Effect of Alloying Elements and Processing Parameters on Mechanical Properties of Austempered Ductile Iron

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Abstract
In the present work, austempering is carried out for three different grades (Unalloyed, copper alloyed and Nickel alloyed) of ductile iron. After that the variation of mechanical properties (Hardness, Tensile strength and Elongation) and microstructure of the austempered ductile iron (ADI) with alloying elements (Copper and Nickel) and austempering process variables (austempering temperature and austempering time) were studied. It is found that, with increasing austempering time hardness, tensile strength and elongation are increasing but with increasing austempering temperature hardness and tensile strength are decreasing and elongation increasing. Austempered ductile iron with alloying element (Cu or Ni) is showing some improved mechanical properties such that: higher strength, hardness and lower elongation, than the unalloyed austempered ductile iron. In Microstructure, higher ferrite fraction is observed for higher austempering time and higher austenite fraction is observed for higher austempering temperature, for all the three grades of austempered ductile iron.

Keywords: *austempering, austempered ductile iron (ADI), ausferrite, tensile strength, hardness, elongation*

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INTRODUCTION

Nowadays, development of light weight, durable and cost effective materials is an important field of research. For this purpose, there is a requirement to continually formulate new materials and checkout those already in account. One such material is ductile iron. Research efforts on this material have mainly focused on possible improvements of mechanical properties by subjected it to appropriate heat treatment and by alloying elements [1–7].

Austempered ductile iron, also known as ADI or ausferritic ductile iron is an important type of ductile iron which is formed by a peculiar isothermal heat treatment process i.e., austempering of conventional ductile iron. The properties of austempered ductile iron, produced by the particular heat treatment is nearly twice as strong as the conventional pearlitic ductile iron and still it retains its high elongation and toughness. Hence, the material provides superior mechanical properties than the conventional ductile iron and many other steels and alloys [8, 9].

In the process of austempering, ductile cast iron undergoes a remarkable transformation when subjected to the heat treatment process. The resulting microstructure, known as "Ausferrite", which consist of unique matrix of fine acicular ferrite with carbon enriched stabilized austenite [10] while, the matrix of conventional ductile iron is mixture of pearlite and ferrite. The new microstructure of ADI has capability superior to many traditional, high performance, ferrous and aluminium alloys and conventional steels. The new microstructure ausferrite exhibits twice the strength for a given level of ductility compared to the pearlitic, ferritic or martensitic structures formed by conventional heat treatments. The superior mechanical properties of the austempered ductile iron are due the ausferrite microstructure [11]. The unusual combination of properties is obtained in austempered ductile iron because of the ausferrite microstructure, which mainly depends on the heat treatment process variables and alloyed elements. The main aim of addition of different alloying elements to austempered ductile iron is due to control the matrix structure. This mode of solidification is obtained by adding a very small, but specific amount of Mg or Ce or both to molten metal of a proper composition.

The base iron is severely restricted in the allowable contents of certain minor elements that can interfere with the graphite spheroid formation. The added Mg reacts with S and O in the molten iron & change the way the graphite is formed. Austempered ductile iron (ADI) is considered to be an important engineering material because of its attractive properties such as good ductility at high strength, good wear resistance and fatigue strength and fracture toughness. Because of these combinations of properties, ADI is now used extensively in many structural applications in automotive industry, defence and earth moving machineries. The optimum mechanical properties of ADI i.e., the adequate combination of strength, toughness, fatigue strength, and wear resistance could be achieved if the microstructure consists of retained carbon-enriched stable austenite (enables ductility), together with one of two bainitic morphologies, namely, carbide-free bainitic ferrite or bainitic ferrite, in which carbides are distributed in the ferrite (affects strength) [12, 13]. The mechanical properties of ADI depend on the microstructure, which in turn depends on the austempering variables, i.e., austempering temperature and the time of holding. In conventional ductile iron the mechanical properties can be attributed to the pearlite and the ferrite present in the matrix but the superiority in the mechanical properties of the ADI are due to the acicular ferrite and carbon enriched stabilized austenite present in the matrix [13]. The proportion in which these two phases are present depends on the austempering variables. The base iron chemistry and the alloy additions in ductile iron, plays important role in ADI technology. Most of the ADI needs to be alloyed for satisfactory austemperability and subsequent improvement in properties. Nowadays many researches for ADI are done to study the effect of the alloying elements on the microstructure, mechanical properties. As an alloying element, copper widens the austenite zone of the phase diagram increasing the transformation rate during austenitising process and the carbon content in the matrix. On the other side, during the austempering process, copper may subdue carbide formation [14].

