CORRELATION BETWEEN MICROSTRUCTURE AND MECHANICAL PROPERTIES OF AN AUSTEMPERED DUCTILE IRON

V.C.C. Alves[1], L. L. A. Baracho[1], E. R. Silva[2], L. C. R. Lopes[1], G. S. Fonseca[1], F. R. F. Silva[1], R. H. Leal[1], C.T.A. Santos[1]
[1] Universidade Federal Fluminense, RJ, Brazil,
[2] Universidade Federal de Santa Catarina, SC, Brazil,
Avenida Lions Club, 111, Vila Santa Cecília, Volta Redonda, RJ – Brasil, 27255-430, viniciuscardilo@id.uff.br

Austempered ductile cast irons (ADI) has received increasing attention in last years because their combined properties of good ductility, high strength and fracture toughness, good fatigue strength, good wear properties and low production cost. Such combination of properties can be reached because of their microstructures consisting of a mixture acicular ferrite (bainite), residual austenite with a high carbon content and nodular graphite. In the present work, the effect of austempering heat treatment on the microstructure of a commercial alloy to produce three different grades of ADI with different strength level is analyzed. Microstructure characterization has been performed using techniques of optical microscopy, scanning electron microscopy, electron backscatter diffraction technique and X-ray diffraction. Also, tensile and impact tests have been realized. The results are discussed in terms of microstructure present in the three grades of ADI and volume fraction of phases. Those results are compared with the microstructure and properties of the original nodular cast iron.

Key-words: Ductile cast iron, Austempered ductile cast iron, Residual austenite, Tensile strength, Impact strength.

INTRODUCTION

The as-cast mechanical properties of ductile iron can be significantly improved through an austempering heat treatment. This has led to a new grade of cast irons, the austempered ductile iron (ADI), with its unique microstructure

composed by an ausferritic matrix with spheroidal graphite [1]. ADI has emerged as an important engineering material in recent years because the combination of properties such as high strength, good ductility, good wear resistance, high fatigue strength and fracture toughness [2]. Furthermore, ADI is also 10% less dense than steel [3], producing high specific strength when compared to other classes of materials [4]. Because of these advantages, allied with low production costs, ADI has been commonly used in many commercial engineering applications, such as in automotive components [5].

The production of ADI consists in the casting of ductile iron, followed by a heat treatment that begins with a heating above the transformation temperature range, maintained long enough to create a fully austenitic matrix (γ) saturated with carbon. Then, the iron is suddenly cooled to a temperature in the bainitic range (260-400°C). At this temperature, if the iron is held for the required amount of time, the austempering reaction takes place. During austempering, part of austenite decomposes into acicular ferrite (α) while the remaining austenite is enriched with carbon (γ_{HC}) [6]. This reaction is often represented [7] by Eq. (A):

$$\gamma \rightarrow \alpha_B + \gamma_{HC} \quad (A)$$

On the other hand, if the austempering temperature is held for too long a second reaction occurs and must be avoided. During this reaction, the high carbon austenite (γ_{HC}) is decomposed into ferrite (α) and carbide (ε), causing the embrittlement of the material [8]. Eq. (B) represents this reaction:

$$\gamma_{HC} \rightarrow \alpha + \varepsilon \quad (B)$$

Therefore, the desired properties and microstructure of ADI are achieved after the completion of the first stage reaction but before the second stage reaction takes place.

The austempering time and temperature determinates the final microstructure and properties of ADI. At lower temperatures, it has high yield strength and hardness, due to the presence of a very thin ferrite and austenite. At higher austempering temperatures, the ferrite becomes coarser with

increased volume fraction of retained austenite, resulting in a significantly increase in ductility with lower values of yield strength [9] [10] [11].

EXPERIMENTAL PROCEDURE

Materials

The chemical composition of ductile iron used in this study is presented in Tab. 1. The material was originally cast in circular cross section bars. From these bars, samples for tension and impact tests were taken.

Tab. 1 – Chemical composition of ductile cast iron.

