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Microstructural Changes in Hadfield Steel

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Abstract: Hadfield manganese steel specimens containing 1.46 wt% C and 12.54 wt% Mn were studied in as received condition, after annealing, normalizing, quenching, tempering and cold working. The microstructure, phase transformation and Rockwell hardness (HRC) were measured after each heat treatment. It was found that normalizing and quenching had no effect on microstructure and hardness but annealing, tempering and cold working cause a change in the microstructure and increase the hardness. The increase in hardness on tempering was due to fine distribution of carbides while on annealing, precipitation of carbides at austenitic grain boundaries and within the grains causes hardness to increase. Cold working may cause the formation of twin boundaries / martensites which increase the hardness of specimen.

Key Words: Rockwell Hardness, Microstructure, Heat Treatments, Precipitation, Carbides, Martensites, Twin Boundaries

Introduction

Normally all alloying elements that are added to steel, including nickel, silicon, aluminum, manganese, chromium, tungsten, vanadium, titanium, sulfur, phosphorous and copper are soluble in ferrite to a varying degree. The elements manganese, chromium, tungsten, and titanium have great tendency to produce carbides Donald's, (1987). Manganese combines with sulfur in steel, forming manganese sulfide (MnS), thus preventing the sulfur from combining with the iron. If sulfur were allowed to combine with iron to form iron sulfide (FeS), the effect would be to produce steel that would be brittle resulting in difficulty and perhaps failure during the forging operations. Any excess manganese (over the amount necessary to satisfy all the sulfur) combines with what carbon is present, forming carbide of manganese (Mn_3C), this carbide associating with iron carbide (Fe_3C) in cementite. Mn_3C has properties similar to Fe_3C, increasing the hardness and strength, and lowering the plasticity of steel Johnson, (1971).

Hadfield steels are of great interest owing to their good mechanical properties (having high strength, high ductility and excellent resistance to wear), especially their high strengthening ratio during plastic deformation Pelletier, (1995): Avner, (1974). Being austenitic in nature it is extremely tough and shock resistant Higgins, (1993). In as-cast condition this steel is very week and brittle Johnson, (1971). When this steel is quenched from 1850 °F, the structure will be fully austenitic (Microstructure of Cast Metals, (1966) with a tensile strength of about 120,000 psi and a BHN of 180. It is mainly used in this condition Avner, (1974): White and Honeycombe, (1962). The most impressive property of Hadfield steel is its work-hardening behavior, when it is placed in service and subjected to repeated impact, the hardness increases about 500 BHN. Hadfield steel is extensively used in railroad track components, rock crushing equipment Coliver and Boyd, (1956) linear plates for balland rod-mills, dreading equipments, elevator chain, crane track wheels, bottom plates for magnates and where non-magnetic properties are required Higgins, (1993). Due to their quick work-hardening property, it is also used in processing of earthen materials, manufacturing of cements and making bulletproof steel helmets ASM Metals Handbook, (1989). The objective of this research is to highlight the strong dependence of hardness on microstructure and phase transformation, which in turn is dictated by the heat treatment parameters in Hadfield steels and to understand the strengthening mechanism after cold working. Water was chosen for the quenching medium because it gave a rapid, reproducible quench and because it produced very little deformation.

Materials and Methods

As-received Hadfield steel was cut using carbides disk wheels, into six samples namely A, B, C, D, E and F. Their chemical composition is given in Table 1.

Table 1: Chemical composition of Hadfield manganese steel

C %	Si %	Mn %	Fe%
1.46	1.03	12.54	Balance

Specimens of Hadfield steel were heat treated at different temperatures for different times as shown in Table 2.

Table 2: Heat Treatments

Spec-imens	Temperature (°C)	Time (hr)	Cooling mode
A	As received	-	-
B	1050	1/3	Water Quenching
C	1050	1/3	Air
D	1050 + 470 + 850	1/3 + 5 + 4	Water + Air + Water
E	1000	1/3	Furnace
F	1000	1/3	Furnace + Cold Rolled

Microstructures of these heat-treated samples were examined. Metallographic specimens were prepared by grinding and polishing followed by etching with 4% nital, alcohol rinse and 15 % hydrochloric acid (HCL), the latter technique resulted in effectively revealing the microstructural features, particularly grain boundaries. The Rockwell Hardness (HRC) of all samples were measured after each heat treatment and cold work using Rockwell Hardness Tester (HR-150A, China). The x-ray diffraction technique was used to study the phase transformation after each heat treatment and cold work. For this purpose a Schimadzu X-ray Diffractometer model XD-5A equipped with Cu-Kα radiation was used in the 2θ range 20-60° to record XRD patterns at room temperature. This research work was conducted at Department of Materials Science, Bahauddin Zakariya University, Multan during the year 1998.

