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Effect of carbon on the density, microstructure and hardness of alloys formed by mechanical alloying

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ABSTRACT

This work aimed to produce iron-based alloys containing resistant microstructures to improve the mechanical properties of the resulting alloy. The effects of both carbon content and compaction pressure on the microstructure, density and hardness of the alloys were examined. Iron-based alloys with initial carbon contents of 0.5%, 1%, 2% and 3% were produced by powder metallurgy following a process that involved ball milling elemental powders, cold pressing and sintering. The composition, density, microstructure, porosity, hardness and ductility of the alloys depended on both compaction pressure and carbon content. As the carbon content increased, the amount of the resistant microstructure bainite in the alloys also increased, as did their hardness. In contrast, the density and ductility of the alloys decreased with increasing carbon content. This study shows that formation of the resistant microstructure bainite in alloys fabricated by powder metallurgy is influenced by both the initial carbon content of the alloy and compaction pressure during cold pressing.

1. Introduction

Iron-based alloys are widely used in vehicle, marine, aviation, structural and power tool components because of their high strength in relation to their cost [1,2]. Powder metallurgy (PM) is a well-established technique that allows alloys to be produced from solid-state samples [3]. Alloys with complex geometries can be prepared, which reduces secondary machining and thus cost, and makes PM competitive with other alloy formation processes [4]. Another advantage of PM is that it can be used to produce resistant microstructures such as tempered martensite and bainite that can withstand large stresses and improve the mechanical properties of the resulting alloy [5].

However, the alloys obtained by PM contain pores, which can induce cracks that may propagate through the alloy [6]. The porosity of alloys formed by PM is in the order of 5–15%, and depends on the compressibility of the alloying powders, amount of carbon and lubricant added to the iron powder base [7]. A heterogeneous porosity distribution in an alloy damages its mechanical properties [8]. To prevent this, resistant microstructures can be formed in steel by adding small quantities of alloying elements to compensate for the microcracks formed by the pores [9]. The interaction of carbon and alloying elements (Cr, Mo, Si and Mn) with dislocations and substitutions of atoms have a substantial effect on the mechanical properties of the resulting alloy. Addition of Cr improves the mechanical properties of sintered steel through solution hardening and carbide precipitation, while addition of Mo promotes formation of bainitic microstructure [10,11].

Carbon is one of the most frequent interstitial atoms in the steel matrix and affects its hardness, density and crystal structure [12]. Bensebaa et al. [13] found that the formation of ferrite nanocrystals with a high carbon content improved the properties of steel. Lonardelli et al. [14] prepared medium carbon steel containing bainitic structure by PM and examined its mechanical properties and thermal stability. They found that samples with a higher carbon content showed reduced thermal stability.

The properties of steels are also affected by processing parameters such as compaction pressure. In a theoretical study, Azadbeh et al. [15] found that compaction pressure strongly influenced the properties of Cr–Mo prealloyed sintered steels because it determined the interparticle contact area. Optimal transverse rupture strength, hardness, and impact energy were calculated for a

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compaction pressure of 700 MPa. Meanwhile, Channankaiah and Ranganath [1] found that the density of AISI 4140 steel increased with compaction pressure until it became saturated at about 450 MPa. They also found that the aspect ratio of the preform and homogenization time influenced density and mechanical properties.

In this work, Fe-based alloys by PM containing different carbon contents were prepared in order to examine the effect of carbon content on the density, microstructure and mechanical properties of the alloys with the aim of forming resistant microstructures. Alloys containing 0.5%, 1%, 2% and 3% C in 1% Mn, 0.25% Mo, 0.3% Si, 1.1% Cr and the balance Fe (hereafter referred to as 0.5%, 1%, 2% and 3% C alloys, respectively) are prepared by mechanical alloying followed by compaction and sintering. The alloys are compacted at different pressures in the range of 100–600 MPa to examine the effect of compaction pressure on their density, microstructure and hardness. Material hardness is influenced by carbon content because it changes the microstructure of the sample. With increasing carbon content, the hardness and tenacity of the samples increase and decrease, respectively.

2. Experimental details

Iron (Aldrich, 99.9%, <10 μm), chromium (Aldrich, 99%, <43 μm), molybdenum (Aldrich, 99.9%, 1–2 μm), silicon (Aldrich, 99%, <10 μm), manganese (Aldrich, 99.9%, <43 μm) and carbon (Aldrich, 99.99%, <43 μm) powders were used as starting materials. Each powder was accurately weighed using an analytical balance with an error of ±0.0001 g. Each mixture was ground for 48 h using a custom-built horizontal stainless steel ball mill 15.2 cm in length and 12.5 cm in diameter containing balls of hardened steel (carburized AISI 1010 steel) with a ball load of 2461 g and ball/powder weight ratio 36:1. Stearate acid (0.8 wt%) was used as a control agent in the milling process. The chamber was filled with 200 kPa of high-purity Ar gas during milling to prevent oxidation of exposed surfaces.

