THE KINETICS TRANSFORMATION OF A LOW ALLOY CAST IRON

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Abstract. The Austempered Ductile Iron (ADI) obtained by heat treating and isothermal hardening, is the material, which combines a lot of the superior attributes of classical Ductile Irons or forged irons, being in a serious competition with the iron used by the moment in the automotive industry.

The paper presents an application for calculating the kinetics and thermodynamics parameters in the case of a phase transformation in solid state in A.D.I. S.G. grade. The studied cast iron has the following chemical composition (% in weight): 3.73% C; 2.77% Si; 0.44% Mn; 0.057% P; 0.009% S; 0.047% Mg; 0.23% Cu; 0.15% Ni; 0.10% Cr. This cast iron was made in an induction furnace. The isothermal bainitic transformation in a Ni-Cu S.G. cast iron was studied in the temperature range of 375÷400 °C and with maintaining time between 1 to 60 minutes.

It is pointed out the influence of some factors (the temperature and the maintained time at the isothermal level) on the phase transformation and properties in the studied cast iron. By the help of Johnson-Mehl-Avrami equation it was described the kinetics of austenitization of S.G. Cast Iron and it was determined the reaction exponent “n” and the bainitic reaction rate "k".

Keywords: cast iron, heat treatment, phase transformation, kinetics transformation

1. Introduction

Austempered ductile iron (ADI) has received considerable attention from researchers and manufactures during the past years for its unique properties (which combines high strength and good wear resistance) and low cost. It has been used for many applications and there have been a number of papers published which refer to the structure and properties of ADI [1, 2].

Recent studies have shown that, this material have excellent mechanical properties.

The combination of high strength and high toughness achieved by A.D.I. suggests the engineering use of this material will continue to expand [3-6].

A wide range of properties can be obtained in these material components owing to changes in proportions of the major phases present in the microstructure: bainitic ferrite, high carbon austenite and graphite nodules. Martensite, ferrite, iron carbides and other alloy carbides may also be present [7].

The paper presents an application for calculating the kinetics and thermodynamics parameters in the case of a phase transformation in solid state in A.D.I. S.G. grade [8]. It is pointed out the influence of some factors (the temperature and the maintained time at the isothermal level) on the phase transformation and properties in the studied cast iron [9].

The kinetics of austenitization of S.G. Cast Iron was described by the Johnson-Mehl-Avrami equation [10, 11].

2. Materials and heat treatment

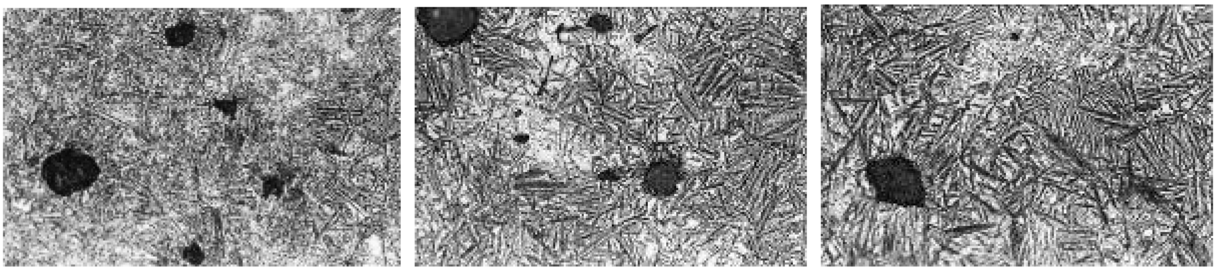
The studied cast iron has the following chemical composition (% in weight): 3.73% C; 2.77% Si; 0.44% Mn; 0.057% P; 0.009% S; 0.047% Mg; 0.23% Cu; 0.15% Ni; 0.10% Cr.

This cast iron was made in an induction furnace. Nodular changes were obtained with the “In mold” methods, with the help of prealloy FeSiCuMg. The microstructure in raw state is perlito-feritic typical for a cast iron with geometrically regular nodular form.

The casted raw iron had the following mechanical properties: R_m = 750 [N/mm^2]; A = 7.7 [%]; HB = 268. The heat treatment was done by using a resistor furnace.

The parameters of the heat treatment done were the following: the austenizing temperature, T_A = 900 [°C]; the maintained time at austenizing temperature, τ_A = 30 [min]; the temperature at isothermal level, T_{iz} = 375, 385 and 400 [°C]; the maintained time at the isothermal level, τ_{iz} = 1; 2; 5; 10; 15; 20; 25; 30; 35; 40; 45, 50, 55 and 60 [min]. All these three experimental lots A (T_{iz} = 375 °C), B (T_{iz} = 385 °C) and C (T_{iz} = 400 °C) were performed at isothermal maintenance in salt-bath, being the cooling after the isothermal maintenance was done in air.