Results and Discussion

The black lines observed in the microstructure of as received sample A (Fig. 2) are austenitic grain boundaries ASM Metals Handbook, (1980) but due to different orientations of grains some are attacked more strongly than others during etching and appear dark (Microstructure of Cast Metals, (1966). The grain size of sample A measured by using line intercept method approaches to ASTM No.2. The black constituents, which are clearly seen in the micrograph (as thick sections of

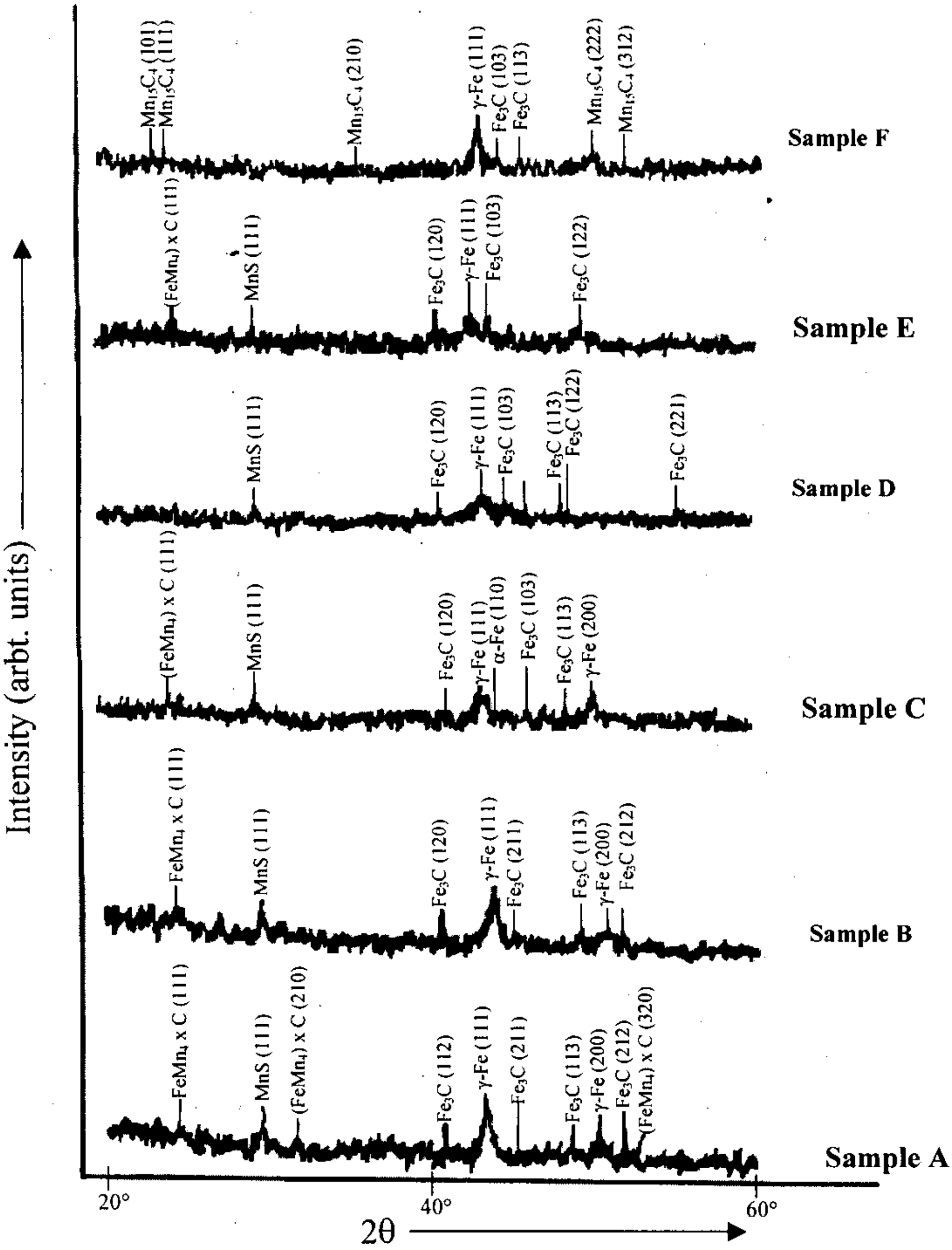

Fig. 1(A, B, C, D, E, F): X-ray diffraction patterns of Samples A, B, C, D, E and F grains), are grain boundary carbides similar to those as reported in (ASM Metals Handbook, (1980). The phases detected by X- ray diffraction pattern (Fig. 1A), confirm the presence of γ-austenite and carbides such as Fe_3C, $(FeMn_4)xC$. The large black spots observed within the grains are found to be inclusions, which may be MnS Higgins, (1993) and confirmed by XRD pattern. These inclusions may some times pass out with slag and remain well distributed throughout the structure of the sample. The Rockwell hardness measured was found to be HRC 9.3 as shown in Fig. 8.

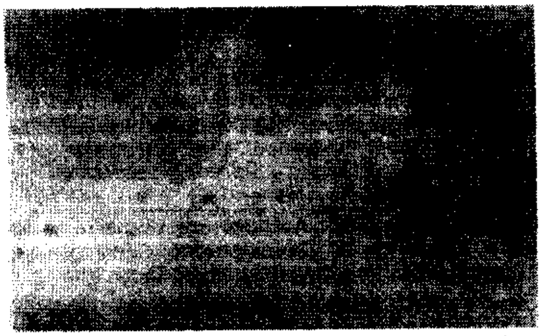

Fig. 2: Microstructure of Sample A (as received)

The microstructure of water-quenched sample B (Fig. 3) is very much similar to that of sample A (as-received). The only difference is in the size of the austenitic grains. The grain size of sample B was found approaching to ASTM No. 3. The decrease in grain size can mainly be attributed to the time at the austenitizing temperature. By increasing or decreasing the soaking time, large or small grains can be produced Avner, (1974). Rockwell