Sintered Fe-Mo-Mn-Si-C alloys

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Abstract

Sintered Fe-Mo-Mn-Si-C alloys were produced by alloying silicon and carbon elements to pre-alloyed Fe-0.5Mo-0.15Mn powder via sintering of mixtures of pre-alloyed powder and varied silicon carbide amounts (0.5-4.0 wt.% with 0.5 increment). The sintered alloys were cooled in a sintering furnace. Microstructures and mechanical properties of the sintered alloys were altered depending on added silicon carbide content. With up to 2.0 wt.% silicon carbide additions, the sintered alloys exhibited polygonal ferrite plus eutectoid decomposition products, showing non-cooperative ferrite and carbide growth mode. With silicon carbide contents of ≥ 2.5 wt.%, the sintered alloys exhibited microstructural feature similar to that of a ductile iron, i.e., a common feature consisted of a black particle enveloped with ferrite and pearlite. Tensile strengths of the sintered alloys increased but elongation values decreased with increasing added silicon carbide content. The sintered alloys produced by 3.5 and 4.0 wt.% silicon carbide showed high strengths and considerably good elongation values.

Keywords: Sintering, Silicon carbide, Eutectoid decomposition, Pearlite, Mechanical property.

1. Introduction

The continuing and growing demands for high-performance and cost-effective parts in automotive industry are the motivation driving the innovation in sintered steel technology. Sintered steel parts with superior performance are produced from different iron (Fe)-based powder grades, such as pre-alloyed and diffusion-bonded powders [1, 2]. These powders contain low alloying element concentrations in the forms of solid solution in pre-alloyed powders or elemental particles bonded on pure-Fe or pre-alloyed powders. Important alloying elements include chromium (Cr), molybdenum (Mo), Nickel (Ni), and manganese (Mn). They act as substitutional alloying elements, which are able to influence phase transformations resulting in transformation product morphologies and types desirable for better properties. Both pre-alloyed and diffusion-alloyed powder grades are designed for flexible carbon (C) additions in order that varieties of mechanical properties can be manipulated by sintered steel parts manufacturers. Different added C contents dictate microstructural feature formation in sintered steels.
and hence affect mechanical properties [3, 4]. In addition to C content, post-sintering cooling rate is also the important parameter controlling microstructure and mechanical property of sintered steels [5].

Recently, it has been discovered that not only graphite but non-oxide silicon carbide (SiC) ceramic can be used as a carbon source for C alloying in sintered steel fabrication [6, 7]. Lately, high content (4.0 wt.%) SiC was admixed to pre-alloyed Fe-Mo and Fe-Cr-Mo powders to produce sintered composites having microstructures similar to those of cast ductile irons [8-10]. The experimental results in the literatures given above suggest that several phenomena, including SiC decomposition, dissolution of Si and C atoms, and phase transformations of Si and C-containing solid solutions, resulting from the interactions between Fe-based and SiC powders during sintering cycle, are complicated but important for sintered steel technology development. They also indicate that the amount of added SiC powder controls microstructural development. In this work, alloying behaviour of different Si and C contents from different SiC amounts in sintered Fe-based powder with lean alloying element contents (pre-alloyed Fe-0.50Mo-0.15Mn powder) has been explored. This work was focused on phase transformations during post-sintering cooling with a slow rate.

2. Experimental procedure

2.1 Sample preparation

The metal powder used in this study was pre-alloyed Fe-0.50Mo-0.15Mn powder, courtesy from Rio Tinto Metal Powders of Canada (via P.S. Steel Co., Ltd., of Thailand and Rio Tinto Iron & Titanium (Suzhou) Co., Ltd., of China). The powder mixtures were made by blending of the pre-alloyed powder with varied SiC amounts of 0.5-4.0 wt.% (with increment of 0.5 wt.%) shown in Table 1. The powder mixtures were compacted into tensile test bars according to MPIF standard 10 with green density 6.50 ± 0.05 g/cm³. The green specimens were sintered at 1280°C for 45 minutes in a vacuum furnace at pressure around 1.0 x 10⁻³ mbar. After sintering, specimens were continuously cooled in a vacuum furnace with cooling rate of about 0.1°C/s. The densities of sintered steels were determined using the Archimedes method according to MPIF Standard 42.

| Material                  | Composition (wt.%) |
|---------------------------|--------------------|
| SiC                       | 0.5  1.0 1.5 2.0 2.5 3.0 3.5 4.0 |
| Pre-alloyed Fe-0.50Mo-0.15Mn | Bal. Bal. Bal. Bal. Bal. Bal. Bal. Bal. |

2.2 Microstructural investigation

Microstructure of sintered steel specimens were observed by using optical microscopy (OM) and scanning electron microscopy (SEM). Specimens were prepared according to standard metallography practice and etched with 2% Nital. Phase identification was conducted by using X-ray diffraction (XRD) technique using Co Kα radiation (wavelength = 1.7902 Å). The diffracting angle (2θ) was scanned from 30 to 110, with scan speed of 0.04°/s and step size of 0.02° in PANalytical model X’Pert PRO.