In Figure 1 is presented the specific microstructure at the 1000× magnification for all these three experimental lots A (T_{iz} = 375 °C), B (T_{iz} = 385 °C) and C (T_{iz} = 400 °C).



a) b) c)

Figure 1. Microstructure: (a) lot A, τ_{iz} = 60 min; (b) lot B, τ_{iz} = 60 min; (c) lot C, τ_{iz} = 60 min (SEI at 200× magnification)

After analyzing the structure presented it was done a general observation: beginning from the sample maintained at T_{iz} = 375 °C and τ_{iz} = 60 min, to the samples maintained at T_{iz} = 400 °C and τ_{iz} = 60 min, all the three structure of the sample has a scales form, characteristic for upper bainitic ferrite [7].

3. Experimental results

From this material, 33 typical hardness (HB) test specimens was done (ϕ 20 × 50 mm) and after the heat treating, it was determined the results of HB. The aim of the experiments is to determine the hardness (HB) at the isothermal temperature. The experimental values of the hardness are presented in Table 1.

The notation from the Table 1 are: H_0 – initial hardness, corresponding τ_{iz} = 1 min; H_t – hardness obtained after a maintaining time (t) at the isothermal level, [%]; H_f – final hardness, corresponding at the maintaining time at the isothermal level, which are considered as a final time for the first stage of transformation of the bainitic reaction.

4. Transformation kinetics

For the study of the phase transformation kinetics, it was used the first stage of the bainitic reaction [2, 3, 4]:

$$\gamma \rightarrow (\alpha) + (\gamma) \qquad (1)$$

where:

γ - metastable austenite;

(α) - bainitic ferrite;

(γ) - austenite enriched in carbon

In this researches work it was used the methods of the variation's hardness analyse function of the time at the isothermal level (τ_{iz}), considering that this values are depended from the proportion of the transformed fraction "$X_{(t)}$".

Table 1. Hardness (HB), for various T_{iz} and τ_{iz}

T_{iz}, [°C]	τ_{iz}, [min]	Hardness, [HB]		
		H_0	H_f	$H_{(t)}$
	1		150	485
	2		157	471
	5		170	451
	10		204	438
	20		213	426
	30		229	415
	35		246	408
375	40	150	257	393
	45		295	390
	50		321	379
	55		341	365
	60		350	345
	1		150	438
	2		160	426
	5		180	415
	10		215	398
	20		224	390
	30		246	375
385	35	150	257	363
	40		272	344
	45		302	333
	50		325	325
	55		333	321
	1		150	415
	2		160	398
	5		180	378
	10		215	363
	20		224	344
400	30	150	246	333
	35		257	321
	40		272	302
	45		298	298
	50		302	278

It was utilised the expression:

$$X_{(t)} = \frac{H_0 - H_{(t)}}{H_0 - H_f}, [\%] \qquad (2)$$

where:

$X_{(t)}$ – the transformed fraction;

H_0 – initial hardness, corresponding τ_{iz} = 1 min;
H_t – hardness obtained after a maintaining time (t) at the isothermal level, [%];
H_f – final hardness, corresponding at the maintaining time at the isothermal level, which is considered as a final time for the first stage of transformation of the bainitic reaction.

In Figure 2 is represented the sigmoidal solid curves of the austenitic transformation during the bainite reaction.

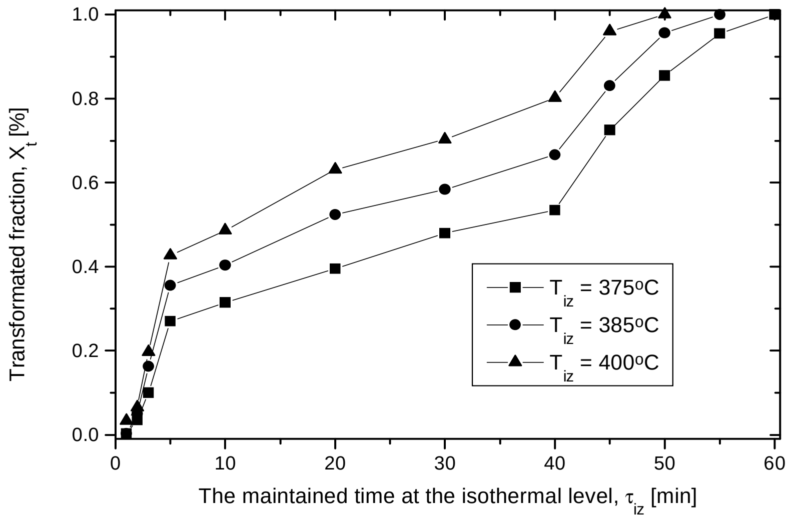


Figure 2: Transformed fraction curves at T_{iz} = 375, 385 and 400 °C, for different maintaining time, τ_{iz}

Like the transformation fraction curves have sigmoidal shape, it was used the "Johnson-Mehl-Avrami" equation [1]:

$$X(t) = 1 - \exp(-k\cdot t^n) \quad (3)$$

where:
X(t) - the transformed fraction;
k - rate constant dependent on temperature;
n - exponent of the reaction.

