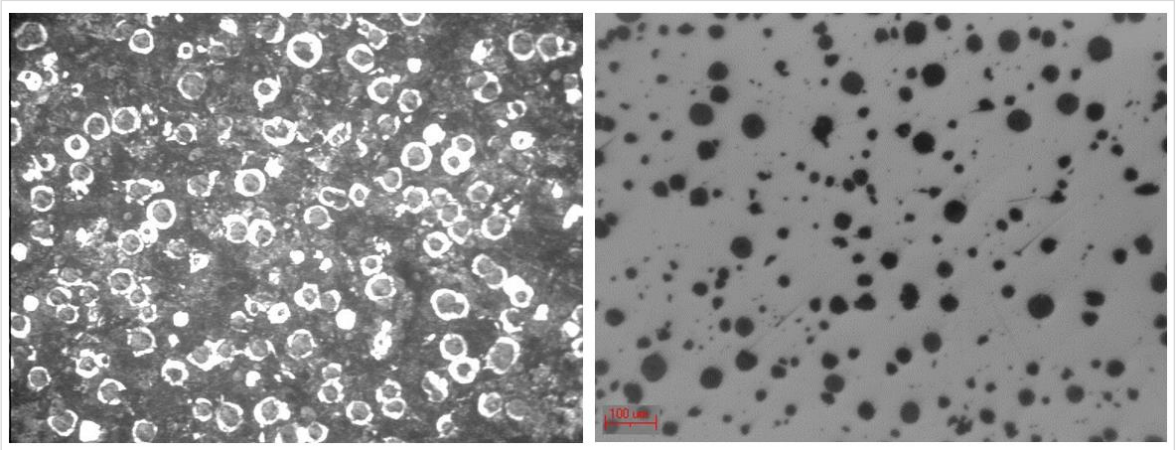

Figure 2. *Microstructure of as-cast sample.*

Figure 2 indicates the microstructure of as-cast sample. According to the Matavis Hard software integrated with the optical microscope, the as-cast sample has a spheroidization level of approximately 95%, with the matrix consisting of around 80% pearlite and the remainder being ferrite. Heat treatment of ductile iron is crucial for achieving desired microstructures and enhancing mechanical properties not attainable in the as-cast condition. Thermodynamic calculations were performed using Thermo-Calc and JMatPro software, assuming equilibrium conditions, to understand phase transformations during heat treatment.

3.2. Phase Diagram and Critical Points

Using Thermo-Calc and JMatPro software, the thermodynamics of the alloy solidification process under equilibrium conditions were calculated. The enthalpy change with respect to temperature during solidification is depicted in Figure 3. The phase fractions during crystallization are shown in Figure 4. The phase diagram in the carbon-saturated austenite region is presented in Figure 5.

