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MICROSTRUCTURAL EVOLUTION IN HEAT-TREATED CAST IRONS

Anwar Manzoor Rana, Abdul Faheem Khan, Sohail Amjad and Tahir Abbas
Department of Physics/Materials Science, Bahauddin Zakariya University, Multan, Pakistan.
email: anwar_manzoor_rana@yahoo.com

Abstract: Samples of two different compositions of cast irons were annealed and quenched at 800 °C and tempered at 600 °C for 30 minutes. The Rockwell hardness (HRC) of the annealed samples was found to decrease. However, HRC values were found to increase for both quenched and tempered samples. It has been investigated that the increased hardness of quenched sample was due to formation of martensitic needles.

Keywords: Microstructure, Annealing, Martensites, Quenched, Rockwell Hardness, Carbides, Heat Treatments.

INTRODUCTION

Cast irons are a family of ferrous alloys with a wide diversity of properties. Besides chemical composition, other important factors, which affect their properties, are solidification process, solidification rate and heat treatments. Since high carbon content tends to make cast iron very brittle, other metallic and non-metallic alloying elements are, therefore, added to control and vary the microstructure and mechanical properties [Campomanes and Goller 1979, Caspers 1980, Hughes 1981, Elliott 1983, Minkoff 1983]. Cast irons has a long and illustrious history and the five types of cast iron produced commercially today are: White, Grey, Malleable, Spheroidal Graphite (SG) or ductile and Compacted. The ductile cast irons are much stronger and has higher elongation than the grey or malleable iron, thus have found a wide range of industrial and structural applications [Avner 1974, Khan *et al.* 1995, Fatahalla *et al.* 1996]. The heat treatment of iron castings produces a significant difference in mechanical properties from as cast condition. Heat treatment procedures such as stress relieving, annealing, normalizing, quenching and tempering, austempering and surface hardening are the most common for the modification of mechanical properties.

All cast irons contain carbon in excess of its solubility limit in austenite, which is precipitated out during solidification by a eutectic reaction either as a thermodynamically stable graphite phase (grey iron) and/or a meta-stable cementite phase. The formation of stable or metastable phase depends on the nature and treatment given to the liquid, in particular, its graphitization potential, inoculation treatment and the cooling rate (as rapid cooling favors metastable carbide formation). Silicon increases the graphitization potential and is always found in higher concentrations in grey irons [Wallace 1975, Cox 1983, Gundlach *et al.* 1984].

The properties of cast irons depend on the form of carbon precipitates and the matrix structure. The carbon precipitated in the eutectic reaction is not a major contributor to mechanical strength. It is responsible for several properties not displayed by steels. Carbides contribute to hardness and abrasion resistance; whereas graphite contributes to machinability, wear resistance, damping and thermal conductivity depending on its shape. The mechanical properties of cast iron are derived mainly from the matrix. This is why irons are often described in terms of their matrix structure, for example, as ferritic or pearlitic types [Evans *et al.* 1981, Papakakis *et al.* 1983].

Spheroidal grey iron has been used to replace cast steel because of its many advantageous properties such as: higher strength-to-weight ratio, higher toughness, damping capacity, better wear resistance, better fluidity, lower melting point, better hot-workability and hardenability [Heine *et al.* 1982, Pan *et al.* 1988]. The low cost of production, very good castability, good machinability and shorter heat treatment processing cycles are its additional merits. Typical applications of these cast irons include locomotive, internal combustion engine, cylinder blocks and heads, flywheels, counterweights for lifts, as a base for erection of machinery, agriculture implements, industrial fan hubs, coke oven doors, crankshafts and gears etc [Carter 1979, Caspers 1980, Parkes 1985, Smith 1990, Higgins 1991, Raghavan 1992].

The current investigation was undertaken as part of an overall effort to understand the microstructural behavior for different compositions of cast iron in the austenitic temperature range. Furthermore, effect of different cooling rates on the high temperature austenitic phase was studied to observe variations in the microstructure, the Rockwell hardness (HRC) and the depth of impression for these cast irons.

MATERIALS AND METHODS

The chemical composition of two different samples of cast iron as determined by MIRDC Lahore is given in Table 1. Specimens of both compositions were annealed, quenched and tempered at different temperatures using the Gallen-hamb muffle furnace for 30 minutes as given in Table 2.