In present research work, the variation of mechanical properties and microstructure of the ADI with heat treatment process variables (austempering time and austempering temperature) and alloying elements (Copper and Nickel) is studied for three different grades od ductile iron (Unalloyed, Cu alloyed and Ni alloyed).

MATERIALS AND METHODS

Materials

Three grades of ductile iron samples have used in the experiment which were produced in a commercial foundry known as L&T Kansbahal. The difference between these three grades is: first one is unalloyed, second one is Copper alloyed and third one is Nickel alloyed. Chemical composition of the three grades of ductile iron samples are given below in the Table 1.

Table 1: *Chemistry of the Three Collected Ductile Iron Specimens.*

Sample	C	Si	Mn	Cr	Ni	Mg	Cu	S	P
Unalloyed	3.57	2.22	0.23	0.03	0.12	0.045	0.001	0.011	0.026
With copper	3.55	2.1	0.18	0.03	0.22	0.038	0.49	0.009	0.024
With Nickel	3.56	2.14	0.18	0.02	0.45	0.042	0.002	0.008	0.023

Test Specimen Preparation for Tensile Test

Dog bone shaped specimen with 6 mm gauge diameter and 30 mm gauge length (as shown in Figure 1) were prepared for tensile test.

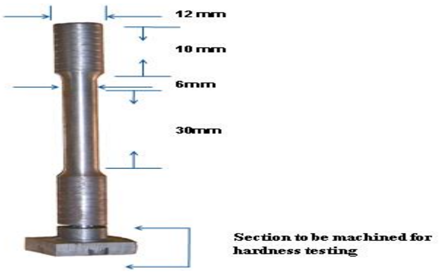

Fig. 1: Test Specimen.

Heat Treatment (Austempering)

Number of samples of each grade have taken and heated to 900°C for one hour (austenisation) and then transferred quickly to a salt bath (salt combination was 50 wt % $NaNO_3$ and 50 wt % KNO_3) maintained at different temperatures(250°C, 300°C, 350°C) for 30 min, 60 min, 90 min and 120 min. In Figure it is shown that specimens before and after austempering.

Microstructure (SEM)

Then the microstructures for different heat treated specimens were observed by using JEOL JSM-6480LV Scanning Electron Microscopy (SEM).

Hardness Measurement

For hardness measurement heat treated samples of dimension 8 mm × 8 mm ×3 mm were cut from the lower portion of the dog bone shaped sample (as shown in Figure 1) and polished in emery papers. Rockwell Hardness test was performed at room temperature to measure the macro hardness of the ductile iron specimens in A scale. Four hardness measurements for each sample were taken covering the whole surface of the specimen the mentioned hardness values are the average of the four readings.

Fig. 2: Dog Bone Shaped Ductile Iron Before and After Austempering.

RESULTS AND DISCUSSIONS

The mechanical properties i.e., tensile strength, yield strength, elongation & hardness of the unalloyed, Copper alloyed and Nickel alloyed samples for various austempering time and temperature are summarized in Table 2.

Table 2: Tensile Strength, Yield Strength and Elongation of Unalloyed, Copper alloyed and Nickel Alloyed ADI.

