https://doi.org/10.26552/com.C.2004.2.12-15

KOMUNIKÁCIE
COMMUNICATIONS

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# FATIGUE PROPERTIES OF ADI IN DEPENDENCE ON ISOTHERMAL TRANSFORMATION DWELL

*As a result of excellent both mechanical and technological properties, austempered ductile iron (ADI) is ranked with very perspective structural materials. Recently it has been applied even to castings for dynamically loaded components and a considerable part of ADI production is applied also in military industry. The structure of ADI matrix, mostly created by the mixture of bainite and stabilized austenite, strongly depends on transformation conditions, i.e. temperature and the length of isothermal transformation dwell. An ADI transformed at 380 °C during a temporal range from 2 minutes to 9 hours was studied in details, with emphasis on structural composition and fatigue properties. The highest level of fatigue properties was obtained for the transformation dwell of 60 minutes when the maximum portion of austenite was found in ADI structure.*

## 1. Introduction

Austempered ductile iron (ADI) is usually made using isothermal heat treatment. Owing to its excellent mechanical as well as technological properties, ADI belongs among prospective structural materials. Recently it has also been applied to castings for strongly dynamically loaded machine details, e.g. gear and traversing wheels, crankshafts of motor-cars, vans and trucks, swivel pins, rail brakes, pressure pipes in oil industry [1, 2]. A considerable part of ADI production is applied in military industry, e.g. in 1995 about 3 % of total ADI production in U.S.A. were used for military reasons [2]. ADI castings are preferably applied in the following cases [3]:

1. The most usual case is the substitution of a detail made of steel (forged piece, workpiece or weldment) when the design remains the same as the design of original detail or only slight changes of the design have been done.
2. Occasionally nodular cast iron with lower level of strength properties (usually with pearlitic matrix) is substituted with ADI to increase loading capacity and/or service life of cast detail.
3. In the case when a new detail is designed specially for ADI application (above all when a complex of heat treated details is substituted with only one ADI casting, e.g. steering swivel pin in motor-cars), the highest effect with the largest savings is obtained.

Microstructure and mechanical properties of ADI can be substantially influenced by the condition of heat treatment. While the austenitization conditions (usual austenitization temperature is from the region of 880 to 920 °C and typical dwell is 1 to 3 hours) play only a marginal role, the conditions of isothermal transformation, i.e. transformation temperature and the dwell at this temperature, influence the resulting structure of ADI 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 structure as well as the static and fatigue properties of unalloyed ADI transformed at temperature of 380 °C.

## 2. Experimental material and techniques

Heat of unalloyed nodular cast iron with chemical composition 3.49 wt. % C, 2.46 % Si, 0.25 % Mn, 0.02 % P, 0.007 % S, and 0.042 % Mg was selected for the study. Austenitization at 900 °C during 1 hour was followed by isothermal transformation in AS 140 salt bath at 380 °C. The dwell at transformation temperature varied in the range from 2 minutes to 9 hours in order to study the dependence between the obtained structural mixture (upper bainite, retained austenite, and martensite if any) and its mechanical properties. Heat treatment was applied to test bars (with the diameter of 6 mm for static tests and of 7 mm for fatigue tests) with small grinding allowance.

The content of retained (stabilized) austenite was determined using quantitative X-ray phase analysis. Basic mechanical properties (yield stress $R_p0.2$, ultimate tensile stress $R_m$, and elongation to fracture $A_5$) were measured using universal loading device of the Zwick Company at room temperature.

For fatigue tests the high frequency pulsator of the Amsler Company was used. Ground test bars with surface roughness of 0.4 $\mu$m were loaded symmetrically in tension-compression at room temperature. The testing frequency of a resonant pulsator, which is significantly dependent on the sample stiffness, was about 202 Hz for all the tested materials. Each of S-N curves was determined by the tests of 12 to 15 test bars. For their regression by the least square method the three-parameter non-linear function proposed by Stromeyer [9] and recommended by Weibull [10]

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$$\sigma = a N^b + K \quad (1)$$

was used, where as $\sigma$ stress amplitude or maximum stress of loading cycle can be considered, $a$, $b$, $K$ are parameters of regression curve, and $N$ is the number of cycles to failure or to test stoppage.

