JMEPEG (2007) 16:485–489
DOI: 10.1007/s11665-007-9069-4

1059-9495/$19.00

Impact Properties of Copper-Alloyed and Nickel-Copper Alloyed ADI

Uma Batra, Subrata Ray, and S.R. Prabhakar

(Submitted November 24, 2005; in revised form July 21, 2006)

The influence of austenitization and austempering parameters on the impact properties of copper-alloyed and nickel-copper-alloyed austempered ductile irons (ADIs) has been studied. The austenitization temperature of 850 and 900 °C have been used in the present study for which austempering time periods of 120 and 60 min were optimized in an earlier work. The austempering process was carried out for 60 min for three austempering temperatures of 270, 330, and 380 °C to study the effect of austempering temperature. The influence of the austempering time on impact properties has been studied for austempering temperature of 330 °C for time periods of 30-150 min. The variation in impact strength with the austenitization and austempering parameters has been correlated to the morphology, size and amount of austenite and bainitic ferrite in the austempered structure. The fracture surface of ADI failed under impact has been studied using SEM.

Keywords austenitization, bainitic transformation, fracture, impact energy

1. Introduction

Austempered ductile iron (ADI) is a further development of ductile iron achieved by austempering heat treatment of the later. By varying the temperature and time of austempering, the strength of ADI may be varied from about 950 MPa at 10-15% elongation to 1760 MPa at 1-3% elongation. In recent years, ADI has emerged as a strong candidate for applications in automotive and other industrial components because of its relatively low cost and an excellent combination of properties like high strength, excellent fatigue, and wear resistance (Ref 1-4). In ADI, the properties attained are dependent on the austenitization and austempering parameters, initial matrix structure, and chemical composition. Investigations related to the effect of austenitization temperature, austempering temperature, and time on austempered microstructure of the irons being studied have been reported earlier (Ref 5-7). Earlier work (Ref 8) has also shown that the austenitization temperature and time have a significant influence on the microstructure and impact properties of the alloy with an initially pearlite matrix structure. Work by Darwish (Ref 9) has investigated the effect of austempering parameter on the toughness of low-Mn ADI. Aranzbal (Ref 4) has reported that the impact energy of ADI increases with the increase in the amount of retained austenite in the austempered structure. The same fact is supported by other studies also which report the coincidence of the contour maps of volume fraction of retained austenite in austempered microstructure of ADI, and retained austenite in the austempered structure of ADI and the impact energy as a function of austempering parameters (Ref 10, 11).

The present work deals with the study of the influence of austempering parameters on the impact properties of copper-alloyed and nickel-copper-alloyed ADI, and establishes the relationship of the impact strength with the austenitization and austempering parameters.

Uma Batra, Department of Metallurgical Engineering, Punjab Engineering College, Chandigarh, India160012; **Subrata Ray,** Department of Metallurgical and Materials Engineering, IIT-Roorkee, Roorkee, UP, India; **S.R. Prabhakar,** Indo Global College of Engineering and Technology, Chandigarh, India. Contact e-mail: umabatra2@yahoo.com.

2. Experimental Procedure

Two ductile irons with chemical compositions given in Table 1 were prepared in a commercial foundry using an induction melting furnace and cast in the shape of 1 in. Y blocks. Unnotched Charpy specimens of size $(55 \times 10 \times 10)$ mm as per ASTM specifications A327-80 were machined from the leg part of Y block castings of both the ductile irons (Ref 12). The samples were austenitized for specified temperature and time (Ref 6) and transferred rapidly to a salt bath held at a pre-selected temperature for austempering for different time periods before quenching in water. The various heat treatment conditions used in the present work are given in Table 2. The average volume fraction of austenite, X_γ and the size of bainitic ferrite needle in the austempered structure were determined using x-ray diffraction patterns taken with CuK_α radiation (λ = 1.54Å) (Ref 13). The fracture surface of copper-alloyed ADI failed during impact testing has been observed using Scanning Electron Microscope.

3. Results and Discussion

The cast microstructures of copper-alloyed and nickel-copper-alloyed ductile irons under study are shown in Fig. 1.