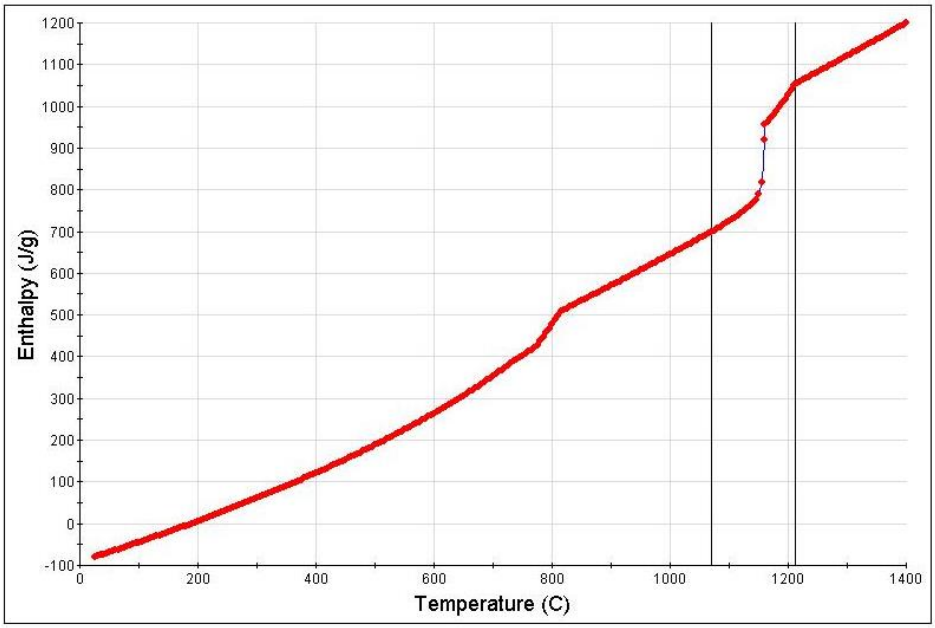

Figure 3. *Enthalpy change with temperature during solidification for ductile cast iron grade ВЧ60 constructed using JMatPro software.*

According to Figure 3, the enthalpy of the cast iron shows three abrupt changes at 770 ℃, 810 ℃, and 1150 ℃. Among these, the starting and finishing temperatures of the phase transformation in the three-phase region are 770 ℃ and 810 ℃, respectively. The crystallization initiation temperature is 1150 ℃.

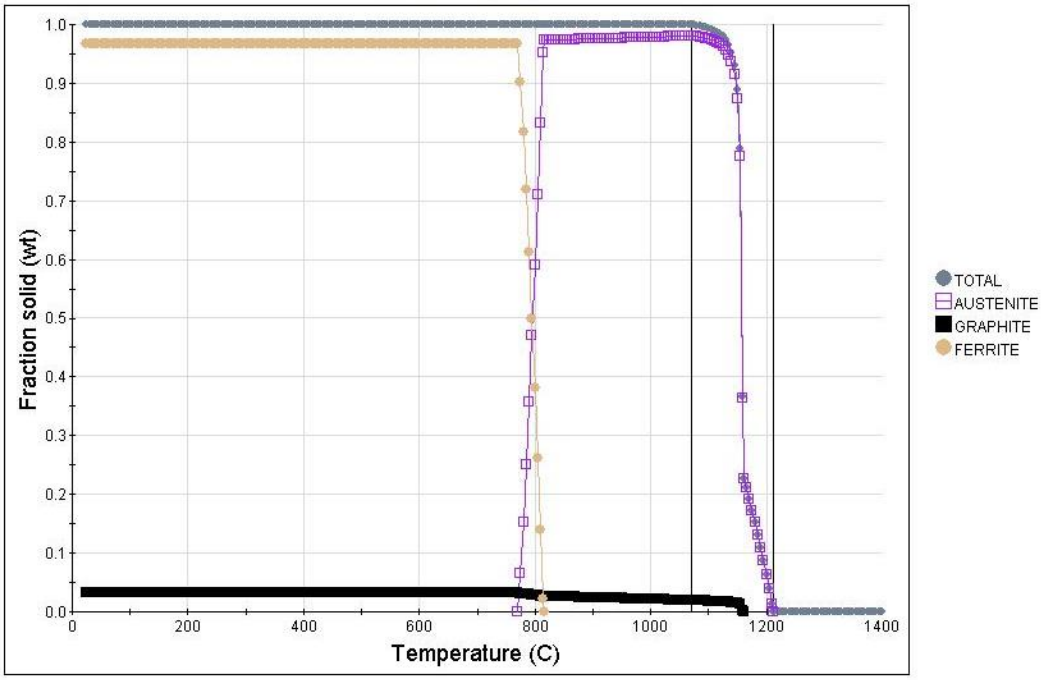

Figure 4. *Phase fraction diagram at different temperatures for ductile cast iron grade ВЧ60 constructed using JMatPro software.*

Figure 4 indicates that in the temperature range of 770-810 ℃, which called the three-phase region, the phase fractions of ferrite and austenite undergo abrupt changes. Clearly, when the cast iron is cooled to 810 ℃, ferrite begins precipitating from carbon-saturated austenite. The transformation from austenite to ferrite completes at 770 ℃. The phase fractions of ferrite and austenite depend on both temperature and holding time within this three-phase region.

