EFFECT OF PRIOR MARTENSITE ON MECHANICAL PROPERTIES OF AUSTEMPERED DUCTILE IRON

CHEN YANG[1], DEREK O. NORTHWOOD[2] & CHENG LIU[1]
[1]College of Mechanical Engineering, Yangzhou University, PR China.
[2]Department of Mechanical, Automotive and Materials Engineering, University of Windsor, Canada.

ABSTRACT

An unalloyed ductile iron, which incorporates C and Si as major and Mn as minor alloying elements, is processed by a novel austempering process, in order to obtain superior mechanical properties. The samples are initially austenitized at 890°C for 20 min, then quenched into patented water-based quenching liquid at 180°C for 0.5, 2 and 3.5 s respectively, and austempered at 220°C for 240 min in an electric furnace. Optical microscopy (OM) and scanning electron microscopy (SEM) are performed to correlate the mechanical properties with microstructural characteristics. It is found that partial martensite can be formed firstly upon quenching, which will accelerate the subsequent bainitic transformation and promote refinement of multiphase colonies during austempering. The prior martensite content increases with increasing holding time during quenching. A tensile strength of 1330MPa, an elongation of 3.13% and a hardness of 45HRC can be achieved by controlling the prior martensite content to 12%. SEM of fracture surfaces reveals a mixed ductile and cleavage rupture morphology type in all samples. The results indicate that the tensile behavior of the investigated ADI is mainly influenced by the content of prior martensite.
Keywords: austempering process, bainitic transformation, prior martensite, tensile strength.

1 INTRODUCTION

Austempered ductile iron (ADI) is an attractive material for industrial applications due to its good mechanical properties. However, a higher strength and hardness, as well as substantial ductility and toughness, is required for ADI to substitute for steel in certain applications such as automotive carburized gears and rails.

It is well known that the austempering process is of importance in determining the specific microstructures and properties of ADI [1–5]. The common austempering process for ADI starts with austenitizing in the range of 840°C and 950°C, then rapidly quenching to an intermediate temperature usually between 250°C and 450°C, and subsequently isothermal austempering for a certain time, followed by final cooling to room temperature [6–12]. This produces a microstructure consisting of bainitic ferrite (BF) and high-carbon retained austenite (RA) with graphite nodules (GN) dispersed in the matrix. However, many studies have suggested that it is difficult to obtain both high strength and high toughness in a single austempering process. Therefore, it is necessary to develop the process technology for a high-performance ADI product.

A novel two-step austempering process for ADI at a lower temperature of 220°C, which is almost the lowest austempering temperature from the open literature, is designed to form a multiphase structure for improving the mechanical properties of ADI in this paper. The transformation mechanism during austempering at lower temperature is also discussed. Special attention is paid to the effect of prior martensite on the austempering process and the mechanical properties of ADI.

2 EXPERIMENTAL PROCEDURE

An unalloyed ductile cast iron was produced in a commercial electric induction furnace. The melt was poured into standard 25.4 mm 'Y' block shaped sand mold (ASTM A-395) (see Fig.1).

Table 1: Chemical composition of the ductile cast iron (wt.%).

C	Si	Mn	P	S
3.5	2.5	0.2	<0.0015	<0.0015

The chemical composition of the ductile iron is given in Table 1. After austenitizing at 890°C for 20 min in a JK-SX2-10-12N electric furnace, the samples were rapidly quenched to 180°C by controlling the patented water-based quenching liquid for 0.5 (sample A), 2 (sample B) and 3.5 s (sample C) respectively, then austempered at 220°C for 240min in another electric furnace, and finally cooled in air.

Tensile samples were machined in accordance with ASTM standard E8M from the 'Y' blocks using a spark machine (electric discharge machining) (see Fig. 1). The tensile tests were performed using a DNS100 universal testing machine, with a 100 kN load at a cross-head speed of 0.05 mm/min. Hardness tests were carried out using a HBE-3000 Brinell hardness tester with a load of 750 kg. For each sample condition, three readings were taken and averaged to represent the hardness value.

After being ground, polished and etched in 2% nital solution, the microstructure of each sample was observed using optical microscopy (LEICA GQ-300). The fracture surfaces of the tensile samples were examined in a XL30-ESEM scanning electron microscope. Image-pro plus 6.0 software was used to quantitatively evaluate the microstructure.

