ISSN 1392–1320 *MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 13, No. 2. 2007*

The Optimization of the Isothermal Transformation Dwell with Emphasis on the Matrix Structural Mixture of Austempered Ductile Iron

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Received 01 December 2006; accepted 21 March 2007

The studied austempered ductile iron (ADI) was obtained by the heat treatment of an unalloyed nodular cast iron consisting of austenitization (900 °C / 1h), an isothermal transformation at 380 °C and water cooling at the end. To study matrix composition changes during the isothermal transformation, the dwell at the transformation temperature was chosen in very wide range of 2 min to 540 min. The isothermal transformation starts by a creation of bainitic ferrite needles resulting in an enrichment of the non-transformed austenite by carbon which increases its stability. For short dwells (2, 5 and 10 min) the stabilization of the austenite is not sufficient yet, therefore the partial martensitic transformation during cooling occurs. With increasing dwell the amount of the stabilized austenite increases and reaches its maximum for the transformation dwell of 60 min. With further dwell lengthening the amount of the stabilized austenite decreases again as a consequence of its continuing transformation into the bainitic ferrite. The maximum fraction of the bainitic ferrite is reached for the longest dwells, i.e. for 270 min and 540 min. For the same dwells iron carbides on the austenite/bainitic ferrite interface have been found.

Keywords: ADI, stabilized austenite, transformation dwell, isothermal transformation stage.

INTRODUCTION

The high-strength variant of the nodular cast iron, ADI (Austempered Ductile Iron), belongs to prospective structural materials and it has been already applied in all important branches of the machine industry [1 – 4]. It is produced from a nodular cast iron by the isothermal heat treatment which includes austenitization, isothermal transformation at temperatures in the bainitic belt, and water cooling. The resulting microstructure of the ADI matrix consists especially of the bainitic ferrite and the stabilized austenite. However, in dependence on the transformation dwell some amount of the martensite or carbides, which cause a degradation of mechanical properties, can appear as well [5, 6]. During the isothermal transformation the material goes through three stages [5]. Within the first stage the bainitic ferrite creation causes enriching the non-transformed austenite by carbon. This leads to the gradual stabilization of austenite, so that it can survive in the structure even after cooling. However, in this stage its partial martensitic transformation during cooling can occur, because the stability of the austenite is not sufficient yet. In the second stage the concentration of the carbon in the non-transformed austenite reaches its maximum, therefore the martensitic transformation during cooling is not possible. This stage is characterized by the maximum amount of the stabilized austenite in the matrix. In the third stage the amount of the stabilized austenite starts to decrease as a consequence of its further transformation into the bainitic ferrite. In this stage carbides on the austenite/bainitic ferrite interface can start to precipitate [5]. In practice most often the conditions that provide the highest values of the plasticity and the toughness are applied. These conditions coincide with the second stage of the transformation which is called heat treatment processing window [6].

The aim of this work was to determine the optimum range of transformation dwells with emphasis on the matrix structural mixture of unalloyed ADI obtained by the isothermal transformation at temperature of 380 °C.

EXPERIMENTAL

An unalloyed nodular cast iron with the bull's-eye matrix structure was studied. Its chemical composition is given in the Table 1.

Table 1. The chemical composition [wt. %].

C	Si	Mn	P	S	Mg
3.56	2.24	0.25	0.02	0.004	0.054

The choosen material was heat treated according to the scheme in Fig. 1.

Regarding the initial matrix structure, the austenitization took 1 hour and was performed in the NaCl salt bath at the temperature of 900 °C. The isothermal transformation was performed in the AS 140 salt bath at temperature of 380 °C. Considering the aim of this study, dwells at the isothermal transformation temperature τ_t = 2, 5, 10, 25, 60, 120, 270 and 540 min were chosen. All transformation dwells were finished by water cooling.

To specify the influence of the heat treatment on the matrix structural mixture, metallographic cuts and two-stage collodion-carbon replicas were prepared from testing specimens. The microstructure was then observed and evaluated using the Olympus GX 71 light microscope (LM) with the Olympus DP 11 camera and using the PHILIPS CM-12 transmission electron microscope (TEM) with the Mega View II camera. Amounts of stabilized

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austenite and martensite, A_S and M, were determined by the imaging quantitative analysis that uses the LUCIA software of the Laboratory Imaging Comp. and the ACC software of SOFO Comp.

