Microstructural Characterization and Mechanical Properties of Austempered Ductile Iron at Different Austempering Temperatures

Herry Oktadinata(✉), Toto Triantoro, and Isal Ardiansyah

Mechanical Engineering Department, Universitas Jenderal Achmad Yani, Bandung, Indonesia
herry.oktadinata@yahoo.com

Abstract. This study investigated the effect of austempering temperature on the microstructure and mechanical properties of austempered ductile iron (ADI). Samples for this experiment were taken from ductile cast iron Y-block. Then they were austenitized to a temperature of 900 °C in an induction furnace for 90 min. Furthermore, they were quenched into a salt bath at 300 °C and 400 °C, respectively. Austempering time of 90 min in the salt bath was maintained for each austempering temperature. Microstructure observation and mechanical tests were performed on the as-cast and austempered treatment samples at different temperatures. The optical microscope was used to characterize the microstructure of ductile cast iron after austempering. The microstructure was evaluated on the samples with etched and non-etched surface conditions. Hardness, tensile and impact tests were performed to obtain their mechanical properties. The observation results revealed that ADI's microstructures, hardness, tensile strength, and toughness strongly depended on applied austempering temperature parameters. The austempering treatment significantly improved the mechanical properties of ductile cast iron. Higher strength and toughness were observed at the austempering temperature of 300 °C compared to austempering at 400 °C.

Keywords: Austempered · Iron · temperature

1 Introduction

Austempered ductile iron (ADI) is used for a wide range of applications in the automotive, rail, agricultural components, and heavy industries. ADI exhibits a good combination of high strength, toughness, and wear resistance. Their excellent mechanical properties are directly related to the ausferrite microstructure, which consists of ferrite and austenite. This is the result of an austempering heat treatment designed to improve the mechanical properties of ductile iron [1–7].

T. P. Syawitri et al. (Eds.): MEST 2022, AER 222, pp. 114–121, 2023.
https://doi.org/10.2991/978-94-6463-134-0_12

Mechanical properties of ADI can be varied over a wide range by changing the heat treatment parameters. It influences the microstructure formation, such as the percentage and morphology of ferrite and austenite during austempering. The initial composition of ductile cast iron strongly affects the final microstructure of ADI. Their final microstructure consists of spherical graphite embedded in an ausferrite matrix. Other phases like martensite and carbide may also exist in the microstructure. The weight fraction of ferrite and high carbon in ausferrite depends on the austempering temperature and carbon content at the austenitizing temperature [2, 5, 8].

The heat treatment of ADI consists of austenitizing in the temperature range of 850–950 °C until complete dissolution of carbon in austenite is reached. Then followed by rapid quenching in a salt bath to a temperature range of 250–400 °C [2–4]. At austenitizing, the as-cast matrix structure is isothermally transformed into ausferrite which is composed of spheroidal graphite embedded in the austenite and ferrite matrix [2, 3, 8, 9]. Increasing the austempering time up to 2 h at an austempering temperature of 300 °C demonstrated martensite disappears from the microstructure [10]. Other researchers reported that austempered for 30 min in a salt bath at temperatures of 300 °C to 360 °C revealed that the retained austenite grow when the austempering temperature increases [9]. The presence of retained austenite crucially affects the toughness and hardness of ADI. When the austempering temperatures increase, ADI's retained austenite percentage tends to grow, and the hardness decrease [11, 12].

Previous work using austempering temperatures of 270 °C, 300 °C, and 330 °C showed the hardness gradually decreased with increasing austempering temperature. Fine ausferrite is formed using an austempering temperature of 270 °C, while its structure tends to be coarse at 300 °C and 330 °C [6]. Another study reported the microstructures of the samples after austempering treatment at 320 °C and 360 °C. The ausferrite of samples with an austempering temperature of 320 °C is finer than 360 °C [13].

The microstructure of ADI is widely known as ausferrite, consisting of ferrite and austenite. As the temperature of the austenitizing increases, the austenite's carbon content and grain size increase. The dual-phase ADI microstructure extensively overcomes the mechanical and fatigue properties of the full ferritic matrix while maintaining very high deformations. In the dual matrix structure, the volume fraction of ferrite and ausferrite could be controlled to affect the strength and ductility [1, 4, 5, 8, 15].