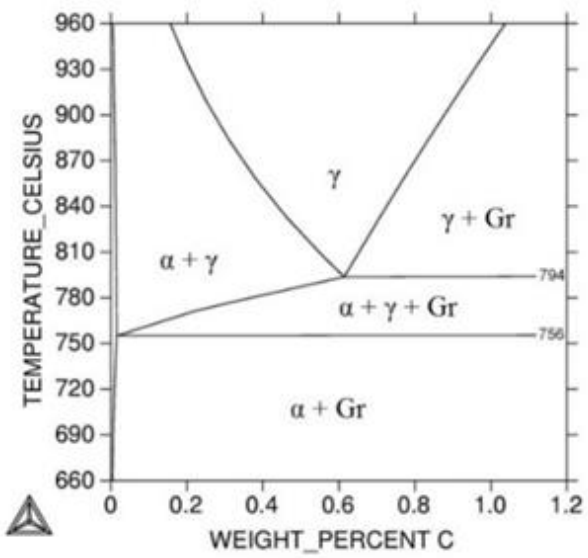

Figure 5. *Phase diagram of ductile cast iron grade ВЧ60 constructed using Thermo-Calc software.*

Additionally, Figure 5 also indicates that the three-phase region also occurs within the 756-794 ℃ range. In this region, the microstructure consists of austenite, ferrite, and graphite. The complete austenitization temperature ranges from 900-930 ℃, assuming a carbon saturation content in austenite of approximately 0.9-1.0%.

Using JMatPro software, we constructed the Time-Temperature-Transformation (TTT) diagram, commonly known as the C-curve (Figure 6a), and the Continuous Cooling Transformation (CCT) diagram of the cast iron (Figure 6b). The alloying elements introduced a secondary kinetic bay and subsidiary arm on the C-curve. The second bay occurs at lower temperature (400 ℃) than the primary bay (650 ℃). Under continuous cooling at 10 ℃/s, bainite formation begins after approximately 80-90 seconds at 270 ℃, while ferrite precipitation initiates at a higher temperature, near 600 ℃. To enhance the mechanical properties of ВЧ60 ductile cast iron through heat treatment, the post-treatment microstructure can be selected as either martensite or bainite. The phase diagram indicates that the critical cooling rate to achieve a martensitic structure during quenching is approximately 150 ℃/s, while obtaining a bainitic structure requires isothermal holding at approximately 360 ℃.