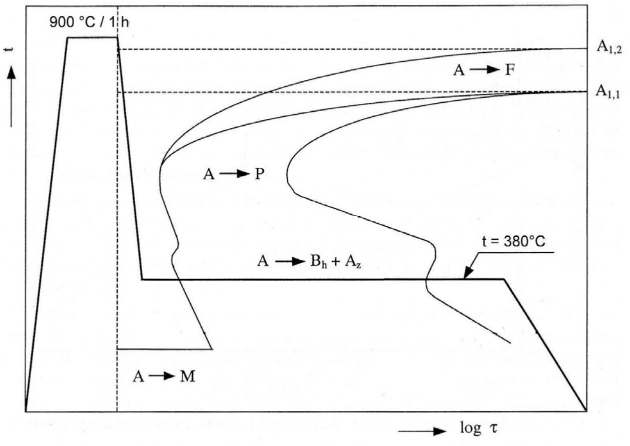

Fig. 1. The scheme of the isothermal heat treatment

Because of the fact that increasing concentration of the carbon causes the increase of austenite cell parameter size a, the changes of the carbon concentration $C\gamma$ in the solid solution γ during the isothermal transformation were determined on the base of the measurements of austenite cell parameter size a. Its measurement was performed by X-ray analysis by the means of the D 500 diffraction arrangement. The concentration of carbon dissolved in austenite was approximately determined by the equation (1), which was proposed by Stránský (Brno University of Technology, Faculty of Mechanical Engineering, Department of Materials Science and Engineering):

$$a = 0.00514 C\gamma + 0.3556 \ , \qquad (1)$$

which is numerically valid for a in nm and $C\gamma$ in wt. %.

RESULTS AND DISCUSSION

The measured size of the austenite cell parameter, the approximate concentration of the carbon in the solid solution γ and the amounts of stabilized austenite as well as martensite are given for studied dwells in Table 2.

Two following figures show the dependence of the austenite cell parameter size (Fig. 2) and the stabilized austenite amount (Fig. 3) on the transformation dwell. In Fig. 3 there are also approximate carbon concentrations in the solid solution γ for studied transformation dwells.

Results given in Table 2 and in Figs 2 and 3 show that in the beginning of the isothermal transformation the concentration of the carbon in the austenite was 0.7 wt. % approximately. It corresponds to the cell parameter size 3.59 Å. The transformation continues by the bainitic ferrite needles nucleation and growth (Fig. 4). Lower solubility of carbon in bainitic ferrite causes the diffusion of carbon atoms from the areas of bainitic ferrite creation into austenite areas and, therefore, carbon concentration in the solid solution γ increases, namely from 0.7 wt. % to 1.5 wt. % (see Table 2 and Fig. 2). With increasing carbon content the cell parameter increases, namely in the transformation dwell range of 2 min to 25 min from 3.59 Å up to 3.63 Å (see Table 2). Gradual increase in the carbon concentration corresponds to the stabilized austenite fraction increase (see Fig. 3). As the stabilization of austenite was not sufficient in this dwell range yet, the partial martensite transformation of the austenite occurs. The extent of martensitic transformation depends on the dwell at the transformation temperature (see Table 2 and Fig. 3). When the transformation dwell of 25 min is reached, the solid solution γ already contains nearly the saturated content of carbon (approximately 1.5 wt. %) and also the saturated value of the cell parameter size (namely 3.63 Å) is reached. At this transformation dwell the martensitic transformation did not already occur during cooling (see Table 2). When the dwell of 25 min is exceeded, the carbon concentration in the solid solution γ does not change markedly (see Fig. 2). In the transformation dwell range from 25 min to 60 min the ADI matrix contains very high amount of the stabilized austenite, its maximum equal to 34.8 vol. % was reached for the transformation dwell of 60 min (see Table 2 and Fig. 3). The microstructure with maximum austenite content is shown in Fig. 5.

