PHASE TRANSFORMATION IN AUSTEMPERED DUCTILE IRONS

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Abstract. Austempered Ductile Iron (A.D.I.) with a bainitic matrix, obtained by heat treatment and isothermal hardening is the material which combines a lot of superior attributes of the classical cast iron or forged iron, being in a serious competition with the iron used by the moment in the automotive industry. Austempered ductile irons usually contain a large quantity of retained austenite that can help to optimise their mechanical properties. Many of the properties of austempered ductile iron depend on the austenite which is retained following the bainite reaction. The paper presents a study that determines the influence of the heat treatment parameters over the the volume fraction of the retained Austenite ($V\gamma_r$) and of the Carbon content (C_γ) of the retained austenite. The studied cast iron has the following chemical composition (% in weight): 3.70% C; 2.46% Si; 0.56 % Mn; 0.038% P; 0.009%S; 0.062%Mg; 0.21% Mo 0.12% Ni, 0.17% Cu. This cast iron was made in an induction furnace. Nodular changes were obtained with the "In mold" method, with the help of prealloy FeSiCuMg with 10-16% Mg, added into the reaction chamber in a proportion of 1.1% of the treated cast iron.

Keywords: ductile iron, heat treatment, phase transformation, retained austenite, bainite

1. Introduction

Austempered Ductile Iron (A.D.I.) with a bainitic matrix, obtained by heat treatment and isothermal hardening is the material which combines a lot of superior attributes of the classical cast iron or forged iron [1], being in a serious competition with the iron used by the moment in the automotive industry [2]. ADI material possesses a wide range of mechanical properties, combining high strength and fracture toughness similar to high strength steels, while its ductility is notably higher that that of other cast irons, albeit lower than high strength steels.

Another benefit of ADI material’s advantages over steel is its lower density, which may influence a higher mass efficiency, or similar mass efficiency at lower cost.

The combination of high strength and high toughness achieved by A.D.I. suggests the engineering use of this material will continue to expand [3].

The heat treatment known as austempering, made the transformation of austenite in the bainite at the bainite transformation temperature range, generating the bainitic ferrite.

A key role in the development of the microstructure of austempered irons is made by the large concentration of silicon typically present in graphitic cast irons.

The bainitic ferrite is generated by the isothermal transformation of austenite in the bainite transformation temperature range; this heat treatment is known as austempering. During the bainite transformation, the silicon hinders the precipitation of carbides [4].

The austempering process is therefore conventionally defined in two stages [5, 6]. The fraction of bainitic ferrite and the enrichment of the austenite correspond to the first stage of process. This stage is characteristic of cast iron manufacture. The second stage is characterized by the onset of carbide precipitation.

This research has a number of objectives which can be started as follows:

1. To determine of the volume fraction of retained austenite ($V\gamma_r$);
2. To determine the Carbon content of the retained austenite (C_γ).

2. Materials and heat treatment

2.1. Materials

The studied cast iron has the following chemical composition (% in weight): 3.70% C; 2.46% Si; 0.56 % Mn; 0.038% P; 0.009%S; 0.062%Mg; 0.21% Ni 0.12% Ni, 0.17%Cu. This cast iron was made in an induction furnace. Nodular changes were obtained with the "In mold" method, with the help of prealloy FeSiCuMg with 10-16% Mg, added into the reaction chamber in a proportion of 1.1% of the treated cast iron.

The structure in raw state is perlito-feritic typical for a cast iron with geometrically regular nodular form [7]. The casted raw iron had the following mechanical properties: tensile strength Rm = 660 N/mm^2, hardness HB = 180; impact strength KC = 12 J/cm^2 and elongation (A) = 7 [%].