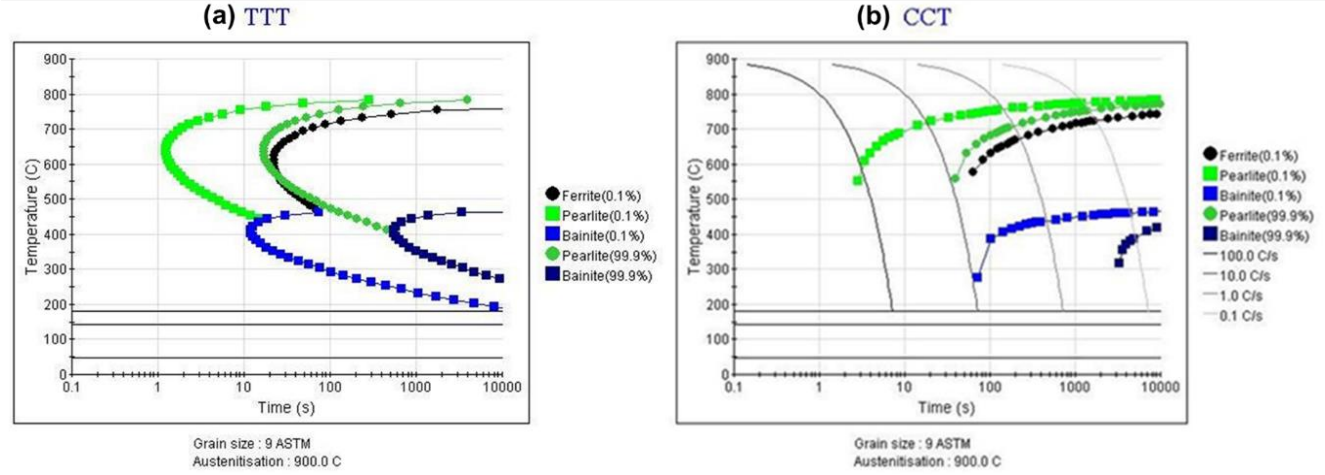

Figure 6. *(a) Time-Temperature-Transformation (TTT) and (b) Continuous-Cooling-Transformation (CCT) diagrams for ductile cast iron ВЧ60, modeled with JMatPro software.*

3.3. Austempered Ductile Iron (ADI)

Based on the results of thermodynamic calculations for producing austempered ductile iron, the as-cast samples were austenitized at 900 ℃ for 2 hours, followed by austempering in the temperature range of 280-400 ℃ for 90 minutes in a salt bath, and subsequent air cooling. The salt bath composition consisted of 50% KNO_3 and 50% $NaNO_3$ by weight.

Figure 7 shows the tensile strength and the elongation and Figure 8 shows the microstructure of samples after austempering at a temperature of 280, 320, 360 and 400 ℃. The microstructure results indicates acicular ferrite in the ausferrite matrix becomes coarser when the austempering temperature increases, and fine-grained when the temperature is higher than 360 ℃. Combined with the mechanical test results (Figure 7), the tensile strength increases from 800-1000 MPa, the elongation also increases and obtains a maximum value (8%) at 360 ℃. It can be predicted that, while the austempering temperature is higher than 360 ℃, the austempering time (90 minutes) has exceeded the process window of ADI, leading to decrease its elongation.

