# Sustainable Mobility Systems Development: Metallurgical Evaluation of Ferromagnetic Materials Manufactured through Additive Manufacturing

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**This doctoral research focuses on the study and analysis of the microstructural development of Fe-Si alloy components fabricated through Additive Manufacturing (Laser Powder Bed Fusion – L-PBF). These components are used in magnetic cores of electric motors, contributing to the development of sustainable mobility systems.**

## INTRODUCTION

Additive manufacturing (AM) is an attractive set of processes that are being employed lately to process specific materials used in the fabrication of electrical machine components. This is because AM allows for the preservation or enhancement of their magnetic properties, which may be degraded or limited when manufactured using other traditional processes. Soft magnetic materials (SMMs), such as Fe–Si, are suitable materials for electrical machine components due to their magnetic, thermal, mechanical and electrical properties.

They are typically produced with a silicon content ranging from 2.0% to 7.0% wt. As the Si content increases, there is a substantial improvement in their soft magnetic characteristics. However, the main limitation of high silicon steels lies in their brittleness when forming phases with ordered structure (B2 and D03) during the cooling stage of manufacturing, which reduces the ductility of the material and limits its machinability using traditional forming processes.

The aim of the present work was to study the microstructural features of the Fe–Si components manufactured by L-PBF, evaluating the influence of the process parameters on the microstructure and magnetic properties.

## MATERIALS AND METHODS

Fe–Si electric steel, with 3.0 wt% and 6.5 wt% Si content (Table 1) were considered to manufacture samples by L-PBF (EOS-M290).

**Table 1.** Chemical composition (wt.%) of the as-received powders of Fe-3.0%Si and Fe-6.5%Si steels used in the L-PBF system.

| Steel | Fe | Si | C | O |
|---|---|---|---|---|
| **Fe-3.0%Si** | Bal. | 3.0 | 0.009 | 0.0001 |
| **Fe-6.5%Si** | Bal. | 6.5 | 0.008 | 0.0001 |

The platform temperature was kept at 200 °C and the process was carried out under an argon atmosphere with oxygen content below 0.4% (Figure 1). Twenty 11×11×11 mm cubes of both steels were manufactured (Table 2).

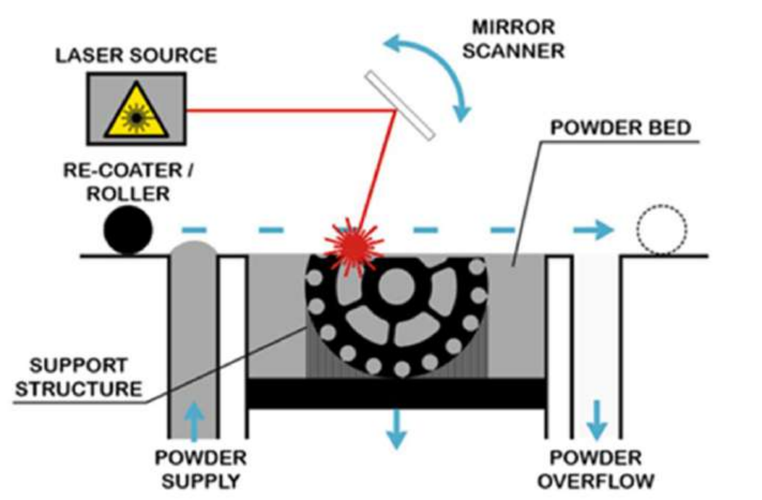


**Figure 1.** Laser Powder Bed Fusion Process

**Table 2.** Process parameters set (specific laser Energy E, scanning speed $v$ and laser power P) to fabricate the cubic samples of both Fe-3.0%Si and Fe-6.5%Si steels.

