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PREDICTION OF MICROSTRUCTURE IN ADI CASTINGS

Tests were carried out on samples of low-alloy ductile iron with additions of Ni, Cu and Mo, subjected to austempering heat treatment. The samples were austenitized at 850, 900 and 950 °C, and then austempered at T = 210, 240, 270, 300 and 330 °C. The ausferritizing treatment was carried out in a salt bath for the time τ = 2 - 8 hours. Additionally, tests and studies covered samples subjected to the ausferritizing treatment at 270 °C with the time of holding castings in a bath from 2 to 24 hours. Evaluation covered the results of the ADI microstructure examinations and hardness measurements. The ADI matrix morphology was identified counting the average number of ausferrite plates and measuring their width and spacing. The regression equations HB = f (τ, T) and τ = f (HB, T) were derived to establish the, so-called, "process window", allowing obtaining *a priori* the required microstructure of ADI and, consequently, the required mechanical properties, mainly hardness, shaping the functional properties of castings, abrasion wear resistance – in particular.

1. Introduction

In the last period, ADI has been the subject of studies carried out by numerous research centres at home [1÷12] and abroad [13÷16]. The goal of these studies is to establish what impact the adopted process parameters can have on the cast iron properties. Parameters of the metallurgical process (chemical composition) and heat treatment (time and temperature) have additive effect on the cast iron mechanical properties. The tensile strength in this type of cast iron as well as toughness and hardness depend on the parameters of the ausferritizing treatment (Fig. 1) [13]. The nature of changes in these parameters is controlled by the kinetics of the reaction of the precipitation of ausferrite and the decomposition of high-carbon austenite γ_{HC} (Fig. 2), which can be expressed as Stage I - $\gamma_o = \alpha + \gamma_{HC}$, Stage II - $\gamma_{HC} = \alpha +$ carbide [14]. The search for process window essential for the manufacturing technology is the goal of many research works.

The cast iron with a well-balanced chemical composition, subjected to austempering in a wide range of time and temperature values, is characterized by a dynamic distribution of hardness values (Fig. 3) [13]. The hardness test can be used as a simple and convenient tool to predict the microstructure and the grade of ADI and to find the process window. Understanding the relationship between the structure parameters and hardness of cast iron can be helpful in the task of defining the process window.

2. Methodology

Tests were carried out on cast iron samples heat treated in the process of austempering after austenitizing at 900 °C (Fig. 4). Several series of samples subjected to isothermal holding at different temperatures comprised in the range of 210÷330°C were prepared. The parameter varying within one series was the holding time of samples ranging from 2 to 8 hours, and thus covering the whole performance area of technology. Additionally, tests also included samples austenitized at different temperatures and austempered at 210°C. The time of austenitizing was 2 hours for all the samples tested. Microstructure of samples was examined on the images of nital-etched metallographic sections. The analysis of the images mainly consisted in counting the number of plates and calculating the average width of one plate. The measurements were taken at random along the selected segments, counting the number of plates intersecting with the segment and measuring their widths (Fig. 5). For each measurement, at least three segments were selected. Examples of microstructures are presented in Figure 6.

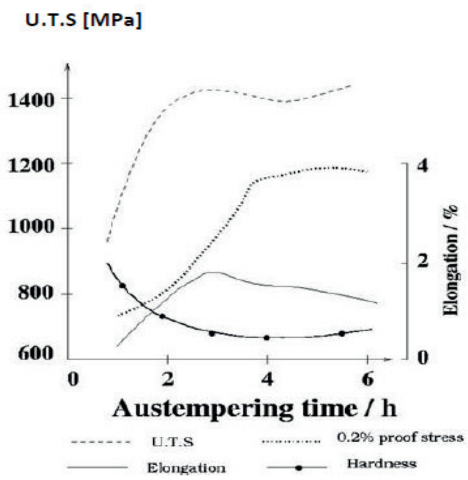

Fig. 1. Ausferritizing treatment vs cast iron mechanical properties [13]

