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The effect of reducing the austempering time on the fatigue properties of austempered ductile iron

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ABSTRACT

The effect of reducing the austempering time on the high-cycle fatigue behavior of austempered ductile iron (ADI) has been investigated by subjecting samples to rotating bending and fatigue crack propagation tests. Starting from the same cast iron, two distinct types of ADI were austempered at the same temperature of 360 °C but for different austempering times, which resulted in two materials whose main difference was the content of carbon in austenite. The first sample was austempered for 1.5 h, while the second was austempered for only 0.6 h. The austenitizing cycle (900 °C, 1.5 h) was the same for both ADIs. Therefore, we investigated the influence of the mechanical stability of austenite in the initiation and propagation of fatigue cracking. Reducing the austempering time increased the fatigue life and did not affect the mechanical properties or the rate of fatigue crack propagation. Reducing the austempering time increased the time to fatigue crack nucleation in ADI in addition to its economic and environmental benefits.

1. Introduction

The fatigue properties of austempered ductile iron (ADI) and the relationship between its mechanical properties and its microstructure are not well characterized enough to fully exploit the material for a number of industrial applications, in spite of its excellent mechanical properties. These studies may help increase the applications of ADI for machines and structural elements subject to fatigue [1–4].

The starting material for ADI is ductile cast iron, which is subjected to an isothermal heat treatment process called austempering. A schematic of the ADI austempering heat treatment is shown in Fig. 1. According to Kovacs [5], if the cooling is fast enough (Fig. 1, lines C and D), after the austenitizing cycle (lines B and C), the nucleation of acicular ferrite begins at point *E* and the full matrix transformation in acicular ferrite and austenite is completed in the period between points *E* and *T*. This is called the first stage; the initial austenite (γ) decomposes into ferrite (α) and high carbon or transformed austenite (γ_{HC}):

$$\gamma \rightarrow \alpha + \gamma_{HC} \quad (1)$$

If the austempering reaction is finished at point *T*, the carbon percentage in austenite reaches 1.2% to 1.6%, making austenite metastable. No appreciable ferrite nucleation occurs in the range of *T*–*Y* (Fig. 1), but the existing ferrite grains still grow and increase the carbon content in the remaining austenite, which can reach values up to 1.8% to 2.2%, depending on the chemical composition of the casting [5].

Lin et al. [3] have investigated the influence of the microstructure properties on the high-cycle fatigue (HCF) of various types of ADI, highlighting the effect of the amount and morphology of graphite and austenite. The maximum values for fatigue resistance in rotating bending tests were obtained for ADI samples produced at an austempering temperature of approximately 360 °C [3,6]. According to these authors, the improvement in HCF strength may be attributed to the larger amount of austenite retained and to the greater fraction of retained austenite with a low carbon concentration. The mechanical stability of the ADI austenite primarily depends on the carbon content and the stress or strain level. Austenite can be transformed into martensite when the material is subjected to large deformations caused by surface treatments or machining [7,8] or plastic deformation due to service loading [3] because ADI austenite presents different levels of carbon content. In this case, the stress- or strain-induced transformation to martensite, in combination with the plastic deformation of austenite, significantly improves the fracture toughness and the fatigue limit for ADI austempered at a temperature of 360 °C [3,9].

Most of the reported research in the literature is related to ADI austempered at point *Y* (Fig. 1) and cooled at room temperature,

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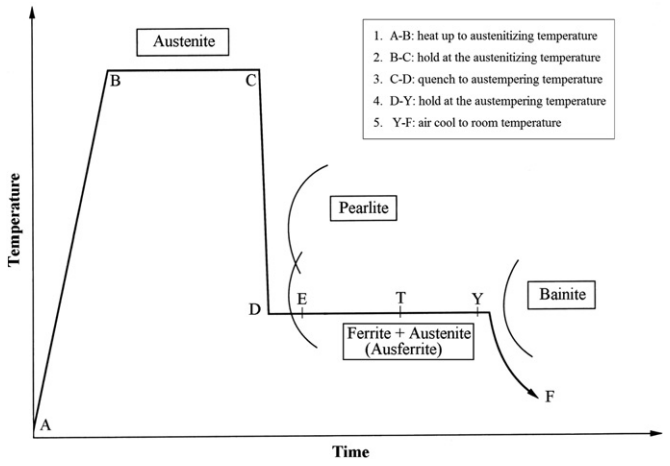

Fig. 1. Schematic of the austempering heat treatment cycle.

just before the bainitic reaction (called the second stage), which avoids the stress- or strain-induced transformation of the metastable austenite into martensite. However, very little specific information is currently available about the fatigue performance for ADI austempered at point *T* (Fig. 1). According to Lin et al. [3], the phase transformation retards the crack growth during the fatigue rotating bending test.

