Abstract: 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 holding 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 and for the determination of the activation energy “Q”, it was used the “Arrhenius” equation.

Keywords: S.G. Cast Iron, Bainite, Phase transformation, Kinetics, Thermodynamic.

1. INTRODUCTION

Spherical graphite cast iron can be treated to produce Austempered Ductile Iron (A.D.I.). 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 [1, 2, 3]. This paper studies the influence of some technological factors on the phase transformation in solid state in A.D.I. S.G. grade [4–10].

2. MATERIALS

The studied cast iron has the following chemical composition (% in weight):
- 3.85% C;
- 2.16% Si;
- 0.42% Mn;
- 0.012% P;
- 0.0036% S;
- 0.076% Mg;
- 0.40% Ni;
- 0.39% Cu.

This cast iron was made in an induction furnace. Nodular changes were obtained with the “In mold” methods, with the help of prealloy FeSiCuMg.

3 HEAT TREATMENT

The heat treatment was done by using a resitor furnace. The parameters of the heat treatment done were the following: the austenizing temperature, \( t_A = 900 \, ^\circ C \); the holding time at austenizing temperature, \( \tau_A = 30 \, [\text{min}] \); the temperature at isothermal level, \( t_{iz} = 380 \) and 400 \( \, ^\circ C \); the holding time at the isothermal level, \( \tau_{iz} = 1; 2; 5; 10; 20; 30; 40 \) and 50 \( \, [\text{min}] \).

All these 2 experimental lots A (\( t_{iz} = 380 \, ^\circ C \)) and B (\( t_{iz} = 400 \, ^\circ C \)) were performed at isothermal holding in salt-bath using a resitor furnace, being the cooling after the isothermal holding was done in air.

3.1 Transformation kinetics

For studying the phase transformation kinetics, it was used the first stage of the bainitic reaction [4, 9]:

\[
\gamma \rightarrow (\alpha) + (\gamma) \tag{1}
\]

where:
- \( \gamma \) - metastable austenite;
- \( (\alpha) \) - bainitic ferrite;
- \( (\gamma) \) - austenite enriched in carbon

In this researches work it was used the method of the variation’s hardness analyse function of the time at the isothermal level (\( \tau_{iz} \)), considering that
this values are depended from the proportion of the transformed fraction “X(t)”. The expression was utilised:

\[ X(t) = \frac{H_0 - H_f}{H_0 - H_t} \times \% \]  

(2)

where:

\( X(t) \) – the transformed fraction, \[%\];
\( H_0 \) – initial hardness, corresponding \( \tau_{iz}=1 \) min, [HV0.01];
\( H_t \) – hardness obtained after a holding time (t) at the isothermal level, [HV0.01];
\( H_f \) – final hardness, corresponding at the holding time at the isothermal level, which is considered as a final time for the first stage of transformation of the bainitic reaction, [HV0.01].

The experimental values of the hardness are presented in table 1.

Table 1. The experimental values of hardness, for various \( t_{iz} \) and \( \tau_{iz} \).

<table>
<thead>
<tr>
<th>( t_{iz} ) [^{\circ}C]</th>
<th>( \tau_{iz} ) [min]</th>
<th>Hardness, [HB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>380</td>
<td>493</td>
<td>302</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>415</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>375</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>363</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>354</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>325</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>302</td>
</tr>
<tr>
<td>400</td>
<td>438</td>
<td>295</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>393</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>354</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>333</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>325</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>311</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>295</td>
</tr>
</tbody>
</table>

The sigmoid solid curves are represented in figure 1.

