Effect of carbon content on microstructure and mechanical properties of sintered Fe-Mo-Mn-C alloys

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Abstract
Sintered Fe-Mo-Mn-C alloys were produced by sintering of mixtures of pre-alloyed Fe-0.5Mo-0.15Mn powder and varied carbon amounts (0.30-1.20 wt.% with 0.15% increments) followed by slow cooling in furnace. Microstructures and mechanical properties of the sintered alloys varied with added carbon content. With up to 0.75 wt.% carbon additions, the sintered alloys exhibited polygonal ferrite plus non-cooperative eutectoid decomposition products. With 0.90 wt.% carbon addition, the whole microstructure of the sintered alloy mainly consisted of non-cooperative eutectoid decomposition products. With 1.05 and 1.20 wt.% carbon additions, the microstructures of the sintered alloys consisted of large grain boundary carbides and mixed non-cooperative and cooperative eutectoid decomposition products within grains. Tensile strength showed the maximum value in the sintered alloy with 1.05 wt.% carbon addition. Elongation values decreased sharply with increasing carbon contents of up to 0.60 wt.%, beyond which the values were constant.

1. Introduction
One advantage of powder metallurgy is the ability to combine sintering and heat treatment into a one-step process, widely known as sinter hardening. It can tailor the microstructures to obtain a variety of mechanical properties by using alloy design and a controlled cooling rate [1]. Carbon steel is widely used in many applications according to its mechanical properties, which strongly depend on carbon content and manufacturing process. Generally, the higher carbon content results in better tensile properties, with less ductility and fabrication difficulty. As a carbon steel is slowly cooled, primary ferrite (hypoeutectoid steel) or primary cementite (hypereutectoid steel) starts to nucleate at austenite grain boundaries until below eutectoid temperature, the rest austenite decomposes into a lamellar structure of two stable phases, by the cooperative growth of cementite (Fe₃C) and ferrite at a common transformation front with the parent austenite by a eutectoid reaction [2]. Although the microstructure becomes lamellar of fully pearlitic as carbon content approaches 0.8 wt.%C, Lu et al. [3] reported that
the precipitation of small cementite particles has been verified in unalloyed steels containing carbon 0.16, 0.60, 0.8, and 1.24 wt.% by using thermal cycling treatment.

The addition of alloying elements can alter the phase transformation scenarios in steels. So far as we know, all alloying elements retard pearlite transformation kinetics with the exception of Cobolt (Co) [4]. Several works have been done about the kinetics of pearlite transformation caused by alloying design [5-8]. Bain [5] proposed the reduction of proeutectoid ferrite fraction because Manganese (Mn) changed the position of the critical point of steels to lower temperature and lower carbon regions. Whereas Ochiai et al. [6] found that the Chromium (Cr) and Molybdenum (Mo) addition increased the eutectoid temperature, which promoted the high strength of pearlite due to the refinement of the inter-lamellar spacing. Moreover, it has been reported that the Silicon (Si) addition could suppress the spheroidization of the cementite lamellae [7]. Previous work reported that the addition of ≥ 1 wt.% Ni could promote bainitic transformation at the expense of proeutectoid ferrite in the Fe-Cr-Mo-C sintered steels [8].

Pandit et al. [2] claimed that when the isothermal heat treatment was employed, the divorced eutectoid transformation (DET) product was clearly shown as spheroidal cementite particles in a ferrite matrix. DET occurred by a non-cooperative growth mode resulted from the parent austenitic phase contains cementite particles with a few microns of spacing. DET occurred due to the incorporation of partitioned carbon into the existing cementite particles. Andersson [9] reported that by using a slow cooling rate, the microstructure of a high-carbon steel alloyed with molybdenum consisted of coarse degenerated pearlite, nanometer-sized molybdenum carbides and ferrite. Upper and lower bainite structures also formed by non-cooperative eutectoid transformations [10]. Taleff et al., [11] found that very fine cementite particles were clearly observed in high-carbon steels around 1.5 wt.%. The transformation front, having a cellular-shaped austenite/ferrite boundary, advanced into an array of austenite plus fine cementite particles in a ferrite matrix. It has been reported by Howell et al. [12] that pearlite with lamellae of ferrite and M\textsubscript{23}C\textsubscript{6} carbide instead of M\textsubscript{6}C plate has been found in Fe-Cr alloys. The partitioning of Mn, Al, and C solutes was clearly observed in the M\textsubscript{23}C\textsubscript{6} pearlite of the Fe-C-Mn-Al alloy [13].

