JMEPEG (2004) 13:537-541
DOI: 10.1361/10599490420656

1059-9495/$19.00

Tensile Properties of Copper Alloyed Austempered Ductile Iron: Effect of Austempering Parameters

U. Batra, S. Ray, and S.R. Prabhakar

(Submitted December 17, 2003)

A ductile iron containing 0.6% copper as the main alloying element was austenitized at 850 °C for 120 min and was subsequently austempered for 60 min at austempering temperatures of 270, 330, and 380 °C. The samples were also austempered at 330 °C for austempering times of 30-150 min. The structural parameters for the austempered alloy austenite (X_γ), average carbon content (C_γ), the product $X_\gamma C_\gamma$, and the size of the bainitic ferrite needle (d_α) were determined using x-ray diffraction. The effect of austempering temperature and time has been studied with respect to tensile properties such as 0.2% proof stress, ultimate tensile strength (UTS), percentage of elongation, and quality index. These properties have been correlated with the structural parameters of the austempered ductile iron microstructure. Fracture studies have been carried out on the tensile fracture surfaces of the austempered ductile iron (ADI).

Keywords austempering, austenitization, percentage of elongation, proof stress, quality index, ultimate tensile strength

1. Introduction

Austempered ductile iron (ADI) has become a material of interest to design engineers due to its high strength, toughness, and exceptional ductility compared with standard grades of ductile iron. Despite the promising gains in mechanical properties through austempering, there has been some hesitation initially about the commercialization of ADI due to the lack of published mechanical property data compared with other materials such as steel. The tensile properties of relatively pure ductile iron austenitized at 927 °C and austempered at 410, 371, and 316 °C have been reported earlier.[1] The effect of common alloying elements like Ni, Mo, Mn, and Cu on the structure and properties of ADI has been reported by others.[2-4] Microstructural changes and mechanical properties have been reported for low-Mn, Cu-alloyed, and low-Mn, Ni-Cu-alloyed ductile irons for various austempering conditions.[5] The purpose of the present article was twofold: first, to study the effect of austempering parameters on the tensile properties of Cu-alloyed ADI; and second, to compare the resulting ADI with the standard ADI on the basis of tensile properties. Tensile properties such as ultimate tensile strength (UTS), 0.2% proof stress, percentage of elongation, quality index (QI), and impact properties have been considered.

U. Batra, Department of Metallurgical Engineering, Punjab Engineering College, Chandigarh, India; **S. Ray,** Department of Metallurgical and Materials Engineering, IIT, Roorkee, India; and **S.R. Prabhakar,** Principal, Indo Global College of Engineering and Technology, Abhipur, Distt. Ropar, Punjab, India. Contact e-mail: umabatra2@yahoo.com.

2. Experimental Procedure

A ductile iron of composition 3.48C wt.%, 2.028Si wt.%, 0.22Mn wt.%, 0.05Cr wt.%, 0.016Ni wt.%, 0.6Cu wt.%, 0.04Ti wt.%, 0.03Mo wt.%, 0.0079Sn wt.%, 0.012V wt.%, 0.02Al wt.%, and balance Fe was prepared in a commercial foundry using an induction-melting furnace. The ingots were cast in the shape of 25 mm (1 in.) Y-blocks. The cast microstructure of the ductile iron consisted of 4% ferrite and 96% pearlite with a nodule count of 250. Tensile test specimens, as per ASTM specification A 536-80,[6] were machined from the leg part of Y-block castings. These specimens were austenitized at 850 °C for 120 min and were transferred rapidly to a salt bath held at a preselected temperature for different time periods before quenching in water. Tensile testing was performed using a universal testing machine of 20-ton capacity. Samples for x-ray diffraction (XRD) that were sliced from the tensile specimens were prepared using standard techniques. The average volume fraction of austenite (X_γ), its average carbon content (C_γ), the product $X_\gamma C_\gamma$, and the mean size of bainitic ferrite particles (d_α) in the austempered structure were determined using XRD patterns obtained with CuKα radiation (λ = 1.54 Å).[7]

