# Influence of microstructure composition on mechanical properties of austempered ductile iron

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**Abstract**

Two austempered ductile iron (ADI) heats transformed at a temperature of 380 °C in periods ranging from 2 minutes to 9 hours have been studied in detail, with emphasis on the relation between the microstructure matrix composition and mechanical properties. The matrix microstructure and mechanical properties of ADI are influenced especially by the dwell time (sometimes also referred to as *holding time*) at isothermal transformation temperature. ADI matrix called ausferrite consists primarily of acicular ferrite and stabilized austenite. However, for short dwells some amount of martensite can occur in the matrix, which degrades the mechanical properties of ADI. The ADI with optimal combination of mechanical properties was obtained for a transformation dwell of 60 minutes, when the maximum amount of stabilized austenite in the matrix microstructure was obtained.

Key words: iron, phase transformation, tensile test, fatigue test, transmission electron microscopy

## 1. Introduction

Austempered ductile iron (ADI) has excellent mechanical and technological properties. Thus it has recently been applied also to castings for heavily dynamically loaded machine details, e.g. gears and traversing wheels, crankshafts, swivel pins, rail brakes, and pressure pipes in oil industry [1, 2]. A considerable part of ADI production is applied in military industry, e.g. about 3 % of the U. S. production in 1995 [2]. ADI castings are preferably applied as a substitution of components made of steel, not so often as a substitution of castings made of nodular cast iron with lower levels of strength properties. The highest effect is reached in the case when new components are designed specially for ADI application [3].

ADI is usually made of nodular cast iron using isothermal heat treatment which includes austenitization, isothermal transformation at temperatures within the ausferritic region, and cooling, usually in water. The microstructure and mechanical properties of ADI can be substantially influenced by the conditions of heat treatment. While austenitization conditions play only a marginal role, the parameters of isothermal transformation influence the resulting structure and consequently its mechanical properties very substantially [4–8]. The present paper is devoted to the study of how the dwell of isothermal transformation in the range of 2 minutes to 9 hours influences the microstructure and subsequently the static and fatigue properties of unalloyed ADI transformed at a temperature of 380 °C.

## 2. Experimental material and technique

Two heats of unalloyed nodular cast iron with the bull's-eye matrix structure were chosen for the experiment. Their chemical composition is given in Table 1. Cylindrical test bars for the static tensile test according to the ČSN EN 10002 Czech standard and cylindrical test bars for fatigue test according to the recommendation of the Amsler Company were made of the materials.

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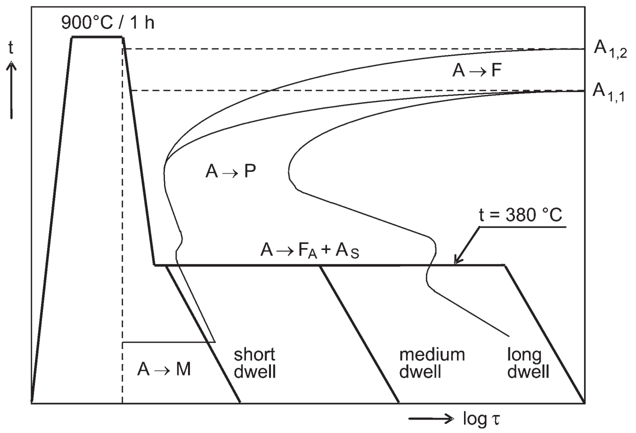


Fig. 1. Heat treatment process of the ADI.

T a b l e 1. Chemical composition of materials under study (in wt.%)

| Heat | C | Si | Mn | P | S | Mg |
|---|---|---|---|---|---|---|
| H380a | 3.49 | 2.46 | 0.25 | 0.02 | 0.007 | 0.042 |
| H380b | 3.56 | 2.24 | 0.25 | 0.02 | 0.004 | 0.054 |

Test specimens were heat treated according to the scheme in Fig. 1. Regarding the initial matrix structure, the austenitization took 1 hour and was performed in a NaCl salt bath at a temperature of 900 ℃. The isothermal transformation was performed in an AS 140 salt bath at a temperature of 380 ℃. With a view to the aim of this study, dwells at the isothermal transformation temperature $\tau_t = 2$, 5, 10, 25, 60, 120, 270 and 540 min were chosen. All transformation dwells were finished by water cooling.

