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KINETICS AND THERMODYNAMIC TRANSFORMATION OF A SPECIAL S.G. CAST IRON

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ABSTRACT

The paper contains a study about the kinetics and thermodynamics transformation of a S.G. Cast Iron during the isothermal heat treatment. With the help of Johnson-Mehl and Arrhenius equations, there were described the activation energy “Q”, rate coefficients dependent on temperature “k”, exponent of reaction “n” and a constant dependent on frequency “A”.

KEYWORDS: bainitic s.g. cast iron, heat treatment, phase transformation

1. Introduction

Austempered ductile iron (ADI) with a bainitic matrix, obtained by heat treatment and isothermal hardening is the material which combines a lot of superior attributes of the classical ductile iron or forged iron [1-4]. 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. 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. The kinetics of austenitization of S.G. Cast Iron, was described by the Johnson-Mehl-Avrami equation. For the determination of the activation energy “Q”, it was used the Arrhenius equation.

2. Materials

The studied cast iron has the following chemical composition (% in weight): 3.63%C; 2.88%Si; 0.45 %Mn; 0.012%P; 0.006%S; 0.05%Mg; 0.40% Ni, 0.42%Cu. This cast iron was made in an induction furnace.

3. Heat treating

The parameters of the heat treatment performed 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} = 350 and 400[°C]; the maintained time at the isothermal level, T_{iz} = 1; 2; 5; 10; 15; 20; 25; 30; 35; 40; 45 and 50 [min].

All these 2 experimental lots A (T_{iz} = 350°C) and B (T_{iz} = 400°C) were performed at isothermal maintenance in salt-bath. The cooling after the isothermal maintenance was done in air.

4. Experimental procedure

From this material, 19 typical HB test specimens were done (ϕ 20 x 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.

5. Experimental results and discussion

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

Table 1. *Experimental values of hardness, for various T_{iz} and τ_{iz}.*

No.	**Temperature at isothermal level**	**Maintained time at the isothermal level**	**Initial hardness**	**Final hardness**	**Hardness after a maintaining time**
Symbol	T_{iz}	τ_{iz}	H_0	H_f	$H_{(t)}$
u.m.	[°C]	[min]	[HB]		
1	350	1	485	365	485
2		2			471
3		5			451
4		10			438
5		20			426
6		30			415
7		35			408
8		40			393
9		45			390
10		50			379
11		55			365
12	400	1	426	325	426
13		2			398
14		5			390
15		10			375
16		20			363
17		30			344
18		35			333
19		40			325

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

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

where:
γ - metastable austenite;
(α) - bainitic ferrite;
(γ) - austenite enriched in carbon

In this research work, it was used the method of the variation hardness analysis function of the time at the isothermal level

(τ_{iz}), considering that these values depend on the proportion of the transformed fraction "$X_{(t)}$". It was utilised the expression:

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

where:
$X_{(t)}$ – the transformed fraction;
H_0 – initial hardness, corresponding to
τ_{iz} = 1 min;
H_t – hardness obtained after a maintaining time (t) at the isothermal level, [%];

H_f – final hardness, corresponding to the maintaining time at the isothermal level, which is considered as a final time for the first stage of the transformation of the bainitic reaction.

In Figure 1 are represented the sigmoidal solid curves of the austenitic transformation during the bainite reaction.

As the transformation fraction curves have sigmoidal shape, it was used the "Johnson-Mehl-Avrami" equation:

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

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:

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

The plot of "log [-log (1-X)]"against "log t" in the isothermal temperature range of 350-400°C [2, 4], for the isothermal level maintaining time range of 1 – 55 minutes, is shown in Figures 2 and 3.

