Effect of two-step austempering on fatigue behavior of austempered ductile iron (ADI)

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Abstract

The effect of two-step austempering on the fatigue properties in alloyed ductile iron was studied. The ductile irons were subjected to conventional and two-step austempering processes. The austempering process was performed by making three batches. In the first batch, samples after austenitizing at 900 °C were conventionally austempered separately at two temperatures, namely 400 °C and 320 °C. In the second batch, samples were austempered first at 400 °C followed by austempering at 320 °C. In the third batch, samples were austempered first at 320 °C followed by austempering at 400 °C. Austempered samples were characterized for morphology and distribution of phases by optical microscope and scanning electron microscope. It was found that the properties increased with the increase in amount of lower bainitic ferrite and retained austenite of high carbon content. The retained austenite with low carbon content was found to transform into martensite during loading and led to decrease the properties.

Keywords Austempered ductile iron · Fatigue · X-ray diffraction

1 Introduction

Austempered ductile cast iron (ADI) is regarded as an essential engineering material as it possesses high strength and good ductility [1–3], good wear resistance [4, 5], fatigue strength [6–8] and fracture toughness [9–11]. Because of these combinations of properties, ADI is now used extensively in many structural applications in automotive industry, defense and earth moving machineries, etc.

When ADI undergoes austempering process, a unique microstructure is obtained that contains ferrite and high carbon austenite. The microstructure involving ferrite and austenite is referred to as ausferrite. During the austempering of ADI, different microstructures are obtained depending on austenitizing time, temperature and austempering time, temperature. When austempered at temperatures lower than 300 °C, the microstructure contains very small ferrite platelets separated by austenite. Such

microstructures lead to high strength and low ductility. On the other hand, austempering at temperatures higher than 350 °C, coarse ferrite is the product separated from each other by austenite. Such microstructures lead to low strength and high ductile properties in ADI. Several researchers [12–16] have reported the effects of heat treatment on mechanical properties of ADI. Effects of moisture [17], stress corrosion cracking [18] and welding [19] were studied in detail.

Both step-down and step-up austempering processes have been applied in case of ADI. It is well reported that step-up austempering leads to remarkable improvement [21–28] in mechanical behavior of ADI due to the presence of finer ferrite and higher austenitic carbon in ADI. However, there exists some controversy about the step-down austempering process. Few researchers [29–31] found some improvement in mechanical properties as a result of the step-down austempering process; others [20, 21] have concluded no remarkable differences in the

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mechanical properties of ADI processed by conventional and step-down austempering processes.

Lin et al. [20] studied the effect of microstructure on high-cycle fatigue (HCF) of different types of ADI. These ADIs were produced from four different base irons with various nodularity, nodule counts and alloy elements. Each base iron was austenitized at 900 °C and then austempered at 300 and ~ 360 °C, respectively, to generate different ADI matrix structures. The improved fatigue behavior was obtained for ADI samples produced at austempering done at 360 °C [32]. These researches show that improvement in HCF strength may be due to higher amount of austenite and low carbon content. 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 [33, 34] or plastic deformation due to service loading [32] 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 [32, 35].

This research aims to study the effect of two-step austempering process on the fatigue behavior of an alloyed ADI considering the microstructural changes.

2 Experimental procedure

2.1 Material

The chemical composition of ductile iron used in this study is given in Table 1. The material was cast in the form of blocks of 150 mm length and 125 mm width and 25 mm thick. The nodule count was measured by using image analyzer which resulted in a nodule count of 100/mm², and the nodules were equally distributed in the matrix. The porosity and other types of defects were found to be at the acceptable level.

2.2 Heat treatment

Initially, austenitization of the specimens at 900 °C for 60 min was done, and a two-step austempering was performed. Two-step austempering (TSA) was done in different ways like two-step austempering TSA-1 and TSA-2.

In TSA-1, austenitized specimens were austempered at 400 °C for 30 min and immediately austempered at 320 °C for duration of 30 min, 60 min and 120 min. In TSA-2, austenitized samples were austempered at 320 °C for 30 min and immediately austempered at 400 °C for 30, 60 and 120 min. For comparing, conventional austempering (CA) was done at two temperatures. In CA-1, specimens were austempered at 400 °C for 150 min, and in CA-2, specimens were austempered at 320 °C for 150 min. Figure 1a–c shows TSA-1, TSA-2 and CA-1, CA-2 processes.

