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Complex effects of alloy composition and porosity on the phase transformations and mechanical properties of powder metallurgy steels

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ABSTRACT

In this study, the combined effects of alloy compositions and porosity in powder metallurgy (P/M) steels on the phase transformation and mechanical properties were investigated. First, carbon steels and Astaloy CrM (Fe–3.0 wt.% Cr–0.5 wt.% Mo) steels with various porosities were produced using powder metallurgy routes, and their microstructure and mechanical properties were examined. Then, the phase transformation and resulting mechanical properties of porosity-free samples were simulated using the commercial software JMatPro® to examine the sole effect of alloy composition. By combining the porosity effect fitting models with the JMatPro results, we attempted to formulate a mathematical material model that describes the mechanical behaviors of the P/M steels.

1. Introduction

Powder metallurgy (P/M) involves energy-efficient and cost-effective processes and results in near-net shape products with a wide spectrum of alloy compositions [1–6]. Hence, the P/M route is often preferred for the manufacture of automotive parts (e.g., gears and rotors) when it wins cost competition over other production technologies, which may originate from its ability to form complex geometrical shapes with higher material utilization and reduced processing steps [7–10].

Many researchers have studied the effect of alloy composition and processing conditions on the microstructure and mechanical properties of P/M steels to increase the competitiveness of P/M steels and to extend the applications of P/M steels in automotive industries. For low-alloy P/M steels, which have great potential for use in powertrain components, Cr and Mo have extensively been employed to improve the mechanical and wear properties [11–21]. The presence of Cr may induce solution hardening and carbide precipitation and can further increase the response to thermal processes, thereby enhancing the impact toughness and tensile strength [11–13]. The addition of Mo can also improve the tensile strength by promoting bainitic phase transformation and, moreover, minimize dimensional changes of the final specimen after sintering [14,15]. Furthermore, these alloying elements, which are used as ferrite stabilizers and carbide formers, have the potential to produce high-strength phases by retarding the continuous cooling transformation (CCT) curve [16,17].

Processing conditions, such as the pressure applied for producing green compacts, sintering temperature, time and atmosphere, also affect the internal structure of P/M steels [3,18–20]. Unlike casting steels, the presence of pores in P/M steels is an important feature that affects both the phase transformation and mechanical properties of the materials. The processing conditions may alter the size, morphology, distribution and fraction of the pores of sintered compacts [21,22], thereby significantly affecting the resulting microstructure and mechanical properties of P/M steels.

As reviewed above, the microstructure and resulting mechanical properties of P/M steels are controlled by various variables, including the alloy composition, pore characteristics, and sintering conditions. However, attention has not yet been paid to the coupled effect of the alloy composition and processing conditions on the microstructure, which includes the pore characteristics and phase transformation kinetics. Furthermore, to apply P/M materials to an automotive structural part, the part design process should be completed before actual part manufacturing. For the design process, a mathematical model should be obtained based on the experimental measurement of the mechanical properties.

In this study, P/M steels were prepared by varying the alloy compositions and porosity, and their combined effects on the phase transformation and mechanical behaviors were investigated. The phase transformation and mechanical behaviors of porosity-free

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samples were simulated using the commercial software JMatPro® to examine the sole effect of the alloy composition. The JMatPro predictions are based on the thermodynamic equilibrium of multi-component alloy systems but have not yet been validated for P/M alloy materials. We then attempted to formulate a mathematical material model that describes the mechanical behavior of the present P/M steel. Based on various fitting models that have been suggested in previous studies [23–26], we attempted to find the appropriate models among the suggested ones by comparing the prediction by each model with the experimental measurement. Finally, we aimed to derive a reasonable mechanical property prediction model for the present P/M steel alloy by combining the porosity effect fitting model with the JMatPro results.

2. Experimental

The samples in this study were fabricated via three steps: i) synthesis of the powder, ii) cold pressing of the powder, and iii) sintering of the green compact. First, water-atomized commercial pure iron powder (~85 μm) and Astaloy CrM powder (~152 μm, Fe–3.0 wt.% Cr–0.5 wt.% Mo[27]) were prepared as shown in Fig. 1. These powders were admixed with 0.55 wt.% graphite (99% purity, Alfa Aesar) and 0.7 wt.% lubricant (zinc stearate, Finelube, Seoul Fine Chemical Ind, Co. Ltd.) using a SPEX mill mixer (8000D Dual Mixer/Mill, SPEX Sample Prep, Inc.) without any milling media for 20 min to add C and lubricant to the powders. The admixed powders starting from the pure iron and Astaloy CrM powders are designated as CS (carbon steel) and CrM in this study, respectively. Table 1 lists the chemical compositions of the CS and CrM powders. Second, the powders were pressed using a 30-ton oil press (30-12, Carver, Inc.) at room temperature to fabricate cylindrical specimens with dimensions of 9.5 mm in height × 8 mm in diameter. Several sets of specimens with a wide range of densities (6.072–7.234 g/cc) were produced by controlling the applied pressure from 300 to 1250 MPa. Because of the high strength of CrM powder, higher pressure was required to reach a certain density of the green compact compared with CS. Furthermore, the density of the green compacts of CS linearly increased up to the actual density (~7.8 g/cm^3) upon increasing the pressure, whereas that of CrM increased up to 7.2 g/cm^3 and was then saturated. Finally, the green compacts were sintered using a tube furnace (PTF-15/100/610, Lenton, Inc.) at 1120 °C for 30 min in mixed gas (90 vol.% N_2–10 vol.% H_2); the samples were heated to 1120 °C at a rate of 5.5 °C/min, dwelled for 30 min, cooled to 800 °C at a rate of 5.5 °C/min, dwelled for 40 min to change mixed gas to Ar gas, cooled to 500 °C at a rate of 10 °C/min, and then air cooled to room temperature. Green compacts with higher densities also exhibit higher densities in the sintered compacts.