Fig. 1 Transformed fraction curves at \( t_{iz} = 380 \) and \( 400 \) °C, for different holding time, \( \tau_{iz} \), at the isothermal level.
Because the fraction curves have sigmoid shape, the “Johnson-Mehl-Avrami” equation was used, which represents the dependence between time and transformed phase volume for a specific temperature.

\[ X(t) = 1 - \exp (- kt)^n \]  \hspace{1cm} (3)

where:

- \( X(t) \) - the transformed fraction, [%];
- \( k \) - coefficient of the reaction, [1/s];
- \( n \) - coefficient dependent on increase and germination processes;

In order to determine “\( k \)” and “\( n \)”, the natural logarithmic expression was used:

\[ \log[-\log(1-X)]=n\log k+\log\text{loge}+n\log t \]  \hspace{1cm} (4)

The graphic representation of “\( \log[-\log(1-X)] \)” against “\( \log t \)” in the isothermal temperature range 380-400 °C [4], for the isothermal holding time range 1 – 50 minutes, is shown in figure 2.

![The graphic representation of “\( \log[-\log(1-X)] \)” against “\( \log t \)”](image)

**Fig. 2** The graphic representation of “\( \log[-\log(1-X)] \)” against “\( \log t \)” in the isothermal temperature 380°C and 400°C.

The obtained equations from the linear regression adjustment are:

\[ Y_{380} = -4.32559 + 1.33043X \]  \hspace{1cm} (5)

\[ Y_{400} = -4.27583 + 1.37189X \]  \hspace{1cm} (6)

Values of “\( n \)” and “\( k \)” coefficients determined from the slopes and intercepts of the linear regression lines are listed in table 2.

<table>
<thead>
<tr>
<th>Lot</th>
<th>( t_{iz} ) [°C]</th>
<th>( n )</th>
<th>( k ) [1/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>380</td>
<td>1.33</td>
<td>1.05 x 10^{-3}</td>
</tr>
<tr>
<td>B</td>
<td>400</td>
<td>1.37</td>
<td>1.40 x 10^{-3}</td>
</tr>
</tbody>
</table>
According to Liu [4], if the “n” coefficient is between 1 and 2.3 the transformation has a controlled interface. At the same holding time in the isothermal level, the transformation process is different for each holding isothermal temperatures. The bainitic reaction coefficient "k" increases when the isothermal temperature increases from 380 to 400°C.

3.2 Determination of the activation energy “Q”

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

\[ k = A e^{−Q/RT}; \quad [1/\text{min}] \]  

where:

- k - constant rate dependent on temperature [1/s];
- A - constant dependent on frequency [1/s];
- Q - activation energy [J/mol];
- T - temperature [K];
- R – gas constant 8.31 [J/mol.K];

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

\[ \log k = - \log e^{\frac{Q}{RT}} + \log A \]  

The graphic representation of “log k” against “1/T” in the isothermal temperature range 380-400°C, for the isothermal maintaining time range 1 to 50 minutes, is shown in figure 3.

Fig. 3 Linear transform of the Arrhenius equation for the studied S.G. cast iron for \( t_{iz} = 380 \) to 400 °C.
The equation of the linear regression is:

\[ Y_{380-400} = -1.1823 - 2717.391X \]  

(9)

Values of “Q” and “A” determined from the slope and intercept of the linear regression line are: \( Q = 52029.891 \) [J/mol] and \( A = 0.0065 \) [1/s].

The activation energy of isothermal transformation is of the same numerical order as the values obtained in the technical scientifical literature \([4, 9, 10]\).

From the linear regression, it was observed that the value of the activation energy increases with the increasing of the holding temperature, from 380 to 400 °C.

4. CONCLUSION

The isothermal bainitic transformation in a Ni-Cu S.G. cast iron was studied in the temperature range of 380-400 °C and with holding time between 1-50 minutes. The main results are summarized as follows:

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

(b) The coefficient dependent on increase and germination processes, “n” = 1.33 – 1.37 and the transformation is interface controlled.

(c) The coefficient of the reaction "k" increases with increasing isothermal temperature from 380 to 400 °C.

(d) The activation energy of isothermal transformation was \( Q = 52029.891 \) [J/mol].

(e) The constant dependent on frequency “A” was: 0.0065 [1/s].

5. REFERENCES


6. ADDITIONAL DATA ABOUT AUTHOR

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