Investigations on the Microstructure and Fracture of Alloyed Austempered Ductile Iron

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Abstract. An investigation has been conducted on two austempered ductile irons (ADI) alloyed with Cu (0.45%) and Cu (1.6%) + Ni (1.5%) austempered at 350°C in a range of times. The microstructure and fracture mode developed throughout these treatments have been identified by means of light and scanning electron microscopy (SEM) and X-ray diffraction analysis. Significantly more retained austenite was observed in ADI alloyed with Cu+Ni than in ADI alloyed with Cu austenitized and austempered under the similar conditions. This yields to the higher impact energy and the substantial plastic deformation of ADI alloyed with Cu+Ni.

Introduction

In recent years, there has been a significant interest in processing and developing of austempered ductile cast iron (ADI). Many workers have reported excellent mechanical properties [1-6] of properly cast and heat-treated ADI. It appears that ADI can be developed into a major engineering material with a wide range of versatile properties.

ADI is a heat-treated alloyed nodular cast iron with a unique microstructure that consists of high carbon austenite and acicular ferrite with graphite nodules dispersed in it. The base iron chemistry and alloy additions in ductile iron play important roles in ADI technology. The addition of alloying elements for the production of ADI is often considerably higher than the levels used for the production of conventional grades of ductile irons [7]. Since the majority of ADI components should posses satisfactory austemperability, alloying elements serve to delay the transformation of austenite [7-11]. The importance of alloying additions depends upon their relative effectiveness on the reactions in stage I and stage II of the austempering process. The effect of Si and the individual or combined additions of Cu, Mo, Ni, and Mn on the transformation characteristics of ADI have been reported earlier. [8,9]. Mn and Mo delay the reactions in stage I and II of the austempering process, wheras Cu does not effect the carbon diffusion in austenite or the stability of austenite. However, it has been reported that Cu suppresses carbide formation in lower bainite [8]. Ni acts in a similar way to Cu. If Ni is present in excess of 0,5%, it slows down the bainitic reaction, and thus, causes the formation of martensite at austenite cell boundaries on cooling.

The findings on the influence of additions of Cu and Cu+Ni on austempering are reported and discussed in this paper. The effect of austempering time and alloy composition on the microstructure and the fracture mechanism after austenitizing at 900°C and the subsequent austempering at 350°C have been studied.