2.2. Heat Treatment

The parameters of the heat treatment done were the following: the austenizing temperature, T_γ = 900 °C; the maintained time at austenizing temperature, τ_γ = 30 min; the temperature at isothermal level, T_{iz} = 300 and 400 °C; the maintained time at the isothermal level, τ_{iz} = 5; 30; 60; 120; and 180 min. All these two experimental lots A (t_{iz} = 300 °C) and B (t_{iz} = 400 °C) were performed at isothermal maintenance in salt-bath (55% KNO_3+45% $NaNO_3$), being the cooling after the isothermal maintenance was done in air.

The austenitising temperature and time determines the carbon concentration C^0_γ of austenite, which is in equilibrium with the graphite at T_A. The determination of the carbon concentration C^0_γ for the studied cast iron taking account of the alloying elements, can made with the next relation [8]:

$$C^0_\gamma = -0.435 + 0.335\times10^{-3}\,T_A + 1.61\times10^{-6}\,T_A^2 + 0.006\,(Mn\,\%) - 0.11\,(Si\,\%) - 0.07\,(Ni\,\%) + 0.014\,(Cu\,\%) - 0.3\,(Mo\,\%) \quad (1)$$

There are major effects of T_{iz} and τ_{iz} on the volume fraction of the retained Austenite ($V\gamma_r$) at ambient temperature and also over the Carbon content (C_γ) of the retained austenite.

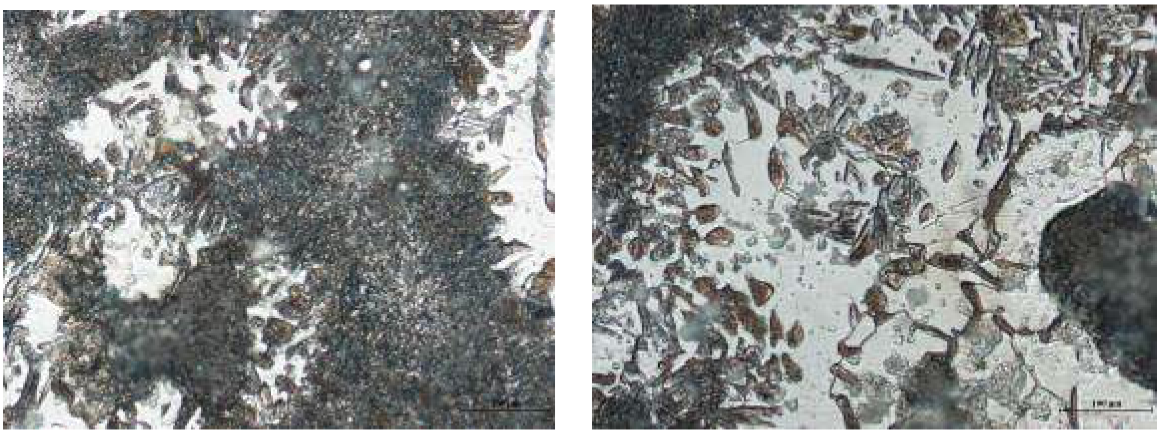
3. Results and discussion

From this material, 10 typical test specimens were done (ϕ 20 × 50 mm) and after the heat treating, it was determined the results of:

- The volume fraction of the retained Austenite ($V\gamma_r$);
- The Carbon content (C_γ) of the retained austenite;

The determination of the volume fraction of the retained Austenite ($V\gamma_r$) was made by help of the images analysis over a surface of 6300 μm^2 (70 × 90 μm) and the determination of the Carbon content (C_γ) of the retained austenite was made by help of the electronic microprobe.

In Figures 1 and 2 are presented the specific microstructure at the 200× magnification for all these two experimental lots A (t_{iz} = 300 °C) and B (t_{iz} = 400 °C) after the isothermal heat treatment.



a) b)

Figure 1. Microstructure of austempered ductile iron (SEI at 200× magnification). Retained austenite (light background), bainitic ferrite (dark shaves) and nodules of graphite
(a) lot A, τ_{iz} = 60 min; (b) lot B, τ_{iz} = 60 min

After analyzing the structure presented it was done a general observation:

- the structure of the sample maintained at T_{iz} = 300 °C and τ_{iz} = 60 min, has an fine acicular form, characteristic for lower bainitic ferrite;
- the structure of the sample maintained at T_{iz} = 400 °C and τ_{iz} = 60 min, has an scales form, characteristic for upper bainitic ferrite [7].