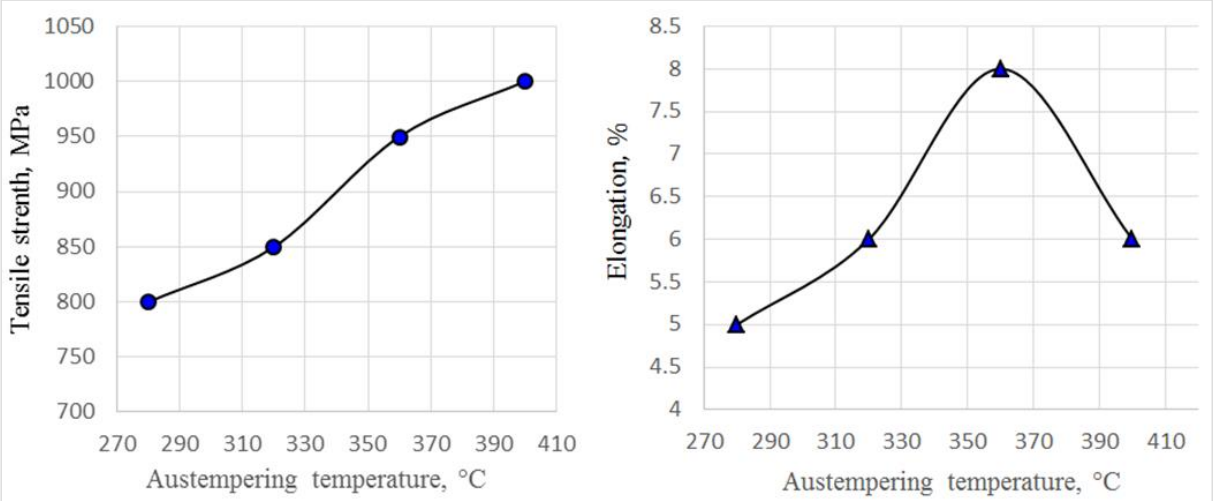

Figure 7. *Mechanical properties of ADI at different austempering temperatures.*

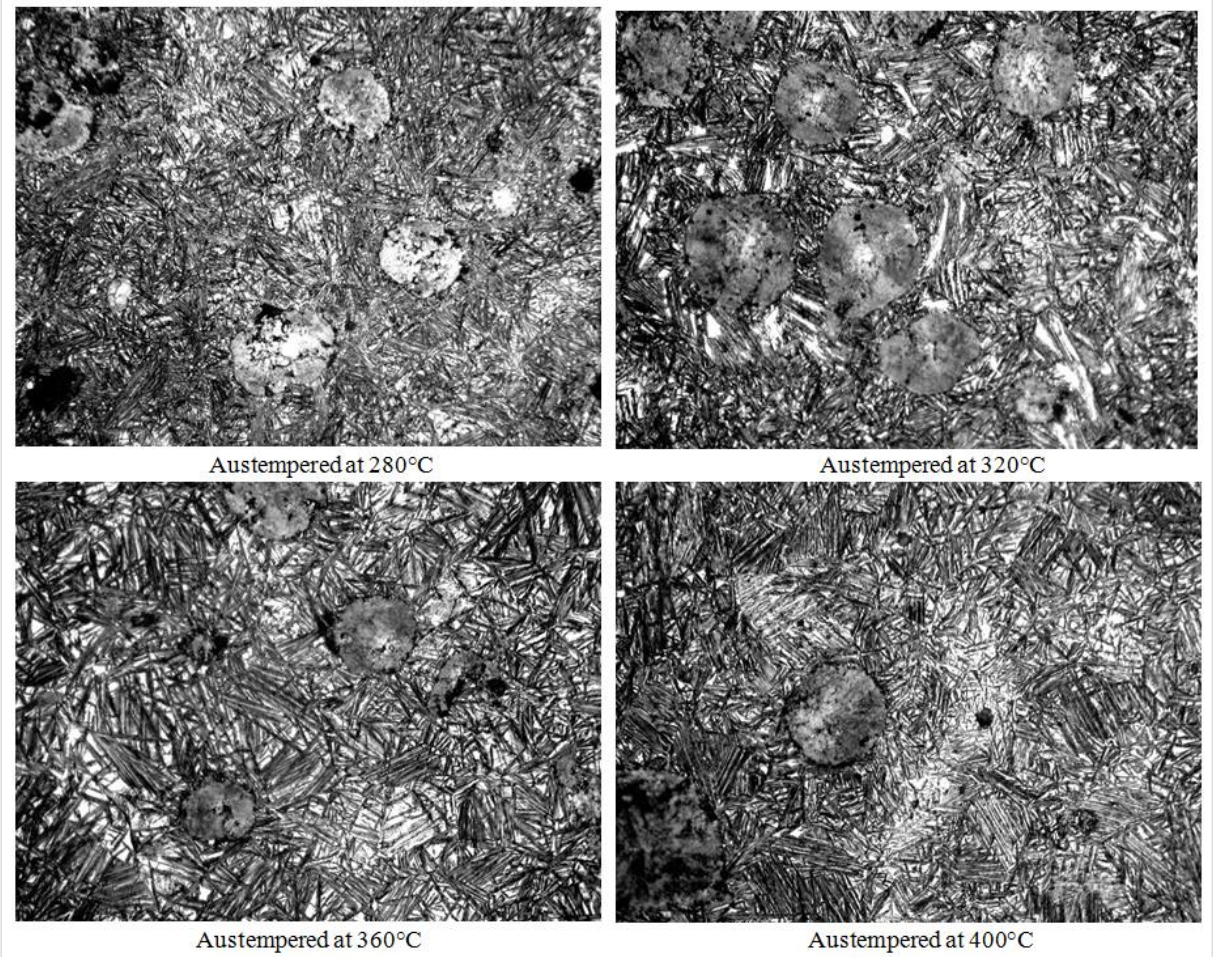

Figure 8. *Microstructure of ductile iron after austempering.*

3.4. The ADI with Dual Phase Matrix

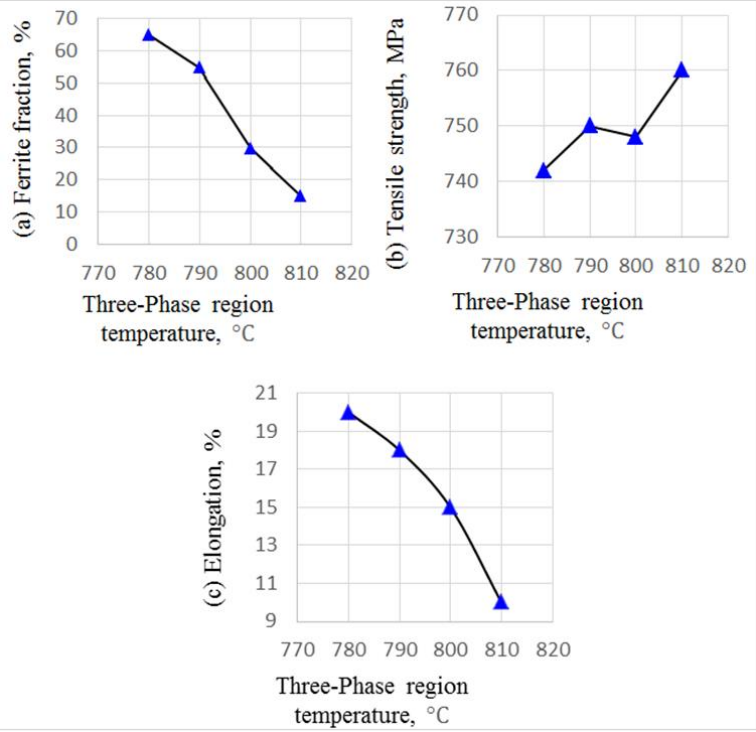

