Research Fund for Coal and Steel project
101034063 — STeELS-EM — RFCS-2020

STeELS-EM Project

Overall evaluation of the stabilizing Elements

Dissemination Day
November 25th 2024

L. Albini

Summary

- Materials
- Magnetic characterization (OCAS, CSM, RWTH-AACHEN)
- Mechanical characterization (VAS)
- Magnetic Aging (OCAS, CSM)
- Conclusions

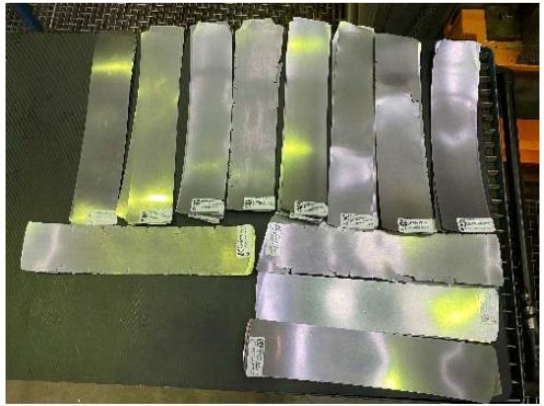
Materials

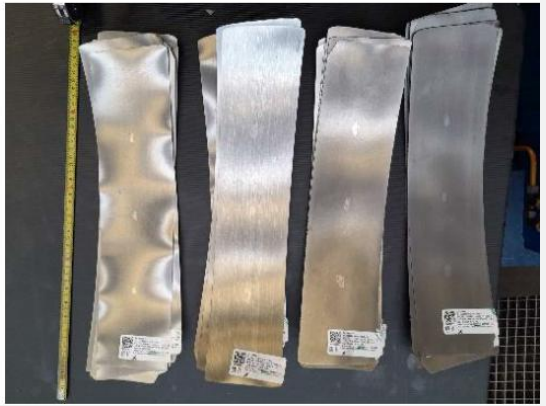
STeELS-EM

Chemical Composition of Reference and Ti added materials

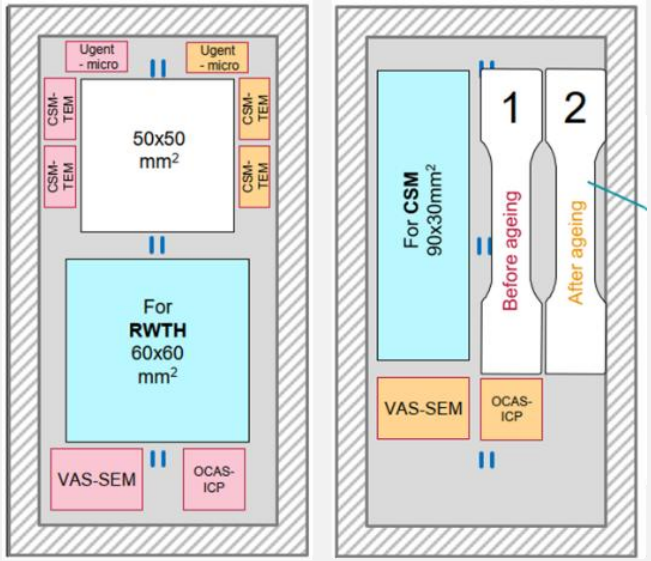
Campaign	Steel	C (ppm)	Mn (%)	Si (%)	Ti (%)	P (%)	S (ppm)	N (ppm)	Al (%)	Cu (%)
Wave 1 Reference 0.001 wt% Ti	LoTi-LoSi	60	0.30	1.02	0.001	0.014	20	47	0.51	0.015
	LoTi-HiSi	60	0.30	2.92	0.001	0.014	20	37	0.98	0.015
Wave 2 Ti-added 0.2 wt% Ti	HiTi-LoSi	53	0.27	1.53	0.200	0.011	20	32	0.51	0.015
	HiTi-HiSi	61	0.32	2.97	0.200	0.012	20	36	0.99	0.015
Wave 3 Ti-added 0.5 wt% Ti	HiTi-LoSi	50	0.30	0.98	0.490	0.008	30	33	0.49	0.015
	HiTi-HiSi	46	0.29	2.98	0.490	0.008	30	23	1.01	0.015

Cold rolled materials (OCAS) at final thickness (0.30 mm)





Magnetic and Mechanical Characterization



Sampling plan for the final annealed sheets
Laboratory characterizations

Magnetic properties

Conventional Magnetic characterizations have been performed by OCAS (SST 50x50 mm2); CSM (Mini-SST 30x90 mm2).

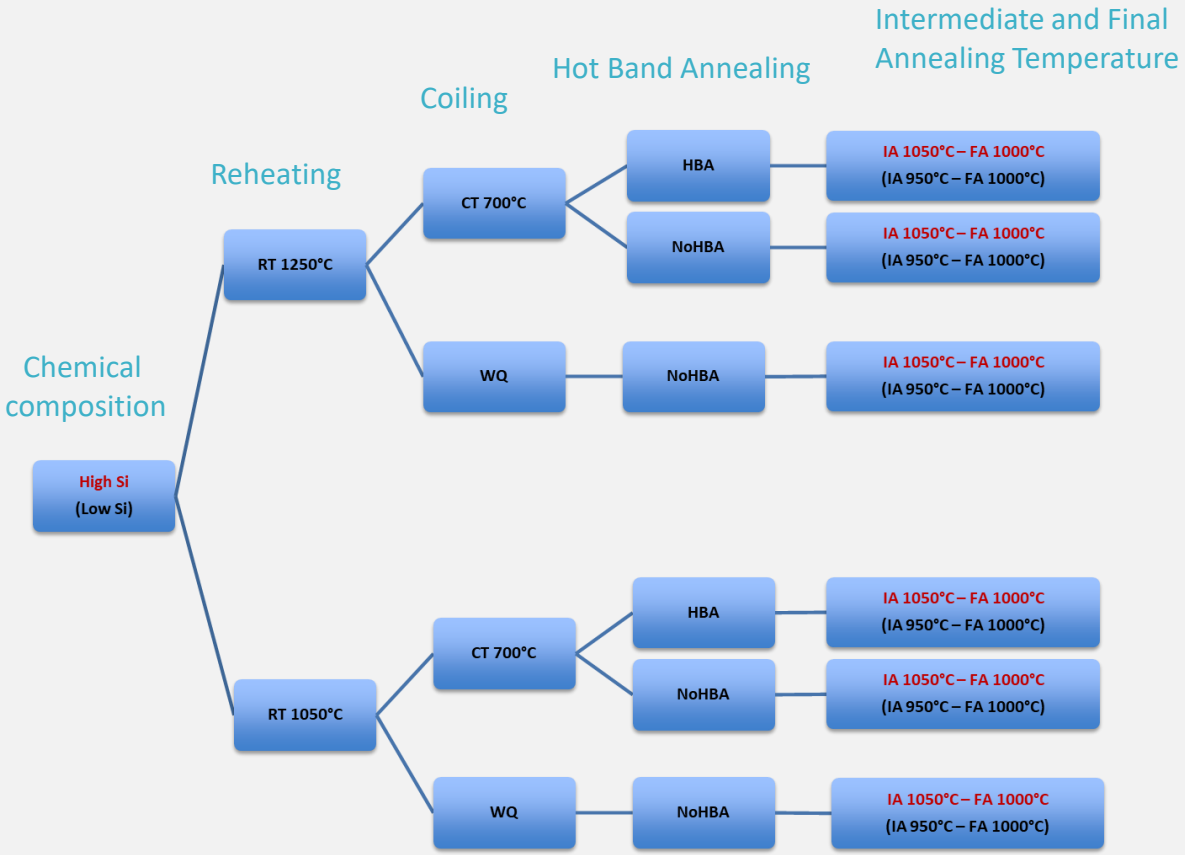
$P_{15/50}$	Core losses @ J=1.5 T; 50 Hz
$P_{10/400}$	Core losses @ J=1.0 T; 400 Hz
J_{2500}	Polarization @ H=2500 A/m
J_{5000}	Polarization @ H=5000 A/m
J_{10000}	Polarization @ H=10000 A/m