Table 2. Austenite cell parameter a, carbon concentration $C\gamma$ in solid solution γ, stabilized austenite A_S and the martensite M amounts in the ADI matrix for studied transformation dwells

τ_t [min]	a [Å]	$C\gamma$ [wt.%]	A_S [vol.%]	M [vol.%]
2	3.594	0.7	18.3	66.8
5	3.615	1.2	28.5	34.4
10	3.628	1.4	31.6	4.8
25	3.633	1.5	33.8	0
60	3.634	1.5	34.8	0
120	3.634	1.5	31.9	0
270	3.633	1.5	25.4	0
540	3.631	1.5	17.7	0

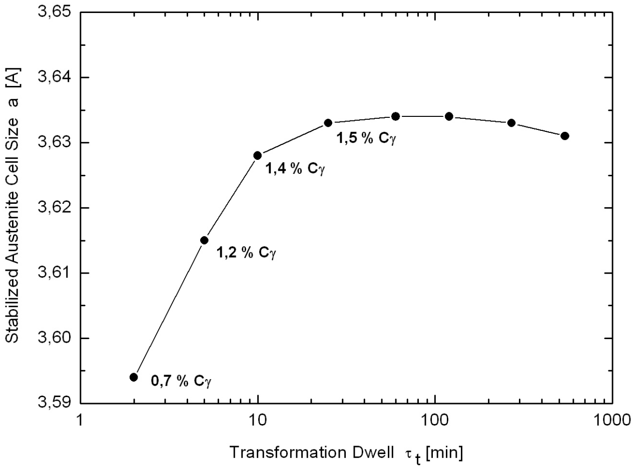

Fig. 2. The dependence of the austenite cell parameter size on the transformation dwell

In the following transformation dwell range of 60 min to 540 min the decrease of the stabilized austenite fraction occurs, as a consequence of continuing transformation into the bainitic ferrite (Fig. 3). When the transformation dwell of 120 min is exceeded, the stabilized austenite cell parameter starts to slightly decrease as well (Table 2). This decline could be an indication of iron carbides precipitation on the bainitic ferrite/austenite interface. Iron carbides were found by the means of TEM for transformation dwells of 270 min and 540 min (Figs 6, 7). It is possible to say, that the reason of the precipitation of carbides is local supersaturation of the γ solid solution with carbon, which is caused by continuing diffusion of carbon atoms into the non-transformed austenite during further transformation of austenite with the lowest carbon content into bainitic ferrite.

The results of the studied ADI matrix analysis have been confronted with the results of previous works [3, 4, 6]. It has confirmed that the range of isothermal transformation dwell is possible to divide into three different stages.

In the first stage the bainitic ferrite needles start to nucleate and grow (Fig. 4). It results in enriching non-transformed austenite by carbon and its stabilization, so that the amount of stabilized austenite in the ADI matrix increases. However, the stability of austenite is insufficient in this stage so that its partial martensitic transformation during sequent cooling happens.

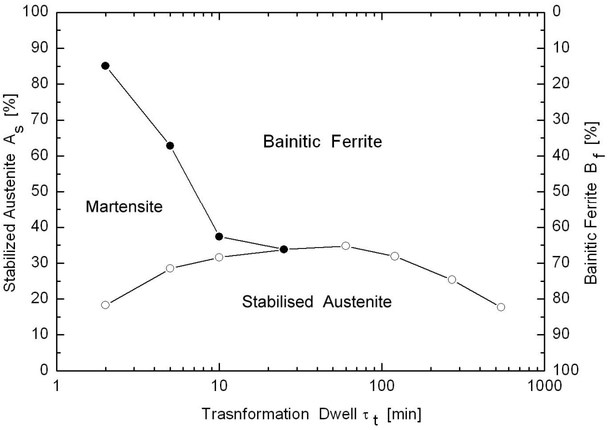

Fig. 3. The fraction of structure components in the resulting ADI matrix microstructure in dependence on the transformation dwell

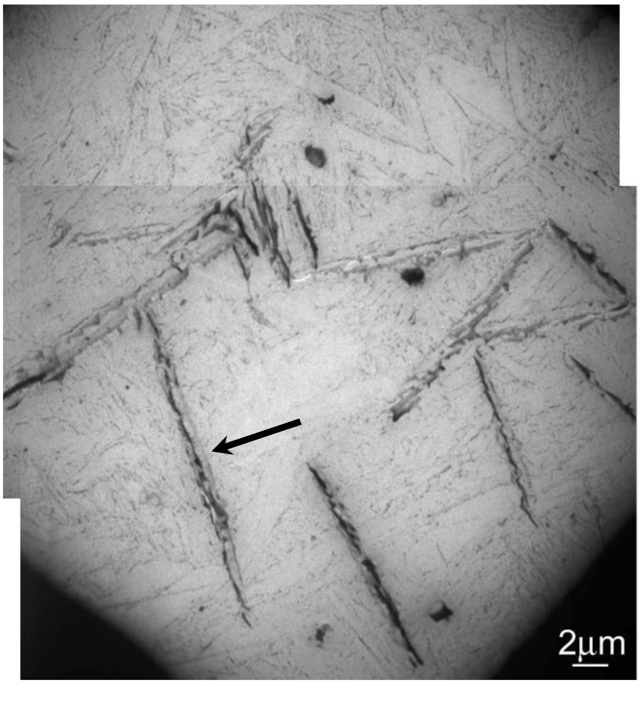

Fig. 4. The bainitic ferrite needles (see the arrow), τ_t = 2 min, the two-stage collodion-carbon replica, TEM