The tensile test was performed at the usual room temperature (i.e. 20 to 25 ℃) on a TIRATEST 2300 testing device with a force range of 100 kN. The crosshead speed was 2 mm min$^{-1}$ corresponding to a loading strain rate of $10^{-3}$ s$^{-1}$. Fatigue tests were performed at the room temperature as well, in a symmetrical loading cycle, using an AMSLER 10FHP 1478 high-frequency resonance pulsator at a test frequency of about 200 Hz. Each of the *S-N* curves was determined by testing 12 to 15 test bars. For data regression by the least square method, the three-parameter non-linear function (1) proposed by Stromeyer and recommended by Weibull [9] was used:

$$\sigma(N) = a\,N^b + \sigma_\infty, \tag{1}$$

where $\sigma$ is the stress amplitude, $a$, $b$ and $\sigma_\infty$ are the regression curve parameters, and $N$ is the number of cycles to fracture.

To evaluate the influence of the microstructure composition on mechanical properties, metallographic cuts on the front faces of screw heads of the cylindrical test bars after the static tensile test and two-stage collodion-carbon replicas were prepared. The microstructure was then observed and evaluated using an Olympus GX 71 light microscope with Olympus DP 11 camera and a Philips CM-12 transmission electron microscope (TEM). Amounts of stabilized austenite $A_S$ and martensite $M$ were determined by the imaging quantitative analysis, which uses the LUCIA software of the Laboratory Imaging Company and the ACC software of the SOFO Company.

## 3. Results

The influence of the transformation dwell on matrix microstructure composition is shown in the Table 2 and Fig. 2. From the results it is evident, that in dependence on the transformation dwell the matrix composition of studied materials is substantially changing. The structural analysis shows that the result-

T a b l e 2. Matrix composition (amount of stabilized austenite $A_S$, acicular ferrite $F_A$ and martensite $M$) of ADIs under study, in dependence on transformation dwell

| Transformation dwell (min) | ADI H380a | | | ADI H380b | | |
|---|---|---|---|---|---|---|
| | $A_S$ (%) | $F_A$ (%) | $M$ (%) | $A_S$ (%) | $F_A$ (%) | $M$ (%) |
| 2 | 9.5 | 28.7 | 61.2 | 18.3 | 14.9 | 66.8 |
| 5 | 24.0 | 38.9 | 36.6 | 28.5 | 37.2 | 34.3 |
| 10 | 27.4 | 67.5 | 5.0 | 31.6 | 62.6 | 4.8 |
| 25 | 31.7 | 68.0 | 0 | 33.8 | 68.5 | 0 |
| 60 | 36.0 | 63.6 | 0 | 34.8 | 70.7 | 0 |
| 120 | 22.6 | 76.8 | 0 | 31.9 | 74.0 | 0 |
| 270 | 4.3 | 96.3 | 0 | 25.4 | 78.8 | 0 |
| 540 | 0 | 100 | 0 | 17.7 | 85.1 | 0 |