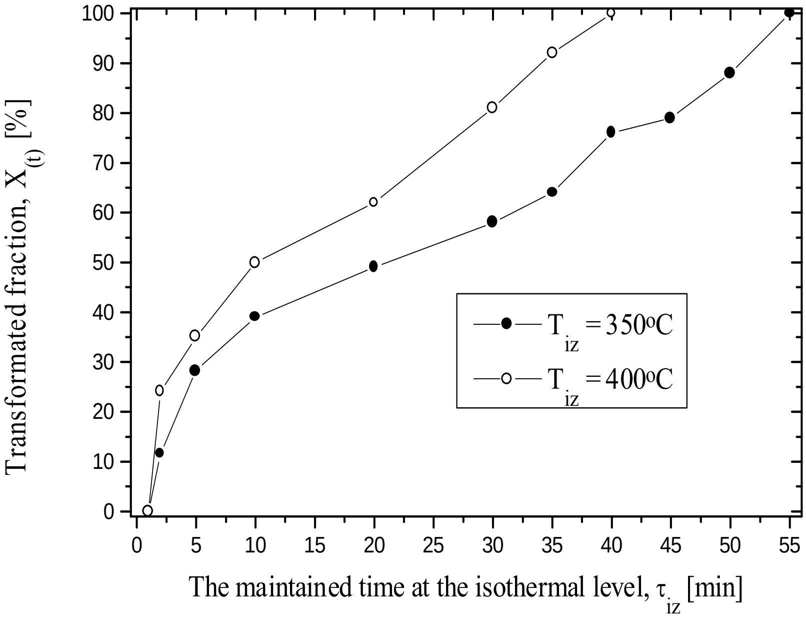

Fig. 1. *Transformed fraction curves at T_{iz} = 350 and 400 °C, for different maintaining time τ_{iz}, at the isothermal level.*

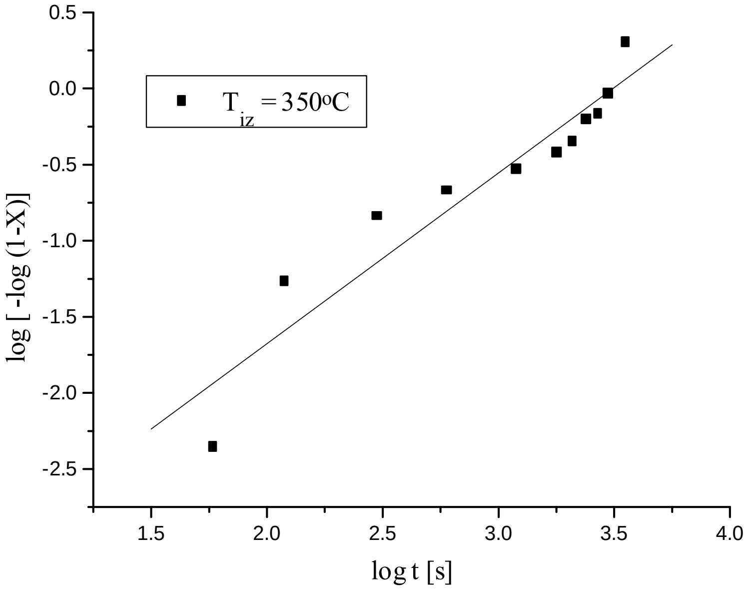

Fig. 2. *Plot of "log[-log(1-X)] against "log t" in the isothermal temperature 350 °C.*

The obtained equations from the linear regression adjustment are:

Y_{350} = - 3.92023 + 1.1218*X (5)

For this equation, the coefficients of determination R^2 = 0.95.

Y_{400} = - 4.05426 + 1.25209*X, (6)

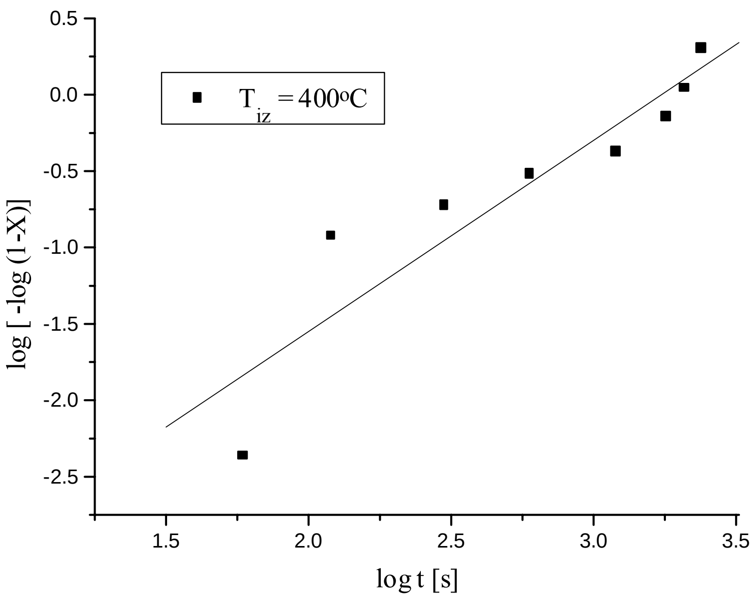

Fig. 3. *Plot of “log[-log(1-X)] against “log t” in the isothermal temperature 400°C.*

For this equation, the coefficients of determination, R^2 = 0.95. Values of “n” and “k” determined from the slopes and intercepts of the linear regression lines are listed in Table 2.