Austempering Temperature (°C)	Time (min)	Unalloyed ADI				Copper alloyed ADI				Nickel alloyed ADI			
		Tensile strength σ^{UTS} (MPa)	0.2% Yield strength, σ^{YS} (MPa)	Elongation (%)	Hardness (RA)	Tensile strength, σ^{UTS} (MPa)	0.2% Yield strength, σ^{YS} (MPa)	Elongation (%)	Hardness (RA)	Tensile strength σ^{UTS} (MPa)	0.2% Yield strength, σ^{YS} (MPa)	Elongation (%)	Hardness (RA)
250	30	997	795	1.9	75	1039	834	1.5	76	1010	815	1.7	75.5
	60	1139	957	2.4	80	1181	995	2.1	82	1156	985	2.2	81
	90	1124	927	2.8	79	1162	967	2.4	80	1160	945	2.6	79.5
	120	1116	906	2.8	78	1168	978	2.3	79	1121	942	2.6	79
300	30	831	693	3.7	69	873	685	3.1	71	852	667	3.5	69.5
	60	983	806	4.2	73	1017	825	3.5	74	1003	822	3.9	73.5
	90	965	759	4.8	71	1034	858	3.7	72	1018	828	4.3	71.5
	120	976	788	4.7	72	1030	851	3.8	73	997	805	4.4	72.5
350	30	724	539	5.9	65	778	591	5.2	68	757	565	5.5	67
	60	871	691	6.7	69	928	735	5.8	72	905	711	6.5	71
	90	849	673	7.2	68	921	733	5.9	70	889	698	6.9	69
	120	861	687	7.1	67	907	716	6	69	898	702	6.6	68

Effect of Austempering Time on UTS

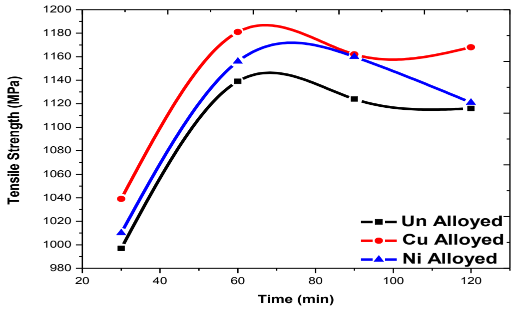

Fig. 3: *Effect of Austempering Time on UTS, Austempered at 250 ˚C.*

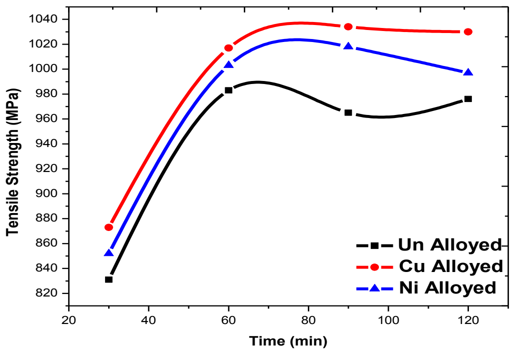

Fig. 4: *Effect of Austempering Time on UTS, Austempered at 300 ˚C.*

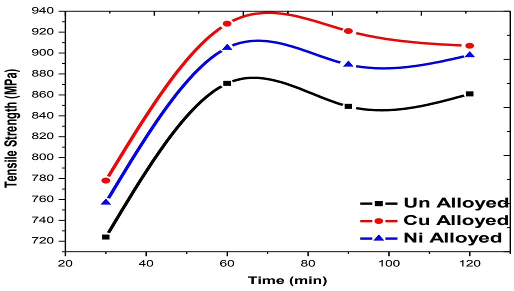

Fig. 5: *Effect of Austempering Time on UTS, Austempered at 350 ˚C.*

Figures 3–5 show the variation of tensile strength with respect to the austempering time at temperature 250°C, 300°C and 350°C, respectively for three grades (Unalloyed, Copper and Nickel alloyed). Tensile strength is increasing from 30 min austempering time to 60 min, from 60 min to 90 min it is decreasing and, from 90 min to 120 min sometimes increasing and sometimes increasing. Overall it is observed that tensile strength is increasing from 30 min to 60 min and after that for 60 min, 90 min and 120 min tensile strength almost same i.e., not showing significance difference for both the grades. Austempered ductile iron alloyed with copper is showing little bit higher strengths than the unalloyed austempered ductile iron.