2.3 Optical and mechanical tests

To identify the matrix structure and morphology, samples were examined using Zeiss Axio Lab A1 optical microscope. Microhardness test was made with a load of 1 kg and a dwell time of 15 s. The micrographs and fractographs were obtained by JEOL 6380LA scanning electron microscope.

2.4 Fatigue test

Fatigue specimens were prepared as per ASTM E466 standard. Fatigue tests were conducted for 10⁷ cycles using Roell Amsler UBM 200 setup. The frequency of the stress cycle was 1400 cycles/min.

2.5 Measurement of the volume fraction of austenite

Quantitative analysis was done by using JEOL-JDX-8P X-ray diffractometer (operated with Cu-K α radiation at 30 kV and 20 mA) according to ASTM E975-84 standard. The 2 θ range was selected between 40° and 50°. The areas under the peaks were measured using the Eva™ software. The angular positions of the austenite peaks were used for the determination of carbon content, and the area under austenite and ferrite peaks was used for the determination of amount of austenite [36, 37].

3 Results and discussion

3.1 Fatigue properties

In this study, the fatigue limit for the as-cast and austempered specimens was estimated by conducting the experiments at different stress amplitudes. Figure 2 shows the

Table 1 Chemical composition of the castings

Element	C	Si	Mn	Cu	P	S	Mg
Weight percent	3.48	2.4	0.31	0.03	0.01	0.01	0.05

Fig. 1 Two-step austempering TSA-1 (a), TSA-2 (b); conventional austempering CA-1, CA-2 (c)

Fig. 2 Stress versus number of cycles curve

stress versus number of cycles curve for as-cast and heat-treated samples.

Considering Fig. 2, five samples' results were used for drawing the S–N curve. Since the CA-1, CA-2, TSA-1 and TSA-2 samples were heat-treated for 150 min. Conventional austempered (at 400 °C) CA-1 sample showed

175 MPa, and CA-2 (at 320 °C) showed 350 MPa. Two-step austempered (at 320 °C) TSA-1 showed 350 MPa, and TSA-2 (at 400 °C) showed 300 MPa. The CA-2 and TSA-1 samples (both at 320 °C) exhibited the highest fatigue strength. The as-cast ductile iron shows a fatigue strength of 150 MPa which is inferior compared to heat-treated samples.

The influence of microstructure on the properties of ADI is clearly observed. Hence, it is necessary to discuss the variation of fatigue properties with microstructure. It is generally reported for steels and other materials that stress amplitude increases with the increase in tensile strength. For steels, ferrite and pearlite control the properties. For ADI, the amount of bainitic ferrite (lower and upper) and amount of retained austenite decide the properties.

The X-ray diffraction profiles obtained for CA, TSA-1 and TSA-2 are shown in Figs. 3, 4 and 5, respectively. The profiles are superimposed for comparison purpose. It is observed that there is a considerable shift in the austenite peak as the austempering time was varied. This signifies a change in the carbon content of the retained austenite and its stability.

Figure 3 shows that the austenite peak of CA-1 specimen corresponds to 43.23° for which corresponding

Fig. 3 XRD profile of CA specimens (CA-1 dotted line and CA-2 thick line)

Fig. 4 XRD profile of TSA-1 specimens. Specimen 1: TSA-1 for 60 min; specimen 2: TSA-1 for 90 min; specimen 3: TSA-1 for 150 min

Fig. 5 XRD profile of TSA-2 specimens. Specimen 4: TSA-2 for 60 min; specimen 5: TSA-2 for 90 min; specimen 6: TSA-2 for 150 min

carbon content was 1.75 wt%, whereas austenite peak of CA-2 specimen is 43.29° and the corresponding carbon content was 1.64 wt%. There was no shift in the ferrite peak as the solubility of carbon in ferrite is very low. Similarly, Fig. 4 shows that a shift in the austenite peak was observed from 43.29° to 43.22° as the austempering time increases from 60 min to 150 min. This shows that carbon content in retained austenite increased from 1.64 to 1.77 wt%. In the same way, in case of TAS-2, there is an increase in carbon content of the retained austenite from 1.62 to 1.73 wt% when the austempering time increased from 60 to 150 min (Fig. 5).