3. Results and Discussion

When the Cu-alloyed ductile iron is austenitized at 850 °C for 120 min, the as-cast matrix completely transforms to austenite, which, upon subsequent austempering, transforms to bainitic ferrite and retained austenite. The austempered microstructure depends on the temperature and time of the austempering process, as reported earlier.[8]

The Cu-alloyed ductile iron when austempered for a fixed time period of 60 min at the preselected austempering temperature of 270, 330, or 380 °C, after austenitization at 850 °C for 120 min showed a variation in its austempered microstructure

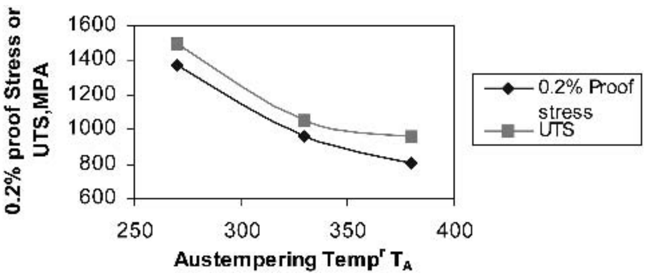

Fig. 1 Variation of 0.2% proof stress and UTS of Cu-alloyed ADI with the austempering temperature (T_A) for a fixed t_A of 60 min after austenitization at 850 °C for 120 min

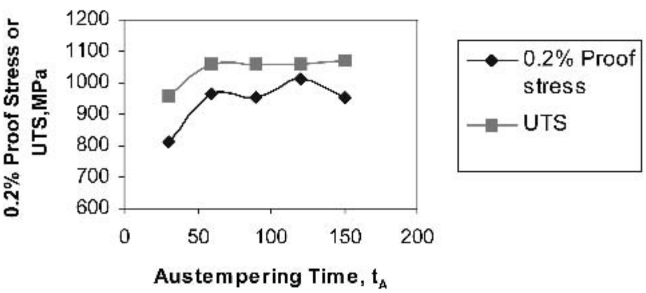

Fig. 2 Variation of 0.2% proof stress and UTS of Cu-alloyed ADI with t_A for austempering at 330 °C after austenitization at 850 °C for 120 min

with the austempering temperature with regard to the morphology, size, and amount of bainitic ferrite and retained austenite.[8] At the austempering temperature of 270 °C, the austempered microstructure consisted of lower bainite and a small volume fraction of austenite, which is present in the form of a lining between the bainitic ferrite needles. When austempered at 330 °C, the austempered microstructure consisted of lower as well as upper bainite with a relatively greater quantity of retained austenite, which is present partly in the form of a lining between the bainitic ferrite needles with the rest present in a blocky form.[8] Austempering the ductile iron at a still higher austempering temperature of 380 °C resulted in the presence of coarse upper bainite along with large quantities of blocky retained austenite.[8] The quantitative variation in the average volume fraction of retained austenite (X_γ), its C_γ, the product $X_\gamma C_\gamma$, and the bainitic ferrite in the austempered structure with the austempering temperature may be observed in Table 1. The changes in the austempered microstructure with austempering time (t_A) also have been reported for Cu-alloyed ductile iron austempered at 330 °C for preselected times of 30-150 min.[8]

When the alloy is austempered for 30 min, the austempered microstructure consisted of bainitic ferrite, retained austenite, and a substantial proportion of martensite. For austempering periods of 60 min, the structure consisted of bainitic ferrite and retained austenite with no martensite visible in the microstructure. No noticeable change in the microstructure could be observed with further increases in t_A until 150 min. The variation in the structural parameters, X_γ, C_γ, and $X_\gamma C_\gamma$ with t_A is reported in Table 1. The X_γ, C_γ, and $X_\gamma C_\gamma$ values are small at

Table 1 Variation of X_γ, C_γ, and d_α in austempered structure of Cu-alloyed austempered ductile iron
Austenitization at 850 °C for 120 min