The result of the carbon concentration C^0_γ of austenite after calculation is C^0_γ = 0.8343 %.

The experimental values of the volume fraction of the retained Austenite ($V\gamma_r$) and of the Carbon content (C_γ) of the retained austenite are presented in figure Table 1 and Figures 2 and 3.

The following observations can be made after analyzing the results:

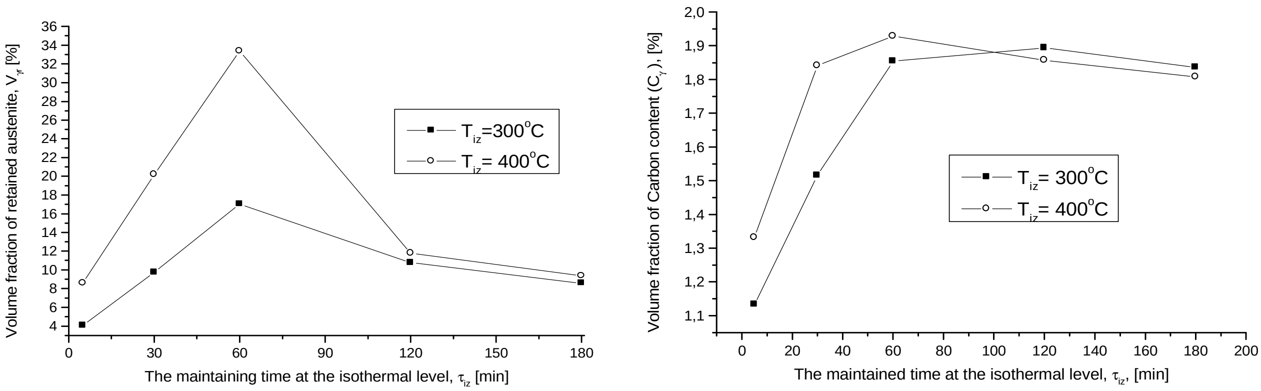
- The volume fraction of the retained Austenite ($V\gamma_r$) increase with the increase of the maintaining time at the isothermal level, from T_{iz} = 300 °C to 400 °C, for the maintained time τ_{iz} = 5, 30 and 60 minutes, being maxim for T_{iz} = 400 °C and τ_{iz} = 60 minutes, $V\gamma_r$ = 33.382 %. This can be explained by the fact that the diffusion of carbon at high temperatures (400 °C) from bainitic ferrite being formed in the residual austenite is more rapid and enriched, which gives them greater stability to subsequent cooling in air;

- From to decreased time at isothermal level, τ_{iz} = 5 and 30 minutes, the volume fraction of the retained Austenite ($V\gamma_r$) is low, for all the maintained temperatures at the isothermal level (T_{iz} = 300 and 400 °C). This is explained by the fact that austenite is low carbon, has low stability, which favors subsequent transformation to martensite cooling in air;

Table 1. The influence of the heat treatment parameters over the volume fraction of the retained Austenite ($V\gamma_r$) and of the Carbon content (C_γ) of the retained austenite

T_γ **[°C]**	τ_γ **[min]**	T_{iz} **[°C]**	τ_{iz} **[min]**	$V\gamma_r$ **[%]**	C_γ **[%]**
900	30	300	5	**4.056** (Std.Err. = 0.02)	**1.133** (Std.Err. = 0.12)
			30	**9.750** (Std.Err. = 0.03)	**1.515** (Std.Err. = 0.18)
			60	**17.029** (Std.Err. = 0.01)	**1.854** (Std.Err. = 0.19)
			120	**11.780** (Std.Err. = 0.1)	**1.894** (Std.Err. = 0.15)
			180	**8.581** (Std.Err. = 0.2)	**1.836** (Std.Err. = 0.16)
		400	5	**8.581** (Std.Err. = 0.19)	**1.332** (Std.Err. = 0.18)
			30	**20.181** (Std.Err. = 0.04)	**1.841** (Std.Err. = 0.17)
			60	**33.382** (Std.Err. = 0.08)	**1.928** (Std.Err. = 0.18)
			120	**10.785** (Std.Err. = 0.02)	**1.857** (Std.Err. = 0.12)
			180	**9.365** (Std.Err. = 0.04)	**1.808** (Std.Err. = 0.11)