From Table 2, it is clear that the retained austenite content decreased with increasing austempering time. Since the bainitic transformation is time-dependent phenomenon, there is an opportunity for the retained austenite to transform into bainitic ferrite which will result in the decrease in austenite retainment at the end of austempering process. Carbon content in the retained austenite is another important microstructural feature. The carbon content was found to increase with austempering time. As the austempering time increases, the rejection of carbon from the growing ferrite also increases which in turn increases the carbon content of retained austenite at the end of the austempering process. The carbon content of the retained austenite for CA-1 and CA-2 specimens was 1.75 wt% and 1.62 wt%, respectively. The higher carbon content in CA-1 is due to faster diffusion of carbon into the surrounding austenite, and more carbon finds its way toward the austenite to enrich it, whereas CA-2 showed relatively less carbon because of low temperature. At 320 °C, diffusion of carbon becomes difficult and maximum carbon is trapped within the ferritic needles in the form of carbide. If one considers TSA-1 and TSA-2, it is the combination of CA-1 and CA-2, the carbon content would fall within the extremities of CA-1 and CA-2.

To have a clear understanding, the microstructure of the fatigue specimens is studied. Since CA-1 sample contained

considerable amount of retained austenite, it is expected to result in improved fatigue properties. But in this study, it resulted in lower stress amplitudes relative to CA-2 sample which had less amount of retained austenite. The point to be noted here is that the number of phases, its location and distribution have a great influence on the fatigue properties. Since ferrite is in a stable phase, retained austenite may transform into martensite. The literature suggests about the strain-induced martensite transformation when the specimen is loaded. The extent of brittleness induced in the material under different heat-treated conditions was measured by taking hardness at the fractured surfaces (Table 3).

From Table 3, it is observed that the hardness value increased at the fracture surface. The increase in surface hardness after fracture is attributed to strain hardening of the material as well as phase transformation. Generally in steels, the effect of strain hardening in increasing the surface hardness is marginal and drastic increase in hardness which is observed here for some specimens should be due to phase transformation during loading. The increased hardness values marked with "*" are accompanied with phase transformation, while in other cases the increased hardness is due to strain hardening.

The additional information was obtained by conducting the fractographic study. Figures 6, 7 and 8 show the fractographs of fatigue specimens. The fractographs show varying amounts of dimples and cleavage facets. Generally, cleavage facets are the characteristic features of brittle fracture, while the presence of dimples is the characteristic sign of ductile fracture. The samples austempered at 400 °C (CA-1) showed completely brittle failure, whereas those austempered at 320 °C (CA-2) showed ductile fracture. The interesting point here is that the samples of CA-1 should have resulted in ductile type of fracture because of the presence of large amount of austenite. But it did not happen because of

Table 2 Details of retained austenite, ferrite and carbon content

Austempering process	Retained austenite %	Ferrite %	Carbon content in retained austenite %
TSA-1, 60 min	37	63	1.64
TSA-1, 90 min	34	66	1.69
TSA-1, 150 min	15	85	1.77
TSA-2, 60 min	38	62	1.62
TSA-2, 90 min	36	64	1.66
TSA-2, 150 min	19	81	1.73
CA-1, 150 min	39	67	1.75
CA-2, 150 min	28	75	1.64

Table 3 Surface hardness of the specimens

Sl. no.	Process/material	Microhardness (VHN) before deformation	Microhardness (VHN) after fracture
1	As-cast ductile iron	260	285
2	TSA-1, 60 min	310	367*
3	TSA-1, 90 min	375	398
4	TSA-1, 150 min	438	378
5	TSA-2, 60 min	302	390*
6	TSA-2, 90 min	352	365
7	TSA-2, 150 min	425	426
8	CA-1, 150 min	320	338
9	CA-2, 150 min	415	476*

