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Influence of Transformation Time on Fatigue Properties of Austempered Ductile Iron

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Mechanical properties determined by tensile and fatigue tests of ADI transformed at the temperature of 400 °C during 11 various transformation dwells in the range from 2 minutes to 25 hours are confronted with obtained matrix structure. Maximum content of retained austenite is obtained for the dwell of 40 minutes for which also the maximum of elongation to fracture was observed. For shorter dwells UTS substantially increases with transformation time while for longer dwells the value of UTS is nearly constant. Yield stress increases in the whole range of transformation time. Fatigue limit is the mechanical characteristic relatively closely connected with the content of retained austenite: the higher its content, the higher fatigue limit. Optimal combination of tensile properties is obtained in rather narrow range of transformation time from 40 to 60 minutes where the maximum of elongation to fracture is observed. The range of the highest values of fatigue limit is wider (10 to 100 minutes with fatigue limit of 260 to 270 MPa) because its dependence on transformation time is weaker. This rather wide *technological window* means that ADI is structural material not very sensitive to keeping technological conditions and, therefore, its good fatigue properties can be obtained also in mass production or in plants with average level of technology.

Keywords: ADI, transformation time, tensile tests, fatigue behaviour, retained austenite.

1. INTRODUCTION

One of the top advantages of austempered ductile iron (ADI) consists in the variability of mechanical properties which can be influenced in very wide range by the choice of isothermal transformation conditions. The influence of transformation conditions, i.e. of temperature and time of isothermal dwell, on tensile mechanical properties has been described in many publications; see e.g. [1 – 3] etc. But probably due to high financial and temporal demands for fatigue tests, the results dealing with fatigue behaviour are quite rare; see e.g. [4 – 8].

To fill *blank areas* in this region is the aim of presented publication which is concentrated to explain the relations among transformation dwell, structure, and tensile as well as fatigue properties of ADI.

2. EXPERIMENTAL

The chemical composition of studied unalloyed nodular cast iron was 3.46 wt. % C, 2.10 % Si, 0.25 % Mn, 0.047 % P, 0.002 % S, and 0.058 % Mg. The heat was isothermally treated: austenitization was performed at 900 °C during 60 minutes in GS540 + C3 salt bath, isothermal quenching was carried out at 400 °C in AS140 salt bath with dwells of 2 minutes to 25 hours. In this way various structural mixtures were obtained (upper bainite with retained austenite, at shorter dwells also with martensite) which allow to study the relation between structure and mechanical properties of ADI.

Metallographical cuts were prepared according to standard procedures. Structures were observed and documented, see Fig. 1 to 3, using Neophot 21 light microscope of Zeiss Company. The content of retained (stabilized) austenite RA (or of martensite M if occurred) was determined by X-ray quantitative method. The results are presented in Table 1.

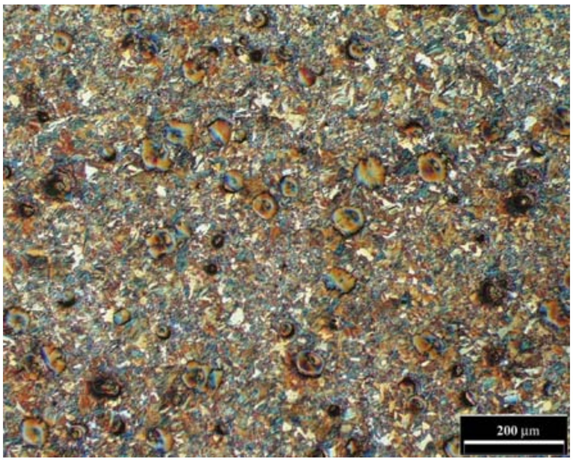

Fig. 1. Structure of ADI transformed during 40 minutes at 400 °C. (Nital etching, the Nomarski method, actual magnification 75×)

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. The test bars used for static tensile tests are drawn in Fig. 4. The crosshead rate was 1 mm/min, for more details see [9]. Average values of mentioned characteristics are given also in Table 1.

Fatigue tests were performed at symmetrical push-pull cycle using high-frequency pulsator of Amsler Company at room temperature at frequency of 180 Hz. For one S-N curve 12 to 15 test bars were used, see Fig. 5. The bars were finely grinded to surface roughness $Ra \approx 0.4$ μm.

