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

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## Abstract

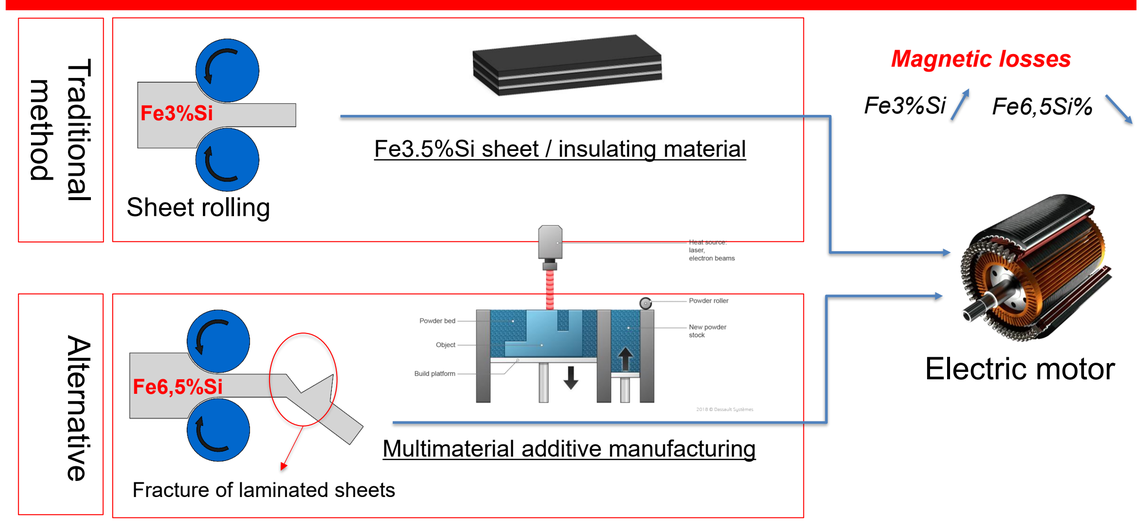
**❑ Context :**

- Electric motor consist of Fe3%Si laminated sheet stacks, separated by insulating layers. The addition of silicon improves magnetic performances but also hardened the material, making the rolling process nearly impossible.
- Additive manufacturing is an alternative, but it leads to Eddy current losses in bulk material due to geometry effect.

**❑ Aims of the work :**

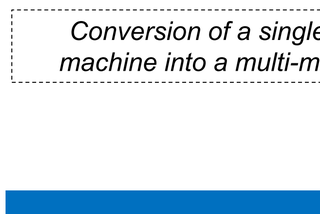
- Adapt our LPBF machine to produce laminated structures using two different materials.
- Design laminated structures alternating FeSi6.5 % layers and $ZrO_2$–$Y_2O_3$ layers using additive manufacturing and compare a bulk FeSi6.5 toroid with a multimaterial toroid processed by A.M.

## Scientific Challenges

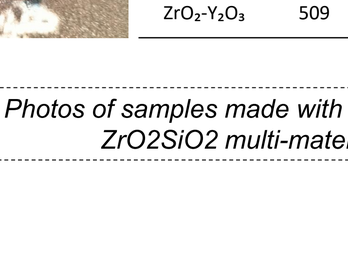



❑ Rolled sheets, alternated with a layer of insulation to reduce magnetic losses due to eddy currents.

$$P = \frac{N^2 \hat{I}^2}{2\pi} \frac{1}{\sigma\delta} \frac{\sinh\frac{\Delta}{\delta} - \sin\frac{\Delta}{\delta}}{\cosh\frac{\Delta}{\delta} + \cos\frac{\Delta}{\delta}} \log\frac{R_2}{R_1}.$$

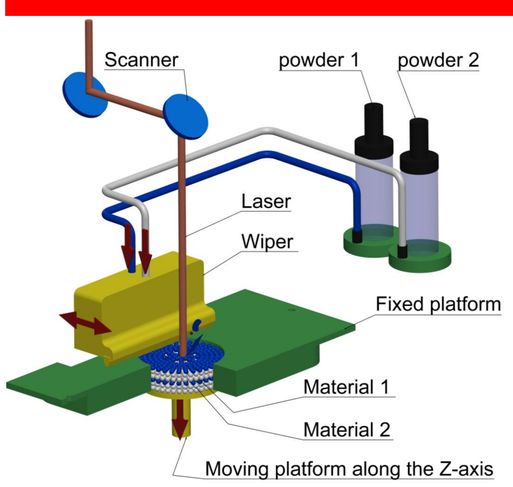



*Numerical model for estimating magnetic losses in a solid material and in a laminated sheet stack [Miroslav Markovic, 2009]*