Mechanical properties

The standard tensile tests are carried out by VAS according to ASTM E 517 standard. The specimens are obtained in longitudinal direction (i.e. rolling direction)

Rp_{02}	Yield Point
Rm	Ultimate Strenght
A_L	Elongation
Unif. Strain	Uniform Strain
Frac. Strain	Fractional Strain

Schematic view of wave 1 and wave 2
Processing conditions



Aging conditions

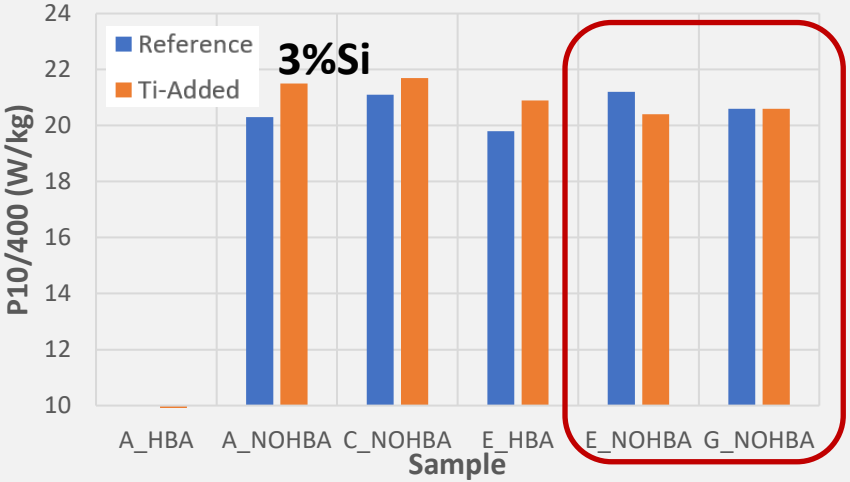
24h @ 225 °C

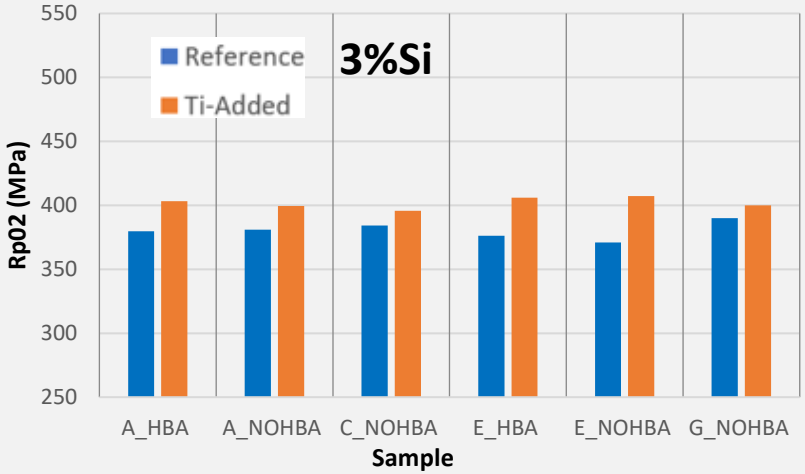
Atmosphere Dry H_2

D.P. - 40°C

Characterization of precipitates in hot strips and final products

Best results in wave 1 and wave 2
High Si





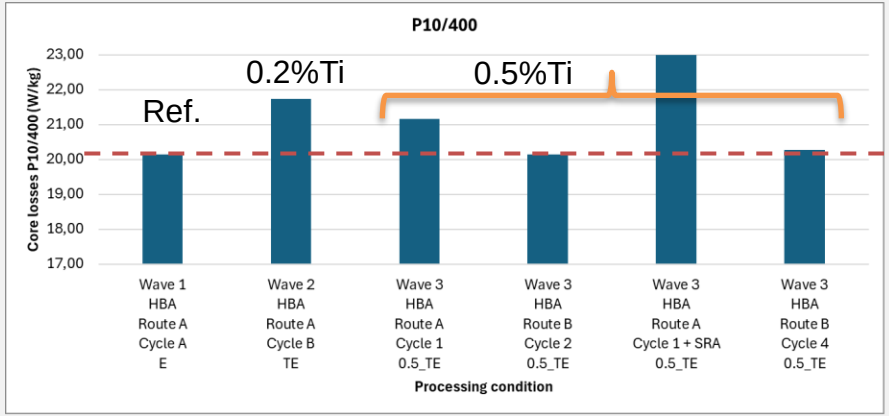
- In general, the core losses of the Ti-added variant are comparable to those of the reference and in some cases, they were found to be slightly better. Lower power power losses at 400 Hz are associated to the variants with lower reheating temperature (1050°C) and coiling at 700°C, without HBA treatment.

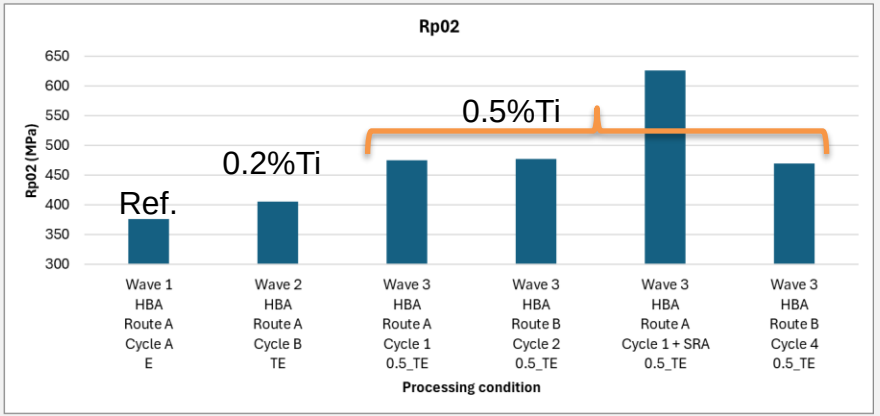
- Titanium also acts as a solid solution hardener increasing the mechanical properties of cold rolled products. In 3%Si steels the addition of titanium produces an average increase of about 22 MPa on Rp02 and about 35 MPa on Rm