Table 1 Chemical composition of ductile irons used for the present work (wt.%)

Element	C	Si	Mn	Cr	Ni	Cu	Ti	Mo	Sn	V	Al	Fe
Cu-iron	3.48	2.028	0.22	0.05	0.016	0.6	0.04	0.03	0.0079	0.012	0.02	Rest
Ni-Cu-iron	3.48	1.83	0.23	0.01	1.05	0.6	0.04	0.015	0.0046	0.002	0.02	Rest

Table 2 Heat treatment conditions

Iron	Treatment no.	Austenitization temperature, T_γ, °C	Austenitization time, t_γ, min	Austempering temperature, T_A, °C	Austempering time, t_A, min
Cu-iron	HT-1	850	120	270	
				330	60
				380	
	HT-2	900	60	270	
				330	60
				380	
	HT-3	850	120	330	30
					60
					90
					120
					150
	HT-4	900	60	330	30
					60
					90
					120
					150
Ni-Cu-iron	HT-5	850	120	270	
				330	60
				380	
	HT-6	850	120	330	30
					60
					90
					120
					150

Their microstructural characteristics are given in Table 3. The microstructure of cast ductile irons has graphite nodules embedded in the matrix of ferrite and pearlite. When the Cu alloyed and Ni-Cu alloyed ductile irons are austenitized at 850 °C for 120 min, their matrix transforms to austenite. Their subsequent austempering results in the transformation of austenite to bainitic ferrite and retained austenite (Ref 14). As has been reported earlier (Ref 7), the austempered microstructure of ADI depends on the temperature and time of austempering process. The variation of austempering temperature results in the variation in the austempered microstructure with regard to the morphology, size, and amount of bainitic ferrite and retained austenite (Ref 7). The iron, after austenitization is austempered for 60 min at low-austempering temperature of 270 °C, the austempered microstructure of both ADI's consists of small volume fraction of austenite in between the fine needles of lower bainite. On austempering the Cu alloyed iron at 330 °C, the austempered microstructure consists of lower as well as upper bainite and relatively higher volume fraction of retained austenite. The retained austenite is partly present between the ferrite needles and the rest in the blocky form (Ref 7). On austempering Ni-Cu alloyed iron at 330 °C for 60 min, the resulting austempered microstructure consists of upper bainite and retained austenite with the later having a similar morphology as observed in Cu alloyed ADI. Austempering at 380 °C resulted in coarser upper bainite and retained austenite present mainly in blocky form in both the ADI's (Ref 7). The effect of austenitization temperature on the austempered microstructure of copper-alloyed iron has been reported earlier (Ref 8). When austenitization temperature was increased from 850 to 900 °C, for a given austempering temperature of 330 °C, the austempered microstructure of Cu alloyed ADI has coarsened, the amount of retained austenite in the austempered structure has increased and is present mainly in the blocky form. The volume fraction of retained austenite in the austempered structure has been calculated from the XRD patterns obtained from the samples of both ADI austenitized at 850 °C.

Figure 2 shows the variation of volume fraction of retained austenite present in austempered structure with austempering temperature for Cu alloyed ADI when given the heat treatments HT1 and HT2, and for Ni-Cu alloyed ADI when given the heat treatment HT5. The volume fraction of retained austenite in austempered structure increases with the rise in the austempering temperature. One may observe higher volume fraction of retained austenite in the austempered structure at all austempering temperatures for Cu-iron when austenitized at 900 °C than for the same iron austenitized at 850 °C, though the difference is negligible for austempering temperature of 270 °C, marginally higher for 330 °C and maximum for austempering at 380 °C. The rise in austenitization temperature has resulted in the coarsening of bainitic ferrite in austempered structure of Cu alloyed ADI as reported earlier (Ref 7) and given in Table 4. It may be observed that the change in the size of bainitic ferrite needles in the austempered structure with the rise in austenitization temperature is marginal for the austempering temperatures of 270 and 330 °C; however, the difference is more pronounced for the austempering temperature of 380 °C.

