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Laser additive processing of Ni-Fe-V and Ni-Fe-Mo Permalloys: Microstructure and magnetic properties

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ABSTRACT

Ni-Fe-Mo/V known as Permalloys are of great interest because of widespread applications in transformers, electric motors, and other electromagnetic devices. This letter focuses on the ability to utilize laser-based additive manufacturing, specifically the laser engineered net shaping (LENS™) process, to deposit soft magnetic Ni-Fe-V and Ni-Fe-Mo alloys. Though these alloys have been deposited from an elemental powder blend, they exhibit relatively uniform *fcc* solid solution microstructures. While the saturation magnetization (M_s) values for the LENS™ deposited alloys is comparable to those of their conventionally processed counterparts, the laser processed alloys exhibit higher coercivity (H_c) values, presumably due to microstructural defects.

1. Introduction

Ni-Fe-Mo/V Permalloys and other soft magnetic materials are of considerable interest due to the large variety of applications in electromagnetic devices, including sensors, transformers, electric motors, etc[1–8]. Conventional Permalloys exhibit low coercivity, high permeability, and moderate saturation magnetizations[9,10]. X-ray diffraction, neutron diffraction, transmission electron microscopy, scanning electron microscopy, and Mössbauer spectroscopy [11] show that short-range or long-range ordering in the alloy affects these properties. Magnetic properties also depend on synthesis techniques and parameters used. Zhang et al. found a change in the magnetic properties of Fe-Ni-Mo sputtered films by changing sputtering parameters such as gas pressure, bias, and temperature[12]. Transport measurements and magnetization dynamics suggest an enhancement of spin-orbit interactions in Pt doped $Ni_{81}Fe_{19}$ thin films [9]. Numerous approaches such as arc melting, ball milling, magnetron sputtering, pulsed laser ablation, etc. have been utilized to improve the performance of these soft magnetic materials [13–18].

This paper explores the feasibility of processing Ni-Fe-V and Ni-Fe-Mo based Permalloys using the laser engineered net shaping (LENS™) process. This additive manufacturing technique allows for customized near-net shaping of dense metallic objects via introduction of pre-alloyed or blended elemental powders into a melt pool produced by a high power laser. The microstructure and magnetic properties of the LENS™ deposited Permalloys have been investigated and compared to those of conventionally processed Permalloys.

2. Experimental procedure

Cylindrical deposits 10 mm in diameter and 25 mm in height of nominal composition Ni-15Fe-5V and Ni-15Fe-5Mo were deposited using an Optomec LENS™ 750 system coupled with a 500 W Nd:YAG laser ($\lambda = 1.064\ \mu m$). The operating parameters used for these depositions were 400 W of power and a vector speed of 20 inches per minute (IPM), or approximately 0.5 m/s. Powder flow rates were calibrated to maintain a 0.025 mm/layer build rate. Elemental blends of iron, nickel, and vanadium/molybdenum in the size range of 40–150 µm were deposited on a nickel plate substrate. An inert argon environment with less than 10 ppm oxygen was maintained in the glovebox during the depositions.

An FEI Nova NanoSEM 230 SEM, and an FEI Tecnai G2 F20 TEM were utilized to analyse the microstructure. A Rigaku Ultima III X-ray diffractometer (XRD) was utilized to obtain crystallographic and phase information. A Lakeshore 7404 vibrating scanning magnetometer (VSM) was utilized to generate magnetic hysteresis curves at 300 K under a 1T field.

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3. Results and discussion

XRD results from both deposited Ni-Fe-V and Ni-Fe-Mo samples are shown in Fig. 1. Diffraction peaks in both samples can be indexed based on an *fcc* phase with the (1 1 1), (0 0 2), and (0 2 2) *fcc* peaks visible within the scan range. The lattice parameter of Ni-Fe-V is a = 3.5532 Å and of Ni-Fe-Mo is a = 3.5697 Å. SEM micrographs from these samples are shown in Fig. 2a and b. These microstructures are generally featureless and exhibit columnar *fcc* grains. A small volume fraction of second phase appears in the form of small scale precipitates, exhibiting substantially darker contrast in these images. Energy dispersive spectroscopy (EDS) analysis of these samples, carried out in the SEM, revealed that the average compositions were Ni-18Fe-4V (wt%) and Ni-19Fe-5Mo (wt%). These samples will be referred to as Ni-Fe-V and Ni-Fe-Mo. Fig. 3a shows a [0 1 1] zone axis electron diffraction pattern from the *fcc* phase, exhibiting a fundamental *fcc* diffraction