Fig. 6 Fractographs of CA-2 (a) and CA-1 (b) specimens **Fig. 7** Fractographs of TSA-1 (a) and TSA-2 (b) (austempering time 90 min) **Fig. 8** Fractographs of TSA-1 (a) and TSA-2 (b) specimens (austempering time 150 min)

the transformation of strain-induced martensite during fatigue testing. During two-step austempering TSA-1 and TSA-2, the type of fracture seems to be different compared to CA-1 and CA-2. In case of TSA-2, the austempering time of 60 min resulted in mixed type of fracture with majority of brittle cleavage facets whereas for TSA-1, the majority is dimple type. However, for higher austempering time of 90 and 120 min, the type of fracture is almost ductile. This is because of the fact that in case of TSA-1, the second-step austempering temperature was 320 °C

and with increasing austempering time the amount of lower bainitic ferrite increases. Besides this, the dimple size is also reduced with increasing time which means to say that the grain refinement has taken place due to increased austempering time. Generally, grain refinement leads to increased strength and toughness of the material. Therefore, the improvement in fatigue properties is attributed to the highly stable austenite, lower bainitic ferrite which is fine in nature.

4 Conclusions

The following conclusions were drawn based on the fatigue behavior of the ductile iron subjected to conventional and two-step austempering processes.

- Conventional austempered CA-2 (at 320 °C) sample and two-step austempered TSA-1 (at 320 °C) showed fatigue strength of 350 MPa. This fatigue strength is 233% higher compared to that of as-cast ductile iron.
- The fatigue limit increased with austempering time in both two-step austempered (320 °C) and (400 °C) specimens. This increase is attributed to more amount of bainitic ferrite formation and also due to higher stability of austenite which reduces the possibility of strain-induced martensite during loading.
- The fractured surface is brittle for conventional austempered specimen (400 °C) and ductile for conventional austempered specimen (320 °C).
- The type of fracture in two step austempered (320 °C) and (400 °C) specimens was dimple type of fracture and the size of the dimples reduced as the austempering time increased. This was due to grain refinement.

Compliance with ethical standards

Conflict of interest Authors declare that there is no conflict of interest regarding publication of this manuscript.