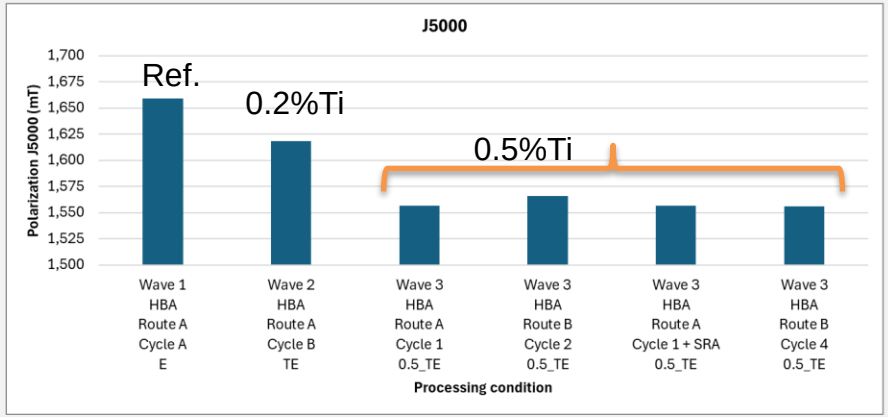
Optimization of the Heats in wave 3

- RT 1050°C and CT 700°C to limit the fine precipitation after hot rolling
- Ti addition 0.5 wt% to decrease the grain growth inhibition and allow the grain size increasing up to the desired size (80-100 micron)
- A different partitioning of the overall cold deformation between the two cold rolling stages imposing a lower reduction in the 2nd stage could be of help in reducing the intensity of the <111>//ND recrystallization components (γ fiber), thus improving the polarization

Magnetic and mechanical properties
High Si materials (HBA)

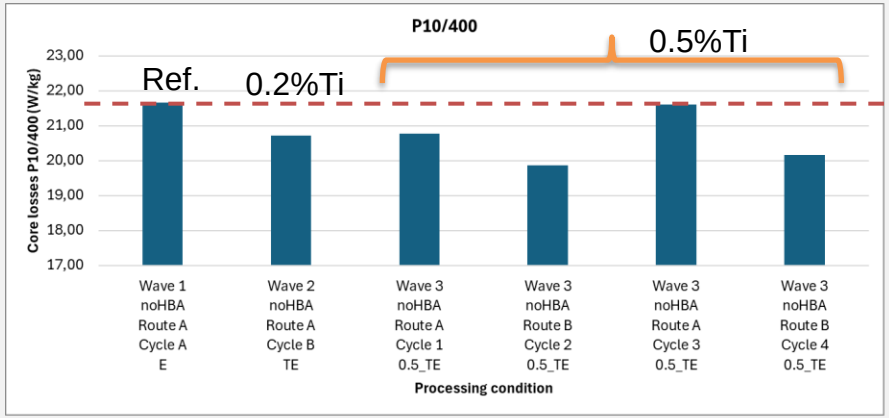


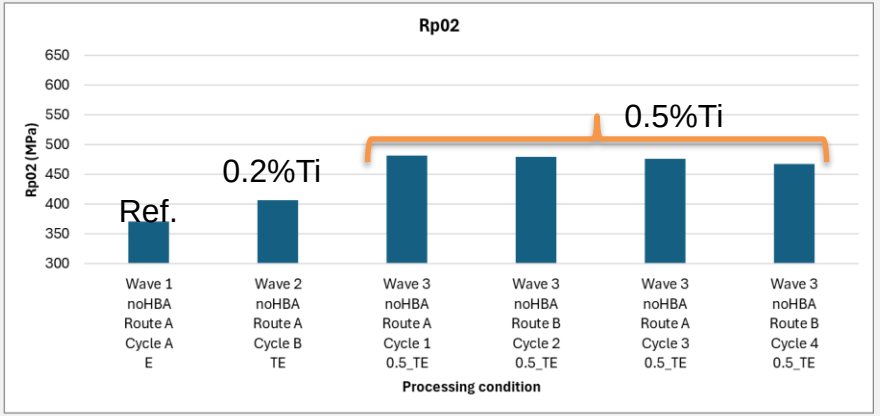


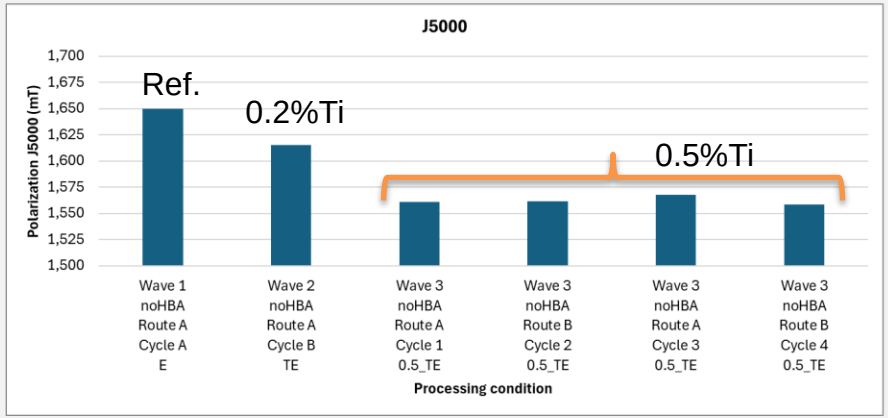


RT 1050°C and CT 700°C

Magnetic and mechanical properties
High Si materials (NoHBA)