Carbon is considered to have an effect on the phase transformation and mechanical properties of specimens, and therefore, the carbon content was determined using a carbon analyzer (CS-600, Eltra, Inc.) before and after sintering. Table 1 shows the variation of the carbon content in the CS and CrM samples before (SPEX-milled) and after sintering. Both the CS and CrM samples of the SPEX-milled state contain 1.03 wt.% carbon, of which 0.55 wt.% is from graphite and 0.48 wt.% is from the lubricant; the lubricant (zinc stearate, $C_{36}H_{70}O_4Zn$) contains 68.4 wt.% carbon, and the powders contain 0.7 wt.% of the lubricant. After sintering, the carbon content was measured to be 0.58 wt.% for CS and 0.6 wt.% for CrM. Although most of the lubricant is vaporized during sintering because of the low boiling point of the lubricant (359.4 °C), ~0.05 wt.% of carbon, possibly from trapped lubricant, appears to remain after sintering. The apparent densities of the green and sintered compacts were calculated using the volumetric measurement. The microstructures of the samples were examined using an optical microscope (OM, PME 3, Olympus Optical Co. Ltd.). Before the microstructural observation, the specimens were polished using standard metallurgical procedures and etched with Nital etchant (3 vol.% nitric acid and 97 vol.% ethanol). The hardness values of the samples were measured using a Rockwell hardness tester (ARK-600, Mitutoyo) with a stainless steel ball indenter (1/16 inch in diameter), which was considered to be large enough to offset the effect of the microstructure. Tests were repeated 5–6 times for each specimen. The uniaxial compression tests were conducted using an Instron-type testing machine (RB Model 301 Unitech T^{TM}, R&B, Inc.) at a constant strain rate of 10^{-3}/s at room temperature. The size of the compression specimens was 2 mm in width × 2 mm in length × 3 mm in height. All the tests were stopped when the plastic strain reached 10%.

Table 1
CS and CrM powder compositions and carbon content analysis results for the water-atomized powder and the sinter.

Sample	Powder composition					Carbon analysis	
	Element content (wt.%)			Additive content (wt.%)		Carbon content (wt.%)	
	Fe	Cr	Mo	C	Lube.	As-SPEX-milled	Sintered
CS	Bal.	–	–	0.55	0.7	1.00	0.58
CrM	Bal.	3.0	0.5	0.55	0.7	1.03	0.60
	As-atomized powder			SPEX-milled powder			

The chemical composition as well as porosity should be considered in predicting the mechanical properties of a sintered P/M steel. The composition effect on the mechanical property was analyzed using the materials property simulation software JMatPro, which provides the yield stress, hardness, tensile strength, density, heat conductivity, elastic constant, viscosity, and TTT/CCT diagrams. The JMatPro software requires three input parameters (the chemical composition of the alloy, cooling rate during solidification, and grain size). For the present P/M steel alloy, the cooling rate after sintering was assumed to be the cooling rate during solidification. The amount of remaining lubricant after the

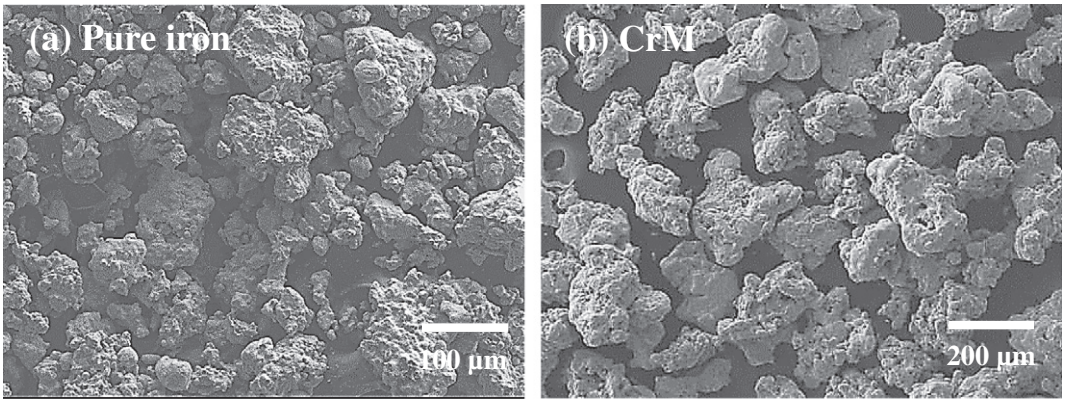

Fig. 1. SEM images of water-atomized (a) pure iron and (b) CrM powders.