T_A, °C	t_A, min	X_γ	C_γ, wt.%	$X_\gamma C_\gamma$	d_α, Å
330	60	0.33	1.8	0.594	185
270	60	0.25	1.6	0.400	160
380	60	0.39	2.0	0.780	213
330	5	0.10	1.0	0.100	…
	15	0.17	1.2	0.204	…
	30	0.29	1.7	0.478	…
	60	0.33	1.8	0.594	…
	90	0.33	1.8	0.594	…
	120	0.33	1.8	0.594	…
	150	0.31	1.7	0.527	…

Note: T_A, austempering temperature; t_A, austempering time; X_γ, austenite; C_γ, average carbon content; d_α, bainitic ferrite.

short t_A values, but increase for a t_A up to 60 min. These remain constant for a t_A up to 120 min when they start decreasing. The austempering involves the formation of bainitic ferrite by rejecting the carbon from the remaining austenite. The austempering progresses further with increases in the amount and size of bainitic ferrite, accompanied by further rejection of additional carbon to the surrounding austenite. At short t_A values, the carbon content of the austenite may be insufficient to make it stable, and, therefore, it transforms to martensite. However, at longer times, the carbon enrichment of austenite may become sufficient, leading to retained austenite upon cooling. The progress of the bainitic transformation is associated with continuing carbon enrichment of the residual austenite. Further enrichment reduces the driving force for the further transformation of austenite to bainitic ferrite with the result that X_γ, C_γ, and $X_\gamma C_\gamma$ reach a plateau. The decrease in X_γ, C_γ, and $X_\gamma C_\gamma$ with further increases in t_A may be due to the onset of stage II austempering where the retained austenite decomposes to give bainitic ferrite and carbide.[8]

The 0.2% proof stress, UTS, the percentage of elongation, and QI have been determined experimentally for Cu-alloyed ductile iron austempered for 60 min at 270, 330, or 380 °C after its austenitization of 120 min at 850 °C.

3.1 The 0.2% Proof Stress and UTS

The variation in the 0.2% proof stress and UTS with austempering temperature is shown in Fig. 1. At 270 °C, the 0.2% proof stress and UTS are quite high, which may be due to the presence of lower bainite and the finer size of the retained austenite in the austempered structure. Both proof stress and UTS decrease upon increases in the austempering temperature to 330 °C. The presence of some upper bainite along with lower bainite and the appearance of retained austenite, partially in the form of blocky austenite in the austempered microstructure, may be responsible for this. When the ductile iron was austempered at 380 °C, proof stress and UTS decreased further. This decrease may be attributed to the presence of coarse upper bainite and a large amount of blocky austenite in the austempered structure.

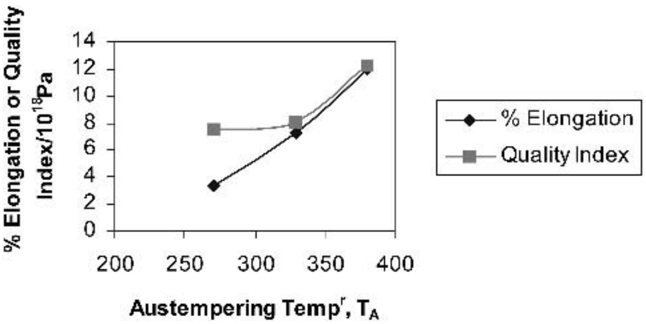

Fig. 3 Variation of the percentage of elongation and QI of Cu-alloyed ADI with austempering temperature (T_A) for a fixed t_A of 60 min after austenitization at 850 °C for 120 min

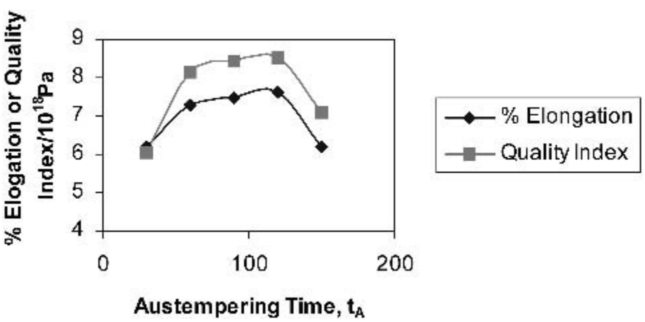

Fig. 4 Variation of the percentage of elongation and QI of Cu-alloyed ADI with t_A for austempering at 330 °C after austenitization at 850 °C for 120 min

