INFLUENCE OF TRANSFORMATION TEMPERATURE ON STRUCTURE AND MECHANICAL PROPERTIES OF AUSTEMPERED DUCTILE IRON

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Abstract
The paper deals with some factors influencing microstructure and mechanical properties of austempered ductile iron (ADI). Final structure and properties of ADI are obtained by exactly controlled process of heat treatment of nodular cast iron. In dependence on transformation temperature, various matrixes can be obtained (i.e. mixture of bainite with retained austenite), containing various content of retained austenite and consequently mechanical properties of ADI are changed. The influence of conditions of isothermal heat treatment on microstructure and mechanical properties of austempered ductile iron, especially different temperature of isothermal transformation of austenite and different holding time at this temperature, is shown in the paper.

Keywords: ADI, isothermal heat treatment, transformation temperature

1 Introduction

Austempered ductile iron (ADI) belongs to structural materials with continuously increasing level of production. Excellent mechanical as well as technological properties together with relatively low price are the reason why ADI is rated among perspective construction materials. ADI is used in many branches of industry as machine-building, civil engineering, transport, military industry, mining etc. It is applied mainly to casting for dynamically loaded components, e.g. gear and traversing wheels, crankshafts of cars, vans and trucks, swivel pins, rail brakes, pressure pipes in oil industry etc. [1,2].

Special properties of ADI are given by unique structure of matrix which is created by acicular ferrite and retained austenite (this mixture is called ausferrite). Technical literature often describes this matrix as bainite (although it does not contain carbides). The structure of ADI is obtained by exactly controlled process of heat treatment of nodular cast iron [3,4].

The isothermal heat treatment consists of the following stages:

- heating to the austenitization temperature;
- holding time at the austenitization temperature;
- quick cooling to the temperature of isothermal transformation of austenite so that no other transformation of austenite is carried out before reaching the temperature of isothermal transformation;
- holding time at this temperature until austenite is transformed into bainite;
- cooling to the ambient temperature which is usually realized slowly in order to prevent formation of stress [5,6].

Microstructure and mechanical properties of ADI can be substantially influenced by the conditions of isothermal heat treatment, above all by the temperature of isothermal transformation of austenite. In dependence on this temperature, various matrices can be obtained (i.e. mixture of bainite with retained austenite), containing various content of retained austenite. The temperature of isothermal transformation is usually in the range from 250 to 450 °C. Higher transformation temperatures (350 to 450 °C) lead to lower strength and hardness but higher elongation and toughness and better fatigue characteristics. Lower transformation temperatures (250 to 350 °C) lead to higher strength, hardness and abrasion resistance but lower elongation and toughness [7].
The influence of temperature of isothermal transformation of austenite on microstructure and mechanical properties of ADI is studied in the paper.

2 Material and experimental methods

The influence of conditions of isothermal heat treatment on microstructure and mechanical properties of austempered ductile iron was searched on several sets of specimens which were different in temperature of isothermal transformation of austenite and holding time at this temperature.
Experimental material was melted in the electric induction furnace ISTOL. The basic charge was formed by pig iron, steel scrap and additives for the control of chemical composition. FeSiMg7 modifier was used for modification and FeSi75 inoculant was used for inoculation [8].
Ferrite-pearlitic nodular cast iron was used as basic material for isothermal heat treatment. Chemical composition of the basic material is presented in **Table 1**.
The heat treatment consisted of austenitization and following isothermal transformation. The austenitization temperature was 920°C and the holding time at this temperature was 30 minutes. The isothermal transformation of austenite was realized in AS 140 salt bath at the temperatures 420, 380, 320 a 250 °C and the holding time at this temperature was from 30 to 300 minutes (by 30 min.) [9].

Table 1 Chemical composition of basic material (after casting)

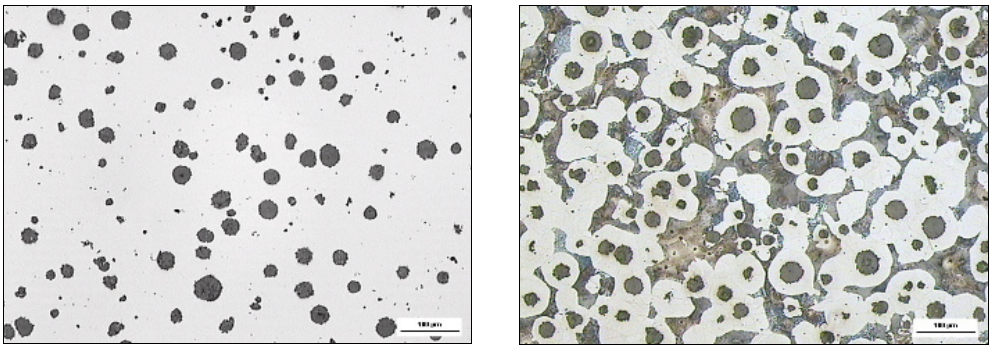
Element	C	Si	Mn	S	P	Cu	Ni
content (weight %)	2.78	4.69	0.49	0.017	0.050	0.92	1.10