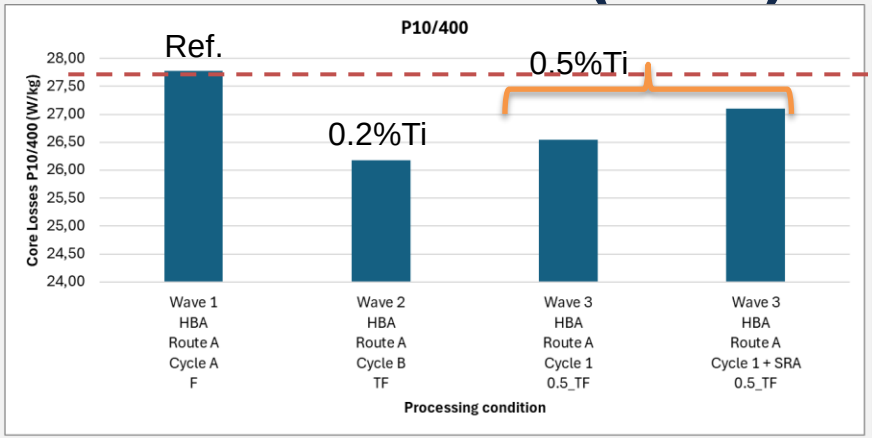


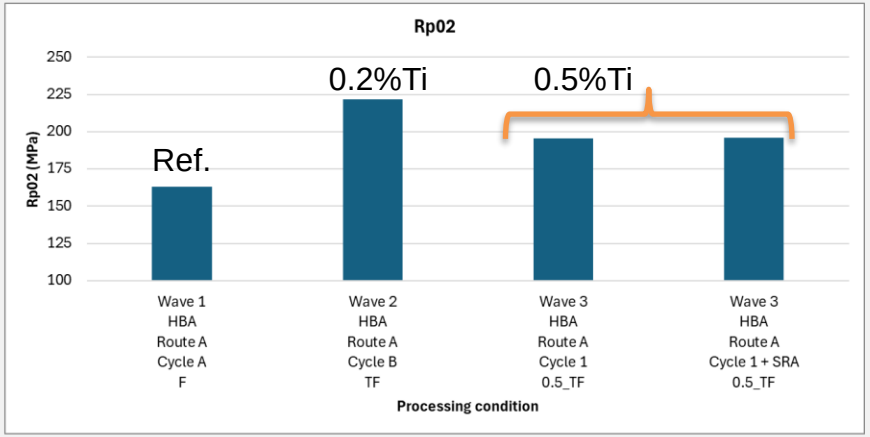


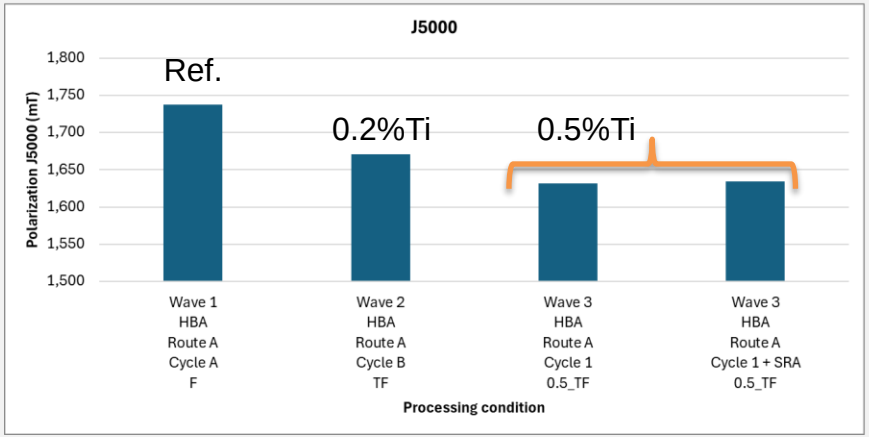


RT 1050°C and CT 700°C

Magnetic and mechanical properties
Low Si materials (HBA)

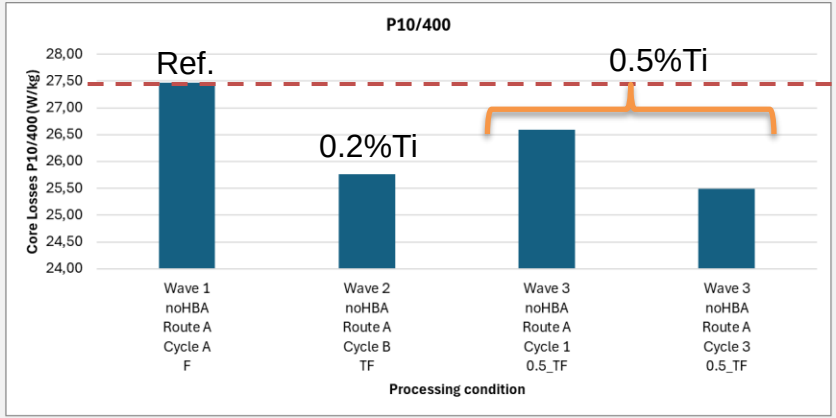


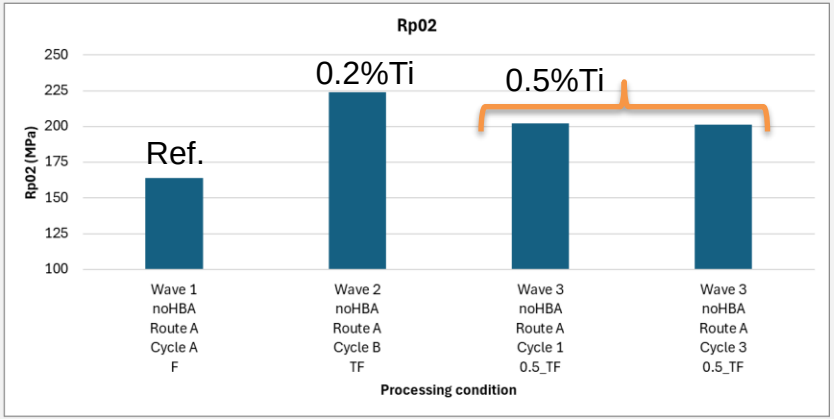


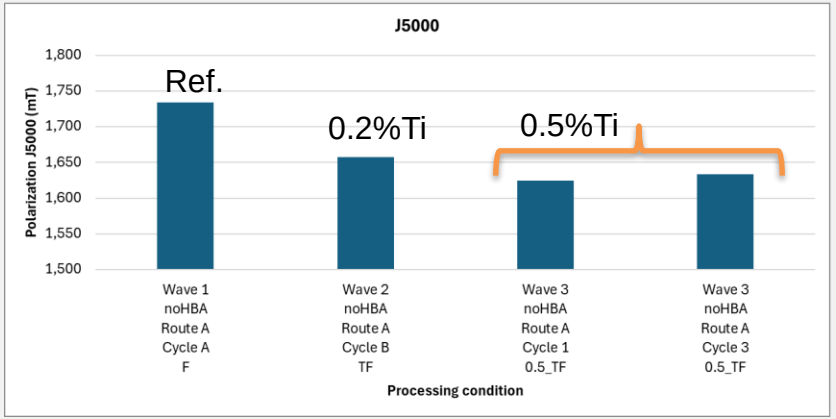


RT 1050°C and CT 700°C

Magnetic and mechanical properties
Low Si materials (NoHBA)