The variation of 0.2% proof stress and UTS with t_A when austempered at 330 °C is shown in Fig. 2. For a t_A of 30 min, the increase in proof stress and UTS may be attributed to the presence of large amounts of martensite in the austempered structure. Upon increasing the t_A to 60 min, the proof stress and UTS increase, which may be due to increased amounts of bainitic ferrite and retained austenite in the austempered structure. Proof stress and UTS remain nearly constant during the time period of 60-120 min, during which there was no noticeable change in the austempered microstructure. When the ductile iron is austempered for 150 min, there was a slight decrease in the proof stress; however, the UTS remained almost constant.

The proof stress of ADI has been related to the volume fraction of the retained austenite and the size of the bainitic ferrite particle in the austempered structure through the use of a Hall-Petch-like expression:

$$\sigma_Y = \sigma_0 + A d_\alpha^{-0.5} + B X_\gamma \quad \text{(Eq 1)}$$

The relative importance of the volume fraction of retained austenite and the bainitic ferrite particle size in the austempered structure on yield stress may be determined by employing multiple linear regression. The values of constants σ_o, A, and B are given in Table 2. The correlation coefficient is 0.85. The coefficient A being much larger than B in all the cases indicates that changes in the bainitic ferrite particle size have a more significant effect on proof stress than do changes in the volume fraction of retained austenite. These findings are in good agreement with those of previous investigations for ADI that were developed from pure ductile iron and from those with Mn additions.[5,9] From Table 1, the bainitic ferrite particle size is effectively controlled through the selection of austempering temperature.

Table 2 Coefficients (σ_0, A, and B) of the Hall-Petch equation (Eq 2)

σ_0	A	B	Correlation coefficient, r
−45.78	11,211	−2654	0.85

3.2 The Percentage of Elongation and QI

The variation in the percentage of elongation and QI with austempering temperature is shown in Fig. 3 for Cu-alloyed ADI when austempered for 60 min at a preselected temperature. At 270 °C, the percentage of elongation is at a minimum due to the presence of a fine distribution of lower bainite and retained austenite in the austempered microstructure.[8] As the austempering temperature increases to 330 °C, the presence of upper bainite along with lower bainite and a larger amount of retained austenite, as reported earlier[8] and as was observed in Table 1, resulted in an increase in the percentage of elongation of ADI. At 380 °C, the increase in the percentage of elongation is quite appreciable and may be attributed to the presence of the coarser upper bainite and the large quantity of blocky retained austenite.

The variation in the percentage of elongation and the QI with t_A is shown in Fig. 4 for ductile iron austempered at 330 °C. For a t_A of 30 min, the low percentage of elongation of the ADI may be due to the presence of martensite in the austempered microstructure. The increase in the percentage of elongation with t_A up to, and including, 120 min may be due to the increase in the amount of retained austenite in the austempered structure. When ductile iron is austempered for 150 min, there is once again a decrease in the percentage of elongation. From Table 1, the decrease in the amount of retained austenite in the austempered structure may be due to the beginning of the second stage of austempering, during which the retained austenite formed in stage I decomposes into carbides and ferrite.[8]

The QI of ductile iron takes into account the combined effect of UTS and the percentage of elongation and may be defined as[10]

$$\text{QI} = (\text{UTS})^2 \cdot (\%\ \text{elongation}) \quad \text{(Eq 2)}$$

The value of the QI is at a minimum at short t_As but increases to a maximum after 120 min, after which time it decreases with further increases in t_A up to 150 min.