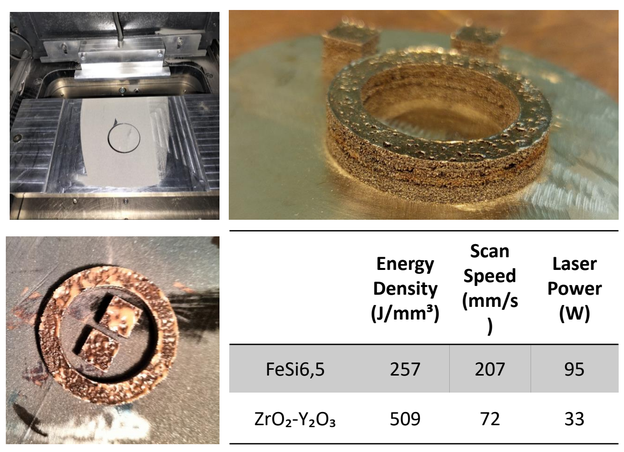



*Comparison of magnetic losses between a 5-sheet laminate and a 20-sheet laminate with the same overall thickness. [Miroslav Markovic, 2009]*

## LPBF process improvement



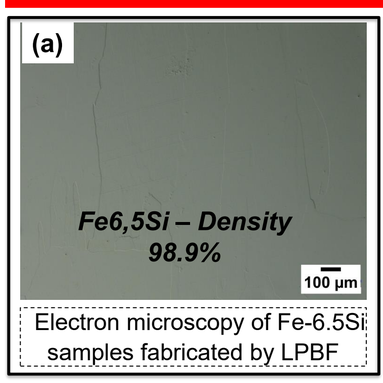

*Conversion of a single-material LPBF machine into a multi-materials machine*



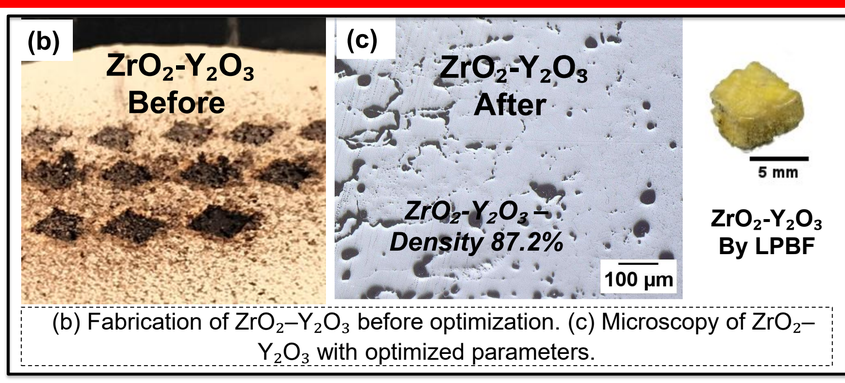
| | Energy Density (J/mm³) | Scan Speed (mm/s) | Laser Power (W) |
|---|---|---|---|
| FeSi6,5 | 257 | 207 | 95 |
| $ZrO_2$-$Y_2O_3$ | 509 | 72 | 33 |