Numerous studies have been reported that softening processes, of bearing steels, to create final structure as coarse cementite particles dispersed in a matrix of ferrite [14, 15, 16]. It also known as a divorced pearlite, since the product phases no longer grew cooperatively. Moreover, Verhoeven et al. [17] found that addition of Cr is most effective in minimizing carbide size. Because the morphology and dispersity of cementite and alloy carbide are important for the strength and ductility of alloyed steels therefore the balance between the carbon content and other alloying in order to control phase transformation, is the key to obtain high performance sintered steel. Mo with amounts of 0.5-1.0 wt.%, is commonly used in high strength steels. It has high affinity for C and trends to transform into carbides during sintering. In addition, Mo also partitions to other carbides and forms its own series of carbides as M\textsubscript{6}C, M\textsubscript{23}C\textsubscript{6}, M\textsubscript{2}C and M\textsubscript{5}C [18].

Nonetheless, there are a few researches work about the effect of high-level carbon addition on phase transformation behaviour’s in quaternary alloy sintered steel. Therefore, the present work aims to investigate the effect of medium-to high-carbon contents on the final microstructures and mechanical properties of pre-alloyed Fe-0.5Mo-0.15Mn sintered steel using slow cooling process.

2. Experimental procedure
As received water atomised steel powder pre-alloyed with 0.5 wt.% Mo and 0.15 wt.% Mn (Atomet 4001) was used as a base material in this investigation. It is produced by Rio Tinto Metal Powders of Canada with average particle size of less than 250 μm. Eight sets of specimens were prepared by varying amounts of added carbon from 0.30 to 1.20 wt.% with 0.15 increment. The set of specimens with no carbon addition was also produced. Zinc stearate of 1.0 wt.% was also added as a lubricant before blending, by using a barrel mixer rotating with the speed of 30 rpm for 1 hour. After that, each set of mixed powders was cold compacted into standard tensile test bars, according to MPIF standard 10 by
using a uniaxial pressing machine. Densities of the green compacts were 6.50 ± 0.05 g/cm³. The densities of the specimens were measured by the Archimedes method according to the MPIF Standard 42. The green compacts were sintered at temperatures of 1,280ºC under vacuum atmosphere for 45 min. After that, the sintered specimens were cooled down in the furnace with the rate of 0.1°C/s. For metallographic examination the specimen cross sections were polished as mirror-like surfaces and etched with a solution of 2% nital for characterization using optical microscopy (OM) using Olympus STM7 and also scanning electron microscopy (SEM) using FESEM-HITACHI/SU8230. Macrophotography of the sintered specimens was carried out using a hardness tester (Rockwell scale B). Tensile properties were tested by using the universal testing machine (Instron 8801).

3. Results and Discussion
3.1 Microstructures
The microstructures of Fe-0.5Mo-0.15Mn sintered at 1280ºC under vacuum atmosphere and cooled at the rate of 0.1°C/s were observed by OM and SEM. The OM and SEM images indicate that sintered alloy microstructure has polygonal ferrite (PF) grains as shown in Figure 1(a) and Figure 1(b) respectively.

![Figure 1. OM (a) and SEM (b) micrographs of Fe-0.5Mo-0.15Mn sintered alloys.](image)

The microstructures of sintered alloys containing carbon contents in the range of 0.30-0.75 wt.% (with increment of 0.15%) changed according to carbon content as shown in Figure 2. The microstructures had dual-phase structures, which composed of PF grains and zones of non-cooperative eutectoid decomposition products. The latter zones contained particles with different sizes and morphologies, which depended on the degree of undercooling, embedded in a soft ferritic matrix. The non-cooperative eutectoid decomposition products formed in these sintered alloys are attributed mainly to the effects of alloying Mo and Mn elements, which can retard the formation of pearlite [19]. Besides, the fraction of these products also increases with increasing carbon content.

The formation of the divorced eutectoid transformation (DET) product occurred under conditions that low undercooling and small inter-particle spacing or fine array of pre-existing cementite due to the advancing transformation front begins to pull-away from cementite [20, 21]. Austenite and pearlite coexist in equilibrium were presented in the three-phase regions, austenite (γ) + ferrite (α) + cementite (θ) of Fe-Fe₃C phase diagram due to Mo and Mn moved the eutectoid temperature and also changed the eutectoid composition to lower carbon content [2].