Composition (% wt)									
C	Si	Cu	Ni	Mo	Mn	Cr	Mg	P	S
3,4	3,1	0,666	0,616	0,293	0,2	0,06	0,042	0,1	0,009

Heat treatment

After machining, the samples were subjected to three distinct heat treatments. One group was austenitized at 910°C for 60 min and austempered at 320°C for 90 min; the second and the third groups were both austenitized at 930°C for 120 min and then austempered at 300°C and 280°C for 40 min respectively.

Microstructural analysis

Metallographic samples were taken from each of the heat-treated condition, including the as cast alloy. These samples were prepared in accordance with standard procedures for optical and SEM analysis.

X-ray diffraction analyses were performed to measure ɣ volume fraction and its carbon content. It was done using a monochromatic Cu-Kα, scanning the angular 2θ range from 40° to 50°, with an angular speed of 0,25°/min and an angular step of 0,02°. The profiles were then analyzed using the software PowderCell. The carbon content of the austenite was determined by Eq. (C) [12]:

$$\alpha\gamma = 0{,}3548 + 0{,}00441C\gamma \qquad (C)$$

where α_γ is the lattice parameter of austenite (in nm) and C_γ is the carbon content of austenite (in wt%).

Mechanical testing

Tensile and Charpy impact toughness tests were performed at room temperature with unnotched specimens and Brinell hardness was measured. For the tensile testing, three samples were tested in each heat-treated condition, with a constant engineering strain rate of 0,2 mm/min. Five specimens were used for each heat-treated condition in Charpy impact tests.

RESULTS AND DISCUSSION

Fig. 1 presents the SEM micrographs of the studied alloy. In the as-cast sample (Fig. 1a), the micrograph shows a structure containing dispersed graphite nodules in a matrix of 50% ferrite and 50% pearlite. A characteristic ferrite layer is observed around the graphite nodules, commonly called bull's eye.

The microstructure of the austempered samples (Fig. 1b-d) also contains dispersed graphite nodules. However, the matrix is composed of acicular ferrite and austenite, also known as ausferrite. The acicular ferrite is presented as the dark needles, while the austenite is the brighter phase between. These micrographs also show the influence of austempering temperature on the resulting microstructure. At 320°C, the microstructure appears coarser with larger interconnected areas of austenite, while at 280°C the microstructure is thinner with less retained austenite. Since 40 and 90 min fits the process window, no carbide formation were observed in all samples.

The volume fraction of austenite and austenitic carbon is presented in Tab. 2 as a function of austempering temperature. The sample austempered at 320°C presented approximately 41% more retained austenite than the other samples. This difference is because it's heat treatment promotes greater carbon enrichment in austenite due to higher austempering time.

The mechanical properties is presented in Tab.3. All three austempering treatments have produced ADI alloys with higher tensile properties than the as-cast condition, but with lower elongation.

