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# Fatigue Properties of Austempered Ductile Iron in Dependence on Transformation Temperature

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Austempered ductile iron (ADI) belongs to structural materials with continuously increasing level of production. Using various conditions of heat treatment, its properties can be changed in rather wide extend according to the purpose of ADI application. The aim of the paper consists in a study of interrelations among the conditions of isothermal transformation, resulting structure of ADI matrix and its static as well as fatigue behaviour. The transformation temperature was changed in the range from 380 °C to 500 °C and fatigue properties of obtained structure were studied in detail determining S-N curves in high-cycle region. Static mechanical properties were compared with fatigue limits obtained by the fit of the whole S-N curves and with the content of stabilized austenite. Optimum fatigue properties were obtained for transformation temperature of 400 °C when ADI matrix obtained the highest content of stabilized austenite.

*Keywords*: austempered ductile iron, isothermal transformation, fatigue behaviour, stabilized austenite.

## 1. INTRODUCTION

Excellent mechanical as well as technological and physical properties together with relatively low price are the reason why isothermally heat treated nodular cast iron called *austempered ductile iron* (ADI) is rated among prospective structural materials. ADI is used in many branches of industry as machine-building, civil engineering, transport, mining and crude oil output. Recently it is applied mainly to castings for dynamically loaded components, e.g. gear and traversing wheels, crankshafts of cars, vans and trucks, swivel pins, rail brakes, pressure pipes and links in oil industry etc. [1, 2]. Considerable part of ADI production is applied also in military industry, e.g. for track links, armour, details of trucks and armoured vehicles or gun components [2].

ADI castings are preferably applied in the following cases [3]: as substitution of details made of steel, instead of castings made of nodular cast iron with lower level of strength properties (usually with pearlitic matrix) and when a new detail is designed specially for ADI application, sometimes substituting a complex of heat treated steel details (e.g. steering swivel pin in motor-cars).

Application of ADI leads to lower product cost (near net shapes of products with reduced weight can be cast), to higher reliability (superior wear resistance decreases the risk of jamming of rotating components) and to smoother run of devices (due to higher vibration damping of ADI in comparison with steels).

Microstructure and mechanical properties of ADI can be substantially influenced by the condition of heat treatment, above all by the temperature of isothermal transformation. In dependence on this temperature, various matrices can be obtained, containing various content of austenite. ADI structure in common with corresponding steel structure was termed as a mixture of bainite with retained austenite. As austenite is a required and relatively stable component in ADI, now it is termed as high-carbon austenite or stable (stabilized) austenite and resulting matrix mixture with acicular ferrite is called ausferrite. Considering usual range of transformation temperatures from 300 °C to 400 °C, higher transformation temperatures lead to very tough ausferrite (due to higher content of austenite), which has also good strength properties. On the contrary, lower transformation temperatures lead to ausferrite with lower austenite content. Its advantages consist in extremely high strength and a satisfactory level of deformability and toughness.

In the paper the influence of temperature of isothermal transformation on structure and mechanical behaviour is studied, above all on fatigue properties, which are the most important in the case of ADI application to dynamically loaded components. The chosen range of studied transformation temperatures from 380 °C to 500 °C represents structures from ADI to pure pearlitic matrix.

## 2. EXPERIMENTAL

Unalloyed nodular cast iron was used for the study with the chemical composition presented in Table 1. Test bars for static tests in tension and for fatigue tests were made of annealed keel blocks. For tensile tests the bars of 6 mm in diameter and of 30 mm in nominal length were used, ended with threaded heads and loaded at a strain rate of $5\cdot10^{-4}\ \mathrm{s}^{-1}$. In fatigue tests the threaded bars of 7 mm in diameter were tested. Heat treatment of both the bar types consisted of austenitization and following isothermal transformation. Austenitization was performed at 900 °C during 60 minutes in GS540 + C3 salt bath, isothermal transformation was carried out in temperature range 380, 400, 420, 450, and 500 °C in AS140 salt bath with common transformation dwell of 20 minutes. Finally the bars were grinded to surface roughness $Ra \approx 0.4$ µm.

Metallographical cuts were prepared according to standard procedures. Structures were observed and documented using Neophot 21 light microscope of Zeiss Company, see Fig. 1 (transformation temperature 380 °C),

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Fig. 2 (400 °C) and Fig. 3 (420 °C). The content of austenite was determined by X-ray quantitative method with results presented also in Table 2.

