Influences of cooling rate and carbon content microstructure and mechanical properties of sintered Fe-1.5Mo-xC alloys

Arisara Wanalerkngam¹, Sarum Boonmee¹, Thapanee Srichumpong², Monnapas Morakotjinda², Nattaya Tosangthum *, Ruangdaj Tongsri²

¹School of Metallurgical Engineering, Institute of Engineering, Suranaree University of Technology 111 University Avenue, Suranaree Sub-District, Muang Nakhon Ratchasima District, Nakhon Ratchasima Thailand 30000
²Particulate Materials Processing Technology (PMPT), National Metal and Materials Technology Center, 114 Paholyothin Road, Khlong Nueng, Khlong Luang, Pathum Thani Thailand 12120

* Corresponding Author: nattayt@mtec.or.th

Abstract
Sintered Fe-1.50Mo-xC alloys were produced by the sintering of powder compacts made from mixtures of pre-alloyed Fe-1.5Mo powder and varied carbon amounts (0.30-1.20 wt.% with 0.15 increment) followed by slow and fast cooling rates. The slowly cooled sintered Fe-1.50Mo-xC alloys (for carbon contents of up to 0.45 wt.%) showed microstructures consisting of polygonal ferrite grains and eutectoid transformation products. When carbon contents were higher than 0.45 wt.%, eutectoid transformation products were dominant. The fast-cooled sintered Fe-1.50Mo-xC alloys (for carbon contents of up to 0.75 wt.%) showed microstructures consisting of upper bainite. When carbon contents were higher than 0.75 wt.%, upper bainite and inverse bainite were dominant. Tensile strength and hardness values of sintered Fe-1.50Mo-xC alloys increased with increasing carbon content. In addition, fast cooling further enhanced mechanical properties of the sintered alloys. It was found that values of ultimate tensile strength (UTS) and hardness on slow and fast cooling rates were 385-565 MPa, 564-743 MPa, 43-78 HRB and 60-82 HRB, respectively.

Keywords: Sintering, Carbon content, Cooling rate, Microstructural development, Mechanical property

1. Introduction
Powder metallurgy (PM) ferrous alloys are increasingly employed in the automotive industry. The automotive industry has accepted PM technology, with the result that over 70% of its production worldwide is aimed at the automobile manufacturing sector [1]. The Fe-1.50Mo (AstaloyMo) is a ferrous based powder pre alloyed with 1.5 wt.% molybdenum (Mo) [2], which is one of alloying elements used for enhancing the mechanical properties of sintered steels [3]. Improvements of mechanical properties in sintered Mo-containing ferrous alloys is due to their sinter hardening ability [4]. Sinter hardening refers to a process where the cooling rate experienced in the cooling zone of the sintering furnace is fast enough that a significant portion of the material matrix transforms to martensite [5]. Since the cooling
rate obtained in a commercial conveyor belt sintering furnace is quite low, the pre-alloyed ferrous powders are designed to have a sinter hardening ability due to the influence of their alloying elements. It is widely known that molybdenum suppresses ferrite and pearlite formations during continuous cooling by shifting both phase transformation fields, to the slow cooling side of a continuous cooling transformation (CCT) curve [6-8]. This means that the Mo effect opens the window for low temperature phase transformations (bainite and martensite transformations) to occur. In previous studies, carbon (C) content and post-sintering cooling rate showed strong influences on microstructures and mechanical properties of sintered ferrous alloys [9-11].

This work was aimed to understand the sinter hardening behavior of sintered Fe-Mo-C alloys. To achieve such goal, different C contents and cooling rates were employed to produce experimental sintered alloys. The influences of these two parameters on mechanical properties of sintered alloys were, as such, investigated.

2. Material and methods

2.1 Materials preparations
The base material employed in this work was pre-alloyed Fe-1.5Mo (AstaloyMo) powder. This powder was mixed with 1.0 wt.% of zinc stearate and varied graphite amounts to obtain 0.30, 0.45, 0.60, 0.75, 0.90, 1.05 and 1.20 wt.% contents in sintered alloys. After mixing, the dog-bone specimens were produced by pressing at 400 MPa to MPIF standard 10, ASTM B783 with green density of 6.58 ± 0.05 g/cm³ (Figure 1) [12]. All specimens were sintered at 1280°C in a vacuum furnace for 45 min. Two different post-sintering cooling rates (0.1 and 5.4°C/s) were employed. The sintering cycle profile is shown in Figure 2.

