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Phase Transformations of Hadfield Manganese Steels

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Abstract

In the present work, the effect of different silicon percentages that were added to Hadfield manganese steel on the microstructure, phases and hardness are investigated. The results show that silicon has the crucial role in changing the hardness and Fe_3C phase morphology from acicular to chunky through different stages. X-ray diffraction line profile analysis shows that two phases are presented in the matrix of Hadfield manganese steels; these phases are austenite and Fe_3C.

Keywords: Hadfield steel, silicon content

دراسة التحولات الطورية لفولاذ هادفيلد المنغنيزي

الخلاصة

يهدف هذا البحث الى دراسة تاثير اضافة نسب مختلفة من السليكون على البنية المجهرية والصلادة والاطوار لفولاذ هادفيلد المنغنيزي. اوضحت النتائج ان اضافة السليكون له دور حاسم في تغيير صلادة فولاذ هادفيلد المنغنيزي اضافة لتغييره شكل طور كاربيد الحديد (Fe_3C) من الشكل الابري (Acicular morphology) الى الشكل الكتلي (Chunky morphology). اوضح فحص حيود الاشعة السينية (X-ray diffraction pattern) وجود طورين رئيسين يظهران في ارضية فولاذ هادفيلد المنغنيزي واللتان تتمثلان بطور الاوستنايت وطور كاربيد الحديد (Fe_3C).

1. Introduction

Austenitic manganese steel, also called Hadfield steel has a chemical composition of 1.2C and 12Mn according to the grades of ASTM A128. Hadfield steel can be considered as one of the most important alloys that has outstanding properties [1]. It is an extremely tough, non-magnetic alloy in which the usual hardening transformation has been suppressed by the high manganese content and rapid cooling from a high temperature [1, 2]. The widespread applications of Hadfield steel urged intensive studies during the past decades [3, 4]. Several researchers focused their attention on studying the work hardening mechanism of Hadfield manganese steel [5-9], while others concentrated their studies on wear properties [10-13]. However, producing satisfactory properties of manganese steel that are casted in sand moulds requires a solution heat treatment at high temperature and long time which in

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turns raise the production cost. Metallic moulds should reduce the cost by introducing sufficient cooling rate during solidification of the melt and release from post heat treatment.

In this paper, an investigation on phase transformations and microstructure is presented after casting Hadfield manganese steel in different silicon percentages in a metallic mould.

2. Experimental Details

Different series of Hadfield manganese steels were cast in this work using RF induction furnace type Elotherm. The chemical composition of the casts is controlled during melting to have suitable percentages with aid of optical emission spectrometer (OES) type thermo ARL 3460. Raw materials used as starting material were low carbon steel, ferrosilicon, ferromanganese and graphite. Six samples were fabricated with different silicon contents (0.05, 0.66, 0.99, 2.15, 2.91 and 3.51%). These samples were denoted by $S_{0.05}$, $S_{0.66}$, $S_{0.99}$, $S_{2.15}$, $S_{2.91}$ and $S_{3.51}$ where the subscripts represent the silicon content. The chemical composition of the as-cast samples is tabulated in Table (I). All ingots were cast at 1500 ^{o}C with dimensions of 32 mm diameter and 8 mm height, in a metallic mould to study the rapid cooling on the phase transformations of the manganese steels. Before metallographic study, all specimens that were cut from ingots were ground using 250, 350, 500 and 1000 SiC emery papers respectively. The ground specimens were primarily polished using slurry of alumina with particle size of 50 µm. Final polishing was carried out using diamond paste with particle size of 1 µm. Etching has been taken place using 2% Nital to make specimens ready for metallographic study. X-ray diffraction unit type Philips was utilised to investigate the phases that presented in Hadfield manganese steels.