**Table 1.** Chemical composition of studied ADI (in wt. %).

| C | Si | Mn | P | S | Mg |
|---|---|---|---|---|---|
| 3.55 | 2.38 | 0.25 | 0.02 | 0.008 | 0.044 |

**Table 2.** Mechanical properties and austenite content in ADI in dependence on transformation temperature $t_T$

| $t_T$ [°C] | $R_{p0.2}$ [MPa] | $R_m$ [MPa] | $A_5$ [%] | $Z$ [%] | $\sigma_C$ [MPa] | $AC$ [vol. %] |
|---|---|---|---|---|---|---|
| 380 | 714 | 1018 | 12.1 | 8.8 | 301 | 34.1 |
| 400 | 674 | 984 | 11.7 | 10.6 | 324 | 35.9 |
| 420 | 661 | 974 | 6.2 | 6.0 | 302 | 18.5 |
| 450 | 701 | 942 | 3.8 | 3.9 | 274 | 2.1 |
| 500 | 621 | 873 | 4.8 | 5.0 | 268 | 0.0 |

Basic mechanical properties, i. e. yield stress $R_{p0.2}$, ultimate tensile stress (UTS) $R_m$, elongation to fracture $A_5$, and reduction of area $Z$, were determined using universal testing device of Zwick Company at room temperature. Fatigue tests were performed at symmetrical push-pull cycle using high-frequency pulsator of Amsler Company at room temperature at frequency of about 180 Hz. For determination of one S-N curve 12 to 15 test bars were tested. Fatigue properties were evaluated on the base of the whole S-N curves, which were fitted with non-linear regression equation proposed by Stromeyer [4] and recommended by Weibull [5]

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

where $\sigma$ means upper stress of loading cycle (equal to stress amplitude for symmetrical push-pull loading), $N$ is the number of cycles to fracture, $a$, $b$ and $\sigma_\infty$ are regression parameters. This equation can be rewritten in the form

$$\sigma(N) = (\sigma_C - \sigma_\infty)(10^{-7} N)^b + \sigma_\infty \tag{2}$$

directly containing fatigue limit $\sigma_C$ for $10^7$ cycles. This expression of the regression curve allows direct calculation of the value and the standard deviation of fatigue limit $\sigma_C$.

## 3. RESULTS

The results of static tensile tests in dependence on the temperature of isothermal transformation are presented in Table 2 and schematically drawn in Fig. 4. Both stress characteristics (i. e. yield stress and ultimate tensile strength UTS) decrease with increasing transformation temperature with single exception, i. e. yield stress at 450 °C. On the other hand, strain characteristics (i. e. elongation to fracture and reduction of area) seem to be closer connected with austenite content, with which they are plotted in Fig. 5.

The results of fatigue tests are plotted in Figs 6 to 8 together with fitted S-N curves. For easier comparison the curves are grouped in couples. Comparison of all five S-N curves without experimental points is done in Fig. 9.

Fatigue limits determined by the regression of fatigue results as fitted stress values for $10^7$ cycles to fracture are presented also in Table 2. Since they have qualitatively the