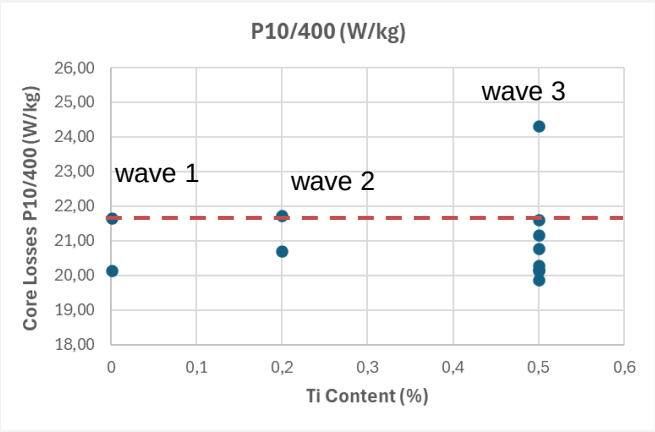


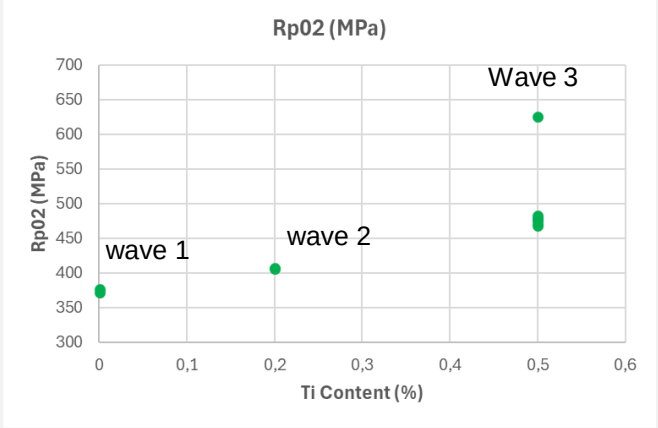


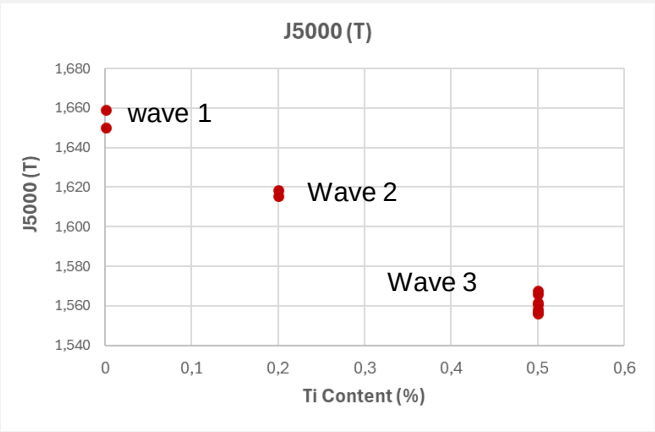


RT 1050°C and CT 700°C

Magnetic and mechanical properties
High Si materials





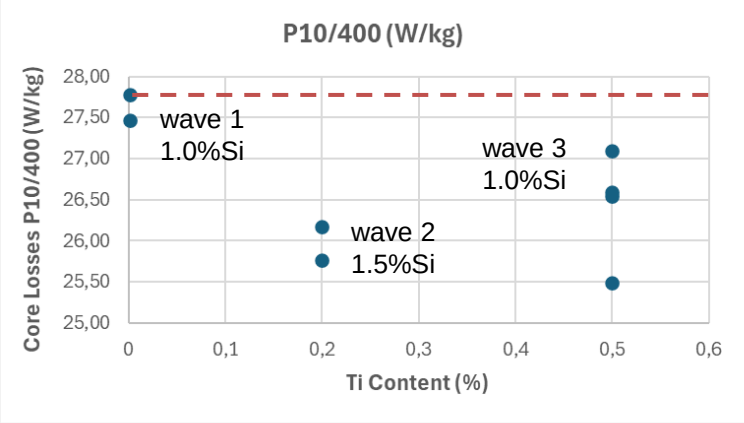


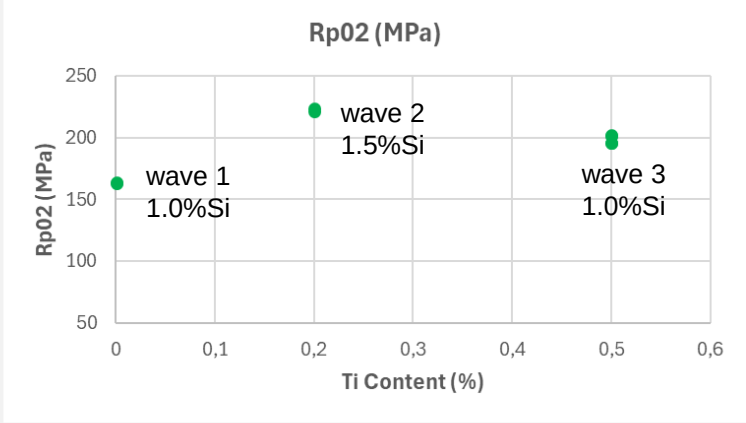
Core losses P10/400 obtained in wave 3 (0.5%Ti) are comparable, and in some cases better than for reference material (wave 1)

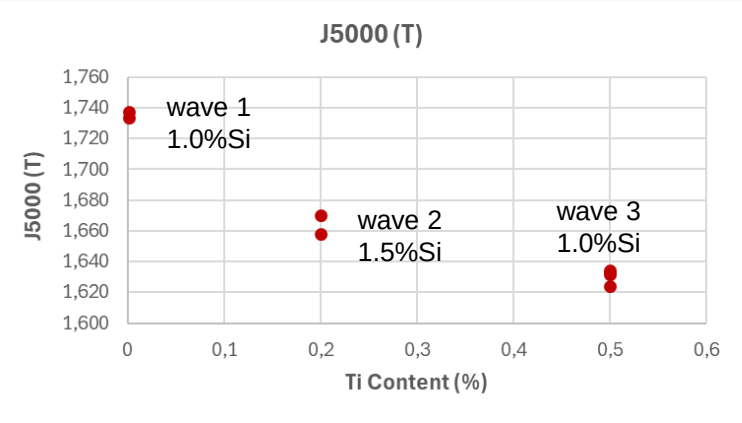
Polarization reduces as Ti content increases.

Mechanical strength tends to increase as the Ti content increases.

Magnetic and mechanical properties
Low Si materials





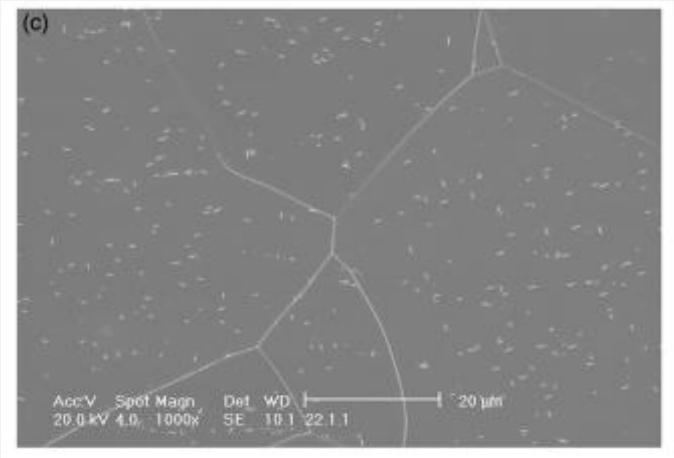


In wave 3 (Ti-Added, 0.5%Ti material) Core losses are Lower with respect to reference materials

Polarization reduces as the Ti content increases.

At fixed Si content, the mechanical yield strength tends to increase as the Ti content increases.

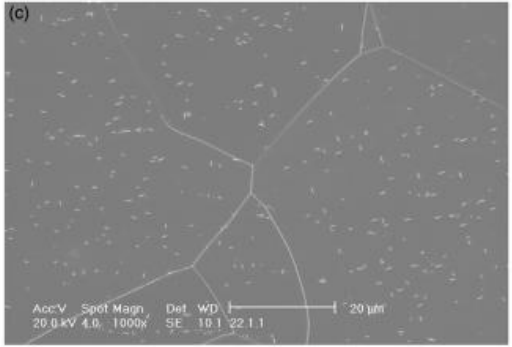
Magnetic Aging Effect



Magnetic Aging in Electrical Steel

Magnetic Aging in Electrical Steels identifies the core losses worsening of FeSi (GO, NGO) due to the precipitation at low temperature (mainly below 300 °C) of fine particles (iron carbides) that occurs during the electrical machines service

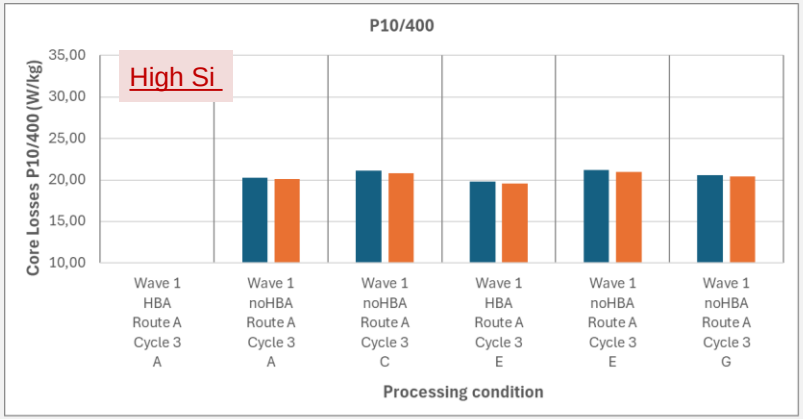
The time in which the precipitation of these particles occurs is highly dependent on temperature and C content.