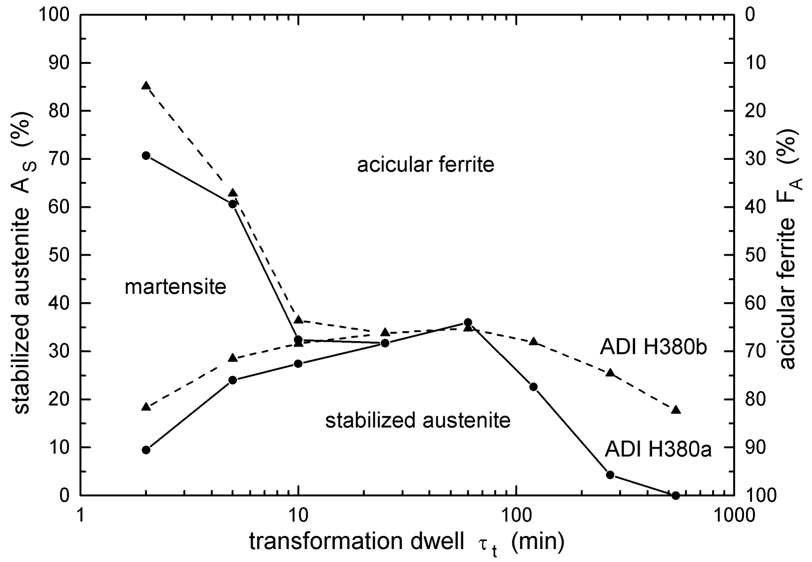


Fig. 2. Influence of the dwell at transformation temperature on the matrix microstructure composition of ADIs under study.

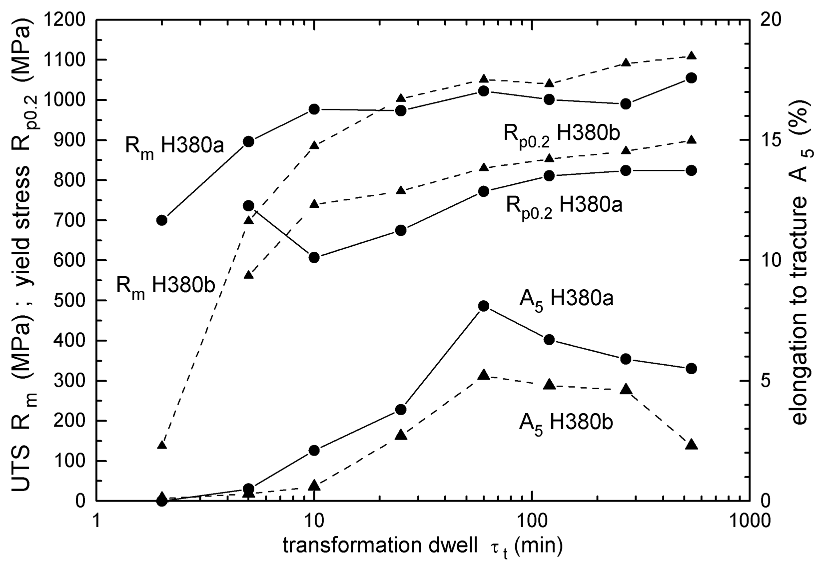


Fig. 3. Influence of the transformation dwell on the static mechanical properties of ADIs under study.

ing microstructure of both materials consists especially of the acicular ferrite and stabilized austenite. However, for short transformation dwells (2, 5, 10 min) some amount of martensite can occur as well, for the shortest dwell (2 min) it is even the dominant structural component. As the transformation dwell is prolonged the amount of martensite decreases to zero, whereas the amount of stabilized austenite and acicular ferrite increases. In the case of both materials the maximum amount of stabilized austenite in the matrix microstructure was obtained for the transformation dwell of 60 minutes. When the transformation dwell of 60 minutes is passed, the amount of stabilized austenite starts to decrease again, whereas the amount of acicular ferrite is still increasing.

The mechanical properties are influenced by the dwell at isothermal temperature as well. As Table 3 and Figs. 3 and 4 show, the values of strength characteristics are increasing gradually in the whole transformation dwell range and they reach for their maximum at the longest dwells. Whereas the values of elongation to the fracture are increasing initially, they reach for their maximum at the transformation dwell of 60 min and than start to decrease again. The fatigue limit is increasing initially as well, reaches its optimal values in the range of 60 to 240 minutes and then starts to decrease rapidly.