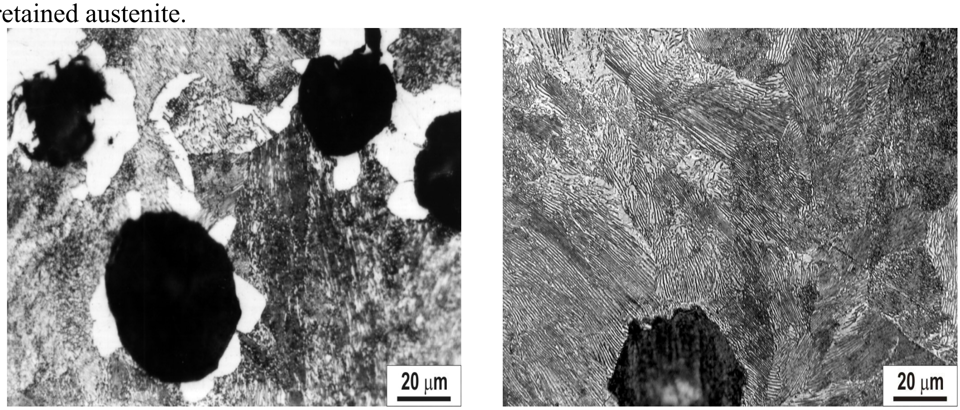
Experimental

Two ductile irons with chemical compositions (in wt.%): (a) 3.6C; 2.5Si; 0.28Mn; 0.04Cr; 0.45Cu; 0.01P; 0.014S; 0.066Mg, and (b) 3.07C; 2.15.Si; 0.26Mn; 0.04Cr; 1.6Cu; 1.5Ni were produced in a commercial electro-induction foundry furnace. Un-notched Charpy specimens (55x10x10mm) were machined from Y blocks. Specimens austenitized in a protective argon atmosphere at 900°C for 2h were rapidly transferred to a salt bath at austempering temperature 350°C, held between 1 and 6h and then air-cooled to room temperature. Standard metallographic preparation techniques (mechanical grinding and polishing followed by etching in Nital) were applied prior to light microscopy (LM) examinations. A "Leitz" metallographic microscope was used for microstructural characterization, whereas "Opton Axioplan" light microscope equipped with the software "Vidas" program was applied to measure the distribution of graphite nodules and the volume fraction of retained austenite. Change in the volume fraction of retained austenite during austempering was determined by the X-ray diffraction technique on diffractometer "Siemens D-500" with Ni filtered CuKα radiation. The diffractograms were analyzed applying direct comparasion method [9]. The austempered Charpy specimens were tested at room temperature in a standard impact testing machine. At least three specimens were tested for each heat treatment. The fractured surfaces were examined by JEOL JSM-6460LV scanning electron microscope (SEM) operated at 25kV.

Results and Discussion

The microstructure of cast Cu alloyed and Cu-Ni alloyed ductile iron contains graphite nodules in a ferrite-pearlite matrix as can be observed in Fig.1a), and Fig.1b), respectively. The effect of austempering time and alloy composition has been studied on the austempered microstructure and austempering kinetics for both the ductile iron, when the samples were austenitized at 900°C for 2h and subsequently austempered at 350°C for different time periods.

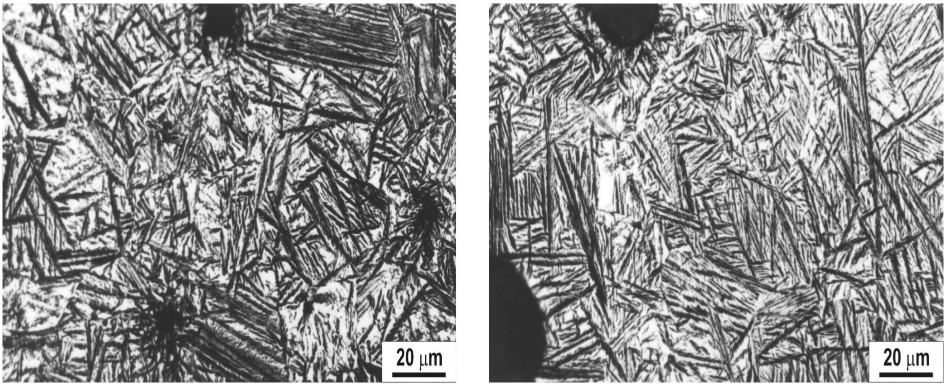
The austempered microstructures of Cu alloyed ADI are given in Fig. 2(a-b) when the iron is austempered at 350°C for 1 and 2h, respectively. The ADI, austempered for 1h consists of a substantial amount of martensite and small amounts of bainitic ferrite and retained austenite.



(a) (b)

Fig. 1. *LM. Microstructure of ADI alloyed with Cu (a) and alloyed with Cu+Ni (b)*

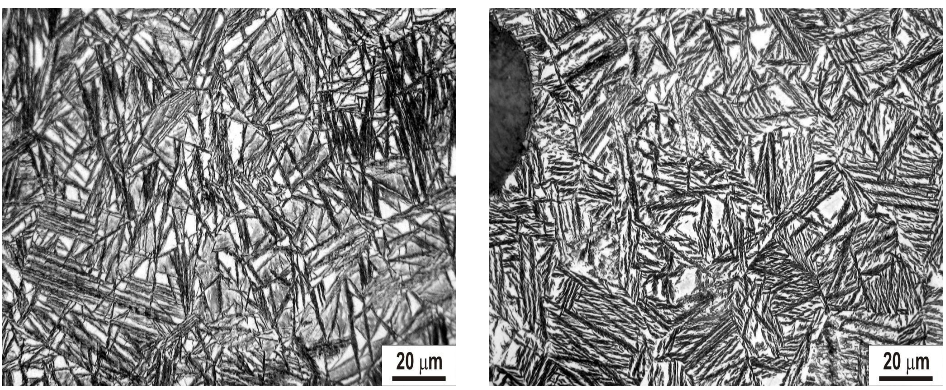
At the longer austempering time of 2h, the microstructure consists of bainitic ferrite and retained austenite, and no martensite is visible in the microstructure.