## 3. Results

Established structural composition, average values of static mechanical characteristics, and by using Eq. (1) calculated values of the fatigue limit for reference number to failure $N_C = 10^7$ are presented for all the studied materials in Table 1.

minutes, even as a dominating structural component). With increasing length of transformation dwell the martensite content decreases very quickly and for transformation dwell of 10 minutes only its debris were found. The content of retained austenite increases reaching for its maximum at transformation dwell of 1 hour. Then it decreases and at the longest dwell (9 hours) no retained austenite is present in ADI structure.

As the fatigue behaviour of ADI is the main object of this paper, the results of fatigue tests are presented at first and in more details. The latest results obtained by testing BH 27 G material, i.e. the ADI transformed during the dwell of 270 minutes, are presented together with fitted S-N curve in Fig. 2. This figure demonstrates a typical scatter of ADI fatigue tests and their fit using Eq. (1). Comparison of fitted S-N curves for nearly all transformation dwells is presented in next two figures: for the dwells of 60 minutes and a shorter one in Fig. 3, for the dwells of 60 minutes and a longer one in Fig. 4. The 60-minute dwell was chosen as a braking point because it leads to the highest fatigue limit. Unfortunately, the fatigue tests of the ADI transformed during the dwell of 120 minutes, which presage very promising results, are not finished yet.

Content of retained austenite or martensite (if any), static mechanical properties, fatigue limit, and fatigue ratio of ADI transformed at 380 °C in dependence on the dwell of isothermal transformation. Table 1

| sign | $\tau_t$ | | $A_R$ | $M$ | $R_p$ 0.2 | $R_m$ | $A_5$ | $\sigma_C$ | $\sigma_C / R_m$ |
|---|---|---|---|---|---|---|---|---|---|
| | [min] | [h] | [vol. %] | [vol. %] | [MPa] | [MPa] | [%] | [MPa] | [-] |
| A | 2 | | 9.5 | 61.2 | - | 700 | 0.0 | 184 | 0.263 |
| B | 5 | | 24.0 | 36.6 | 736 | 896 | 0.5 | 188 | 0.209 |
| C | 10 | | 27.4 | 5.0 | 607 | 977 | 2.1 | 200 | 0.204 |
| D | 25 | | 31.7 | 0.0 | 675 | 973 | 3.8 | 199 | 0.204 |
| E | 60 | 1 | 36.0 | 0.0 | 772 | 1022 | 8.1 | 231 | 0.225 |
| F | 120 | 2 | 22.6 | 0.0 | 811 | 1001 | 6.7 | – | – |
| G | 270 | 4.5 | 4.3 | 0.0 | 824 | 990 | 5.9 | 230 | 0.233 |
| H | 540 | 9 | 0.0 | 0.0 | 824 | 1055 | 5.0 | 179 | 0.170 |

As shown in Table 1 and Fig. 1, the composition of structural mixture in the matrix of ADI transformed at 380 °C is strongly influenced by the dwell of isothermal transformation. The structure mostly consists of upper bainite and retained austenite, only when short transformation dwells are applied then also martensite is present in the structure (in the case of the shortest dwell, i.e. 2

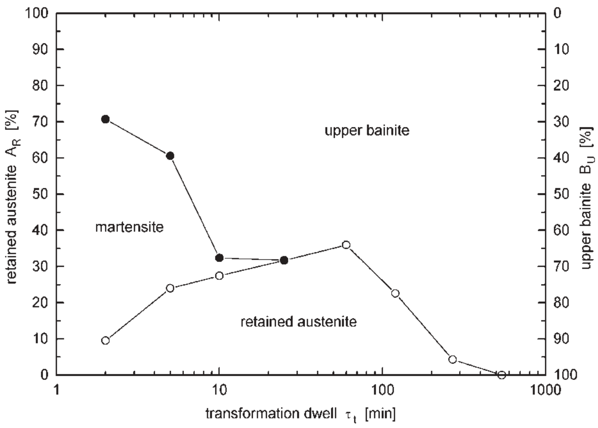


*Fig. 1: Structural composition of ADI in dependence on the length of transformation dwell.*

Similarly as the composition of structural mixture of ADI matrix, also the length of isothermal dwell in salt bath substantially influences static and fatigue properties, see Table 1 and Fig. 5. Not considering small waviness, UTS and yield stress increase with an increasing length of transformation dwell and reach maxima for the longest dwells, with the only exception of yield stress value at transformation dwell of 5 minutes. Elongation to fracture, in contrast to both the stress characteristics, increases at first but after reaching for maximum of 8.1 % at dwell length of 60 minutes a slight decrease follows. Maximum of fatigue limit is reached at the same dwell but the value for 270-minute dwell is only negligibly lower, see also fully comparable high-cycle parts of S-N curves for both mentioned dwells in Fig. 4. Comparing with retained austenite content, the increases of elongation to fracture as well as of fatigue limit are very closely connected with the increase of austenite content for increasing transformation dwell up to 60 minutes. On the other hand, for longer dwells the decrease of elongation to fracture and namely of fatigue limit is considerably delayed with respect to the decrease of austenite content.