3.3 Comparison of Mechanical Properties of the Present ADI With Standard ASTM A 897 (1990)

A wide range of mechanical properties can be achieved for ADI by changing the austempering temperature. Figure 5

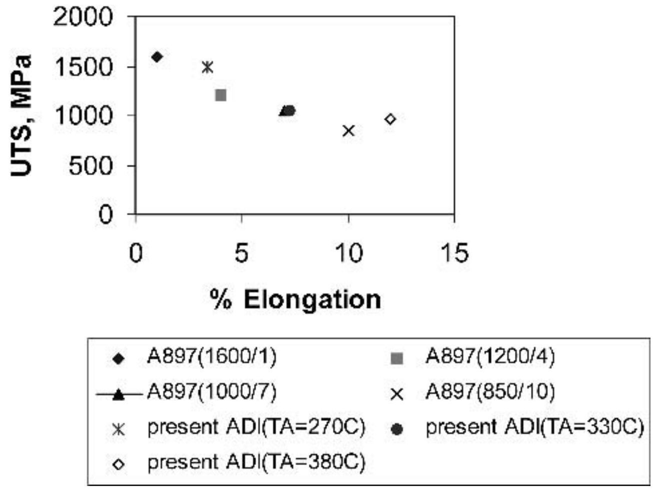

Fig. 5 Comparison of the tensile properties of Cu-alloyed ADI achieved by austempering for 60 min at different austempering temperatures of 270, 330, and 380 °C with different grades of standard ADI ASTM A 897. T_A, austempering temperature

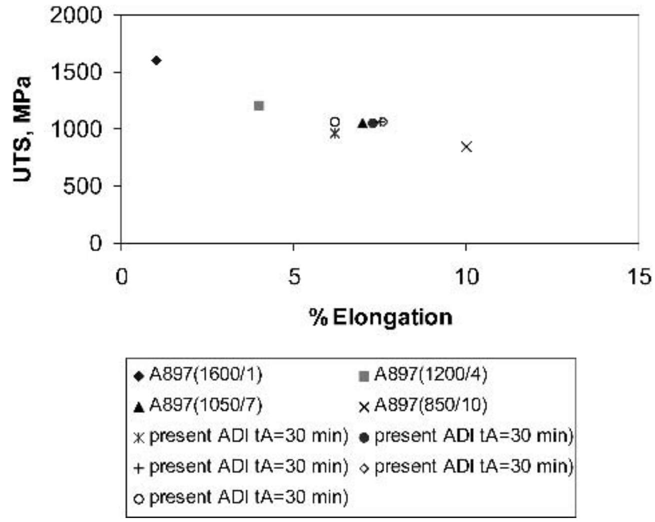

Fig. 6 Combination of mechanical properties observed in Cu-alloyed ADI at an austempering temperature of 330 °C after austenitization at 850 °C for 120 min

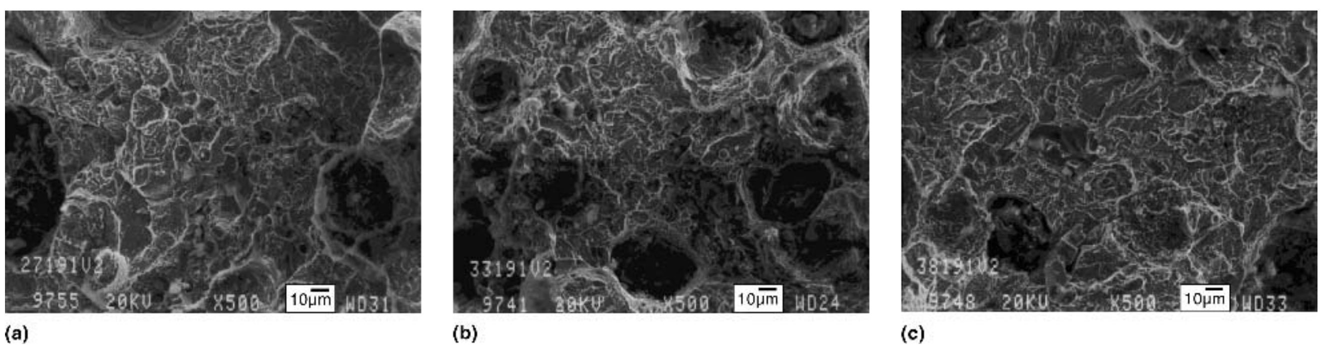

Fig. 7 SEM micrographs of the fractured surface of the Cu-alloyed ADI fractured under tensile conditions after austempering for 60 min at (**a**) 270 °C, (**b**) 330 °C, and (**c**) 380 °C

shows the comparison of the mechanical properties of ADI with standard A 897 alloys for different austempering temperatures. Austempering Cu-alloyed ductile iron for 60 min at 270, 330, and 380 °C has provided ADI grades close to the standard ADI ASTM A 897 grades 1200/4, 1050/7, and 850/10, respectively.