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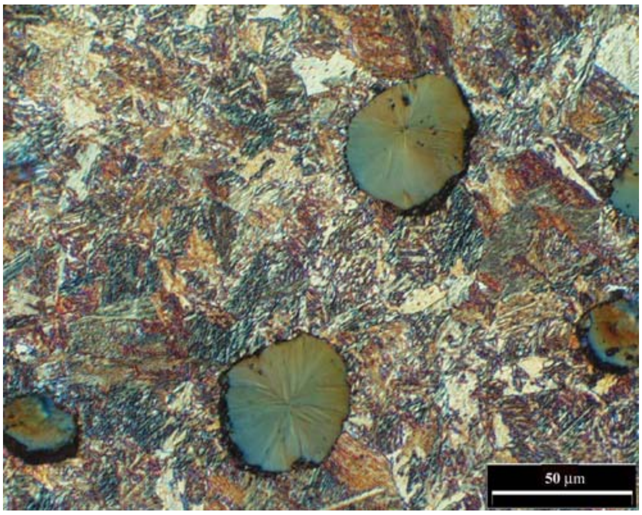

Fig. 2. Structure of ADI transformed during 40 minutes at 400 °C. (Nital etching, the Nomarski method, actual magnification 375×)

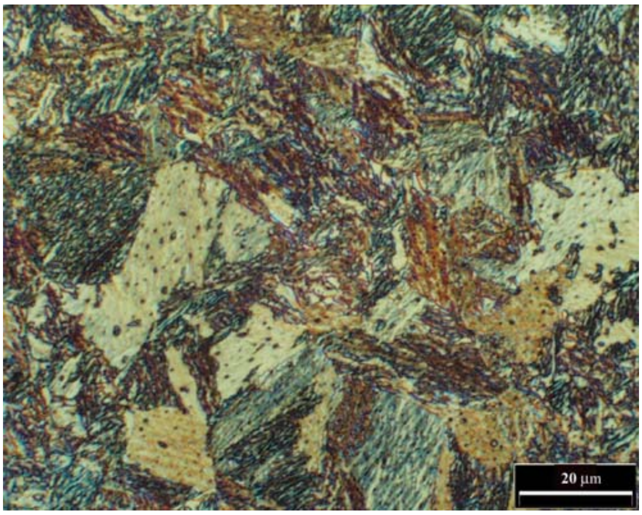

Fig. 3. Structure of ADI transformed during 40 minutes at 400 °C. (Nital etching, the Nomarski method, actual magnification 750×)

Table 1. UTS, yield stress, elongation to fracture, fatigue limit, fatigue ratio, content of retained austenite, and content of martensite in ADI transformed at 400 °C in dependence on isothermal transformation dwell.

τ_t [min]	R_m [MPa]	$R_{p0.2}$ [MPa]	A_5 [%]	σ_C [MPa]	σ_C/R_m [–]	RA [vol.%]	M [vol.%]
2	454	–	0.0	–	–	13.0	57.0
5	805	633	0.6	248	0.308	26.9	31.5
10	868	652	1.8	268	0.309	24.7	0.0
25	925	739	4.7	267	0.289	33.6	0.0
40	1011	780	7.4	259	0.256	34.4	0.0
60	1001	778	6.4	266	0.265	31.0	0.0
100	1019	768	5.4	260	0.255	–	0.0
180	1008	795	4.8	253	0.251	16.6	0.0
270	1013	837	3.1	247	0.244	2.6	0.0
540	992	838	3.0	213	0.215	0.0	0.0
1500	967	845	2.7	–	–	0.0	0.0

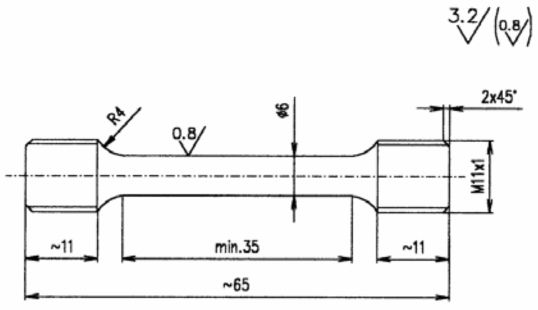

Fig. 4. Test bar for static tensile test

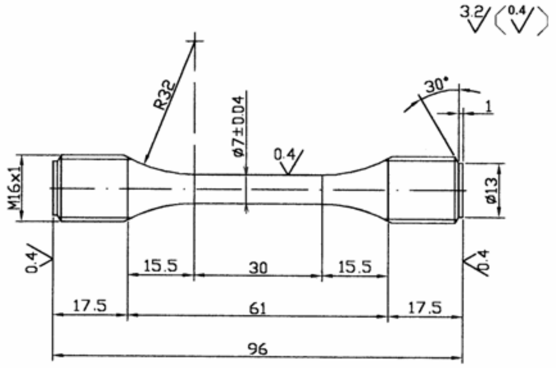

Fig. 5. Test bar for fatigue test

Fatigue properties were evaluated on the base of S-N curves which were fitted with non-linear regression equation proposed by Stromeyer [10] and recommended by Weibull [11]

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

where σ 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 σ_∞ are regression parameters. This equation can be rewritten in a more suitable form

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

directly containing fatigue limit σ_C for 10^7 cycles. The values of this limit are also given in Table 1.