| **Sample** | **S1** | **S2** | **S3** | **S4** | **S5** |
|---|---|---|---|---|---|
| **E (J·m$^{-1}$)** | 150.0 | 150.0 | 200.0 | 200.0 | 225.0 |
| **$v$ (m·s$^{-1}$)** | 0.50 | 1.0 | 0.83 | 0.50 | 0.75 |
| **P (W)** | 75.0 | 150.0 | 167.0 | 100.0 | 168.8 |
| **Sample** | **S6** | **S7** | **S8** | **S9** | **S10** |
| **E (J·m$^{-1}$)** | 250.0 | 250.0 | 275.0 | 275.0 | 275.0 |
| **$v$ (m·s$^{-1}$)** | 0.67 | 1.0 | 0.50 | 0.61 | 0.94 |
| **P (W)** | 167.0 | 250.0 | 137.5 | 167.0 | 259.0 |
| **Sample** | **S11** | **S12** | **S13** | **S14** | **S15** |
| **E (J·m$^{-1}$)** | 300.0 | 300.0 | 300.0 | 310.0 | 325.0 |
| **$v$ (m·s$^{-1}$)** | 0.56 | 0.86 | 1.0 | 0.70 | 0.51 |
| **P (W)** | 167.0 | 259.0 | 300.0 | 217.0 | 167.0 |
| **Sample** | **S16** | **S17** | **S18** | **S19** | **S20** |
| **E (J·m$^{-1}$)** | 325.0 | 325.0 | 350 | 350 | 400 |
| **$v$ (m·s$^{-1}$)** | 0.80 | 1.0 | 0.50 | 0.74 | 0.60 |
| **P (W)** | 259.0 | 325.0 | 175.0 | 259.0 | 240.0 |

After manufacturing, the samples underwent stress-relieving heat treatment at 700°C, followed by annealing heat treatment at 1150°C for 1 hour. Test samples were machined in a plane parallel to the build direction (BD). The microstructure was analyzed using optical microscopy (OM). Additionally, DSC analysis was conducted up to a temperature of 550°C with a heating rate of 10°C/s on the powders, as-built samples, and stress-relieved samples for both alloys.

Samples of specific geometries (Figure 2) were manufactured to measure the magnetic properties (Figure 3) of Fe–3.0%Si and Fe–6.5%Si steels. The ring samples were heat treated at 1150 °C for 1 h.

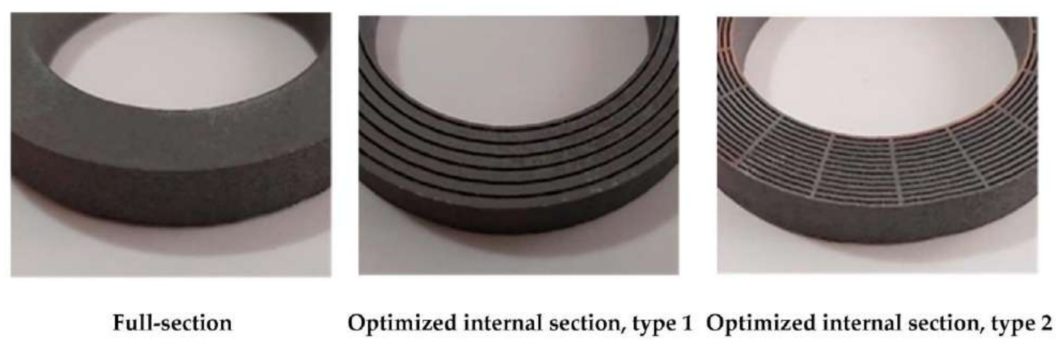


**Figure 2.** Internal section of sample-ring manufactured for magnetic characterization of Fe–3.0%Si and Fe–6.5%Si

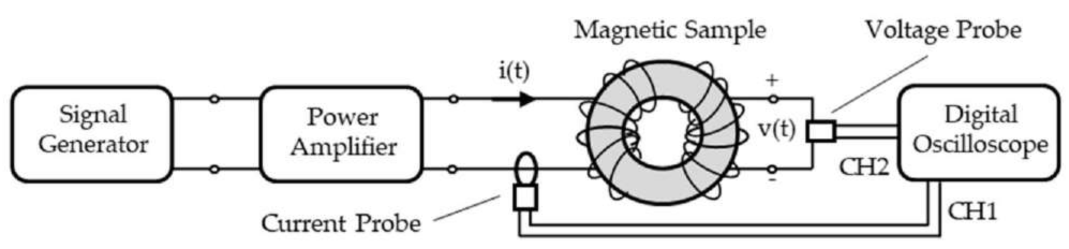


**Figure 3.** Experimental set-up for the magnetic property measurement of the samples in Fe–3.0%Si and Fe–6.5%Si

## RESULTS

Figure 4 and Figure 5 show polished cross sections showing that the Fe-3.0%Si steel is completely free of cracks, while all the Fe-6.5%Si steel samples show cracks orthogonal to the BD, which increase as that the specific laser energy E increases.