In the austempering process of ductile iron, it was found that increasing the austenitizing temperature increased the strain-induced tendency of martensite formation at all austempering temperatures. Fine-grained acicular ferrite provides an excellent combination of high tensile strength with good ductility and toughness. ADI can be given various properties through control of austempering conditions. UTS, elongation, and impact strength are highly dependent on the amount of pro-eutectoid ferrite and ausferrite present after heat treatment [1, 2, 16].

The present work is taken to investigate the effect of the austempering temperature on ADI's microstructural characterization and mechanical properties. Various austempering temperatures were applied to the as-cast ductile iron. This study includes microstructural observation and mechanical tests.

2 Experimental Method

Ductile cast iron used in this experiment was produced using an electric arc furnace with a capacity of 2500 kg. Melting was conducted in some stages. Initially, the charging consisted of 60% steel scrap and 40% return ductile iron scrap. Furthermore, alloying such as Fe-Ni, Fe-Si, Fe-Mn, Fe-Cr, and Fe-Mo were added to the furnace. Before tapping into a preheated ladle, the molten iron temperature was between 1510 to 1540 °C. The nodularization process was carried out in a ladle by employing Fe-Si-Mg using the sandwich technique at the time of tapping. After inoculation using a Fe-Si-Al-Ca alloy, the molten iron was poured into Y-block sand molds. The nominal chemical composition was measured using an optical emission spectrometer, and the result is displayed in Table 1.

The mechanical and microstructural test samples were cut and machined from the Y-block castings. They were then heat-treated according to austempering cycle, as shown in Fig. 1. Furthermore, the samples were austenitized to a temperature of 900 °C in an induction furnace for 90 min. Then they were quenched into a salt bath at temperatures 300 °C and 400 °C, respectively. Austempering time of 90 min in the salt bath was maintained for each austempering temperature. According to austempering temperatures of 300 °C and 400 °C, the samples were labeled as A and B, respectively. The as-cast sample was labeled as N for reference.

After finishing the heat treatment, the samples' surface was cleaned from the salt by immersing them in a water bath and then allowed to cool in the air. Furthermore,

Table 1. The nominal chemical composition of material (wt.%)

Element	C	Si	Mn	P	S	Cr	Ni	Mo	Mg	Al	Cu	V	Ti
Composition (wt.%)	3.45	2.6	0.635	0.03	0.002	0.275	1.58	0.177	0.1	0.026	0.024	0.011	0.013

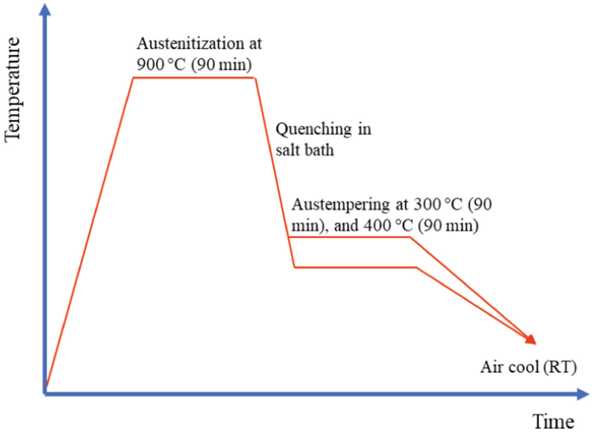


Fig. 1. Schematic diagram of austempering cycle used in this experiment

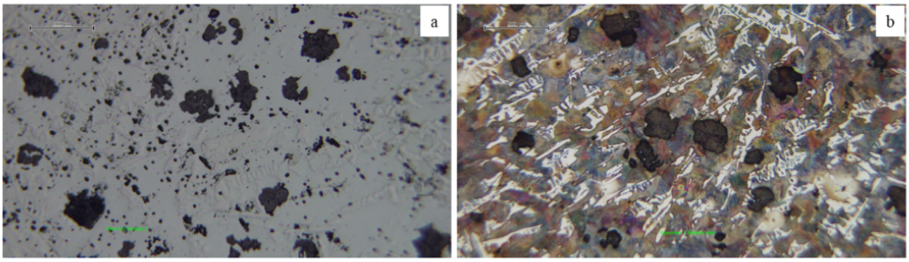


Fig. 2. Microstructure of as cast sample (sample N) on different surface conditions: a) non-etched, b) etched

mechanical tests and microstructural examinations were performed. Mechanical properties were evaluated, which consist of tensile strength, hardness, and impact toughness. The tensile test was conducted as per ASTM E-8, and the impact test was carried out as per ASTM E-23. The mechanical tests, such as tensile and impact, were performed on three samples and averaged to represent the data for each austempering temperature treatment.

