Microstructural Analysis of Directed Energy Deposited Iron Silicon Alloy

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ABSTRACT

Directed Energy Deposition (DED) is fundamentally an additive manufacturing (AM) technique, capable for the fabrication of Fe-Si soft magnetic materials, which are important for transformers, motors and other energy structures. This study utilizes optical microscopy (OM), X-ray Diffraction (XRD), Electron Backscatter Diffraction (EBSD) and Vickers microhardness testing for the microstructural and mechanical investigation of DED Fe-Si alloy. This study demonstrates the fabrication consists of detrimental porosity, cracks, characteristic columnar grain growth, and predominant BCC Fe, Si and SiO_2. The crystallographic texture ⟨001⟩ corroborates DED's ability to tailor soft magnetic materials for easy magnetization.

KEYWORDS: Directed Energy Deposition; Fe-Si Soft Magnetic Alloys; EBSD; X-ray Diffraction; Porosity

1. INTRODUCTION

The fabrication of Fe-Si alloys using AM has been accelerated due to the enhanced demand for soft magnetic alloys, due of exceptional magnetic characteristics and low core losses. These are vital parts of energy translational systems, transformers and motors [1]. The conventional methods limit the flexibility in design and microstructural regulation. DED, where localized control on microstructure, straightly affects the part both magnetically and mechanically [1][2]. This study establishes the structure-property relationship by evaluating the microstructural and hardness for optimum magnetic properties in energy applications.

2. MATERIALS AND METHODS

DED was utilized to fabricate Fe-4.6%Si alloy with 800 W laser power, 600 mm/min scanning speed and 8 g/min powder feed rate.

2.1. Microstructural Characterization & Hardness Testing

The phase analyses were carried out utilizing XRD Cu-K α radiation (λ = 1.5406 Å) from 20° to 90°. OM was used to examine porosity and crack density, EBSD investigates grain size, orientation and grain boundaries using Kernel Average Misorientation (KAM). Also, Vickers hardness testing was utilized for hardness analyses.

3. RESULTS

The analysis of micrograph through binary segmentation calculated the defect density for pores and cracks as presented in the Table 1 including the average hardness. The (110), (200), (211), Si and SiO_2 distinct peaks were identified in the XRD pattern, showing that it is not solid solution. The epitaxial columnar grains 20-80 μm were revealed by EBSD mapping parallel to the build direction (BD). The temperature gradient-driven solidification was confirmed by ⟨001⟩ and ⟨101⟩ texture via inverse pole figure (IPF), where massive thermal residual stress-induced lattice deformation was related by KAM of 4.49°. The large columnar grains separated by distinct boundaries are predominated by High-Angle Grain Boundaries (HAGBs > 92%) with only 7.79% Low-Angle Grain Boundaries (LAGBs) as shown in the figure 1.

Table 1. This table presents average hardness and defects densities.

Porosity	Pore Density	Crack Density	Hardness
~ 1-5%	~10-50 pores/mm²	~ 0.5-2 mm/mm²	~ 250 HV

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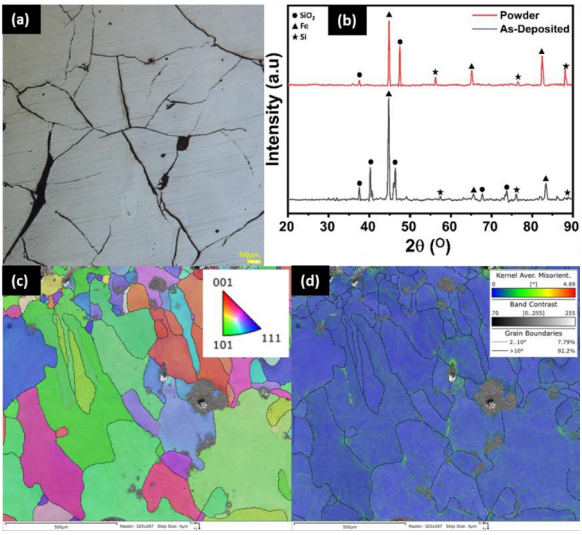


Figure 1. (a) Optical micrograph, (b) XRD pattern, (c) EBSD mapping with IPF and (d) KAM map.

4. DISCUSSION

Improper Ar gas shielding, oxygen entrapment and localised vaporisation creates vapor bubbles during rapid solidification results in porosity. These pores act as crack initiators. Cracks are caused by pores and thermal residual stresses through cyclic heating and cooling evident by KAM ~ 4.49°. While the ⟨001⟩ and ⟨101⟩ texture are structurally and magnetically favourable, defects (porosity compromises mechanical performance and insists domain wall pinning, cracks disrupt magnetic flux path, dislocations degrade permeability) counteract these benefits by increasing brittleness, coercivity and core losses. The post-deposition annealing is recommended to homogenize it mechanically, reduce brittleness and relieve residual stresses while preserving favourable grain orientation [1-3].

5. CONCLUSION

This study presents exploration of employing DED as an efficacious fabrication technique for high silicon soft magnetic alloys. The formation of critical features 2-7 μm pores and intergranular cracks concentrated at boundaries caused by residual stresses and oxidation are detrimental to both mechanical and magnetic performance. The ⟨001⟩, ⟨101⟩ texture and 250 HV average hardness, interprets the feasibility for magnetic devices utilizing enhanced optimized parameters, defect free fabrication and post processing.

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