After milling, each powder (10 g) was compacted at 100–600 MPa and velocity of 40 mm s^{-1} using a hydraulic press (Rps200, Lauffer, capacity of 200 tons) to obtain a pellet with a diameter of 22 mm and thickness of 10 mm. The green density of each pellet was measured using a bushing-type exterior micrometer (0–25 mm, resolution: 0.001 mm, Model 293, Mitutoyo America Co., Aurora, USA). Green pellets were sintered in a continuous furnace (GmbH High Temperature Sintering Furnace, MAHLER, Plochingen, Germany) under a flow of reducing gas at 500 °C for 40 min and then at 1200 °C for 35 min with a heating rate of 10 °C min^{-1}. The density of the sintered particles was measured according to Metal Powder Industries Federation Standard 42 [16].

Table 1
Post-milling compositions of alloys with different initial carbon contents.

Element (%)						
Initial C	Final C	Mn	Mo	Si	Cr	Fe
0.5	0.68	1.16	0.36	0.41	1.40	95.99
1.0	1.09	1.18	0.32	0.38	1.25	95.78
2.0	2.08	1.13	0.29	0.39	1.15	94.99
3.0	3.11	1.15	0.33	0.37	1.21	93.83

The microstructure of the alloys was observed with an optical microscope (Axio Visio, Carl Zeiss, Germany) and scanning electron microscope (SEM, JSM 6490, JEOL, Japan). Samples were polished and etched with 2% natal before observation. Sample hardness was measured with a Vickers microhardness tester (HM 112, Mitutoyo, Japan) using a diamond indenter with a load of 100 g for 8 s. Powder X-ray diffraction (XRD) measurements were obtained on a diffractometer (D8 Focus, Bruker, Germany) at a voltage of 35 kV, current of 25 mA and scan velocity of 2° min^{-1}.

After power ball milling for 48 h, samples for impact experiments were prepared by compacting each powder (60 g) in a steel mold using the same hydraulic press at a pressure of 500 MPa to give samples with a cross section of 12 mm × 12 mm and length of 600 mm. Samples were sintered in a continuous furnace (Mahler) and machined to obtain Charpy-type samples with dimensions of 5 mm × 10 mm × 55 mm according to ASTM: E-23-12c. Standard Charpy impact tests were carried out using a pendulum Izod impact test apparatus and a Charpy impact testing machine (model JBW-300, PTE, Shandong, China). Transmission electron microscope (TEM) characterization of the sintered samples was performed using a TEM (2000FX, JEOL, Tokyo, Japan), operating at 200 kV equipped with an energy-dispersive spectrometer (EDS) and also by high-resolution TEM (HRTEM, 2100, JEOL, Tokyo, Japan), operating at 200 kV, using a LaB_6 filament.

3. Results and discussion

Representative SEM images of the 2% C alloy showing its morphology after milling are presented in Fig. 1. The milled alloy is composed of flakes. The overall compositions of the alloys after milling are given in Table 1; each is similar to the nominal composition of the corresponding sample. The elemental distribution of the 2% C alloy after milling is presented in Fig. 2. All of the elements are relatively well distributed through the alloy, although some particles of CrFe and CrFeMn are observed. These results are consistent with those of Arik and Turker [17], who achieved a homogeneous distribution of Fe_3C particles in the matrix by high-energy mechanical alloying. The other alloys contained

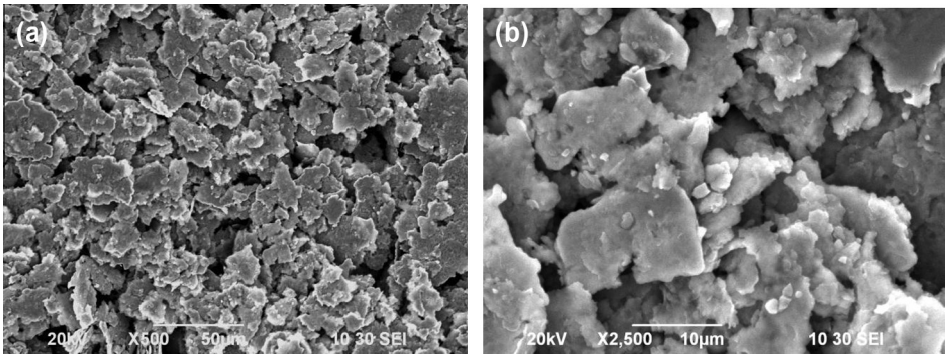

Fig. 1. SEM micrographs of 2% C alloy at a magnification of (a) ×600 and (b) ×2500.