Figure 9. *The relation of (a) Ferrite fraction, (b) tensile strength, and (c) elongation of ADI with dual phase at different holding temperatures in the three-phase region.*

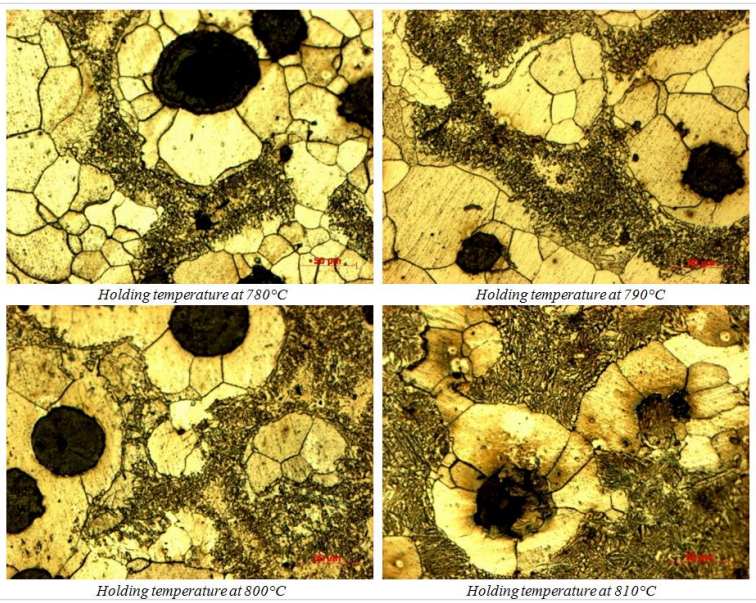

Figure 10. *Microstructures of ADI with dual phase matrix at different holding temperatures in the three-phase region.*