3 RESULTS AND DISCUSSION

Figure 2a shows a typical optical micrograph of the as-cast ductile iron sample, with nodules of graphite in a matrix, which is a mixture of fine pearlite and ferrite (see Fig. 2b).The OM
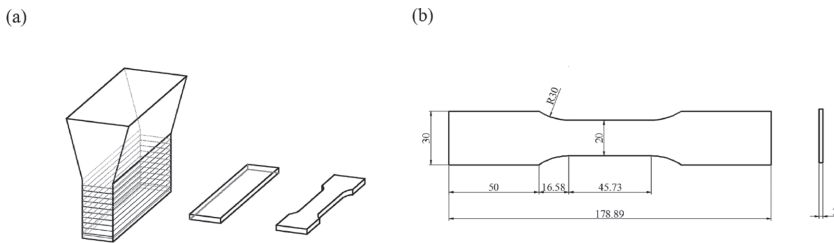

Figure 1: Schematics of (a) samples machined from Y blocks; (b) tensile test samples.
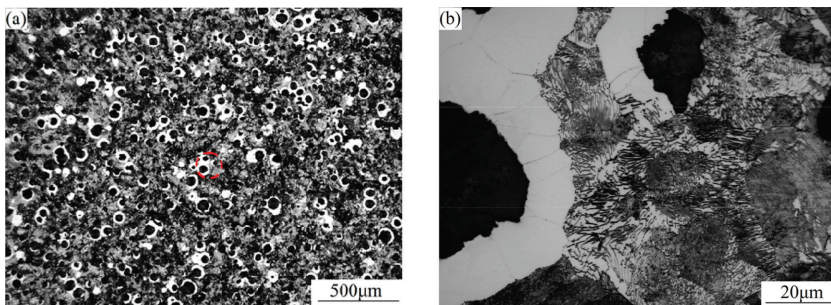

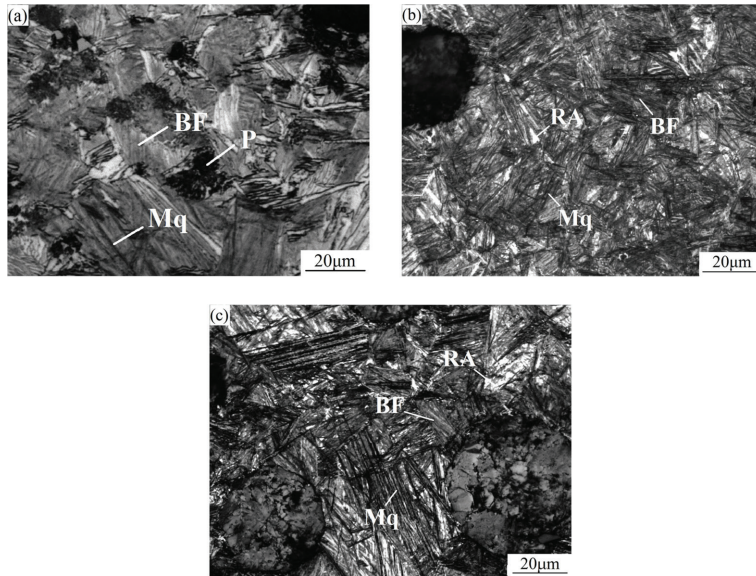Figure 2: OM micrographs of (a) as-cast ductile iron; (b) magnified area of red dash circle in (a).

Figure 3: OM micrographs of (a) sample A; (b) sample B; (c) sample C.

micrographs in Fig. 3 show that the matrix after austempering contains three main constituents, including BF (grey), RA (white) and needle-like prior martensite (Mq, dark black) in all samples. This is different from the normal ADI where the microstructure only consists of BF and RA. With increasing holding time during quenching, the amount of Mq increases (see from Fig. 3a and c) and the BF needle becomes much finer. Table 2 summarises the volume fraction of Mq obtained from the various austempering processes. With increasing holding time during quenching, the Mq content increases.

Figure 4 illustrates the influence of volume fraction of prior martensite on the mechanical properties of the samples. The tensile strength increases as the Mq content increases from 3 to 12% and drops with further increases to 29% in Mq content. The elongation has the same trend of change with increasing volume fraction of Mq. The optimum combination of tensile strength and elongation can be achieved at 12% volume fraction of Mq in sample B. Compared with as-cast ductile iron, each of three samples has a higher hardness value after austempering (Table 3). However, the hardness increases with increasing holding time during quenching from 0.5 s in sample A to 3.5 s in sample C.

The designed austempering process in this paper consists of initially rapid quenching and finally austempering at low temperature. In the process of rapid quenching, it is not surprising that a certain amount of Mq is formed during quenching to 180°C (see Fig. 3) since the start temperature of the martensite formation (Ms) is approximately 220°C according to the calculation formula given in Ref. [13]. On quenching to 180°C for a short time of 0.5 s, the temperature in a few local areas of the sample can reach this temperature,

Table 2: Volume fraction of Mq of sample (%).