On austempering both ductile irons at 330 °C for a short austempering period of 30 min following austenitization at 850 °C for 120 min, the austempered structure consists of

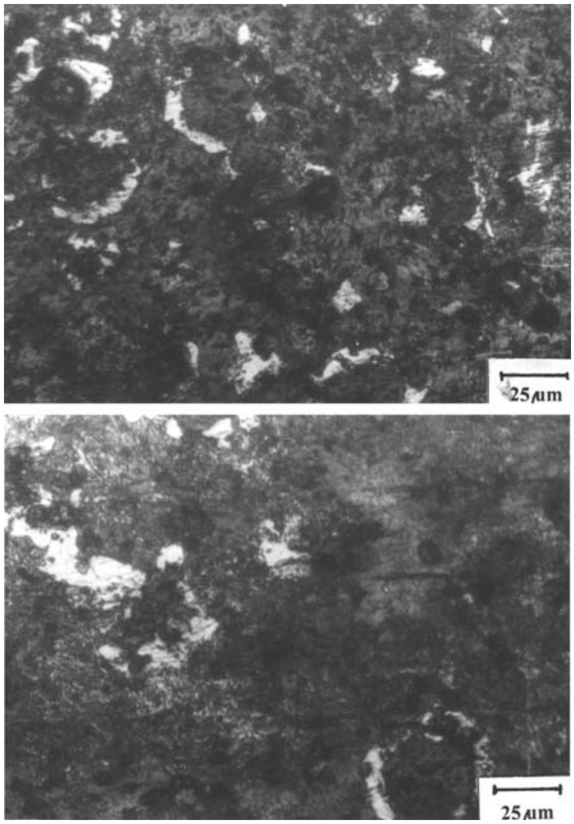

Fig. 1 Microstructure of cast ductile irons: (a) copper-alloyed iron and (b) nickel-copper-alloyed iron

Table 3 Microstructural characteristics of cast irons

Characteristics	Cu-iron	Ni-Cu iron
Nodule size, mm	0.04	0.043
Nodule count	250	198
Amount of ferrite, %	5	4
Amount of pearlite, %	95	96

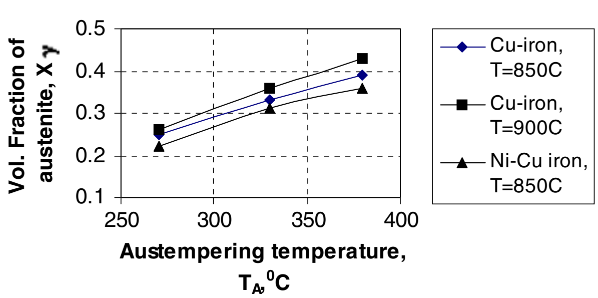

Fig. 2 Variation of volume fraction of retained austenite, X_γ in the austempered structure of Cu alloyed ADI and Ni-Cu alloyed ADI with austempering temperature, when austempered for 60 min following austenitization at 850 °C for 120 min or 900 °C for 60 min

small amount of bainitic ferrite and retained austenite but a considerable amount of martensite. At longer austempering time of 60 min, the austempered structure consists of bainitic ferrite and retained austenite. Further increase in austempering time till 150 min shows only a marginal change in the austempered microstructure with regard to the morphology and the size of bainitic ferrite and the distribution of retained austenite though XRD patterns have shown a variation in volume fraction of retained austenite in the austempered structure with austempering time. Figure 3 shows the variation of volume fraction of retained austenite in the austempered structure with austempering time for Cu alloyed ADI when given heat treatments HT3 and HT4, and for Ni-Cu alloyed ADI when given the heat treatment HT6. It may be observed that the trend of variation of the volume fraction of retained austenite with austempering time is similar irrespective of the variation in the composition of the iron or the austenitization temperature used. At short austempering time of 30 min, the volume fraction of retained austenite is small, which increases gradually on increasing the austempering time till it reaches a plateau followed by a slight decrease at longer austempering time. The progress of bainitic transformation with continuing carbon enrichment of residual austenite reduces the driving force for further transformation of austenite to bainitic ferrite with the result that further transformation slows down and thus volume fraction of austenite and its carbon content reaches a plateau. The decrease in volume fraction of austenite and its carbon content with further increase in austempering time may be due to onset of stage II of austempering when retained austenite decomposed to give bainitic ferrite and carbide. For copper-alloyed ADI austempered following austenitization at 900 °C, the austempered structure has slightly higher amounts of retained austenite than that obtained in the same iron austempered following austenitization at 850 °C.