Std. Err. = Student Error determination



a) b)

Figure 2. The volume fraction: (a) of the retained Austenite ($V\gamma_r$), (b) of the Carbon Content (C_γ) of the retained austenite

- The volume fraction of the Carbon content (C_γ) of the retained austenite, increase with the increasing of the maintained temperatures at the isothermal level from T_{iz} = 300 °C to 400 °C and τ_{iz} = 5, 30 and 60 minutes, the maximum (C_γ = 1.928 %) being at T_{iz} = 400 °C and τ_{iz} = 60 minute;

- For the maintaining time at the isothermal level, τ_{iz} = 120 and 180 minute, the volume fraction of the Carbon content (C_γ) is the maximum for T_{iz} = 300 °C and is the minimum for T_{iz} = 400 °C. This is explained by the fact that longer time at the isotermal level at higher temperatures, promote the transformation to a higher proportion of the retained Austenite ($V\gamma_r$) in bainitic ferrite and carbide, which lowers the percentage of the Carbon content (C_γ) from the retained Austenite;

- The volume fraction of the Carbon content (C_γ) of the retained austenite, is influenced by the percentage of silicon from the chemical composition (Si = 2.46%), element that reduces carbon solubility from the retained Austenite ($V\gamma_r$) for all the maintained temperatures at the isotermal level, which leads to a decrease of ferrite development process;

- For the growth to continue, silicon must disseminate the austenite to ferrite vicinity. The diffusion process is slow, however, because silicon substitutional solid solution formed of iron [9, 10].

6. Conclusions

The isothermal bainitic transformation in a Mo-Ni-Cu S.G. cast iron was studied in the temperature range of 300-400 °C and with maintaining time between 1-180 minutes. The main results are summarized as follows:

(a) The structure of the sample maintained at T_{iz} = 300 °C and τ_{iz} = 60 min, has an fine acicular form, characteristic for lower bainitic ferrite;

(b) The structure of the sample maintained at T_{iz} = 400 °C and τ_{iz} = 60 min, has an scales form, characteristic for upper bainitic ferrite;

(c) The volume fraction of the retained Austenite ($V\gamma_r$) increase with the increase of the maintaining time at the isothermal level, from T_{iz} = 300 °C to 400 °C, for the maintained time τ_{iz} = 5, 30 and 60 minutes, beeing maxim for T_{iz} = 400 °C and τ_{iz} = 60 minutes, $V\gamma_r$ = 33.382 %.

(d) From to decreased time at isothermal level, τ_{iz} = 5 and 30 minutes, the volume fraction of the retained Austenite ($V\gamma_r$) is low, for all the maintained temperatures at the isothermal level (T_{iz} = 300 and 400 °C).

(e) The volume fraction of the Carbon content (C_γ) of the retained austenite, increase with the increasing of the maintained temperatures at the isothermal level from T_{iz} = 300 °C to 400 °C and τ_{iz} = 5, 30 and 60 minutes, the maximum (C_γ = 1.928 %) being at T_{iz} = 400 °C and τ_{iz} = 60 minute;

(e) The volume fraction of the Carbon content (C_γ) of the retained austenite, is influenced by the percentage of silicon from the chemical composition (Si = 2.46%), element that reduces carbon solubility from the retained Austenite ($V\gamma_r$) for all the maintained temperatures at the isotermal level, which leads to a decrease of ferrite development process.

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