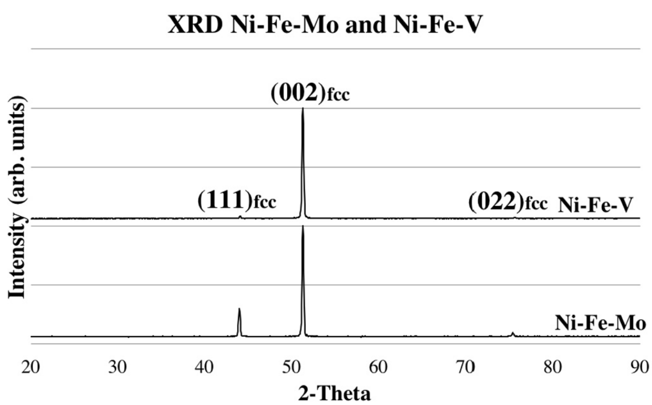

Fig. 1. XRD patterns of LENS™ processed Ni-Fe-V and Ni-Fe-Mo alloy.

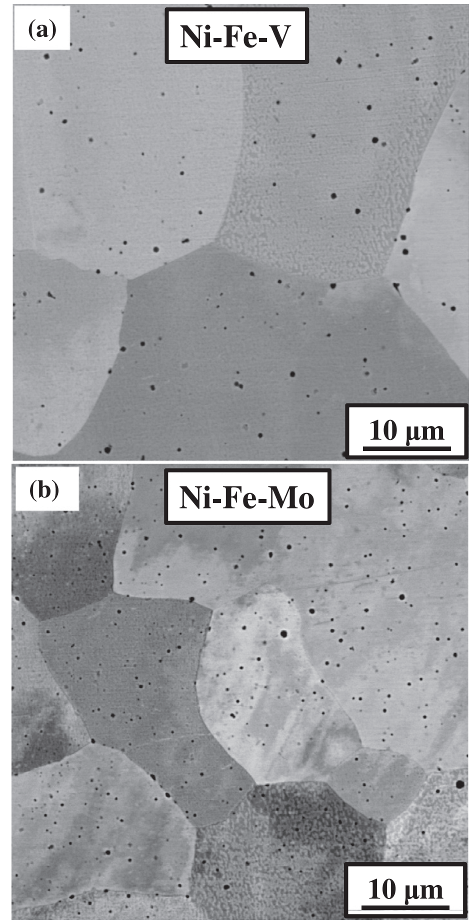

Fig. 2. SEM images of LENS™ deposited (a) Ni-Fe-V and (b) Ni-Fe-Mo alloy.

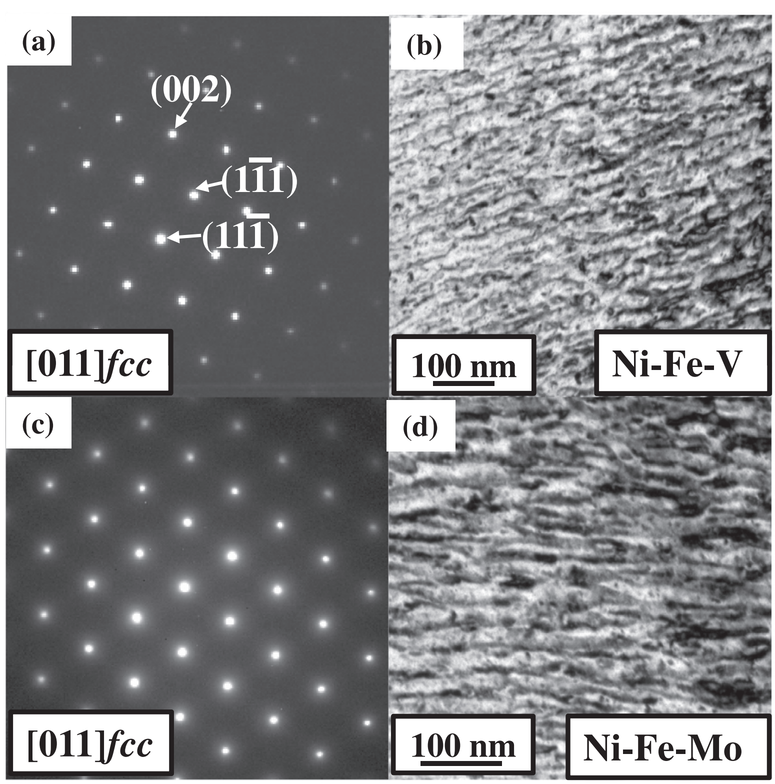

Fig. 3. Selected area diffraction pattern and bright field TEM images of Ni-Fe-V (a, b) and Ni-Fe-Mo (c, d) alloys respectively.