Table 4 Size of the bainitic ferrite needle in the austempered structure of copper-alloyed ADI

Austempering temperature, °C (t_A = 60 min)	270	330	380
Bainitic ferrite size, Å (for T_γ = 850 °C, t_γ = 120 min)	160	185	213
Bainitic ferrite size, Å (for T_γ = 900 °C, t_γ = 60 min)	162	190	252

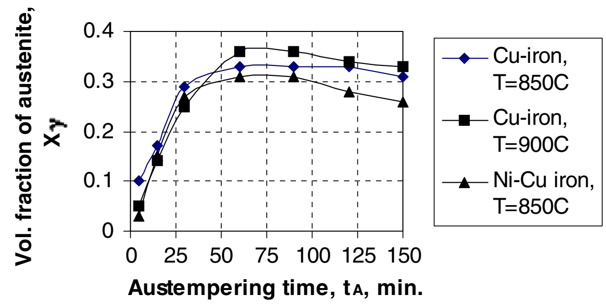

Fig. 3 Variation of volume fraction of retained austenite, X_γ in austempered Cu alloyed ADI and Ni-Cu alloyed ADI with austempering time when austempered at 330 °C following austenitization at 850 °C for 120 min or 900 °C for 60 min

Figure 4 shows the effect of austempering temperature on the impact energy of Cu alloyed and Ni-Cu alloyed ADI austenitized at 850 °C for 120 min and austempered at preselected austempering temperature for 60 min. It may be observed that the impact energy of the ADI is low when austempered at 270 °C, increases when the austempering temperature is increased to 330 °C and it further increases

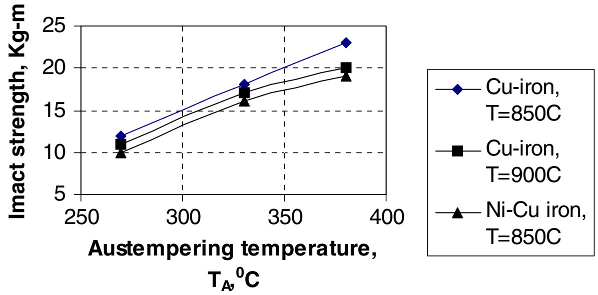

Fig. 4 Variation of impact strength of Cu alloyed ADI and Ni-Cu alloyed ADI with austempering temperature, when austempered for 60 min following austenitization at 850 °C for 120 min or 900 °C for 60 min

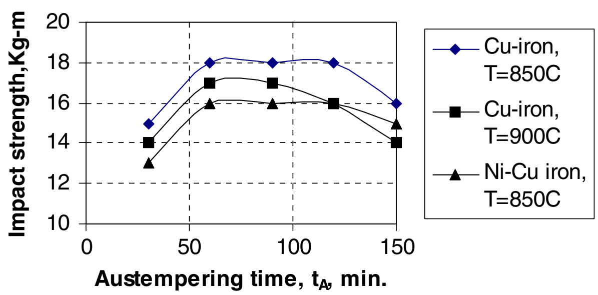

Fig. 5 Variation of impact strength of Cu alloyed and Ni-Cu alloyed ADI with austempering time, when austempered at 330 °C following austenitization at 850 °C for 120 min or 900 °C for 60 min

when the austempering temperature is increased to 380 °C. The significant improvement of impact energy with the rise in austempering temperature for both the ADI's may be attributed to the change of morphology of bainite from lower bainite to upper bainite and increase in the volume fraction of retained austenite in austempered structure associated with the rise in the austempering temperature. One may observe from Fig. 2 and 4 that the trend of variation of impact energy of both ADI's with austempering temperature is similar to that of the volume fraction of austenite in the austempered structure with austempering temperature. The impact strength of Cu alloyed ADI austempered following austenitization at 850 °C is higher than that obtained for the same ADI when austempered following austenitization at 900 °C. This may be attributed to the coarsening of microstructure with the rise in austenitization temperature. Thus it is not only the volume fraction of austenite but also the morphology as well as the size of the bainitic ferrite in the austempered structure which effects the impact strength of the ADI.

