Reducing Magnetic Losses in FeSi6.5 Electric Machines through Multi-Material Additive Manufacturing

M.A. Amitouche [a,b], O. Marconot [a], Y. Danlos [a], A. Ospina [b], N. Fenineche [a]

[a] *ICB PMDM LERMPS, UMR 6303, CNRS, Université Marie et Louis Pasteu, Belfort, France.*
[b] ROBERVAL, UMR 7337, CNRS, Université de Technologie de Compiègne, Compiègne, France

Electric machines are composed of laminated sheets of FeSi3, separated by insulating polymer layers. The ferromagnetic material FeSi6.5 exhibits lower magnetic losses than FeSi3, making it a promising candidate for the production of electric machines. However, its high silicon content complicates its production by conventional lamination processes. Additive manufacturing offers a viable alternative but is currently limited to single-material structures. Research on multi-material additive manufacturing is still in its early stages. The challenge lies in manufacturing laminated electric machines using additive manufacturing with thin ceramic insulating layers and FeSi6.5 layers. In this work, we have developed our additive manufacturing machine and successfully fabricated a FeSi6.5/ceramic/FeSi6.5 multi-material using Laser Powder Bed Fusion (LPBF).

Keywords: Magnetic material; Additive Manufacturing; bi-material; multi-material

1. Introduction

Electric machines (EM) are essential in modern industry for various applications, from propulsion to electricity generation. Additive manufacturing offers a promising alternative for producing soft magnetic materials, thereby reducing energy losses.[1] [2]. Electric motors are composed of thin layers of FeSi3 alternating with insulating polymer layers. In additive manufacturing, our goal is to replace the polymer with a ceramic and the FeSi3 with FeSi6.5, which has superior magnetic properties [2]. However, ceramics and metals have very different physical characteristics, making their combination challenging, particularly due to their differing melting points. To overcome this difficulty, we have chosen to use yttria-stabilized zirconia (ZrO_2-Y_2O_3), a ceramic whose coefficient of thermal expansion is very close to that of steel. [3]. Although the fabrication of ceramics by laser powder bed fusion (LPBF) has already been demonstrated, the realization of a laminated structure had not yet been achieved. In this work, an LPBF machine was modified, and the processing parameters were optimized for both FeSi6.5 and the ZrO_2-Y_2O_3 ceramic. This enabled the successful fabrication of a multilayer structure of the type FeSi6.5/ZrO_2-Y_2O_3/FeSi6.5.

2. Results and discussion

Electron microscopy reveals the formation of an intermediate zone between FeSi6.5 and YSZ. Electron microscopy analysis shows that this zone is composed of Zr, Fe, and Si. This can be explained by the fact that during the fusion of YSZ, the melt pool depth exceeds the thickness of the YSZ layer and reaches the underlying FeSi6.5. As a result, the melt pool consists of a mixture of FeSi6.5 and YSZ. During solidification, the YSZ remains trapped within the FeSi6.5, forming this mixing zone. This zone corresponds to the diffusion of YSZ into FeSi6.5. The elemental composition of this zone varies depending on the number of remeltings of the YSZ deposited layer Figure1 (a).

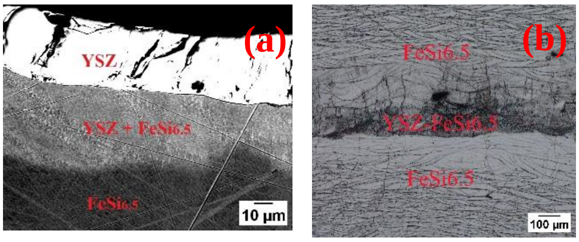

Figure 1: (a) corresponds to the deposition of ZrO_2-Y_2O_3 on FeSi6.5, with the appearance of an intermediate zone. (b) corresponds to a layered structure of the type FeSi6.5/ZrO_2-Y_2O_3/F eSi6.5.

During the deposition of FeSi6.5 onto ZrO_2 (YSZ), using previously optimized processing parameters for FeSi6.5, good adhesion could not be achieved. Poor bonding of FeSi6.5 to the YSZ substrate was observed. To address this issue, two test plans were implemented to optimize the deposition process. Figure 1(b) shows an example of successful layering. The next steps in our study involve the fabrication of a toroid, the execution of magnetic measurements, and a comparison with results obtained from a toroid made of bulk FeSi6.5 material.

References

[1] D. Goll et al., « Additive manufacturing of soft magnetic materials and components », Additive Manufacturing, vol. 27, p. 428-439, mai 2019, doi: 10.1016/j.addma.2019.02.021.

[2] M. Zaied, A. Ospina-Vargas, N. Buiron, J. Favergeon, et N.-E. Fenineche, « Additive Manufacturing of Soft Ferromagnetic Fe 6.5%Si Annular Cores: Process Parameters, Microstructure, and Magnetic Properties », IEEE Transactions on Magnetics, vol. 58, no 11, p. 1-9, nov. 2022, doi: 10.1109/TMAG.2022.3202631.

[3] Q. Liu, Y. Danlos, B. Song, B. Zhang, S. Yin, et H. Liao, « Effect of high-temperature preheating on the selective laser melting of yttria-stabilized zirconia ceramic », Journal of Materials Processing Technology, vol. 222, p. 61-74, août 2015, doi: 10.1016/j.jmatprotec.2015.02.036.

Acknowledgements: This project is part of the ANR Falstaff Consortium. Thanks to the agency for funding the work.