The microstructure was characterized by optical microscopy. Evaluation of the microstructure was carried out with etched and non-etched surface conditions. Metallographic analysis with a non-etched surface aims to identify changes in graphite nodules (size and distribution) produced in three different austempering temperatures. Metallographic analysis with an etched surface was conducted to determine the phases present.

3 Results and Discussion

3.1 Microstructure Analysis

The microstructure observation was performed on ductile cast iron in as-cast condition and after the austempering process. Figure 2 shows the microstructures in the as-cast condition. Microstructure on a non-etched surface shows the graphite nodules and their distribution (Fig. 2a). The morphology of graphite observed in the microstructure of the as-cast ductile iron is spherical. On etched surface shows a microstructure consisting of pearlite, ferrite, and graphite (Fig. 2a). The as-cast structure of the ductile iron consists of the mixed phases of pearlite and ferrite in the matrix. Some carbides were observed, possibly chromium carbides, due to Cr addition.

Microstructure observation on the non-etched surfaces for samples after austempering treatment: A and B show the existence of graphite nodules (see Fig. 3). It can be seen that the diameter of the graphite nodules of sample A is significantly larger than samples B. Increasing austempering temperature may decrease the size of the nodules.

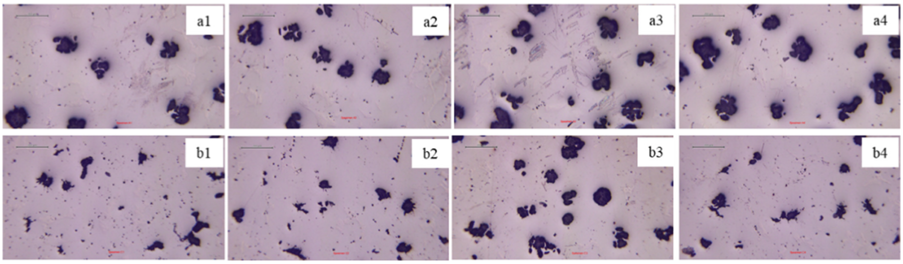


Fig. 3. Microstructure on the non-etched surface condition: (a1-a4) sample A, and (b1-b4) sample B

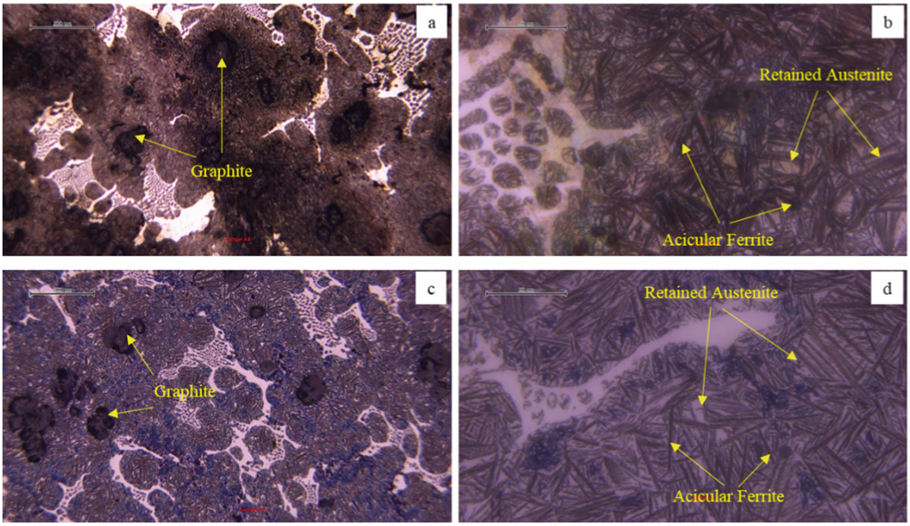
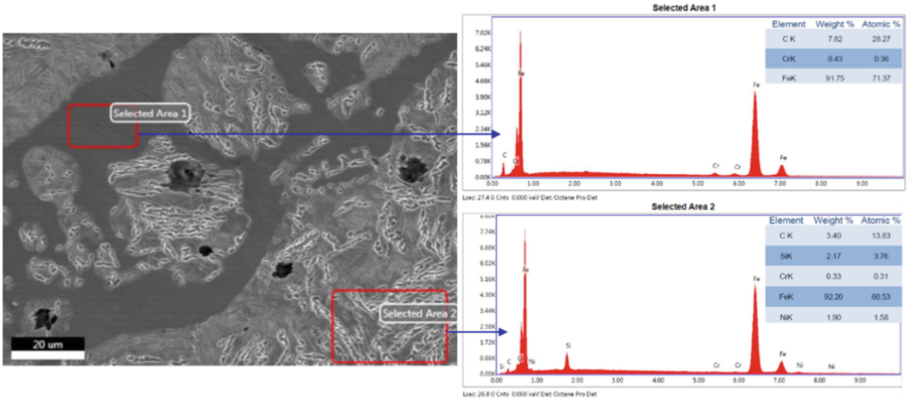