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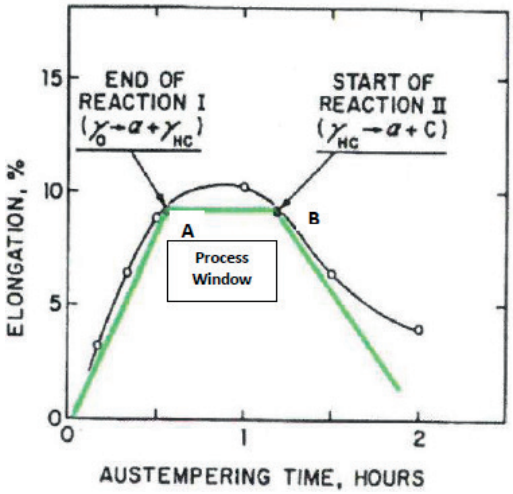

Fig. 2. An idealized picture showing the effect of two-stage heat treatment on ductile iron toughness during austempering [14]

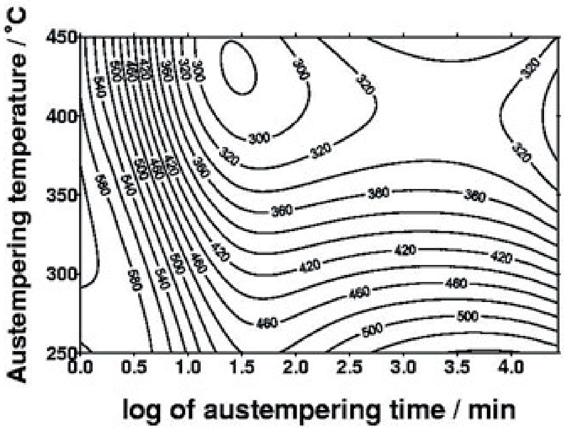

Fig. 3. The map of austempered hardness values [13]

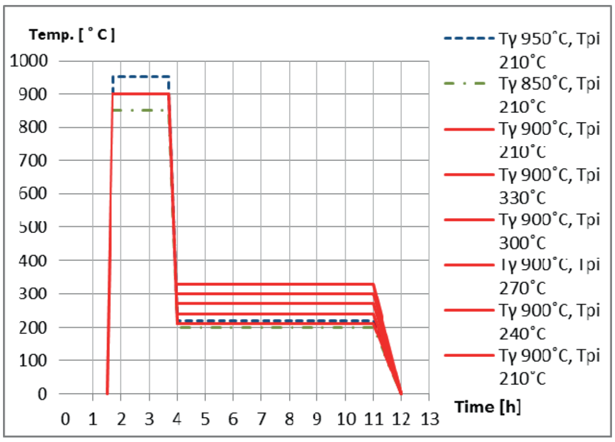

Fig. 4. General idea of the ductile iron austempering process

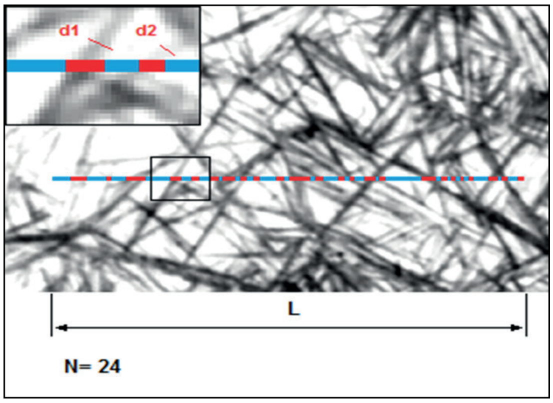

Fig. 5. A method for calculating the interlamellar spacing in ADI

The interlamellar spacing was expressed as a ratio of the total number of counts on all sections to the length of the line marked in the photo. As an average width of the plate was adopted the mean of minimum 35 measurements taken in the direction perpendicular to the axis of the plate in the vicinity of its intersection with the reference segment. The average interlamellar spacing was calculated from these results.