2.3 Hardness and tensile tested

Microhardness measurement was conducted by using Rockwell hardness tester (Wilson, Rockwell 574) in F scale using 60 kgf load for 6 indentations per a sample. Tensile test was carried out by using Instron Universal Instrument. The samples were tested according to the ASTM E8M standard.
3. Results and discussion

3.1 Microstructure and phase analysis

Microstructures of sintered Fe-Mo-Mn-Si-C alloys varied with added SiC contents as shown in Figure 1. Without SiC addition, the sintered alloy had only polygonal ferrite (PF) grains (Figure a1, b1 and c1). With 0.5 wt.% (Figure 1 (a2, b2 and c2)) and 1.0 wt.% (Figure 1 (a3, b3 and c3)) SiC additions, the sintered alloys had PF grains and eutectoid transformation zones (ETZs). The ETZ showed Widmanstätten ferrite (WF) plates and ferrite/discrete carbide mixture, termed as bainite (B). With 1.5 wt. % (Figure 1 (a4, b4 and c4)) and 2.0 wt.% (Figure 1 (a5, b5 and c5)) SiC additions, the fraction of PF grains was reduced whereas that of ETZs was increased. The carbide particles in some ferrite/carbide mixtures changed from discrete to lamellar shape. The ferrite/carbide lamellae dominated and PF grains returned to the microstructure of the sintered Fe-Mo-Mn-Si-C alloy with 2.5 wt.% SiC addition (Figure 1 (a6, b6 and c6)).

The microstructural feature consisting of residuals of SiC decomposition, appeared as black particles, surrounded with PF grain halo and ferrite/carbide lamellae were observed in sintered alloyed added with 3.0 wt.% (Figure 1 (a7, b7 and c7)), 3.5 wt.% (Figure 1 (a8, b8 and c8)) and 4.0 wt. % (Figure 1 (a9, b9 and c9)).

XRD patterns of some sintered alloys are shown in Figure 2. Strong peaks were corresponding to body-centered cubic (bcc) crystal structure of α-ferrite. Weak peaks were corresponding to face-centered cubic (fcc) crystal structure of M23C6 carbide in sintered alloys with low SiC additions. In the sintered alloy with 4 wt. % SiC addition, XRD pattern showed weak peaks corresponding to M3C carbide.

The microstructures given in Figure 1 suggest that added SiC powder particles undergo decomposition, which results in alloying of Fe-based matrix with Si and C atoms. Similar alloying phenomena were previously reported in [6-10]. With low SiC additions, no SiC decomposition residuals were remained in microstructures [6, 7]. In contrast with 4.0 wt.% [8-10] and 5 wt.% or more [11, 12] SiC additions, SiC decomposition residuals were reported to remain as black particles. The Si and C atoms, alloyed in Fe-Mo-Mn matrices, influence phase transformations during post-sintering cooling. In low Si and C matrices, phase transformations start with ferrite transformation and followed by eutectoid decomposition. In the latter, the decomposition proceeds by WF plate formation followed by decomposition of austenite strips between WF plates. The decomposition of austenite strips depends strongly on the added SiC content, indicating Si and C content dependence. The decomposition resulting in ferrite/discrete carbide mixture occurs in sintered alloys with low added SiC content whereas that resulting in ferrite/carbide lamellae occurs in sintered alloys with low added SiC content. The austenite decomposition into WF plates and ferrite/carbide mixtures in strips between WF plates was previously investigated and the mechanisms involved were explained clearly [13].

Precipitation of carbides in sintered Si-containing alloy matrices is an interesting subject as it is generally accepted that cementite is inhibited in steels containing judicious Si contents [14-17]. The reason is due to the fact that the dissolution of Si in cementite is thermodynamically unflavored condition [18]. In our works, cementite precipitation is truly inhibited but is replaced by M23C6 carbide precipitation in low Si-containing matrices. Moreover, in high Si-containing matrices M3C carbide precipitation is not prevented.
SiC (wt.%) | OM image Low magnification | OM image High magnification | SEM image
---|---|---|---
0.0 | ![Image](a1.png) | ![Image](b1.png) | ![Image](c1.png)
0.5 | ![Image](a2.png) | ![Image](b2.png) | ![Image](c2.png)
1.0 | ![Image](a3.png) | ![Image](b3.png) | ![Image](c3.png)
1.5 | ![Image](a4.png) | ![Image](b4.png) | ![Image](c4.png)
2.0 | ![Image](a5.png) | ![Image](b5.png) | ![Image](c5.png)
2.5 | ![Image](a6.png) | ![Image](b6.png) | ![Image](c6.png)
3.2 Mechanical property
Tensile strength and hardness increased whereas elongation decreased with added SiC contents (Figure 3). The mechanical properties of sintered alloys are influenced by microstructures. The increase of
strength and hardness is sharp when microstructures contain both PF grains and ETZs. The ETZs with ferrite/discrete carbide mixtures contribute strongly on strength and hardness. When the microstructures have only ETZs but with ferrite/carbide lamellae nature, their contribution on strength and hardness is observed to be low. The contribution of ferrite/carbide lamellae may be compensated by another unknown factors. This issue will be further studied.

![Figure 3](image)

**Figure 3.** Mechanical properties of experimental sintered alloys.

4. Conclusions
Experimental sintered alloys, produced from pre-alloyed Fe-0.50Mo-0.15Mn powder mixed with varied SiC contents, were studied. It was found that with up to 2.0 wt % SiC additions, the sintered alloys exhibited PF grains and ETZs, showing ferrite/discrete carbide mixtures. With SiC contents in the range 2.0 to 2.5 wt %, the fraction of PF grains decreased and that of ETZs increased. Some ETZs showed ferrite/carbide lamellae. With SiC contents ≤2.5 wt %, the sintered alloys exhibited microstructural feature similar to that of a ductile iron, i.e., a common feature consisted of a black particle enveloped with ferrite and pearlite. Tensile strengths of the sintered alloys increased but elongation values decreased with increasing added silicon carbide content. The sintered alloys produced by 3.5 and 4.0 wt % silicon carbide showed high strengths and considerably good elongation values.

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