Table 1: Chemical Composition (wt.%) of Cast Iron Samples

	C	Si	Mn	S	P	Ni	Cr	Mo	Fe
Sample A (SG)	3.27	2.70	0.70	0.012	0.051	-	0.07	0.056	Balance
Sample B (Grey)	3.36	2.51	0.54	0.122	0.08	0.16	0.43	-	Balance

Microstructures of all the heat-treated samples were examined by Epimet Metallurgical Microscope N334, (U.K.), equipped with 120 mm camera (Centon DF). Metallographic specimens were prepared by grinding and polishing using standard techniques [Fatahalla 1993] followed by etching with nitric acid (HNO_3) + alcohol solution, the latter technique resulted in effectively revealing the microstructural features, particularly grain boundaries. Hardness of all samples was measured after each heat treatment using Rockwell Hardness Tester (HR-150A, China), the depth of impression was also calculated. Results are presented in Table 3.

Table 2: Heat Treatments of Cast Iron Samples.

Sample A	Sample B	Temperature (^{o}C)	Time (min)	Cooling mode
A_1	B_1	As received	-	-
A_2	B_2	800	30	Furnace Cooling
A_3	B_3	800	30	Quenched in Brine
A_4	B_4	800+600	30+30	Tempered

Table 3: Microstructural phases and HRC values of as received and heat-treated Cast Irons.

Sample	Sample Condition	Phases Present	Rockwell Hardness (HRC)	Mean Depth of Impression (mm)
A_1	As Received	G.N surrounded by F in P-matrix	16.3	0.1677
B_1	As Received	G.F and free Cb in P-matrix	11.3	0.1773
A_2	Annealed	G.N + more F in about 5%P	5.3	0.1893
B_2	Annealed	Large G.F, free Cb and more F in P-matrix	4.1	0.1915
A_3	Quenched	G.N, Random M needles and a little F	52.2	0.0955
B_3	Quenched	G.F, free Cb, M needles and a little F	48.1	0.1029
A_4	Tempered	G.N, uniform M needles and more F	27.9	0.1440
B_4	Tempered	G.F, Sec. Graphite and uniform M needles	22.2	0.1557

Note: G.N = Graphite Nodules, G.F = Graphite Flakes, F = Ferrite, P = Pearlite, Cb = Carbides, M = Martensites.

RESULTS AND DISCUSSION

The microstructure of as received sample A_1 (Fig. 1a) shows typical bull's eye structure [ASTM 1973, Mehl 1973] of graphite nodules (spheroids) surrounded by ferrite (white) in a matrix of pearlite. Whereas microstructure of as received sample B_1 (Fig. 1b) shows distribution of graphite flakes similar to type C flakes, which are embedded in pearlite matrix with small amount of free carbides as reported in literature [Avner 1974, Smith 1990, Higgins 1991, Raghavan 1992, Elliott 1995]. The amount of ferrite in as received specimen depends on the composition and rate of cooling. The Rockwell hardness (HRC) of sample A_1 is found to be HRC 16.3 and depth of impression 0.168mm. For sample B_1 the HRC value is 11.3 and depth of impression is 0.177 mm, which is smaller than that for sample A_1. Since spheroidal/nodular irons are inferior to flake irons with respect to physical properties but exhibit better mechanical properties [Elliott 1995]. The variation in hardness of these cast iron samples may also be due to the size, amount and distribution of graphite flakes/spheroids and the matrix structure [Avner 1974, Elliott 1995].