Figure 5 shows the variation of impact energy with austempering time for both the ADI's austempered at 330 °C following austenitization at 850 °C for 120 min. At short austempering time, the impact energy of both the ADI's is poor due to the presence of martensite in the austempered structure. On increasing the austempering time to 60 min the impact strength increases because of increase in the volume fraction of retained austenite and bainitic ferrite in the austempered structure. Further increase in the austempering time from 60 to 120 min results in only marginal change in the impact energy. Correspondingly, the trend of variation of volume

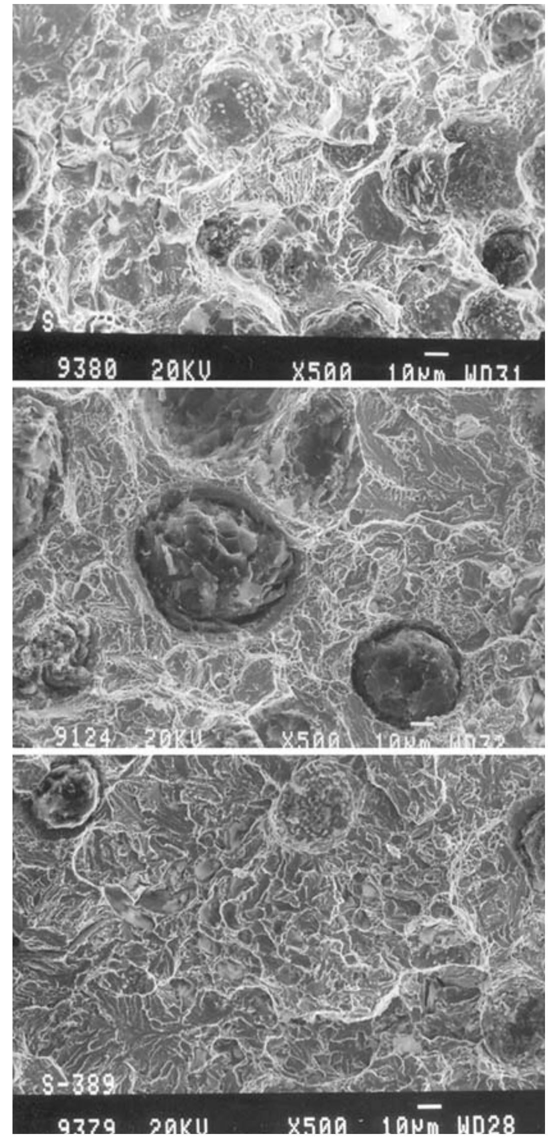

Fig. 6 Fracture surface of copper-alloyed ADI fractured under impact conditions, tested after austenitization at 900 °C for 60 min and austempering at (a) 270 °C, (b) 330 °C, and (c) 380 °C for 60 min

fraction of retained austenite in the austempered structure with austempering time is also similar. At still longer austempering time of 150 min, there is a fall in the impact energy of both the ADI's, which may be due to decrease in the volume fraction of austenite in the austempered structure.

In the present work, it is pragmatic that for given austenitization and austempering conditions, while keeping Cu at the same level, Ni addition in the ADI has resulted in the formation of upper bainite but lower volume fraction of retained austenite in the austempered structure. Other researchers have already reported that Ni shifts down the transformation temperature range which results in the transformation taking place corresponding to higher temperature transformation products i.e., upper bainite (Ref 15). Besides that Ni if present in excess of 0.5%, slows down the bainitic reaction and therefore it may cause the formation of martensite at the austenite cell boundary. Therefore, the Ni-Cu alloyed ADI despite showing the presence of upper bainite in the austempered structure results in poor impact strength because of the relatively lower volume fraction of retained austenite as a result of slow kinetics.

The fracture surfaces of copper-alloyed ductile iron austenitized at 900 °C for 60 min and austempered at 270, 330, or 380 °C for 60 min and fractured under impact conditions were examined using Scanning Electron Microscope and the fractographs are shown in Fig. 6. At low-austempering temperature of 270 °C, when the austempered structure consists of lower bainite and relatively small volume fraction of retained austenite, the impact energy is low and the plastic deformation is restricted primarily to the regions near nodule. There is very little deformation in the intercellular regions. Many dimples of small size are present near the graphite nodule. As the austempering temperature is increased to 330 °C, the dimpled region spreads and the size of the dimple increases. For the austempering temperature of 380 °C, the austempered microstructure consists of upper bainite and a large volume fraction of retained austenite. The fracture surface shows a large number of dimples spread uniformly over the entire surface.