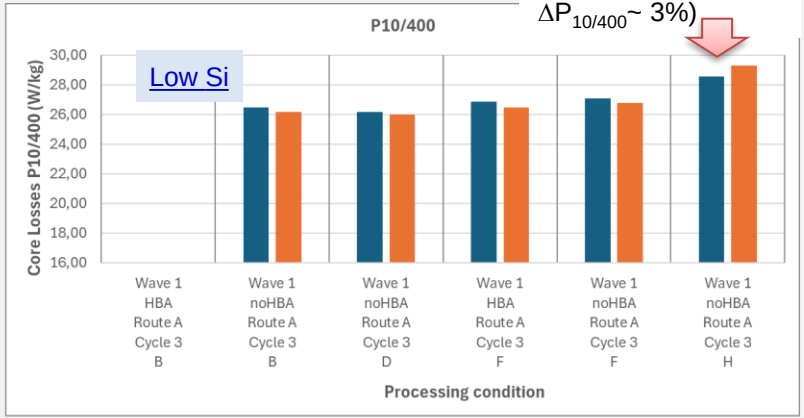


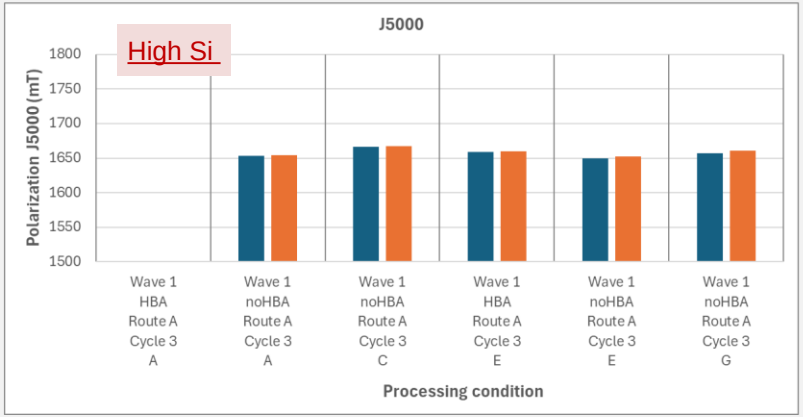
ε-carbides in FeSi NGO observed after aging @ 225°C [1]

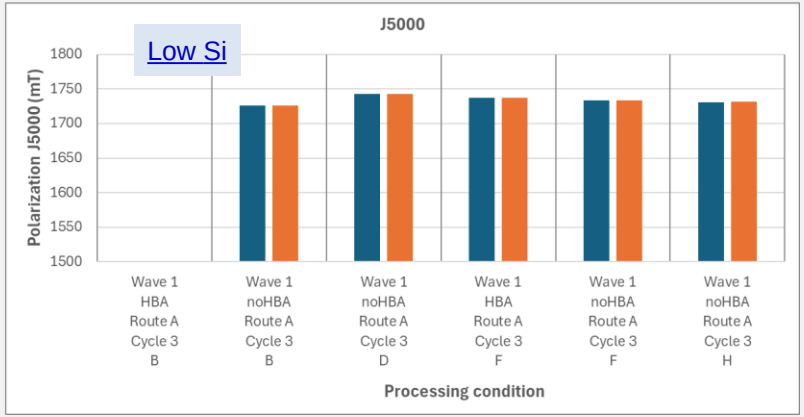
[1] José Rogério de Oliveira Júnior et al. - Kinetics of Magnetic Ageing of 2%Si Non-oriented Grain Electrical Steel - Materials Research. 2018; 21(1): e20170575; doi: http://dx.doi.org/10.1590/1980-5373-MR-2017-0575

Magnetic Aging Evaluation
Wave 1 (225°C x 24h; 100%H2)