3. Results and Discussion

The expected phases in Hadfield steel are austenite and iron carbide (Fe_3C). XRD patterns of the fabricated samples are shown in Figure (1). For silicon-free sample ($S_{0.05}$), there are two dominant peaks. The first peak (at $2\theta = 44^{o}$) is difficult to diagnose, because austenite and Fe_3C are overlapped at this reflection position. The second peak is related to austenite. Increasing silicon content results in drastic changes in the structure. $S_{0.99}$ shows that austenite is became dominant. The highest peak at $2\theta = 44^{o}$ corresponds to austenitic γ-phase. For samples of high silicon content ($S_{3.51}$), carbide existence becomes dominant. The nature of carbide distribution is different with any increase in silicon content; this will be demonstrated later when studying the microstructure. This result indicates that silicon content affects essentially the carbide existence and distribution, and explains the degradation in manganese steel strength at high silicon contents. For extremely high silicon content (i.e., $S_{3.51}$) the XRD spectrum demonstrates a domination of carbide constituent rather than austenite, it is obviously shown that (200) plane of austenite phase decreases significantly with simultaneouse increase in carbide phases. The sample of moderate silicon content ($S_{0.99}$) exhibits maximum reflection peak for (200) austenite phase.

Figure (2) illustrates the microstructure of Hadfield manganese steel in different silicon percentages. It is clear from this figure that these steels consist of two phases regardless of silicon percentage as explained from XRD patterns, these two phases are austenite and Fe_3C. It is important to recognise that Fe_3C phase distributes in size and morphology depending on silicon percentage. Moreover, Fe_3C phase changes its morphology from acicular to chunky with increasing silicon percentage. For silicon-free cast ($S_{0.05}$), Fe_3C phase evolved as acicular shape; this morphology is converted to fine and very fine precipitates as in $S_{0.66}$ and $S_{0.99}$. Globular carbide can be presented early when silicon content is 2.15% ($S_{2.15}$). It is noticed that globular carbide distributed randomly in the austenite grain and at the grain boundary. A change from globular to chunky carbide occurs in samples $S_{2.91}$ and $S_{3.51}$. Chunky carbide increases in amount with increasing silicon percentage from 2.91 to 3.51% and distributes inside the austenite grain and along the grain boundary as a chain of carbides. Some authors [14] explained chunky carbide to be a special kind of pearlite, called degenerated or orthopearlite, which is thought to be due to low degree of cooperation between the ferrite and carbide during the transformation. This result does not coincide with the present work, in which the chunky carbide is Fe_3C phase except that it is established in different morphologies. This can be illustrated on the basis of X-ray charts of Hadfield manganese steel with 2.91 and 3.51% Si ($S_{2.91}$, and $S_{3.51}$). It is important to show that silicon has the crucial effect on changing Fe_3C phase from acicular to chunky through a series of different Fe_3C morphologies, this is attributed to the increase in carbon activity due to the repulsive force between silicon and carbon, also silicon raises the eutectic temperature [14].

Figure (3) depicts the relationship between hardness and silicon content of Hadfield manganese steel. It is presented from this figure that silicon affects the hardness behaviour in which the hardness curve decreases and then increases to a higher value. This behaviour can be related to Fe_3C phase morphology that presents in the matrix, when Fe_3C phase morphology is acicular as in $S_{0.05}$ the hardness has a given value (229 HB), this value will be decreased when the silicon content increases to 0.66%, this can be explained to the precipitation of Fe_3C in the matrix as fine precipitates. This means that large amount of Fe_3C dissolved in the matrix. Therefore, the volume fraction of Fe_3C phase will decrease largely with increasing silicon percentage up to 0.99% and then hardness begins to increase, this increasing in hardness value continues until the hardness reaches to 329 HB. This can be explained on the basis that with increasing silicon content beyond 0.99%, the volume fraction of Fe_3C will increase as showed in Figure (2).

It is important to optimise Hadfield manganese steel according to silicon content. It must be known that the best structure of Hadfield manganese steel is produced when the matrix has only austenite phase. This can be produced by a proper solution heat treatment at 1050 °C followed by quenching in water [1]. In this work, metallic mould is used to obtain rapid cooling instead of using solution heat treatment.