hardness of sample B was HRC 9.1, which is in good agreement with the hardness measured after quenching Hadfield steel Higgins, (1993) from 1050°C in water. The X-ray diffraction pattern given in Fig. 1B, reveals the presence of same phases as observed in sample A.

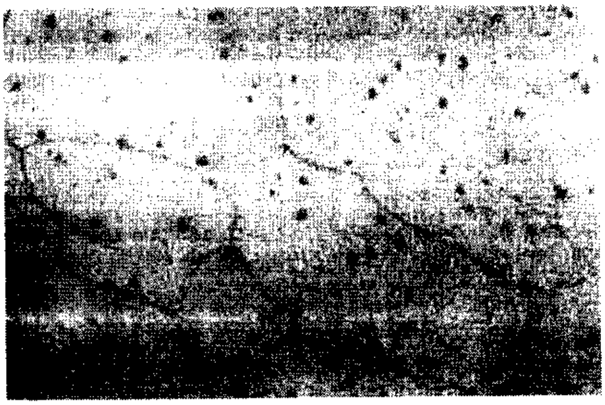

Fig. 3: Microstructure of Sample B (quenched)

The observed microstructure of sample C (Fig. 4) consists of large black lines, which are austenitic grain boundaries as observed in samples A and B. The black spots seen in the microstructure are again inclusions. Which may be MnS particles as discussed above. Their presence was also confirmed by X-ray diffraction pattern (Fig. 1C). The austenitic grain size in this case approaches to ASTM No. 1. The slow cooling (normalizing) causes the grain size to increase as compared to sample A. The Rockwell hardness of sample C was slightly lower i.e., HRC 8.9 as compared to sample A and B as shown in Fig. 8.

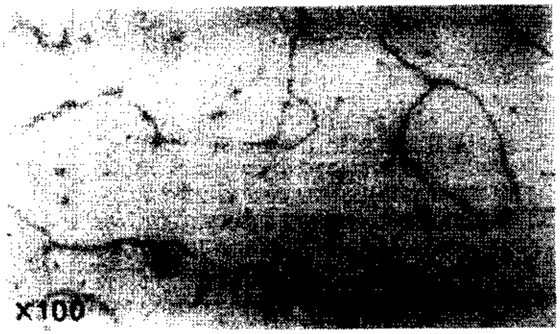

Fig. 4: Microstructure of Sample C (normalized)

The micrograph of the sample D (Fig. 5) consists of austenitic grain boundaries. Some finely dispersed cementite (Fe_3C) particles are also present within these austenitic grains. The presence of cementite particles was also confirmed by X-ray diffraction pattern shown in Fig. 1D. Presence of these finely dispersed cementite particles causes the Rockwell hardness to increase from HRC 9 to 25 (Fig. 8), as Fe_3C phase is harder than the austenitic phase. The purpose of heat treatment cycle applied to sample D was to increase hardness and toughness of Hadfield steel as reported in Ref. Kondraluk, (1985). The observed large increase in hardness confirms the desired result.