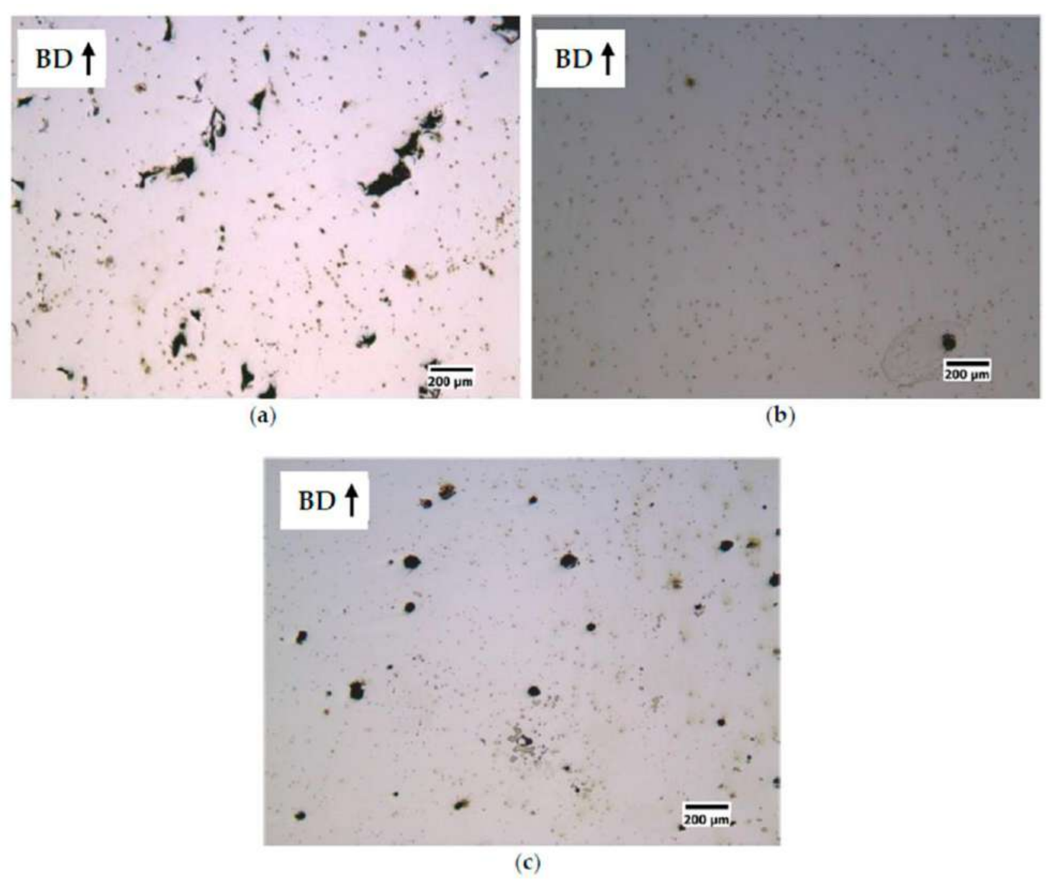


**Figure 4.** Effect of the specific laser energy E [J·m$^{-1}$] on the densification of Fe–3.0%Si steel samples. (a) sample S1 (relative density of the sample 99.93% and pores with irregular shape); (b) sample S7 (relative density of the sample 99.99%); (c) sample S18 (relative density of the sample 99.98% and pores with spherical shape).