![Figure 1. The tensile test specimen follows by MPIF standard 10, ASTM B783](image1.png)

![Figure 2. Temperature versus time in setting up the sintering process.](image2.png)
2.2 Materials characterizations
For metallographic examination, all specimens were ground by 60, 120, 240, 400, 600, 800, 1200-grit silicon carbide abrasive papers, respectively, then polished by 1, 3 and 6µm diamond pastes. Etching was carried out by using 2% Nital acid solution for microstructural analysis. The microstructures were observed under optical microscopy (OM) by using Olympus STM7, Tokyo Japan and under scanning electron microscopy (SEM) by using HITACHI SU-8030, Tokyo, Japan.

Tensile tests were conducted using the Instron Universal testing machine employing a strain rate of 5 mm/min. Hardness studies were tested by using Rockwell scale B hardness testing 20, in which specimens were indented with the load of 0.3 kg and loading time of 15 s.

3. Results and discussions

3.1 Microstructures of slowly cooled sintered alloys
Microstructures of slowly cooled sintered Fe-1.50Mo-xC alloys are shown in Figure 3 marked as (a) to (d) to represent C contents of 0.30 to 1.20 wt.%, respectively. With 0.30 wt.% C addition (figure 3 (a), the sintered alloy showed proeutectoid ferrite grains in a polygonal shape and eutectoid transformation products in the forms of ferrite/carbide (F/C) aggregates. The formation of polygonal ferrite grains and F/C aggregates in sintered Fe-1.50Mo-0.30C alloy (figure 3 (a)) is similar to that of sintered low-carbon Fe-Cr-Mo-C steels [10], and hypoeutectoid steels [13]. However, the F/C aggregates in sintered Fe-1.50Mo-0.30C alloy was not identified as pearlite due to non-cooperative growth of ferrite and carbide components. With 0.45 wt.% C addition (Figure 3 (b)), proeutectoid ferrite grains changed shape from polygonal to elongated ones and the eutectoid transformation zones distributed more homogeneously. SEM image in Figure 4 (a) clearly showed the shape of proeutectoid ferrite grains and F/C aggregates. The sintered alloys with 0.60 and 0.75 wt.% C contents (Figure 3 (c), (d) and Figure 4 (b)) had F/C aggregates as dominant microstructural feature whereas polygonal ferrite grains were hardly observed. Pro-eutectoid carbide particles started to form, in addition to F/C aggregates, in sintered Fe-1.50Mo-0.90C alloy (Figure 3 (e)). This type of carbide particle become larger and prominent in sintered alloys with 1.05 and 1.20 wt.% C contents (Figure 3 (f) and (g)). A new F/C aggregate feature with nodular carbide particles formed next to a large pro-eutectoid carbide particle shown in Figure 4 (c). The disappearance of polygonal ferrite and conventional lamellar pearlite in most of slowly cooled sintered Fe-1.50Mo-xC alloys confirms the influence of Mo on suppression of ferrite and pearlite transformations [6-8]. The Mo influence becomes stronger when C contents are higher. However, the synergy of Mo and C is insufficient to keep austenite stable down below martensite transformation start temperature. Thus, only F/C aggregates with features like that of upper bainite can be obtained in slowly cooled sintered Fe-1.50Mo-xC alloys.
3.2 Microstructures of fast-cooled sintered alloys
Microstructures of fast cooled sintered Fe-1.50Mo-xC alloys are shown in Figure 3 marked as (h) to (n) to represent C contents of 0.30 to 1.20 wt.%, respectively. There were no polygonal ferrite grains observed in all sintered alloys. Clearly shown in Figure 4 (d), (e) and (f), only F/C aggregates dominated microstructures of all fast-cooled sintered Fe-1.50Mo-xC alloys. With close observation on the microstructure of the sintered Fe-1.50Mo-1.05C alloy (Figure 4 (f)), there were two types of F/C aggregates, i.e., the first was upper bainite and the second contained carbide particles showing nature of splines and branches, which are characteristics of inverse bainite [14]. Due to a similar response to etching, the OM images in Figure 3 (k), (l) and (m) suggest that inverse bainite starts to form in addition
to upper bainite in sintered alloys with C contents of ≥ 0.90 wt. %. Again, the synergy of Mo, C content and fast cooling rate (5.4°C/s) is insufficient to keep austenite stable down below martensite transformation start temperature. Thus, only finer F/C aggregates can be obtained in fast-cooled sintered Fe-1.50Mo-xC alloys.