It is shown from Figure (2) that $S_{0.99}$ illustrates good structure with unnoticeable carbide precipitation. This structure is obtained without further solution heat treatment.

4. Conclusions

Metallic mould can give proper Hadfield steel without post-heat treatment; this can contribute to reducing the production cost. Among the various crucial restrictions in the production of Hadfield manganese steel, silicon content is very restricted parameter and it is preferred to use silicon in moderate percentage. Silicon changes the Fe_3C phase from acicular to chunky through several stages. Two phases are presented in the matrix of Hadfield manganese steel regardless of silicon content which are austenite and Fe_3C. Furthermore, remarkable changes in the hardness value can be recognized with increasing silicon content.

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Table (I). Chemical Composition of the As-Cast Samples Obtained from OES.

Sample	**C%**	**Si%**	**Mn%**	**P%**	**S%**	**Cr%**	**Ni%**	**Mo%**	**Fe%**
$S_{0.05}$	1.26	0.05	13.85	0.05	0.03	0.13	0.07	0.04	Re.
$S_{0.66}$	1.24	0.66	13.56	0.05	0.03	0.14	0.07	0.04	Re.
$S_{0.99}$	1.25	0.99	13.49	0.05	0.03	0.14	0.07	0.04	Re.
$S_{2.15}$	1.23	2.15	13.23	0.05	0.03	0.14	0.07	0.04	Re.
$S_{2.91}$	1.23	2.91	12.98	0.05	0.03	0.14	0.07	0.04	Re.
$S_{3.51}$	1.28	3.51	12.92	0.05	0.02	0.16	0.06	0.04	Re.