3. Test results

The effect of the ausferritizing treatment parameters on cast iron structure is shown as an example in Figures 6 ÷ 9. To describe the hardness - holding time relationship, the nature of changes occurring in cast iron during heat treatment was examined (Fig. 10). Hardness mainly depends on the number of plates falling to a unit segment; other factors include the uniformity of the distribution of plates in a volume of casting and changes in microstructure depending on the time and temperature of holding the samples in a quenching bath (Fig. 11).

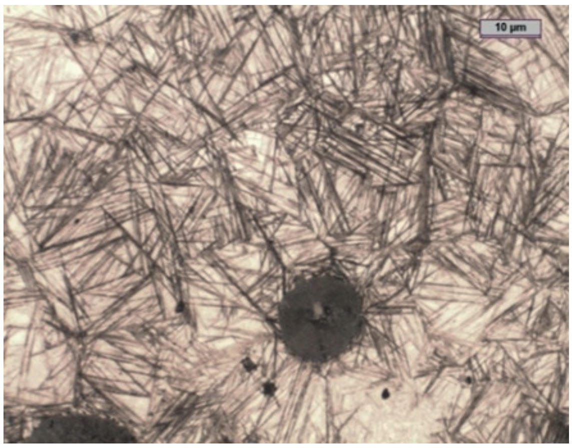

Fig. 6. Microstructure for Tγ - 900°C, Tpi - 210°C, t - 2h, 1000x

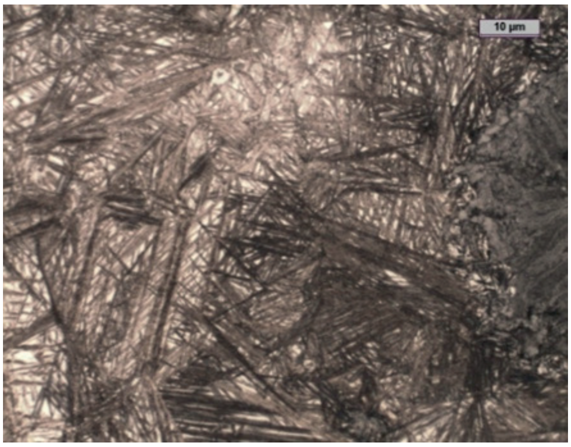

Fig. 7. Microstructure for Tγ - 900°C, Tpi - 210°C, t - 8h, 1000x

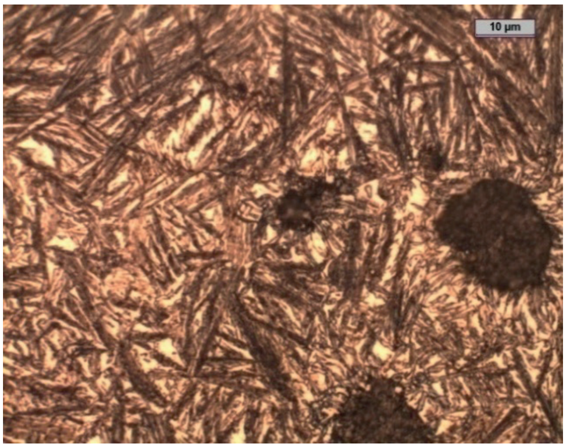

Fig. 8. Microstructure for Tγ - 900°C, Tpi - 330°C, t - 2h, 1000x

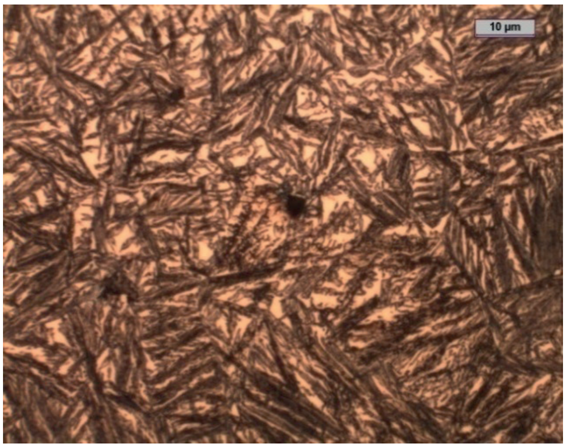

Fig. 9. Microstructure for Tγ - 900°C, Tpi -330°C, t - 8h, 1000x

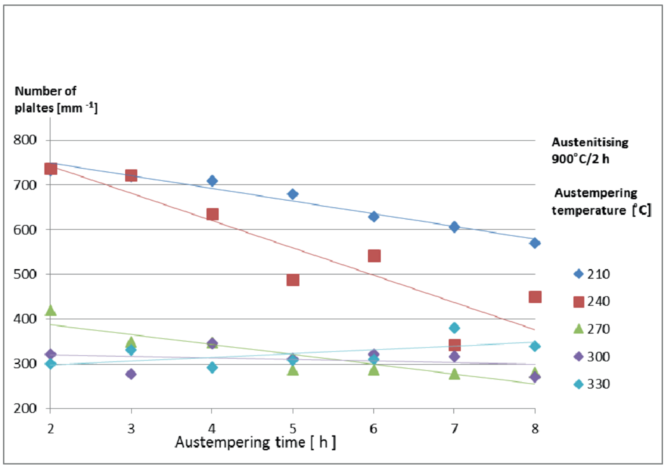

Fig. 10. Parameters of ausferritizing treatment vs number of ausferrite plates