Table 2. *Values of the reaction exponent “n” and the bainitic reaction rate “k” for the formation of bainite*

Lot	**Temperature at isothermal level**	**Reaction exponent**	**Bainitic reaction rate**
Symbol	T_{iz}	n	k
u.m.	[°C]		[1/s]
A	350	1.12	6.66 x 10^{-4}
B	400	1.25	11.26 x 10^{-4}

According to Liu [2], if the “n” exponent is between 1 and 2.3, the transformation is interface controlled.

At the same maintaining time in the isothermal level, the transformation process is different in each of the maintaining isothermal temperatures. The bainitic reaction rate "k" increases when the isothermal temperature increases from 380 to 400° C.

For the determination of the activation energy “Q”, it was used the Arrhenius equation:

$$k = A\, e^{-Q/RT};\ [1\ /\text{min}] \qquad (7)$$

where:

k-constant rate dependent on temperature [1/s];

Q-activation energy, [J /mol];

T-temperature, [K]

R-gas constant 8.31, [J/mol.K]

A-constant dependent on frequency [1/s].

In order to determine “Q” and “A”, the natural logarithmic expression of eqn. (7) was used:

$$\log k = -\log e\ \frac{Q}{R}\frac{1}{T} + \log A \qquad (8)$$

The plot of “log k” against “1/T” in the isothermal temperature range of 350 - 400°C, for the isothermal maintaining time, in the range of 1 – 55 minutes, is shown in Figure 4.

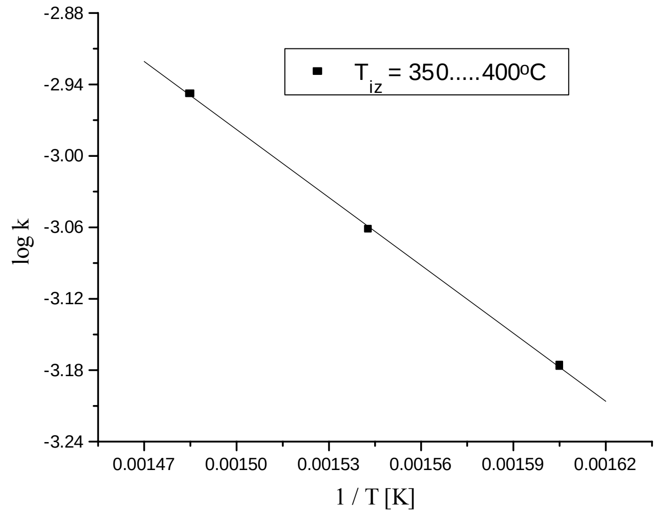

Fig. 4. *Linear transform of the Arrhenius equation for the studied S.G. cast iron, T_{iz} =350...400°C.*

The equation of the linear regression is:

$Y_{380-400}$=-0.1245–1902.18772*X, (9)

For this equation, the coefficients of determination, R^2 = 0.99.

Values of “Q” and “A” determined from the slope and intercept of the linear regression line are: Q = 37036 [J/mol] and A = 0.75 [1/s]

The activation energy of isothermal transformation is the same numerical order like the values obtained in the technical specialized literature [2, 4].

From the linear regression, it was observed that the value of activation energy increases with the increasing of the maintaining temperature, from 350 to 400°C.

6. Conclusions

The isothermal bainitic transformation in a Ni-Cu S.G. cast iron was studied in the temperature range of 350-400° C and with a maintaining time between 1-55 minutes.

The main results are summarized as follows:

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

(b) The reaction exponent “n”= 1.12–1.25 and the transformation is interface controlled.

(c) The bainitic reaction rate "k" increases with increasing isothermal temperature from 350 to 400°C.

(d) The activation energy of isothermal transformation was 37036 [J/mol]

(e) The constant dependent on frequency was 0.75 [1/s].

References

[1]. Simon, D., *ADI- a new material for the automotive engineer*, Foundry Trade J., 2, p. 66, 1996.

[2]. Liu, Y.C., Schissler, J.M., Chabout, J.P., Vetters, H., *Study of The Structural Evolution of Austempered Ductile Iron (ADI) during Tempering at 360°C”*, Metallurgical Science & Tech. 13, p. 12, 1995.

[3]. Pérez, M. J., Cisneros, M. M., Valdés, E,, Mancha, H., Calderón, H. A. and Campos, R. E., *Experimental Study of the Thermal stability of Austempered DuctileIrons,* Journal of Materials Engineering and Performance, Volume11 (5), October, p. 519, 2002.

[4]. Milosan, I. - *The Kinetics and Thermodynamic Transformation of a Cr-Ni-Cu Low-Alloy S.G. Cast Iron,* Metalurgia International, 10, p. 70, 2009.