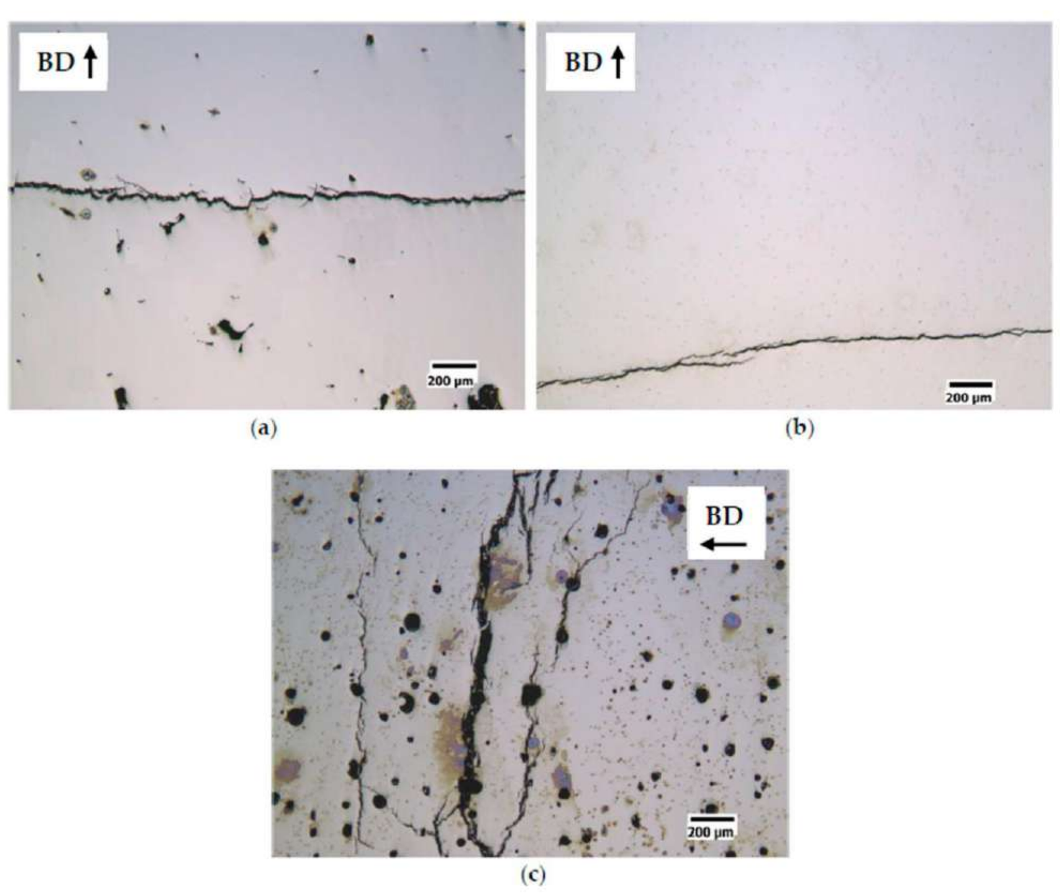


**Figure 5.** Effect of the specific laser energy E [J·m$^{-1}$] on the densification of Fe–6.5%Si steel samples. (a) sample S1 (relative density of the sample 99.93% and pores with irregular shape); (b) sample S3 (relative density of the sample 99.99%); (c) sample S18 (relative density of the sample 99.98% and pores with spherical shape).

In the as-built condition, the microstructures appear completely columnar with grains directed parallel to the BD with epitaxial growth (Figure 6a and 6c).

After the annealing heat treatments, for the Fe–3.0%Si steel the microstructural variation is not very evident (Figure 6b), the structure remains columnar with an average size that passes from 103.1±5.2 to 123.8±6.2 µm after treatment. For Fe–6.5%Si steel the microstructure changes signifcantly: starting from a microstructure with columnar grain (average grain size of 11.3±0.6 µm) and after the annealing heat treatment the microstructure evolves from columnar to equiaxed with an average grain size of 81.2±4.1 µm (Figure 6d).