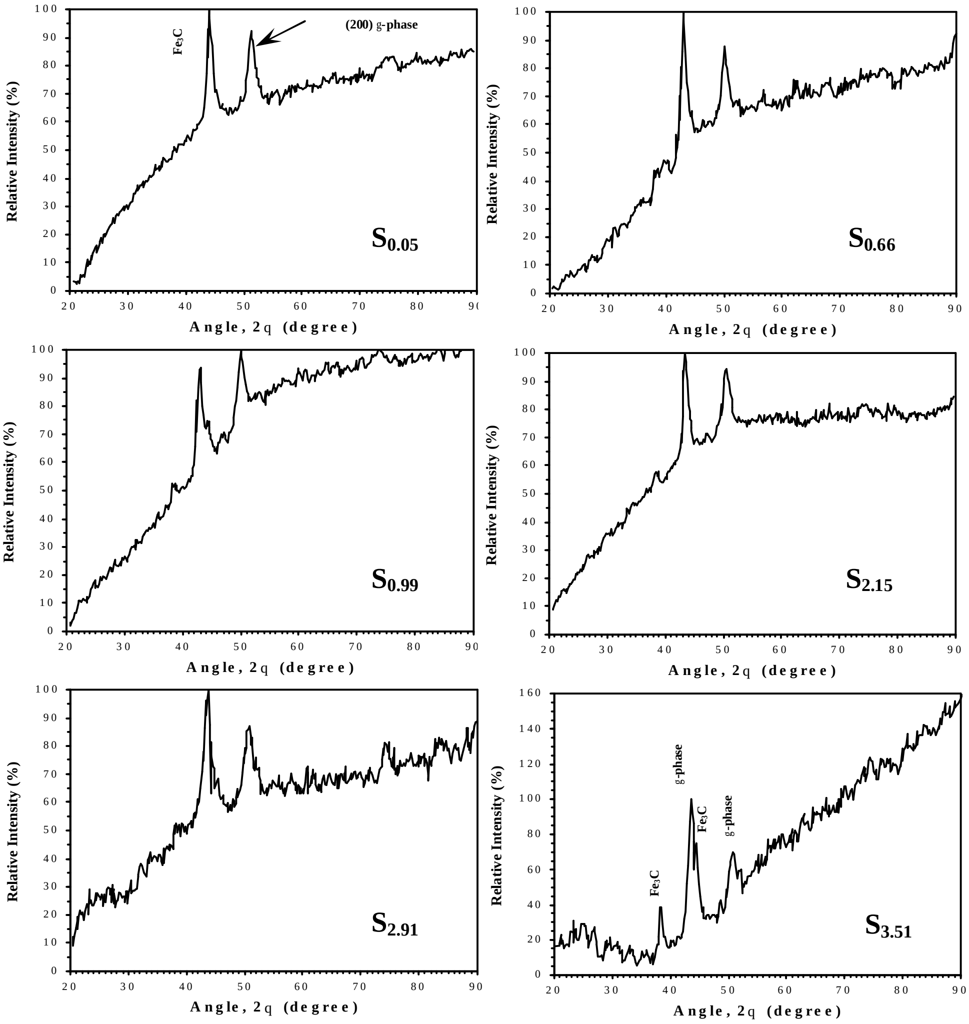

Figure (1). XRD Spectra of Manganese Steel with Different Silicon Contents.

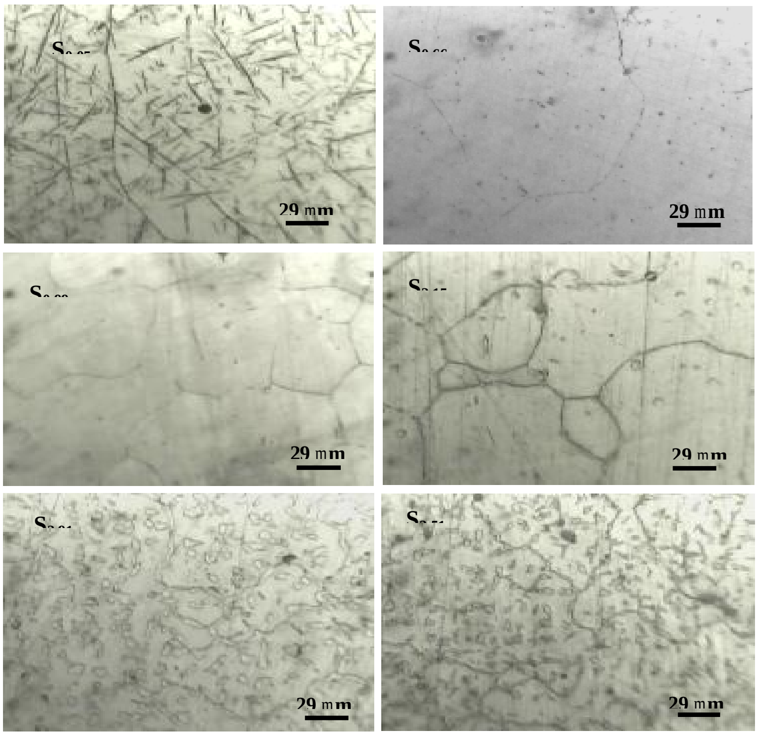

Figure (2). Microstructure of the Hadfield Manganese Steels.

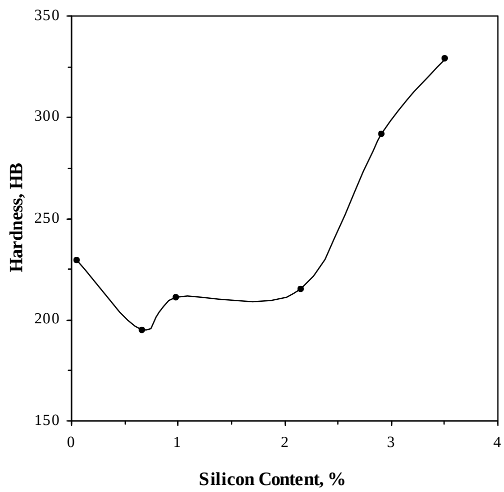

Figure (3). Relationship between Hardness and Silicon Content.