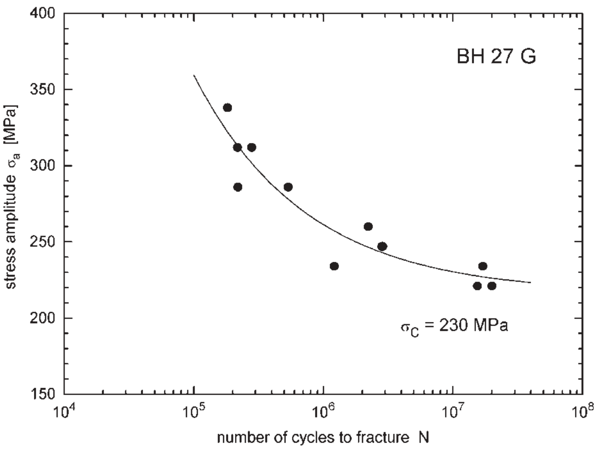


*Fig. 2: S-N curve of ADI transformed at 380 °C for the dwell of 270 minutes.*

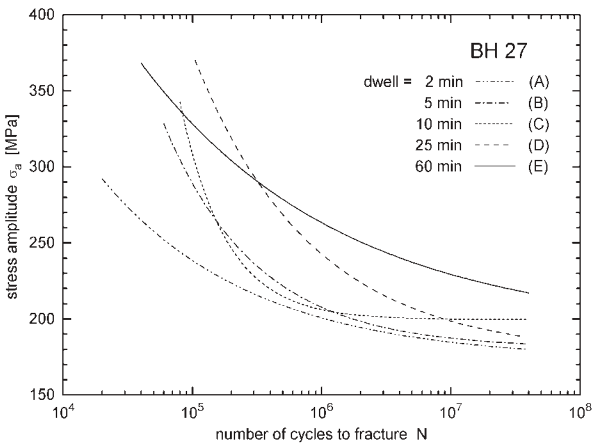


*Fig. 3: Comparison of S-N curves of ADI for various lengths of transformation dwell (up to 60 minutes).*

## 4. Discussion

Presented results show an already described fact [11, 12] that, in contrast to most structural steels and cast irons, increasing UTS is not followed by increasing fatigue limit in the case of ADI. The maxima of elongation to fracture, of fatigue limit, and of austenite content obtained at the same value of transformation dwell (60 minutes) are evidence of certain internal connection among these quantities. Retained austenite is an extremely deformable structural component of ADI and, therefore, the maximum content of austenite means maximum deformability expressed through the elongation to fracture. Then fatigue, which is considered to be an accumulation of plastic deformation, should be closely dependent on the content of retained austenite. High values of fatigue limit were also determined for ADI structures with a high content of retained austenite, which isothermally transformed at 400 °C [13].

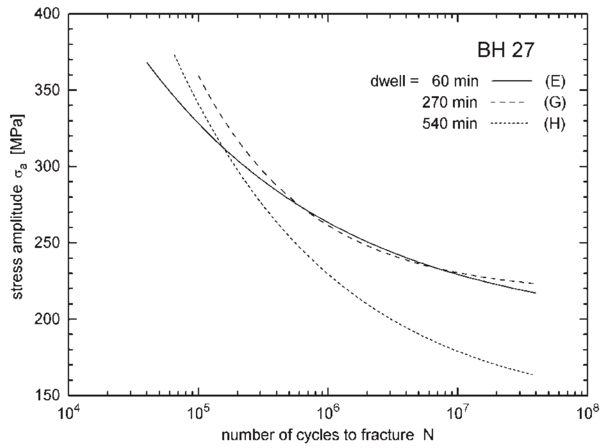


*Fig. 4: Comparison of S-N curves of ADI for various lengths of transformation dwell (60 minutes and longer).*