The metallographic analysis of specimens of basic material (after casting) and specimens after isothermal heat treatment was made by the light metallographic microscope Neophot 32. The microstructure was evaluated by STN EN ISO 945 (STN 42 0461) and by image analysis (using Lucia software) [10-13].
The tensile test was made by STN EN 10002-1 by means of the testing equipment ZDM 30 with loading range F = 0 to 50 kN. The Rockwell hardness test was made by STN EN ISO 6508-1 by means of the testing equipment LECO LR-3E with a diamond cone forced into specimens under the load F = 1 471 N. The measured values of Rockwell hardness were converted to Brinell hardness by STN EN ISO 18265.
The fatigue tests were made by STN 42 0362 at high-frequency sinusoidal cyclic push-pull loading (frequency f ≈ 20 kHz, load ratio R = –1, temperature T = 20 ± 5 °C) using the ultrasonic testing equipment KAUP-ZU and the testing procedures [14].

3 Results and analysis

3.1 Metallographic analysis

From the microstructural point of view the basic material (after casting) is ferrite-pearlitic nodular cast iron (**Fig. 1**) with 57% content of ferrite in a matrix. Graphite occurs only in a perfectly-nodular (80%) and imperfectly-nodular (20%) shape. The size of graphite is within 15 and 60 μm, number of graphitic nodules is 205 mm^{-2} and circularity (shape factor) is 0.80 (**Table 2**).



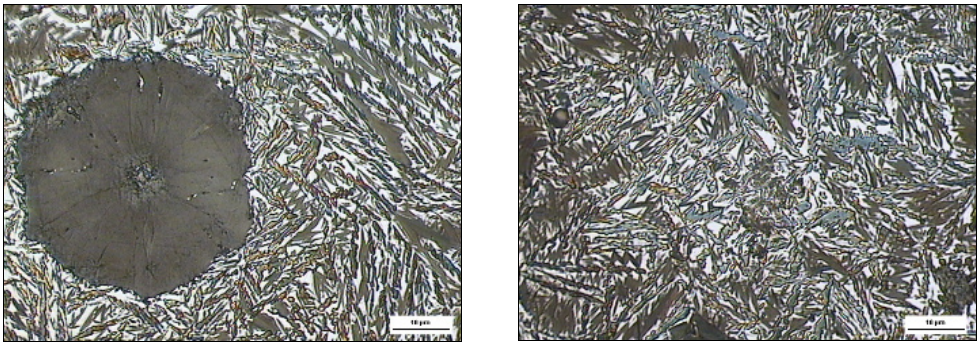
a) non-etched b) etched by 3 % Nital + pikric acid

Fig.1 Microstructure of basic material (after casting) – ferrite-pearlitic nodular cast iron

Table 2 Evaluation of microstructure of basic material by etalons and by image analysis

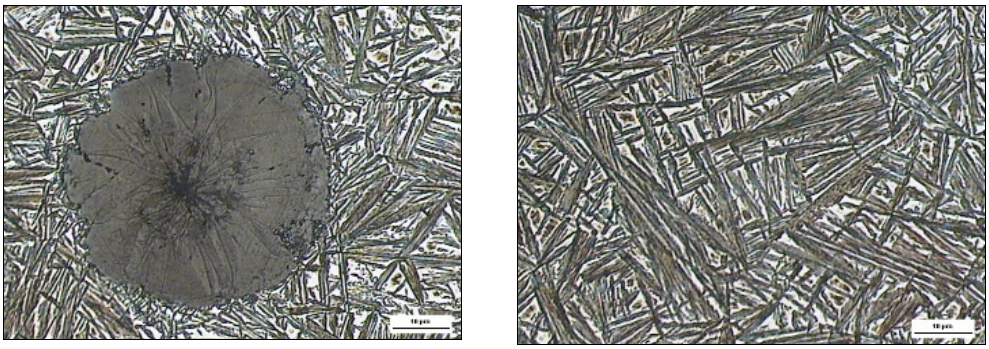
Microstructure STN EN ISO 945 (STN 42 0461)	Content of ferrite (%)	Count of graphitic nodules (mm^{-2})	Circularity (shape factor)
80 % VI 6/7 + 20 % V 6/7 – Fe 55	57	205.4	0.80