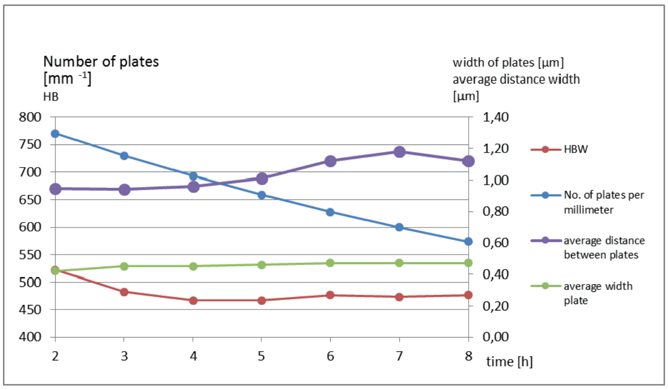

Fig. 11. Time of ausferritizing treatment vs hardness and morphology of the precipitated plates of ausferrite

These parameters vary during the diffusion of constituents, which occurs in the process of isothermal holding. In the relevant description, a multiplicative model was used (1).

The adopted model has the following form:

$$HB(\tau) = \Delta HB * EXP(-(\tau-2)/t) + HBmin \qquad (1)$$

where:

τ – sample holding time [h],

t - time constant of the process [h],

HB - hardness.

The time constant of the process T should be understood as the time which it takes for the phases present in the alloy to achieve the state of dynamic equilibrium in respect of each other as a result of the different rates of diffusion stabilized at an equal level. Since the diffusion rate is proportional to the process temperature, and coefficient T is inversely proportional to this rate, the equations involve different coefficients depending on the temperature of isothermal transformation (Fig. 12) and austenitizing treatment. The maximum and minimum value of HB also undergoes changes within the examined range.