While strong decrease of austenite content with increasing transformation dwell above 60 minutes is followed by moderate decrease of elongation to fracture, the fatigue limit decreases in

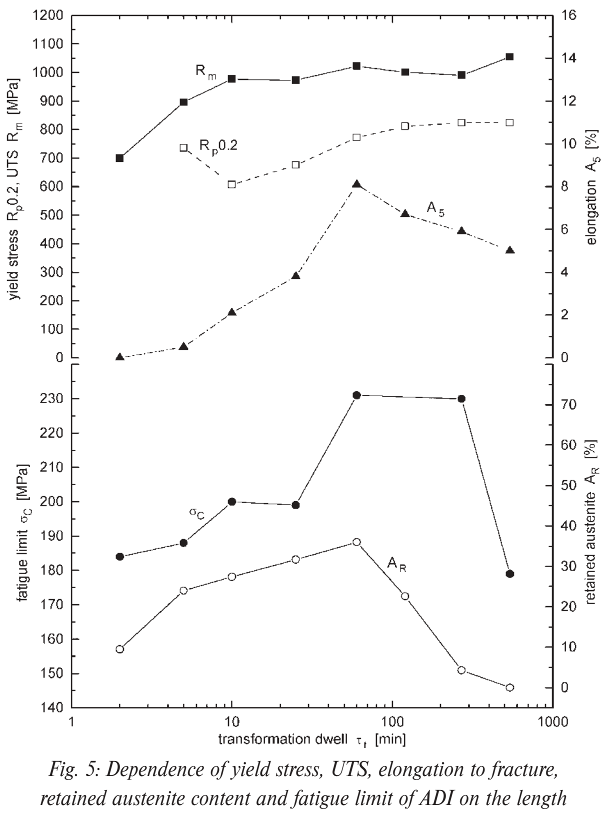


*Fig. 5: Dependence of yield stress, UTS, elongation to fracture, retained austenite content and fatigue limit of ADI on the length of transformation dwell.*

fact only for dwells longer than 4.5 hours, see Fig. 5. It means that not only the content of retained austenite contributes to relatively high values of fatigue limit. More information will be obtained after finishing the fatigue tests for the 120-minute dwell, now the other factors raising fatigue limit can be only suspected. In phenomenological considerations two following facts can be considered:

(i) The increase of elongation to fracture with increasing austenite content is higher than the following decrease of the elongation with decreasing austenite content.
(ii) Stress characteristics, i.e. UTS and yield stress, increase with increasing transformation dwells in fact in the whole studied range of transformation dwells.

Then slower decrease of deformability together with continued increase of stress characteristics could lead to nearly constant level of fatigue limit.

The root of slightly decreasing fatigue limit with substantially decreasing austenite content in dwell range from 60 to 270 minutes consists probably in increasing deformability of bainitic ferrite with increasing length of transformation dwell. The mechanisms of this increase should be the same or similar to those applied in martensite during its tempering at not very high temperatures. To support this idea, the tetragonality of bainite should be determined in dependence on the transformation dwell, which is planned for the future.

## 5. Conclusions

Summarizing the obtained results and their analysis, the following items can be asserted:

1. The length of isothermal transformation dwell very substantially influences the composition of structural mixture in the matrix of ADI transformed at 380 °C.
2. Maximum content of retained austenite was obtained in the ADI structure for transformation dwell of 60 minutes.
3. UTS and yield stress values increase with increasing transformation dwell practically in the whole studied range of transformation dwells.
4. Maximum elongation to fracture of about 8 % was measured for transformation dwell of 60 minutes corresponding with the maximum content of retained austenite.
5. The length of isothermal transformation dwell strongly influences also fatigue limit. Optimum fatigue properties were obtained for the transformation dwell, for which ADI structure contains the maximum amount of retained austenite, i.e. for 1 hour.
6. High level of fatigue limit appears also when austenite content starts to decrease. The reason of this effect is probably increasing deformability of bainitic ferrite with increasing transformation dwell.
7. Technological window in transformation dwells to obtain high fatigue limit was found in the range from 1 to 4.5 hours.
8. Low values of fatigue limit for short transformation dwells are the consequence of martensite presence as well as low content of retained austenite in ADI matrix.

**Acknowledgement**

Presented studies were partially supported by the grant projects 106/01/0376 and 106/03/1265 of the Grant Agency of the Czech Republic.

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