For manufacturing the ADI with dual phase matrix, the as-cast samples were also austenitized at 900 ℃ for 2 hours, then rapidly transferred to holding furnace, where samples were held at a three-phase region temperature (780, 790, 800 and 810 ℃) for 90 minutes. After this stage, the samples were also moved to a salt bath (50% KNO_3 and 50% $NaNO_3$ by weight) for isothermal transformation at a temperature of 360 ℃ for 90 minutes, and subsequent air cooling.

The micrographs in Figure 10 depict the microstructure of the samples at different holding temperatures in the

three-phase region. It can be seen that the expected dual-phase matrix was obtained. This matrix consists of pro-eutectoid ferrite-α and ausferrite. On the other hand, increasing holding temperature led to reduce ferrite fraction, consequently increasing tensile strength while decreasing elongation (Figure 9). Compared to conventional ADI, the dual-phase matrix samples exhibit marginally lower tensile strengths but significantly improved elongation, attributable to the presence of pro-eutectoid ferrite in the matrix. This ferrite phase enhances the elongation by providing deformation pathways while the ausferrite maintains tensile strength, achieving an optimal strength-ductility balance.

4. Conclusions

Both manufaturing process for producing ADI and ADI with dual phase matrix have the same austenitization and austempering temperature (900 ℃ and 360 ℃, respectively), the same austenitization and austempering time (120 minutes and 90 minutes, respectively) and the same austempering enviroment (50% KNO_3 and 50% $NaNO_3$ by weight). In contrast, the manufaturing process for producing ADI with dual phase matrix has an intermadiate isothermal holding step in the three-phase region for 90 minutes. This step generates pro-eutectoid ferrite in dual phase matrix. Hence, depend on holding temperatures, the elongation can be increased approximately from 10 to 20%, while the ausferrite maintains tensile strength up to 760 MPa.

The experimental results demonstrate that controlling the heat treatment parameters significantly influence the microstructure and mechanical properties of ВЧ60 ductile iron. Microstructural observations align well with Thermo-Calc and JMatPro simulations, confirming predicted phase transformations. The simulation results provide a foundation for optimizing processing conditions to meet specific engineering requirements in industrial applications.

Abbreviations

ADI	Austempered Ductile Iron
CCT	Continuous Cooling Transformation
TTT	Time-Temperature-Transformation
ASTM	American Society for Testing and Materials

Author Contributions

Nguyen Hong Hai: Conceptualization, Formal Analysis, Investigation, Methodology, Writing - review & editing

Nguyen Hoang Viet: Data curation, Software, Supervision, Writing - original draft

Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Nguyen Hong Hai is a lecturer at Hanoi University of Science and Technology (HUST), School of Materials Science and Engineering (SMSE), Department of Materials Engineering. He completed his PhD in Metallurgy Engineering from Technical University of Ostrava, Czech Republic in 2013, and his Master of Science in Materials Technology from Hanoi University of Science and Technology, Vietnam in 2006. Dr. Hai currently serves as Vice Director of the Center of Materials Testing and Analyzing, SMSE, HUST. His research interests include light metals, exothermic materials as well as discrete materials.

Nguyen Hoang Viet is a leading expert in powder metallurgy, specializing in amorphous metals, quasicrystals, and Al/Cu/Fe-based alloys. With a PhD from the University of Ulsan (2009, South Korea) and extensive research experience, he has made significant contributions to advanced materials development. In recent years, he has been developing research that integrates Artificial Intelligence into metallurgy, optimizing blast furnace and industrial processes. As Deputy Director of the Innovative Materials Research Center at Hanoi University of Science and Technology, he drives innovation in smart manufacturing while mentoring future scientists. Committed to bridging academia and industry, his research focuses on high-performance materials and sustainable metallurgical solutions.