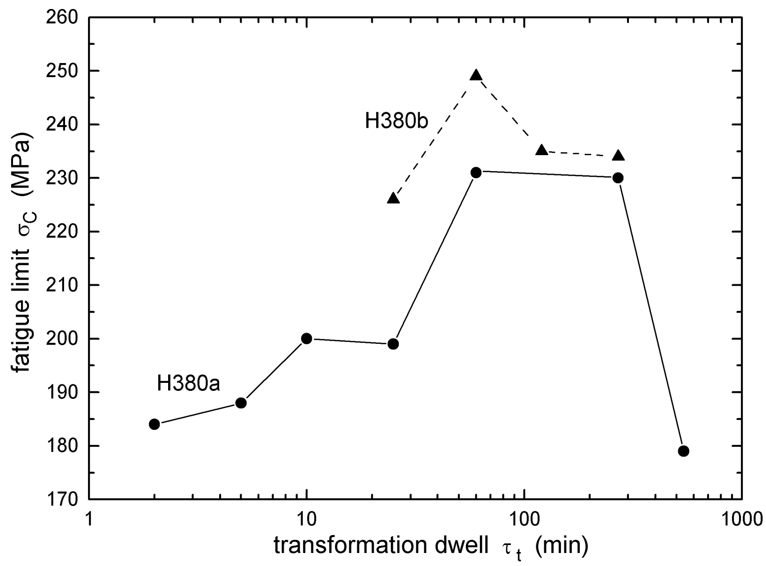


Fig. 4. Influence of the transformation dwell on the fatigue properties of ADIs under study.

Table 3. Values of mechanical properties (UTS $R_{\mathrm{m}}$, yield strength $R_{\mathrm{p0.2}}$, elongation to fracture $A_5$, and fatigue limit $\sigma_{\mathrm{C}}$) of ADIs under study, in dependence on transformation dwell

| Transformation dwell (min) | ADI H380a | | | | ADI H380b | | | |
|---|---|---|---|---|---|---|---|---|
| | $R_{\mathrm{m}}$ (MPa) | $R_{\mathrm{p0.2}}$ (MPa) | $A_5$ (%) | $\sigma_{\mathrm{C}}$ (MPa) | $R_{\mathrm{m}}$ (MPa) | $R_{\mathrm{p0.2}}$ (MPa) | $A_5$ (%) | $\sigma_{\mathrm{C}}$ (MPa) |
| 2 | 700 | – | 0.0 | 184 | 138 | – | 0.1 | – |
| 5 | 896 | 736 | 0.5 | 188 | 698 | 562 | 0.3 | – |
| 10 | 977 | 607 | 2.1 | 200 | 885 | 739 | 0.6 | – |
| 25 | 973 | 675 | 3.8 | 199 | 1003 | 773 | 2.7 | 226 |
| 60 | 1022 | 772 | 8.1 | 231 | 1051 | 830 | 5.2 | 249 |
| 120 | 1001 | 811 | 6.7 | – | 1040 | 853 | 4.8 | 235 |
| 270 | 990 | 824 | 5.9 | 230 | 1091 | 872 | 4.6 | 234 |
| 540 | 1055 | 824 | 5.5 | 179 | 1109 | 899 | 2.3 | – |

## 4. Discussion of the results

The results of the study show that mechanical properties of ADI are influenced by the matrix microstructure composition and that the microstructure composition depends on the dwell at isothermal transformation temperature. Isothermal transformation starts by the nucleation and growth of acicular ferrite needles. It caused enriching of the surrounding non-transformed austenite by carbon, which enhances its stability in the matrix. However, at the beginning of isothermal transformation (2, 5 and 10 minutes) the stability of non-transformed austenite is insufficient and thus its partial martensitic transformation occurs during cooling. Prolonging the transformation dwell will increase the saturation of the non-transformed austenite by carbon, with two consequences: (i) martensitic transformation of austenite during cooling is now impossible; (ii) the amount of stabilized austenite in the matrix gradually increases. This amount reaches its maximum (60 min) and then starts to decrease again as a consequence of onward transformation into acicular ferrite (see Fig. 2 and Table 2). This onward transformation causes supersaturation of stabilized austenite by carbon, which shows up by carbide precipitating on the austenite-acicular ferrite interface during the longest dwells (270 and 540 min, see Fig. 5).