Effect of Austempering Time on Elongation

Figures 6–8 show the variation of elongation with respect to the austempering time at temperature 250°C, 300°C and 350°C, respectively for all the three grades i.e., unalloyed, Cu alloyed and Ni alloyed ductile iron.

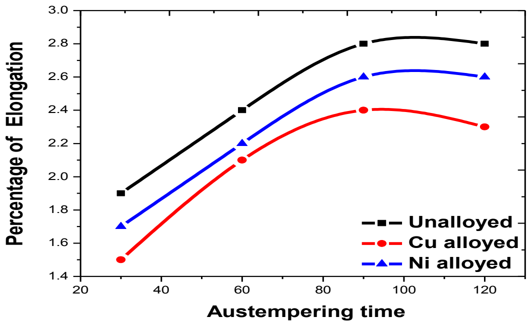

Fig. 6: *Effect of Austempering Time on Elongation, Austempered at 250 ˚C.*

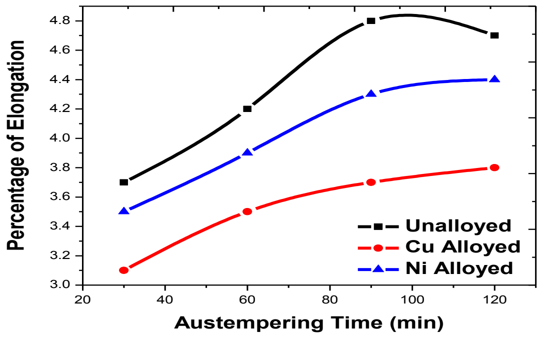

Fig. 7: *Effect of Austempering Time on Elongation, Austempered at 300 ˚C.*

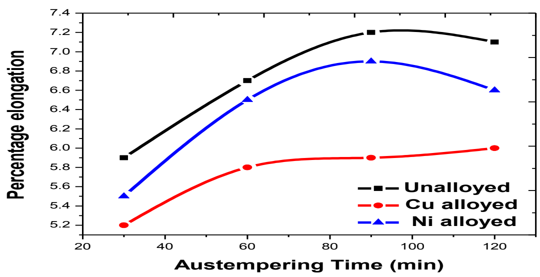

Fig. 8: *Effect of Austempering Time on Elongation, Austempered at 350 ˚C.*

Elongation is increasing from 30 min austempering time to 60 min, from 60 min to 90 min it is decreasing and from 90 min to 120 min sometimes increasing and sometimes increasing. Overall it is observed that elongation is increasing from 30 min to 60 min and for 60 min, 90 min and 120 min elongation almost same i.e., not showing significance difference for all the grades. Austempered ductile iron alloyed with copper is showing little bit lower elongation than the unalloyed austempered ductile iron while ductile iron alloyed with nickel is showing intermediate value.