3. RESULTS AND DISCUSSION

Metallographical as well as X-ray analysis showed that the structure of nodular cast iron isothermally treated at 400 °C contains above all upper bainite and retained austenite whose content is strongly dependent on transformation dwell, see Fig. 6. At two shortest dwells also the presence of martensite was observed because only a limited part of austenite finished the trasformation into bainite and during following cooling in water some other part of austenite transformed into martensite. At longer dwells carbon diffusing into austenite stabilized it and no martensite was created during final water cooling.

Mechanical properties as well as retained austenite content are strongly influenced by the dwell of isothermal transformation in salt bath, see Fig. 7 and 8. Yield stress increases with increasing transformation dwell and reaches its maximum at the longest dwell. Not considering slight decrease for the longest dwells, also UTS increases with increasing dwell length. Very low values of UTS reached at the shortest dwells are connected with the early fractures appearing as a consequence of martensite presence in the structure. Also elongation to fracture representing plastic behaviour of matrix is strongly dependent on the length of transformation dwell but its course is substantially different. The highest values of elongation were obtained in relatively narrow temporal interval from 40 to 60 minutes (i.e. in the middle of studied temporal range if logarithmic scale is considered). Maximum elongation very well coincides with maximum content of retained austenite.

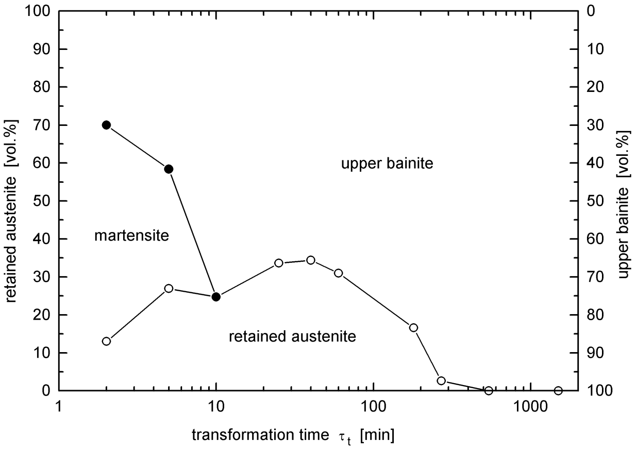

Fig. 6. Influence of isothermal transformation time on composition of ADI structure transformed at 400 °C

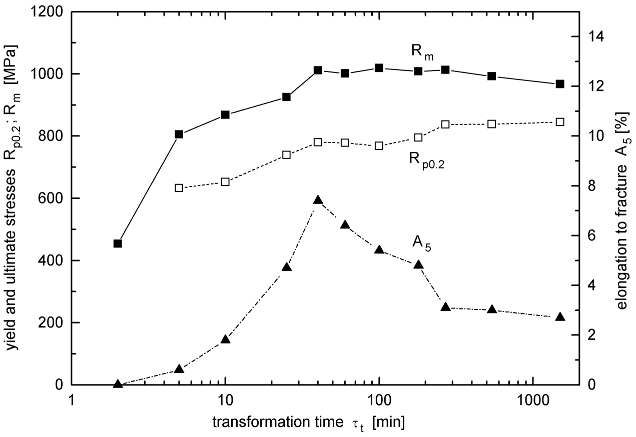

Fig. 7. Dependence of UTS, yield stress, and elongation to fracture of ADI transformed at 400 °C on isothermal transformation time

The dependence of fatigue limit on transformation dwells, which could be roughly approximated with slightly bent concave parabola, differs from the courses of stress as well as from strain characteristics and approaches to the course of retained austenite content. In temporal range 10 to 100 minutes the values of fatigue limit differ only weakly and they cover the range 259 to 268 MPa. Shorter (2 and 5 minutes) as well as longer (270 and 540 minutes) dwells lead to lower values of fatigue limit. At shorter dwells some martensite appears in structure whose presence decreases the fatigue limit. At longer dwells the fatigue limit decrease is the consequence of very low content of retained austenite [12].