ADI matrix was previously denoted as a mixture of bainite and austenite, see e.g. [6]. Now the term *ausferrite* is strongly recommended using argumentation that ADI matrix in contrast with bainite in steel contains no carbides. Our experience shows that it is true only for shorter transformation dwells or when the microstructure is studied at standard magnifications. If ADI matrix transformed during longer dwells is observed at high magnifications (best using TEM), the presence of carbides can be unambiguously evidenced

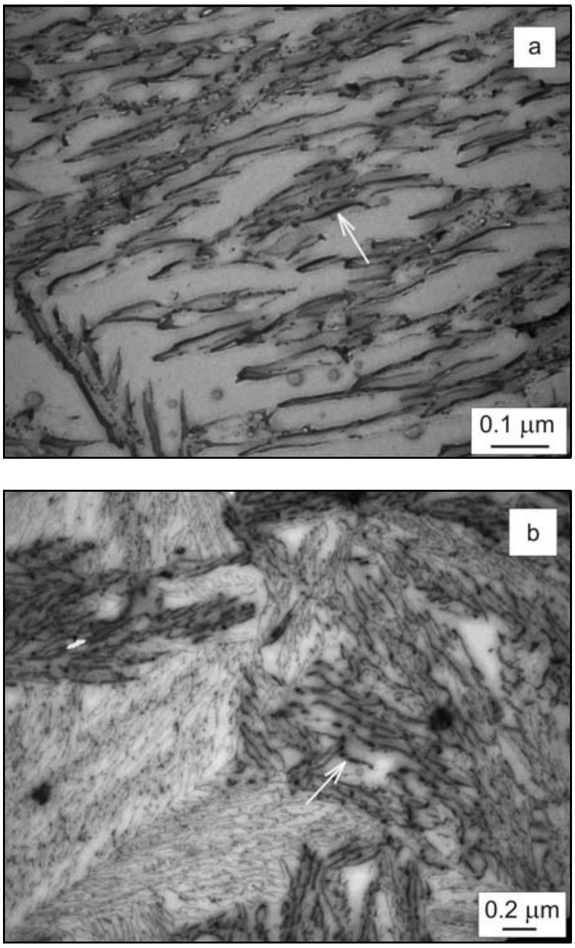


Fig. 5. Carbide precipitation (shown by the arrows) on the austenite-acicular ferrite interface: ADI H380b, the two-stage collodion-carbon replica, TEM. a) transformation dwell of 270 min, b) transformation dwell of 540 min.

at least on the austenite-ferrite interface, see Fig. 5.

It was shown that the matrix consists in particular of acicular ferrite and stabilized austenite. However, in dependence on the transformation dwell the matrix could also contain martensite or carbides. Acicular ferrite is the strength carrier and thus the strength of the material under study gradually increases over the whole transformation dwell range and so does the amount of acicular ferrite. On the other hand, stabilized austenite is the plasticity carrier and thus the values of elongation to fracture reach the maximum during the transformation dwell, when the amount of stabilized austenite in the matrix is the highest. The dependence of fatigue properties has a trend similar to the elongation to fracture. Their optimal values coincide with the transformation dwell range, when stabilized austenite in the matrix reaches the highest amount. Other phases (martensite, carbides) degrade the mechanical properties of ADI. Martensite is very hard and causes brittle failure and this is why the plasticity of ADI matrix is nearly zero for the shortest dwells. Carbides could contribute to increasing strength and decreasing plasticity for the longest transformation dwells.

## 5. Conclusion

The study shows that in dependence on the transformation dwell many varieties of ADI matrix microstructure composition and, consequently, many varieties of the combination of its mechanical properties could be obtained. Regarding the optimal combination of mechanical properties it was shown that the ADI matrix should contain only acicular ferrite and stabilized austenite, and the amount of stabilized austenite should preferably be the highest.

In the case of the ADI under study the optimum values of static mechanical properties were obtained in the dwell range of 60 to 120 minutes and the optimum values of fatigue properties were obtained in the transformation dwell range of 60 to 240 minutes. Thus in the case of ADI obtained by isothermal transformation at a temperature of 380 °C, depending on the application, the transformation dwell in the range of 60 to 240 minutes should be used. However, to obtain an optimum combination of static as well as fatigue properties, the transformation dwell of 60 minutes should be used.

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