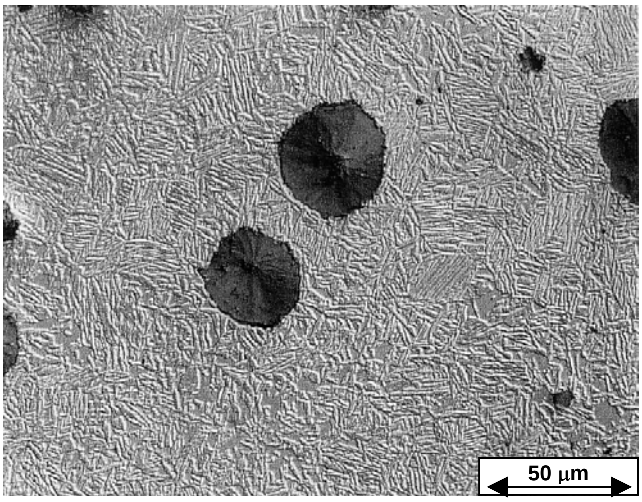

**Fig. 1.** Structure of ADI transformed at 380 °C (Nital etching, the Nomarski method, original magnification 500×)

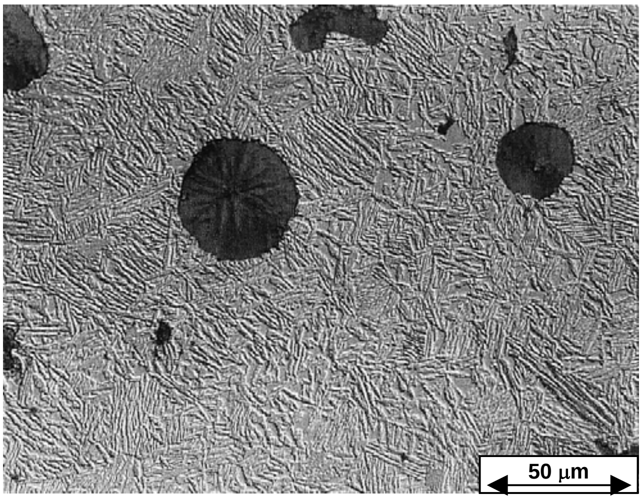

**Fig. 2.** Structure of ADI transformed at 400 °C (Nital etching, the Nomarski method, original magnification 500×)

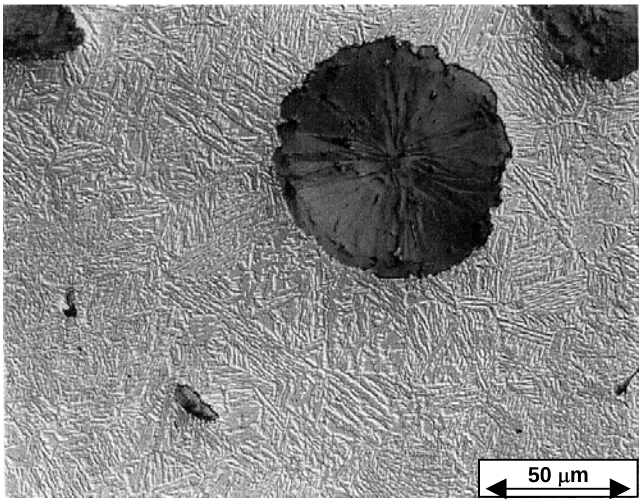

**Fig. 3.** Structure of ADI transformed at 420 °C (Nital etching, the Nomarski method, original magnification 500×)

same course in dependence of temperature of isothermal transformation as austenite content, they are drawn commonly in Fig. 10.