Effect of Austempering Time on Hardness

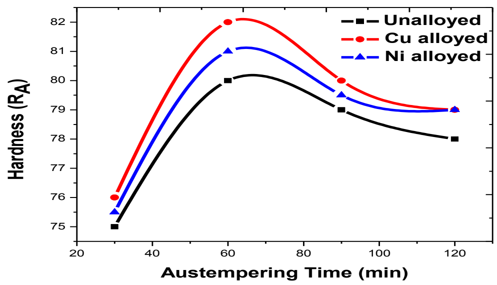

Fig. 9: *Effect of Austempering Time on Hardness, Austempered at 250 ˚C.*

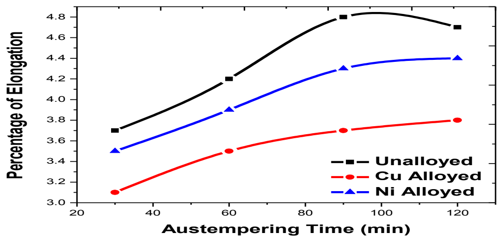

Fig. 10: *Effect of Austempering Time on Hardness, Austempered at 300 ˚C.*

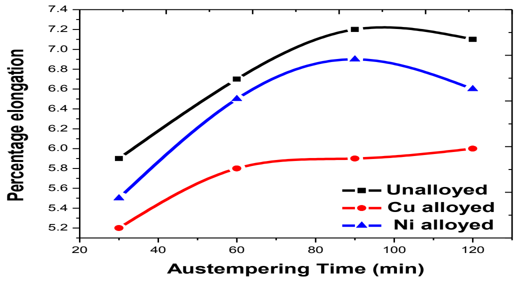

Fig.11: *Effect of Austempering Time on Hardness, Austempered at 350 ˚C.*

Figures 9–11 show the variation of hardness with respect to the austempering time at temperature 250°C, 300°C and 350°C, respectively for all the grades. Hardness is increasing from 30 min austempering time to 60 min time, from 60 min to 90 min it is decreasing and from 90 min to 120 min sometimes increasing and sometimes increasing. Overall it is observed that hardness is increasing from half an hour to one hour and for one hour, one and half an hour and two hours tensile strength almost same i.e., not showing significance difference for both the grades. Austempered ductile iron alloyed with copper is showing little bit higher hardness than the unalloyed austempered ductile iron.

Effect of Austempering Temperature on UTS

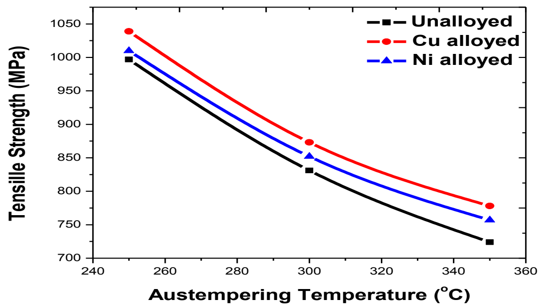

Fig. 12: *Effect of Austempering Temperature on UTS for 30 min.*

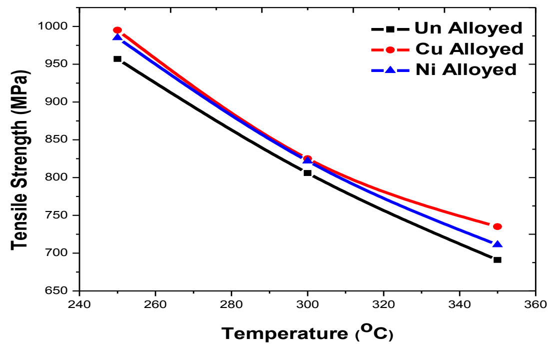

Fig. 13: *Effect of Austempering Temperature on UTS for 60 min.*

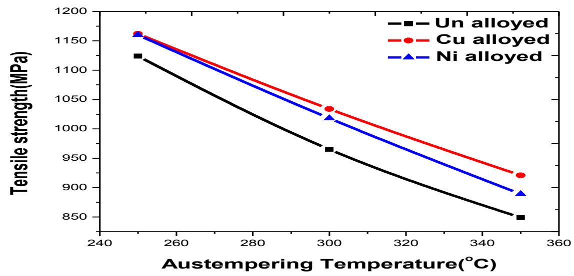

Fig. 14: *Effect of Austempering Temperature on UTS for 90 min.*

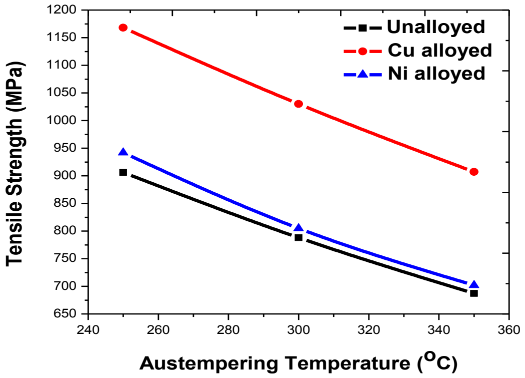

Fig. 15: *Effect of Austempering Temperature on UTS for 120 min.*

Figures 12–15 show the variation of tensile strength with respect to the austempering temperature for 30 min, 60 min, 90 min and 120 min respectively for all the grades. Tensile strength is decreasing with respect to the austempering temperature i.e., with increasing austempering temperature tensile strength is decreasing in all the grades.

