Microstructure and Mechanical Properties of ADI Depending on Austenitization Methods and Parameters

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Abstract

Ductile iron was quenched using two-variant isothermal transformation. The first treatment variant consisted of one-phase austenitization at a temperature \( t_a = 830, 860 \) or \( 900 \)°C, cooling down to an isothermal transformation temperature of 300 or 400°C and holding from 8 to 64 minutes. The second treatment variant consisted of two-phase austenitization. Cast iron was austenitized at a temperature \( t_a = 950 \)°C and cooled down to a supercritical temperature \( t_y = 900, 860 \) or \( 830 \)°C. Isothermal transformation was conducted under the same conditions as those applied to the first variant. Ferrite cast iron was quenched isothermally. Basic strength \( (R_{p0.2}, R_m) \) and plastic \( (A_5) \) properties as well as matrix microstructure and hardness were examined.

As a result of heat treatment, the following ADI grades were obtained: EN-GJS-800-8, EN-GJS-1200-2 and EN-GJS-1400-1 in accordance with PN–EN 1564:2000 having plasticity of 1.5÷4 times more than minimum requirements specified in the standard.

Keywords: ADI, Austenitizing, Isothermal Process, Mechanical Properties

1. Introduction

ADI castings fabrication involves quenching process using isothermal transformation (usually within a range of 250-400°C) in order to obtain high-carbon austenite and carbon-oversaturated ferrite in the matrix. Such microstructure composition is called ausferrite and the process of isothermal transformation of overcooled austenite – ausferritization [1-6].

During cast iron quenching, the austenitization process, consisting of applying a temperature higher than \( \text{Ac}_1 \), should enrich austenite with carbon to the limit marked with the E’S’ line and make the metal matrix more uniform. During austenitization of cast iron with initial ferritic microstructure to obtain ausferrite, only carbon atoms originating from graphite releases are diffused. The work describes the process of austenitization of a metal matrix and the role of graphite in its carburization [7].

Austenitization occurs usually within temperatures of 815–950°C. The effect of cast iron austenitization depends on chemical composition, initial structure, nodular graphite dispersion, heating temperature and time as well as on the uniformity of elements arrangement in eutectic grains and the size of matrix grains.

A classic method for cast iron austenitization prior to isothermal transformation is one-phase austenitization [1-13]. This work compares selected mechanical properties for one-phase austenitization (classic) at a temperature of 830, 860 or 900°C or two-phase austenitization. The two-phase variant involved austenitization at a temperature of 950°C and cooling down to a supercritical temperature of 830, 860 or 900°C. The assumed supercritical temperatures are identical to austenitization.
temperatures in the one-phase variant. Isothermal transformation conditions for both austenitization variants were identical: temperature of isothermal transformation – 300 or 400°C with a holding time of 8 to 64 minutes. It was expected when choosing the two-phase austenitization variant that better mechanical properties would be obtained compared to one-phase austenitization. The first austenitization phase should contribute to better matrix uniformity with cooling down reducing carbon concentration in austenite. Smaller carbon content in initial austenite contributes to improvement of plastic properties [3].

2. Material, program and research methods

Ductile iron was smelted in an industrial hot-blast cupola with acid lining. Cast iron spheroidization was conducted in the cupola container using the wire method and ML5 magnesium alloy. Ferrosilicon was used in the modification process. Cast iron was founded into damp sand moulds. Castings had the shape of YII ingots in accordance with PN-EN 1563:2000. Based on the static tensile test, cast iron was classified as EN-GJS-500-7 grade. Cast iron matrix had a ferritic-pearlitic structure (10% pearlite) and graphite had a correct ball-like form. Graphite volume fraction was 11.5% and the amount of releases was 112 per mm² of the microsection surface.

Chemical composition and properties of ductile cast iron are given in Table 1.