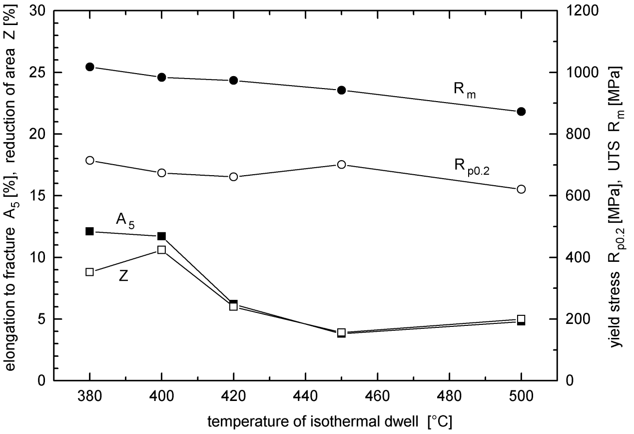

**Fig. 4.** Tensile mechanical properties of ADI in dependence on transformation temperature

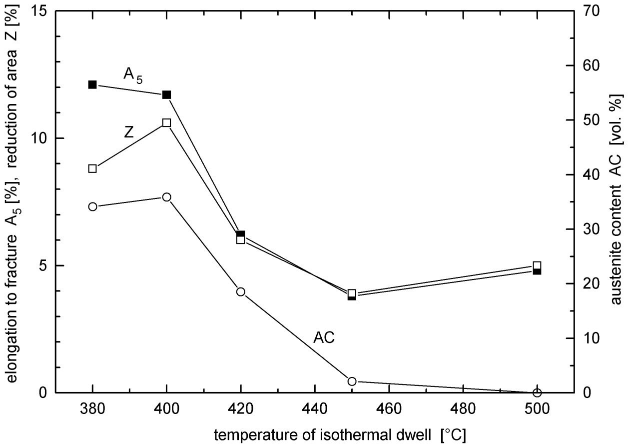

**Fig. 5.** Strain characteristics together with austenite content in dependence on transformation temperature

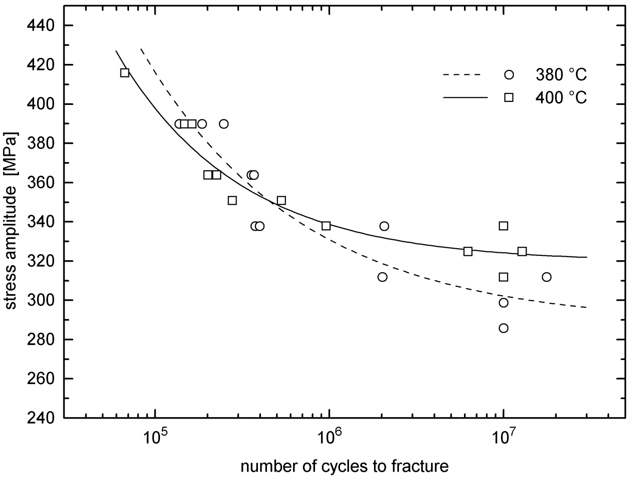

**Fig. 6.** S-N curves with plotted experimental results for ADI transformed at 380 °C and 400 °C

## 4. DISCUSSION

The higher transformation temperature is, the lower stress characteristics are observed. Only yield stress presents local maximum for transformation temperature of 450 °C, which is probably connected with substantial decrease of austenite content. With increasing pearlite content in temperature interval 450 °C to 500 °C stress characteristics decrease and strain characteristics increase. In temperature interval 380 °C to 450 °C the course of strain characteristics (especially of reduction of area) follows the course of austenite content because extremely deformable austenite substantially contributes to matrix deformability.

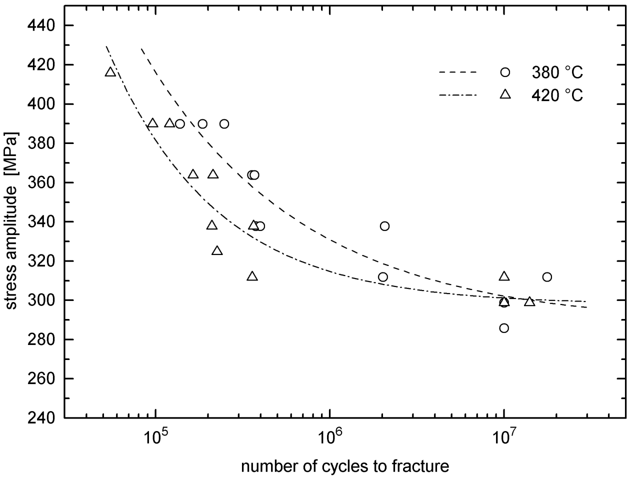

**Fig. 7.** S-N curves with plotted experimental results for ADI transformed at 380 °C and 420 °C

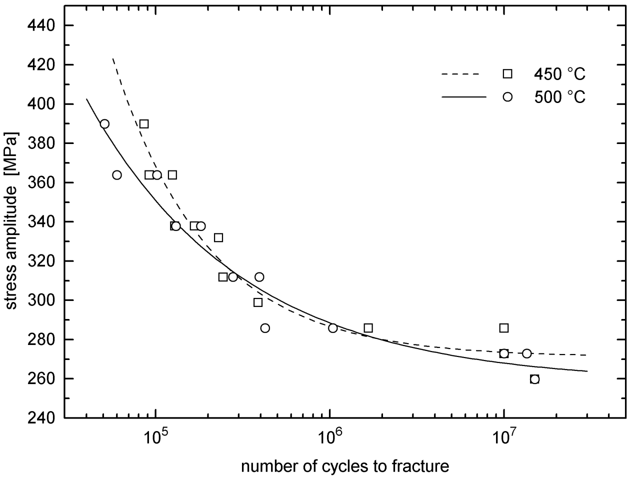

**Fig. 8.** S-N curves with plotted experimental results for ADI transformed at 450 °C and 500 °C

Fig. 9 comparing all S-N curves shows that ADI transformed at 400 °C has the best fatigue properties in high-cycle region. But ADI transformed at 380 °C, which is comparable in high-cycle region with ADI transformed at 420 °C, seems to be the best in the region of finite life. Irons transformed at 450 °C and 500 °C are comparable, especially in the region of $10^6$ cycles to fracture. On the other hand, comparison of mutually close S-N curves must be done with certain reserve due to relatively large dispersion, see Figs 6 to 8, which is typical for the results of fatigue tests and for ADI as cast material it is increased due to certain level of casting defects.