After isothermal heat treatment ADI was obtained. The specimens after isothermal heat treatment with the temperature of isothermal transformation of austenite 420 and 380 °C have a matrix created by upper bainite and retained austenite (**Fig. 2**). The specimens after isothermal heat treatment with the temperature of isothermal transformation of austenite 320 and 250 °C have a matrix created by lower bainite and retained austenite (**Fig. 3**). The content of retained austenite is slightly decreased with increasing holding time in all sets of specimens. The shape, size and count of graphitic nodules in the specimens after isothermal heat treatment are not changed in comparison with the specimen of basic material (after casting).



a) graphite b) matrix created by upper bainite and retained austenite

Fig.2 Microstructure of ADI (after isothermal heat treatment) – 380°C/ 60’, etched by Klemm I



a) graphite b) matrix created by lower bainite and retained austenite

Fig.3 Microstructure of ADI (after isothermal heat treatment) – 320°C/ 60', etched by Klemm I

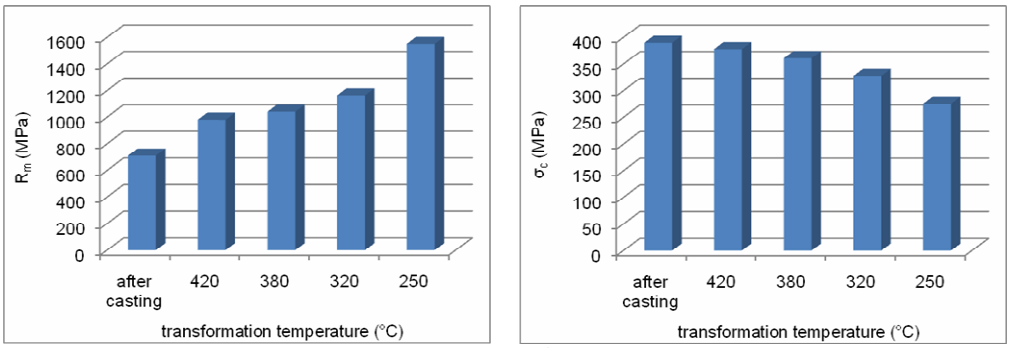
3.2 Mechanical properties

The changes in microstructure of specimens after isothermal heat treatment caused a change in mechanical properties (**Table 3**).

Table 3 Mechanical properties of specimens after casting and after isothermal heat treatment

Specimen	Matrix	R_m (MPa)	HB	σ_c (MPa)
basic material	ferrite + pearlite	711	250	390
420 °C/ 60'	upper bainite + retained austenite	980	474	378
380 °C/ 60'		1040	495	361
320 °C/ 60'	lower bainite + retained austenite	1164	492	328
250 °C/ 60'		1551	530	276

Tensile strength of the basic material (ferrite-pearlitic nodular cast iron) is 711 MPa, hardness of the basic material is 250 HB. The isothermal heat treatment induced considerable improvement of tensile strength and hardness in comparison with the basic material. The tensile strength and hardness of the specimens after isothermal heat treatment are increased with a decreasing temperature of isothermal transformation of austenite (**Fig. 4a**). The hardness is decreased with an increasing holding time at the temperature of isothermal transformation of austenite in all sets of specimens.



a) tensile strength b) fatigue strength

Fig.4 Comparison of mechanical properties

Fatigue strength of the basic material is about 390 MPa. The isothermal heat treatment induced a decrease of fatigue properties in comparison with the basic material. Fatigue endurance of the specimens after isothermal heat treatment is decreased with a decreasing temperature of isothermal transformation of austenite (**Fig. 4b**).

The increase of tensile strength and hardness with a decreasing temperature of isothermal transformation of austenite is caused by a change of matrix from upper bainite to lower bainite. The decrease of fatigue strength with a decreasing temperature of isothermal transformation of austenite is due to the same change of microstructure.

The measured values of tensile strength, hardness and fatigue strength correspond to results of similar experiments abroad, for example [15,16].

4 Conclusion

Final microstructure and consequently also mechanical properties of casts from ADI are markedly dependent on the temperature of isothermal transformation of austenite and holding time at this temperature. Their influence on the microstructure and mechanical properties of ADI can be summarized in following points:

- the specimens with higher temperature of isothermal transformation of austenite have the matrix consisted of upper bainite and retained austenite and the specimens with lower temperature of isothermal transformation of austenite have the matrix consisted of lower bainite and retained austenite;
- the content of retained austenite is decreased with increasing holding time at the temperature of isothermal transformation;
- the shape, size and count of graphitic nodules are not changed in dependence on the temperature of isothermal transformation of austenite and in dependence on the holding time at this temperature;
- the tensile strength and hardness of the specimens are increased with decreasing temperature of isothermal transformation of austenite, but the elongation and toughness is decreased;
- the hardness of the specimens is decreased with increasing holding time at the temperature of isothermal transformation;
- the fatigue strength is decreased with decreasing temperature of isothermal transformation of austenite.

The choice of temperature of isothermal transformation of austenite and holding time at this temperature depends on a required combination of mechanical properties.

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