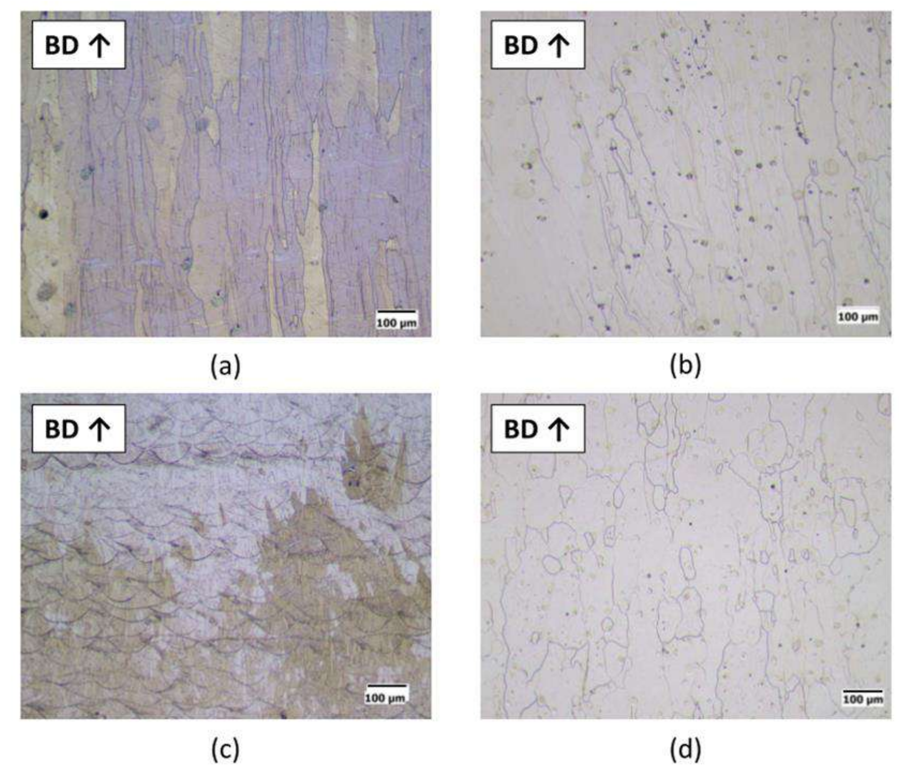


**Figure 6.** Microstructure evolution of Fe–3.0%Si and Fe–6.5%Si after annealing heat treatment at 1150 °C for 1 h. (a) Fe–3.0%Si in as-built condition and (b) after heat treatment; (c) Fe–6.5%Si in as-built condition and (d) after heat treatment

Figure 7 shows the DSC curves for Fe-Si powder, as-built and as-built and stress relieved samples. As expected for the Fe–3.0%Si there is not transformation in ordered phases. The DSC curve of the Fe–6.5%Si powder shows an exothermic peak corresponding to the transformation from the disordered structure A2 to ordered structures B2 or D03.

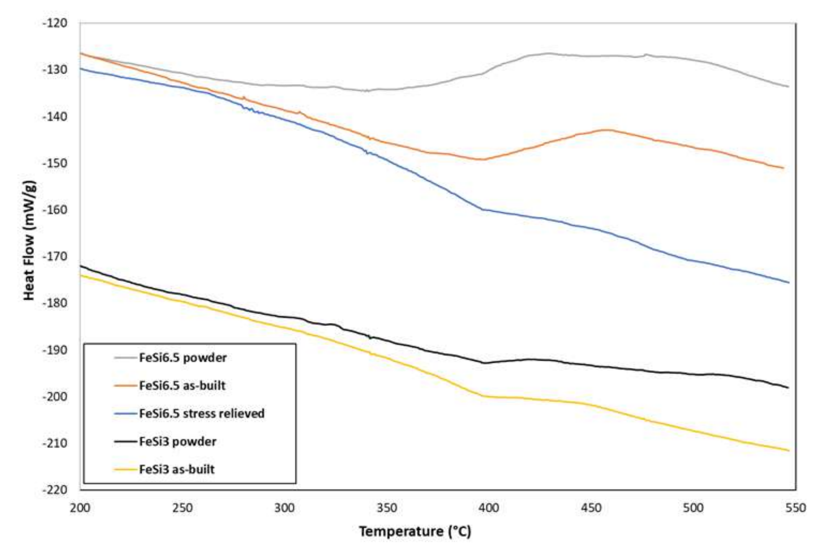


**Figure 7.** DSC heating curves of powder, as-built sample and stress relieved sample of Fe–3.0%Si and Fe–6.5%Si steels

AM technology enables the creation of complex geometries, optimizing component structures to reduce power losses. In fact, samples with 6.5 wt% Si exhibit higher magnetic permeability and magnetization, as well as lower power losses compared to samples with 3.0 wt% Si, reducing power losses by more than 50%.

## CONCLUSIONS

The main challenge in achieving high-density and crack-free printed parts lies in the narrow range of process parameters. Cracks form as a result of the high thermal gradients in the process, while porosities originate from insufficient fusion at low laser energies and keyhole formation at high energies.

The samples exhibit a fully columnar solidification microstructure along the build direction, due to epitaxial growth from the consolidated material of the underlying layers.

DSC analysis reveals that in the Fe-6.5% Si alloy, the rapid solidification in the AM process produces a primarily disordered structure, ensuring its processability.

The Fe–6.5%Si alloy show better magnetic properties than the Fe–3.0%Si alloy, with higher magnetic permeability and magnetization

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**Position with scholarship financed by SEAMTHESIS SRL on funds under the D.M. 351/2022 - PNRR**