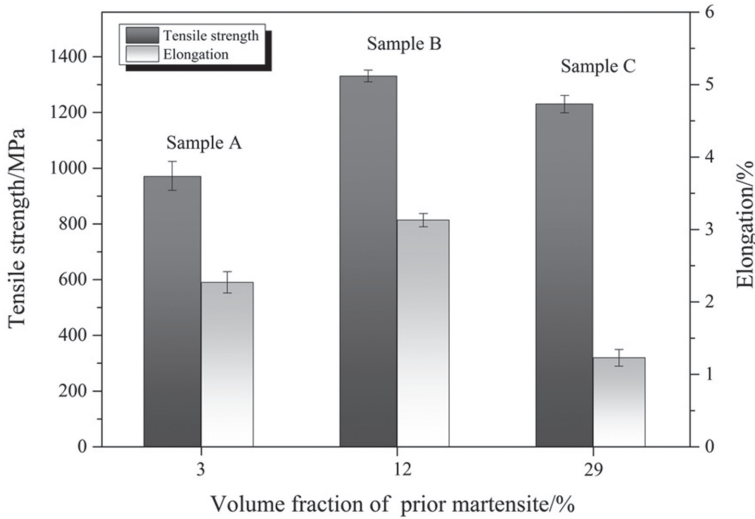| Sample A	Sample B	Sample C
3±0.6	12±0.9	29±1.4

Figure 4: Influence of volume fraction of Mq on tensile strength and elongation.

Table 3: Hardness values of samples

	As-cast ductile iron	Sample A	Sample B	Sample C
Hardness/HB	203±1.8	370±1.4	422±2.2	464±1.6
Hardness/HRC[*]	17±0.1	40±0.1	45±0.2	50±0.1

*by conversion

which is lower than Ms point, thus only about 3% Mq can be detected. After a longer hold-ing time during quenching, the amount of Mq is increased to 29% since the martensite transformation can occur in more local areas of sample C during quenching (see Fig. 3 and Table 2).