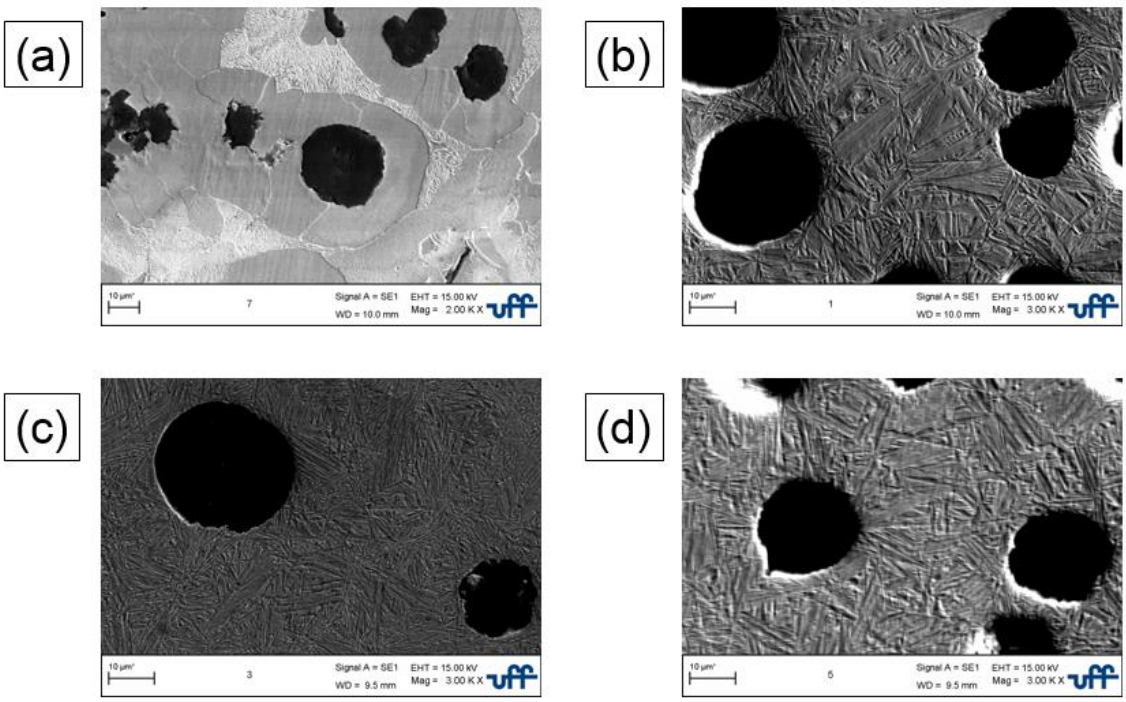

Fig. 1 - SEM micrographs of ductile iron in (a) as-cast condition and austempered at (b) 320°C, (c) 300°C and (d) 280°C.

Tab. 2 - Volume fraction of austenite and austenitic carbon.

Austempering temperature (°C)	**Volume fraction of austenite (%)**	**Volume fraction of austenitic carbon ($V_{\gamma C_\gamma}$)**
320	27,30	0,44
300	15,60	0,27
280	19,40	0,36

Fig. 2 shows the tensile and yield strengths initially increases with volume fraction of austenite and then decrease. Elongation behaves the same way, although these effects are less pronounced.

Brinell hardness improved significantly from the as-cast condition to the austempered samples; moreover, hardness presents a decrease with austempering temperature. As the microstructure becomes coarser at higher austempering temperatures, hardness tends to decrease.

Tab. 3 - Mechanical properties of ADI.

Austempering temperature (°C)	Yield strength (MPa)	UTS (MPa)	Elongation (%)	Brinnel hardness	Impact energy (J)
As-cast	673	870	7,24	255	45,00
320	1242	1433	3,52	370	99,90
300	1292	1495	3,43	395	67,92
280	1427	1599	3,12	445	76,17