Figure 6 shows the variation in tensile strength and the percentage of elongation with t_A in a format that may be used to compare the present ADI with the standard A 897 alloys. The value of the properties of standard A 897 ADI alloys is also given in Fig. 6. It is only at the t_A of 30 min that the mechanical properties of the Cu-alloyed ADI fall below those of the standard ADI.

3.4 Fracture Study

Figure 7 shows scanning electron microscope (SEM) micrographs of the tensile fracture surface of the samples austempered for 60 min at 270, 330, and 380 °C. Shallow dimples may be observed for an ADI austempered at 270 °C, and may be due to the presence of lower bainite and a low quantity of retained austenite in the microstructure. The dimples become deeper and more numerous for ADI austempered at 330 °C. The fracture surface for the sample austempered at 380 °C again shows deep dimples, but, unlike the other samples, it also shows the presence of "riverlike" features in a few places. The dimples become deeper and more numerous as the austempering temperature increases to 330 and 380 °C due to the presence of upper bainite and a large volume fraction of austenite in the austempered structure. The presence of the riverlike feature for the sample austempered at 380 °C is due to martensite at the center of the retained austenite.

4. Conclusions

In Cu-alloyed ADI, when the austempering temperature increases from 270-380 °C, the proof stress and UTS decrease due to the change in morphology of the bainitic ferrite. However, the percentage of elongation and the QI increase monotonically. The proof stress, UTS, and the percentage of elongation, as well as the QI, are relatively low at short t_As, and these values increase as the austempering process progresses. The proof stress may decrease at longer t_As, while the UTS remains, more or less, constant. Austempering the Cu-alloyed ductile iron for 60 min at 270, 330, or 380 °C resulted in an ADI close to the 1200/4, 1050/7, and 850/10 grades of ASTM A 897.

The UTS and the percentage of elongation of this ADI alloy that was austempered at 330 °C fall below those specified in the ASTM standard for t_As less than 30 min; however, these properties improve for t_As of 60-150 min.

References

1. K.L. Hayrynen, D.J. Moore, and K.B. Eundan, Tensile and Fatigue Properties of Relatively Pure ADI, *Trans. AFS,* Vol 100, 1992, p 93-104
2. T.N. Rouns, D.J. Moore, and K.B. Eundan, On the Structure and Mechanical Properties of Austempered Ductile Iron, *Trans. AFS,* Vol 92, 1984, p 815-840
3. D.J. Moore, T.N. Rouns, and K.B. Eundan, The Relationship Between Microstructure and Tensile Properties in ADI, *Trans. AFS,* Vol 95, 1987, p 765-774
4. D. Krishnaraj, H.N.L. Narasimhan, and S. Seshan, Structure and Properties of ADI as Affected by Low Alloy Additions, *Trans. AFS,* Vol 100, 1992, p 105-112
5. 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.,* Vol 10, 1994, p 35-40
6. K.D. Mills, Spheroidal Graphite Cast Iron: Its Development and Future, *Br. Foundryman,* Vol 65, 1972, p 34
7. B.D. Cullity, *Elements of X-Ray Diffraction,* Addison Wesley Publishing Company, 1956, p 390-396
8. U. Batra, S. Ray, and S.R. Prabhakar, Austempering and Austempered Ductile Iron Microstructure in Copper Alloyed Ductile Iron, *J. Mater. Eng. Perf.,* Vol 12 (No. 4), 2003, p 426-429
9. K.L. Hayrynen, D.J. Moore, and K.B. Eundan, Tensile Properties and Microstructure of a Clean ADI, *Trans. AFS,* Vol 98, 1990, p 471-476
10. Ductile Iron Data for Design Engineers, QIT-Fer et Titane and Miller & Company, Montreal, Quebec, Canada 1990