The carbon concentration of RA is an important factor in determining the mechanical properties of ADI [14–18]. In the process of austempering at 220°C for 240 min, the untransformed austenite during the initial quenching process will transform to BF, and Mq will become carbon depleted martensite rather than conventional tempered martensite [19]. The high content Si can suppress cementite precipitation in the ductile iron. The excess carbon from supersaturated martensite migrates to the adjacent untransformed austenite during austempering at 220°C (above Ms), which can enrich and retain austenite, instead of forming quenched martensite with high carbon content at room temperature upon final quenching. It can be seen from Fig. 5 that a multiphase structure of Mq surrounded by fine BF and film austenite with the thickness less than 100 nm is formed in sample B after aus-tempering at 220°C for 240 min. This result is consistent with the literatures, and such a microstructure is claimed to exhibit excellent mechanical properties [20, 21]. This suggests that the Mq can accelerate the subsequent nanobainitic transformation due to the similar orientation between Mq and adjacent BF needles. For the formation of Mq, dislocations with a high density in the austenite near Mq lath boundary are introduced to increase the nucleation rate of BF and thus refine the microstructure [21, 22]. When the Mq content increases from 3% (sample A in Fig. 4) to 12% (sample B in Fig. 4), more fine multiphase structures can be formed, which leads to a better combination of strength and elongation.
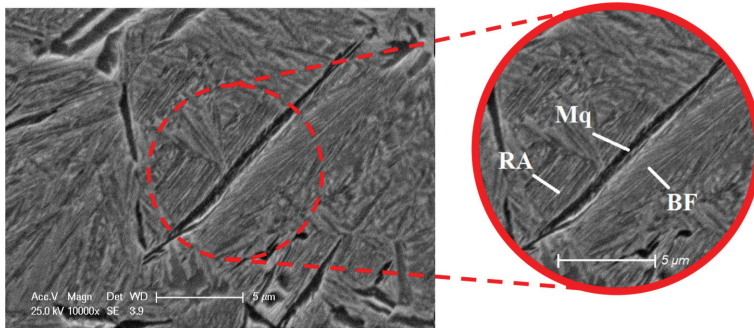
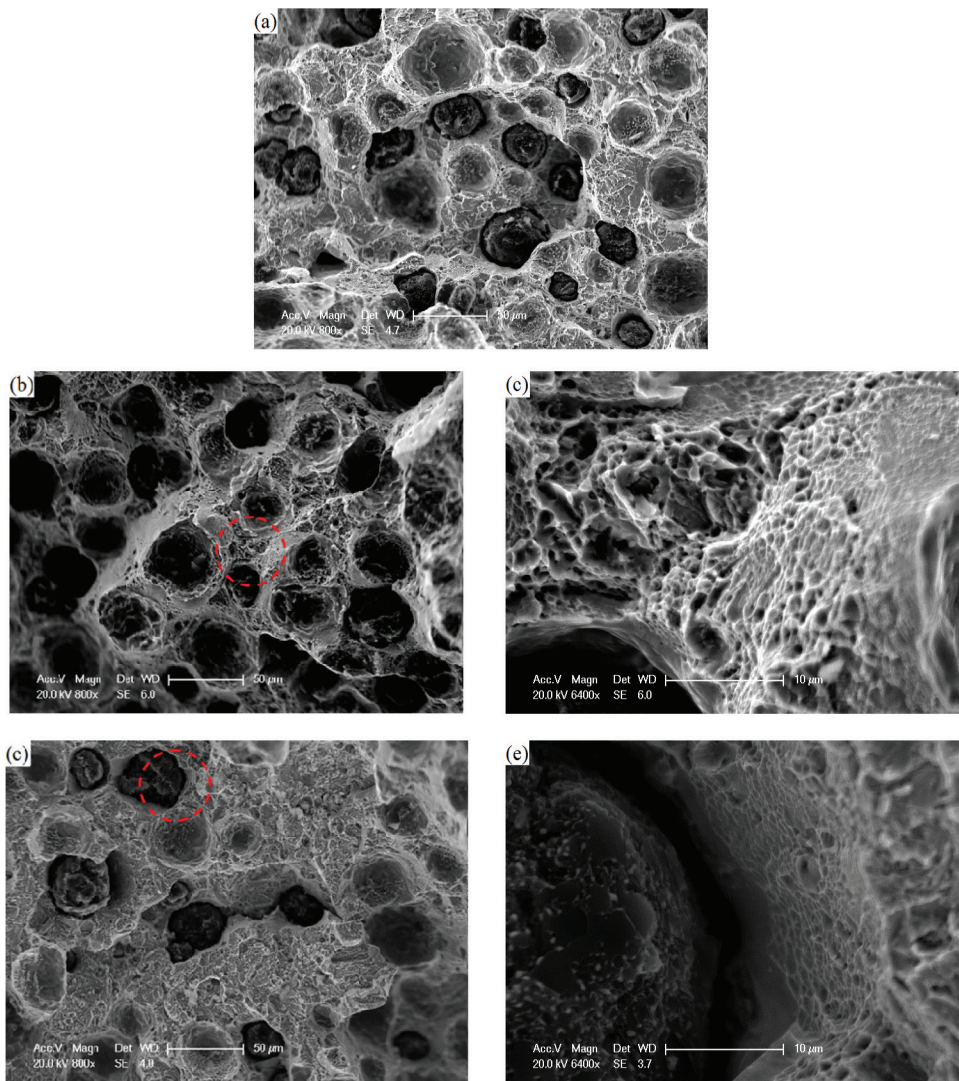Figure 5: SEM micrograph of sample B austempered at 220°C for 240 min.

Figure 6: SEM fractographs of (a) sample A; (b) sample B; (c) area marked by red dash circle in Fig. 6b, d sample C; (e) area marked by red dash circle in Fig. d.

Figure 4 shows that both the tensile strength and elongation decrease with increasing Mq content from 12% (sample B in Fig. 4) to 29% (sample C in Fig. 4). This corresponds to a relative reduction in the amount of multiphase structure with the increased amount of Mq.

Generally, the hardness increases as the martensite content increases [23]. Thus, the reason why the hardness value increases with increasing holding time during quenching, might be explained by the amount of Mq (see Table 3).

Typical SEM fractographs for the samples after tensile testing are shown in Fig. 6. For sample A with 3% Mq, the fracture is a cleavage type (see Fig. 6a). For sample B with 12% Mq, there are a large amount of dimples and some cleavage facets (see Fig. 6b and c). When the amount of Mq is increased to 29% in sample C, there is a mixture of ductile and cleavage fracture mechanism (see Fig. 6d). Figure 6e indicates that less microductility can be found at the pull-out area of graphite nodule. Fracture observations support the tensile experimental results. Thus, sample B with 12% Mq displays a mostly ductile fracture.

4 CONCLUSIONS

The tensile behavior of a ductile iron treated by a novel austempering process is evaluated. The designed austempering treatment consists of initial rapid quenching to 180°C for different times and finally austempering at 220°C for 240 min. A multiphase structure of prior martensite and fine lath bainitic ferrite with a film retained austenite is obtained. The optimum mechanical properties, with a tensile strength of 1330 MPa and an elongation of 3.1% can be achieved by controlling the prior martensite content to 12%. This is mainly attributed to prior marteniste, which can accelerate the subsequent bainitic transformation and promote refinement of multiphase colonies.

ACKNOWLEDGEMENTS

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