![Figure 4. SEM images showing microstructures of sintered Fe-1.50Mo-xC alloys: (a), (b) and (c) represent slowly-cooled sintered alloys with C contents of 0.45, 0.75 and 1.05 wt. %, respectively and (d), (e) and (f) represent fast-cooled sintered alloys with C contents of 0.45, 0.75 and 1.05 wt. %, respectively.](image)

3.3 Mechanical property

Tensile properties (ultimate tensile strength (UTS), yield strength (YS) and elongation) and hardness of all experimental sintered alloys are shown in Figure 5. All mechanical properties of the fast-cooled sintered alloys were better than those of the slowly cooled sintered ones. This is attributed to finer scale
of F/C aggregates in the former group of alloys. The inferior mechanical properties of the slowly cooled sintered alloys with high C contents are due to microstructural heterogeneity and the presence of large proeutectoid carbide particles. The proeutectoid carbide particle is long and large at high carbon content which affects the strength properties decrease, but the hardness properties increase. Especially, carbon contents higher than 0.75 wt.%, pro-eutectoid carbide is clearly visible (Figure 3 (e), (f) and Figure 4 (c)).

![Graphs showing the effects of carbon content and cooling rate on mechanical properties of sintered alloys.](image)

**Figure 5.** Effects of carbon content and cooling rate on mechanical properties of sintered alloys.

4. Conclusions
The effects of C content and cooling rate on mechanical properties were studied. Under slow cooling, microstructures of sintered Fe-1.50Mo-xC alloys become finer due to morphological changes of ferrite grains and F/C aggregates. When C contents were ≥ 0.90 wt.%, large proeutectoid carbide particles formed in addition to F/C aggregates. Large carbide particles deteriorated mechanical properties. Under fast cooling, only F/C aggregates (upper bainite and inverse bainite) dominated microstructures. When C contents were ≥ 0.90 wt.%, inverse bainite formed in addition to upper bainite. Mechanical properties of the fast-cooled sintered alloys were superior to those of the slowly-cooled sintered alloys due to microstructural refinement and homogeneity of the former alloys.

Acknowledgments
The authors are grateful for financial support from National Science and Technology Development Agency (NSTDA) under the project P1951261. The authors are also grateful for support from National Metal and Materials Technology Center.

References
[1]  Ramakrishnan P 2013 *Advances in Powder Metallurgy*, ed I Chang and Y Zhao (USA: Woodhead Publishing) pp 493-519
[2]  Höganäs A B 2017 *Iron and steel powders for sintered components* (Sweden)
[3] Thakur S N, Newkirk J, Fillari G B, Murphy T, and Narasimhan K. 2004. Int J Powder Metall 40(3) 45-54
[4] Moghaddam K S, Ghambari M, Farhangi H, and Solimanjad N. 2012. J. Iron Steel Res. Int. 19(10) 43-46
[5] Rutz H, Graham A H, and Davala A. 1997. International Conference on Powder Metallurgy and Particulate Materials. (Chicago, Illinois)
[6] Ackermann M, Resiak B, Buessler P, Michaut B, and Bleck W. 2020. Steel Res. Int. 91 1-9
[7] Capdevila C, Ferrer J P, Garcia-Mateo C, Caballero F G, Victor L, and Andres C G. 2006. ISIJ International 46(7) 1093-1100
[8] Hannula J, Porter D, Kaijalainen A, Somani M, and Kömi J. 2019. Metals 9(3) 350
[9] Koetniyom W, Chantawet P, Tosangthum N, Morakotjinda M, Thanyaporn Y, Wila P, and Tongsri R. 2019. J. Met., Mater. Miner. 29(1) 22-30
[10] Srijampan W, Morakotjinda M, Krataitong R, Thanyaporn Y, Tosangthum N, Wiengmoon A, and Tongsri R. 2016. Chiang Mai J. Sci. 43(2) 358-364
[11] Srijampan W, Wiengmoon A, Morakotjinda M, Krataitong R, Yotkaew T, Tosangthum N, and Tongsri R. 2015. Mater. Des. 88 693-701
[12] ASTM B783-19. 2019. ASTM International, (West Conshohocken, Pennsylvania)
[13] Choi S. 2003. Mater. Sci. Eng. A 363(1) 72-80
[14] Borgenstam A, Hedström P, Hillert M, Kolmskog P, Stormvinter A, and Ågren J. 2011. Metall. Mater. Trans. A 42(6) 1558-1574