4. Conclusions

When the austempering temperature is increased, the impact strength increases because of increased amount of retained austenite and a change in the morphology of bainitic ferrite from lower to upper bainite. The impact strength is very poor at short austempering time, which may be attributed to the presence of martensite. When the austempering time is increased the impact strength increases because the amount of martensite decreases and the amount of retained austenite increases in the austempered microstructure. The impact strength decreases at longer austempering times, which may be due to the onset of the second stage of austempering. The trends of variation of impact energy and the volume fraction of retained austenite with austempering temperature and time are similar. Although the trend of variation of impact energy with austempering temperature and time is similar in both Cu-alloyed and Ni-Cu alloyed ADI's, but the impact strength of Ni-Cu alloyed ADI is relatively poorer than that of copper-alloyed ADI for all the austempering times between 30 and 150 min. Impact strength decreases with increasing austenitization temperature because of coarsening of microstructure. The difference is relatively less at lower austempering temperature of 270 and 330 °C, but it is more pronounced at higher austempering temperature of 380 °C.

References

1. M. Grech, An Update on Austempered Ductile Iron, *International Conference on Mechanical Behavior of Ductile Iron and Other Cast Metals*, Aug, 1993 (Kitakyushu, Japan), 1993, p 18–25
2. P.A. Blackmore and R.A. Harding, The Effect of Metallurgical Process Variables on the Properties of Austempered Ductile Irons, *Proceedings of the 1st International Conference on ADI*, Chicago, Illinois, USA, 1984, p 117–134
3. D.J. Moore, T.N. Rouns, and K.B. Rundman, The Relationship Between Microstructure and Tensile Properties in ADI, *AFS Trans*, 1987, **95**, p 765–774
4. J. Aranjbal, I. Gutierrez, J.M. Rodriguez-Ibabe, and J.J. Urcola, Influence of Heat Treatments on Microstructure and Toughness of Austempered Ductile Iron, *Mater. Sci. Technol.*, 1992, **8**(11), p 263–273
5. U. Batra, S. Ray, and S.R. Prabhakar, Austempering and Austempered Ductile Iron Microstructure in Copper Alloyed Ductile Iron, *J. Mater. Eng. Perform.*, 2003, **12**(4), p 426–429
6. U. Batra, S. Ray, and S.R. Prabhakar, Effect of Austenitization on Austempering and Austempered Microstructure of Copper Alloyed Ductile Iron, *J. Mater. Eng. Perform.*, 2003, **12**(5), p 597–601
7. U. Batra, S. Ray, and S.R. Prabhakar, The Influence of Nickel and Copper in Ductile Iron on its Austempering, *J. Mater. Eng. Perform.*, 2004, **13**(1), p 64–68
8. M. Delia, M. Alaalam, and M. Grech, Effect of Austenitizing Conditions on the Impact Properties of an Alloyed Austempered Ductile Iron of Initially Pearlitic Matrix Structure, *Int. J. Cast Met. Res.*, 1997, **9**(6), p 345–351
9. N. Darwish and R. Elliot, Austempering of Low Manganese Ductile Irons. Part 3. Variation of Mechanical Properties with Heat Treatment Conditions, *Mater. Sci. Technol.*, 1993, **9**(10), p 882–889
10. T.S. Shih, C.S. Chang, L.Z. Hwang, and C.R. Loper Jr., Tensile properties of Ni-Cu alloyed austempered ductile iron, *AFS Trans.*, 1991, **99**, p 793
11. A.S. Hamid Ali, K.I. Uzlov, N. Darwish, and R. Elliot, Austempering of Low Manganese Ductile Irons. Part 4. Relationship Between Mechanical Properties and Microstructure, *Mater. Sci. Technol.*, 1994, **10**, p 35–40
12. K.D. Mills, Spherical Graphite Cast Iron – Its Development and Future, *Brit. Foundry Man*, 1972, **65**, p 34
13. B.D. Cullity, *Elements of X-Ray Diffraction*. Addison Wesley Publishing Company, Inc, Reading, MA, 1956, 390–396
14. "Heat treating", *ASM Handbook*, vol 4, 1991
15. H.G. Gerlach, Bainitic Transformations, *Metallurgia*, 1965, **72**, p 215