Table 1.
The chemical composition and mechanical properties in ductile iron

| Chemical element, % mas. | C  | Si  | Mn  | P  | S  | Mg |
|--------------------------|----|-----|-----|----|----|----|
| C                         | 3.65 | 2.59 | 0.18 | 0.052 | 0.014 | 0.06 |

| Mechanical properties |
|-----------------------|
| Rm, MPa               | 507 |
| A5, %                 | 12.1 |
| H, HV10               | 156 |
| KCG, J/cm²            | 106 |

To obtain a matrix that is fully ferritic, lower parts of an ingot YII were annealed ferritically in a two-phase manner. Then ingots were cut into three flat bars. Flat bars cut from the ingot were marked in accordance with their positioning and five standardised strength test pieces with a gauge diameter of 10 mm were made.

The strength test pieces were quenched applying isothermal transformation in accordance with diagrams provided in Figure 1 and 2. For each treatment, measurements of mechanical properties were carried out for three test pieces originating from one ingot YII. Austenitization was conducted in a chamber furnace and ausferritization in a salt-bath furnace S0140.

Static tensile test was carried out using the testing machine INSTRON type 8502. The tests were aimed to determine tensile strength Rm, proof stress Rp0.2 and unit elongation A5.

To assess microstructure, metallographic microsections were made from the gripping part of thermally treated strength test pieces. Inspection and image recording were conducted using a SEM scanning microscope.

Hardness measurements were made on the microsection surface using Vickers method applying a load of 294N. Vickers hardness was converted using comparative tables (PN-93/H-04357) into hardness in Brinell units.
3. The results of the research and their analysis

Hardness in isothermal cooling time function at a temperature $t_{pi} = 300$ and $400^\circ\text{C}$ for variant I and II is presented in Table 2.

### Table 2.
The results of hardness measurements

| Austenitizing temperature $t_{pi}^1$, $t_{pi}^2$, $^\circ\text{C}$ | Isothermal transformation temperature $t_{pi}^1$, $^\circ\text{C}$ | Variant of heat treatment | Isothermal transformation time $t_{pi}$, min | Hardness, HB |
|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------|-------------------------------------------|--------------|
| 300                                                          | I                                                             | 160 | 170 | 161 | 163 |
| 300                                                          | II                                                            | 388 | 377 | 360 | 386 |
| 400                                                          | I                                                             | 158 | 161 | 156 | 152 |
| 400                                                          | II                                                            | 249 | 251 | 258 | 248 |
| 300                                                          | I                                                             | 172 | 222 | 151 | 155 |
| 300                                                          | II                                                            | 385 | 381 | 372 | 388 |
| 400                                                          | I                                                             | 211 | 210 | 195 | 199 |
| 400                                                          | II                                                            | 251 | 254 | 253 | 255 |
| 300                                                          | I                                                             | 402 | 407 | 376 | 396 |
| 300                                                          | II                                                            | 387 | 382 | 369 | 382 |
| 300                                                          | I                                                             | 251 | 261 | 259 | 258 |
| 300                                                          | II                                                            | 260 | 258 | 261 | 269 |

1. $t_{pi}$ - austenitization temperature in variant I
2. $t_{pi}^2$ - second-phase austenitization temperature in variant II

Tensile strength in isothermal cooling time function at a temperature $t_{pi} = 300$ and $400^\circ\text{C}$ for variant I and II is presented in Table 3.

### Table 3.
The results of measurements of tensile strength

| Austenitizing temperature $t_{pi}^1$, $t_{pi}^2$, $^\circ\text{C}$ | Isothermal transformation temperature $t_{pi}^1$, $^\circ\text{C}$ | Variant of heat treatment | Isothermal transformation time $t_{pi}$, min | Tensile strength $R_{m}$, MPa |
|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------|-------------------------------------------|-----------------------------|
| 300                                                          | I                                                             | 473 | 613 | 468 | 453 |
| 300                                                          | II                                                            | 1422 | 1395 | 1385 | 1425 |
| 400                                                          | I                                                             | 450 | 455 | 448 | 534 |
| 400                                                          | II                                                            | 956 | 957 | 974 | 976 |
| 300                                                          | I                                                             | 655 | 998 | 545 | 642 |
| 300                                                          | II                                                            | 1416 | 1437 | 1411 | 1419 |
| 400                                                          | I                                                             | 760 | 841 | 805 | 855 |
| 400                                                          | II                                                            | 953 | 955 | 956 | 980 |
| 300                                                          | I                                                             | 1408 | 1435 | 1443 | 1462 |
| 300                                                          | II                                                            | 1340 | 1379 | 1368 | 1384 |
| 400                                                          | I                                                             | 957 | 970 | 984 | 947 |
| 400                                                          | II                                                            | 929 | 943 | 964 | 977 |