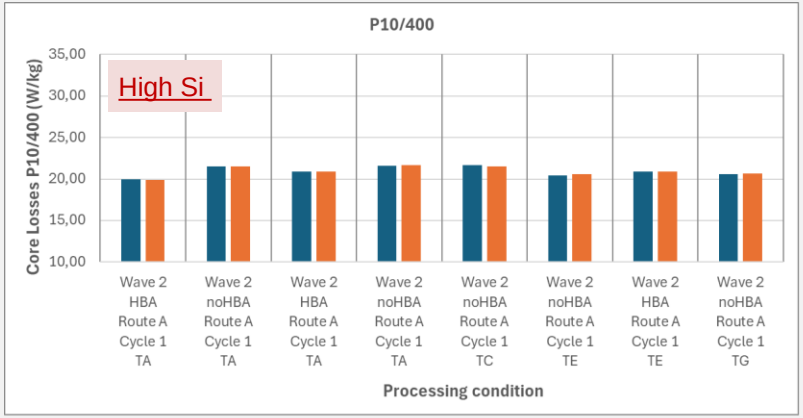


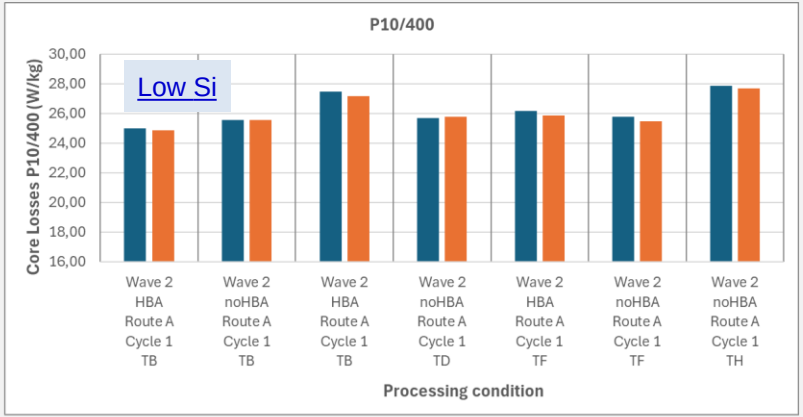


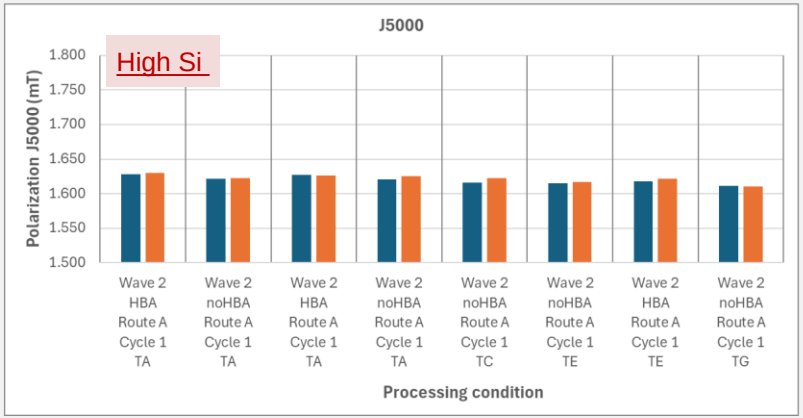




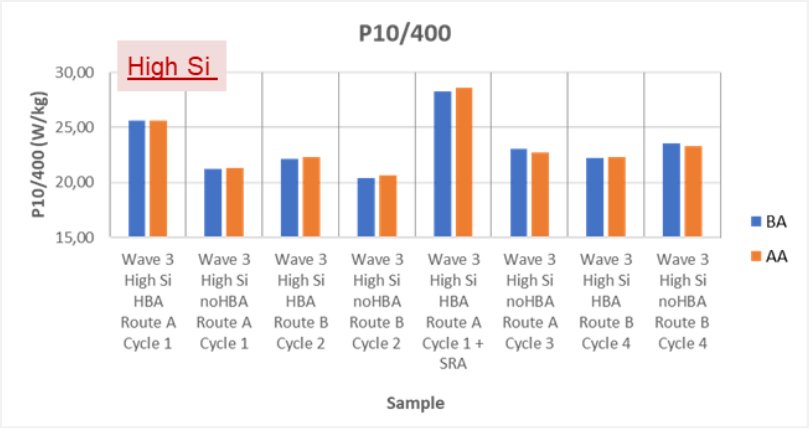
Magnetic Aging Evaluation
Wave 2 (225°C x 24h; 100%H2)

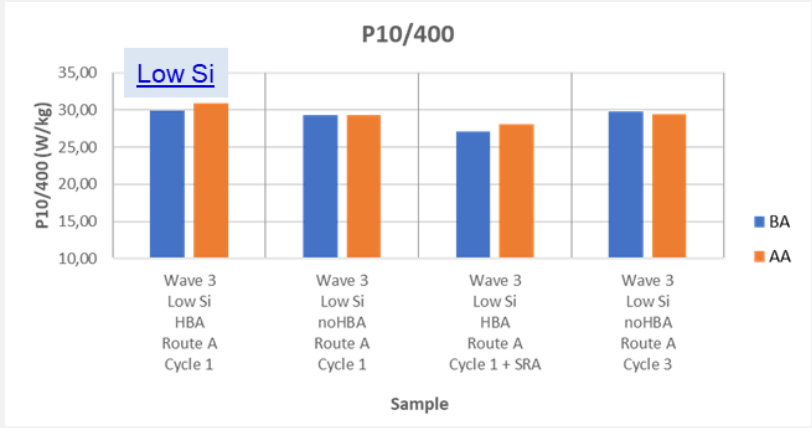


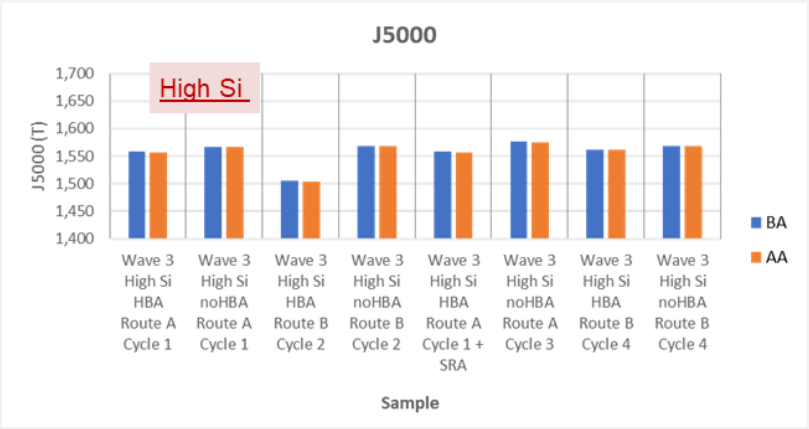


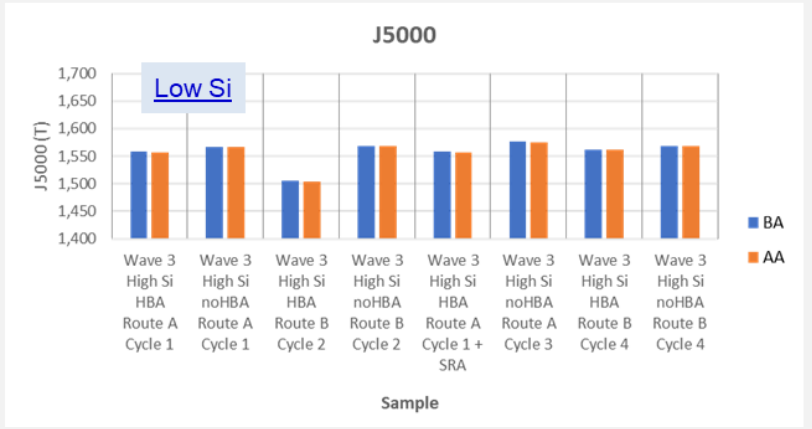


Magnetic Aging Evaluation
Wave 3 (225°C x 24h; 100%H2)









Comments on magnetic aging effect

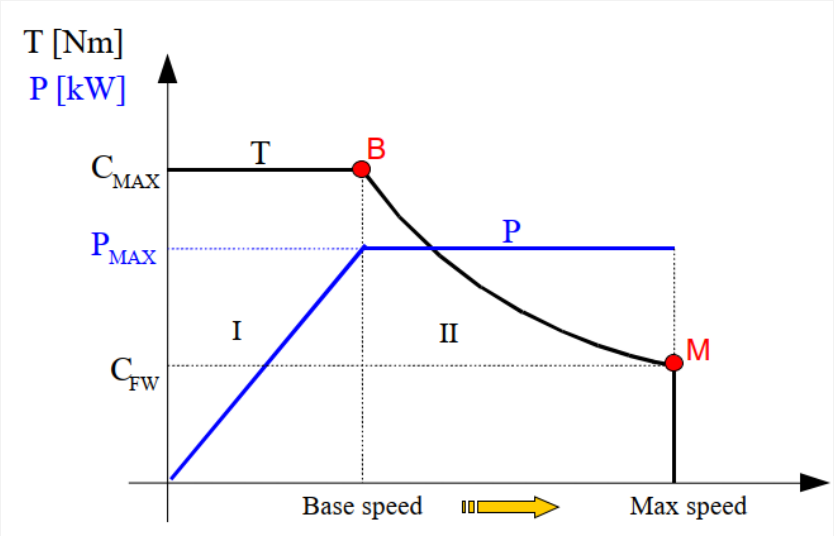
- No effects of magnetic aging were observed in Ti-Added materials (wave 2 and wave 3)
- An aging effect is observed in wave 1 (Reference; 0.001 wt%Ti) in case of lowSi material treated by water quench (WQ) after hot rolling. In this case, about 3% of worsening on P10/400 is found.
- Titanium is effective in eliminating the aging of core losses which has been found in the low Si reference material in case of WQ treatment after hot rolling.
- No effects on polarization J5000 are observed after aging treatment

Main Question

Are the materials studied within the STeELS-EM project suitable for applications in new electric motors for EV/HEV traction?