Effect of Austempering Temperature on Elongation

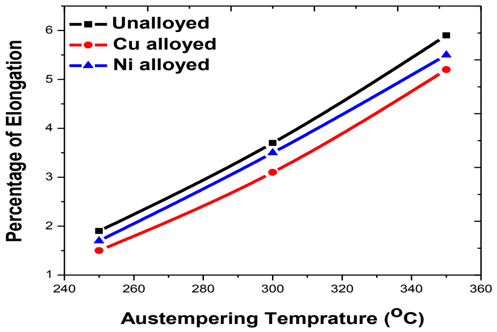

Fig. 16: *Effect of Austempering Temperature on Elongation for 30 min.*

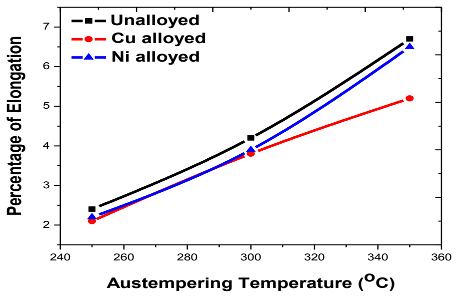

Fig. 17: *Effect of Austempering Temperature on Elongation for 60 min.*

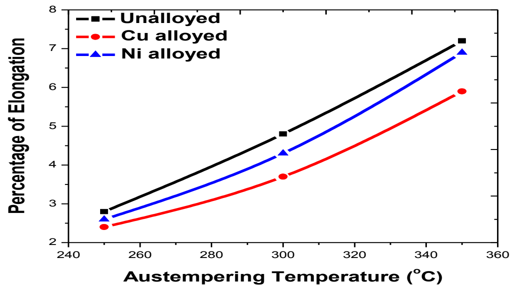

Fig. 18: *Effect of Austempering Temperature on Elongation for 90 min.*

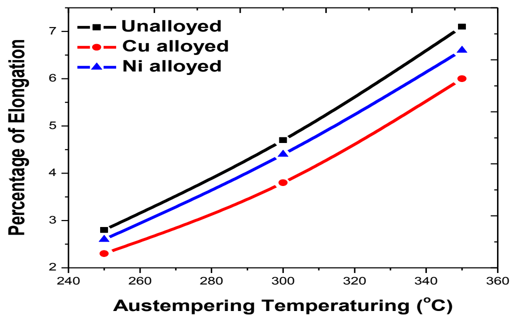

Fig. 19: *Effect of Austempering Temperature on Elongation for 90 min.*

Figures 16–19 show the variation of elongation with respect to the austempering temperature for 30 min, 60 min, 90 min and 120 min repeatedly for all the three grades. Elongation is increasing with respect to the austempering temperature i.e., with increasing austempering temperature elongation is increasing in all the three grades.