*Photos of samples made with FeSi6.5 and ZrO2SiO2 multi-materials*

## Microstructure characterization

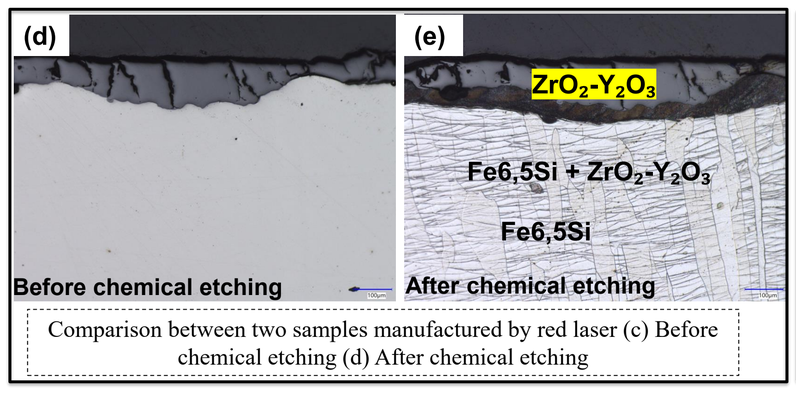



Electron microscopy of Fe-6.5Si samples fabricated by LPBF

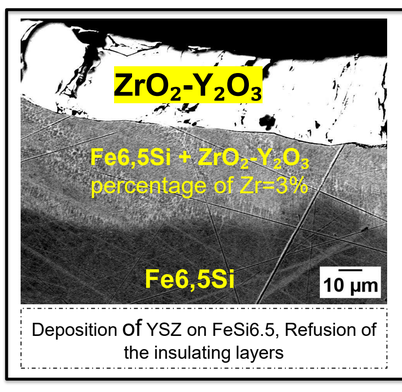



(b) Fabrication of $ZrO_2$–$Y_2O_3$ before optimization. (c) Microscopy of $ZrO_2$–$Y_2O_3$ with optimized parameters.

Parameters optimization

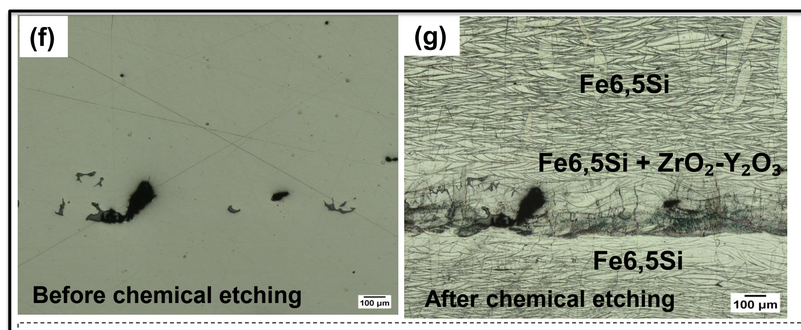



Comparison between two samples manufactured by red laser (c) Before chemical etching (d) After chemical etching




Deposition of YSZ on FeSi6.5, Refusion of the insulating layers

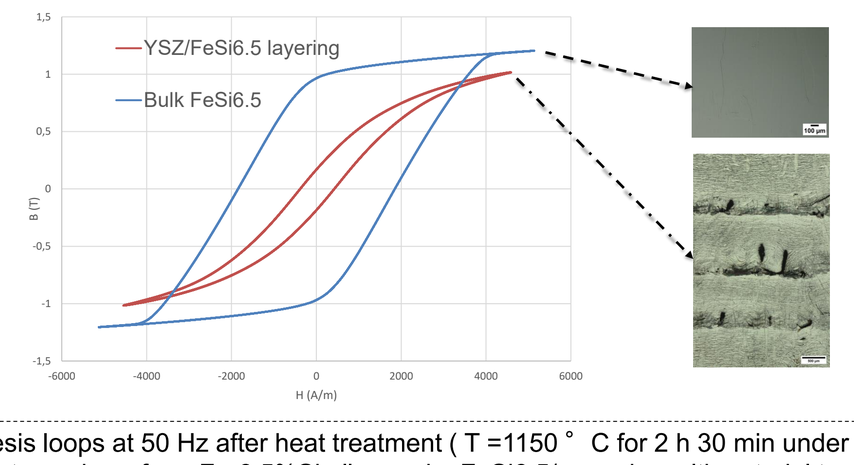
Deposition of $ZrO_2$–$Y_2O_3$ on Fe–6.5%Si




Comparison between two samples manufactured by red laser (f) Before chemical etching (g) After chemical etching, (h) Image illustrating the alternating layering of FeSi6.5 and $ZrO_2$-$Y_2O_3$.

Fe–6.5%Si / $ZrO_2$–$Y_2O_3$ / Fe–6.5%Si

## Magnetic characterization




Hysteresis loops at 50 Hz after heat treatment ( T =1150 ° C for 2 h 30 min under hydrogen atmosphere.for a Fe-6.5%Si alloy and a FeSi6.5/ceramic multi-material toroid

## Conclusion

❑ **Parameters Optimization**: We successfully optimized the manufacturing parameters for FeSi6.5 and $ZrO_2$-$Y_2O_3$ ceramic using the LPBF technique.

❑ **Successful Fabrication**: We successfully manufactured a ceramic/FeSi6.5 laminated structure.

❑ **Magnetic properties**: The layered YSZ/FeSi6.5 structure exhibits reduced magnetic losses (smaller hysteresis loop area) compared to bulk FeSi6.5

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