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Characterization of the Fe-Co-1.5V soft ferromagnetic alloy processed by Laser Engineered Net Shaping (LENS)

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ABSTRACT

Processing of the low workability Fe-Co-1.5V (Hiperco® equivalent) alloy is demonstrated using the Laser Engineered Net Shaping (LENS) metals additive manufacturing technique. As an innovative and highly localized solidification process, LENS is shown to overcome workability issues that arise during conventional thermo-mechanical processing, enabling the production of bulk, near net-shape forms of the Fe-Co alloy. Bulk LENS structures appeared to be ductile with no significant macroscopic defects. Atomic ordering was evaluated and significantly reduced in as-built LENS specimens relative to an annealed condition, tailorable through selection of processing parameters. Fine equiaxed grain structures were observed in as-built specimens following solidification, which then evolved toward a highly heterogeneous bimodal grain structure after annealing. The microstructure evolution in Fe-Co is discussed in the context of classical solidification theory and selective grain boundary pinning processes. Magnetic properties were also assessed and shown to fall within the extremes of conventionally processed Hiperco® alloys.

Hiperco® is a registered trademark of Carpenter Technologies, Readings, PA.

1. Introduction

Additive manufacturing (AM) has seen a substantial increase in publication rate over the past several years, motivated by global efforts to develop higher efficiency, next-generation manufacturing processes [1]. A wide array of AM techniques have now been developed for processing metals, the most common of which are powder bed fusion and direct energy deposition techniques that utilize either laser or electron beam energy sources to consolidate powders [2]. These processes have been successfully used to produce bulk, near net-shape geometries from a relatively small set of metals, including Ti-, Al-, Ni-, and steel alloys for structural applications [3]. Functional materials, specifically soft ferromagnetic alloys, by comparison have received far less attention in the literature, with only a handful of reports over the past few years that include Selective Laser Melting (SLM) of Fe-Ni alloys and high-silicon content electrical steels [4–6], and Laser Engineered Net Shaping (LENS) of Fe-Ni alloys, permalloys, Finemet-based alloys, and a range of $Fe_{1-x}Co_x$ alloys [7–10]. These reports suggest an emerging interest in exploration of AM with magnetic materials. However, in comparison to the wealth of information on structural alloys, there is substantial untapped potential in AM processing and characterization of soft ferromagnetic alloys.

The purpose of this study then was two-fold: 1) explore AM, and specifically LENS, on the Fe-Co-1.5 V (Hiperco® equivalent) alloy as a model soft ferromagnetic engineering material, and 2) provide a detailed characterization of process-structure-properties relationships. Bulk forms of the soft ferromagnetic alloy were produced *via* LENS using a range of geometries and processing conditions. Microstructures were characterized in terms of the degree of atomic ordering, grain morphology and crystallographic texture, and these characteristics were connected to the processing conditions. Characterization of the quasi-static magnetic properties was also conducted.

2. Background

2.1. Laser Engineered Net Shaping (LENS)

Detailed descriptions of the LENS process have been published elsewhere [11,12]. A brief overview is presented here. As an alternative to hot- and cold-working processes, LENS is a highly localized

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solidification technique that utilizes a high-power continuous-wave laser to consolidate/melt fluidized powder that is directed toward the focal point of the beam through a concentric inert gas powder feed system [12]. The laser and powder feed unit remain stationary and the substrate/build plate is translated along the scan direction to form a bulk structure through the progressive addition of layers. Translation of the specimen during processing creates thermal conditions in the melt pool characterized by highly localized, rapid solidification at rates of 10^2–10^4 K/s and sharp thermal gradients [13–15]. These thermal characteristics of LENS reside in a regime between those encountered in most conventional solidification (e.g., casting, welding) and rapid solidification (e.g., splat quenching, melt spinning) processes [16–18]. Melting and solidification in LENS are performed iteratively to create near net-shape geometries following a computer-aided design (CAD) model that are difficult or impossible to produce using traditional processing routes.

Due to the layer-by-layer nature of LENS, a complex thermal history is generated during processing that involves cyclic layer remelting and reheating [14,15]. While sophisticated models are often employed to predict these histories and connect process parameters with material structure, the idealized heat transfer model proposed by Rosenthal can be used as a first-order approximation for estimating the cooling rates during AM [13,19]. In the Rosenthal model, a steady-state thermal gradient is assumed for a traveling heat source along a semi-infinite medium, giving rise to the following approximate expression for estimating cooling rate:

$$\frac{dT}{dt} \cong \frac{\kappa v_b}{\alpha Q}(T_m - T_0)^2 \tag{1}$$

where dT/dt is the cooling rate, α is the laser absorption coefficient (assumed 0.3 in this study [20]), Q is the laser power, v_b is the build velocity, κ is the thermal conductivity, T_m is the alloy melting temperature, and T_0 is the initial surface temperature. Eq. (1) was used to estimate cooling rates as the main output parameter, and quantify the role of multiple LENS processing parameters on microstructure development (i.e., atomic ordering and grain morphology) of the Fe-Co-1.5V alloy. Thermophysical properties for the model were taken from [21]. Note, T_0 was assumed to be room temperature (300 K) for the analysis. While this does not accurately describe the temperatures of the previously deposited layers for a thin wall specimen, it allowed for a first-order analysis of the expected cooling rates for guiding selection of processing parameters. The model estimated predicted cooling rates of approximately 10^3 K/s, which is in general agreement with the magnitude of the experimental values in this study and those reported elsewhere [14,15]. Cooling rate was chosen as the independent variable of interest due to its pronounced impact on atomic ordering and corresponding mechanical properties of Fe-Co alloys [22–24]. This is discussed in more detail in the following section. It should be noted that while unconventionally rapid cooling rates are common in LENS processing, several AM methods impose similar thermal conditions. Only LENS is detailed in this study, however it is conceivable that other AM processing approaches would also be applicable for exploring control of the disorder-order transformation in Fe-Co alloys. In fact, SLM powder bed AM has been demonstrated with the Fe-Co system by the authors (unpublished data, publication is forthcoming).

2.2. Fe-Co alloys

The Fe-Co alloy system was selected for two primary reasons. The first is because of its favorable magnetic properties for use in various electromagnetic applications, for example as bulk components in electric motors and switches. Fe-Co alloys at or near the equiatomic composition (close to the composition investigated in this study) possess the highest saturation induction (B_s) of any known soft ferromagnetic engineering alloys, high permeability (μ), high curie temperature, low coercivity (H_c), and low core loss [25]. These properties are primarily influenced by the material composition and microstructure (i.e., grain size and crystallographic texture). For ferromagnetic alloys at fixed compositions, a desired soft magnetic performance is promoted by a coarse grain size and well-aligned crystallographic texture with the easy magnetization directions closely aligned to the applied magnetic field. The easy magnetization directions are fundamental attributes of the material and are typically determined by the first (K_1) and second (K_2) magnetocrystalline anisotropy constants [26]. For cubic metals, when K_1 and K_2 are < 0, as is the case for near equiatomic Fe-Co alloys [27,28], the easy and hard magnetization directions are expected to be $\langle 111\rangle$ and $\langle 001\rangle$, respectively. Thus, a softer magnetic performance is achieved as the $\langle 111\rangle$ directions become more aligned with the direction of the applied field [27]. It has recently been shown that site-specific control of the crystallographic texture can be accomplished in AM processing through modification of the solidification conditions [29,30], and motivates characterization of the texture in Fe-Co alloys processed by LENS.

Second, this alloy also has extreme composition-driven low workability, making it an ideal system for evaluating the general potential of AM processing with low workability alloys. Their poor ductility and low workability have long frustrated the use of conventional thermomechanical methods (e.g., rolling, forging, extrusion, etc.) [31]. The mechanism responsible for the low workability is a disorder-order phase transformation from α-BCC to $L2_0$ (or B_2), which promotes cracking during plastic deformation [24]. Unfortunately, this transformation is difficult or impractical to avoid with conventional hot- and cold-working processes due to the rapid kinetics and high transformation temperatures (~1000 K for near equiatomic Fe-Co) of the B_2 phase [31]. Typical cooling rates required to (kinetically) suppress the ordering transformation are large, $dT/dt > 10^3\,\mathrm{K\,s^{-1}}$ [24], and exceed those achievable for most conventional bulk processes. Consequently, the conventional approach to reduce the influence of ordering is to modify the binary alloy chemistry through the addition of ternary constituents. Additives that have been explored include C, Cr, Ni, Nb, Mo, Ta, W, and V [32]. Vanadium has been among the most extensively studied and has led to the featured Hiperco® 50A (Fe-Co-2V) alloy produced by Carpenter [33]. In general, ternary additions degrade the magnetic performance, but the loss in performance is justified by the improved workability to enable conventional processing of various bulk products, such as laminated sheet, bars, strips, etc. [31]. The rapid and localized solidification characteristics of LENS provide a fundamentally different approach for processing soft ferromagnetic alloys and a unique opportunity to suppress or reduce the effects of the B_2 ordering transformation. Tailoring of the degree of ordering in the Fe-Co-V alloy system *via* LENS was explored in this study.

In addition to the potential advantages of overcoming the disorder-order phase transformation in Fe-Co alloys, AM provides opportunities to produce near net-shape bulk forms that would require minimal secondary processes, such as machining, stamping, etc. These processes are also difficult to employ with Fe-Co alloys due to their intrinsic low workability. Despite these potential advantages of using AM, there are also some obstacles worth noting. Perhaps the most significant, as has been discussed for structural materials [34], is the processing-induced defects unique to AM. Residual stress, voids, and oxide inclusions, which are typical of AM processing, are expected to serve as barriers to the microscale magnetization processes in soft ferromagnetic alloys and have a negative impact on the magnetic softness of these materials [26]. Thus, while near net-shape forms may be produced with minimal secondary processes required to modify the shape of thematerial, post-processing annealing treatments may become essential for developing alloys with the desired soft magnetic response. Optimization of processing parameters will be critical to minimize these defects to create a successful future for AM of magnetic alloys.