Effect of Austempering Temperature on Hardness

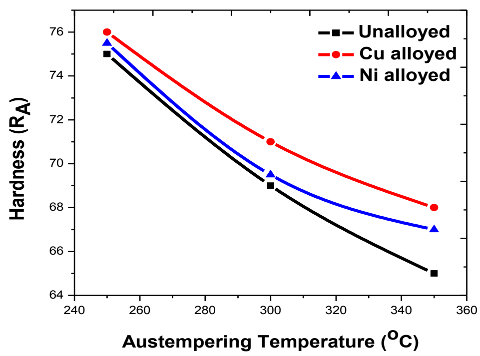

Fig. 20: *Effect of Temperature on Hardness for 30 min.*

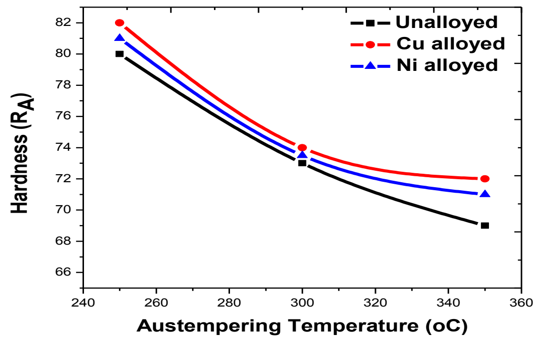

Fig. 21: *Effect of Temperature on Hardness for 60 min.*

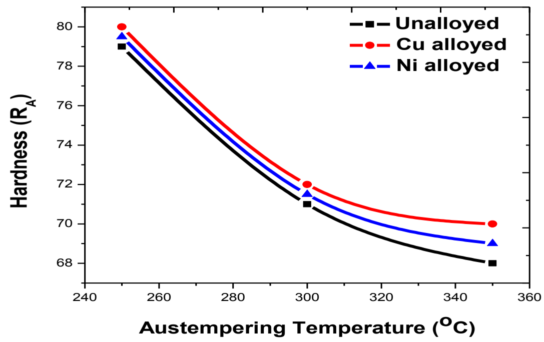

Fig. 22: *Effect of Temperature on Hardness for 90 min.*

Figures 20–23 show the variation of hardness with respect to the austempering temperature for 30 min, 60 min, 90 min and 120 min respectively for all the three grades of austempered ductile iron. Hardness is decreasing with respect to the austempering temperature i.e., with increasing austempering temperature hardness is decreasing in all the three grades.

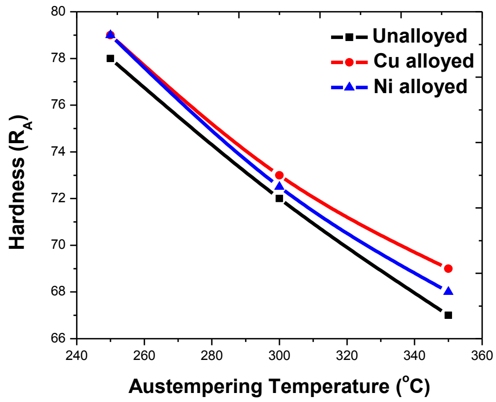

Fig. 23: *Effect of Temperature on Hardness for 120 min.*

Microstructure

The microstructures of unalloyed and alloyed ductile iron samples were observed under the scanning electron microscope and are shown in following Figures:

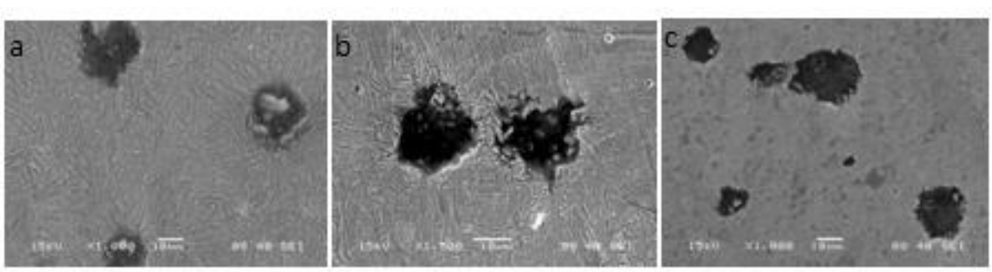

Fig. 24: *Microstructure of the Austempered Ductile Iron (unalloyed) Austempered at (a) 250°C for 30 min (b) 350°C for 60 min (c) 300°C for 60 min.*

