J MATER RES TECHNOL. 2013;2(4):376–385

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jmr&t
Journal of Materials Research and Technology
www.jmrt.com.br

Original Article

Microstructures and properties of solid and reticulated mesh components of pure iron fabricated by electron beam melting

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ARTICLE INFO

Article history:
Received 5 June 2013
Accepted 10 October 2013
Available online 6 November 2013

Keywords:
δ-Fe phase
α-Fe
Electron beam melting
Dynamic stiffness
Light and electron microscopy

ABSTRACT

This research examines rapidly solidified, atomized pure iron powder and solid and reticulated mesh components fabricated by electron beam melting (EBM) from this powder precursor. Especially significant was the characterization of associated microstructures and corresponding mechanical properties. Atomized Fe powder was used to fabricate solid and reticulated mesh components by EBM. Powder and component microstructures and phase structures were examined by light (optical) metallography, scanning electron microscopy, X-ray diffractometry, and transmission electron microscopy. Corresponding Vickers microindentation hardness measurements were also made and compared to tensile data along with measurements of dynamic stiffness for mesh components having varying densities. The atomized Fe powder was observed to contain δ-Fe which was retained in the solid, EBM-fabricated components where it was observed to be homogeneously distributed in equiaxed α-Fe grains as δ-phase platelets measuring ∼0.5 μm to 2 μm in length and ∼40 nm thick; coincident with the α-Fe matrix {1 0 0} or {1 1 0} planes. A log–log plot of E/E_s versus ρ/ρ_s resulted in $(E/E_s) = (\rho/\rho_s)^{2.8}$. Novel, δ-Fe phase platelets have been observed in α-Fe components fabricated by EMB.

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2238-7854 http://dx.doi.org/10.1016/j.jmrt.2013.10.002

1. Introduction

Iron represents one of the most abundant and historically oldest metal used by humans, beginning roughly 3500 years ago at the start of what is often called the Iron Age. Basic iron production world-wide generally exceeds 1 billion tons [1]. Iron and steel account for roughly 80 percent of all metal powders produced annually, and iron powder represents the largest tonnage of raw materials used in powder metallurgy (P/M) fabrication [2].

The mechanical properties of iron are sensitive to purity and tensile and yield strengths can vary from ∼150 to 300 MPa and 90 to 150 MPa, respectively. Young's modulus has been recorded from less than 100 GPa to 200 GPa. Tensile elongations have been shown to vary from 15 to 25 percent.

Iron has three allotropic phases: δ-phase (bcc) between the melting point at 1537 °C to ∼1390 °C, γ-phase (fcc) between ∼1390 °C to 910 °C, and α-phase (bcc) below 910 °C. The lattice constant for δ-Fe and α-Fe varies linearly from ∼2.93 Å to 2.87 Å, and from 2.87 Å to 2.82 Å, respectively, interrupted by the γ-Fe phase between 1390 °C and 910 °C, where the lattice parameter varies from 3.68 Å to 3.63 Å [3].

As a high-temperature phase, δ-Fe has no influence on iron metallurgy, and its microstructure has not been well documented. α-Fe is usually characterized by irregular, equiaxed grain structure which can be better controlled in P/M processing which is employed to produce high wear iron products with small grain sizes [2]. At the Curie point (770 °C) α-Fe becomes magnetic.

In this study, the fabrication of iron components from atomized, rapidly solidified, high-purity iron precursor powder was explored using electron beam melting (EBM). Special interest involved the observations of the precursor powder microstructure and the EBM-fabricated components along with their residual tensile and hardness properties. Reticulated mesh components were also fabricated by EBM, and the Young's modulus (dynamic stiffness) measured for these components with varying density (or porosity) using resonant frequency detection.