Table 2 shows that quenched cast iron using variant I at a temperature $t_{pi} = 900^\circ\text{C}$ and cast iron held isothermally at $t_{pi} = 300$ or $400^\circ\text{C}$ had a hardness corresponding to ausferritic microstructure. Hardness in this case was within a range of 376.6.407 HB at $t_{pi} = 300^\circ\text{C}$ and 251.261 HB for $t_{pi} = 400^\circ\text{C}$. Inspections of the microstructure of cast iron test pieces following heat treatment using variant I demonstrate that austenitization for $t_{pi} = 830^\circ\text{C}$ occurred within a subcritical range, while for...
t_\gamma = 860^\circ C within an intercritical range of eutectoidal transformation. Therefore, as a result of isothermal transformation, both at a temperature 300 and 400\(^\circ\)C, a ferritic (t_\gamma = 830\(^\circ\)C) or ferritic-ausferritic (t_\gamma = 860\(^\circ\)C) matrix was obtained. Sample microstructure of cast iron subjected to heat treatment using variant I is presented in Figure 3.

In variant II of heat treatment, austenite was transformed into lower austenite at a temperature t_\gamma = 300 \(^\circ\)C. On the other hand, at a temperature t_\gamma = 400 \(^\circ\)C austenite changed into upper austenite. This statement is based on hardness test results (Table 2) and microscopic tests. Sample microstructures are presented in Figures 4 and 5.

**Fig. 3.** Microstructure of quenched ductile iron using variant I (t_\gamma=860\(^\circ\)C, t_\pi=300\(^\circ\)C, t_\pi=8). 1000x magnification, SEM, etched using 2% alcoholic solution of HNO_3

Tensile strength (R_m), proof stress (R_{p0.2}) and elongation (A_5) in holding time function are presented in tables 3÷5.

Results of tensile tests on test pieces quenched using variant I (t_\gamma = 830, 860 and 900 \(^\circ\)C) at a temperature t_\pi = 300 \(^\circ\)C show that only cast iron quenched from a temperature t_\gamma = 900 \(^\circ\)C had microstructure and properties meeting requirements for EN-GJS-1400-1 grade ADI. Austenitization time t_\pi had no effect on R_m and A_5. The results were within a range of 1408\textasciitilde1462 MPa for R_m and 3\textasciitilde4% for A_5. The effect of isothermal quenching time on proof stress R_{p0.2} was significant. With the increase in holding time, up went the value R_{p0.2}. The difference in proof stress \Delta R_{p0.2} of ausferritized cast iron within a time from 8 to 64 minutes was 342 MPa (Table 4).

Cast iron quenching using variant I and ausferritization at a temperature t_\pi = 400 \(^\circ\)C allowed parameters corresponding to ADI to be obtained only for the highest temperature t_\gamma = 900 \(^\circ\)C. Cast iron austenitized at a temperature t_\gamma = 860 \(^\circ\)C due to the obtained values R_m, R_{p0.2} and A_5 met requirements for grade EN-GJS-800-8 (except for t_\pi = 8 min). The microstructure of this cast iron not only consisted of ausferrite, as required by the definition of ADI, but it also included free ferrite. Ductile iron quenched isothermally within an intercritical range having the structure of free ferrite and ausferrite is marked in literature as FADI [6]. The resulting microstructure corresponding to FADI cast iron is presented in Figure 6.
Two-phase austenitization using variant II and ausferritization at $t_{\text{au}} = 300^\circ\text{C}$ resulted in ductile iron having mechanical properties ($R_{\text{m}}, R_{0.2}, A_{5}$) corresponding to standardized grades of ADI. Based on the mechanical properties $R_{\text{m}}, R_{0.2}$ and $A_{5}$, cast iron treated using variant II and ausferritized at $t_{\text{au}} = 400^\circ\text{C}$ was classified as belonging to EN-GJS-800-8 grade. Regardless of the second-phase austenitization temperature, its effect on $R_{\text{m}}$ and $A_{5}$ was negligible. On the other hand, proof stress changed depending on the cooling temperature $t_{\text{c}} = 830, 860$ and $900^\circ\text{C}$: the lower the temperature interval between austenitization and ausferritization, the higher proof stress. As isothermal holding time grew, so grew the values $R_{0.2}$.