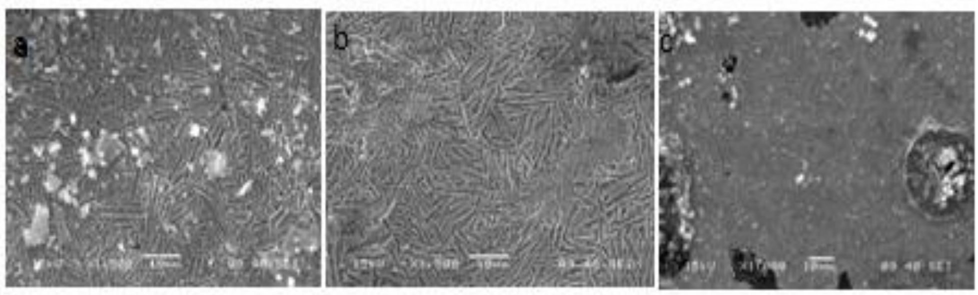

Fig. 25: *Microstructure of the Austempered Ductile Iron (with copper) Austempered at (a) 250°C for 60 min (b) 300°C for 60 min (c) 350°C for 60 min.*

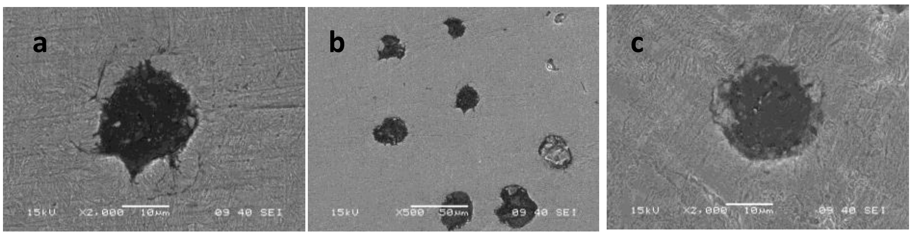

Fig. 26: *Microstructure of the Austempered Ductile Iron (with nickel) Austempered at (a) 250°C for 60 min (b) 300°C for 60 min (c) 350°C for 60 min.*

In the above microstructure, it is observed that the samples which are austempered at higher temperatures having upper bainitic structure and the samples which are austempered at lower temperatures are having lower bainitic structure. When the austempering temperature increasing the morphology of bainite also changing from acicular to plate like. The amount of retained austenite is increasing at higher temperature. At lower austempering temperatures the strength is higher. There is no significance difference between alloyed ductile iron and unalloyed ductile iron.

The general trends, observed by analysing the results are that for constant austempering time, strength (both UTS and YS) and hardness decreases with the increase in temperature and ductility (which is represented by % elongation) increases with temperature.

The increase in ductility with the increase in austempering temperature is also supported by the study of microstructure and analysis of fractured surface as we find more amounts of austenite in the specimens, austempered at higher temperature.

If we consider the effect of austempering time then we can see that for a constant temperature initially there is an increase in strength and hardness but after one hour (60 min) of austempering, the hardness becomes almost constant and the strength becomes constant or there is a slight decrease in the value. As far as ductility is concerned, the property is improved with the austempering time however, it becomes almost constant after a period of one and half hours (90 min). This is also true for all the three grades.

However, it has been observed that Cu has an effect on the rate of change in the values of the properties. From the results it is obvious that there is a sharp rise in strength when the austempering time is increased from 30 min to 60 min and this has happened for all the three temperatures used in the experiment but the percentage of increase in both UTS and YS is significantly higher for the grade without copper. The effect is reversed in case of ductility.

CONCLUSIONS

So by analysing the results we may draw the following conclusions:

- For a constant period of austempering, strength (both UTS & YS) and hardness decrease and ductility increases with the increase in temperature.
- For a particular austempering temperature, initially there is a sharp rise in the values of both strength and hardness with the increase in austempering time. After one hour of austempering, there is no significant increase in the values of these properties and there may be a slight decrease in strength. As far as ductility is concerned, the property is improved with time for a constant austempering temperature but it reaches a saturation point after a period of around 90 minutes.
- The increase in ductility with the time of austempering can be noticed in both microstructure and UTS value. Copper and Nickel plays a significant role in the property development of austempered ductile iron (ADI). It retards the rate of increase in strength and accelerates the rate of increase in ductility (% of elongation) to a considerable extent.

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