The whole microstructure of the sintered alloy added with 0.90 wt.% carbon consisted mainly of non-cooperative eutectoid decomposition products. These products appeared as fine needle-shaped particles dispersed in the ferrite matrix similar to upper bainite as shown in Figure 3. The microstructures of sintered alloys containing 1.05 and 1.20 wt.% carbon consisted of large grain boundary carbides and mixtures of non-cooperative and cooperative eutectoid decomposition products. Comparison between these two sintered alloys, the more carbon content, the larger grain boundary carbide was observed.
Variation of carbon contents are specified.

Figure 2. Optical (a-d) and SEM (e-h) micrographs of Fe-Mo-Mn sintered steels. Variation of carbon contents are specified.
The micrographs of these sintered alloys are shown in Figure 4. It can be explained that the transformation started by proeutectoid carbide precipitation at grain boundary. After that, the austenite transformed by eutectoid reaction into mixtures of non-cooperative and cooperative of ferrite and carbide. With increasing undercooling and carbon content, the transformation products became smaller and more densely dispersed. The transformation sequence can be explained by partitioning of the substitutional and interstitial element C coupled with a change in the mechanism of transformation with undercooling [22]. The results given above are in line with Andersson’s work [9], in which under slow...
cooling rate, the microstructure of a high-carbon steel alloyed with molybdenum consisted of a coarse
degenerated pearlite, nanometre-sized of molybdenum carbides and ferrite and the work of Taleff et al.
[11] also found that very fine cementite particles were clearly observed in high-carbon steels around 1.5
wt.%C. In such work, a transformation front, in which a cellular-shaped austenite/ferrite boundary,
advanced into an array of austenite plus fine cementite particles in a ferrite matrix.

3.2 Mechanical properties
The mechanical properties of sintered Fe-0.5Mo-0.15Mn-xC alloys (x = 0.0, 0.30, 0.45, 0.60, 0.75, 0.90,
1.05 and 1.20 wt.% carbon), such as tensile strength, yield strength and hardness, strongly depended on
carbon content. They showed a similar trend, i.e., they notably increased with increasing carbon content
up to 1.05 wt.% but beyond that carbon content the values decreased as shown in Figure 5. Due to the
increase of precipitate volume fraction with increasing carbon content, the precipitation strengthening
phenomenon contributes its effect to mechanical properties of sintered alloys. The decrease of tensile
properties and hardness in specimen containing 1.2 wt.% C, may be caused by large continuous networks
of carbides along the grain boundaries.

![Graphs showing mechanical properties](image)

**Figure 5.** Mechanical properties, (a) ultimate tensile strength, (b) yield strength (c) elongation
and (d) hardness of Fe-Mo-Mn sintered steels with variation in carbon content.

Elongation values decreased sharply with increasing carbon contents of up to 0.60 wt.%, beyond
which the values were constant. The decrease in soft ferrite phase fraction results in a decrease in the
ductility of sintered alloys. In sintered alloys with C contents higher than 0.60 wt.%, there are no
polygonal ferrite grains. The constant ductility value may be due to the similar microstructural feature
of ferrite and carbide mixtures in such alloys. Perhaps, the fine scale of ferrite and carbide mixtures has
something to control alloy ductility. According to the work conducted by using thermomechanical processing on the two steels with 0.46% C and 0.76% C, finer pearlite interlamellar spacing and spheroidized pearlite showed increase of strength without loss of toughness and ductility [23]. In our work, there are no hardness values reported for the specimens containing less than 0.45 wt.% C because they were too soft to be measured by using the HRB scale.

4. Conclusion
The influence of varied carbon contents (0.30-1.20 wt.% with 0.15% increments) on microstructures and the mechanical property of sintered alloys were investigated. By using a sintering temperature of 1280°C and cooled in the furnace with 0.1°C/s, the experimental results indicated that carbon played important roles in microstructural development by changing the microstructure from dual-phase structure composed of polygonal ferrite grains and non-cooperative eutectoid decomposition products to fully non-cooperative eutectoid decomposition products with different sizes and shapes depending on the degree of undercooling. Increase of carbon addition tended to increase tensile properties and macro-hardness. The formation of thick continuous carbide networks along the grain boundaries in sintered alloy containing 1.2 wt.% carbon resulted in the decrease of mechanical properties.

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