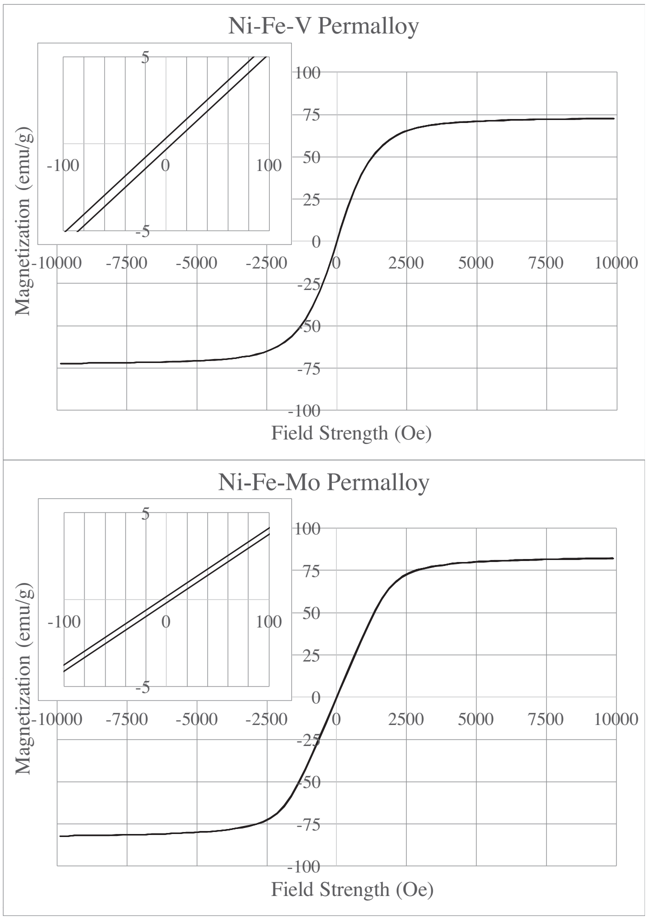

Fig. 4. VSM results of LENS™ processed Ni-Fe-V and Ni-Fe-Mo alloy.

pattern, while Fig. 3b shows a bright-field image from the Ni-Fe-V sample. This image was recorded using a two-beam condition with g = (200) excited near the [011] zone axis. Strain contrast consisting of near-regularly spaced striations, with intervals of 15–20 nm was observed. This contrast is aligned along the {200} planes of the *fcc* matrix. This strain contrast could be related to a phase separating tendency within the *fcc* matrix. A [011] zone electron diffraction pattern and a g = (200) two-beam bright-field TEM image from the Ni-Fe-Mo sample are shown in Fig. 3c and d respectively. Both the diffraction pattern as well as bright-field image are similar to those observed in case of the Ni-Fe-V alloy. More detailed investigations are required in order to establish the origin of the striated patterns seen.

The magnetization (M-H) curves of both Ni-Fe-V and Ni-Fe-Mo deposited alloys are shown in Fig. 4, both exhibiting well-defined hysteresis loops. The saturation magnetization (M_s) and coercivity (H_c) values for the Ni-15Fe-5V sample are 72 emu/g and 6.0Oe, respectively, while the values for the Ni-15Fe-5Mo sample are 82 emu/g and 4.9Oe, respectively. The closest available composition in the literature, Ni-11Fe-6V, exhibits coercivity (H_c) ranging between 0.009Oe and 0.03Oe, with saturation magnetization (M_s) of approximately 50 emu/g [19]. In case of Ni-Fe-Mo Permalloy, the H_c of Ni-17Fe-4Mo was found to be between 0.005Oe and 0.03Oe with an M_s value of approximately 80 emu/g [19,20]. The larger coercivity and saturation magnetization in our laser processed Permalloys (Ni-15Fe-5V and Ni-15Fe-5Mo) compared to conventional Permalloys (Ni-11Fe-6V and Ni-17Fe-4Mo) may be due to their distinct material composition since magnetic properties depend strongly on the composition. The higher coercivity values in our LENS™ deposited alloys can be attributed to microstructural defects such as fine scale porosity, unmelted particles, and other impurities. Nonetheless, the combination of M_s and H_c values exhibited by these samples make them promising candidates for soft magnetic applications. The ability to process these Permalloys in near-net shape form in 3D geometries via AM processes can be highly advantageous in translating complex designs to novel components in an efficient and reproducible manner.

4. Conclusions

Using laser engineered net shaping (LENS™), soft magnetic alloys based on Ni-Fe-V and Ni-Fe-Mo have been successfully deposited from a blend of elemental powders. While the saturation magnetization of these alloys is comparable to conventionally processed versions of similar composition, the coercivities were higher for the laser processed alloys. The microstructure and magnetic properties of these AM processed alloys are promising for component application, especially considering the ability to process them in near-net shape form. Potential applications of such AM processed magnetic materials would be in transformers, electric motors, inductive, and other electromagnetic devices where complex geometries are required.

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