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Microstructure and tensile properties of iron parts fabricated by selective laser melting

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ABSTRACT

Iron, as the basic industry material was extensively studied in the past, but it could still offer extended possibilities with the use of new processing techniques such as selective laser melting (SLM). In this work, the manufacturing of iron parts using SLM technology was investigated. The effect of processing parameters on density of the iron parts was studied. Fully dense iron parts have been fabricated at the laser power of 100 W using different laser scanning speeds. By means of metallographic observation and TEM characterization, it can be found that the grains size decreased with increasing scanning speed and high dislocation density was observed. Tensile specimens were fabricated using optimal parameters and mechanical tests allowed observing an ultimate tensile strength of 412 MPa and the yield strength of 305 MPa. Multiple self-strengthening mechanisms during SLM process are proposed to explain this high mechanical strength. The grain refinement seems to be the most significant strengthening mechanism, followed by work hardening arising from the high cooling rate.

1. Introduction

Selective laser melting (SLM), as one of the most promising additive manufacturing (AM) technologies, enables the quick production of complex-shaped three-dimensional (3D) parts directly from powders, especially metal powders [1–3]. Details of the SLM process have been described elsewhere [4–6], and will be summarized here. In a layer-by-layer fashion, the SLM process creates bulk parts by selective melting and consolidation of thin powder layers using a laser beam. Each scanned layer represents a two-dimensional (2D) cross-section of the mathematically sliced CAD model of the object. After the consolidation of one cross-section layer, a fresh layer of powder is deposited and the process is repeated until a fully dense 3D part is completed. In addition, the extremely rapid heating/cooling stages during the SLM process may lead to the formation of particular structures in the laser-processed parts. Based on the above description, SLM has four significant advantages when compared with traditional manufacturing methods: (i) flexibility; (ii) ability to form extremely complex-shaped parts; (iii) possibility of adjusting phase structure according to the design requirements; (iv) rapid solidification process. In the near future, SLM technology will probably be widely applied to fabricate metal parts directly from the feedstock. Until now, SLM process of different materials could be found, such as Fe [7], Ti [8], Ti6Al4V [9–12], Ti6Al7Nb [13], Ni718 [14,15], 316 L [16–18], 304 stainless steel [19], AlSi10Mg [20–22] FeAl [23], TiC/Ti bulk nanocomposites [24,25] and Al/Fe_2O_3 composites [26].

Although iron as the basic industry material was of course extensively studied in the past and many traditional processing methods already could prepare iron parts inexpensively, the research and exploration about processing methods of iron has been continuing to realize many very complex-shaped iron molds and some non-standard parts with a low cost, etc. Simchi et al. [27,28] have previously studied the effects of laser sintering processing parameters and the role of particle size on the microstructure and densification of iron powder. Murali et al. and Simchi et al. [29,30] have reported the role of graphite addition in the laser sintering process of iron powder. Kruth et al. [7] have reported the influence of different SLM parameters on density of iron parts. These reported works focused on the optimization of SLM processing parameters to obtain dense parts, while the influence of SLM parameters on the phase and microstructure were not presented. And also the tensile test was rarely involved. In fact, the tensile test for most of SLM-fabricated parts is an important way to examine the mechanical properties before the industrial application. In a sense, SLM process of iron parts as a new processing technique is a meaningful topic to be studied. It is necessary to relate the mechanical properties of SLM-processed iron with its microstructure and processing conditions. Probably by investigating their relationship, it allows to give more optimal parameters correlating the dense parts with high mechanical properties.

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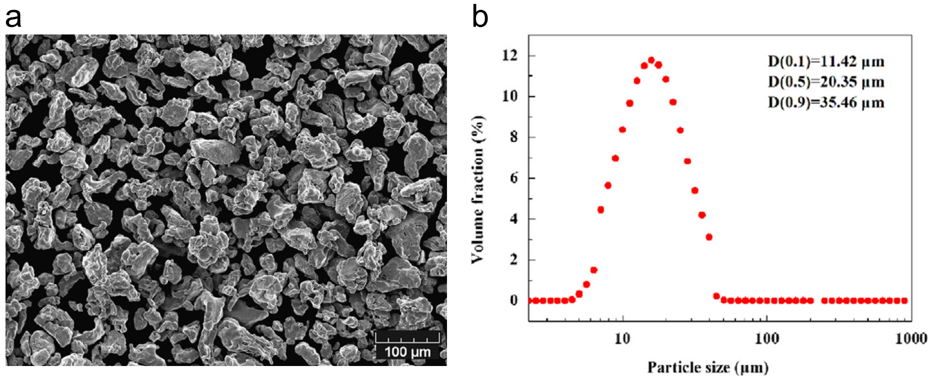

Fig. 1. (a) Particles morphology and (b) size distribution of the iron powder.