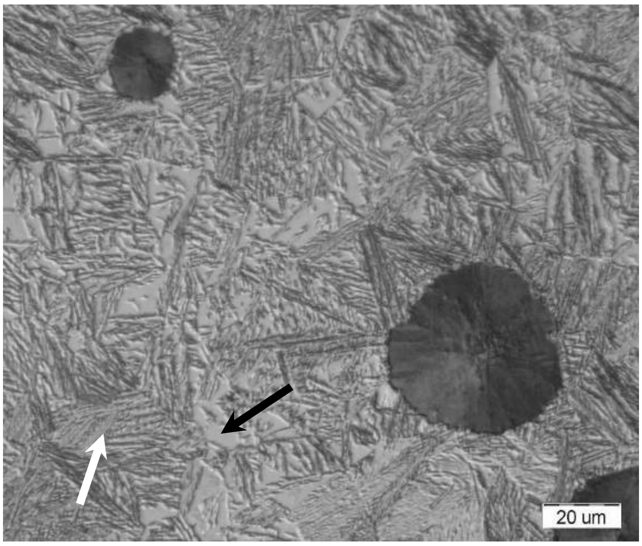

Fig. 5. The ADI matrix microstructure, τ_t = 60 min, 34.8 vol.% of the stabilized austenite (bainitic ferrite – the white arrow, stabilized austenite – the black arrow)

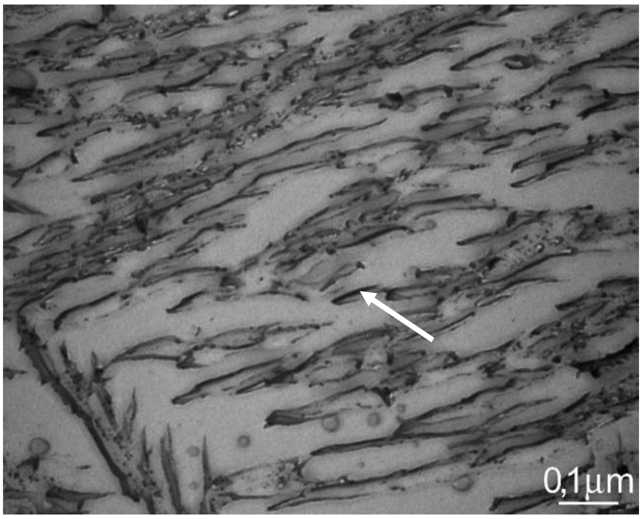

Fig. 6. The carbide situated on the bainitic ferrite/austenite interface (see the arrow), τ_t = 270 min, the two-stage collodion-carbon replica, TEM

When the transformation dwell of 25 minutes was reached, the martensite did not already occur in the final matrix structure, which is now created only by bainitic ferrite and stabilized austenite. For that reason this transformation dwell could be specified as the dividing limit between the first and the second transformation stages (see Fig. 8).

When the transformation dwell of 25 min is passed over, the amount of stabilized austenite increases until the transformation dwell of 60 min is reached. For this dwell the maximum content of stabilized austenite was obtained. With following elongation of transformation dwell the amount of stabilized austenite starts to decrease and the carbides on the austenite/bainitic ferrite interface start to appear (Figs. 6, 7). The maximum content of stabilized austenite as well as the start of carbide creation are the arguments that the transformation dwell of 60 min as the limit between the second and the third transformation stages can be considered (Fig. 8).