The microstructure of annealed sample A_2 (Fig. 2a) shows that the most of the pearlite has decomposed into ferrite (white portion has increased as compared to A_1). By comparing it with American Foundryman's Society (AFS) standard micrographs [ASTM 1973, Mehl 1973, Elliott 1995], it is

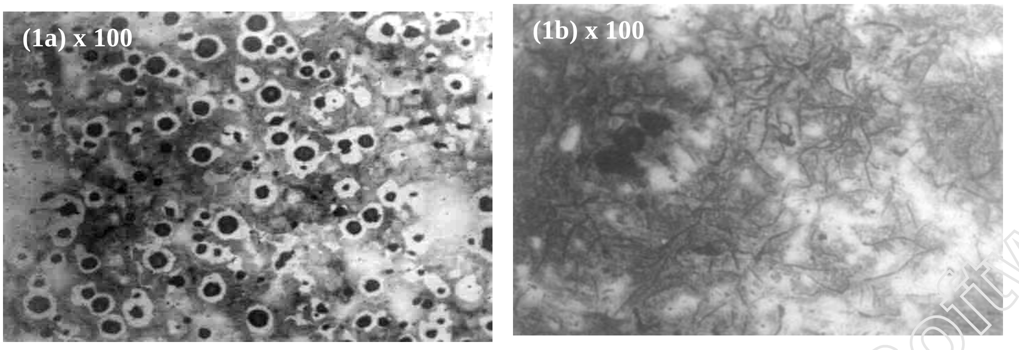

Fig. 1(a & b): Microstructure of as received a) Sample A, b) Sample B

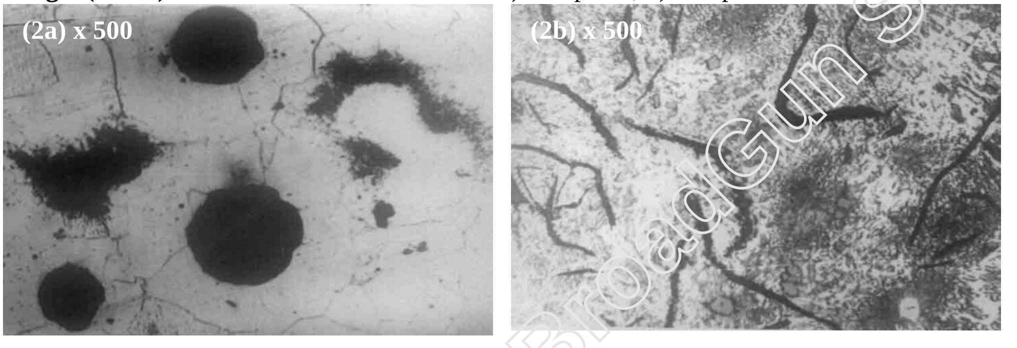

Fig. 2(a & b): Microstructure of annealed a) Sample A, b) Sample B

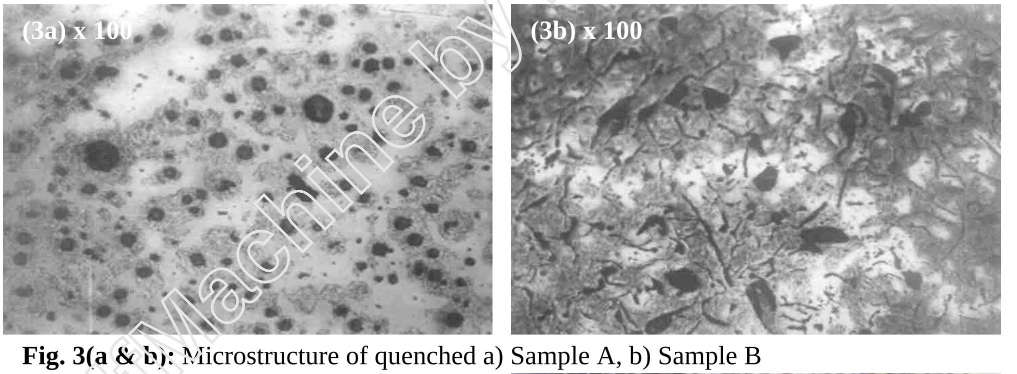

Fig. 3(a & b): Microstructure of quenched a) Sample A, b) Sample B

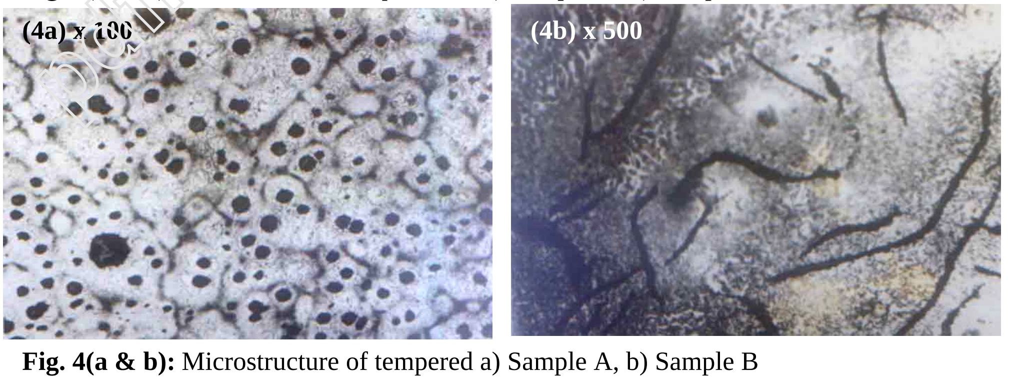

Fig. 4(a & b): Microstructure of tempered a) Sample A, b) Sample B

concluded that nearly 5% pearlite is still present as indicated in Fig. 2a by the irregular black portion. The microstructure of annealed sample B_2 (Fig. 2b) shows large graphite flakes, free carbides and much of the ferrite, but small amount of pearlite is still present. The annealing process decomposes carbides and homogenizes the structure by converting the matrix (pearlite) into ferrite by precipitating all the carbon in solution onto pre-existing graphite [Elliott 1995]. Since ferrite is a softer phase, therefore, Rockwell hardness of these specimens has been reduced to HRC 5.3 (A_2) and HRC 4.1 (B_2) as compared to A_1 and B_1. The depth of impression has, therefore, increased to 0.189mm (A_2) and 0.192mm (B_2).
Microstructure of quenched sample A_3 (Fig. 3a) consists of randomly distributed martensitic (extremely hard and brittle) needles around graphite nodules with small amount of ferrite. Whereas quenching of the sample B_3 has increased the number of super-imposed graphite flakes (Fig. 3b) and produced very fine martensitic needles alongwith very small amount of ferrite. But the free carbides are still present in the microstructure (Fig. 3b). The Rockwell hardness due to quenching has found to rise to HRC 52.2 (A_3) and HRC 48.4 (B_3), which is much greater than that of A_1, A_2, B_1 and B_2. The residual stresses produced by quenching may also be a cause of increase in hardness alongwith the formation of martensitic needles. These quenched specimens have minimum depth of impression i.e. 0.095mm (A_3) and 0.103mm (B_3).