Comparing the dependence of fatigue limit, retained austenite content, and elongation to fracture on transformation dwell, see Fig. 7 and 8, it can be said that the maximum values of fatigue limit are influenced by dwell length substantially less than retained austenite content and especially than elongation to fracture. This finding considerably corrects generally accepted opinion that sufficiently high fatigue limit can be obtained only for structure with maximum elongation to fracture [13] and, moreover, has basic importance for industrial praxis: optimum fatigue properties can be obtained in relatively wide range of transformation dwell because they are not very sensitive to heat treatment performance.

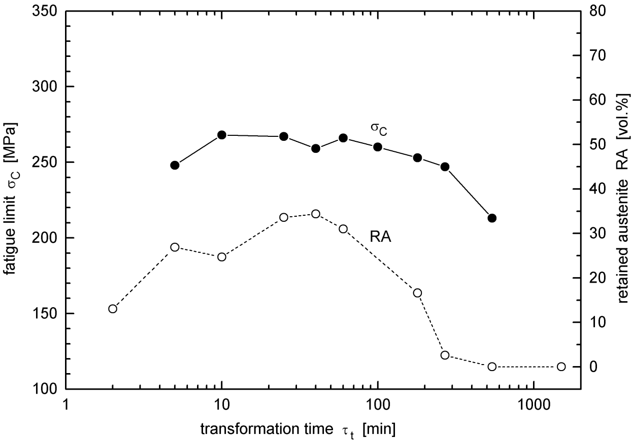

Fig. 8. Dependence of fatigue limit and retained austenite content in ADI transformed at 400 °C on isothermal transformation time

The dependence of fatigue ratio on the length of transformation dwell can be expressed very well by linear function

$$\sigma_C / R_m = 0.344 - 0.0445 \log \tau_T \qquad (3)$$

if logarithmic scale of dwells is used. It means that fatigue ratio decreases with increasing transformation dwell in the whole range of studied dwells, see Fig. 9.

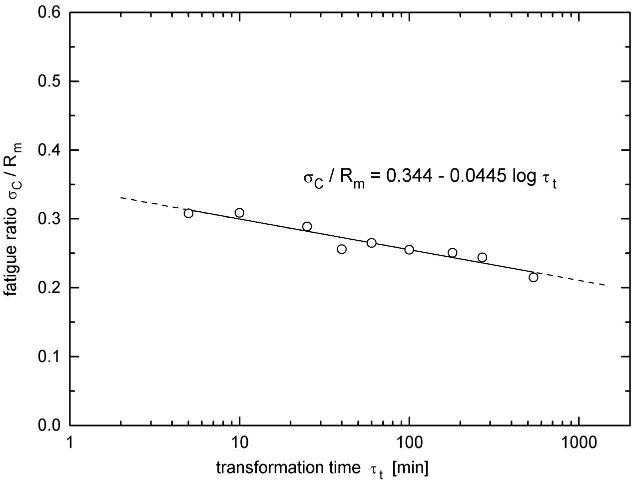

Fig. 9. Dependence of fatigue ratio of ADI transformed at 400 °C on isothermal transformation time

On the other hand, in practical use the general validity of this last relation is limited in the range of dwells shorter than 10 minutes: the maximum value of fatigue ratio at transformation dwell of 5 minutes was not reached due to high value of fatigue limit but due to substantially decreased UTS which dropped due to the presence of martensite more than fatigue limit, see Fig. 7 to 9.

4. CONCLUSIONS

1. Mechanical properties in static tension of ADI with upper bainite structure (temperature of isothermal dwell 400 °C) are very strongly influenced with the length of transformation dwell.
2. UTS values increase with increasing transformation dwell to maximum in temporal range 40 to 270 minutes. Then slight decrease occurs.
3. Maximum values of elongation to fracture were determined in relatively narrow range of transformation dwells (40 to 60 minutes) where also the maximum content of retained austenite was measured.
4. Fatigue limit is not substantially influenced with the length of transformation dwell. For the studied ADI the maximum values of fatigue limit were reached in temporal interval approximately 10 to 100 minutes. Their range was 259 MPa to 268 MPa which can be considered to be optimum.
5. Lower values of fatigue limit at shorter transformation dwells are connected with the presence of martensite in structure which causes low plasticity of matrix.
6. Decreased values of fatigue limit at long transformation dwells can be connected with low or zero content of retained austenite.
7. Fatigue ratio decreases linearly with the logarithm of transformation dwell.

Acknowledgments

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