References

- Dodd J (1978) High-strength, high-ductility, ductile irons. *Mod Cast* 68(5):60–66
- Gundlach RB, Janowak JF (1983) Development of a ductile iron for commercial austempering. *AFS Trans* 94:377–388
- Harding RA, Gilbert GNJ (1986) Why the properties of ductile irons should interest engineers. *Br Foundrym* 79:489–496
- Johansson M (1977) Austenitic bainitic ductile iron. *AFS Trans* 85:117–122
- Putatunda SK et al (1993) Influence of microstructure on high-cycle fatigue behavior of austempered ductile cast iron. *Mater Charact* 30:221–234
- Shanmugam P, Rao PP, Udupa KR, Venkataraman N (1994) Effect of microstructure on the fatigue strength of an austempered ductile iron. *J Mater Sci* 29:4933–4940
- Bartosiewicz L, Duraiswamy S, Sengupta A, Putatunda SK (1991) In: Morris fine symposium, TMS, Detroit, pp 135–138
- Bartosiewicz L, Krause AR, Sengupta A, Putatunda SK (1990) In: International symposium for testing and failure analysis. ISTFA, ASM, vol 16, pp 323–336
- Janowak JF, Norton PA (1985) Guide To mechanical properties possible by austempering, 1.5% Ni, 0.3% Mo Iron. *AFS Trans* 88:123–135
- Wilkinson G, Grupke C (1986) Design consideration and product applications of ADI casting. In: 2nd international conference on ductile iron. Ann Arbor, MI, pp 349–358
- Panasiewicz J, Grupke C, Huth J (1991) In: Chryslers world conference on austempered ductile iron, Bloomington, Mar 1991, pp 176–94
- Dorazil E, Barta B, Munsterova E, Stransky L, Huvar A (1982) High-strength bainitic ductile cast iron. *AFS Int Cast Metal* 7:52
- Janowak JF, Gundlach RB (1983) Development of a ductile iron for commercial austempering (retroactive coverage). *AFS Trans* 91:377
- Rouns TN, Rundman KB, Moore DM (1984) On the structure and properties of austempered ductile cast iron (retroactive coverage). *AFS Trans* 92:815
- Darwish N, Elliot R (1993) Austempering of low manganese ductile irons. Part 3 variation of mechanical properties with heat treatment conditions. *Mater Sci Technol* 9:882
- Moore DJ, Rouns TN, Rundman KB (1985) Structure and mechanical properties of austempered ductile iron. *AFS Trans* 93:705
- Masud L, Martinez R, Simison S, Boeri R (2003) Embrittlement of austempered ductile iron on contact with water—testing under applied potential. *J Mater Sci* 38:2971. <https://doi.org/10.1023/A:1024425727963>
- Lin C, Yang C, Wang J (2003) Corrosion fatigue of austempered ductile iron. *J Mater Sci* 38:1667. <https://doi.org/10.1023/A:1023211323116>
- Li D, Zhou Z, Sun D (2004) Analysis on the welding heat-affected zone microstructures of austempered ductile iron. *J Mater Sci* 39:7119. <https://doi.org/10.1023/B:JMSC.0000047563.46550.e6>
- Pereloma EV, Anderson CS (2006) Microstructure and properties of austempered ductile iron subjected to single and two-step processing. *Mater Sci Technol* 22:1112–1118
- Grech M, Bowen P, Young JM (1991) Effect of austempering temperature on the fracture toughness and tensile properties on ADI alloyed with copper and nickel. Paper presented at the world conference on ADI, Chicago, 15–18 July 1991
- Yang J, Putatunda SK (2003) A novel processing of austempered ductile cast iron. *Mater Sci Forum* 426–432:913–918
- Putatunda SK (2001) Development of austempered ductile cast iron with simultaneous high yield strength and fracture toughness by a novel two-step austempering process. *Mater Sci Eng A* 315:70–80
- Yang J, Putatunda SK (2004) Improvement in strength and toughness of austempered ductile cast iron by a novel two-step austempering process. *Mater Des* 25:219–230
- Yang J, Putatunda SK (2004) Influence of a novel two-step austempering process on the strain hardening behavior of austempered ductile iron. *Mater Sci Eng A* 382:265–279
- Yang J, Putatunda SK (2005) Near threshold fatigue crack growth behavior of austempered ductile cast iron processed by a novel two-step austempering process. *Mater Sci Eng A* 393:254–268
- Yang J, Putatunda SK (2005) Effect of microstructure on abrasion wear behavior of austempered ductile cast iron processed by a novel two-step austempering. *Mater Sci Eng A* 406:217–228
- Francucci G, Sikora J, Dommarco R (2008) Abrasion resistance of ductile iron austempered by the two-step process. *Mater Sci Eng A* 485:46–54
- Ahmadabadi MN, Ohide T, Niyam E (1992) Effects of successive stage austempering on the structure and impact strength of high Mn-ductile iron. *Cast Metal* 5(2):62–72
- Bayati HK, Elliot R (1998) Stepped austempering heat treatment of a 0.67% Mn–Mo–Cu ductile iron. *Mater Sci Technol* 13:117–123

31. Hsu CH, Chuang TL (2001) Influence of stepped austempering process on the fracture toughness of austempered ductile iron. *Metall Mater Trans A* 32:2509–2513
32. Lin CK, Lai PK, Shih TS (1996) Influence of microstructure on the fatigue properties of austempered ductile irons—I. High-cycle fatigue. *Int J Fatigue* 18:297–306
33. Garin JL, Mannheim RL (2003) Strain-induced martensite in ADI alloys. *J Mater Proc Technol* 143–144:347–351
34. Zimba J, Simbi DJ, Navara E (2003) Austempered ductile iron: an alternative material for earth moving components. *Cem Concr Compos* 25(6):643–694
35. Putatunda KS (2001) Development of austempered ductile cast iron (ADI) with simultaneous high yield strength and fracture toughness by a novel two-step austempering process. *Mater Sci Eng (A)* 315:70–80
36. Cullity BD (2001) *Elements of X-ray diffraction*, 3rd edn. Prentice Hall, Upper Saddle River
37. Rouns TN, Rundman KB (1987) Constitution of austempered ductile iron and kinetics of austempering (retroactive coverage). *AFS Trans* 95:851–874

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