In order to determine "k" and "n", the natural logarithmic expression was used:

$$\log[-\log(1 - X)] = = [n\cdot \log k + \log(\log e)] + n\cdot \log t \quad (4)$$

The plot of "log[–log(1 – X)]"against "logt" in the isothermal temperature range 375 to 400 °C [2, 3, 4], for the isothermal maintaining time range 1 to 60 minutes, is shown in Figure 3.

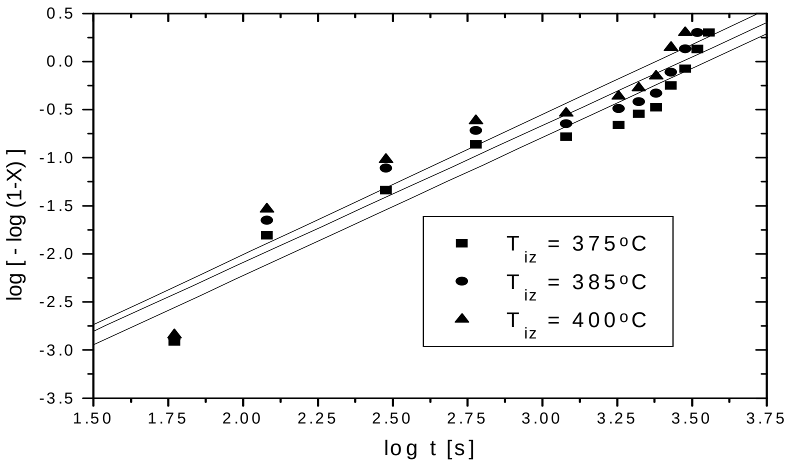


Figure 3. The plot of "log[–log(1 – X)]" against "logt" in the isothermal temperature: 375, 385 and 400 °C

The obtained equations from the linear regression adjustment are:

$$Y_{375} = -5.10156 + 1.4375{*}X,\ R^2 = 0.96; \quad (5)$$

$$Y_{385} = -4.94205 + 1.4456{*}X,\ R^2 = 0.95; \quad (6)$$

$$Y_{400} = -4.92282 + 1.4573{*}X,\ R^2 = 0.95. \quad (7)$$

Values of "n" and "k" determinate from the slopes and intercepts of the linear regression lines are listed in table 2.

Table 2. Values of "n" and "k" for the formation of bainite

Lot	T_{iz} [°C]	n	k [s^{-1}]
A	375	1.437	5.05×10^{-4}
B	385	1.445	6.79×10^{-4}
C	400	1.457	7.43×10^{-4}

According to Liu [1], if the "n" exponent is between 1 and 2.3 the transformation is interfacing controlled.

At the same maintaining time in the isothermal level, the transformation process is different in the each maintaining isothermal temperatures. The bainitic reaction rate "k" increases when the isothermal temperature increases from 375 to 400 °C.

5. Discussion

Examining the data revealed that at shorter austempering time for all maintaining temperature, the bainitic transformation is not enough and austenite converts to martensite with the increasing the values of hardness (HB).

All the lots are specific for the formation of the superior bainitic ferrite, presented as a full plate-like morphology of bainitic ferrite with the higher amount of retained austenite is expected, as illustrated in figure 1.

It is obvious that at austempering time longer than 60 min at this at this maintaining temperature (400 °C), no presence of martensite could be detected. When the heat treating parameters are changing and the temperature is growing for isothermal maintenance than the hardness (HB) are decreasing [9]. When maintaining time at the same temperature of the isothermal level is increasing then the hardness (HB) are decreasing.

This evolution of the hardness properties is determined by the structural changes reported to the parameters of the heat treating. Together with increasing the level of the isothermal maintenance temperature inside the structure will appear the superior bainite and the martensite will disappear [6].

6. Conclusions

The isothermal bainitic transformation in a Ni-Cu S.G. cast iron was studied in the temperature range of 375÷400 °C and with maintaining time between 1 to 60 minutes. The main results are summarized as follows:

(a) The classical isothermal bainitic heat treatment combines a lot of superior attributes used in the automotive industry.

(b) The kinetics of austenitization of S.G. cast iron, can be described by an Johnson-Mehl-Avrami equation.

(c) The reaction exponent "n"= 1.43 ÷ 1.46 and the transformation is interface controlled.

(d) The bainitic reaction rate "k" increases with increasing isothermal temperature from 375 to 400 °C.

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