Fig. 5: Microstructure of Sample D (Tempered)

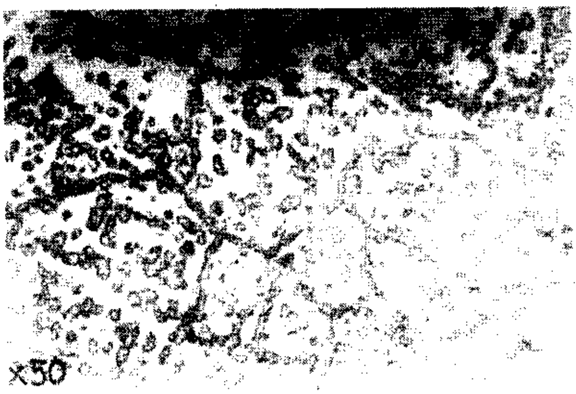

Fig. 6: Microstructure of Sample E (annealed)

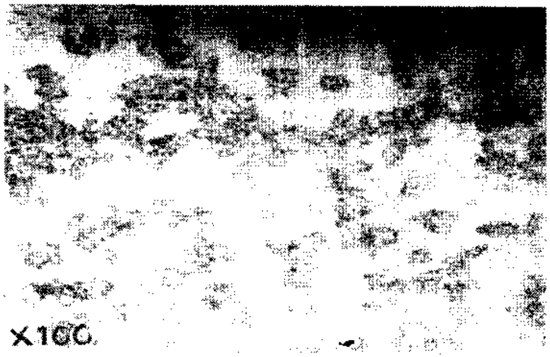

Fig. 7: Microstructure of Sample F (cold worked)

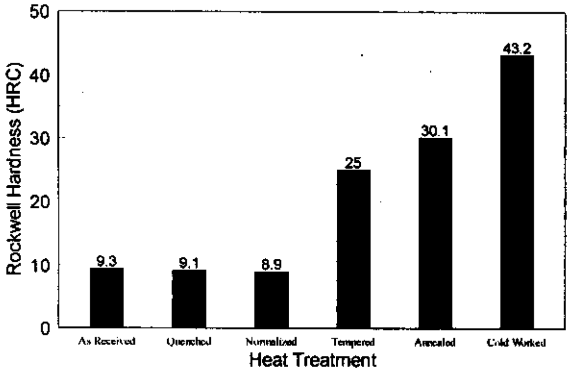

Fig. 8 Rockwell Hardness (HRC) Vs Heat Treatments

The microstructure of annealed sample E (Fig. 6) consists of large carbides, which are mainly present at austenitic grain boundaries and also inside the grains. The presence of these carbides was confirmed by X-ray diffraction pattern given in Fig. 1E. The formation of carbides after annealing was also reported by Rodionov, 1986) which could affect the hardness of the material Hadfield steel). The Rockwell hardness of sample E was HRC 30.1. The grain boundary carbides are mainly responsible for this large increase in hardness.

The annealed sample was subjected to cold work by controlled hammering. The microstructure of cold-worked sample F (Fig. 7) consists of compressed carbides, which were grown earlier at grain boundaries during the process of annealing. Within these grain boundary carbides some needle like martensitic structures can also be seen. The X-ray diffraction pattern given in Fig. 1F also reveals the presence of hcp-carbide ($Mn_{15}C_4$) alongwith Fe_3C (cementite) and γ-Fe (austenite). The hardness of sample F was found to be HRC 43.2 (Fig. 8). This large increase in the hardness of cold-worked sample was due to the presence of martensite phase as reported in Chu, (1995).

Conclusions

It was concluded that: Quenching and normalizing had no effect on the microstructure and hardness.

The increase in hardness on tempering was due to fine distribution of carbides, while on annealing precipitation of carbides at the austenitic grain boundaries and within the grains causes hardness to increase.

Cold working may cause the formation of twinning / martensites which increase the hardness of the specimen.

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