(a) (b)

Fig. 2. *LM. Microstructure of ADI alloyed with Cu after austempering at 350 ^{o}C for 1h (a) and for 2h (b).*

The austempered microstructures of ADI alloyed with Cu+Ni are shown in Fig. 3a, b. At a shorter austempering time (1h), the austempered microstructure reveals blocky darkened areas containing a high fraction of plate-like martensite. At the longer austempering time (3h), there is an appreciable decrease in the amount of martensite and an increase in the amounts of bainitic ferrite and retained austenite. Comparing the austempered microstructure of ADI alloyed with Cu, one could observe a relatively higher amount of upper bainite in Cu+Ni alloyed ADI. The addition of Ni lowered the bainitic transformation temperature range resulting in transformation to upper bainite range.



(a) (b)

Fig. 3. *LM. Microstructure of ADI alloyed with Cu+Ni after austempering at 350 ^{o}C for 1h (a) and for 3h (b).*

Fig.4 shows the variation of impact energy for ADI alloyed with Cu and ADI alloyed with Cu+Ni with austempering time at 350^{o}C. The results show that the impact energy increases as the austempering time increases. The maximum impact energy of ADI alloyed with Cu (106J) is achieved after 2h. On the other side, the maximum impact energy of ADI alloyed with Cu+Ni (112J) is achieved after 3h of austempering.

The fracture surface of an un-notched impact specimens of ADI alloyed with Cu and ADI alloyed with Cu+Ni after austempering at 350°C for 2h and 3h are shown in Fig. 5 a, b, respectively. The microfractographs correlates quite well with both the corresponding microstructures and the results of impact energy. Substantial plastic deformation is associated with the higher impact energy of ADI alloyed with Cu+Ni. Many dimples are due to the size and disorder of the bainite subgrains (Fig. 5b).

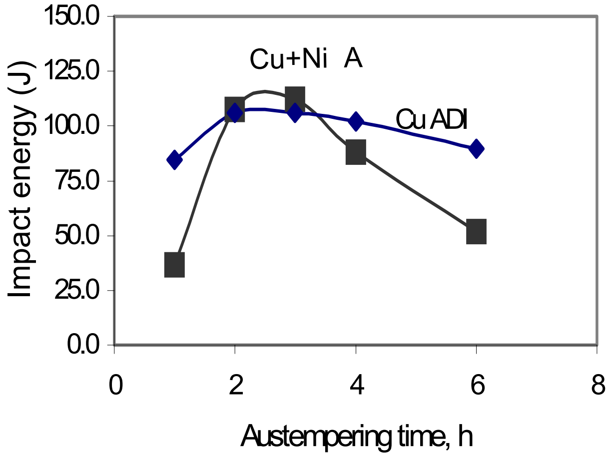
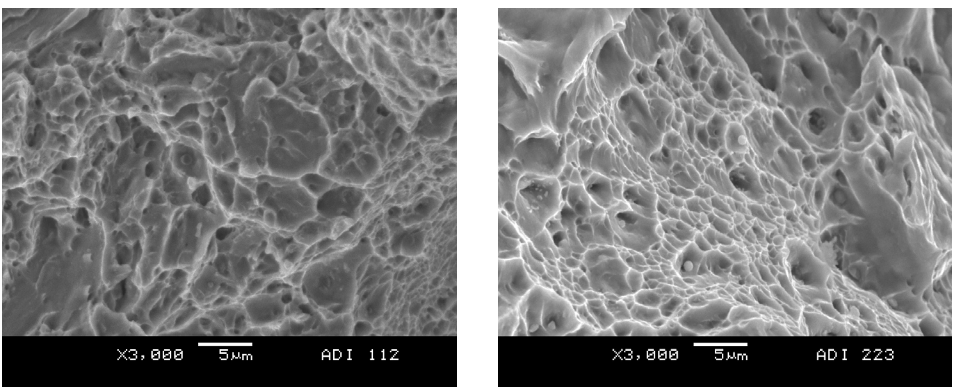


Fig. 4. *The effect of austempering time on impact energy at 350°C for Cu and Cu+Ni alloyed ADI.*



(a) Cu-ADI *(b) Cu+Ni ADI*

Fig.5 *SEM. Fracture morphology after austempering at 350°C for 2h (a) and 3h (b).*

Conclusions

ADI alloyed with Cu+Ni has higher amount of retained austenite than ADI alloyed with Cu when austenitized and austempered under the similar conditions. This results in the higher impact energy and the substantial plastic deformation of ADI alloyed with Cu+Ni.

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