Fig. 4. Microstructure on the etched surface condition: (a-b) sample A, and (c-d) sample B

Figure 4 shows the phases in each sample, A and B, respectively. The microstructure of all studied ADI samples shows graphite nodules dispersed in an ausferrite matrix. Retained austenite appears as the bright phase, while acicular ferrite appears as the dark phase. Carbon graphites were also observed as black nodules dispersed within the matrix. Figure 5 shows the microstructure of the austempered sample observed by energy dispersive spectroscopy (EDS). The result indicates the presence of carbides. It can be due to carbon content in the material and Cr addition during the casting process. The certain phases present in the sample influence their mechanical properties.

Austempering treatment of ductile cast iron makes pearlitic matrix transform become acicular ferrite and retained austenite. The microstructure mainly consists of ausferrite (ferrite and austenite), graphite nodules, and carbides. Austempering parameters, such as austempering temperature, austempering time, and austenitizing temperature, can influence this result. Previous work reported that increasing austempering temperature resulted in more ausferrite forming, and its needle became coarser [6].



Selected Area 1

Element	Weight %	Atomic %
C K	7.82	28.27
CrK	0.43	0.36
FeK	91.75	71.37

Selected Area 2

Element	Weight %	Atomic %
C K	3.40	13.83
SiK	2.17	3.76
CrK	0.33	0.31
FeK	92.20	80.53
NiK	1.90	1.58

Fig. 5. EDS results which show presence of carbides

Table 2. Mechanical test results

Sample	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Hardness (HRC)	Impact energy (J)
N	533	255	16	41.5	1.9
A	741	274	15	45.4	6.4
B	520	191	14	39.5	5.0

3.2 Mechanical Properties

The results of mechanical tests (tensile strength, yield strength, elongation, hardness, and impact energy) are presented in Table 2. Figure 5 shows the broken tensile test samples. The tensile strength, hardness, and toughness of ductile cast iron obtained in the as-cast condition are 533 MPa, 41.5 HRC, and 1.9 J, respectively. After austempering treatment at 300 °C, those values increase to 741 MPa, 45.4 HRC, and 6.4 J, respectively. It can be attributed to the presence of ausferrite in the microstructure. However, the mechanical properties tend to decrease at a higher austempering temperature, 400 °C. Tensile strength, hardness, and toughness become 520 MPa, 39.5 HRC, and 5.0 J, respectively. This can be caused by increasing the area fraction of retained austenite.

During the austempering process, the pearlite matrix transforms into an ausferrite matrix consisting of austenite and ferrite. The austempering temperature affected the mechanical properties. The highest strength and toughness were achieved at an austempering temperature of 300 °C. Lower hardness and toughness were observed at 400 °C. It may be caused by reducing the acicular ferrite and increasing the retained austenite. Previous works reported that when a higher austempering temperature was applied, the area fraction of retained austenite increased, and acicular ferrite reduced [6, 7] (Fig. 6).

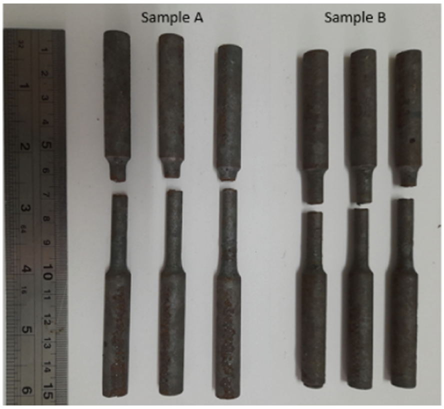


Fig. 6. Tensile test samples

4 Conclusion

An experiment using different austempering temperatures, 300 °C and 400 °C, has been done. Austempering treatment improved the strength and toughness of ductile cast iron in the as-cast condition. This study shows that the toughness of ADI is still much better than as-cast ductile iron. The impact energy of the ADI (samples A and B) has shown to be higher than the as-cast (sample N). Higher strength and toughness were achieved after the austempering temperature at 300 °C compared to 400 °C. The amount of retained austenite and acicular ferrite in the ausferrite matrix of ADI significantly contributed to improving their properties.