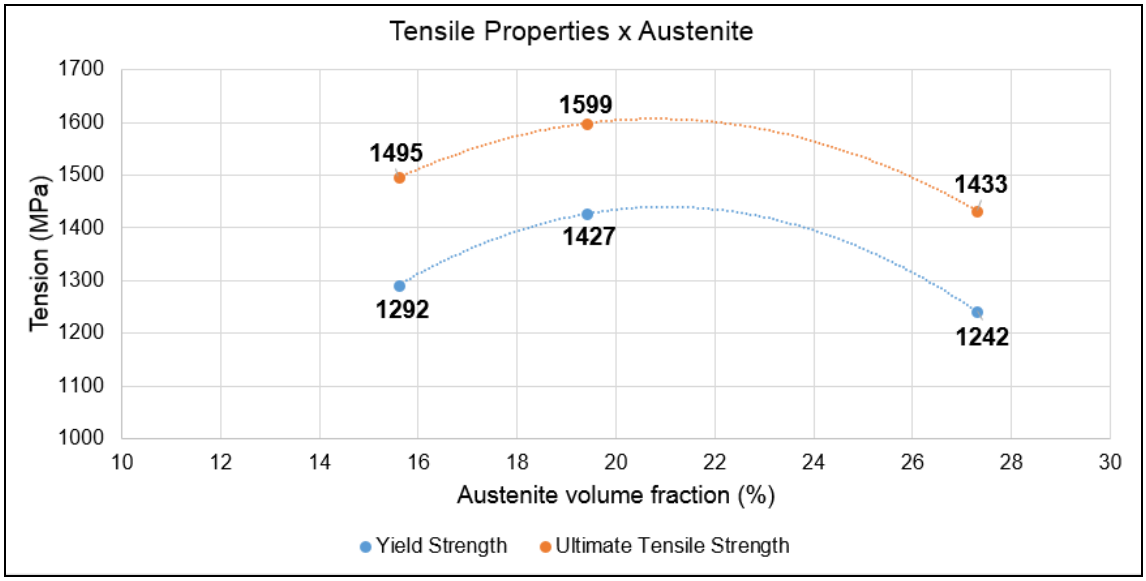

Fig. 2 – Relationship between tensile properties and retained austenite.

Impact energy also improves with austempering temperature. For austempered samples, brittleness increased as the volume fraction of austenite decreases. A direct relationship between impact energy and austenite volume fraction can be observed in Fig 3.

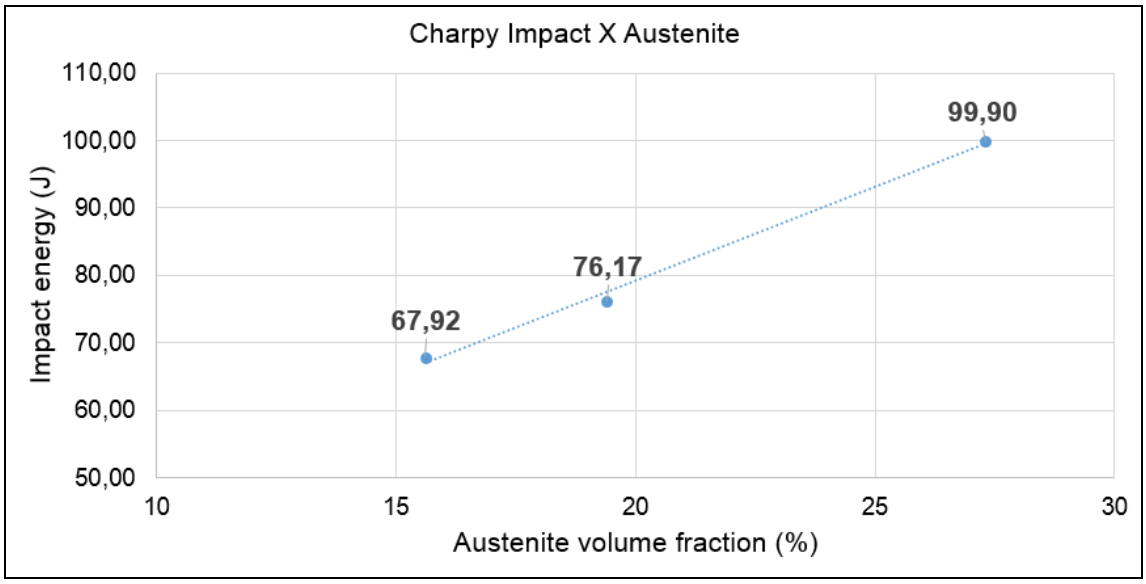

Fig. 3 - Relationship between impact energy and retained austenite.

This relationship between austempering temperature and strengthening effects is in agreement with previous results [9] [10] [13]. At higher austempering temperature, upper bainite transformation takes places. In this range, ADIs can enhance ductility but smaller increase in strength and hardness than those transformed at lower bainite temperature ranges.

CONCLUSIONS

The effect of austempering temperature and time on the mechanical properties of an ADI has been studied. The following conclusions can be drawn:

1. The samples showed a strong correltion between austempering temperatures and mechanical properties. The samples treated at lower austempering temperatures presented high tensile strength and hardness. High austempering temperatures lead to higher volumes of retained austenite, with enhanced ductility.
2. Austenite stability at room temperature is mostly defined by carbon enrichment during austempering reaction. Higher austenitization times showed no great influence on samples austempered for 40 min when compared with the sample with an austenitization of 1 h and austempered for 90 min.
3. The graphite nodules has no great influence on ausferrite matrix, leading to great uniformity.

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