On tempering the quenched samples, microstructure for sample A_4 (Fig. 4a) shows martensitic needles distributed uniformly (commonly called tempered martensitic structure) in the matrix. Similarly microstructure of tempered sample B_4 (Fig. 4b) shows graphite flakes embedded in the matrix of martensite, which are uniformly distributed. In both microstructures, the effect of secondary graphitization may be seen as secondary graphitization occurs by tempering cast irons above 430°C by the decomposition of martensite to form small graphite precipitates throughout the matrix [Danko and Libsch 1955, Askeland and Farinez 1979, Voigt and Loper Jr. 1982]. Due to this high temperature tempering, Rockwell hardness of these specimens has been reduced to HRC 27.9 (A_4) and HRC 22.2 (B_4), which is greater than A_1, A_2, B_1 and B_2, but smaller than A_3 and B_3. The depth of impression (0.144mm for A_4 and 0.156mm for B_4) shows the reverse behavior. The decrease in hardness in the tempered sample may be due to the removal of internal stresses setup during quenching, uniform distribution of martensitic needles and the formation of secondary graphite [Avner 1974, Elliott 1995].

CONCLUSIONS

The hardness of cast iron depends upon the amount and distribution of carbides and/or martensites, both of which are hard and brittle. The rapid cooling (quenching) produced the random distribution of martensitic needles with small amount of ferrite (soft). Due to these martensitic needles and their random distribution, Rockwell hardness of both samples increased strongly. While tempering caused a decrease in hardness but gave maximum strength by removing most of the residual stresses setup during quenching. It also made the samples relatively ductile due to the uniform distribution of martensitic needles and secondary graphitization throughout the matrix. The annealing process increased the amount of ferrite by decomposing pearlite (a mixture of ferrite and carbides); as a result the material became soft and ductile.

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