Based on tensile tests and hardness measurements, respective heat treatment variants were ascribed appropriate ADI grades (Table 6).

Table 6. ADI grades classified according to requirements PN-EN 1564 after hardening in accordance with variant I and II

| Temp. $t_{\text{au}}$ °C | Time $\tau_{\text{au}}$ min | Heat treatment | $R_{\text{m}}$ | $R_{0.2}$ | $A_{5}$ |
|--------------------------|--------------------------|----------------|------------|-----------|--------|
| 8                        | -                        | Variant I      | 830        | 860       | 900    |
|                          | -                        | Variant II     | 830        | 860       | 900    |
| 16                       | -                        |                |            |           |        |
| 32                       | -                        |                |            |           |        |
| 64                       | -                        |                |            |           |        |

- kind EN -- GJS-- 800-8, ⨍ - kind EN -- GJS-- 1000-5
- kind EN -- GJS-- 1200-2, ⨍ - kind EN -- GJS-- 1400-1

Table 6 shows that, notwithstanding the variant, only EN-GJS 800-8 grade was obtained at an isothermal transformation temperature of $400^\circ\text{C}$. Following ausferritization at a temperature of $300^\circ\text{C}$, ADI EN-GJS 1400-1 grade was obtained for variant I and EN-GJS 1400-1, EN-GJS 1200-2 grades for variant II.

In the case of variant I, ADI was obtained only after austenitization at a temperature of $900^\circ\text{C}$, while for variant II at each second-phase austenitization temperature.

The relation between ausferritization time and hardness, tensile strength and elongation was on the whole insignificant. Specific ADI grade was usually obtained already after the shortest ausferritization time (Table 6). Ausferritization time extension does not lead in the majority of cases to changes in ADI grade. To reduce costs and energy consumption, ausferritization could be finished in most cases after 8 minutes of isothermal holding. After this time, no martensite is observed any longer in cast iron structure. However, due to the continuous and significant increase in proof stress, it is advisable to extend ausferritization time. The relation $R_{\text{m}}/R_{0.2}$ increases considerably (from 0.59 to 0.82) with the unit elongation value remaining virtually the same. Proof stress is a basic material indicator used in strength calculations. The dependence of $R_{0.2}$ on time has a degressive nature. As demonstrated by tests, an optimal ausferritization time is around one minute.

4. Conclusion

Based on test results and their analysis, the following conclusions were reached:

1. Heat treatment of ductile iron using variant I allowed ADI to be obtained only after austenitization at a temperature $t_{\text{au}} = 900^\circ\text{C}$. After austenitization at this temperature, ADI with lower ausferrite had strength and plasticity corresponding to EN-GJS-1400-1 grade, while that with upper ausferrite to EN-GJS-800-8.
2. Ductile iron treated using variant II had strength and plasticity corresponding to the following ADI grades: EN-GJS-800-8, EN-GJS-1200-2 and EN-GJS-1400-1.
3. Ductile iron castings with initial ferritic structure may be used for production of ADI.
4. An increase in ausferritization time contributes to a steady and significant increase of proof stress with tensile strength and unit elongation remaining virtually at the same level. The relation $R_{\text{m}}/R_{0.2}$ is increased within a range of 0.59 to 0.82.

Ausferritization time ensuring optimum combination of ADI strength and plastic properties is around one hour.

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