The main purpose of this work is to investigate the austenite stability effect in ADI fatigue behavior and to evaluate the effect of reducing the austempering time on the ADI fatigue life and its mechanical properties. Furthermore, this research intends to ascertain whether the austenite phase transformation affects fatigue crack initiation and fatigue crack propagation. Reducing the ADI's austempering time during the manufacturing process could be extremely important for reducing the environmental impact and increasing the sustainable development of these materials. As mentioned previously, manufacturing ADI with a less stable austenite can increase the resistance to crack fatigue that is usually obtained by surface deformation treatments, such as conventional machining operations, or special treatments, such as shot peening or surface rolling.

2. Experimental procedures

The fatigue behavior of the ADI was studied in samples extracted from blocks with a Y-shaped cross section, as standardized by ASTM A-897 [10]. The web portion of the blocks had the following dimensions: 50 mm (high) × 13 mm (thick) × 240 mm (long). This material was produced by a Brazilian commercial foundry [4] using the sand cast process. The austenitizing temperature (point *E*, Fig. 1) and austempering times (point *T*, Fig. 1) were defined with a quenching dilatometer, model DT1000, made by Adhamel Lhomargy [4]. The time required for the austempering reaction ranged from 21 min to 24 min, based on the results of tests performed on three specimens. Two batches with distinct austempering times were treated at 360 °C to evaluate the influence of the austempering time and austenite stability on fatigue behavior. The first batch, denoted by ADI-T1, was treated at 360 °C for 1.5 h, which created a material with a high carbon content in the austenite phase, while the second batch, denoted by ADI-T2, was treated at 360 °C for 0.6 h, which produced a material with a metastable austenite phase. Therefore, ADI-T2 had a greater tendency than the first batch (ADI-T1) to present strain-hardening or to undergo phase transformation induced by strain. The austenitizing cycle (900 °C, 1.5 h) was the same for both materials (ADI-T1 and ADI-T2). No martensitic transformation in either material was observed during the cooling process at room temperature during the simulation of these thermal cycles in the dilatometer.

The materials were characterized by chemical analysis and optical and electronic microscopy. Additionally, X-ray diffraction analysis was performed to estimate the microstructural parameters of the ADI, the austenite volume fraction ($X\gamma$), the ferritic cell size (d) and the carbon content of austenite ($C\gamma$), following the same procedures used by Putatunda [9]. The ferritic cell size was estimated using Scherrer's formula, as recommended by Putatunda [9]. Samples were prepared for tensile, hardness and impact testing from blocks with a Y-shaped cross section following ASTM A-897 specifications [10].

Samples (d=6.35 mm, no notches) were subjected to fatigue tests in a rotating bending fatigue testing machine at a frequency of 100 Hz (6000 rpm). The tests were performed at constant stress amplitudes (CA) with two stress ranges (Table 1). The fatigue limit (S_e) was estimated from the ultimate tensile strength (S_u) of the ADI-T2, according to Lee et al. [11].

Compact tension specimens (CTSs) were extracted from ADI Y blocks [4] and were prepared according to ASTM E-647 [12] to investigate the fatigue crack growth rate. The CTSs were 12 mm thick and 40.4 mm wide. The pre-cracking procedure and the fatigue crack growth test were also performed following ASTM E-647 specifications [12]. All tests were carried out at room temperature in environmental atmosphere. A sinusoidal waveform loading was applied at a constant load ratio (R=0.3) with a cyclic frequency of 15 Hz on a 250-kN closed-loop servohydraulic Instron test machine attached to a computer, which controlled the testing and acquired the data. Three identical specimens from each heat-treated material (ADI-T1 and ADI-T2) were tested.

3. Results and discussion

3.1. Chemical composition, microstructure and mechanical properties

The chemical compositions of ADI-T1 and ADI-T2 are presented in Table 2. The elements Cu and Ni were added to provide the necessary material austemperability. The microstructures of the materials were very similar (Fig. 2a and b, ADI-T1 and ADI-T2, respectively). In both cases, the microstructure consisted of dark needle-shaped ferrite interwoven with bright etching austenite, with nodular graphite dispersed in the matrix. The materials had an average of 162 graphite nodules per square millimeter and a nodularity of 96%.

The phases of the matrix, the carbon content of the austenite and the average ferritic cell size for ADI-T1 and ADI-T2 are given in Table 3. Both materials presented equivalent values for most of the parameters, except for the carbon content in austenite, which was lower for ADI-T2 than for ADI-T1. These carbon contents were close to, if not within, the ranges predicted by Kovacs [5]. The ADI mechanical properties were influenced by the ferritic cell size (d) and the total carbon content in the matrix ($X\gamma$, $C\gamma$,%) [1,4]. The values obtained for the ferritic cell size (d) were within the

Table 1
Parameters for the rotating bending fatigue tests. $S_e = 0.4 \times S_u = 450$ MPa.

Stress amplitude	Value (MPa)	Specimens	Ratio S_e/S_{yield}	
			ADI-T1	ADI-T2
$S_a = 1.3\ S_e$	585	8	0.67	0.68
$S_a = 1.1\ S_e$	495	8	0.57	0.58