For determination of *permanent* fatigue limit (mostly fatigue limit $\sigma_C$ for $10^7$ cycles to fracture) various procedures are applied. The procedure used in this paper is based on regression of the whole S-N curve with regression function (2), when all results of fatigue tests influence resulting fatigue limit. This approach leads to precise value of fatigue limit and no other can determine the standard deviation of fatigue limit more reliably.

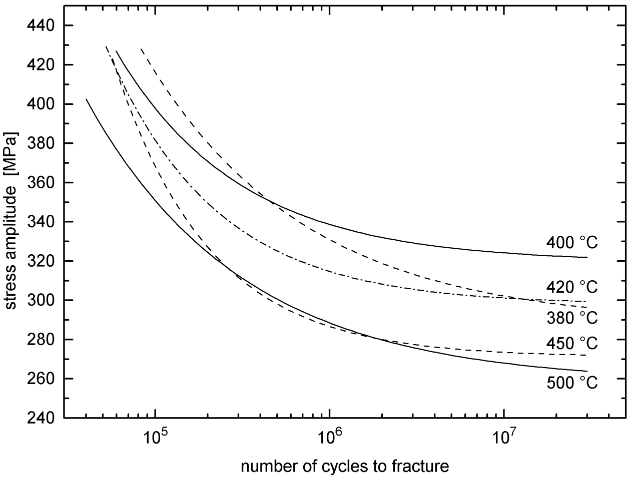

**Fig. 9.** Comparison of S-N curves for ADI transformed at all studied temperatures

Extremely close courses in dependence on transformation temperature can be observed for fatigue limit and austenite content, see Fig. 10. It means that austenite plays crucial role in fatigue processes in ADI, which is not surprising: austenite deformability allows extensive accumulation of plastic deformation and, consequently, high fatigue resistance. The same results were obtained during study of ADI fatigue behaviour in dependence on the length of transformation dwell [6].

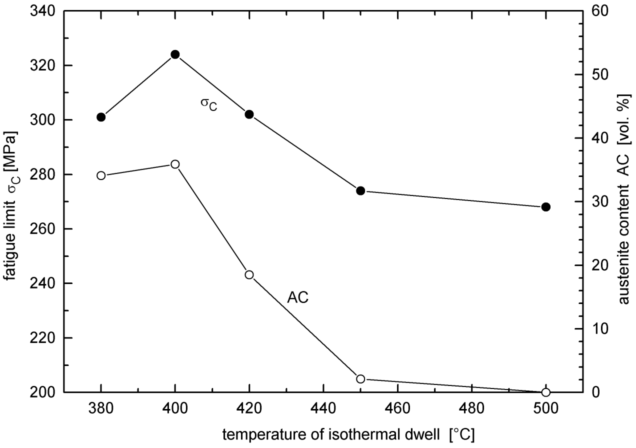

**Fig. 10.** Fatigue limit together with austenite content in dependence on transformation temperature

The obtained results show that austenite content and, consequently, fatigue behaviour of ADI depends very intensively on temperature of isothermal transformation. Previous paper [6] studying the same topics in dependence on dwell of isothermal transformation led to conclusion that the range of dwells for which optimum fatigue behaviour of ADI is observed is relatively wide. It means that determining *technological window* for isothermal transformation of ADI with good fatigue behaviour the main attention must be given to temperature choice while dwell length is not so critical.

New terminology for ADI structural components abandoning bainite with retained austenite and introducing ausferrite respects the difference between ADI and bainitic steel structures. On the other hand, it blurs the differences between upper, lower and transient bainite distinguished earlier in ADI. The main reason for new terminology, i. e. absence of carbides in ausferrite, is also relative: they are not found using light microscopy, but they can be observed using transmission electron microscopy [7]. Also austenite saturated with carbon is stable only partially: tensile loading and/or decreased temperature can cause its partial transformation into martensite.

## 5. CONCLUSIONS

1. Structure and consequently also mechanical properties of studied isothermally heat treated nodular cast iron are substantially influenced by transformation temperature.
2. The best fatigue properties were observed for the structure transformed at the temperature of 400 °C. Increase as well as decrease of transformation temperature gives structures with lower fatigue limit.
3. The worse fatigue properties were observed for the structure created by acicular ferrite and pearlite, which transformed at 500 °C. This structure contains no austenite.
4. Optimum combination of fatigue properties with stress and strain properties determined in static tensile tests can be obtained for ADI structures with sufficiently high content of austenite (at least 20 vol.%).

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