Thus, in this work, small iron cubes were at first prepared to determine suitable processing parameters. Then the microstructure and the phase composition of these SLM-processed iron samples and the mechanical properties of tensile specimens were studied in detail. Multiple self-strengthening mechanisms were studied considering the effects of the processing parameters on the grain size and tensile properties.

2. Materials and experimental methods

2.1. Feedstock material

A hydrogen-reduced sponge iron powder (MH 300, Hoganas Company), which displays a general multi-prismatic shape, was used as feedstock (Fig. 1a). The composition of the feedstock is pure Fe with 0.02 wt% C. The particle size distribution of the iron powder determined by laser light scattering (MASTERSIZER 2000 equipped with a fluid powder module, Malvern Instruments Ltd, UK) shows a mean value of about 20 μm (Fig. 1b).

2.2. SLM process

A commercial SLM machine (Realizer 250, MCP Ltd) was used. The laser source is YLR-100-SM single Mode CW Ytterbium fiber laser (1064–1100 nm). The working chamber provides a closed environment filled with argon with an outlet pressure of 10 mbar. The protective gas allows maintaining the oxygen content below 0.2% to prevent the oxidation of iron during the fabrication process. The investigated range of laser melting parameters was as follows: laser power P is adjusted as 60, 80 and 100 W, and the scanning speed is 0.02–1.4 m.s^{-1}, using the diameter of the laser beam of 34 μm, scan line spacing of 40 μm and the thickness of each powder layer of 50 μm.

A stainless steel plate with dimensions 300 mm × 300 mm × 5 mm was used as the building platform. Before being installed, this platform was grit-blasted with alumina.

At first, small iron cubes measuring 5 mm × 5 mm × 5 mm dimensions were preliminarily fabricated using several parameter sets in order to study the effect of processing parameters on the density of SLM-processed iron parts and to select "optimal" parameters to fabricate tensile specimens and the complex 3D piece. The preliminary criterion of "optimal parameters" is the acquisition of dense parts. Then the fabrication of the tensile specimens and the complex piece (see Fig. 2) was carried out using the "optimal" parameters, according to euro-norme 10002. Porous support layers (5 mm × 5 mm × 3 mm) were fabricated at the bottom of all the designed specimens in order to easily remove the specimens from the stainless steel building platform by a saw.

2.3. Characterization

The density of the SLM-fabricated samples was determined using the Archimedes method. The measuring details have been described in the literature [31]. The top-surface microstructure of the melted iron parts was observed using a scanning electron microscope (JEOL, JSM-5800LV). The detailed microstructures of those iron parts were also observed by transmission electron microscopy (Tecnai G2F30). The element analysis was also carried out by energy dispersive spectrometry (EDS) during TEM or SEM observations. XRD measurements were conducted on a Brvker (D8Focus) instrument, operating with a cobalt anticathode (λ=1.78897 Å) at 35 kV and 40 mA; the scan rate was 10° min^{-1} in the angular range (2θ) 20–80°. Samples for metallographic examination were prepared using standard techniques and etched in 3% Nital reagent. The cross-sectional microstructure of the etched samples was examined by optical microscopy (OM) and SEM. Tensile tests were performed at room temperature at a cross head velocity of 2.01 mm/min and loading rate of 35.2 MPa/s. For each experiment, five specimens were measured. The tensile fracture surfaces were also observed by SEM.

3. Experimental results

3.1. Processing parameters and relative density of SLM-fabricated specimens

During the process of selective laser melting, the melting of the powder layer strongly depends on the amount of energy supplied to the material, which is mainly controlled by two parameters, namely the laser power and the scanning speed of the laser beam. Based on the formation quality of the specimens during the SLM process, four processing windows could be defined over the considered range of the laser power and the scanning speed (Fig. 3):

(I) Deformation zone. The designed cube specimens could not be accomplished due to the warpage which would hinder the roller to spread powders. Because the input energy is too high, which leads to high thermal stress, resulting in deformation of the cube, accordingly, the fabrication of the designed models was terminated before the end of SLM program.

(II) Formation zone. In this zone, the density of input energy is so high that iron powders could be melted in a relatively stable melt pool. Thus, the pieces with a relatively high density and full desired dimensions could be obtained by SLM.

(III) Zone of poor formation. Compared to those formed parts with full desired dimensions, all cubes using the laser parameters