2. Experimental procedures

Rapidly solidified, gas atomized pure iron powder having sizes, size distribution, and microstructures as shown in Figs. 1–3 were processed in an upgraded, Arcam S-12 electron beam melting (EBM) system illustrated schematically in Fig. 4. Figs. 1(a) and 3(a) show the details of the precursor powder morphologies and size distribution, with an average particle size of 19 μm as shown in Fig. 3(a). Fig. 1(b) shows polished and etched particle cross-sections illustrating an irregular but equiaxed grain structure of roughly 3 μm diameter as illustrated in the magnified scanning electron microscope (SEM) image in Fig. 2. Although the powder crystal structure exhibited primarily α-Fe (bcc: $a = 2.87$ Å), a δ-Fe (1 1 0) (bcc: $a = 3.0$ Å) peak was observed by X-ray diffraction (XRD) analysis as indicated by the arrow in Fig. 3(b).

The EBM system (Fig. 4) upgrade consisted of an air-cooled electron gun (at G in Fig. 4), with an insulating space between the gun and the build chamber (below C in Fig. 4). The system also incorporated additional heat shielding to decrease heat loss during component fabrication. The electron optical system includes beam focus at F in Fig. 4 as well as beam deflection at D. The atomized powder (Fig. 1(a)) was loaded into cassettes (P) where the powder was gravity fed to the build table and raked into layers (at R in Fig. 4). The powder layer was preheated in successive electron beam scans at speeds of $\sim 10^3$ mm/s at low beam current to achieve temperatures around 300 °C. Preheating was followed by a melt scan

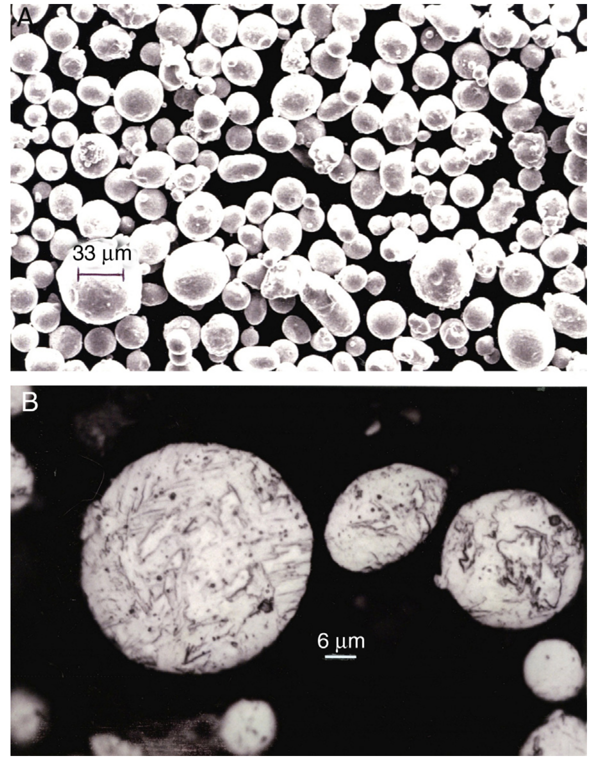

Fig. 1 – Atomized, pure iron powder. (a) SEM image showing particle sizes and size distribution. (b) Optical metallograph image showing interior particle microstructure.

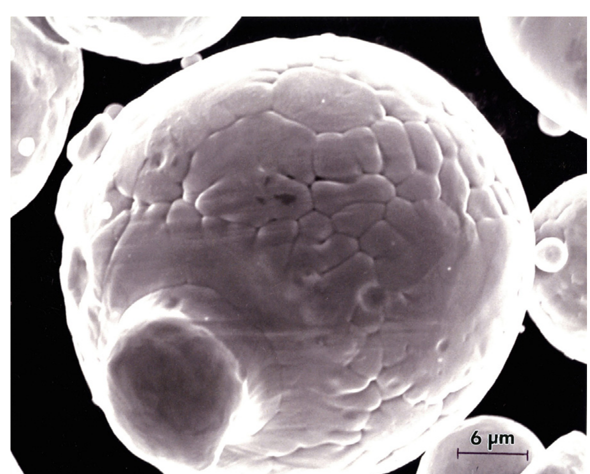

Fig. 2 – Magnified SEM view of Fe powder microstructure.