Required Performance of Electric motors and electric characteristics of the steel

The performance of an electric motor in terms of torque and power is a function of speed



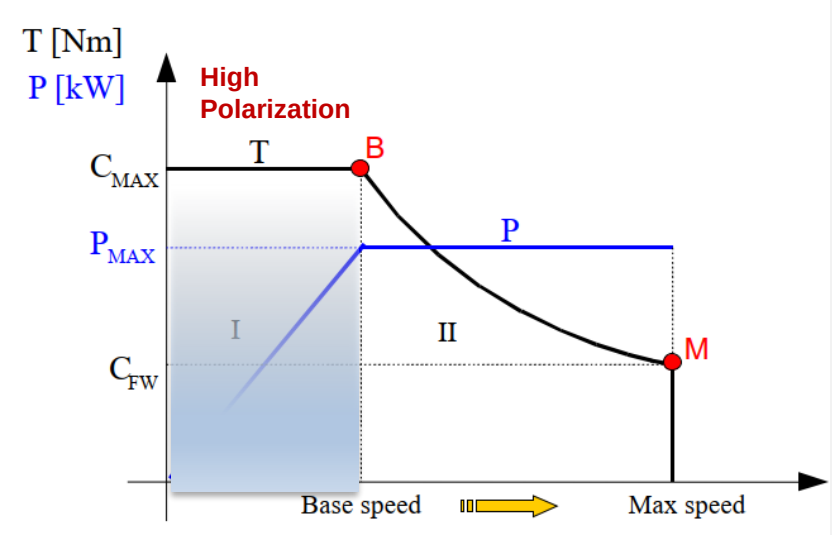
At low speeds: The torque is ideally constant up to the base speed and the dominant component of the losses are the copper losses.

At high speed, The power is ideally constant, and the dominant component of losses are the core losses in the iron.

I. Constant Torque region -> high acceleration
II. Constant Power region (Flux-Weakening region) -> high Speed

Required Performance of Electric motors and electric characteristics of the steel

What are the characteristics that the material must have to improve Electric motor performances?



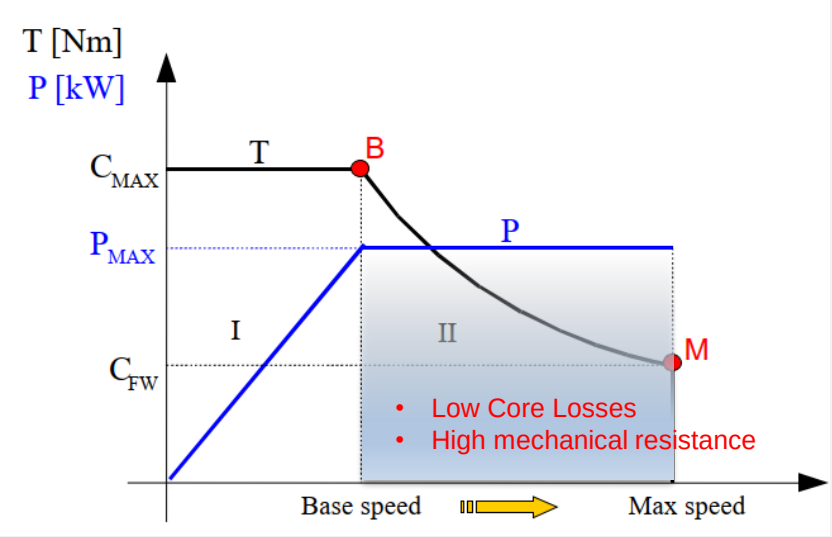
At low speeds: The torque is ideally constant up to the base speed;

The motor must provide high torque, this allows to accelerate quickly.

A high polarization of the NGO material allows to increase motor Torque and vehicle acceleration

Required Performance of Electric motors and electric characteristics of the steeel

What are the characteristics that the material must have to improve Electric motor performances?



At high speed: The motor power is ideally constant, and the dominant component of losses are the core losses in the iron.

It is necessary to control core losses in iron (low thickness, high resistivity)

It is mandatory to guarantee the motor integrity at high speed (rotation speed >16000 r.p.m.)

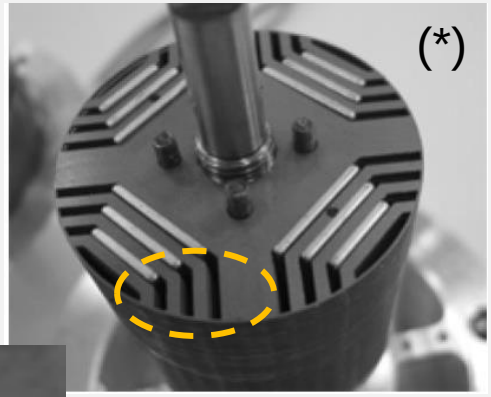
High Strength Electrical Seels for EV/HEV motors

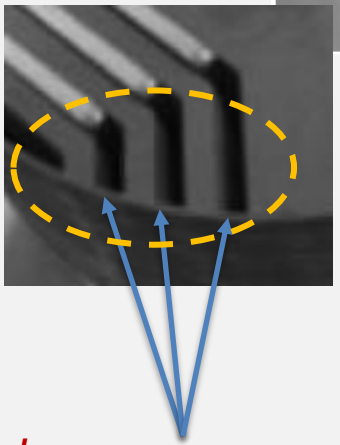
In permanent magnet synchronous machines (PMSM) with embedded magnets, as well as in reluctance motors having very complex rotor figures with presence of thin bridges there are additional restrictions for the mechanical properties of the rotor core material.

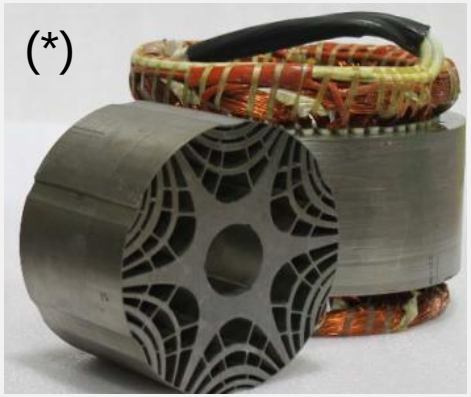
Thinner bridges are preferable for the following reasons:

- Lower leakage of the magnetic flux
- Magnet material reduction
- Lower weight of the motor
- Reduction of machine size and costs

High mechanical strength is required to allow the integrity of the rotor at high speed.







(*) M. Villani et al. Univ. De L'Aquila

Conclusions

The best compromise in terms of magnetic and mechanical characteristics is obtained in wave 3 HighSi materials. In this case, core losses ***P10/400 = 19.86 W/kg; J5000=1554 mT*** *and a yield strength* ***Rp02=479 MPA*** *was obtained.*

Main characteristics of the new Ti-Added materials developed within the STeELS-EM project are the following:

- *Core Losses comparable with reference materials*
- *Absence of magnetic aging effects (Carbon content of 50-60 ppm)*
- *High mechanical strength Rp02*

These materials are therefore a valid choice for EV/HEV traction motors applications.

ACKNOWLEDGEMENT

This project entitled STabilized ELectrical Steels for Electric Mobility (STeELS-EM) has received founding from the Research Fund for Coal and Steel, Grant Agreement No. 101034063.

For more info:

Thank you for your attention

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