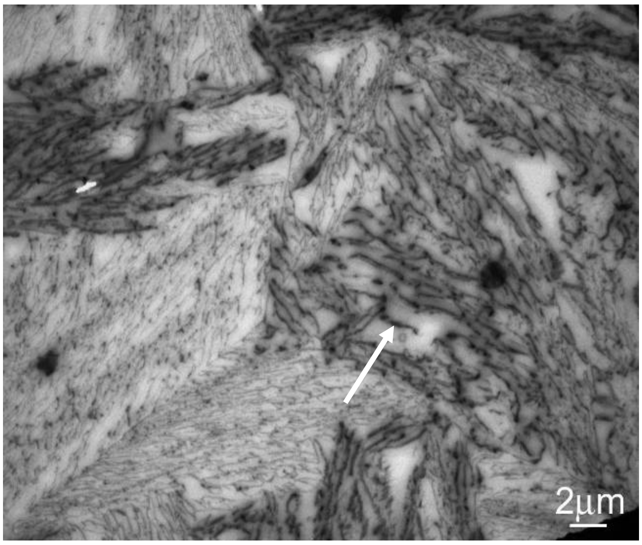

Fig. 7. The carbide situated on the bainitic ferrite/austenite interface (see the arrow), $\tau_t = 540$ min, the two-stage collodion-carbon replica, TEM

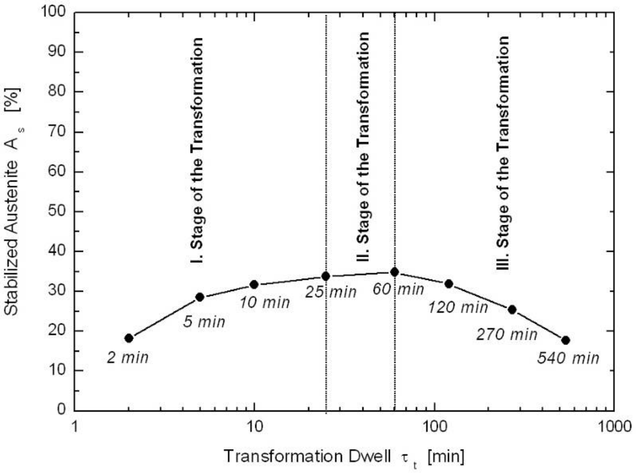

Fig. 8. The approximate division of isothermal transformation dwells into stages for studied ADI

CONCLUSIONS

Regarding analysis results it is possible to say, that the heat processing window of the ADI obtained by the isothermal transformation of the unalloyed nodular cast iron at the temperature of 380 °C is situated in the isothermal transformation dwells range from 25 min to 60 min. In this range the highest values of the plasticity and the toughness should be reached. But the content of the stabilized austenite in the matrix increases in this dwell range and its maximum (34.8 vol. %) is reached for the transformation dwell of 60 min (Table 2). Considering the results of previous works, where the relations between microstructure and mechanical properties have been already studied [5 – 9], it is possible to say that, requiring the highest values of the plasticity and the toughness of the studied ADI, the transformation dwell of 60 min could be specified as optimum.

Acknowledgments

Financial supports of the Grant Agency of the Czech Republic within the project 106/03/1265 and the Ministry of Defence of the Czech Republic within the research project MO0FVT0000404 are gratefully acknowledged.

REFERENCES

1. **Keough, J. R.** An ADI Market Primer *Foundry Management and Technology* 123 (11) 1995: pp. 27 – 31.
2. **Hataway, R. M.** Converting Steel Weldments to Ductile Iron Castings *Modern Casting* 85 (3) 1995: pp. 26 – 30.
3. **Tanaka, Y., Hidehiko, K.** Development and Application of Austempered Spheroidal Graphite Cast Iron *Material Transcations JIM* 33 (6) 1992: pp. 543 – 557.
4. **Navara, E.**, **Zimba, J.** Ausferritic Ferrous Alloys – a Challenge to Industry and Research *Acta Metallurgica Slovaca* 10 (1) 2004: pp. 244 – 252.
5. **Dorazil, E.** High-Strength Bainitic Nodular Cast Iron. Academia, Praha (Czech Republic), 1985 (in Czech).
6. **Věchet, S., Kohout, J., Bokůvka, O.** Fatigue Properties of Nodular Cast Iron. Žilinská univerzita, Žilina (Slovakia), 2002 (ISBN 80-7100-973-3) (in Czech).
7. **Věchet, S., Kohout, J., Hanzlíková, K.** Influence of Isothermal Dwell on Tensile and Fatigue Properties of Austempered Ductile Iron *Material Science Forum* 482 2005: pp. 371 – 374.
8. **Ghang, L. C.** An Analysis of retained Austenite in Austempered Ductile Iron *MMTrans* A 34A 2003: p. 211.
9. **Garcia-Mateo, C., Caballero, F. G., Bhadeshia, H.K.D.H.** Development of Hard Bainite *ISIJ International* 43 2003: p. 1283.