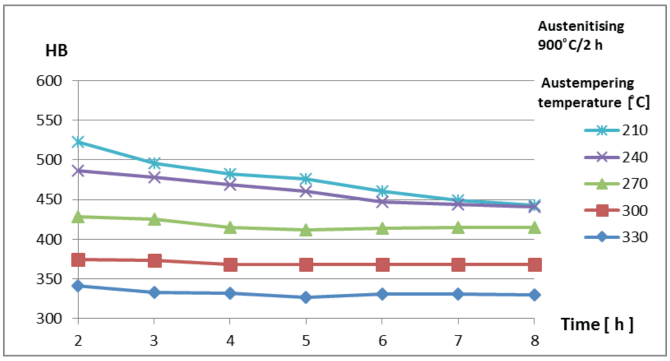

Fig. 12. Time and temperature of ausferritizing treatment vs cast iron hardness

It was decided to adopt for the maximum and minimum values of hardness HB and time constant the data ensuring the best fit between the proposed relationship and the experimental measurements. After solving the equation with respect to time, a relationship has been derived which allows controlling the heat treatment time to obtain the required hardness HBtask (1). Therefore, the required value of hardness should be selected from the min-max range of the HB values, which can provide for the, so called, "process window".

$$\tau = - \ln [(HBtask - HBmin) / \Delta HB] * t - 2\ h \qquad (2)$$

The relationship should also give the possibility of hardness determination for a time shorter than 2 hours and longer than 8 hours, which might, however, require further confirmation by way of relevant experiments.

Considering the high level of uncertainty of the HB hardness measurements in the range of high values and the specific morphology of samples, it was decided to measure the hardness HV 30 yielding more accurate values, first, and convert next the obtained values to HB scale using data given in respective tables.

To analyze the obtained relationships, a statistical verification was carried out using the STATISTICA software. Then, the standard error of estimation and the correlation coefficients R and R2 were calculated. The low value of the estimation error (<7.5%) indicates a good fit between the derived relationship and the measurement data obtained in experiments.

Additionally, the goodness of fit indicating the average percent deviation of the model value from the measured value was determined. The results show that, on the average, the obtained value differs from the measured value by no more than one percent of the preset value of HBtask. Therefore, to obtain the minimum acceptable hardness, it is recommended to introduce the correction P (Table 1) specific to a given model (3).

$$\tau = - \ln [((P * HBtask) - HBmin) / \Delta HB] * t - 2\ h \qquad (3)$$

The range of occurrence of the minimum hardness of cast iron corresponds at the same time to its maximum toughness, and it is the toughness of the high-strength cast iron that determines ADI competitiveness as an engineering material.

4. Summary

The conducted studies and the statistical analysis of results allow drawing the following conclusions:

1. Changing the ADI heat treatment parameters enables obtaining the ausferritic structure with a wide dispersion (distance) of the ferrite and austenite plates.
2. To estimate the degree of ausferrite dispersion, counting of the plates identified in cast iron microstructure has been applied with success.
3. For the preset temperature of ausferritizing treatment, the derived mathematical models describe changes in the cast iron hardness and relate them to the time of the austempering treatment of ductile iron castings.
4. Based on the obtained relationships, for a given level of hardness, the time of the ausferritizing treatment providing the searched "process window" was determined to predict later the ADI microstructure and, consequently, hardness of castings operating under the conditions of severe abrasion wear.

Thus, the developed method has proved to be a valuable tool in predicting the ADI microstructure and properties, including the ADI grades with high plastic properties obtained for the austempering time of less than 2 hours.

TABLE 1

The estimated goodness of fit of the ADI hardness values

Parameters	TY 900 ˚C Tpi 210 ˚C	TY 900 ˚C Tpi 240 ˚C	TY 900 ˚C Tpi 270 ˚C	TY 900 ˚C Tpi300 ˚C	TY 900 ˚C Tpi 330 ˚C	TY 850 ˚C Tpi 210 ˚C	TY 950 ˚C Tpi 210 ˚C
HB_{max}	520	486	428	375	340	505	505
HB_{min}	280	350	410	368	330	335	220
T	15	15	2	1	1	15	19
Standard deviation	4,9544	2,5461	2,8349	0,9717	1,4394	4,2159	5,7292
R	0,987	0,99	0,908	0,938	0,933	0,982	0,982
R^2	0,975	0,979	0,826	0,88	0,87	0,964	0,965
Statistical fitting	HBmax	HBmax	HBmax	0,0%	0,0%	0,0%	0,0%
P	1,008	1,004	1,006	1,002	1,003	1,007	1,01

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