References

1. S. Daber, K. S. Ravishankar, and P. Prasad Rao, "Influence of austenitising temperature on the formation of strain induced martensite in austempered ductile iron," *J. Mater. Sci.*, vol. 43, no. 14, pp. 4929–4937, 2008.
2. T. U. N. Thein and K. T. LWIN, "Optimizing the microstructure and mechanical properties of austempered ductile iron for automobile differential gear," *J. Met. Mater. Miner.*, vol. 18, no. 2, pp. 199–205, 2008.
3. O. Vázquez-Gómez, J. Barrera-Godínez, B. Hernández-Morales, E. López-Martínez, and H. Vergara-Hernández, *Mathematical model of thermal and microstructural evolution during austempering of ductile iron*. ASTM International, 2012.
4. A. S. Benam, "Effect of alloying elements on austempered ductile iron (ADI) properties and its process," *China Foundry*, vol. 12, no. 1, pp. 54–70, 2015.
5. V. Dakre, D. R. Peshwe, S. U. Pathak, and A. Likhite, "Mechanical characterization of austempered ductile iron obtained by two step austempering process," *Trans. Indian Inst. Met.*, vol. 70, no. 9, pp. 2381–2387, 2017.
6. R. Bendikiene *et al.*, "Influence of austempering temperatures on the microstructure and mechanical properties of austempered ductile cast iron," *Metals (Basel).*, vol. 11, no. 6, p. 967, 2021.
7. B. Wang, G. C. Barber, C. Tao, X. Sun, and X. Ran, "Characteristics of tempering response of austempered ductile iron," *J. Mater. Res. Technol.*, vol. 7, no. 2, pp. 198–202, 2018.

8. Y. Amran, A. Katsman, P. Schaaf, and M. Bamberger, “Influence of copper addition and temperature on the kinetics of austempering in ductile iron,” *Metall. Mater. Trans. B*, vol. 41, no. 5, pp. 1052–1058, 2010.
9. P. Sellamuthu, D. G. H. Samuel, D. Dinakaran, V. P. Premkumar, Z. Li, and S. Seetharaman, “Austempered ductile iron (ADI): Influence of austempering temperature on microstructure, mechanical and wear properties and energy consumption,” *Metals (Basel).*, vol. 8, no. 1, p. 53, 2018.
10. O. Erić, M. Jovanović, L. Šid, D. Rajnović, and S. Zec, “The austempering study of alloyed ductile iron,” *Mater. Des.*, vol. 27, no. 7, pp. 617–622, 2006.
11. L. N. D. G. Pereira, R. G. de C. Medeiros, P. G. M. de Freitas, C. F. da Silva, L. M. da Silva, and R. H. Leal, “Microstructural Evaluation of an Austempered Cast Iron Alloy,” *Mater. Res.*, vol. 25, 2022.
12. A. H. Elsayed, M. M. Megahed, A. A. Sadek, and K. M. Abouelela, “Fracture toughness characterization of austempered ductile iron produced using both conventional and two-step austempering processes,” *Mater. Des.*, vol. 30, no. 6, pp. 1866–1877, 2009.
13. W. Sckudlarek, M. N. Krmasha, K. S. Al-Rubaie, O. Preti, J. C. G. Milan, and C. E. da Costa, “Effect of austempering temperature on microstructure and mechanical properties of ductile cast iron modified by niobium,” *J. Mater. Res. Technol.*, vol. 12, pp. 2414–2425, 2021.
14. A. Basso, M. Caldera, M. Chapetti, and J. Sikora, “Mechanical characterization of dual phase austempered ductile iron,” *ISIJ Int.*, vol. 50, no. 2, pp. 302–306, 2010.
15. V. Kilicli and M. Erdogan, “The nature of the tensile fracture in austempered ductile iron with dual matrix microstructure,” *J. Mater. Eng. Perform.*, vol. 19, no. 1, pp. 142–149, 2010.
16. C. Valdés, M. J. P. Lopez, M. Figueroa, and L. E. Ramírez, “Austempered ductile iron with dual matrix structures,” *Rev. Mex. Física*, vol. 55, no. 1, pp. 48–51, 2009.